Chinese Journal of Oceanology and Limnology
Vol. 33 No. 3, P. 802-808, 2015
http://dx.doi.org/10.1007/s00343-015-4064-3

Ex situ echo sounder target strengths of ice krill *Euphausia crystallorophias**

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Received Mar. 27, 2014; accepted in principle May 28, 2014; accepted for publication Sep. 22, 2014

Abstract Ice krill is the keystone species in the neritic ecosystem in the Southern Ocean, where it replaces the more oceanic Antarctic krill. It is essential to understand the variation of target strength (TS in dB re 1 m^2) with the different body size to accurately estimate ice krill stocks. However, there is comparatively little knowledge of the acoustic backscatter of ice krill. The TS of individual, formalin-preserved, tethered ice krill was measured in a freshwater test tank at 38, 120, and 200 kHz with a calibrated split-beam echo sounder system. Mean TS was obtained from 21 individual ice krill with a broad range of body lengths (*L*: 13–36 mm). The length (*L*, mm) to wet weight (*W*; mg) relationship for ice krill was W=0.001 218×10^3×$L^{3.53}$ (R^2=0.96). The mean TS-to-length relationship were $TS_{38\ kHz}$=-177.4+57log$_{10}$(L), (R^2=0.86); $TS_{120\ kHz}$=-129.9+31.56log$_{10}$(L), (R^2=0.87); and $TS_{200\ kHz}$=-117.6+24.66log$_{10}$(L), (R^2=0.84). Empirical estimates of the relationship between the TS and body length of ice krill were established at 38, 120, and 200 kHz and compared with predictions obtained from both the linear regression model of Greene et al. (1991) and the Stochastic Distorted Wave Born Approximation (SDWBA) model. This result might be applied to improve acoustic detection and density estimation of ice krill in the Southern Ocean. Further comparative studies are needed with in situ target strength including various body lengths of ice krill.

Keyword: ice krill; *Euphausia crystallorophias*; ex situ target strength; split-beam echo sounder

1 INTRODUCTION

Ice krill is the keystone species in the neritic ecosystem in the Southern Ocean, replacing the more oceanic Antarctic krill at latitudes above 74°S (Hosie, 1994; Pakhomov, 1998; Sala et al., 2002). They form high-density aggregations and constitute a crucial intermediate link between primary production and top predators (Bushuev, 1986) at the high latitudes around Antarctica. To understand the role of ice krill in coastal ecosystems, it is important to determine their density distributions, spatial and temporal variability, and how their populations are controlled by the environmental conditions.

Acoustic surveys are widely regarded as the best approach for estimating the distribution and abundance of krill (Hewitt et al., 2002). For this reason, acoustic detection has been adopted by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) as a key tool for the estimation and monitoring of living marine resources in the Southern Ocean. To obtain accurate acoustic estimates of ice krill stocks, the target strength (TS) is an essential component to convert volume backscattering strength to absolute krill biomass. The TS varies according to acoustic frequency, body length, orientation, shape, density and sound-speed contrast in the body. The frequency and body length are especially important as TS basically depends on the ratio of wavelength to body length and the frequency dependence of TS is applied to discriminate krill from other animals. Thus, it is necessary to determine the relationship between acoustic

* Supported by the Korea Polar Research Institute (No. PP14020) and the Korea Institute of Ocean Science and Technology (No. PN65250)

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Table 1 Echosounder specifications

Parameters	38 kHz	120 kHz	200 kHz
Beam type		Split beam	
Source level (dB)	217.8	221.6	221.5
Pulse length (ms)		0.1	
Ping rate (s)		0.5	
Beam width (°)	10.4	7.5	6.6
Absorption coeff. (dB/m)	0.006 7	0.041	0.074
Calibration offset (dB)	1.7	0.5	0.1
TVG-function		40 log *R*	

backscatter and organism parameters, such as TS vs. log(L) (Foote et al., 1987). However, there is little information on the TS of ice krill, although there are many studies on the TS of Antarctic krill (Foote et al., 1990; McGehee et al., 1998; Demer and Conti, 2005; Amakasu et al., 2006) and acoustic properties of euphausiids (Chu and Wiebe, 2005; Smith et al., 2010). It has been assumed that TS of ice krill would be similar to that of Antarctic krill (Azzali et al., 2006) even though they are biochemically somewhat different (Bottino, 1974) and their acoustic properties are also different in that the density contrast of ice krill is little lower than that of Antarctic krill (Chu and Wiebe, 2005). This would decrease the TS predictions for ice krill, thereby resulting in higher estimates of ice krill biomass.

In this study, the relationship between the TS and length in ice krill was investigated using split-beam echo sounders with three different frequencies. The results were compared with both the empirical formula of Greene et al. (1991) and the Stochastic Distorted Wave Born Approximation (SDWBA) model (McGehee et al., 1998; Demer and Conti, 2005) with the values for density and sound-speed contrasts given by Chu and Wiebe (2005).

2 MATERIAL AND METHOD

Ex situ TS measurements were conducted in August 2012 in a 5 m×5 m×5 m tank filled with fresh water. Split-beam echo sounders (BioSonics DT-X series) with three different frequencies (38, 120, and 200 kHz) were used for the experiments. The transducer was placed at 0.3 m below the water surface in the water tank, facing downwards.

The transducers (BioSonics, 2005), which had -3 dB beam widths of 10.4°, 7.5°, and 6.6°, were mounted on a tow body and centered in the water tank at a depth of 0.3 m. Pulses 0.1 ms in duration were

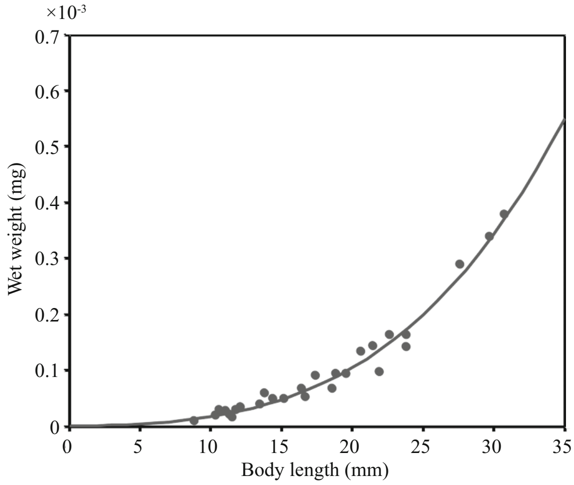

Fig.1 Sizes of the ice krill used in the experiments

Body length (L; mm) and wet weight are displayed on a linear scale. The regression equation is W=0.001218×10^{-3}$L^{3.53}$.

sequentially transmitted every 0.5 s and received about 500 pings with each krill. Short pulses improve range resolution and reduce the reverberation volume and the number of overlapping echoes. The minimum threshold level for all frequencies was set at -120 dB, based on the expected minimum TS for the smaller ice krill. The specifications of the echo sounders are listed in Table 1. Prior to the experiments, the transducers were calibrated via the standard target method (Foote et al., 1987) using copper spheres with respective diameters of 38.1, 23.0, and 16.0 mm for the 38, 120, and 200 kHz units. After data had been collected at all frequencies, each ice krill was removed from the water and weighed.

The ice krill were collected using a bongo net (0.5-m^2 mouth area, 505-μm mesh) in polynyas of the coastal Amundsen Sea in January 2011. On recovery samples were preserved in 10% buffered formalin. For ice krill, individual body length was measured from the anterior margin of the eye to the tip of telson, excluding the setae (Morris et al., 1988). Body lengths specimens ranged from 13 to 36 mm (mean=22.54 mm), and their weights ranged from 0.01 to 0.38 mg (mean W=0.10 mg) (Fig.1). The overall length of ice krill has been characterized from juvenile to adult stage (Sala et al., 2002). Individual ice krill were placed at a depth of 2.5 m along a vertical tether of monofilament that exhibited negligible acoustic energy target strength at 200 kHz. A thin needle with a diameter of 0.1 mm, attached to a 0.1-mm monofilament line, penetrated the first or second abdominal segment of the krill. After the needle was removed from the monofilament line, the end of the vertical line was tied to a 0.5-kg

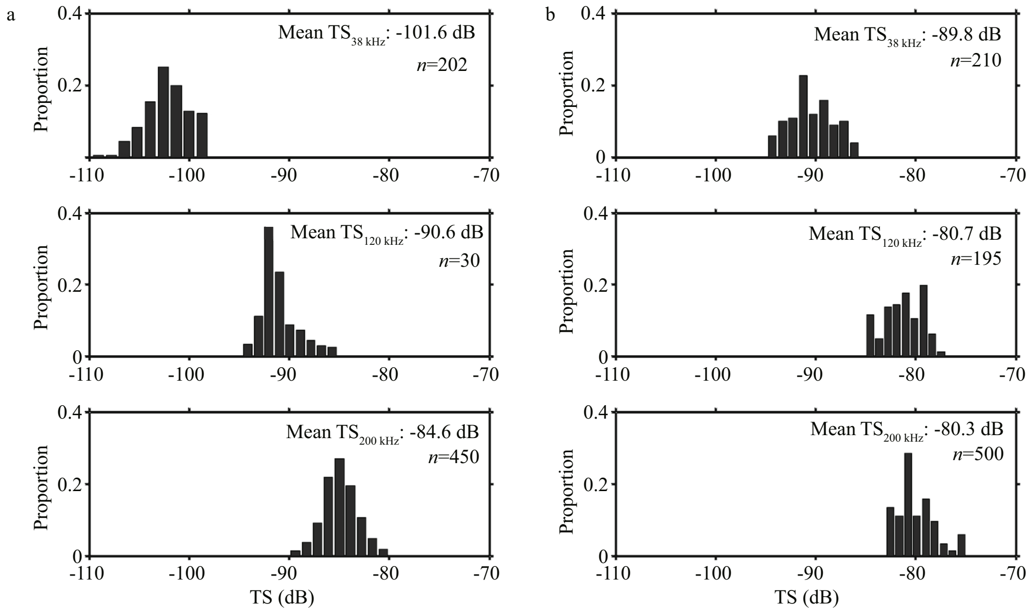

Fig.2 TS histograms for ice krill with lengths of 20 mm (a) and 36 mm (b)

weight. The distance between the connecting line and the weight was 1 m, which was sufficient to separate the ice krill echo from those of the weight and the bottom. Twenty individual specimens were measured during a 2-day period in August of 2012. After measuring the TS, the weight of each ice krill was measured. The ice krill were maintained at an orientation of around 11° with small variations.

3 DATA PROCESSING

Acoustic TS values were extracted via a single-target detection split beam method 2 (Soule et al., 1997) of the Myriax Echoview software (v. 4.50) for split-beam data, which applies compensation estimates to the peak selection based on split-beam angle data. A target-strength threshold of -120 dB was used, and the pulse-length determination level (the value in dB below the peak value considered when determining the pulse length of single-target detection) was 6 dB. The normalized pulse length (measured pulse length divided by transmitted pulse length) was required to be between 0.8 and 1.5. The maximum beam compensation for correcting transducer directivity was set at 4 dB. To confirm that all scattering sources within the measured pulse length were from a single target, all samples within this pulse envelope were required to have an angular standard deviation of less than 10° both along and perpendicular to the direction of the transducer beam. Identified single targets were later analyzed independently. To prevent the inclusion of multiple or unwanted targets, data were selected for analysis based on target depth.

The concept of the relative target strength was used to compare measurement data and empirical acoustic model. The backscattering cross-section (σ_{bs}) is a function of the relative wavelength and relative body length. The relative target strength combines these variables into one expression: relative target strength=10 $\log_{10}[\sigma_{bs}(L/\lambda)/L]$, where λ is predicted length (Medwin and Clay, 1998).

4 RESULT

During the experiments, the water temperature was 25°C, and the salinity was 0, so that the speed of sound was 1 495 m/s. The L vs. wet weight (W; mg) relationship for ice krill was W=0.001 218×10^{-3}×$L^{3.53}$ (R^2=0.96) (Fig.1). The shapes and spreads of the TS histograms differed according to acoustic frequency (Fig.3). For Antarctic krill, many authors have employed a linear relationship between the TS and the logarithm of the length, as it is a simple procedure both for presentation and for later use in applied work (SC-CAMLR, 2005).

$$TS=m\log_{10}(L)+n, \quad (1)$$

where m and n are, respectively, the slope and intercept of the line, and L denotes the length of the krill.

The parameters m and n were estimated using linear regression,. The overall measured mean TS values are plotted against the body lengths of the ice krill in Fig.2. The TS maximum was -89 dB at 38 kHz,

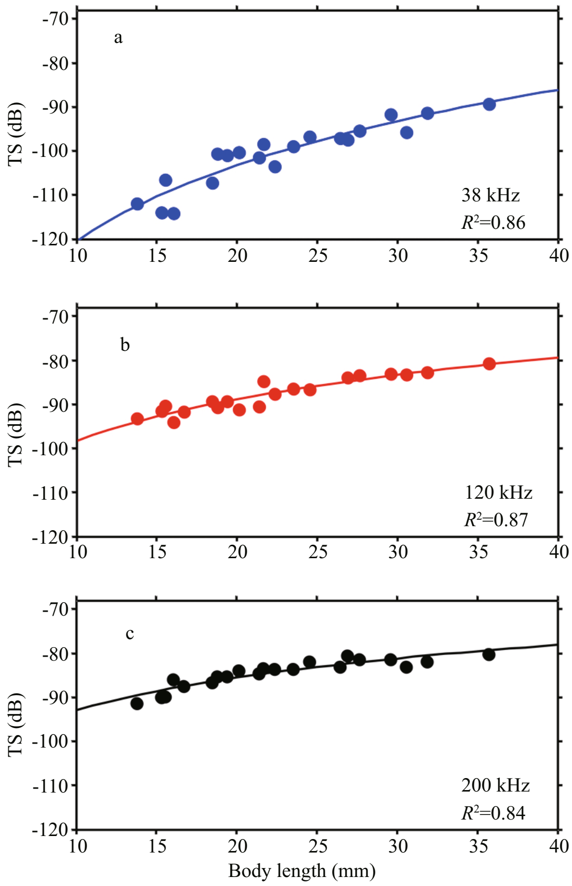

Fig.3 Mean TS (dB re 1 m^2) of ice krill at 38 kHz (a), 120 kHz (b), and 200 kHz (c)

The solid lines represent the linear regression model, TS=m log$_{10}$(L)+n.

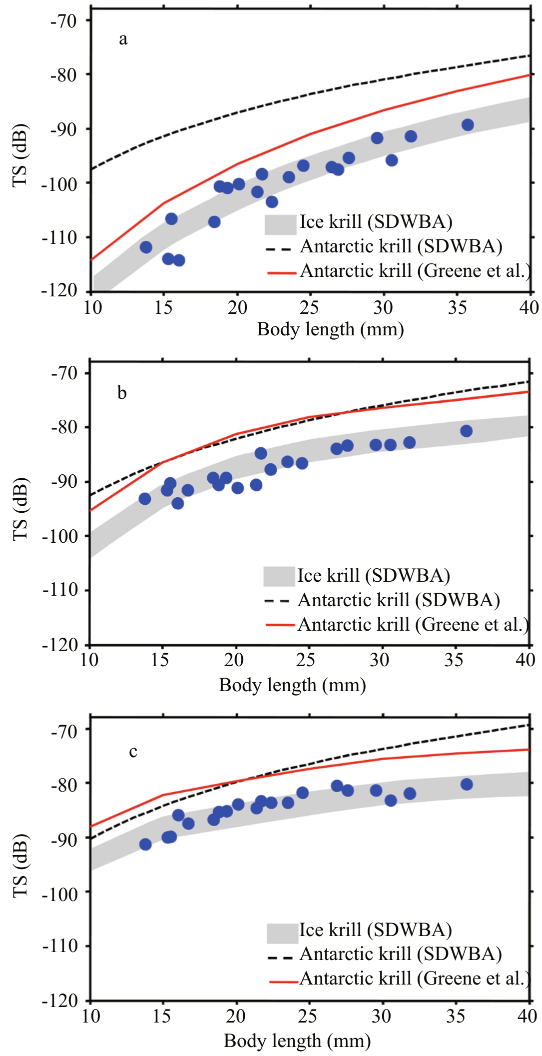

Fig.4 Comparisons of the measured mean TS values with the model predictions as functions of body length at 38 kHz (a), 120 kHz (b), and 200 kHz (c)

The dashed line indicates the predictions from the SDWBA model for Antarctic krill using generic input parameters (L=20 mm, density contrast g=1.035 7, and h=1.027 9). The solid line indicates the TS predictions estimated by the empirical model of Greene et al. (1991). The shaded regions represent the range of TS predictions obtained from the SDWBA model by using the acoustic properties of ice krill. The density and sound-speed contrasts are 1.000–1.009 and 1.025–1.029, respectively (Chu and Wiebe, 2005).

-81 dB at 120, and -80 dB at 200 kHz. The mean TS values for the 20 ice krill ranged from -114 dB to -89 dB at 38 kHz, -94 dB to -81 dB at 120 kHz, and -91 dB to -80 dB at 200 kHz. Overall, the mean TS increased linearly with the length of the ice krill, and the values were lower at 38 kHz than at 120 and 200 kHz. The higher the frequency was, the higher the mean TS values became. The least-square regressions of the 20 paired observations of TS vs. log(L) are (Fig.3):

$TS_{38\ kHz}$=-177.4+57.00log$_{10}$(L) (95% CI: -162.3 to -192.5, 45.8 to 68.7; R^2=0.86), (2)

$TS_{120\ kHz}$=-129.9+31.56log$_{10}$(L) (95% CI: -122.2 to -137.7, 25.8 to 37.3; R^2=0.87), (3)

$TS_{200\ kHz}$=-117.6+24.66log$_{10}$(L) (95% CI: -110.0 to -124.6, 19.5 to 29.9; R^2=0.84), (4)

where R^2 is the coefficient of determination, and the CI are the respective confidence intervals for m and n. The measured results were compared with the result of model predictions.

Figure 4 shows the measured mean TS values with predictions obtained from the representative empirical formula of Greene et al. (1991) and the validated physics-based SDWBA TS model (Demer and Conti, 2005). To predict the TS using the SDWBA model, input parameters that include the density contrast, sound-speed contrast, orientation, fatness, and shape must be determined. Each of the parameter values and the details of the implementation of the SDWBA model have been described elsewhere.

The dashed lines in Fig.4 denote the predictions

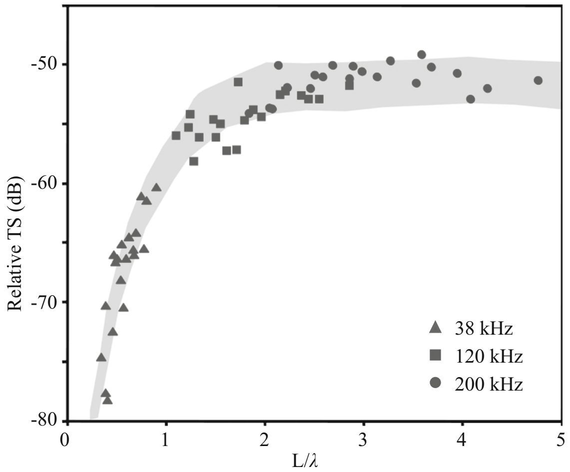

Fig.5 Relative measured mean TS values compared with SDWBA predictions using the respective density and sound-speed contrasts 1.000–1.009 and 1.025–1.029 (Chu and Wiebe, 2005)

The triangle, square and circle indicate the TS of 38 kHz, 120 kHz and 200 kHz, respectively. The gray area indicates the results predicted by the SDWBA model.

obtained from the model of Greene et al. (1991). The measured mean TS values were 11–24 dB lower than the predicted values at 38 kHz, 4–9 dB lower than the predictions of both models at 120 kHz, and 3–9 dB lower than the predictions of both models at 200 kHz. The difference between the predictions and the data is conspicuously larger at 38 kHz than at 120 and 200 kHz. The solid lines in Fig. 4 show the SDWBA results for Antarctic krill using a density contrast of g=1.035 7 and a sound-speed contrast of h=1.027 9. The measured mean TS values were 2–12 dB lower than the predicted values at 38 kHz, 4–9 dB lower than the predictions of both models at 120 kHz, and 3–8 dB lower than the predictions of both models at 200 kHz. The shaded areas denote the ranges of TS values predicted by SDWBA for ice krill with a density contrast of 1.000–1.009 and a sound-speed contrast of 1.025–1.029. The measured mean TS values fell within the ranges of the SDWBA model outputs. An overall comparison of experimental and predicted values reveals that the measured results for Antarctic krill were lower than the predictions of both models, whereas the SDWBA predictions for ice krill (based on the previously published density and sound-speed contrasts) were in reasonably good agreement with the measured data.

Figure 5 shows the relative TS per body length vs. L/λ for ice krill via the SDWBA model with the density contrast of 1.000–1.009 and sound-speed contrast of 1.025–1.029 (shaded area), together with

Table 2 Error quantity *E* over all ice krill samples for each frequency

Frequency	*E*		
	g=1.000 h=1.0025	g=1.0045 h=1.0245	g=1.009 h=1.019
38 kHz	1.96	0.50	1.62
120 kHz	2.16	1.07	1.62
200 kHz	1.06	0.56	2.60

the corresponding measured data. The TS values fell between -115 and -89 dB at 38 kHz, between -95 and -85 dB at 120 kHz, and between -92 and -82 dB at 200 kHz, and they increased with increasing body length.

5 DISCUSSION

Density contrast and sound-speed contrast are dominant acoustic properties for the TS values of zooplankton. The TS values from the least-square regressions of this study fall within the ranges of the SDWBA model outputs predicted with g=1.000–1.009 and h=1.025–1.029, exhibiting the best fit to the model predictions with g=1.004 5 and h=1.027 5. To compare the TS predictions from the SDWBA model with the measurements, an error quantity E was defined as follows:

$$E_{(38,\ 120,\ \text{and}\ 200\ \text{kHz})}=\frac{\sum\sqrt{(\text{TS}_{\text{obs}}-\text{TS}_{\text{SDWBA}})^2}}{n}, \tag{6}$$

where TS_{obs} and TS_{SDWBA} denote the least-square regressions from the measured mean TS values and the TS predictions from SDWBA, respectively, and n denotes the total number of measurements. Twenty pairs of mean TS values were used to calculate, error quantity E (Table 2).

It is common to represent krill target strength as a function of length (Foote et al., 1990; Greene et al., 1991; Hewitt and Demer, 1991). Previous studies have attempted to define the TS of Antarctic krill as a function of length or wet weight. Foote et al. (1990) measured the mean target strengths of 14 individual krill in the range 30–39 mm using a dual-beam transducer (38 and 120 kHz). The TS values were in the range -88 to -83 dB at 38 kHz and -81 to -74 dB at 120 kHz. Chu et al. (1993) measured the backscattering coefficients of caged live krill at 38 and 120 kHz and studied a scattering model for zooplankton as deformed finite cylinders. The target strengths for 13 krill (30–39 mm) ranged from -88 to -84 dB at 38 kHz. McGehee et al. (1998) carried out backscattering measurements on 14 live individual Antarctic krill (30.5–43.6 mm) at 120 kHz in a chilled insulated

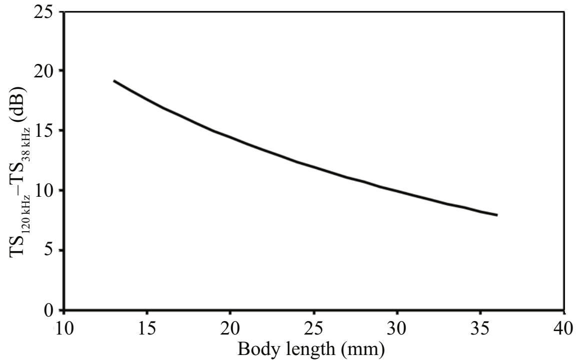

Fig.6 The differences in TS values between 38 and 120 kHz vs. ice krill length

tank. However, there have been relatively a few investigations of the TS of ice krill.

Figure 5 shows the relative TS per body length vs. L/λ for ice krill via the SDWBA model with the density contrast of 1.000–1.009 and sound-speed contrast of 1.025–1.029 (shaded area), together with the corresponding measured data. The TS values fell between -115 and -89 dB at 38 kHz, between -95 and -85 dB at 120 kHz, and between -92 and -82 dB at 200 kHz, and they increased with increasing body length.

The difference in sound frequency S_V between 120 kHz and 38 kHz is a useful indicator for identifying Antarctic krill among other scatters in the Southern Ocean (Madureira et al., 1993). Selecting S_V values characterized by $S_{V120\,kHz}$–$S_{V38\,kHz}$ in the range of 2–16 dB (Hewitt et al., 2002) eliminated most of the non-krill targets. Figure 6 shows the differences in TS between 38 and 120 kHz for measured ice krill in the range of 13–36 mm. It indicates that the linear regression of all the measured ice krill TS values matched the criteria in this study (8 dB$<TS_{120\,kHz}-TS_{38\,kHz}<$19 dB) and was therefore attributed to ice krill. Table 3 represents the ΔTS of three acoustic frequency pairs to classifying acoustic backscatter for krill, which was recently recommended by CCAMLR (CCAMLR, 2007). This relative sound scatter at these frequencies might be used to identify krill acoustically.

Preserved zooplankton in fresh water can have an effect on TS variation (Greenlaw, 1977; Richter, 1985). Following Greenlaw (1977), the TS of the preserved zooplankton has often been measured greater by 10 dB than predicted by models (Anderson, 1950; Johnson, 1977) while it is about 3 to 9 dB lower than the TS of live zooplankton. This may be due to the physical condition of species with buffered solutions (Steedman, 1976), or a more reflective orientation of zooplankton (Greenlaw, 1977). The TS

Table 3 ΔTS range of ice krill for the three frequency pairs

Length range (mm)	ΔTS range (dB)		
	120−38 kHz	200−120 kHz	200−38 kHz
13 to 36	8 to 19	2 to 5	9 to 24

may also vary in ways associated with density and sound-speed, as modulated by water temperature (Greenlaw, 1977; Azzali et al., 2010). The density of *P. antarcticum* bodies change less than 0.03% between 4°C and 30°C, a change which is likely to be negligible. Preserved *Calanus marshallae* does not represent clear density and sound-speed differences between 9°C and 19°C. However, there is little research to clarify the relative TS or acoustic properties (density and sound-speed differences) between preserved and live ice krill in relation to water temperature. This study thus provides useful experimental data to allow better understanding of the TS variation between preserved and live ice krill.

6 CONCLUSION

Ex-situ TS measurements were conducted for individual ice krill with a broad range of sizes using split-beam transducers at 38, 120, and 200 kHz. The measured TS values were compared to predictions obtained from the Greene et al. model and the SDWBA model. Overall, the measured mean TS for sizes between 13 and 36 mm fell between -114 and -89 dB at 38 kHz, -94 and -81 dB at 120 kHz, and -91 and -80 dB at 200 kHz, and they increased linearly with ice krill length. The measured TS values were lower than the predictions from both the Greene et al. model and the SDWBA model for Antarctic krill with g=1.035 7 and h=1.027 9, while the measured data fell within the SDWBA model predictions with g=1.000–1.009 and h=1.025–1.039 for ice krill. Least-squares regressions of the observed TS vs. $\log_{10}(L)$ were compared to the SDWBA model predictions, and the best-fit curve was found with g=1.004 5 and h=1.027 5.

Ice krill is a key species in the neritic Southern Ocean, but its distribution and biomass estimates are still associated with large uncertainties. In particular, there is a lack of information about the magnitude and variability of the TS of ice krill in the field both with respect to body length and to its behavior. Here, we present ex situ measurements of ice krill TS with split-beam echo sounders at 38, 120, and 200 kHz. This result will be useful to improve acoustic detection and density estimates of ice krill. Further experimental work is needed to examine the TS pattern of live ice krill related to the sound frequency, length, and orientation. Acoustic properties of ice krill also need to investigate with the effect of different body length as a comparative study between ice krill and Antarctic krill.

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