SOURCES OF LONG-TERM AMBIENT OCEAN SOUND NEAR THE ANTARCTIC PENINSULA

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Abstract: *Hydrophone arrays (250–1000 Hz) were deployed within the Bransfield Strait and Scotia Sea (Antarctic Peninsula region) from 2005 to 2009 to study sources of ambient ocean sound. Icequakes, which are broadband, short duration signals derived from fracturing of large free-floating icebergs, are a prominent feature of the ocean soundscape. Icequake activity peaks during austral summer and is minimum during winter, likely following freeze-thaw cycles. Iceberg grounding and rapid disintegration also releases significant acoustic energy, equivalent to large-scale geophysical events. Overall ambient sound levels can be as much as ~10–20 dB higher in the open, deep ocean of the Scotia Sea compared to the relatively shallow Bransfield Strait. Noise levels become lowest during the low annual temperatures of the austral winter, likely due to freezing of regional sea ice of all scales. Ambient noise levels are highest during austral spring and summer, presumably due to melting and cracking icebergs. Vocalizations of blue (Balaenoptera musculus) and fin (B. physalus) whales also dominate the long-term spectra records in the 15–28 and 85 Hz bands. Blue whale call energy is a maximum during austral summer-fall in the Drake Passage and Bransfield Strait when ambient noise levels are a maximum and sea-ice cover is a minimum. Fin whale vocalizations were also most common during austral summer-early fall months in both the Bransfield Strait and Scotia Sea. The hydrophone data overall do not appear to show sustained anthropogenic sources (e.g. ships), likely due to low coastal populations and the difficult marine conditions of the Southern Ocean.*

Keywords: *ocean ambient sound, ice noise, seasonality, baleen whales*

INTRODUCTION

The climate of the Antarctic Peninsula is the most rapidly changing in the Southern Hemisphere, with a few degrees Celsius rise in both atmospheric and surface ocean temperatures over the last few decades[1-3]. Associated with this ongoing warming is a cycle of ice sheet and iceberg breakup and grounding that is accompanied by the release of acoustic energy into the Southern Ocean. Although much attention has been given to the increasing anthropogenic contributions to ocean noise, which may be as much as 12 dB over the last several decades[4], the sounds created by ice breakup at the poles may represent an underappreciated, yet significant, natural contribution to the ocean noise budget.

To study these ice-related and other sources of natural sound, we deployed arrays of hydrophone moorings in the Bransfield Strait, a protected sea along the western Antarctic Peninsula, and the Scotia Sea, an area of the South Atlantic northeast of the Antarctic Peninsula. A variety of cryogenic sounds were recorded, from iceberg grounding and breakup to sea-ice "quakes." Icequakes are impulsive broadband signals with durations between 10 and 80 sec and dominant energy over the ~10–125 Hz band. Other sources of low-frequency sound are vocalizations of large baleen whales, which dominate the 15–28 and 85 Hz frequency bands[5,6] and the waterborne acoustic phases of seafloor earthquakes[7]. The goal of this paper is to present the various sources of ambient sound in these regions and estimate long-term variability in acoustic energy levels to identify what processes characterize and influence the soundscape in this part of the Southern Ocean.

HYDROPHONE INSTRUMENTATION

In order to monitor the levels and determine the sources of acoustic energy near the Antarctic Peninsula, two arrays of hydrophone instrument moorings were deployed in the Bransfield Strait and Scotia Sea (Fig. 1). The Bransfield Strait arrays consisted of five and six hydrophone moorings deployed December 2005–2007 and November 2008–December 2009, respectively[7,8]. One hydrophone mooring was deployed in the Drake Passage, north of the Bransfield Strait, during December 2005–2006. A total of five hydrophones were deployed in the Scotia Sea from 2007 to December 2008.

The autonomous hydrophone instrument package consists of a single ceramic hydrophone, a filter/amplifier stage, an accurate clock, a low-power processor, and a battery package. The instrument is capable of recording at 16-bit data resolution between 250 and 1000 Hz (phone in Drake Passage) for periods of 1 to 2.5 years, respectively. The pre-amplifier is designed to equalize the spectra against typical ocean noise over the pass-band with an 8-pole anti-aliasing filter. A micro-processor controlled, temperature-correcting crystal oscillator with an average time drift of 400 ms yr^{-1} provided accurate timing during the typical 1–2 year deployment duration. The electronics are housed in a titanium pressure case rated for 1200 m depths. The instrument case is attached to an anti-strumming oceanographic mooring with anchor, acoustic release, mooring line, and a syntactic foam float to place the sensor at depths of 300–500 m.

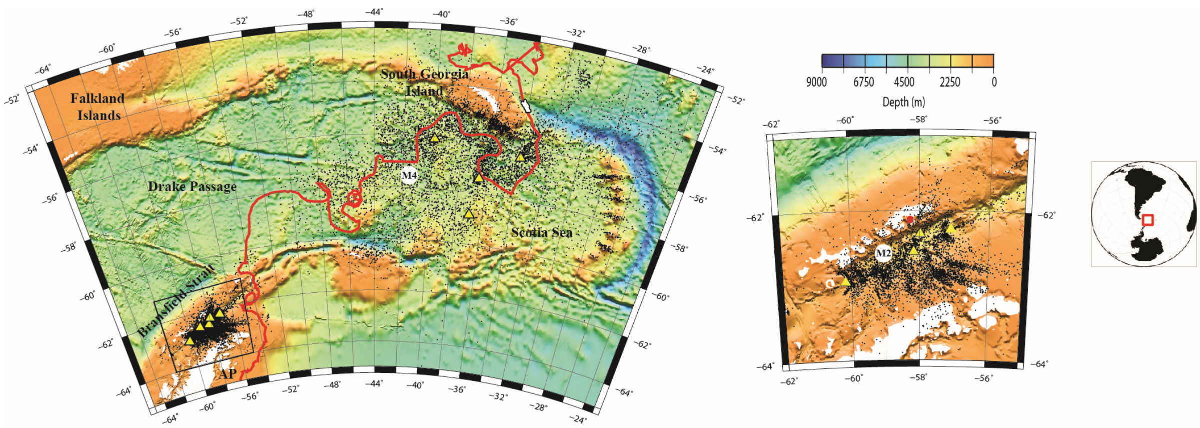

Fig.1: Maps showing icequakes (black dots) and geographic location of the Antarctic Peninsula (AP), Bransfield Strait (BS), Drake Passage (DP), and Scotia Sea. Yellow triangles show 2005–2006 hydrophone mooring deployments within the Bransfield Strait (elongated basin northwest of AP) and Drake Passage, as well as the 2006–2007 deployments within Scotia Sea. Circles M2 and M4 show locations of hydrophone moorings used to make spectrograms in Fig. 4. Red line is satellite track of iceberg A53a through arrays during early 2008. Outline of iceberg shown for scale. Red dot is location of wind station in Fig. 5.

SOURCES OF AMBIENT SOUND

Figure 2 shows the spectrograms of the most common acoustics signal sources recorded on the Bransfield Strait and Scotia Sea hydrophones, which vary from biological to geophysical to cryogenic. The signals (Fig. 2a,b) that dominate the record are the broadband acoustic arrivals of icequakes from the breakup of large-scale sea ice. Icequakes can be emergent (Fig. 2a) or impulsive and short duration (Fig. 2b), and it seems both signal types are likely due to source affects at the iceberg[9]. Figure 2c shows the fundamental frequency and harmonic overtones of tremor from a grounding iceberg. Figure 2d shows the distinct Antarctic blue whale call, characterized by a repeating 28 Hz tone plus downsweep[6]. Figure 2e shows the acoustic coda of a seafloor earthquake (referred to as a “T-wave”) with broadband signals of an airgun in the background. Lastly, Fig. 2f shows the characteristic sound created by a ship, generated by cavitation from the propeller. The sound energy level is roughly equivalent for all sources, but each varies in prevalence through the year.

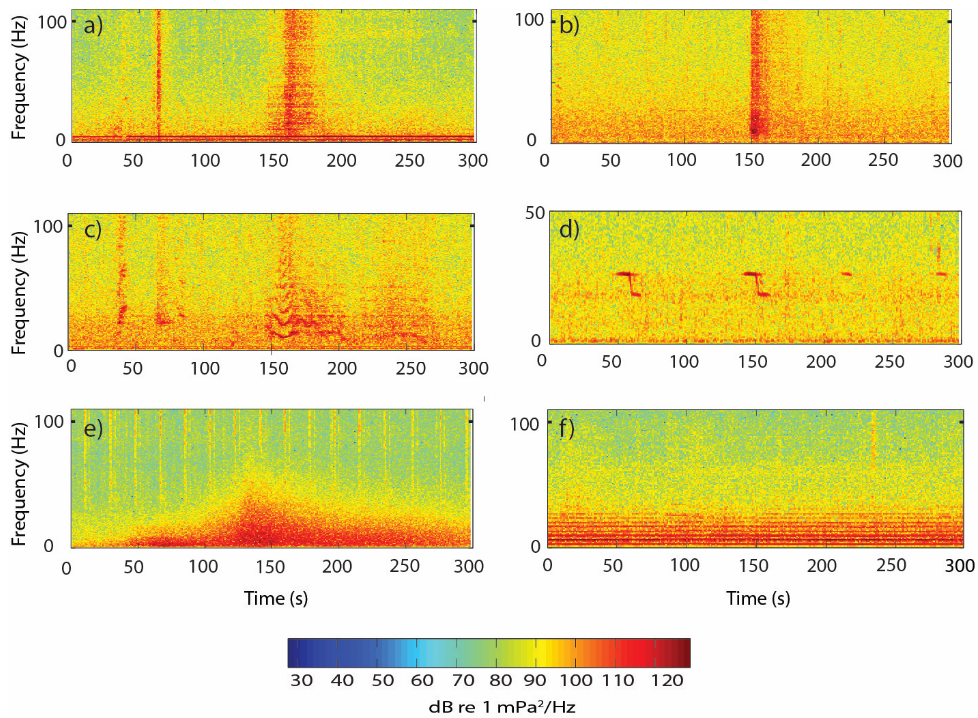

Fig.2: Spectrograms of the varied acoustics sources recorded on hydrophone arrays. (a) emergent icequake; (b) impulsive, short duration icequake, indicating that icequake may be closer to receiver; (c)) fundamental and harmonic overtones of iceberg tremor; (d) Antarctic blue whale vocalization; (e) is earthquake (T-wave) packet with broadband airgun arrivals in background; and (f) is noise from a ship, generated by cavitation from the propeller. The received sound energy levels appear roughly equivalent for all sources; however, each varies in prevalence through the year.

LONG-TERM AMBIENT SOUND SOURCES AND LEVELS

Long-term spectrograms of the acoustic power spectral density and the daily average sound levels recorded on hydrophone M2 in the Bransfield Strait and M4 in the Scotia Sea are shown in Figs. 3 and 4. Since the Bransfield array was a three-year deployment as compared to a one-year deployment in the Scotia, the signals in Fig. 3 appear much more compressed in the Bransfield spectra. For consistency in comparison, the frequency-dependent hydrophone instrument response was removed from both spectra prior to display.

From Fig. 3, overall noise levels appear to be higher in the Scotia Sea than the Bransfield Strait. The near constant, broad-band, short-duration impulsive signals present in both spectra in Fig. 3 during the austral summer to fall (December to June) are icequakes, or ice-breakup sounds, likely due to increased summer temperatures, and wind-driven ocean waves. There is also continuous, low-frequency energy present in both regions. This energy is focused under 5 Hz in the Bransfield, and under 10 Hz in the Scotia. During several periods of time, which can last from weeks to months, the energy develops into tremor-like signals with a fundamental at 1–3 Hz and several overtones. We interpret this low energy to be from a combination of sources, including broadband energy created by sea-state (storms, waves, and wind), minutes-to-hours long periods of iceberg grounding tremor, as well as periods of tonal “strumming” caused by fast moving ocean currents that make mooring line vibrate. Although the icequakes show a clear seasonal variation, this low-frequency energy remains present throughout the year. This is consistent with the idea that this energy is caused by currents, storms, and grounding icebergs that are present year-round in the Southern Ocean.

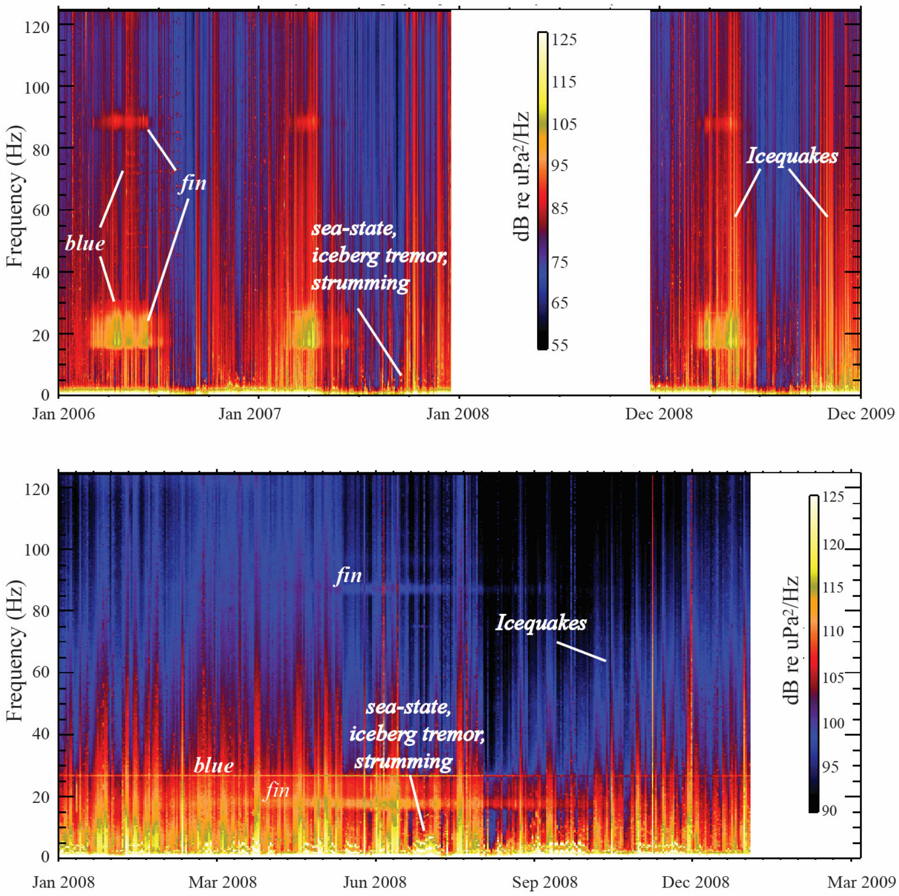

Fig.3: Long-term spectrograms of the acoustic power spectral density in units of dB re 1 $\mu Pa^2 Hz^{-1}$ at the Bransfield Strait (top) and Scotia Sea (bottom). Spectrograms are calculated from 2 second FFT windows with each vertical time slice representing the cumulative energy over a 1 day interval.

The acoustic energy focused in the 15–28 and 85 Hz bands (Fig. 3) are fin whale calls[5,10]. The steady signals within the 28 Hz band are the vocalizations of Antarctic blue whales[5,6,10], which overlap in time with fin whale calls. The blue whale vocalizations (most easily seen in the Scotia Sea data) are characterized by a long duration (~10 sec) 28 Hz tone, infrequently followed by a downsweep to 19–20 Hz[6] (Fig. 2d). However, the long-term spectrogram (Fig. 3) shows the blue whale signal energy is predominantly focused in the 28 Hz band with little downsweep energy apparent. Blue whales can also generate overtones up to 80 Hz that are occasionally seen in the spectra but are apparent during February 2006 in the Bransfield data. The fin whale vocalizations show a clear seasonality and reach a maximum during the austral fall-winter months, following the peak in icequake activity. The blue whale calls are, however, present nearly year-round (this can be most readily seen in the Scotia record), which is also consistent with the previous findings[5]. As can be seen from Fig. 3, the vocalizations of these whales are a significant, nearly continuous, component to the ambient sound field in this region.

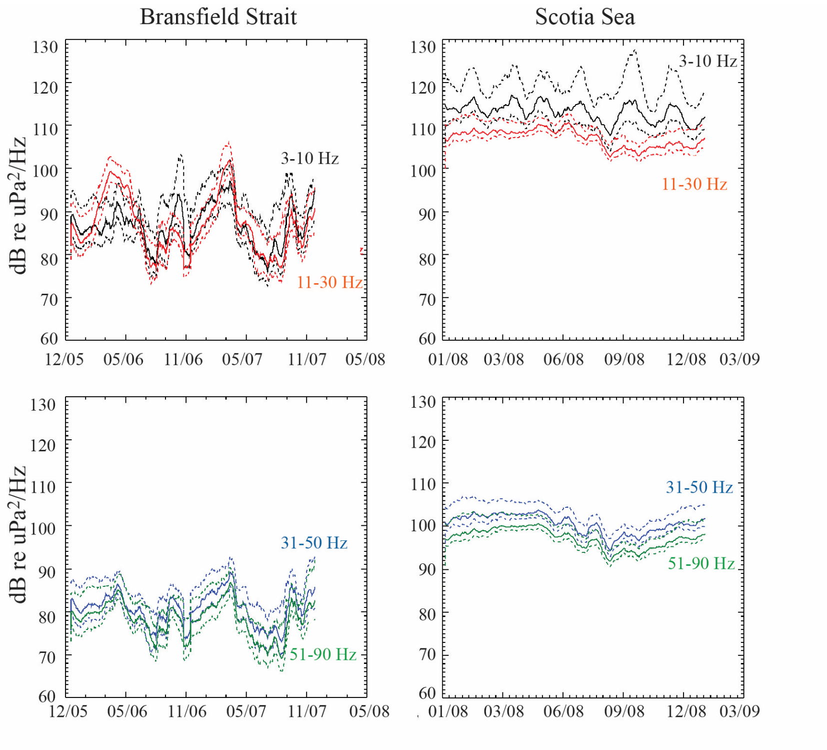

Fig. 4: Diagram shows selected percentiles from the cumulative distribution of spectral energy (daily average) recorded on hydrophone M2 in the Bransfield Strait (2005–2007) and M4 in the Scotia Sea (2008–2009). Solid line shows the dB levels of 50% of the cumulative spectral energy in the given frequency band; lower dashed line shows the dB level of 5%; and upper dashed line shows the dB level of 95% of the cumulative spectral energy.

The difference in sound levels between the Scotia Sea and the Bransfield Strait can be more clearly seen in the comparison of sound levels between the two regions in Fig. 4, which shows selected percentiles of the long-term, cumulative distribution of spectral energy (daily average) recorded on hydrophones M2 (Bransfield Strait) and M4 (Scotia Sea). The noise levels were separated into four distinct frequency bands to examine the influence of different sound sources on overall levels, with the 3–10 Hz band for iceberg tremor, and to avoid potential mooring line strumming noise (from fast ocean currents), which is <3 Hz, 11–30 Hz for blue and fin whales, 31–50 Hz for icequakes, and 51–90 Hz for a combination of icequakes and fin whale pulses. The three lines shown in Fig. 4 represent the sound level (dB) distribution for that day in each frequency band, where the solid line shows the 50%, or median, distribution, where 50% of the sound energy falls below this level during the given day. The lower dashed line is the 5% level and the upper dashed line shows the 95% level. The Scotia Sea ambient sound levels were not overlain with the Bransfield Strait data because the data sets are not time synchronous. Nonetheless, the Scotia Sea noise levels show similar seasonal variations as the Bransfield Strait and Drake Passage levels. The 51–90 Hz bands have peak energy during austral fall-winter (May–June), likely due to an increase in sea-ice cover and contributions from peak blue and fin whale vocalizations during this time. The downward trend in noise levels leading to a minimum during August (late austral winter) also mirrors the minimum levels observed in the Bransfield Strait and Drake Passage, likely due to freezing, or “locking,” of sea ice, in that it does not break apart and create sound. In contrast, all frequency bands show a significant rise in noise levels during spring-summer (September–December), possibly a result of increased ice melt due to seasonal increases in ocean and air temperatures. Even though the Bransfield Strait and Scotia Sea show similar variations in annual noise levels, the sound levels are from10 to 20 dB lower in the Bransfield than the Scotia in all frequency bands.

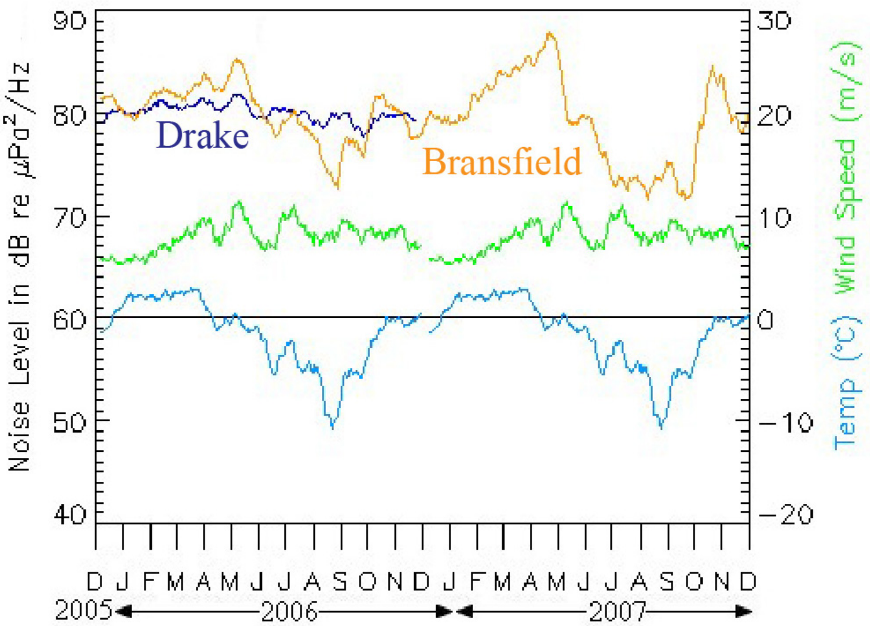

Fig. 5: Examples of ambient noise levels (averaged over 51–80 Hz) in the Bransfield Strait (yellow) and Drake Passage (light blue), air temperature (dark blue), and wind speed (green) from December 2005 to December 2007. Wind speed and air temperature were measured at King Sejong Station, on King George Island (red dot on Fig. 1).

Figure 5 shows ambient noise levels averaged over 51–90 Hz from one hydrophone in the Bransfield Strait and one in the Drake Passage. We chose this band to minimize the blue and fin whale call energy contribution, in an attempt to highlight the ambient noise levels due to ice, meteorological, and geophysical (non-biological) sources. One caveat is that this band still includes the 85 Hz fin whale overtone, which will influence ambient sound levels during peak calling months. The sound average from the Bransfield Strait and Drake Passage was then compared to the daily record of air temperature and wind speeds measured at King George Island, located between the Bransfield Strait and Drake Passage, illustrating the relationship between environmental factors and noise levels. Interestingly, ambient noise levels become lowest in the Bransfield Strait during the lowest annual temperatures of the austral winter months. Also, there is a correlation between wind speed and noise levels, although this correlation is weaker than with temperature. We interpret the low noise during this period as due to the freezing of sea ice, where little to no ice breakup is occurring. Noise levels are highest in the Bransfield Strait during austral fall, presumably when the amount of sea ice and sea-ice cover is increasing, causing more noise. The Drake Passage does not show as large a variation in noise levels as the Bransfield Strait, possibly due to its lack of extensive ice cover[11]. However, the highest noise levels in both the Bransfield Strait and Drake Passage correlate with the times of the highest recorded wind speeds during the austral fall-winter (May–September). Thus, it seems the wind induces high noise conditions by increasing wave heights[4], thereby facilitating sea-ice breakup during the fall; but as air temperatures decrease through the winter, large patches of sea ice become frozen, effecting a reduction in noise caused by ice breakup and wave action.

Although both ships and airgun (for research and/or oil exploration) sounds are occasionally present on the hydrophone data (Fig. 2e,f) we do not see a sustained contribution to the long-term noise spectra from these anthropogenic sources as is seen in the north Atlantic and European Arctic[12]. It is well established that there are much greater levels of ship traffic in the Northern Hemisphere as compared to the Southern Hemisphere[4]. The lack of ships and oil exploration in the Southern Ocean is easy to understand given the low coastal populations, generally hazardous marine weather, and presence of sea ice. The lower density of ship traffic has been used to explain the ~20 dB lower average noise levels observed at some Southern Hemisphere sites[13].

ACKNOWLEDGEMENTS

The authors thank the captain and crew of the R/V *Yuzhmorgeologiya*, and captain and personnel of the South Korean King Sejong Base, King George Island, Antarctica. This work was sponsored by the Department of Energy contract number 09NA28654, NOAA Ocean Exploration and Research Program and the Korea Ocean and Polar Research Institute, projects number 08NA28654, PE13050 and PM12020, respectively. NOAA/PMEL contribution number 4142.

REFERENCES

[1] **A.J. Cook, A.J. Fox, D.G. Vaughan, and J.G. Ferrigno**, Retreating glacier fronts on the Antarctic Peninsula over the past half-century, *Science*, 308, pp. 541–544, 2005.

[2] **E. Domack, D. Duran, A. Leventer, S. Ishman, S. Doane, S. McCallum, D. Amblas, J. Ring, R. Gilbert, and M. Prentice**, Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch, *Nature*, 436, pp. 681–685, doi: http://dx.doi.org/10.1038/nature03908, 2005.

[3] **M.P. Meredith and J.C. King**, Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century, *Geophysical Research Letters*, 32, L19604, doi: http://dx.doi.org/ 10.1029/2005GL024042, 2005.

[4] **J. Hildebrand**, Anthropogenic and natural sources of ambient noise in the ocean, *Marine Ecology Progress Series*, 395, pp. 5–20, 2009.

[5] **A. Širović, J.A. Hildebrand, S.M. Wiggins, M.A. McDonald, S.E. Moore, and D. Thiele**, Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula, *Deep-Sea Research II*, 51, pp. 2327–2344, 2004.

[6] **S. Rankin, D. Ljungblad, C. Clark, and H. Kato**, Vocalisations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001/2002 and 2002/2003 IWC/SOWER circumpolar cruises, Area V, Antarctica, *Journal of Cetacean Research and Management*, 7, pp. 13–20, 2005.

[7] **R.P. Dziak, M. Park, W.S. Lee, H. Matsumoto, D.R. Bohnenstiehl, and J.H. Haxel**, Tectonomagmatic activity and ice dynamics in the Bransfield Strait back-arc basin, Antarctica, *J. Geophys. Res.*, 115, B01102, doi: 10.1029/2009JB006295, 2010.

[8] **H. Matsumoto, R. Dziak, M. Park, T.-K. Lau, W.-S. Lee, D. Bohnenstiehl, J. Haxel, K. Stafford, and D. Mellinger**, Sound of climate change: Anthropogenic impact to the world oceans, In *Scientific Committee Antarctic Research: Antarctic*

Science and Policy Advice in a Changing World, Session 6 (abstract), July 16–19, 2012, Portland, Oregon, 2012.

[9] **K. Warren**, Underwater acoustic energy generated by icebergs in the Scotia Sea. M.S. Thesis, North Carolina State University, 100 pp., http://repository.lib.ncsu.edu/ir/handle/1840.16/7365, 2011.

[10] **A. Širović, S.M. Wiggins, and J.A. Hildebrand**, Blue and fin whale call source levels and propagation range in the Southern Ocean, *Journal of the Acoustical Society of America*, 122, pp. 1208–1215, 2007.

[11] **E. Rignot, J. Bamber, M.R. van den Broeke, et al.**, Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, *Nature Geoscience*, 1, pp. 106–110, 2008.

[12] **H. Klinck, S.L. Nieukirk, D.K. Mellinger, K. Klinck, H. Matsumoto, and R.P. Dziak**, Seasonal presence of cetaceans and ambient noise levels in polar waters of the North Atlantic, *Journal of the Acoustical Society of America–Express Letters*, 132(3), doi:http://dx.doi.org/10.1121/1.4740226, 2012.

[13] **D.H. Cato**, Ambient sea noise in waters near Australia, *Journal of the Acoustical Society of America*, 60, pp. 320–328, 1976.