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Volume backscattering strength of ice krill (*Euphausia crystallorophias*) in the Amundsen Sea coastal polynya

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ABSTRACT

Volume backscattering strength (S_v in dB re 1 m^{-1}) of ice krill (*Euphausia crystallorophias*) was observed at two frequencies (38 and 120 kHz) with a calibrated split-beam echosounder system in the Amundsen Sea coastal polynya. The horizontal and vertical scattering layers in the upper 200 m of the water column were known with the existence of predominant ice krill (>95%) in this region. Acoustic identification using a two-frequency dB window between S_v at 38 and S_v at 120 kHz separated echoes originating from dominant ice krill from other zooplankton species. The frequency dependence of ice krill at 38 and 120 kHz was examined and the result presented that ice krill might have different acoustic characteristics from other Southern Ocean zooplankton species including *Euphausia superba*. This result could be applied to improve the ability of acoustic identification and precise density estimation of ice krill in the high-latitude coastal waters of Antarctica.

1. Introduction

Euphausia crystallorophias, commonly known as 'ice krill', is a keystone species of the neritic ecosystem in the Southern Ocean, replacing *Euphausia superba* (Antarctic krill) in the shelf water close to the Antarctic continent (Siegel, 1987; Siegel and Piatkowski, 1990; Boysen-Ennen et al., 1991; Hosie and Cochran, 1994; Pakhomov and Perissinotto, 1996; Guglielmo et al., 2009). Ice krill is a principal food source for various Antarctic animals such as Minke whales (Bushuev, 1986), Weddell seals (Plotz, 1986), Adélie penguins (Puddicombe and Johnstone, 1988; Whitehead et al., 1990) and fish (Hubold, 1985; Williams, 1985). It might play an important role in the carbon cycle in the Antarctic coastal ecosystem (Kittel and Presler, 1980). However, its overall spatial distribution and ecosystem are not well quantified in comparison with Antarctic krill.

Amundsen Sea coastal polynya is considered to be the most productive polynya in the Southern Ocean (Arrigo and van Djijken, 2003), as well as being an important habitat for ice krill (La et al., 2015a). High densities of ice krill were detected along the ice shelf and near the boundary between pack ice and coastal polynya during the summer season (La et al., 2015a). Ice krill and copepods are highly abundant mid-trophic level organism in this region, causing significant grazing pressure, which can be linked to heightened phytoplankton productivity during summer (Lee et al., 2013).

Acoustics is a useful method to study zooplankton distribution (Holliday and Pieper, 1995). Acoustic surveys have been widely conducted to determine the spatial distribution of krill abundance and its ecology in the Southern Ocean since the early 1970's (Everson, 1988). Target identification methods using multi-frequency echo sounders are often used for identifying Antarctic krill in biomass surveys and in krill ecology studies (Demer and Conti, 2005; CCAMLR, 2010) and also to observe the spatial and temporal distribution and abundance variation of Antarctic krill (Trathan et al., 1995; Hewitt et al., 2004; Lawson et al., 2008; Jarvis et al., 2010). On the other hand, only a few acoustic surveys have been conducted to study ice krill distribution and estimate density. In addition, there is little knowledge on the acoustic properties of ice krill such as the volume backscattering strength, target strength, sound speed contrast (h) and density contrast (g). In some studies ice krill has been considered similar to Antarctic krill and the target strength of Antarctic krill was applied to estimate ice krill density (Azzali et al., 2006; Amakasu et al., 2011). However to our knowledge, the generalized dB identification method has not been applied to distinguish between acoustic signals from ice krill and those from other Antarctic zooplankton. La et al. (2015a) applied a model-calculated dB difference window for ice krill to estimate ice krill density in the

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Amundsen Sea but it is important to validate with repetitive in-situ observations.

This paper considers the important question of whether the range and absolute values of volume backscattering strength (S_v dB re 1 m^{-1}) of ice krill is different from other Antarctic zooplankton. We present S_v distributions of two acoustic frequencies commonly used during fisheries acoustic surveys. The relationship between S_v at 38 and S_v at 120 and the S_v threshold for ice krill are examined to compare six Antarctic zooplankton species. Thus providing basic knowledge of acoustic information for ice krill identification and potentially improving the ability to generate validated of acoustic estimates of ice krill abundance during acoustic surveys in the high-latitude Antarctic coastal waters.

2. Materials and methods

Acoustic data presented here were collected in the Amundsen Sea coastal polynya aboard IBRV *Araon* for 329 km on 12 (09:54 UTC)-13 (23:11 UTC) February 2012 (Fig. 1). A Simrad EK60 scientific echosounder was used with split-beam transducers at 38 and 120 kHz to observe S_v. System calibration using standard spheres was conducted after the survey (Foote et al., 1987; Table 1). A pulse length of 1 ms and a ping rate of 2–5 s were employed at all frequencies with a constant ship speed of 6 knots.

Acoustic data were processed using Myriax Echoview software (v. 4.50). The data was filtered to remove acoustic signals corresponding to the surface aeration, ice noise from the ship's passage through the ice breaking, and then the data were resampled at a vertical resolution of 5 m between 7 m to 400 m below the transducer and a horizontal resolution of 1850 m (1 nmi) bins. The background noise of each frequency was removed with a time-varied threshold (TVT) function (Myriax, 2012). The acoustic signals of noise-free echograms were attributed to backscattering from ice krill by use of the expected dB identification technique (Watkins and Brierley, 2002; La et al., 2015a). The method used for ice krill identification was detailed in La et al. (2015a), and thus a summary is given here. The data thresholded using maximum threshold values of −80 dB at 38 kHz and −65 dB at 120 kHz with a two-frequency ($S_{v120-38}$) dB window identification of 12.4–17.9 dB. A stochastic distorted-wave born approximation (SDWBA) target strength model (McGehee et al., 1998; Demer and Conti, 2005) was used to determine $S_{v120-38}$, and estimate in-situ distribution of orientations for the measured length-frequency distribution of ice krill. In the SDWBA parameterization, the density and sound-speed contrast (g and h) were used with 1.0357 and 1.0279 (Foote, 1990), respectively. A generic body shape was 40% fatter (Conti and Demer, 2006) than the one by McGehee et al. (1998). The orientation distribution was N[13°,19°], which was inverted by the least-square estimate to give the best fit to the in situ acoustic data (Conti and Demer, 2006). Actually 12.4–17.9 dB calculated from SDWBA model in La et al. (2015a).

Oblique net hauls were conducted with a Bongo net (mouth area of 0.5 m^{-2}, 500-μm mesh) on the scattering layer from 250 m to the surface within coastal polynya (Fig. 1 and Table 2). Each haul was conducted about 1 h with 2–4 knots. The samples were used to verify the length–frequency distribution of ice krill for the acoustic identification.

3. Results and discussion

The echograms clearly indicate the existence of a horizontally continuous and vertically distinguished scattering layer (Fig. 2). Under the calm and flat sea surface, the minimum *Sv* detected was as low as −110 dB. Under these low noise conditions the echograms revealed a vertically structured pattern of acoustic backscatter in the upper 400 m of the water column. Horizontal layers were observed below the thermocline at 40 m and mainly distributed at depths from 50 to 200 m. Horizontal scattering layers were continually detected throughout the transect, and appeared to be persistent during both day and night. Ice krill was the predominant euphausiid at depths from 50 m to 200 m of the water column (more than 95% of the composition of all the net samples) where the acoustic data presented here were recorded within the

Table 1
Calibration specifics for transceivers (EK60).

Frequency (kHz)	38	120
Transmitted power (W)	2000	500
Pulse duration (ms)	1.024	1.024
Two-way beam angle (dB)	−20.60	−21.00
Receiver bandwidth (kHz)	2.43	3.03
Transducer gain (dB)	21.35	26.17
3-dB Beam angle (along/athwart) (°)	7.06/6.99	6.67/6.57
Absorption coefficient (dB km^{-1})	9.90	24.84
s_A correction	−0.44	−0.35
Sound speed (m s^{-1})	1449	1449

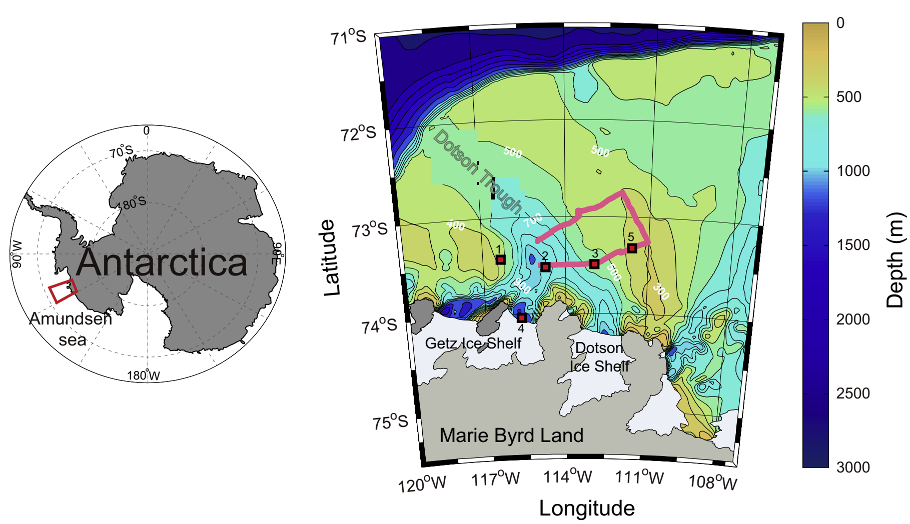

Fig. 1. A map of the region with the acoustic transect (solid red line) and net (red squares) on the bathymetry within the Amundsen Sea coastal polynya. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Amundsen Sea coastal polynya (La et al., 2015a). Length–frequency distribution for ice krill in these essentially monospecific layers had a mean length of 18.7 mm, with a range from 10 to 37 mm.

The relationships between S_v at 38 kHz and S_v at 120 kHz for ice krill was given in Fig. 3. Fig. 3a is a scatter plot of S_v at 120 kHz against corresponding S_v at 38 kHz between 50 and 200-m depth. The gray dots represent the whole S_v within the scattering layer while the green dots represent S_v after classification with an $S_{v120-38}$ dB window of 12–18 dB for ice krill. This dB window corresponds to 25th to 75th percentile of the whole $S_{v120-38\ kHz}$ (Fig. 3d). A linear regression equation was given with 95% confidence limits for the slopes and intercepts on the scatter plot (green dots) (Table 3). The histograms were examined to observe S_v distribution of ice krill at frequency dependence (Fig. 3b and c). The mean and standard deviation of the histograms were −96.3 dB (SD=6.6) at 38 kHz and −82.3 dB (SD=6.3) at 120 kHz, which did not show the differences with −94.9 dB (SD=5.1) at 38 kHz and −81.4 dB (SD=6.4) at 120 kHz from the whole S_v (gray lines) (Mann–Whitney *U*-test, $p<0.05$). Both frequencies have a clear uni-modal distribution between −110 and −60 dB. Overall, the mean S_v increased with frequency, and the values were lower at 38 kHz than at 120. The S_v ranged from −110 dB to −80 dB at 38 kHz and −98 dB to −68 dB at 120 kHz. Approximately, 80% of the integrated energy ranged between −100 and −90 dB at 38 kHz and −85 and −75 dB at 120 kHz. The S_v distribution and maximum threshold of ice krill at 120 kHz were only 70% of values for Antarctic krill (Hewitt et al., 2003). S_v distribution of Antarctic krill observed from 1996 to 2002 was between −90 and −50 dB, with 80% of the integrated energy occurring between −70 and −50 dB. The maximum threshold at 120 kHz was set up with −50 dB attributed to backscattering for the echograms from Antarctic krill from 1992 to 1995 when no dB differences were available as only 120 kHz data were collected.

We suggest that the differences in the S_v distributions observed for Antarctic krill and ice krill are due to the differing size ranges of krill but also can be due to acoustic properties (*h* and *g*), shape differences and orientation. In this study, there are two effects: (1) different threshold levels related to differences in packing densities of the aggregations and (2) dB difference related with an animal size effect. Theory estimation and field measurements have explained that the difference between 38 and 120 kHz caused by krill is dependent on krill size (Stanton et al., 1994; Brierley et al., 1998). Ice krill length varied from 10 to 37 mm while Antarctic krill was larger, between 15 and 57 mm. The different acoustic properties caused by their different diets may be another reason (Bottino, 1974; Kattner and Hagen, 1998). Chu and Wiebe (2005) has observed that *g* for ice krill is 1.000–1.009, which is lower than *g* for Antarctic krill of a similar body length (1.026–1.027), which can cause the lower target strength (La et al., 2015b). Both the smaller body length and lower *g* can cause the lower S_v. However, both the limited data set of Chu and Wiebe (2005) and ex situ TS experiment of La et al. (2015b) imply a further study to verify the acoustic properties of ice krill.

Antarctic krill has been distinguished from other Southern Ocean zooplankton species on the basis of relative S_v. Three common Southern Ocean macrozooplankton, *Euphausia frigida, E. superba, and Themisto gaudichaudii* were classified using the S_v differences of two frequencies (38 and 120 kHz) (Madureira et al., 1993b). Brierley et al. (1998) successfully recognized these species and additionally classified two more species (*Rhincalanus gigas and Thysanoessa macrura*) using the discriminant function analysis of S_v differences at three frequencies (38, 120, and 200 kHz). However, they did not set dB difference window to classify the species but generate the dB difference from layers that were identified by net sampling. Thus, it is possible to see how many values for the krill layer fell outside the dB

Table 2
The net station details including station location, start date and time, and water depth.

Net #	Latitude (S)	Longitude (W)	Date (YYYY. MM.DD)	Start time (HH:MM, UTC)	Water depth (m)
1	73.4312	116.3570	2012.02.11	21:00	374
2	73.5070	114.9965	2012.02.15	22:20	938
3	73.4999	112.9566	2012.0214	15:00	570
4	74.0042	115.6616	2012.02.18	07:40	1060
5	73.3216	111.6105	2012.02.19	14:47	330

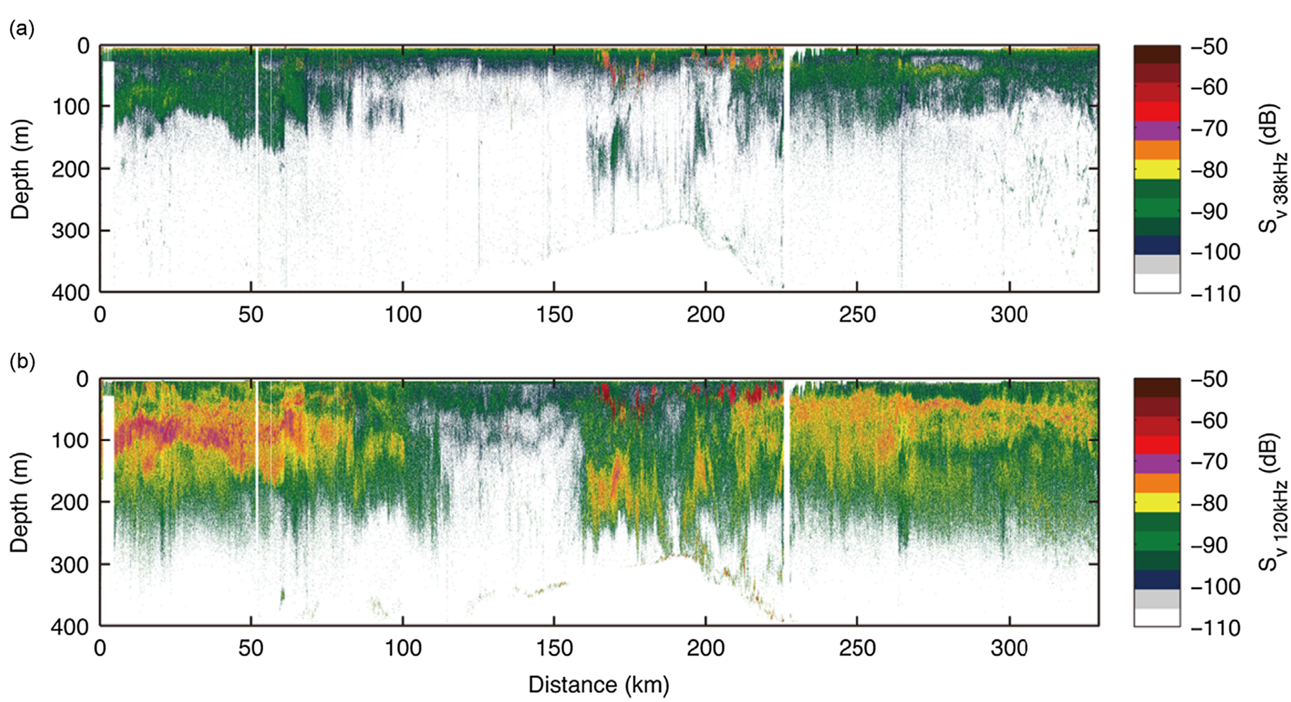

Fig. 2. Echograms of the acoustic transect for the top 400 m of the water column. (a) 38 kHz and (b) 120 kHz.

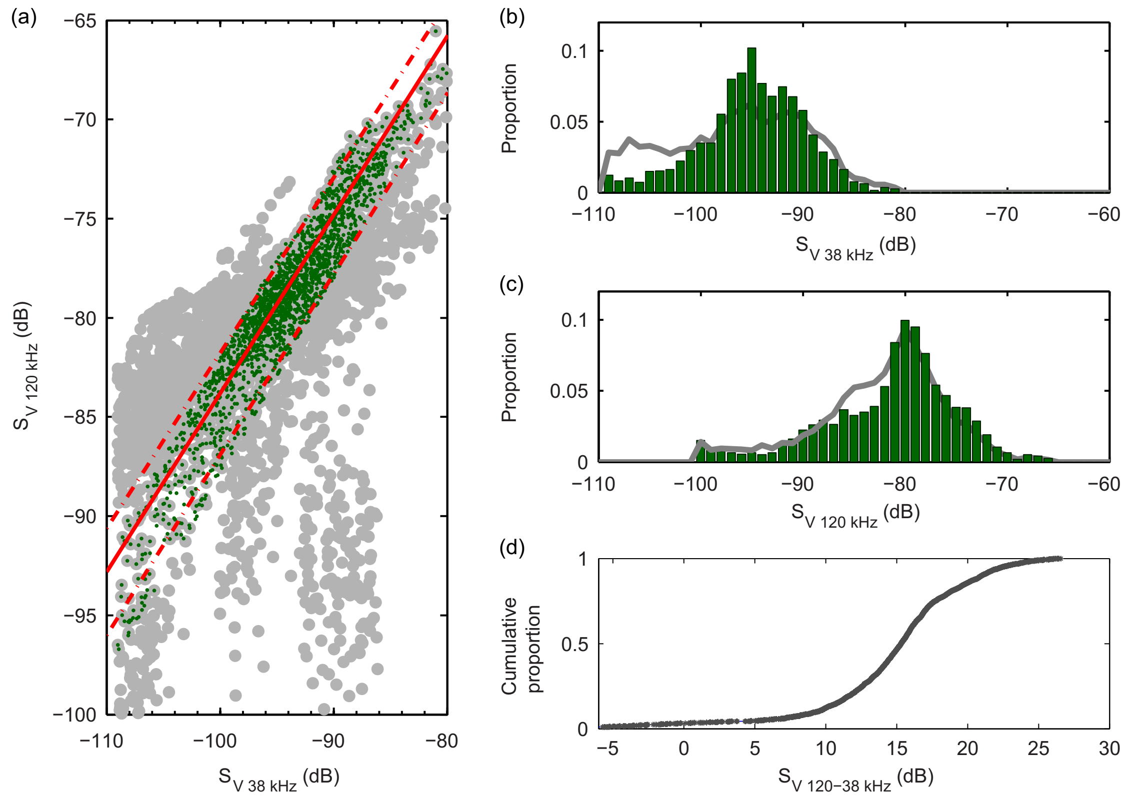

Fig. 3. Scatter plot of volume backscattering strength (S_v) at 120 kHz against 38 kHz between 50 and 200 m (a). The gray and green dots indicate the whole S_v and S_v classified with dB difference window of 12–18 dB for ice krill, respectively. The solid red line and dashed red line represent the linear relationship between S_v at 38 and S_v at 120 kHz with 95% confidence limits, respectively. Regression equation is $S_{v120\ kHz}=5.50+0.89\ S_{v38\ kHz}(r^2=0.90,\ n=1950)$. Histograms of S_v distribution at (b) 38 kHz and (c) 120 kHz. The gray lines and green bars indicate the whole S_v of each frequency and S_v classified with dB differece window of 12–18 dB for ice krill, respectively. The cumulative distribution function (CDF) of the whole $S_{v120-38\ kHz}$ between 50 and 250 m (d). Note that 25th and 75th percentile of CDF are 13 and 18 dB, respecitvely. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Regression equations between S_v at 120 kHz (y) and 38 kHz (x) for ice krill and Antarctic zooplankton species.

Zooplankton species	n	Regression equation	Intercept ±95	Slope ±95	
Euphausia crystallorophias	1950	$y=5.50+0.89x$	3.96–7.05	0.88–0.91	This study
Euphausia superba	180	$y=16.8+1.13x$	13.06–20.54	1.08–1.18	Brierley et al. (1998)
	–	$y=7.61+1.05x$	–	–	Madureira et al. (1993b)
Euphausia frigida	939	$y=-30.3+0.66x$	−35.70 to −24.90	0.60–0.71	Brierley et al. (1998)
	–	$y=-25.1+0.50x$	–	–	Madureira et al. (1993b)
Antarctomysis maxima	88	$y=13.7+1.06x$	11.80–15.60	1.04–1.08	Brierley et al. (1998)
Rhincalanus gigas	1086	$y=-33.2+0.56x$	−35.58 to −30.82	0.53–0.59	
Thysanoessa macrura	273	$y=-27.6+0.60x$	−32.35 to −22.85	0.55–0.65	Brierley et al. (1998)
Themisto gaudichaudii	218	$y=-40.1+0.56x$	−46.51 to −33.69	0.49–0.63	Brierley et al. (1998)
	–	$y=20.44+1.13x$	–	–	Madureira et al. (1993b)

difference window of 2−12 dB. In further investigations, the relationship of S_v between 38 and 120 kHz for ice krill could be used to compare data from other zooplankton species. It could be useful to determine whether ice krill is separable from other species. Fig. 4 shows scatter plots of S_v at 120 kHz against corresponding S_v at 38 kHz for ice krill with the linear regression relationship for each of the seven macrozooplankton. The regression equation and 95% confidence limits for the slopes and intercepts of these relationships are represented in Table 3. The y-intercept and slope of the linear regression for ice krill both fall outside of other zooplankton's 95% confidence intervals for these values. The slope value for ice krill is similar to the slope value of *E. superba* given by Madureira et al. (1993b) but the y-intercept falls below *E. superba* reported by Brierley et al. (1998), Madureira et al. (1993b), and La et al. (2015a). The relatively high increase of $S_{v120-38}$ for ice krill was observed that $S_{v120-38}$ is higher than $S_{v120-38}$ of *E. superba*. It could be possibly related to the different scattering response at different frequencies due to the different acoustic properties of ice krill, even if they have similar body lengths. (Chu and Wiebe, 2005; La et al., 2015b).

4. Conclusion

Species identification using S_v at multi-frequency acoustic signals is a fundamental study in the context of acoustic surveys. In this study, we have described the different frequency response of ice krill between S_v at 38 and S_v at 120 kHz, which have not been reported before in order to compare them with the values of other Southern Ocean zooplankton. Ice krill has shown acoustically different frequency response from other Southern Ocean

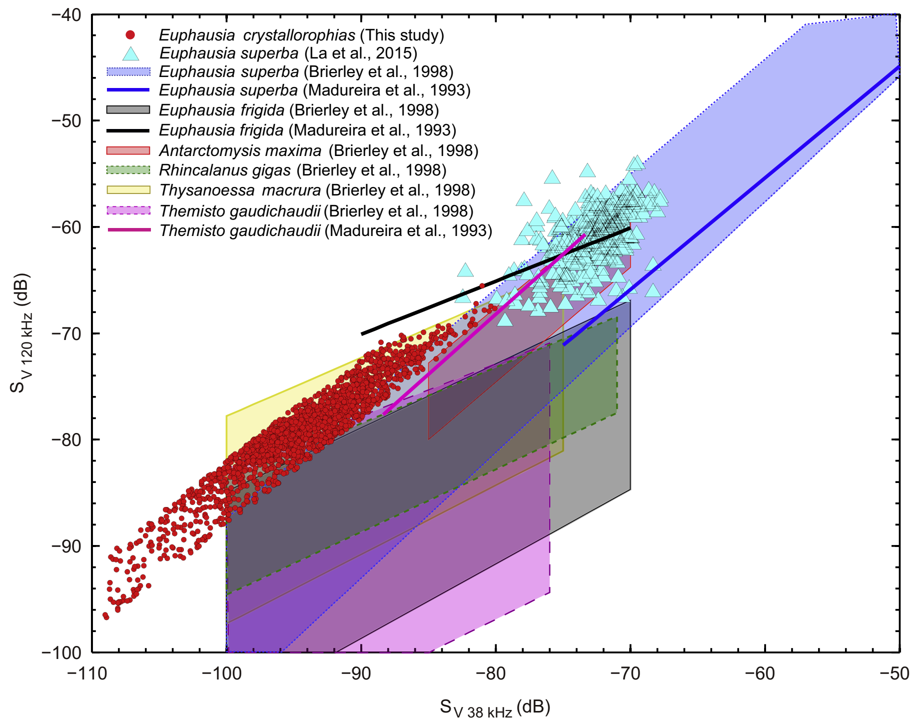

Fig. 4. Comparison of the relationship between $S_{v38\ kHz}$ and $S_{v120\ kHz}$ for ice krill (red circles) with other Southern Ocean zooplankton. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

zooplankton. In particular, ice krill could be separated from *E. superba* using their characteristic differences in S_v at 38 and 120 kHz, as $S_{v120-38}$ for ice krill was higher than that for *E. superba*. Biomass estimation of ice krill using acoustics can therefore be more accurate if this result is applied for acoustic survey in the high-latitude coastal waters, Antarctica. Also, in situ measurements of the target strength and acoustic properties (h and g) on live ice krill are necessary to verify the acoustic signal characteristics as species descriptors with a wide range of frequencies.

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