Sound-channel observations of ice-generated tremor in the Indian Ocean

Emily Chapp  
Lamont-Doherty Earth Observatory of Columbia University, P.O. Box 1000, Palisades, New York 10964, USA  
Now at Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawaii, 1680 East-West Road, Honolulu, Hawaii 96822, USA (chapp@soest.hawaii.edu)  

DelWayne R. Bohnenstiehl and Maya Tolstoy  
Lamont-Doherty Earth Observatory of Columbia University, P.O. Box 1000, Palisades, New York 10964, USA

[1] Mid to low southern latitude hydrophone stations within the Indian Ocean have recorded two distinct types of low-frequency (<100 Hz) tremor that can be correlated with drifting icebergs and glacial features along the Wilkes Land coast of eastern Antarctica. The most common of these signals is a variable harmonic tremor (VHT), with spectral peaks that exhibit frequency fluctuations through time. These signals typically display a 4 to 10 Hz fundamental frequency and may have as many as ten harmonic bands. Individual VHT signal packets have durations of up to ~30 min and occur throughout the year in clusters that continue for hours to days. A second, less commonly observed signal is characterized by shorter duration (25 to 90 s) pulses with a convex-upward spectrogram appearance. These cusped pulse tremors (CPT) often exhibit a near-uniform pulse spacing, with episodes continuing for minutes to hours. Tremor received levels at hydrophones near 32°S, 114°E and 7°S, 72°E reach as high as 142 and 133 dB re 1 μPa (peak to peak), respectively. Propagation likely occurs as a sea surface–reflected phase at high latitudes and a sound channel phase north of the convergence zone, with low-frequency transmission loss estimates suggesting maximum acoustic source levels of ~245 dB re 1 μPa at 1 m. Source locations for a subset of the loudest VHT signals correlate with the satellite-derived locations of a large iceberg (B-15D) that migrated westward along the Wilkes Land shelf region during 2002 and early 2003. Most VHT sources, however, cannot be correlated with known iceberg locations, suggesting that these signals also may be sourced from smaller unnamed icebergs and/or associated with outlet glaciers distributed along the Wilkes Land coast. CPT signals have a more limited spatial distribution, originating from five specific regions where ice streams are observed. The harmonic nature of both signal types is consistent with the resonance of an ice layer or fluid-filled cavity within an ice mass.

Components: 7377 words, 9 figures, 1 table.  
Keywords: Antarctica; hydroacoustics; tremor.  
Index Terms: 3099 Marine Geology and Geophysics: General or miscellaneous; 4259 Oceanography: General: Ocean acoustics; 9310 Geographic Location: Antarctica (4207).

Received 30 November 2004; Revised 21 March 2005; Accepted 23 March 2005; Published 7 June 2005.

1. Introduction

[2] Shallow submarine volcanic eruptions can produce tremor signals that couple efficiently into the ocean’s low-velocity sound channel [e.g., Talandier and Okal, 1987; Dziak and Fox, 2002]. Both island-based seismic stations and moored hydrophones have recorded these signals, which exhibit a diverse suite of broadband, monochromatic and polychromatic spectral properties. In late 2000, island-based seismic stations belonging to the Polynesian Seismic Network recorded ice-generated noises associated with drifting icebergs within the Ross Sea [Talandier et al., 2002]. The spectral characteristics of these signals resembled those of previously identified volcanic tremor, exhibiting a 4 to 7 Hz fundamental frequency with multiple overtones; however, the spatial and temporal distribution of the signals correlated closely with recently calved and drifting icebergs. Talandier et al. [2002] proposed that the source of these tremors was the resonance of a large iceberg or fluid filled cavity within the ice mass. As the signals were only recorded when the iceberg remained on the shallow bathymetric shelf, they suggested that excitation of the resonator could be driven by the scraping of the iceberg across the seafloor.

[1] Three International Monitoring System (IMS) hydroacoustic stations, Diego Garcia North (DGN or H08N), Diego Garcia South (DGS or H08S) and Cape Leeuwin (CL or H01W) have been monitoring the Indian Ocean Basin since the beginning of 2002 (Figure 1). Each site has a triad of hydrophones moored ~2 km apart and floated within the SOund Fixing And Ranging (SOFAR) channel. Analysis of these data has identified reoccurring ice-generated tremor signals at both the CL and the DGS hydrophone stations, which provide unblocked paths to the Wilkes Land section of the eastern Antarctic coast (85°E to 149°E longitude). Location analysis of the tremor signals and available ground-truth information provided by satellite imagery suggest these signals may be associated with a diverse set of environments, including drifting icebergs, outlet glaciers and ice streams.

[3] With respect to spectral content and duration, these signals are the most diverse hydroacoustic arrivals observed within the 1 to 100 Hz frequency range for the Indian Ocean, and their prevalence may make them a significant contributor to the ambient noise within the basin. Below we characterize their signal properties and describe their spatial and temporal associations with Antarctic ice. Relative to previous observations using island-based seismometers [e.g., Talandier et al., 2002], IMS hydrophone-based observations allow for characterization at somewhat higher frequencies of up to ~100 Hz. Moreover, the location of the IMS sensors within the oceanic water column avoids the complexity associated with acoustic-to-seismic conversion along a submerged island slope [e.g., Talandier and Okal, 1998] and allows us to better constrain the acoustic source levels of these signals.

2. Signal Detection and Identification

[5] IMS hydrophone stations DGN (6.3°S, 71.0°E), DGS (7.6°S, 72.5°E) and CL (34.9°S, 114.1°E) were deployed in support of the Comprehensive Test Ban Treaty and designed to detect the sounds generated by explosions that may be carried out at or below the ocean surface [e.g., Okal, 2001]. The data used in this study were made available in support of a broader project of Indian Ocean noise characterization, under contract from the Defense Threat Reduction Agency. The northern two stations DGN and DGS are located ~180 km to the northwest and ~25 km to the south of the Diego Garcia island atoll, respectively. The CL station is located ~100 km to the southwest of the Australian coast (Figure 1). The stations consist of three hydrophones deployed in a triangular configuration (triads) with approximately 2 km spacing between instruments. Hydrophone sensors are moored to the seafloor and floated near the sound channel axis, where they record continuously at a sample rate of 250 Hz and 24-bit A/D resolution. The system’s pressure response is flat to within 3 dB over the frequency range ~3–100 Hz.

[6] Hydrophone data were inspected visually using a software interface originally developed for the analysis of regional hydrophone array data [Fox et al., 2001]. This software displays both signal traces and spectrograms, which can be scrolled through time. The occurrence of tremor signals was flagged by an analyst, with the arrival times, station name and descriptive comments saved. Available data between January 2002 and May 2003 are examined in this study.

[7] Tremor was observed to be most prevalent and exhibited the largest amplitude at the most southerly station CL. Tremor signals with the loudest
received levels at CL could also be identified at station DGS, where they arrived with a relative delay of 35 to 50 min, suggesting a source region within the southern Indian Ocean. These signals could not be clearly identified at station DGN, as the shallow bathymetry of the Diego Garcia atoll blocks hydroacoustic paths from many southern azimuths. Unless otherwise noted, the received levels of the tremor signals are characterized using the maximum peak-to-peak amplitude within the signal packet, reported in decibels (dB) relative to a reference value of 1 \( \mu \text{Pa} \).

3. Location Analysis

3.1. Azimuthal Constraints From Hydrophone Triads

To localize the source regions of the hydroacoustic tremor, travel time differences between each pair of hydrophones \( (t_{ij}) \) within a station’s triad were derived from the cross correlation of the signal arrivals. These delay times were used in a plane wave fitting inversion to determine the horizontal slowness components \( (p_x, p_y) \) and estimate the back-azimuth to the source region \([\text{e.g., Del Pezzo and Giudicepietro, 2002}]\). This relation between the time delay and horizontal slowness can be expressed as the dot product \( t = p \cdot \Delta \) and solved in a least squared sense:

\[
p = (\Delta^T \Delta)^{-1} \Delta^T t.
\]

where \( \Delta \) describes the geometric position of the hydrophone sensors, and \( T \) indicates the matrix transpose. The velocity \( (v) \) and azimuth \( (\alpha) \) are then given as \( v = 1/|p| \) and \( \alpha = \tan^{-1}(p_x/p_y) \). When \( \alpha \) can be determined at both the CL and DGS stations, the projection of these azimuthal pairs provides a method for locating the signal source region.

As the sound velocity in the vicinity of the mid-latitude to low-latitude arrays is well constrained, the slowness value returned by the inversion, along with the correlation coefficient between instruments, can be used to assess the quality of the azimuthal estimates. The former is particularly useful for purely harmonic signals with correlation functions that exhibit significant structure. To quantify the error in these azimuthal calculations, well-located earthquakes at distances of 130 to 3500 km were used as reference sources \([\text{e.g., Hanson and Givens, 1998}]\). The angular differences between the estimated and predicted azimuths of these plane wave arrivals were com-
puted using a suite of 27 signals at DGS and 34 signals at CL. The standard deviations of the misfits are 1.51 ° and 1.26 ° at the respective stations. These errors are taken to represent the 1-σ limits in our azimuthal calculations. We acknowledge, however, that additional azimuthal uncertainty may arise due to the differences in the waveform and spectral characteristics between ice-generated noise and seismically generated T waves.

3.2. Differential Travel Time Constraints

[10] The absolute arrival time information from the two stations, DGS and CL, are insufficient to invert for the location and origin time of the tremor signals; however, the set of all possible source locations that satisfy the observed arrival-time differences (ΔT) between these distant stations can be defined. To evaluate the consistency of our azimuthal locations with the ΔT observations, we consider the simple case of a uniform propagation medium with constant velocity (v), which is taken to represent the mean group velocity from a Wilkes Land source to the IMS stations. The differential arrival time between the stations is then given by the following relationship:

\[ ΔT = \frac{d_{DGS} - d_{CL}}{v}, \]  

where \( d_{DGS} \) and \( d_{CL} \) are the distance between the source location and the receiving hydrophones.

[11] The points satisfying equation (2) were found with a grid search method using a 3-by-3 km node spacing. For each arrival time pair, this generated a curve defined by a set of points for which the same ΔT values are predicted due to the trade off between location and origin time. Assuming a propagation velocity of 1.475 km/s, a reasonable average for a signal whose path originates south of the convergence zone, resulted in the best overall consistency between the azimuthal locations and the ΔT curves, with each of these curves passing through the error field of the azimuthally derived location. As not all signals are well recorded on the more distant DGS station, azimuthal crossings and ΔT information can only be used to locate a subset of the signals observed.

4. Variable Harmonic Tremor (VHT) Observations

4.1. VHT Signal Characterization

[12] The dominant tremor type observed at the DGS and CL stations consists of multiple harmonic bands with spectral peaks that fluctuate in frequency through time, hereinafter referred to as Variable Harmonic Tremor (VHT) (Figure 2). These tremors are comparable to the iceberg-related signals observed by Talandier et al. [2002] at lower frequencies (<16 Hz) using Polynesian seismic stations. Our sound-channel based observations indicate a fundamental frequency that is typically within the 4 to 10 Hz range (Figures 2b and 2e), but can reach as high as 30 Hz in some instances (Figure 2b, right column). As many as ten spectral bands can be seen in some tremor packets, with significant power above 80 Hz (Figure 2, middle column). VHT signal packets can persist continuously for ~1 to 30 min, and their occurrence is spatially clustered with periods of activity lasting from hours to days.

[13] As illustrated in Figures 2a and 2b, VHT signals commonly exhibit abrupt onsets and terminations, and in some instances these polychromatic signals evolve from or into a continuous monochromatic signal or broadband noise. Within a signal packet, azimuthal estimates do not change significantly through time, despite changes in the spectral character of the signal (Figure 2c). This suggests that these various portions of the signal packet likely originate from the same source region or within a narrow source zone.

[14] The received signal strengths of the VHTs at DGS range from 119 to 133 dB re 1 μPa and those at CL range from 126 to 142 dB re 1 μPa (peak to peak). VHT signals, as identified by the analyst, were seen throughout the year with no clear temporal trend. Many of the loudest and longest duration signals, however, were observed during the Austral fall and winter. Between January 2002 and May 2003, VHTs were identified within ~15% (1301 h/yr) and ~5% (446 h/yr) of the records at the CL and DGS stations, respectively.

4.2. Localization of VHT Sources

[15] In keeping with the observations of Talandier et al. [2002], a subset of the loudest VHT episodes show a possible temporal and spatial correlation with a large (~8 × 27 km) iceberg that migrated westward along the eastern Antarctic coast during 2002 and early 2003 (Figure 3). This iceberg, B-15D, was originally calved from the same ice mass that spawned the B-15B iceberg tracked by Talandier et al. [2002] within the Ross Sea. The azimuths for six pairs of VHT signals that were recorded at both the CL and DGS stations are shown in Figure 3a, with shaded areas
representing error bounds for each signal. Satellite-derived iceberg locations, color coded in time, show the westwardly migrating iceberg B-15D (National Ice Center (NIC), Antarctic Icebergs, 2003, http://www.natice.noaa.gov/products/iceberg/index.htm). As iceberg positions are not updated daily, we have used iceberg locations on or within three days of the VHT arrivals. The NIC locations for B-15D typically fall within the one standard deviation error bounds of our azimuthal constraints, being within a few iceberg lengths (Table 1, Figure 3). Iceberg drift rates approaching 1 km/h are not unusual; however, icebergs commonly exhibit nonlinear speeds and trajectories. Iceberg drift is controlled by the size and shape of the iceberg, wind direction and speed, currents, as well as factors such as the distribution of surrounding land and sea ice [Wadhams, 2000; Thomas and Dieckmann, 2003].

[16] For B-15D correlated VHT signals, the absolute values of the ΔT residuals are between 3 and 43 s (Table 1), assuming the locations derived from the intersection of azimuthal pairs and $v = 1.475$ km/s. The set of possible locations that satisfy the differential arrival time data for stations CL and DGS are shown in Figure 3b. These curves also show reasonable agreement with the B-15D locations that are temporally closest to the time of the VHT observations (National Ice Center, Antarctic Icebergs, 2003, http://www.natice.noaa.gov/products/iceberg/index.htm), as well as the azimuthally derived locations (Figure 3a).

[17] Most of the VHT azimuths, however, do not align with drifting icebergs, as tracked by the NIC. Figure 4 shows azimuthal paths and locations calculated for all the VHT signals from 2002 through mid-2003, with green and red lines representing azimuths calculated from CL and DGS, respectively. The prevalence of these signals suggests that VHTs may be generated by smaller icebergs, which are not tracked, but litter the Antarctic shelf region, or that VHT signals also can be generated in association with coastal ice sources. The Wilkes Land region, for example, is populated by a number of outlet glaciers and ice streams, which are distributed throughout the region where azimuthal data indicate the VHT signals originate (Figure 4). These glaciers may source many small icebergs that scrape against the seafloor or rub against each other in the near-coastal environment. Alternatively, as the glacier itself scrapes over the bedrock and enters the ocean, harmonic signals could be generated in an...
Figure 3. (a) Azimuths of six VHT signals from CL and DGS hydrophones along with iceberg locations. Each colored circle represents the National Ice Center (NIC) location of iceberg B-15D at various times throughout 2002 and 2003 (westerly migration). Each colored path corresponds to the azimuth and error bounds (±1.26 degrees for CL and ±1.51 for DGS, derived from known earthquake locations) calculated from signals arriving at CL and DGS hydrophones within three days of the NIC reported locations. Black stars represent hydrophone locations. (b) Differential travel time curves for each of the six VHT signals that exhibit a possible correlation with B-15D. Each curve represents a set of locations that are consistent with the arrival time differences (ΔT) observed between the distant CL and DGS stations. Points along these curves were found using a 3 × 3 km grid search and assuming a mean propagation velocity of 1.475 km/s along the source-to-receiver paths (equation (2)). White dots indicate iceberg locations derived from azimuthal calculations. NIC locations are color coded in time.

Table 1. Correlation of VHT Signals With B-15D

<table>
<thead>
<tr>
<th>Hydrophone Arrival Date</th>
<th>NIC Obs. Date</th>
<th>Arrival at CL</th>
<th>Arrival at DGS</th>
<th>NIC Location</th>
<th>Azimuthal Location</th>
<th>ΔT Residual, c s</th>
<th>ΔL Residual, d km</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002, 113</td>
<td>2002, 115</td>
<td>12:43:30</td>
<td>13:33:30</td>
<td>65.4°S, 143.4°E</td>
<td>64.9°S, 139.0°E</td>
<td>3.3 s</td>
<td>208.4 km</td>
</tr>
<tr>
<td>2002, 289</td>
<td>2002, 289</td>
<td>06:45:43</td>
<td>07:32:05</td>
<td>65.4°S, 123.5°E</td>
<td>65.7°S, 122.8°E</td>
<td>43.1 s</td>
<td>46.4 km</td>
</tr>
<tr>
<td>2003, 087</td>
<td>2003, 089</td>
<td>04:52:08</td>
<td>05:35:14</td>
<td>65.1°S, 115.5°E</td>
<td>65.9°S, 114.9°E</td>
<td>12.0 s</td>
<td>93.2 km</td>
</tr>
<tr>
<td>2003, 099</td>
<td>2003, 103</td>
<td>16:01:00</td>
<td>16:42:24</td>
<td>65.3°S, 109.6°E</td>
<td>65.1°S, 110.8°E</td>
<td>−11.9 s</td>
<td>60.2 km</td>
</tr>
<tr>
<td>2003, 128</td>
<td>2003, 131</td>
<td>23:32:55</td>
<td>00:10:50 b</td>
<td>65.0°S, 101.9°E</td>
<td>64.8°S, 101.4°E</td>
<td>28.9 s</td>
<td>32.4 km</td>
</tr>
<tr>
<td>2003, 158</td>
<td>2003, 159</td>
<td>20:00:58</td>
<td>20:34:26</td>
<td>63.7°S, 096.9°E</td>
<td>63.9°S, 094.3°E</td>
<td>−22.5 s</td>
<td>129.6 km</td>
</tr>
</tbody>
</table>

a Locations derived by interpolating latitude and longitude positions at azimuth intersections.

b Arrival at DGS on the following day 2003, 129.

c Difference between the predicted and observed ΔT value. Predicted value calculated for the azimuthally derived location and v = 1.475 km/s (equation (2)).

d Great circle distance between NIC iceberg locations and calculated azimuthal locations. Iceberg B-15D has been approximated from satellite images to be 8 × 27 km.
analogous manner. Consistent with these ideas, Talandier et al. [2002] have identified at least two tremor episodes not associated with drifting icebergs on 14 January 2001 and 8 November 2000 that appear to source from the Mertz Glacier ($\sim$68°S, 145°E) and the Tucker Glacier ($\sim$72°S, 170°E), respectively. Our data show the area near the Mertz glacier to be very active in 2002 and 2003 with several VHT azimuths aligning with this section of the coast. A direct hydroacoustic path does not exist, however, between the hydrophone stations and the Tucker glacier within the Ross Sea region.

5. Cusped Pulse Tremor (CPT) Observations

5.1. CPT Signal Characterization

[18] A second signal, a cusped pulse tremor (CPT), is characterized by curved harmonic bands of energy in the 4 to 80 Hz frequency range, with fundamental frequencies ranging from 4 to 10 Hz (Figure 5). The CPT signals were only seen on 31 days in 2002 and on 7 days in 2003 (as of May 2003), occurring primarily in the Austral fall and winter. The received levels of these signals range from 126 to 139 dB re 1 μPa at CL and 120 to 131 dB re 1 μPa at DGS. Their appearance is very similar to some hydroacoustically observed volcanic tremor [e.g., Dziak and Fox, 2002], with the duration of a single pulse and the typical interval between pulses ranging from 25 to 90 s. Pulsed signal trains can last anywhere from 10 min to over 1 hr. They commonly exhibit a near-regular pulse spacing (Figure 5, left column); however, some series have pulses at variable intervals (Figure 5, right column).

[19] Azimuth calculations show fixed azimuths throughout each pulse, as well as the entire pulse series (Figure 5c), with pulses exhibiting high correlation coefficients. Unlike the more continuous VHT signals that exhibit both harmonic and broadband signals within the same arrival packet, there is no coherent energy between the harmonic pulses (Figure 5d).

5.2. Localization of CPT Sources

[20] CPT azimuthal locations were checked against iceberg locations from the NIC. While icebergs were present within the error bounds of a small minority of signals, the majority of the signals did not originate from known iceberg locations. Moreover, those CPT signals that did have icebergs near their azimuthal track were observed later in the year originating from the same location after the
iceberg had drifted out of the error bounds, suggesting that the sources for the CPT signals remain fixed.

Unlike the VHT azimuths that included most of the Antarctic coast from 90°/C176 E to 160°/C176 E, CPT signals only originate from five geographic areas. CPT azimuths are shown in Figure 6a with green and red lines representing azimuths calculated from both CL and DGS, respectively. Composite images of RADARSAT data collected in 1997 [Jezek and RAMP Product Team, 2002] suggest that each CPT source region, as constrained from intersecting azimuthal pairs, includes one or more ice streams (Figure 6). Free floating ice blocks are observed trailing off some of the streams, which likely indicates ongoing activity at that time; however, other presumably active ice streams do not produce detectable CPT signals.

Figure 6b shows sets of possible CPT source locations based on the arrival time differences (ΔT) between the CL and DGS stations. As with the VHT signals that were correlated with iceberg B-15D, each curve falls within the errors of our azimuthally calculated source locations. If the arrival times at CL and DGS are forward modeled using the azimuthally derived source locations and assuming a velocity of 1.475 km/s, the absolute values of the ΔT residuals are <20 s.

6. Discussion

6.1. Sources and Mechanisms

Both the VHT and CPT signal types are similar to some subareal [e.g., Hagerty et al., 2000; Johnson and Lees, 2000] and submarine [e.g., Dziak and Fox, 2002] volcanic tremor. Location estimates, however, are inconsistent with sources within the volcanically active regions of the Kerguelen Plateau or Ross Sea (Figures 4, 5, and 7). Likewise, azimuthal data (Figures 3a and 6a) suggest that the source regions are located too far to the south to be associated with the South East Indian Ridge (SEIR). The pervasiveness of these signals also would imply a much greater eruption frequency than commonly observed along intermediate-spreading rate ridge systems, and the CPT
and VHT signals are not associated with submarine earthquakes that typically accompany seafloor eruptive activity [e.g., Fox and Dziak, 1998]. As there is no evidence for a longitudinally extensive chain of shallow seamounts extending along the Wilkes Land shelf region, we conclude that the tremor signals are unlikely to be volcanogenic.

Arguably the CPT signals also resemble the pulsed harmonic series produced by some cetaceans. Even the largest whale species, however, are not known to produce fundamental modes below 15 Hz, and the duration of their pulses is typically less than ~20 s [e.g., Stafford et al., 2001, 2004]. These observations are inconsistent with CPT signals that show fundamental frequencies as low as 4 Hz and pulse durations of up to 90 s (Figure 5). Rather, the spatial and temporal correlations outlined in sections 4 and 5 argue that the observed VHT and CPT tremors are generated in association with drifting icebergs and possibly coastal ice sources, such as outlet glaciers and ice streams.

Similarities between the VHT signals described here and ice-related signals reported by Talandier et al. [2002] are consistent with a common source mechanism. Talandier et al. [2002] have suggested that the harmonic nature of the Ross Sea tremors results from resonance of a drifting iceberg or fluid filled cavity within the iceberg. The dominant 4 to 10 Hz fundamental frequency observed within the VHT signals is

---

**Figure 6.** (a) Azimuthal traces for CPT signals recorded on CL hydrophones (green) and DGS hydrophones (red) in 2002 and 2003. Blue dots indicate USGS named glaciers, red dots represent glacier tongue locations, and black stars represent hydrophone locations. RADARSAT imagery from a 1997 composite mosaic is shown for each CPT source region. Blue dots on the images are the same glacier locations as those on the map. Note the presence of several different ice streams connecting the glaciers to the ocean. Some ice streams also have floating blocks of ice trailing from the ends of the streams, which suggests ongoing activity at the time of data collection. (b) Differential travel time curves for the CPT series. Each curve represents a set of locations that are consistent with the arrival time differences (ΔT) observed between the distant CL and DGS stations. Points along these curves were found using a 3 × 3 km grid search and assuming a mean propagation velocity of 1.475 km/s along the source-to-receiver paths (equation (2)). White dots indicate the CPT locations derived from intersection of azimuthal data shown in Figure 6a. Note some curves overlap for different CPT locations.
consistent with the observations of Talandier et al. [2002]; however, in some instances, these hydroacoustic data show fundamental frequencies exceeding 30 Hz (Figure 2, right column). If similar high-frequency energy were generated during the Ross Sea tremor events, those signals would have been aliased by the Polynesian seismic sensors, as would many of the high-order overtones in Figure 2. Talandier et al. [2002] and Okal et al. [2002] have discussed possible types of resonators in some detail. As they point out, the lowest frequency /C24 3 Hz fundamentals could corresponded to the eigenfrequency of a vertical shear mode within a /C24 300 m thick ice layer (assuming /C176 = 1.8 km/s). This thickness is consistent with that predicted for iceberg B-15, and sufficient to allow the ice mass to scrape across portions of the shelf. Higher-frequency fundamentals (~10 to 30 Hz) would suggest resonance within an ice layer having a thickness of only a few tens of meters. The observation shown in Figure 2b (right) indicates the pitch of the resonator can evolve from 30 to 8 Hz during a period of a few minutes, suggesting that different portions of variable thickness ice mass are resonating or that the physical properties of the resonator are evolving rapidly.

[26] Other possible resonator scenarios include the excitation of a fluid (water and air) filled cavity within the ice, making the eigenfrequency a complex function of the cavity’s shape and size, as well as the impedance contrast between the fluid and surrounding ice mass [Chouet, 1988; Garces and McNutt, 1997]. Changes in these parameters during ice movement could help to explain spectral fluctuations during the tremor events [Talandier et al., 2002].

[27] Despite the correlation of some VHT signals with a large iceberg being tracked by the NIC, our observations suggest that tremor signals also may be linked to the movement of smaller icebergs and/or coastal ice sources along eastern Antarctica. As shown in Figure 7, there is a rough correlation between VHT signal azimuth and the predicted azimuths to named outlet glaciers along the portions of the coast with unblocked propagation paths to the CL hydrophones. The land-based portion of these glacial ice masses and their glacial tongues are known to be active in many areas. These ice tongues extend over the water where they can break up into smaller blocks of ice that could become mobile due to the influence of wind and waves [Menzies, 1995]. A concentration of icebergs, which scrape the shallow seafloor or against one another in these settings, could account for this observation. Conceivably, glacial slip events also could excite resonance directly within the attached ice tongue, where acoustic energy could efficiently radiate into the water column (Figure 8).

[28] The abrupt onset and termination of many of the VHT and CPT signals (Figures 2 and 5) suggests the ice is moving in stick-slip manner, and there is mounting evidence for such behavior within Antarctic glaciers and ice streams. For example, a continuous GPS study recently demonstrated tidally influenced stick-slip motion within a Siple Coast ice stream in western Antarctica. Individual slip events lasted from 10 to 30 min with an average slip velocity of ~1 m/h [Bindschadler et al., 2003]. This duration is similar to the VHT signals observed in...
the IMS hydroacoustic data, and the surging nature of the ice movement during these events could act to excite resonance. Similarly, Ekstrom et al. [2003] have identified a series of unusual long-period surface wave events (equivalent to an earthquake with $M > 4.5$) located in glacial regions, including tectonically stable areas such as Greenland and coastal Antarctica. The radiation pattern of these events can be described by a single force couple model (applicable for landslide events), as opposed to a standard double-couple earthquake source. This led the authors to suggest that these events were generated by glacial quakes. Two of these quakes were located within the Wilkes Land region, albeit hundreds of kilometers inland ($C_{24}^2C_{176}^2S$, $110^\circ C_{176}^2E$) from the regions that source the tremor signals.

[29] The instantaneous velocities and style of movement of the coastal Wilkes Land glaciers and ice streams are not presently constrained by GPS studies. Long-term slip rates derived from Landsat imagery of the Mertz Glacier ($\sim 68^\circ S$, $145^\circ E$), however, show velocities exceeding 1000 m/year in some portions of the glacier [Scambos et al., 2000a]. If this displacement is taken up during periods of stick-slip motion with instantaneous velocities similar to the 1 m/h observed by Bindschadler et al. [2003], then more than 1000 hours of slip could be expected annually within the Mertz Glacier alone.

[30] Although CPT signals are observed to originate near a subset of the presumably active ice streams within the Wilkes Land region, the environmental conditions necessary to generate these signals are not well understood. The near-uniform spacing of CPT signals is reminiscent of a geyser-like process, as observed within volcanic systems [e.g., Dziak and Fox, 2002]. Consequently, we speculate that the process may be hydrologically driven, with a periodic recharge that allows the ice to slip in a repeating manner. As water fills a chamber within or beneath the ice stream, slip may occur when some threshold is reached and friction is overcome. Thus far, CPT signals have only been observed in the Austral fall and winter months. This seasonality must be verified over a longer period of observation; however, such temporal behavior could reflect a change in the hydrologic regime and the development of a uniform subglacial hydrous layer that allows the ice streams to move in a more continuous manner during the warmer months [Menzies, 1995]. It is not clear why some ice streams generate CPT signals and others do not.

6.2. Propagation of Sound From the High Southern Latitudes

[31] In Figure 9a, an acoustic parabolic equation model [Smith, 2001] is used to investigate sound propagation from a source near the Mertz Glacier to the SOFAR moored hydrophone triad CL. The range-dependent variation in the ocean sound velocity structure shown in Figure 9b is typical for sources propagating northward from the Wilkes Land region. In high-latitude regions, colder oceanic temperature profiles do not facilitate the existence of a deep sound channel. Consequently, acoustic energy from a shallow source along the shelf must initially propagate as a surface reflected phase. These signals then cross through the Ant-
arctic Convergence Zone (ACZ), a zone of rapidly changing oceanographic properties near the 50th parallel of latitude. Here cold surface water moving north away from the continent meets the warmer southerly moving surface water of the sub-Antarctic zone. Beyond the ACZ, the model predicts that some of this energy becomes coupled at mid latitudes into a deep sound channel, which extends in a laterally continuous manner to the CL and DGS hydrophone stations (Figure 9).

[32] Model transmission loss estimates from various points along the Wilkes Land coast to the CL station are on the order of \(103 \pm 2\) dB re 1 \(\mu\)Pa, implying maximum source levels of \(245\) dB re 1 \(\mu\)Pa at 1 m for the tremor signals. This is equivalent to the source level of the more transient, impulsive signals produced by a small air-gun array [Richardson et al., 1995].

7. Conclusions and Summary

[33] During the period January 2002 through May 2003, two distinct types of hydroacoustic tremor were recorded on IMS hydrophone stations within the Indian Ocean: variable harmonic tremors (VHTs), which are characterized by continuous harmonic bands with spectral peaks that fluctuate in frequency through time, and cusped pulse tremors (CPTs), which are short pulses having a convex-upward appearance in a spectrogram. Azimuthal calculations and travel time information suggest that both signals are sourced from the near-coastal regions of Wilkes Land, eastern Antarctica. The harmonic nature of these signals is consistent with the resonance of ice masses within such a setting, as proposed by Talandier et al. [2002] to explain similar low-frequency tremors originating from the Ross Sea.

[34] A subset of the loudest VHT signals can be correlated temporally and spatially with the westward migration of a large iceberg (B-15D) across the shelf region. The prevalence of VHT signals, however, suggests that they also may be generated in association with the many smaller, unnamed icebergs in the region. Our observations suggest a rough correlation between VHT source regions with the density of known glacial features along the coast (Figure 7). This is consistent with there being a dense population of small icebergs near these glacier source regions, or with glacier sliding events exciting resonance within a partially sub-
merged glacier tongue. CPT-like signals were not reported by Talandier et al. [2002]. They are detected less commonly at the mid-latitude to low-latitude hydrophone stations and appear to be sourced from relatively few locations along the eastern Antarctic coast. The mechanics of CPT generation are not well constrained; however, we speculate that the regular nature of their pulses, which could be viewed as reminiscent of a geyser, may be hydrologically driven.

Despite the absence of a well-developed sound channel within the southern portions of the Indian Ocean, ice-generated tremor signals can be detected at near-equatorial latitudes, over 7500 km away. Sound propagates first as a sea surface–reflected phase, with energy then transferred into the deep sound channel that develops to the north of the Antarctic convergence zone. The maximum peak-to-peak source level of the observed tremors may be as large as ~245 dB re 1 μPa at 1 m. Since VHT tremors may persist continuously for up to 30 min, they can dominate the noise spectra during some time periods. Conceivably, warming in the Antarctic region [e.g., King and Comiso, 2003] and the degradation of the Antarctic ice sheets [e.g., Scambos et al., 2000b] have increased the amount of free-floating ice and/or modified the dynamics of outlet glaciers and ice streams. Due to the absence of historical data, however, it is not known if the noise contribution from these types of ice-generated signals has increased in recent years.

Acknowledgments

We thank E. Okal and R. Dziak for helpful and constructive reviews of this manuscript. This work was partially supported by the United States Air Force under contract DTRA01-01-C-0070. Publication 6754 of Lamont-Doherty Earth Observatory.

References


