A sound budget for the southeastern Bering Sea: measuring wind, rainfall, shipping and other sources of underwater sound

Jeffrey A. Nystuen[a)]

Applied Physics Laboratory,

University of Washington,

Seattle,

WA 98105

Sue E. Moore

NOAA Fisheries,

Office of Science & Technology,

Seattle,

WA 98115

Phyllis J. Stabeno

NOAA,

Pacific Marine Environmental Laboratory,

Seattle,

WA 98115

(Dated: April 13, 2010)

Abstract

Ambient sound in the ocean contains quantifiable information about the marine environment. A Passive Aquatic Listener (PAL) was deployed at a long-term mooring site in the southeastern Bering Sea from 27 April through 28 September 2004. This was a chain mooring with lots of clanking. However, the sampling strategy of the PAL filtered through this noise and allowed the background sound field to be quantified for natural signals. Distinctive signals include the sound from wind, drizzle and rain. These sources dominate the sound budget and their intensity can be used to quantify wind speed and rainfall rate. The wind speed measurement has an accuracy of ± 0.4 m s^{-1} when compared to a buoy-mounted anemometer. The rainfall rate measurement is consistent with a land-based measurement in the Aleutian chain at Cold Bay, AK (170 km south of the mooring location). Other identifiable sounds include ships and short transient tones. The PAL was designed to reject transients in the range important for quantification of wind speed and rainfall, but serendipitously recorded peaks in the sound spectrum between 200 Hz and 3 kHz. Some of these tones are consistent with whale calls, but most are apparently associated with mooring self-noise.

PACS numbers: 43.30.Pc

I. INTRODUCTION

There are many ocean environments where maintaining surface moorings to monitor oceanographic processes is constrained by severe weather and remote locations. The Bering Sea is one such place. The Bering Sea supports one of the largest commercial fisheries in the world and is a location where climate change is likely to have a big impact on the ecosystem[1]. To monitor the physical environment, an array of moorings has been maintained in the southeastern Bering Sea since 1995[2]. Augmenting these moorings with passive acoustic sensors compliments the suite of measurements of the physical environment, and allows monitoring of surface conditions from sub-surface moorings during all seasons. This latter capacity is especially important in high latitude regions where weather conditions are harsh, and destroy surface-mounted equipment. Bering Sea surface moorings are not maintained during the winter. Furthermore, passive acoustic sensors provide capability to monitor sound-producing biological activities, including the detection and identification of cetaceans[3]. Passive Acoustic Listeners (PALs), used in this study, are robust, proven for long-term deployment, relatively inexpensive, and subsurface, avoiding the harsh conditions and potential for vandalism at the surface[4].

In the frequency range from 200–50,000 Hertz, naturally generated sound at the sea surface is predominately produced by wind-driven breaking waves and precipitation. These physical processes generate sound principally through the production of bubbles during splashing at the ocean surface. And on the scale of individual bubbles, the sound is the resonant ring of newly formed individual bubbles within the splashes[5,6]. Because wind-driven breaking waves and raindrop splashes generate different distributions of bubbles sizes, the sound from breaking waves can be distinguished from the sound of precipitation. This allows changing physical conditions to be monitored acoustically (Fig. 1). Furthermore, the sound intensity can be used to quantify the physical processes, in particular, allowing acoustic measurements of wind speed and rainfall rate[4,7,8].

[a)]nystuen@apl.washington.edu

Beyond physical processes, there are many other sounds in the marine environment. Other important sources of underwater sound include marine mammals, especially cetaceans. Knowledge of the activities and whereabouts of many marine mammal populations is important for conservation, and yet much of this information is unknown. By using passive aquatic listening instruments, these animals can be detected, even under conditions where visual observations are infrequent or impossible. Furthermore, PALs are passive, introducing no sound into the environment themselves.

NOAA has an ongoing program known as Ecosystems & Fisheries Oceanography Coordinated Investigations (EcoFOCI) to monitor the biological, chemical and physical properties of the marine environment in Alaskan waters. One of the moorings, Site M2 at 56.87°N, 164.05°W, has been occupied since 1995[2] and during the summer of 2004, a PAL was included on the mooring. Sound sources, including wind, rain, drizzle and ships, were identified. The acoustic signal from wind, drizzle and rain is used to quantify these physical processes, allowing the sound budget for the southeastern Bering Sea to describe the relative importance of these processes. Other transient sounds are also detected including tones, whistles and bangs. Some of these sounds are consistent with marine mammal vocalizations although mooring self-noise was also evident.

The experimental setup and processing of the acoustic data are described in Section II. The results and discussion are presented in Section III, including the methodology for classifying the sound source, the acoustic wind speed measurement, rainfall detection and rainfall rate estimation, ship and transient sound detection. Section III ends with a description of the ambient sound budget during the deployment. Conclusions are presented in Section IV.

II. METHODS

A. Experimental Setup

The mooring is at Site M2 (Fig. 2) on the continental shelf in the southeastern Bering Sea in water about 70 m deep. This was a chain mooring with instruments in line and connected by shackles. The mooring includes a variety of physical oceanographic sensors, including vertical profiles of temperature, salinity and currents, plus biochemical measurements including florescence and nutrients. During the summer season, meteorological measurements such as wind vector, atmospheric pressure, relative humidity and radiation are available from surface-mounted instruments. During the winter it is impossible to maintain a surface mooring because of the harsh environment including high winds and the possibility of sea ice.

The PAL is a passive acoustic recorder that consists of a low-noise wideband hydrophone (ITC-8263), signal pre-amplifiers and a recording computer (Tattletale-8). The nominal sensitivity of this instrument is -160 dB relative to 1 V/μPa with an instrument noise equal to an equivalent oceanic background noise level of about 28 dB relative to 1 $\mu\text{Pa}^2\text{Hz}^{-1}$. Band-pass filters are present to reduce saturation from low frequency sound (high pass at 300 Hz) and aliasing from above 50 kHz (low pass at 40 kHz). The hydrophone sensitivity also rolls off above its resonance frequency, about 40 kHz. A data collection sequence takes about 15 seconds and consists of four 10.24 ms time series each separated by 5 seconds. Each of these time series is fast Fourier transformed (FFT) to obtain a 512-point (0–50 kHz) power spectrum. These four spectra are spectrally compressed to 64 frequency bins, with frequency resolution of 200 Hz from 100–3000 Hz and 1 kHz from 3–50 kHz. The PAL was deployed at 22-m depth.

B. Acoustic Data

For this deployment the PAL was designed to monitor the physical processes rather than detect and monitor marine mammals. The sounds generated from rain, drizzle or wind are generally stationary over a 15-sec time interval (background sound), whereas banging from ships or moorings, or chirps, whistles or clicks from biological sources are signals that usually are non-stationary over a 15-sec time interval (transient sounds). Thus, an important preliminary evaluation of the sound source is performed by comparing the four spectra from a single data collection sequence. A non-stationary signal between 3–15 kHz is rejected as noise, and another data sequence is collected. This is the frequency band used to quantify wind speed[7] and rainfall[4,8]. Otherwise, the four spectra are averaged into a single spectrum that is stored to computer memory for later analysis. This average spectrum is evaluated to determine the acoustic source (rain, wind or drizzle) and the source identification is used to set the time interval to the next data collection sequence. For example, if "rain" is detected, the time interval to the next data collection sequence is set to 30 sec, whereas if "wind" is detected, the time interval to the next data collection sequence is set to 5 min. This allows the PAL to conserve energy between data collection sequences, but maximizes the sampling interval during periods of rainfall when the time scale for changes is shorter.

There is a residual frequency dependent instrument sensitivity that needs to be removed from the data. This is accomplished by assuming that the signal from wind generated wave breaking is a signal with a uniform spectral slope from 1–40 kHz[4]. At low wind speeds the recorded signal includes a component from the ambient background and from instrument noise. At high wind speeds, there is a change to the spectral shape of the wind signal due to attenuation of the signal from ambient bubbles in the water. But at moderate wind speeds (4–8 $\mathrm{m\ s^{-1}}$), the sound signal is well above the background noise and has a uniform spectral slope between 1–40 kHz. The difference between the observed spectral shape and a uniform spectral slope is assumed to be the frequency dependent sensitivity correction for the PAL (Fig. 3). This procedure might remove a real small scale feature of the wind generated sound signal, but such a feature should not be present in the sound signal from a different sound source, such as rain, drizzle or ships. Thus, the correction procedure is confirmed by examining the data from other sound sources, such as rain, drizzle or ships, and observing that the spectral features of the sensitivity correction (usually smaller than 1 dB) have been removed.

An offset for instrument sensitivity has also been applied. This is accomplished by assuming that the acoustic wind speed algorithm from Ref.7 is valid. This is an empirical algorithm given by:

$$U = (10^{(\mathrm{SPL}_8/20)} + 104.5)/53.91 \quad (1)$$

where SPL_8 is the sound pressure level at 8 kHz in decibels relative to 1 $\mu\mathrm{Pa}^2\mathrm{Hz}^{-1}$. The offset at 8 kHz is chosen to minimize the mean square error of the acoustic wind speed measurements using Eqn. 1 and observed buoy anemometer wind speeds (± 0.4 m s^{-1} for this deployment).

III. RESULTS AND DISCUSSION

A. Multiple Sound Sources

The first component of using ambient sound to investigate the environment is to identify the sound source. An eight day section of data shows a typical oceanic acoustic time series including a slowing changing background sound interspersed with short loud events (Fig. 4). The background sound levels are closely correlated with wind speed and can be used to quantify it[7]. Shorter events generating sound include rain, drizzle, ship passages and chain clanks. To identify these events, a multivariate analysis using spectral components for different physical processes is applied (Fig. 5a). Sound intensities at multiple frequencies and the slope of the sound spectrum between 8–15 kHz are used in this analysis. Two of the most useful parameters, a contrast of the sound level at 8 kHz versus the sound level at 20 kHz are shown in Fig. 5b. For wind generated sound, the ratio of these two frequencies is a linear relationship for wind speeds from 3–10 m s^{-1}. Sound from rainfall contains relatively more high frequency energy and is detected by points lying above the wind-only line. In contrast, ships typically have relatively more low frequency energy and are detected as points lying below the wind line. In addition to the background physical processes, the short loud bangs, tones and whistles associated with transient sounds also have unique spectra, but are often detected by their short duration.

Validation of the acoustic source classification is difficult, as human observers are generally not present. There were several visits to the M2 mooring by a NOAA research ship that were clearly detected acoustically. The anemometer on the mooring provided verification data for wind speed measurement. These data show that the wind speed measurement is excellent when other noises are removed by classification analysis. There were no ancillary measurements of precipitation as rain gauges on buoys are notoriously difficult to maintain and are generally unreliable. However, the acoustic signal from rainfall is well known[4,8] and these spectra were observed. Spectra of tones and bangs were also present. Such transient sounds can usually be identified if a continuous underwater recording is available. An Acoustic Recording Package (ARP) deployed at M2 recorded such data[9], however the quantity of data collected proved to be overwhelming and only a portion of the ARP data have been analyzed.

B. Wind Speed

When measuring wind speed, special attention needs to be given to assure that the sound measured is due to the breaking waves from wind-generated whitecaps, and not from some other sound source. Once this is accomplished the acoustic wind speed estimate is very highly correlated with the anemometer wind speed estimate (Fig. 6). The root mean square difference is 0.4 m s^{-1}. When the wind speed is less than 3 m s^{-1}, there is no wave breaking at the ocean surface and thus there is no sound source for an acoustic wind speed measurement. In fact, the algorithm (Eqn. 1) has a minimum value of 2.2 m s^{-1}. The sound levels at 8 kHz are used in this algorithm and had to be offset -4.5 dB to achieve minimum rms error. This is assumed to be due to the instrument sensitivity offset, but also could be an indication of local sound level enhancement due to the relatively shallow water (70-m depth) of the M2 mooring location. In either case, the high correlation ($r = 0.97$) shows that wind speed can be measured acoustically, even from a “noisy” mooring.

There was good agreement between mean wind speed for each month as measured by the acoustic and buoy-mounted anemometer (Table I). Minimum mean wind occurred during July when no large weather systems were recorded and was highest in September when several high wind events occurred. A more detailed examination of the distribution of wind speeds shows two discrepancies between the acoustic and buoy-mounted anemometer measurements (Fig. 7). The acoustic measurement has relatively higher occurrence at 3 m s^{-1} because the acoustic technique does not measure any values below 2.2 m s^{-1}. Thus all of the very light wind conditions are falsely recorded as 3 m s^{-1}. More properly they should be recorded as "less than or equal to" 3 m s^{-1}. The second discrepancy is apparent above 12 m s^{-1}, where the acoustic measurements are low relative to the buoy anemometer. This discrepancy occurred during the storm on Day 269/270 (25/26 Sept.) and is likely due to absorption of sound at 8 kHz due to extensive bubble clouds stirred down into the water[10]. These results confirm that the wind speed range for Eqn. 1 is 3 m $s^{-1} < U <$ 12 m s^{-1} as predicted by Ref.7. The range of the Ref.7 algorithm can be extended to higher wind speeds by applying a modified algorithm at a lower frequency, e.g. 2 or 5 kHz, where the bubble absorption effect is lower or absent[7].

C. Rainfall Detection and Rainfall Rate Estimation

The sound generated by rainfall is loud and distinctive[8], making the detection of rainfall robust[11]. There are two distinctive spectra from precipitation because of the physics of sound generation from different sized raindrops. A small raindrop (1 mm diameter) is particularly effective at producing sound between 13–25 kHz[6,8] and larger raindrops produce sound by a different mechanism at frequencies as low as 2 kHz. Thus, drizzle, containing only small raindrops generates a distinctive sound from 13-25 kHz (Fig. 5a), while a heavier rainfall, containing raindrops larger than 2-mm diameter, produces sound as low as 1–2 kHz (Fig. 5a). The wind affects the sound generation mechanism for small raindrops and so the signal of drizzle (the peak at 13–25 kHz) becomes suppressed as the wind speed increases.

While rainfall detection is robust, validating the rainfall rate measurement is difficult, as other physical measurements of rainfall rate at sea are generally not available. Indeed, there were no ancillary measurements of precipitation available on the M2 surface mooring. Experience has demonstrated that physical collection-type rain gauges do not work well on ocean surface platforms (moorings and, especially, ships). The nearest land-based precipitation station is at Cold Bay, AK (55.2°N, 162.7°W) in the eastern Aleutian chain, roughly 170 km away. This is far enough away that one should not expect a close correlation of smaller rain events, but large atmospheric weather systems are likely to affect both locations, and the seasonal accumulations of rainfall are likely to be similar.

Acoustic quantification of rainfall rate depends on empirical algorithms developed in different marine environments and may be biased by local conditions. Two algorithms are available, from Ref.8:

$$R = 10^{(\mathrm{SPL}_5 - 50)/17} \tag{2}$$

where SPL_5 is the sound level at 5 kHz (units: decibels relative to 1 $\mu\mathrm{Pa}^2\mathrm{Hz}^{-1}$) developed in a shallow, brackish pond (2 m deep with a sandy bottom), and from Ref.4:

$$R = 10^{\left(\frac{\mathrm{SPL}_5 - 42.4}{15.4}\right)} \tag{3}$$

developed in deep water ocean moorings in the tropical Pacific Ocean. When the Ref.4 algorithm was applied in coastal waters in the Ionian Sea it was found to be biased high by 40%[11]. Fig. 8 shows the accumulation of rainfall during August using these algorithms. Also shown are the accumulation data from the National Weather Service (NWS) station at Cold Bay, AK.

The interaction of rainfall with wave breaking due to wind is not fully understood. It is a "well known" observation that rain "calms" the seas, suggesting that rain suppresses wave breaking[12] and thereby reduces the sound production by wind. However any sound generated by breaking waves, and interpreted as rain-generated sound energy, should result in an overestimation of rainfall rate[4]. This is suggested in Fig. 9 where the mode of the rainfall distribution is not at the lowest rainfall rate, which is a more typical rainfall rate distribution. To attempt to remove this wind-generated sound intensity contamination, the wind speed measurement from the buoy-mounted anemometer is used to estimate the sound intensity due to wind using Eqn. 1. This sound intensity energy is then subtracted from the observed sound intensity to estimate the sound intensity from the rain alone. The corrected sound intensity is used to estimate rainfall rate using Eqn. 3. The rainfall rate distributions using this correction are also shown in Fig. 9. The corrected accumulations are closer to the land-based observations at Cold Bay, AK (Fig. 8), suggesting that it is appropriate to make this correction.

D. Detection of Ships

Relatively few ship detections occurred during the deployment. Typically a ship passage takes tens of minutes and are identified by elevated sound in the low-frequency (200 Hz) frequency band (Fig. 10). Two types of ship passages are noted: close and distant. A close approach is presumably within 1 km of the mooring and produces noise at all frequencies monitored by the PALs and is usually very loud. The distant shipping classification category occurs during very quiet periods (calm ocean surface) and is characterized by very low high frequency sound levels and relatively high low frequency sound levels, resulting in a very steep spectral slope between 2 and 8 kHz (Fig. 5a). The exact character of the noise may or may not be stationary during a data collection sequence, and thus, the ship noise may or may not be filtered out by the PAL sampling strategy (transient rejection). Known ship visits to the mooring occurred during the deployment, especially during the period of Aug 7–10 when the *NOAA ship McArthur* was operating at the mooring (Fig. 11). The low sound levels at high frequency are due to high absorption rates for high frequency sound in the ocean and no local wind-generated sound (calm conditions). At lower frequencies, absorption is less and if the surface of the ocean is very flat allowing propagation (no propagation loss due to surface roughness) even at 2–8 kHz. Truly distant shipping (30–50 km away) detection is only likely at low frequencies (under 1 kHz) and in deeper water where acoustic propagation doesn't interact with the ocean bottom. The Bering Sea shelf is only about 70 m deep and so bottom interactions (absorption and reflections) inhibit long distant sound propagation.

E. Transient Sounds: Tones, Whistles and Banging

In addition to background sound, many short duration transient sounds were present at the mooring site. Some of these records are tones (single frequency) and others are clanks/clicks (broad band). Tones can be produced by the ringing of chain (in the mooring line) or from animals (whale calls) (Fig. 12a). In addition, killer whales are known to produce echo-location clicks centered at roughly 30 kHz. Spectra consistent with killer whale calls and clicks are shown in Fig. 12b. These transient sounds were detected and selectively filtered out the data for the frequency range from 3–15 kHz, the frequency range used for wind and rainfall measurement. However, they were not filtered out for frequencies less than 3 kHz and thus a record of low frequency tones in the sound field were recorded. The distribution of these tones shows two modes: one at 900 Hz and one at 2.8 kHz. In fact the peak at 2.8 kHz may be the edge of a distribution peak that extends above 3 kHz, but the filtering strategy of the PAL was to eliminate peaks above 3 kHz. These underwater tones are consistent with humpback and killer whales calls, respectively. These animals are known to occur near the mooring site in the southeastern Bering Sea[13,14]. To attempt to verify the source of these tones, periods containing a high numbers of transients were identified and compared to the continuous record from the ARP deployed near M2[9]. Most of the transient sounds were identified as ubiquitous chain clanking, i.e., mooring noise (Oleson, pers. comm.). However, there were some killer whale calls identified (Day 179). Future refinements to the detection algorithms for marine mammals should allow marine mammal calls and clicks to be distinguished from mooring noise (chain clanking). The sampling strategy for this deployment was designed to "listen between" transient sounds and thereby monitor the background sound field. A different sampling strategy designed to detect killer whales using PALs has been successfully demonstrated[15].

F. Sound Budgets

The goal of a sound budget is to partition the sound field into its components, and then to describe the features of those components. The sound classification step identifies various sound sources, in particular, rain, drizzle, ships and transient calls/clanking. When none of these sound sources are detected, then wind is assumed to be the dominant sound source. Within each category various statistics such as mean sound level or the sound level at a chosen frequency can be calculated, as shown in Table II, a sound budget for the month of May. Examination of these numbers points out several features of the mean sound from the different sources. In particular, the mean sound of rain is louder than wind, especially at high frequency (20 kHz), resulting in a relatively flat spectral slope between 2–20 kHz. Drizzle is only detectable at low wind speeds and thus the mean sound intensity during drizzle is low, but the sound level at 20 kHz is relatively high. Distant ships are usually detected by low sound intensity levels at high frequency (Fig. 10), but overall are much louder than rain or wind. The spectral slope between 2–20 kHz is therefore relatively steep. However, the close approach of a ship, e.g. the *NOAA ship McArthur* in August, is very loud at all frequencies. Overall, wind was the dominant sound source 93% of the time, rain was detected 4.7% of the time; drizzle 1.5% of the time and ships were present 0.4% of the time.

IV. CONCLUSIONS

The underwater ambient sound field contains quantifiable information about the physical and biological marine environment. A low-duty cycle recording instrument, e.g. a PAL, can be used to access this information and provide useful measurements of wind speed and rainfall rate. This is important as high-duty cycle instruments (continuous recorders) produce massive amounts of data that have proven difficult to analyze. In other words, it is important to be able to sub-sample the environment to effectively use the underwater ambient sound. The background ambient sound budget is easily obtained, even when the mooring has a lot of self-noise (clanking of chains, etc.) by employing a sampling strategy that rejects short transient noises associated with chain clanking and other mooring noises.

The quantitative acoustic measurements of wind speed are highly correlated to the measured wind speed measurements for the buoy-mounted anemometer for wind speeds from 3–12 m s^{-1}. Below 3 m s^{-1} the acoustic measurement has no signal (no breaking waves) and thus the distribution of wind speeds below 3 m s^{-1} can not be obtained. However, the calm conditions ($U \leq 3$ m s^{-1}) are identified and such winds result in a very low wind stress on the ocean surface. Above 12 m s^{-1}, the wind speed algorithm using 8 kHz (1) underestimates wind speed because of extensive bubble clouds in the water column as predicted by Ref.7. This condition can be identified acoustically and should be useful for predicting mixing of the upper ocean by intense storms. Furthermore, a more accurate wind speed estimate may be available by using a wind speed algorithm based on a lower frequency, e.g. 2 or 5 kHz.

The qualitative detection of rainfall is based on an understanding of the physics of sound production by raindrop splashes[6,8]. Two types of precipitation are detected: drizzle and heavier rain containing large raindrops. These spectra are observed in the data, indicating acoustic detection of drizzle, and light to moderate rainfall rates in moderate (∼4–6 m s^{-1}) to high (∼10–12 m s^{-1}) wind speed conditions. No intense downpours, such as observed in the tropical Pacific Ocean[4] were detected, although the storm on 5 August 4 had rainfall rates over 10 mm hr^{-1}. The quantitative estimate of rainfall rate is potentially contaminated by background noise due to wind wave breaking, although the role of rain to suppress wave breaking is not fully understood. While no ancillary rainfall estimates were available on the mooring, comparison to a land-based weather station at Cold Bay, AK (170 km away) showed general agreement with the acoustic rainfall accumulation statistics including the detection of major storm events and overall accumulations.

The PAL instrument will also detect ships, both distant and local, and can be modified to detect marine mammal calls[15]. Species-specific marine mammal calls can be used to identify seasonal occurrence in remote habitats[3]. The filtering strategy of the PAL for this deployment filtered out calls in the frequency range from 3–15 kHz. This frequency range eliminated most killer whale calls, a species known to occur in the southeastern Bering Sea. However, the sampling strategy did allow peaks (tones) in the spectra below 3 kHz to be recorded. The distribution of these peaks in frequency is consistent with humpback whale calls at 900 Hz and killer whale calls at 2.8 kHz. Indeed, several killer whale calls were verified on Day 179. However, the continuous recordings also revealed ubiquitous mooring noise—chain clanking, and so the verification of the transient tones within this PAL data record is uncertain. Using a different sampling strategy, PALs have proven successful at detecting killer whales[15].

The sound budget for the southeastern Bering Sea showed that wind-only sound dominated 93% of the time, with rainfall and drizzle present 4.7% and 1.5% of the time, respectively. Ships were detected only 0.4% of the time, but are the loudest events when the sound intensity is integrated over the full frequency spectrum. The mean rain signal was roughly twice as loud (3 dB) than wind overall, and especially at the higher frequencies, e.g. 20 kHz, where small raindrops produce sound underwater. In fact, at 20 kHz rain is louder than "distant" shipping. However, the approach of a ship to close range, e.g. the *NOAA ship McArthur* in August, shows that "close" shipping is responsible for the loudest sound levels at all frequencies.

Acknowledgments

This work was supported by NOAA/EcoFOCI and a grant from Navy N45 (F. Stone and E. Young). We thank the crew of the NOAA ship Freeman who deployed and recovered the M2 mooring (W. Floering and C. DeWitt), and to Erin Oleson for listening to the ARP data. This is contribution EcoFOCI-N727 to NOAA's North Pacific Climate Regimes and Ecosystem Productivity research program and contribution 3450 to the Pacific Marine Environmental Laboratory.

References

[1] G. L. Hunt, Jr., P. J. Stabeno, G. Walters, E. Sinclair, R. D. Brodeur, J. M. Napp, and N. A. Bond, "Climate change and control of the southeastern Bering Sea pelagic ecosystem", Deep-Sea Res. **49**, 5821–5854 (2002).

[2] P. J. Stabeno and G. L. Hunt, Jr., "Overview of the Inner Front and Southeast Bering Sea Carrying Capacity programs", Deep-Sea Res. **49**, 6157–6168 (2002).

[3] S. E. Moore, K. M. Stafford, D. K. Mellinger, and J. A. Hildebrand, "Listening for large whales in the offshore waters of Alaska", BioScience **56**, 49–55 (2006).

[4] B. B. Ma and J. A. Nystuen, "Passive acoustic detection and measurement of rainfall at sea", J. Atmos. and Oceanic Tech. **22**, 1225–1248 (2005).

[5] H. Medwin and M. M. Beaky, "Bubble sources of the Knudsen sea noise spectrum", J. Acoust. Soc. Am. **83**, 1124–1130 (1989).

[6] H. Medwin, J. A. Nystuen, P. W. Jacobus, L. H. Ostwald, and D. E. Snyder, "The anatomy of underwater rain noise", J. Acoust. Soc. Am. **92**, 1613–1623 (1992).

[7] S. Vagle, W. G. Large, and D. M. Farmer, "An evaluation of the WOTAN technique for inferring oceanic wind from underwater sound", J. Atmos. and Oceanic Tech. **7**, 576–595 (1990).

[8] J. A. Nystuen, "Listening to raindrops from underwater: An acoustic disdrometer", J. Atmos. and Oceanic Tech. **18**, 1640–1657 (2001).

[9] L. M. Munger, S. M. Wiggins, S. E. Moore, and J. A. Hildebrand, "North Pacific right whale (Eubalaena japonica) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea", Mar. Mamm. Sci. **24**, 795–814 (2008).

[10] D. D. Lemon, D. M. Farmer, and D. R. Watts, "Acoustic measurements of wind speed and precipitation over a continental shelf", J. Geophys. Res. **89**, 3462–3472 (1984).

[11] J. A. Nystuen, E. Amitai, E. N. Anagnostou, and M. N. Anagnostou, "Spatial averaging of oceanic rainfall variability using underwater sound: Ionian Sea rainfall experiment 2004", J. Acoust. Soc. Am. **123**, 1952–1962 (2008).

[12] J. A. Nystuen, "A note on the attenuation of surface gravity by rainfall", J. Geophys. Res. **95**, 18353–18355 (1990).

[13] S. E. Moore, J. M. Waite, N. A. Friday, and T. Honkalehto, "Cetacean distribution and relative abundance on the central-eastern and the southeastern Bering Sea shelf with reference to oceanographic domains", Prog. Ocean. **55**, 249–261 (2002).

[14] J. Hildebrand and E. Oleson, "Acoustic monitoring for killer whales in the Bering Sea", Marine Physical Laboratory (MPL) Technical Memorandum TM-494 (2007).

[15] J. A. Nystuen, M. B. Hanson, and C. Emmons, "Acoustic monitoring for killer whales in the Bering Sea", 2nd International Underwater Acoustic Measurements Conference, Heraklion, Crete, June 2007 (2007).

TABLE I. Mean wind speed by month (units are m s^{-1})

	May	**June**	**July**	**Aug.**	**Sept.**
Acoustic	5.9	5.5	4.9	5.7	6.5
Buoy	5.6	5.4	4.9	5.7	6.6

TABLE II. The sound budget during May. S_0 is the integrated sound intensity in dB rel 1 μPa and SPL_2 and SPL_{20} are the sound intensity densities at 2 and 20 kHz, respectively in dB rel 1 $\mu Pa^2 Hz^{-1}$. Each 3 dB is a doubling of sound intensity.

	Wind	**Rain**	**Drizzle**	**Distant ship**	**McArthur**
Fraction of time	.91	.03	.02	.002	–
$\mathbf{S_0}$	102	103	95	115	120
$\mathbf{SPL_2}$	60	62	49	71	78
$\mathbf{SPL_{20}}$	42	47	41	36	60

List of Figures

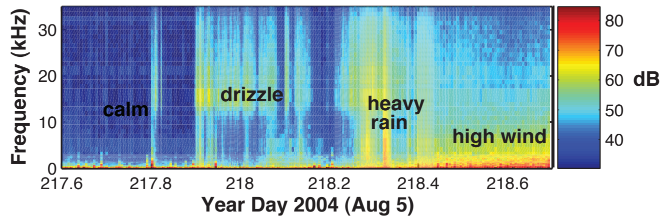

FIG. 1. The underwater acoustic record of a storm passing on August 5, 2004 (Year Day 218) at the M2 mooring in the Bering Sea. The colorized units for sound intensity are in decibels (dB) relative to 1 μPa^{2}Hz^{-1}. A period of calm is followed by drizzle, heavy rainfall and finally high winds as a strong atmospheric front crosses over the mooring location.

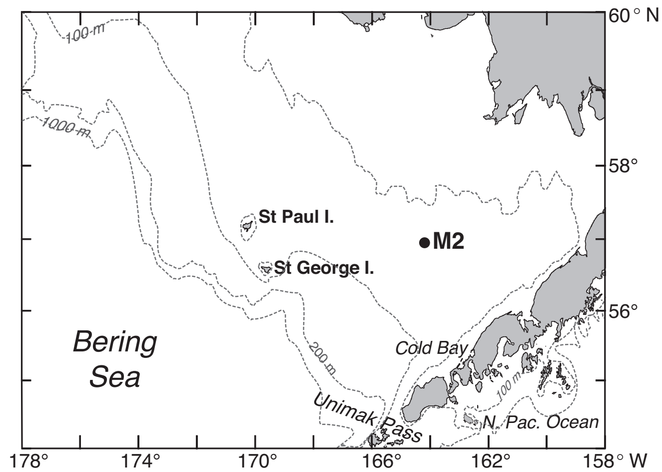

FIG. 2. The location of the Site 2 mooring (M2) is 56.87°N, 164.05°W on the continental shelf in water about 70 m deep in the southeastern part of the Bering Sea.

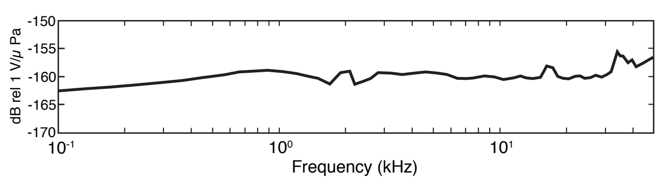

FIG. 3. Sensitivity correction for the PAL deployed at M2 during the summer of 2004. This curve has been generated by assuming that the signal from wind generated sound has a uniform spectral slope.

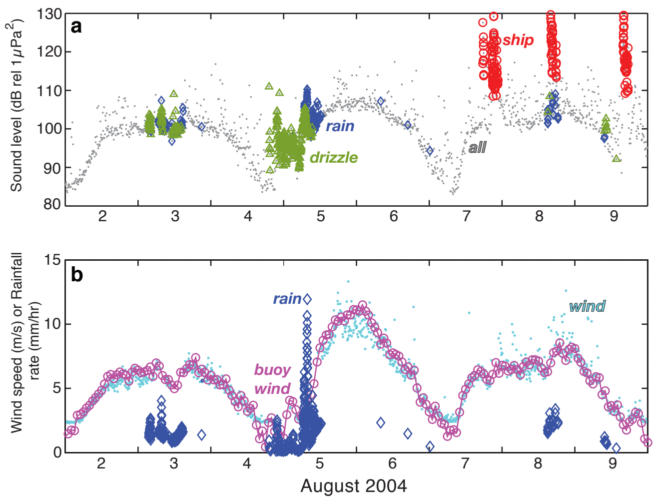

FIG. 4. A sample of the acoustic data recorded between JD 215 (Aug. 2) and JD 223 (Aug. 10). (**a**) The top panel shows the integrated sound pressure. The sound source for different points have been identified using a multivariate analysis. Note the ship passages on Days 221 and 222. (**b**) The bottom panel shows the geophysical interpretation (wind speed and rainfall rate) of the top panel. The wind speed is compared to the buoy wind anemometer.

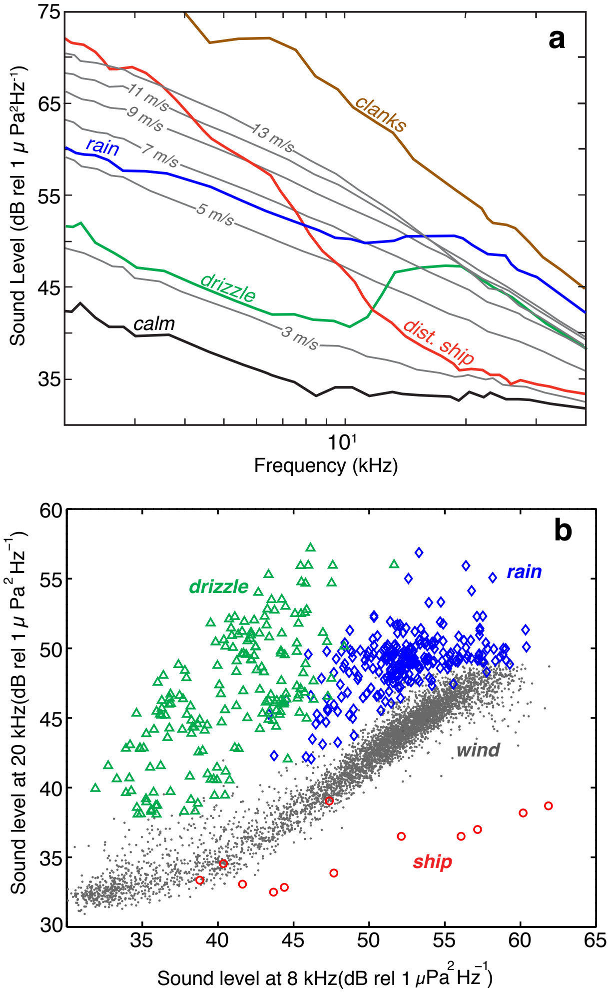

FIG. 5. (**a**) Examples of sound spectra from wind, drizzle, rain and distant ships. The spectra from different wind speeds are shown. Spectra from a drizzle on Day 141, rain on Day 218, a distant ship passage on Day 146 and clanking on Day 137 are labeled. (**b**) Scatter diagram showing the relationship between the sound level at 8 kHz and 20 kHz for the month of May. Different sound sources occupy distinctive loci on this type of diagram. Loci for wind, rain, drizzle and a distant ship (on Day 146) are shown.

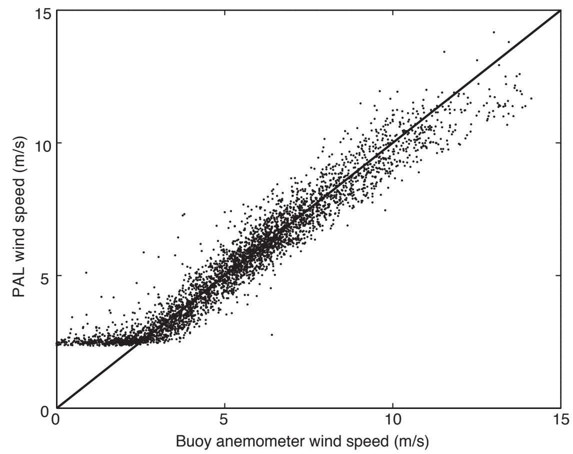

FIG. 6. Comparison of wind speed measurements from the PAL and the buoy anemometer during May.

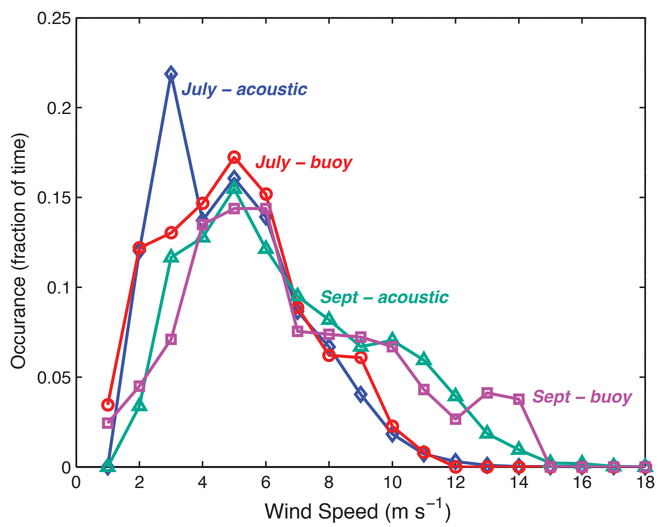

FIG. 7. Histogram showing the distribution of wind speed during July and September. The peak in the distribution at 3 m s^{-1} in July is false, and is due to the limitation of the acoustic technique to distinguish different wind speeds below 3 m s^{-1}.

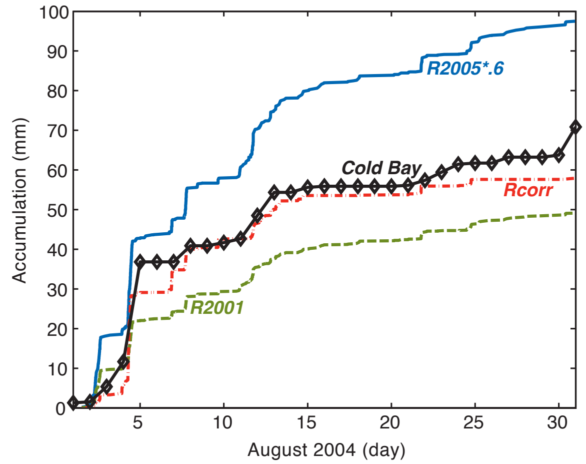

FIG. 8. The accumulation of rainfall during August and overall using Ref.[8] (R2001) and Ref.[4] (R2005). Data from Cold Bay, AK (170 km away) is also shown. Rcorr is the Ref.[4] algorithm corrected for contamination by wind noise.

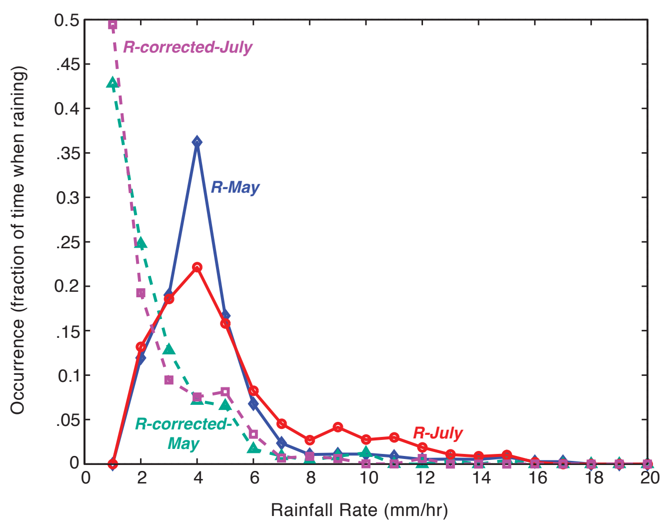

FIG. 9. The distribution of rainfall rates in May and August. The measured peak in the distribution is due to contamination (extra energy) from wind (breaking waves). When it is removed, a more typical distribution of rainfall rates shows maximum occurrence at lowest measured rainfall rates.

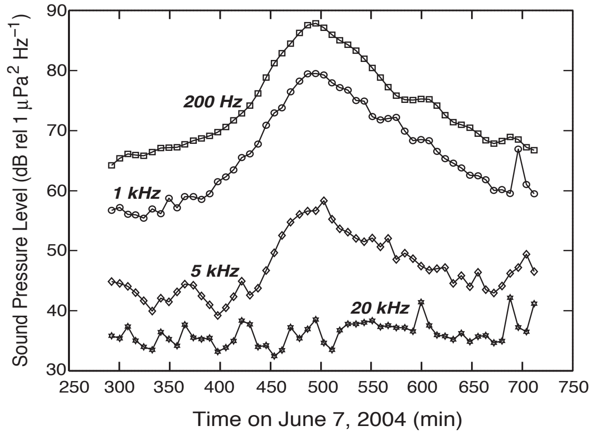

FIG. 10. Distant ship passage. The sound levels at 20 kHz are very low, indicating calm local surface conditions.

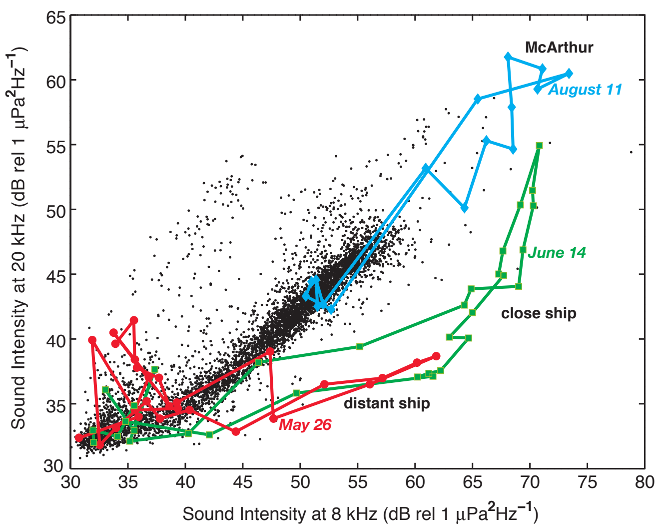

FIG. 11. Ship detections. The *NOAA ship McArthur* was operating in the vicinity of the M2 moorings on four occasions in August (Days 221/222) (also shown in Fig. 5). The black dots show typical wind, rain and drizzle data.

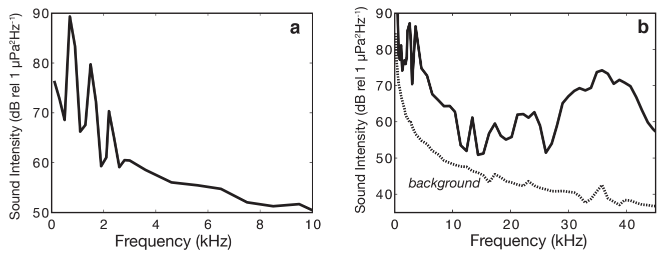

FIG. 12. Examples of transient sounds. These spectra are consistent with tones, whistles, clicks and banging. Left is a tone at 900 Hz; right is a tone at 2.8 kHz and a click at 30 kHz (consistent with killer whale calls and clicking). A background sound spectrum, during the absence of a transient sound, is shown for comparison.