Life and Death Sounds of Iceberg A53a

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Atmospheric and surface ocean temperatures in the Antarctic Peninsula region have increased by a few degrees Celsius over the last few decades, and they are the most rapid changes recorded in the Southern Hemisphere during this time period (Cook et al., 2005; Meredith and King, 2005). Associated with this ongoing warming are ice-sheet breakup, iceberg calving, and subsequent iceberg grounding that are 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 few decades (Hildebrand, 2009), the sounds created by ice breakup at the poles may represent an underappreciated, yet significant, natural contribution to the ocean noise budget.

Previous acoustic studies have tracked the paths of drifting icebergs and characterized the sounds generated when they run aground (Scambos et al., 2003; Muller et al., 2005; Martin et al., 2010); however, it is unusual to record the sound of an iceberg breaking apart in the open ocean. Here, we present the hydroacoustic signals of iceberg A53a as it disintegrated. We used an array of underwater hydrophones (250–1,000 Hz sample rate) deployed in the Scotia Sea and Bransfield Strait off Antarctica to record the full life-cycle sounds of this iceberg, from grounding harmonic tremor (HT) to "icequakes" that occurred as it melted and broke apart (Figure 1). These recordings permit an assessment of the sound energy levels projected into the marine environment by a disintegrating iceberg.

During April–June 2007, the iceberg A53a (~ 55 × 25 km) drifted out of the Weddell Sea and through Bransfield Strait (Figure 1A). Hydrophones first detected HT from A53a (Figure 1B) when it encountered a 124 m deep shoal, which caused the berg to rotate 192°. At this time, it began generating six days of semicontinuous HT as it ground across the seafloor (Figure 1A, position 1). The iceberg then entered Bransfield Strait where it became fixed over a 265 m deep shoal and began to pinwheel (Figure 1A, position 2). The HT became shorter in duration (40–60 s) in this area. The tremors' fundamental frequencies, overtone spacings, and signal lengths are a direct function of the size and duration of the ice-seafloor contact and the speed of the iceberg as it is driven by wind and ocean currents (Martin et al., 2010). At both locations, it seems likely that periodic, discrete stick-slip bursts caused by contact of the moving iceberg with the seafloor generated the iceberg tremors rather than resonant vibration (Macyeal et al., 2008; Winberry et al., 2013). The approximate keel depth of iceberg A53a is also given by the depth of the seafloor at these locations, and it seems keel depths vary significantly along the iceberg's 60 km length.

The iceberg then drifted north during July 2007 into the Scotia Sea, and it began to melt in the warmer waters (Jansen et al., 2007). Photos taken from the International Space Station on January 15, 2008, show visible melt ponds on the surface of the iceberg (Figure 1A,

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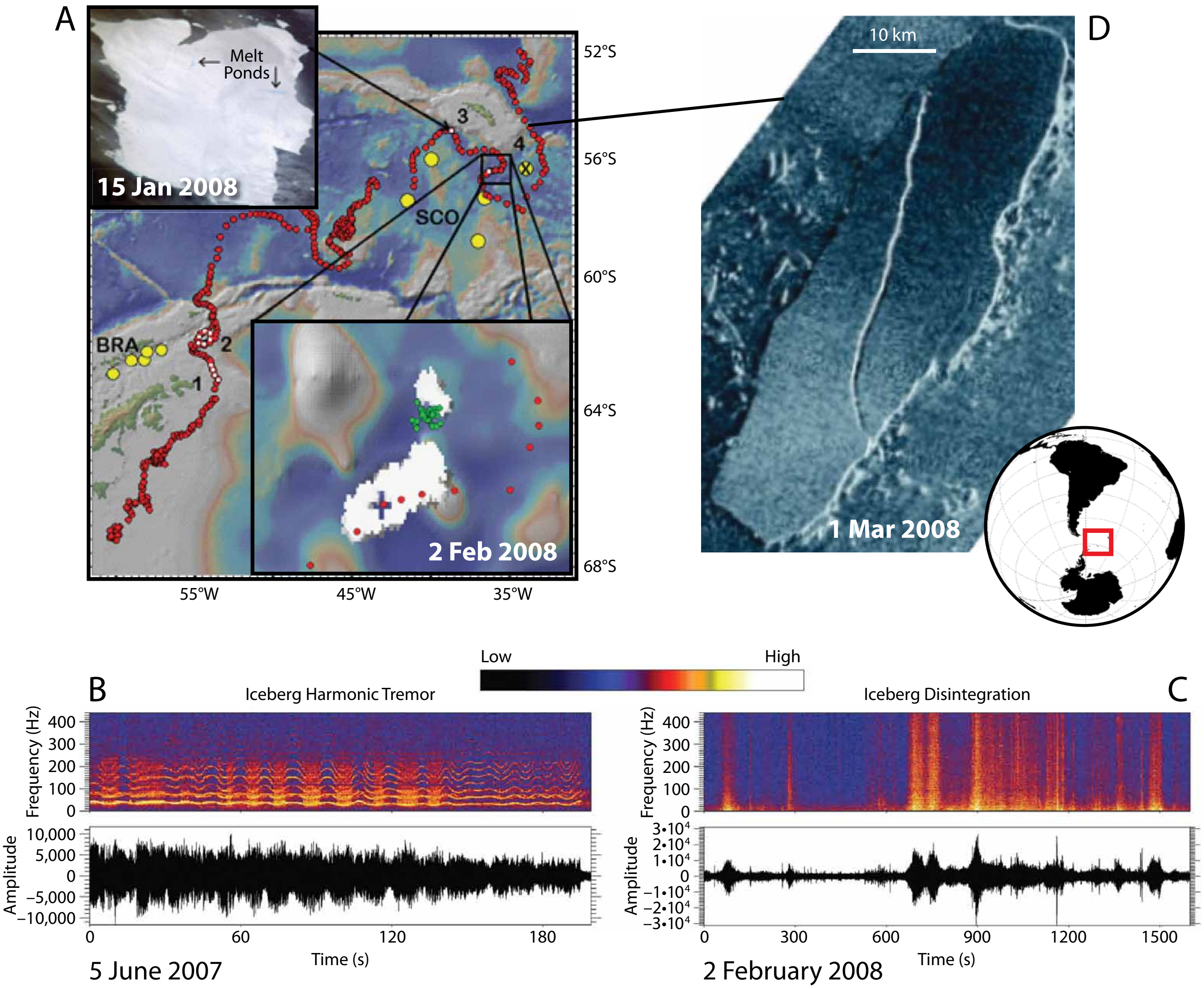

Figure 1. (A) Daily position of iceberg A53a (red dots) in Bransfield Strait (BRA) and the Scotia Sea (SCO) near South Georgia Island observed using NASA's QuikSCAT satellite backscatter images (BYU Scatterometer Climate Record Pathfinder; http://www.scp.byu.edu). Hydrophone locations are shown as yellow dots. Positions (1) and (2) show iceberg locations where harmonic tremor was observed, with the exact sites where tremor was produced highlighted by white dots. Top left inset is an image of iceberg A53a on January 15, 2008, from the International Space Station, with blue melt ponds visible. (3) Location of the iceberg when these melt ponds were seen. The bottom right inset is a QuikSCAT image of A53a after the breakup event on February 2, 2008, showing hydrophone locations of icequake sounds (green dots). (4) Iceberg location during the breakup event. (B) Example spectrogram and time series of harmonic tremor from position 2 (see map in A). The fundamental frequency is 40 Hz, with 40 Hz overtone spacing. As many as 15 overtones are visible in the spectra. (C) Spectrogram and time series of the February 2, 2008, icequake and breakup events recorded on the northeast Scotia hydrophone (farthest east yellow dot with "X" in A). Note signal duration is significantly longer than the example shown in B. (D) Satellite image showing a large fracture forming in iceberg A53a as it approaches South Georgia following the major breakup events on February 2, 2008 (http://www.esa.int/ESA). Inset global map shows the location of the study area.

top left inset). The presence of melt ponds indicates it had entered a period of rapid disintegration (Scambos et al., 2003; e.g., Figure 1D); indeed, within two months, the iceberg broke apart and was no longer being tracked via satellite. However, because it disintegrated within the hydrophone array aperture, the acoustic signature of the iceberg breaking apart while adrift could be identified. These disintegration sounds (Figure 1C), or icequakes, are short-duration, broadband signals (from 1–440 Hz) generated by ice cracking and crack propagation (similar to earthquake processes) and are clearly distinct from the harmonic tremor (Martin et al., 2010).

The icequake sounds (Figure 1C) averaged ~ 220 dB-rms re 1 μPa @ 1 m, yielding a total energy flux density of 252 dB μPa^2-sec over the ~ 20 minute duration of the entire sequence (see Methods below). This energy flux density, which is just a fraction of the total acoustic energy released during the life of this iceberg, is equal to an energy release of 6.9×10^7 Joules or the equivalent sound energy of ~ 214 supertankers operating over this same 20 minute time period. These totals demonstrate that sound from ice breakup in the Southern Ocean can be significantly greater than anthropogenic noise sources and thus are a major contributor to the overall ocean noise budget. Moreover, the acoustic output from these massive bergs may have unrecognized impacts on marine animals, many of which use sound to facilitate life-sustaining activities such as feeding, breeding, and navigation. Studies indicate these ice sounds propagate over long distances (thousands of kilometers) in the ocean (e.g., Talandier et al., 2002; Chapp et al., 2005), and tremors from near the Antarctic Peninsula are readily detected at the equator (Matsumoto et al., 2012). Thus, it is important to continue acoustic monitoring of the breakup of Antarctic ice shelves to understand how spatially and ecologically widespread their impact is on the global ocean.

METHODS

The decibel energy flux density (EFD) of the icequake signals are estimated by adding their decibel acoustic source levels (SL) to $\log_{10}$ of the total signal duration T in seconds (Warren, 2011):

$$EFD_{dB} = SL_{dB\text{-}rms} + 10 \log_{10}(T) \qquad (1)$$

Source level for each ice breakup event in Figure 1C was estimated by taking the received acoustic signals at each hydrophone, removing the hydrophone gain, then adding in acoustic transmission loss along the signal path from source to receiver. The amount of energy released in Joules is estimated from the EFD (expressed here in linear units of Pa^2-sec) using the relation

$$\text{Energy (Joules)} = 2\,\pi/\rho c\,[EFD], \qquad (2)$$

where r and c are the density (1,000 kg m^{-3}) and velocity (1,500 m s^{-1}) of seawater, respectively. The equivalent supertanker energy calculation assumes a continuous wave source with a bandwidth of 5–100 Hz and 195 dB_{rms} re 1 μPa^2 @ 1 m source level (Hildebrand, 2009). The acoustic pressure recorded on a hydrophone is a time history of ocean pressure perturbations (ΔP) relative to background ocean pressure at the recording water depth. These excess ocean sound pressures are usually small (~ 10^{-2} Pa), and it has been the standard in the ocean acoustic literature to express sound pressure in log-scale decibels (dB) relative to a reference pressure (P_o) of 1 μPa (Urick, 1975). Moreover, it is convention to use 1 m as the reference distance (r_o) when calculating the acoustic pressure of the source.

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REFERENCES

Chapp, E., D.R. Bohnenstiehl, and M. Tolstoy. 2005. Sound-channel observations of ice-generated tremor in the Indian Ocean. *Geochemistry Geophysics Geosystems* 6, Q06003, http://dx.doi.org/10.1029/2004GC000889.

Cook, A.J., A.J. Fox, D.G. Vaughan, and J.G. Ferrigno. 2005. Retreating glacier fronts on the Antarctic Peninsula over the past half-century. *Science* 308:541–544, http://dx.doi.org/10.1126/science.1104235.

Hildebrand, J. 2009. Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series* 395:5–20, http://dx.doi.org/10.3354/meps08353.

Jansen, D., M. Schodlok, and W. Rack. 2007. Basal melting of A-38B: A physical model constrained by satellite observations. *Remote Sensing of Environment* 111:195–203, http://dx.doi.org/10.1016/j.rse.2007.03.022.

MacAyeal, D.R., E.A. Okal, R.C. Aster, and J.N. Bassis. 2008. Seismic and hydroacoustic tremor generated by colliding icebergs. *Journal of Geophysical Research* 113, F03011, http://dx.doi.org/10.1029/2008JF001005.

Martin, S., R. Drucker, R. Aster, F. Davey, E. Okal, T. Scambos, and D. MacAyeal. 2010. Kinematic and seismic analysis of giant tabular iceberg breakup at Cape Adare, Antarctica. *Journal of Geophysical Research* 115, B06311, http://dx.doi.org/10.1029/2009JB006700.

Matsumoto, H., R. Dziak, M. Park, T.-K. Lau, W.-S. Lee, D. Bohnenstiehl, J. Haxel, K. Stafford, and D. Mellinger. 2012. Sound of climate change: Anthropogenic impact to the world oceans. Poster presented at Scientific Committee Antarctic Research: Antarctic Science and Policy Advice in a Changing World, Session 6, July 16–19, 2012, Portland, OR.

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

Muller, C., V. Schlindwein, A. Eckstaller, and H. Miller. 2005. Singing icebergs. *Science* 310:1,299, http://dx.doi.org/10.1126/science.1117145.

Scambos, T.A., C. Hulbe, and M.A. Fahnestock. 2003. Climate-induced ice shelf disintegration in the Antarctic Peninsula. Pp. 79–92 in *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives*. E. Domack, A. Leventer, A. Burnett, R. Bindschadler, P. Convey, and M. Kirby, eds, Antarctic Research Series, vol. 79, American Geophysical Union, Washington, DC, http://dx.doi.org/10.1029/AR079p0079.

Talandier, J., O. Hyvernaud, E.A. Okal, and P.-F. Piserchia. 2002. Long range detection of hydroacoustic signals from large icebergs in the Ross Sea, Antarctica. *Earth and Planetary Science Letters* 203:519– 534, http://dx.doi.org/10.1016/S0012-821X(02)00867-1.

Urick, R.J. 1975. *Principles of Underwater Sound*. Kingsport Press, 384 pp.

Warren, K. 2011. 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?mode=full.

Winberry, J.P., S. Anandakrishnan, D.A. Wiens, and R.B. Alley. 2013. Nucleation and seismic tremor associated with the glacial earthquakes of Whillans Ice Stream, Antarctica. *Geophysical Research Letters* 40:312–315, http://dx.doi.org/10.1002/grl.50130.