Abundance and distribution of Antarctic krill (Euphausia superba) nearshore of Cape Shirreff, Livingston Island, Antarctica, during six austral summers between 2000 and 2007

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Abstract: Abundance and distribution of Antarctic krill (Euphausia superba) in the nearshore waters north of Livingston Island, Antarctica, were characterized from six small-boat surveys conducted in late January or early February from 2000 to 2007. The first three surveys (2000, 2002, 2004) were conducted using a 120 kHz split-beam echosounder to measure water column acoustic backscatter. The last three surveys (2005–2007) were conducted using 38 kHz and 200 kHz single-beam echosounders. A portion of the acoustic backscatter was attributed to Antarctic krill based on the results of net tows, underwater video observations, and a multiple-frequency acoustic classification algorithm. The annual mean krill biomass density in the survey area ranged from 11 to 84 g m⁻². Results are compared with the western Scotia Sea area of the US Antarctic Marine Living Resources (AMLR) program’s acoustic surveys of krill biomass density for the same years. Nearshore krill biomass densities were significantly larger (t test, \( p < 0.05 \)), more stable, and the coefficients of variation were smaller than the much larger AMLR surveys. Increased competition between seals, penguins, and humans for the nearshore krill resource, especially during the austral summer months, could impact the recruitment success of these land-based krill predators. Implications of nearshore krill biomass on small-scale management units are discussed.

Introduction

Antarctic krill (Euphausia superba) are the main food resource for many of the fish, seabirds, and marine mammals in the Southern Ocean ecosystem. In addition to its ecological importance (Marr 1962; Croxall et al. 1999; Siegel 2000), krill are also the basis of a commercial fishery (Agnew 1997; Jones and Ramm 2004). To effectively manage this fishery, accurate estimates of the abundance and distribution of Antarctic krill are required. Towards this goal, several nations, as part of the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR), conduct surveys of the krill population using both echosounders and net tows to measure the krill population (Hewitt and Demer 2000). The results of these surveys are then used to set precautionary catch limits for the fishers (Hewitt et al. 2004b).
In the Scotia Sea region of the Southern Ocean (UN Food and Agriculture Organization’s statistical area 48), the US Antarctic Marine Living Resources (AMLR) program has conducted annual krill surveys for more than two decades (Hewitt and Demer 1991; Hewitt et al. 2003). To survey this very large area (Fig. 1), a series of transect lines and more than 100 sampling stations are conducted at least once per year during the austral summer (Hewitt et al. 2003).

The AMLR survey data from 1999 and 2000 were combined with the results of surveys from multiple other nations and identified three areas of consistently high krill biomass in the vicinity of the South Shetland Islands: eastern end of Elephant Island; midway between Elephant Island and King George Island; and the north side of Livingston Island (Hewitt et al. 2004a). However, the large-area surveys did not sample much of the shallow, on-shelf regions of the South Shetland Islands or Antarctic Peninsula. Because the nearshore areas have a much smaller spatial area (relative to the offshore large-area surveys), it is unlikely that higher nearshore krill abundances would affect annual estimates of krill biomass. However, the importance of the nearshore areas to predator foraging, fishing, and thus small-scale management units (CCAMLR 2006) may be disproportionately large.

Nearshore regions are defined here as areas on the continental shelf that are within tens of kilometres of land. These regions are important areas for several land-based species (e.g., penguins (Pygoscelis spp.) and Antarctic fur seals (Arctocephalus gazella)) that have established colonies and rookeries in the South Shetland Islands and, in particular, Livingston Island (Boveng et al. 1998; Croll and Tershy 1998). During the austral summer months, the adult animals regularly forage in and transit through the nearshore area of Cape Shirreff to provide food for their young on land.

The abundance and behavior of several different types of krill predators (e.g., flying sea birds, penguins, and fur seals) in the nearshore area are affected by changes in nearshore krill biomass (Miller and Trivelpiece 2008; Warren et al. 2009). However, the relationship between the breeding success of these land-breeding predators and the offshore krill abundance may be complex. For example, Croll et al. (2006) found that penguin reproductive success was correlated with offshore krill abundance, but penguin foraging effort was not. These findings suggest a possible lack of coherence between the nearshore and offshore krill abundances. If nearshore krill biomass is sufficiently large and annually stable, this could explain the long-term persistence of penguin and seal breeding colonies along the Antarctic Peninsula (Croll and Tershy 1998; Hinke et al. 2007).

Alternatively, if krill abundance within the foraging ranges and during the breeding season of penguins and seals is reduced by natural variability, climate change, or fishing effort, the apparent ecosystem balance could falter. Much of the commercial krill fishing takes place in these nearshore areas of the Antarctic Peninsula (Jones and Ramm 2004) and may directly compete with foraging seals and penguins, particularly during their breeding season. As both the native animals (fish, seabirds, and marine mammals) and humans are consuming the limited krill resource in the nearshore areas, increased competition may negatively impact the reproductive success of animals confined to forage from their land breeding sites.

To explore the hypothesis that nearshore krill biomass density is larger and more stable interannually than the offshore krill biomass density, a method was developed and a series of surveys were conducted to measure the abundance and distribution of krill in the nearshore region north of Cape Shirreff, Livingston Island, Antarctica. Cape Shirreff is the site of several colonies of Antarctic fur seals and chinstrap (Pygoscelis antarctica) and gentoo (Pygoscelis papua) penguins. The AMLR field camp there served as a base for the nearshore survey operations. Because of the shallow depths and lack of accurate bathymetric charts of the area,
instrumented small craft were developed and used to study the previously inaccessible nearshore region.

**Materials and methods**

During six austral summers (late January and early February) of 2000, 2002, and 2004–2007, an instrumented small craft (R/V Ernest) was used to survey the area surrounding Cape Shirreff (Table 1). This area is characterized by shallow (less than 100 m) depths except for two large submarine canyons that exist to the northeast and northwest of the Cape (Fig. 1). These canyons extend to the shelf break approximately 30–40 km offshore. The bathymetry of the non-canyon regions contains many pinnacles and other pronounced underwater features, some extending to within a few metres of the surface. There is also a small sheltered cove with a rocky beach that served as an anchorage for R/V Ernest. Transit to and from Cape Shirreff was on R/V Yuzhmorgeologiya during the first leg of the annual AMLR survey of the Scotia Sea krill population. The duration of each nearshore survey ranged from 2 to 10 days (Table 1), depending on several factors including the duration of the AMLR cruise, weather delays during the large-area survey, and weather and sea conditions during the transfer to and from the field site and during the nearshore survey period.

**R/V Ernest**

Two people (captain, scientist) served as crew for R/V Ernest, which had two distinct forms during this study. During the first three field seasons, an aluminum pilothouse was fitted into the 6 m inflatable (Zodiac Mark V) boat. The insert contained batteries supplying power to a variety of communication and safety equipment (radar, VHF radio, EPIRB), as well as scientific instruments. Sensors onboard the vessel included a meteorological station (WeatherPak 2000; Coastal Environmental Systems Inc., Seattle, Washington), which measured temperature, humidity, barometric pressure, bearing, and apparent and true wind speed and direction; multiple global positioning system (GPS) receivers; and a 120 kHz split-beam echosounder (Simrad EY500; Kongsberg Maritime AS, Horten, Norway). GPS, meteorological, and acoustic backscatter data were recorded on a laptop computer. A liquid-crystal display, mounted behind a waterproof window, provided the scientist with a real-time display of position and meteorological and echosounder data. A motorized downrigger was used to deploy a small conductivity–temperature–depth (CTD) profiler (SBE 19; Sea-Bird Electronics, Inc., Bellevue, Washington) and an underwater video-camera system (Sony Handycam with Light and Motion Stingray housing and lights; Sony Inc., Tokyo, Japan) at stations throughout the survey area. The video camera was used to confirm the classifications of acoustically detected targets. The boat was also equipped with survival and tool kits, manual and automatic bilge pumps, three survival suits, four fuel tanks, binoculars, and anchorage equipment. Transit operations used a 55-hp gas outboard engine, whereas survey operations used a 9.9-hp outboard engine with generator to allow remote steering, conserve fuel, charge batteries, and minimize noise in the

### Table 1. Nearshore survey timing and duration, total length of all transects, depths sampled by acoustic echosounder, coverage of canyons east and west of Cape Shirreff, and timing of echosounder calibration.

<table>
<thead>
<tr>
<th>Date</th>
<th>Survey length (km)</th>
<th>Depth recorded (m)</th>
<th>Coverage</th>
<th>Echosounder calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>6–10 February 2000</td>
<td>148</td>
<td>250</td>
<td>West, east</td>
<td>Before</td>
</tr>
<tr>
<td>17–23 February 2002</td>
<td>250</td>
<td>100</td>
<td>West, east</td>
<td>Before</td>
</tr>
<tr>
<td>7–09 February 2004</td>
<td>130</td>
<td>250</td>
<td>East</td>
<td>During</td>
</tr>
<tr>
<td>1–10 February 2005</td>
<td>280</td>
<td>400</td>
<td>East</td>
<td>Before and after</td>
</tr>
<tr>
<td>3–08 February 2006</td>
<td>234</td>
<td>400</td>
<td>East</td>
<td>Before and after</td>
</tr>
<tr>
<td>29–30 January 2007</td>
<td>77</td>
<td>400</td>
<td>East</td>
<td>Before</td>
</tr>
</tbody>
</table>

**Fig. 2.** (a) R/V Ernest I was used to survey the nearshore waters of Livingston Island for krill abundance and distribution in 2000, 2002, and 2004. It contained a single-frequency (120 kHz) split-beam echosounder, a meteorological station (not shown), and an electric downrigger for cast deployments of a CTD. (b) R/V Ernest II was used in 2005–2007 and contained a multiple-frequency (38 and 200 kHz) single-beam echosounder, a sea-surface temperature and salinity sensor, and a meteorological station.
acoustic record. During the 2000 and 2002 field seasons, the transducer was deployed on a portside gimbal mount; however, transducer movement in certain sea conditions reduced data quality so a transom-mounted transducer arm was installed in 2004 and used thereafter.

For the 2005–2007 field seasons, the aluminum insert was replaced by two waterproof equipment cases and a dodger made of stainless steel, canvas, and vinyl (Fig. 2). These changes reduced the weight of the boat, allowed the vessel to plane when transiting between survey locations, and provided more protection from the elements for the crew. The smaller engine was removed and the larger one was used for both transiting and survey operations. This change allowed for faster survey speeds and an increase in survey coverage. The single-frequency echosounder was replaced with 38 kHz and 200 kHz echosounders (SIMRAD dual-frequency single-beam ES60; Kongsberg Maritime AS), which used a 802.11 g wireless network to link the echosounder to a laptop computer on Ernest. In addition, a temperature and salinity sensor (SBE 37 microCAT; Sea-Bird Electronics, Inc.) was deployed on the transom-mounted transducer arm to record subsurface (1 m) hydrography during the survey.

Survey operations

Meteorological and position data were recorded whenever the boat was transiting or surveying. The vessel transited at high speeds (ca. 8 m s\(^{-1}\)) to the beginning of a transect line. The transducer arm was then lowered and acoustic and hydrographic data recording commenced. Depending on the track lines to be run each day, transits between track lines were made either slowly (2–5 m s\(^{-1}\)) while recording echosounder data or rapidly with the transducer raised out of the water. Meteorological, date, time, and position data were recorded every 20 s on the laptop computer. Hydrographic data (temperature, salinity, and pressure) from the CTD were recorded every 5 s. Occasionally, when large aggregations of scatterers were observed on the echosounder near the surface (<75 m depth), the digital video camera was lowered to record images and identify the scatterers. Weather conditions, sea state, fuel supply, and crew endurance determined the length of survey operations each day, but typically 5 to 8 h each day were spent collecting data and transiting. Surveys were conducted in all types of weather (often in the same day) and were suspended when seas grew greater than 4 m, visibility was reduced to less than 10 m, or winds exceeded those for safe vessel operation (e.g., >10 m s\(^{-1}\)).

The survey transects varied in length and direction during the first few years of this study, as the operational capabilities and limits of Ernest were identified. Also, as measurements from Ernest were used to map the nearshore bathymetry, increasing portions of the nearshore area were safely surveyed from Yuzhmorgeologiya. The survey strategy soon stabilized, and since 2004, nearly identical transect legs east of Cape Shirreff were surveyed from Ernest. Transits to the western side of Cape Shirreff can be difficult in certain sea-state or fog conditions, so efforts were focused on a higher spatial coverage of the eastern side of the Cape when survey time became limited during the 2004 field season. The direction of the transects during the 2004 to 2007 surveys were chosen to align with cruise tracks that Yuzhmorgeologiya surveyed during the large-area survey so that comparisons could be made between the data collected from the two observational platforms. However, survey tracks (direction and distance) were often adjusted depending on the direction and size of the waves and wind. The 2004 nearshore survey consisted of only 3 days of operations due to severe weather and sea conditions during 4 days of the scheduled weeklong survey period. Similarly, the 2007 nearshore survey was reduced to less than 2 days as a result of severe weather during both the large-area and nearshore survey periods.

Acoustic data

Calibration

The echosounders were calibrated for each survey using the standard sphere method (Foote et al. 1987) with a 38.1 mm tungsten carbide sphere (Table 1). Using a single monofilament tether, the sphere was lowered beneath Ernest until it appeared on the echogram and the target strength (TS), uncompensated for beam directivity effects (TS\(_1\); dB), was maximized. Several hundred TS\(_1\) measurements of the sphere were recorded at this depth while both the sphere and transducer moved with water and vessel motion. For the 120 kHz split-beam measurements, the sphere position in the beam was measured and the TS\(_1\) were compensated for the beam directivity (dB). In the cases of the single-beam 38 kHz and 200 kHz transducers, the location of the sphere within the acoustic beam was unknown. For most of the single-beam calibration experiments, the distributions of TS measurements were examined to confirm that some on-axis measurements were achieved. These measurements were used to calculate the on-axis calibrated system gain (Foote et al. 1987).

In 2005, on-axis calibration measurements were obtained for the target for both frequencies of the echosounder. However, in 2006, because of strong currents, TS measurements were intermittent with the narrower beamwidth (7\(^\circ\)) of the 200 kHz transducer, but continuous with the wider beamwidth (13\(^\circ\) longitudinal and 21\(^\circ\) transverse) of the 38 kHz transducer. In this case, theoretical beampatterns were calculated for both transducers, and the differences in TS\(_1\) at the two frequencies were predicted for a range of off-axis angles. This information was used to constrain the possible locations for the sphere within the beam. The data were then fit to the theoretical predictions using the method of least squares to estimate the minimum off-axis angle achieved (i.e., 5\(^\circ\)). The TS measurements were then compensated for the beampattern and used to estimate the calibrated echosounder gain. In 2007, a calibration was not possible due to the short survey duration and inclement weather and sea-state conditions. Consequently, the 2006 settings were used for the 2007 survey. For the first four field seasons, the calibration accuracy is estimated to be better than 1 dB (one-way gain accuracy ≤ 0.5 dB or ~12%). For the 2006–2007 field seasons, the aforementioned procedure is thought to result in calibration accuracy of better than 2 dB for each frequency (one-way gain accuracy ≤ 1.0 dB or ~26%).

Data collection

Survey speeds varied depending on sea state, wind, and
Scattering strengths (transmitted every 1 s at 120 kHz (2000, 2002, and 2004) the surface. Acoustic pulses of 1.024 ms duration were the transducer was located between 1 and 1.75 m beneath the surface. Acoustic pulses of 1.024 ms duration were transmitted every 1 s at 120 kHz (2000, 2002, and 2004) and 2 s at 38 and 200 kHz (2005–2007), and volume backscattering strengths \(S_v\) dB re 1 m\(^{-1}\) were recorded every 20 to 30 cm from the transducer to depths of 250 m (2000), 100 m (2002), 250 m (2004), and 400 m (2005, 2006, and 2007) (Table 1). All locations in the survey area were shallower than 400 m, and only the middles of the canyons were deeper than 250 m.

Acoustic backscatter provides indirect measures of the distribution and abundance of biological organisms in the marine environment. Validation of this metric was achieved with a series of 2.5 m\(^2\) Isaac–Kidd midwater trawl net tows during the 2002, 2004, and 2005–2007 field seasons. The tows were conducted from Yuzhmorgeologiya in adjacent areas (Fig. 1). The net-tow contents were enumerated and identified to species onboard Yuzhmorgeologiya and then preserved in a buffered (10%) formalin solution. During the 2005–2007 surveys, adult Antarctic krill were sexed and their lengths were measured before preservation. At least once during each field season (except for 2004 and 2007), an underwater video camera was lowered into a patch of near-surface scatterers that were observed on the echosounder. Ernest drifted as the camera was lowered to the depth of the scattering aggregation and then retrieved. This method was occasionally unsuccessful if the scatterers dispersed or the aggregation moved while the camera was lowered. Successful video observations indicated that aggregations of large euphausiids (likely \(E. superba\)) were the dominant mesozooplankton in the water column.

Volume backscattering coefficients \(s_v\) (m\(^{-1}\)), where \(S_v = 10 \log_{10}(s_v)\) were summed from 3 to 10 m below the sea surface to the shallower of 100 m or 1 m above the seafloor (observation range common to all years) and averaged over 185 m (0.1 nautical miles (n.mi.)) trackline distances, yielding nautical area backscattering coefficients \(S_v;\) m\(^2\)-n.mi.\(^{-2}\). Selected regions were excluded from the integration, including the acoustic near-field and scatter from nonbiological sources such as bubbles, suspended sediments (e.g., mud or sand), or the seafloor (particularly the dead zone above high-relief hard substrates; see Demer et al. 2009). In the 2004–2007 data, noise from the engine was also removed by coherent subtraction (Hewitt et al. 2004b) and filtered by thresholding below \(S_v = –80\) dB re 1 m\(^{-1}\).

### Conversion of backscatter data

The dual-frequency echosounder data were filtered using the \(\Delta S_v\) method (Watkins and Brierley 2002; CCAMLR 2005) prior to the calculations of \(s_A\). The \(\Delta S_v\) method aims to accept \(S_v\) from krill and reject that from other biological scatterers. Following the procedure of CCAMLR (2005, 2009), the minimum and maximum length of krill caught in the net samples for each year were used to calculate the \(\Delta S_v\) range for attributing acoustic backscatter to krill. The stochastic distorted wave Born approximation (SDWBA) model (Demer and Conti 2005; Conti and Demer 2006; CCAMLR 2009) was used to calculate the predicted difference in scattering \(\Delta S_v\) for the smallest and largest krill lengths. These two \(\Delta S_v\) values formed the upper and lower bounds for filtering the acoustic backscatter data (Table 2). This technique could not be applied to the single-frequency 120 kHz data collected during the 2000, 2002, and 2004 nearshore surveys.

The \(s_A\) were converted to estimates of krill biomass density using the length distribution of krill caught in nets and a theoretical acoustic scattering model (Demer and Conti 2005; Conti and Demer 2006; Reiss et al. 2008) that has been adopted by CCAMLR as the standard method for producing estimates of krill biomass (CCAMLR 2005, 2009). Because the nearshore trackline lengths and directions were not standardized for all survey years, the method of Jolly and Hampton (1990) was used to measure the mean weighted density and coefficient of variation (CV) for a series of transects comprising the survey for each year. These values were then comparable between the six nearshore surveys and the AMLR Scotia Sea surveys, which were analyzed in a similar manner (method 3 from Reiss et al. 2008).

### Table 2. Conversion of acoustic backscatter data to estimates of krill biomass density used krill length information from net tows and the SDWBA scattering model to determine the criteria to identify backscatter from krill.

<table>
<thead>
<tr>
<th>Year</th>
<th>Range of krill lengths (mm)</th>
<th>(38) kHz</th>
<th>(200) kHz</th>
<th>(38) kHz</th>
<th>(200) kHz</th>
<th>(\Delta S_v) range used to identify krill</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>40–55</td>
<td>–81.3</td>
<td>–74.4</td>
<td>–73.0</td>
<td>–71.2</td>
<td>2.6–7.0</td>
</tr>
<tr>
<td>2006</td>
<td>45–58</td>
<td>–78.7</td>
<td>–73.5</td>
<td>–73.6</td>
<td>–71.5</td>
<td>2.0–5.2</td>
</tr>
<tr>
<td>2007</td>
<td>22–60</td>
<td>–94.5</td>
<td>–79.3</td>
<td>–74.5</td>
<td>–71.9</td>
<td>1.8–15.2</td>
</tr>
</tbody>
</table>

Note: \(\Delta S_v\) is the \(S_v\) at 200 kHz minus the \(S_v\) at 38 kHz. This method was only applied to the data from 2005 to 2007 as the 2000, 2002, and 2004 surveys used a single-frequency echosounder.
Thus the mean TS for a krill aggregation can be calculated by weighting the orientation-averaged backscattering cross section for krill at each length by the proportion of krill of this length caught in the net. This has the effect of dampening the TS versus length oscillations in the geometric scattering regime (where the krill length is large relative to the acoustic wavelength).

Because $S_v$ data were recorded to different maximum depths (Table 1), the minimum requisite survey depth was explored. Most of the scattering was observed in the upper 100 m of the water column, so the effect of not integrating $S_v$ deeper than 100 m is assumed to be insignificant. This assumption is supported by independent observations of krill throughout the Scotia Sea during the austral summer of 2000 (see fig. 9 in Demer 2004). To further validate this assumption, the scatterer aggregations in the 2005 and 2006 data that were identified as krill using the $D_s$ method were further characterized with regard to their size and depth.

Results

Net-tow samples for all years indicate that adult and juvenile *Euphausia superba* were the largest contributors to zooplankton biomass in this region, although other smaller euphausiids (*Thysanoessa macrura*, *Euphausia frigida*) were also frequently caught in smaller numbers. Other zooplankton and nekton in the net catches were copepods (*Metridia gerlachei*, *Calanoides acutus*, *Calanus propinquus*, *Rhinocalanus gigas*, and *Paraeuchaeta* spp.), salps (*Salpa thompsoni*), amphipods (*Cyclops lucasii*, *Primo macropra*, and *Themisto gaudichaudii*), chaetognaths, larval fish (*Lepidonotothen larseni* and *Electrona* spp.), and gastropods (*Lima- cina helicina*, *Spongiobranchaea australis*, and *Clione limacina*). The three taxa that accounted for the overwhelming majority of biomass were Antarctic krill, copepods, and salps. Neither copepods nor salps are considered to be strong acoustic targets at these frequencies compared with the krill (Demer 1994; Stanton et al. 1996; Stanton and Chu 2000), so these acoustic estimates of biomass should not be strongly affected by the presence of either. Larval fish, however, are relatively strong scatterers, but they were found infrequently in the net tows, generally only at nighttime, and always in low numerical densities. Pteropods are also strong scatterers; however, they were only found in the shelf-break net tows (i.e., those farthest from the nearshore survey region) and were caught in very low numerical abundances, so their contributions to the nearshore backscatter are likely to be small.

A key factor in the conversion of $A_s$ to estimates of biomass is the estimated probability density function (pdf) of krill lengths. This length pdf is used to calculate both the weighted scattering cross-section and the biomass per krill. For 2000, 2002, and 2004, the length pdfs for the nearshore area were assumed equivalent to those measured in the western area of the AMLR broad-scale survey, which includes the South Shetland Islands. For the 2005–2007 surveys, the length pdfs were calculated from net samples from the nearshore area (Fig. 3). In 2005, the nearshore and AMLR western area distributions were nearly identical (coefficient of determination, $R^2 = 0.96$), whereas the 2006 ($R^2 = 0.52$) and 2007 ($R^2 = 0.81$) distributions showed slightly (approximately 5 mm) larger krill in the nearshore waters. Additionally, in 2007, smaller (juvenile) krill were caught in both regions, although the nearshore region had fewer of these.
younger krill. Given the general agreement between the nearshore and western area distributions in the 2005–2007 surveys, errors resulting from using the western area length pdfs in 2000, 2002, and 2004 are likely small.

Using the 38 kHz and 200 kHz data from 2006, biomass densities calculated from the 38 or 200 kHz data, without the \( S_v \) method, were, as expected, higher than those derived with the dual-frequency algorithm (Fig. 4). Therefore, the biomass densities estimated from the single-frequency data collected in 2000, 2002, and 2004 are probably overestimated. To account for this bias, a correction factor was developed and applied. First, biomass densities were calculated for each of the 2005–2007 surveys using only the 200 kHz data (i.e., replicating a single-frequency echosounder) and using both frequencies (i.e., the \( S_v \) method). The differences between the biomass densities calculated using the single-frequency (200 kHz) and \( S_v \) methods were fairly uniform across all values of measured backscatter (Fig. 4b) and for each survey. The 2006 data included the largest range of biomass density values and were therefore used to estimate the correction factor, but the 2005 and 2007 data had the same pattern where they overlapped. This suggests that the \( S_v \) method, tuned by the krill length pdfs, is not affected by the overall level of backscatter and that scatter from small (e.g., salps and smaller euphausiids) and large organisms (fish) was rejected, as desired, using the \( S_v \) method.

The length-weighted TS for krill at 120 kHz for each year of the survey using the SDWBA model (Conti and Demer 2006) were 0.45 ± 0.15 dB larger than that at 200 kHz. To account for this small, expected difference, the \( S_v \) at 120 kHz were reduced by 0.45 dB before calculating the \( s_A \) (Demer 2004). Next, a correction formula was found for the 2006 data by fitting a straight line (in log–log space) to the 200 kHz biomass density data and then transforming these data to match the biomass density using the \( S_v \) method (Fig. 4). The correction equation, based on the 200 kHz biomass density data, was applied to the adjusted 120 kHz biomass density (\( BD_{120\text{kHz}} \)) from 2000, 2002, and 2004 data, resulting in a revised biomass density estimate (\( BD_{120\text{new}} \)) that was used in all subsequent analyses (Fig. 4): \( BD_{120\text{new}} = 10^{-1.551} \cdot BD_{120\text{kHz}}^{1.084} \).

During each nearshore survey, krill biomass density was observed to be high throughout the shallow regions proximate to Cape Shirreff (Fig. 5). High biomass densities were mapped both along the edges and within the canyon east of Cape Shirreff. Areas to the southeast and south of the eastern canyon had relatively lower biomass. Coupling the 2000 and 2002 Ernest surveys of the canyon west of Cape Shirreff with observations from Yuzhmorgeologiya (Warren et al. 2009), there is an indication that krill are equally as abundant there as in the eastern canyon.

In addition to examining horizontal distributions, the vertical distributions of krill aggregations were examined in both 2005 and 2006. Unlike the echo-integration analyses, which were limited to the upper 100 m of the water column, krill aggregations were examined throughout the water column (as the maximum observational depth of 400 m exceeded the maximum bottom depth in these surveys). Aggregations of krill were identified from acoustic-backscatter data within the \( S_v \) range corresponding to the range of krill lengths observed each year. Data from both years showed that krill aggregations had similar depth distributions with mean (±1 standard deviation, SD) depths of 62 (±26) m in 2005 and

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**Fig. 4.** Comparison between values of integrated krill biomass density (BD) (g m\(^{-2}\)) (circles) estimated from single-frequency backscatter data at (a) 38 kHz and (b) 200 kHz (\( BD_{38\text{kHz}} \) and \( BD_{200\text{kHz}} \), respectively) and from the two-frequency \( S_v \) method (\( BD_{S_v} \)). The value of the single-frequency estimates is on the horizontal axis, while the two-frequency \( S_v \) estimates are on the vertical axis. The shaded broken line in both plots represents where the single-frequency and \( S_v \) method estimates of biomass density are equal. To correct single-frequency survey data (which cannot discriminate between krill and non-krill scatterers), an equation (shown in (b)) was found that related \( BD_{200\text{kHz}} \) and \( BD_{S_v} \), which was used to produce corrected 200 kHz biomass estimates (\( BD_{\text{new}} \), shaded circles). The black broken line in (b) is a linear regression fit to the data that was used to calculate the correction function.
53 (±27) m in 2006. The center of mass of krill aggregations (e.g., depth of krill aggregations weighted by the biomass of the swarm) was 55 m in 2005 and 48 m in 2006. During both 2005 and 2006, the overwhelming majority of krill aggregations (92% and 95%, respectively) and their biomasses (97% and 99%, respectively) were located at depths less than or equal to 100 m (Fig. 6).

To compare estimates of biomass from each survey, a series of roughly parallel transects were selected from each nearshore survey. The transect directions were not the same each year because of the different survey designs; however, for the last three years of the survey, the transects were roughly oriented northwest to southeast. Following Jolly and Hampton (1990), the mean biomass density for each
segment and the transect lengths were calculated. The mean biomass density for each transect, weighted by transect length, were then calculated for each survey along with their coefficients of variation (CV values; Table 3; Fig. 7). The CV values were generally similar between years, except for 2000 and 2007, which were higher. In 2000, this is likely the result of the longest transect in that survey having a mean biomass density six times larger than the other transects. In 2007, the large CV is due to the short duration of the survey and, consequently, only three transects available for analysis.

Annual mean krill biomass densities ranged from 11 to 84 g·m⁻² and were significantly larger than krill biomass density estimates from the AMLR western area survey (t test, p < 0.05; Table 3; Fig. 7). The estimates of biomass density in 2004 and 2007 (57.9 and 84.3 g·m⁻², respectively) were substantially larger than those for the other years, motivating a thorough re-examination of the echograms. The high biomass estimates were the result of krill aggregations in both years being both more numerous and dense. In every year except 2002, the nearshore biomass density was greater in the nearshore region than in the western area of the AMLR survey (AMLR 2008), and in some years, nearshore biomass densities were substantially greater than those offshore (Table 3; Fig. 7). The mean nearshore biomass density estimates were larger (mean, 38.6 g·m⁻²; SD, 28.0 g·m⁻²) and always greater than 11 g·m⁻², whereas the western area estimates were smaller (mean, 14.1 g·m⁻²; SD, 13.1 g·m⁻²), exhibited a much larger variance from year to year, and in some years were very small (i.e., less than 1 g·m⁻²). Based on these six years of survey data, krill biomass densities remained high in the nearshore regions even when the offshore krill biomass densities were low.

### Table 3. Comparison of mean krill biomass densities (BD) and coefficient of variation (CV) for the transects from the nearshore survey and the AMLR Western Area (AMLR 2008), and the number of nearshore transects and total transect distances used to calculate BD.

<table>
<thead>
<tr>
<th>Year</th>
<th>Nearshore survey</th>
<th>AMLR Western area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transects (number)</td>
<td>Distance (km)</td>
</tr>
<tr>
<td>2000</td>
<td>9</td>
<td>93</td>
</tr>
<tr>
<td>2002</td>
<td>11</td>
<td>103</td>
</tr>
<tr>
<td>2004</td>
<td>7</td>
<td>84</td>
</tr>
<tr>
<td>2005</td>
<td>24</td>
<td>222</td>
</tr>
<tr>
<td>2006</td>
<td>17</td>
<td>162</td>
</tr>
<tr>
<td>2007</td>
<td>3</td>
<td>32</td>
</tr>
</tbody>
</table>

Note: Analyses of both the AMLR Western Area and nearshore data use the same SDWBA scattering model and procedure for converting acoustic backscatter to krill biomass. AMLR surveys occurred once or more each year in January (A) or February (D). Biomass densities from 2000 to 2004 (single-frequency data) were corrected using the relationship shown in Fig. 4.
Discussion

This multiyear study has demonstrated that a small boat equipped with a scientific echosounder and either video or nets to verify the acoustic scatterers as krill can successfully survey shallow, nearshore waters of Antarctica. The estimates of nearshore krill biomass density are significantly larger, exhibit smaller interannual changes, and have smaller CV values within each survey year than the acoustic surveys of the much larger offshore areas of the Scotia Sea. For the area north of Cape Shirreff, during the austral summers of the years of this study, krill were consistently found in similar areas, had a minimum biomass density of at least 11 g m$^{-2}$, and had mean biomass densities that were much larger than the adjacent offshore waters in all but one year. The western area of the AMLR survey often had biomass densities that were one order of magnitude smaller than the nearshore areas, although in some years, biomass differences were even greater. Physical (advection) and biological (upwelling, increased phytoplankton biomass) factors in the nearshore area are possible reasons for the consistently higher krill biomass in this region.

Note that the AMLR survey data collected at three acoustic frequencies (38, 120, and 200 kHz) are currently analyzed using two $\Delta S$ ranges to identify acoustic scattering from krill (e.g., Reiss et al. 2008), following CCAMLR (2005, 2009). These differences in survey data and analysis techniques may partially explain their smaller estimates of krill biomass density. However, because of the absence of small krill in the nearshore net tows, the nearshore survey had a much smaller $\Delta S$ range (except in 2007 when the ranges are comparable) than that used by the AMLR survey. Consequently, the data presented here are conservative estimates of the nearshore krill biomass density (CCAMLR 2009). In addition to the nearshore waters having larger and more uniform krill densities compared with the nearby offshore region, the nearshore waters generally contain more large adult krill and fewer juvenile krill. Thus, the nearshore region may avail the land-based predators with higher-quality prey (i.e., more biomass per krill). Why larger krill preferentially aggregate nearshore is yet to be discovered.

Although the sampling methods and instrumentation changed somewhat between the nearshore surveys, the differences probably do not affect the overall results. The mean krill biomass densities from 2000, 2002, and 2004 are similar (and in general smaller) than those from the years when the dual-frequency discrimination was done, suggesting that our method of correcting these data did not produce positively biased results. The different integration depths used for different years do not contribute appreciable biases because the majority of the krill biomass was in the upper 100 m of the water column and all the integration depths were greater than or equal to 100 m. These distributions are similar to that observed for krill surveyed over the entire Scotia Sea during 2000 (Demer 2004) and in other studies of Antarctic krill (Miller et al. 1993; Siegel and Kalinowski 1994). Moreover, Miller and Trivelpiece (2008) found that chinstrap penguins did not exhibit foraging dives deeper than 93 m (2005) and 88 m (2006) during the day, which suggests that sufficient krill prey resources exist shallower than 100 m.

The relative importance of nearshore krill in terms of the total krill stock in the Scotia Sea (e.g., Hewitt et al. 2004b) is unknown; however, the spatial area of this nearshore survey is quite small (~200 km$^2$) when compared with that of the Scotia Sea. The relatively high and stable densities of krill biomass in the nearshore regions of the South Shetland Islands may be important to include in some estimates of krill biomass, particularly in subregions considered for small-scale management units. Although the three identified “hot spots” of krill biomass from the CCAMLR 2000 multinational, Scotia Sea survey (Hewitt et al. 2004a; CCAMLR 2006) are all proximate to nearshore areas, the surveys used to identify these hot spots did not extensively sample the shallower nearshore waters, as was done in this study. The large nearshore krill biomass is generally most accessible and attractive to the land-breeding predators, as well as to human fishers competing for this valuable resource. Animals and fishers alike are drawn to the nearshore hot spots during the austral summer months (Jones and Ramm 2004). Given the different objectives of research vessels (standardized survey effort to collect high quality data) and fishing vessels (maximize profits by catching more animals), fishing vessels may be willing to work closer to land than research vessels, which may increase competition between land-based predators and fishers for the krill resource.

This study focused on a relatively small nearshore region of Livingston Island, and it is difficult to say whether these results are applicable to other shallow, nearshore areas along the South Shetland Islands, Antarctic Peninsula, or elsewhere in the world. Acoustic surveys of krill backscatter further south along the Antarctic peninsula (Marguerite Bay) have also observed higher levels of backscatter in the shallower, nearshore regions (Lawson et al. 2004) that have been related to the distribution or abundance of at least one krill predator (Friedlaender et al. 2006), so the results of this study corroborate surveys in other areas conducted by larger vessels (but not in as shallow a region as this study).

The nearshore surveys were conducted over a very small area (hundreds of square kilometres) and very short time scale (days) over six of eight consecutive years. Because of these spatial and temporal sampling constraints, these data are susceptible to biases associated with short-term or small-scale phenomena that would be “smoothed out” by a larger area or longer survey period (Warren et al. 2009). Potential disturbances that may affect the nearshore survey results include mesoscale meteorological events such as low-pressure systems or storms passing through the region or possibly even the difference that a spring or neap tide might have on the ecosystem close to shore. Some of these events (particularly storms) are frequent occurrences in the study area, so these data may reflect some of these biases. However, the data from the nearshore survey during 2005 did not exhibit the same reduction in krill biomass that Warren et al. (2009) observed in the waters immediately adjacent to the nearshore survey area during the same time period, suggesting that the nearshore areas may be resistant to the effects of these submesoscale perturbations.

This study demonstrates that acoustic surveys conducted from instrumented small craft can augment larger-vessel surveys and extend the multidisciplinary investigations into waters commonly inaccessible, but ecologically important.
Results show that krill biomass can be as high or higher in some nearshore areas, possibly influencing the sites and success of penguin and seal rookeries, and should be considered in krill-fishery management schemes utilizing small-scale management units (Hewitt et al. 2004b). During the austral summer months, many of these highly productive nearshore areas are preferred foraging areas for large populations of penguins and Antarctic fur seals (Croll and Tershy 1998; Croll et al. 2006) and commercial fishing activities (Jones and Ramm 2004).

When rearing their chicks and pups on land, adult penguins and fur seals need a reliable food resource in the nearshore areas to assure reproductive success. Without adequate prey nearshore, the land-breeding krill predators must forage on other species, or further offshore, consequently jeopardizing the health of their offspring and themselves. Also, it should be noted that even in times of large nearshore krill abundance, the land-breeding predators might switch preferred prey. For example, Miller and Trivelpiece (2008) found that in 2004, the year with the second highest observed nearshore krill biomass density, the chinstrap penguins at Livingston Island preferentially foraged on fish instead of krill. The reason for this switch is unknown but may be due to increased accessibility of more nutritious prey. Increased competition between seals, penguins, and man for the nearshore krill resource, especially during the austral summer months, could have a large impact on the recruitment success of these land-based krill predators. Consequently, the biomass of krill within the foraging ranges of breeding penguins and seals should be routinely surveyed and considered when developing small-scale units, both in space and time, for managing the krill resource.

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