Ocean Sci. J. (2020) 55(3):391–403
http://dx.doi.org/10.1007/s12601-020-0031-9

Article

Available online at http://link.springer.com
SpringerLink

Ocean Science Journal

pISSN 1738-5261
eISSN 2005-7172

Verification of the Backscattering Strength Based on the Swimming Behavior of Antarctic Krill

Inwoo Han[1], Wooseok Oh[2], Hyoung Sul La[3], Seok-Gwan Choi[4], Sukyung Kang[5], Euna Yoon[6], and Kyounghoon Lee[2]*

[1]*Climate Change Research Division, National Institute of Fisheries Sciences, Busan 46083, Korea*
[2]*Division of Fisheries Science, Chonnam National University, Yeosu 59626, Korea*
[3]*Division of Polar Ocean Environment, Korea Polar Research Institute, Incheon 21990, Korea*
[4]*Distant Water Fisheries Resources Research Division, National Institute of Fisheries Science, Busan 46083, Korea*
[5]*Fisheries Resources Management Division, National Institute of Fisheries Science, Busan 46083, Korea*
[6]*Fisheries Resources Research Center, National Institute of Fisheries Science, Tongyoung 53064, Korea*

Received 7 May 2020; Revised 14 June 2020; Accepted 15 June 2020

Abstract – This study provides an estimate of the SDWBA-modelled mean target strength for given sets of krill length and swimming orientation. The range of the dB identification window for krill length was between 28 mm and 67 mm and the distribution of swimming orientation N[11.0°, 4.0°] was estimated to be between 0.06–10.97 dB, while the range estimated using N[53.1°, 21.4°], i.e., the distribution of orientation obtained under the brightest illuminance level, was 5.21–9.82 dB. The range of the dB window calculated using N[45.2°, 23.0°], obtained under the second brightest illuminance level, was 3.83–11.76 dB, and the range calculated with N[48.1°, 23.0°], obtained under the third illuminance level, was 3.83–11.76 dB. The range of the dB window calculated by N[45.9°, 23.0°] was 3.41–11.75 dB, and the range of the dB window for krill length ranging from 28 mm to 67 mm was 4.05–11.34 dB. In all the swimming orientations, the smaller the krill size was the lower the averaged target strength value was; likewise, the larger the krill size was the higher the averaged target strength value was. The result indicated that swimming orientation impacted greatly on the range of frequency differences of Antarctic krill.

Keywords – Antarctic krill, SDWBA model, swimming orientation, target strength

1. Introduction

Krill are found in all the world's oceans, but those inhabiting the Southern Ocean play a particularly crucial role. Antarctic krill (*Euphausia superba*) plays an important role in the marine food chain of the Southern Ocean as the species is the primary source of food for top predators including penguins, whales, and seals. So if these species did not feed on krill, they would consume krill eating predators. Due to its abundant status and rich omega-3 content, Antarctic krill is used as source of various nutritional supplements including dementia prevention supplements and dietary supplements (Kang et al. 1999; Everson 2000; Greenpeace 2018).

Korea began krill fishing in 1978 and is the third largest krill fishing nation in the world, following Norway and China. The waters of the South Shetland Island (Subarea 48.1), South Orkney Island (Subarea 48.2), and South Georgia (Subarea 48.3) where Korean krill fleets operate, contain ecosystems where marine living organisms who feed on Antarctic krill inhabit. SC-CAMLR-XXII, an annual Scientific Committee meeting of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), has noted a possible conflict between the Antarctic marine living resources and the krill fishing vessels in the said three Subareas (CCAMLR 2003). Accordingly, the CCAMLR, in order to reduce the impact of krill fisheries on the Antarctic ecosystems, has been providing an annual total allowable catch of krill in Area 48 of the Atlantic sector of the Southern Ocean since 1982. Furthermore, joint research initiatives including the estimation of resources using scientific echosounder systems led by the Member states of CCAMLR have been conducted for the management of Antarctic krill resources.

*Corresponding author. E-mail: khlee71@jnu.ac.kr

It is important to determine the density distribution and standing stock in order to promote the sustainable management and rational use of Antarctic krill resources. Approaches used to estimate the density distribution and standing stock of krill in the Southern Ocean include mainly trawl surveys, zooplankton net surveys, and acoustic surveys. One of the strengths of surveys associated with a trawl net or a zooplankton net is that accurate species identification can be done, while setting gears may be difficult depending on the environmental factors such as water depth, seabed topography, current, and wind. Furthermore, the results produced from such types of surveys are often not sufficient as the survey area is limited to stations, and the surveys may experience difficulties due to time and financial constraints. On the other hand, an acoustic survey is often used to estimate the spatio-temporal distribution and the standing stock, as its sampling covers the water column of a wide area in a relatively short period of time.

In order to estimate the standing stock using an acoustic survey method, accurate target strength estimates are needed (Maclennan and Simmonds 2013). Generally, a method for obtaining estimates regarding the strength of a target animal would either be an experimental approach or a theoretical approach. An experimental approach can be categorized as either an ex-situ or in-situ type of method, and a theoretical approach includes using a theoretical acoustic scattering model. Direct measurement is often impractical for zooplankton and other small organisms. In that case, a theoretical approach should be taken, using a theoretical acoustic scattering model to estimate the target strength of the living organism (Lee et al. 2010). In order to determine the target strength of an animal using a theoretical acoustic scattering model, estimates for parameters such as the animal's shape, size, internal density contrast, sound speed contrast, frequency, and swimming orientation must be obtained. An accurate target strength (TS) value at a given swimming orientation must be determined as any change of orientation caused by an animal's swimming behavior will accompany a change in the TS value and will eventually lead to a change in the estimate of the standing stock.

Previous studies on the TS of Antarctic krill includes Everson et al. (1990), Foote et al. (1990), Furusawa et al. (1994), Hewitt and Demer (1996); however, few studies have been conducted to date on the TS estimates at a given swimming orientation and illuminance level. Therefore, this study aims to analyze the acoustic scattering properties of Antarctic krill with regard to its swimming orientations at given illuminance levels, using the SDWBA (Stochastic Distorted-Wave Born Approximation) model, one of the theoretical acoustic scattering models, to make comparisons with previous studies, and to use the result as a basis to increase the level of precision in estimating the standing stock of Antarctic krill.

2. Materials and Methods

Sampling of Antarctic krill

Samples used were 20 Antarctic krill individuals collected using a zooplankton net during the acoustic survey conducted by R/V *ARAON*, Korea Polar Research Institute (7,507 tonnage, KOPRI, Korea) from 16th to 21st February 2019. The net used to collect the samples was an FMT (Framed Midwater Trawl) midwater trawl net installed on IBRV *ARAON* with 2 m of net height, 2 m of net width, and 330 μm of mesh size. Antarctic krill samples were collected at 7 stations in the Ross Sea area, kept in the acrylic water tank, and observed for their swimming orientations (Fig. 1).

Experimental water tank and illuminance device

This study used an acrylic water tank of 40 cm in width, 25 cm in length, and 32 cm in height (Fig. 2). Collected Antarctic krill individuals were tamed in the tank for 24 hours to allow them to adapt to a new environment. Krill were left undisturbed so they

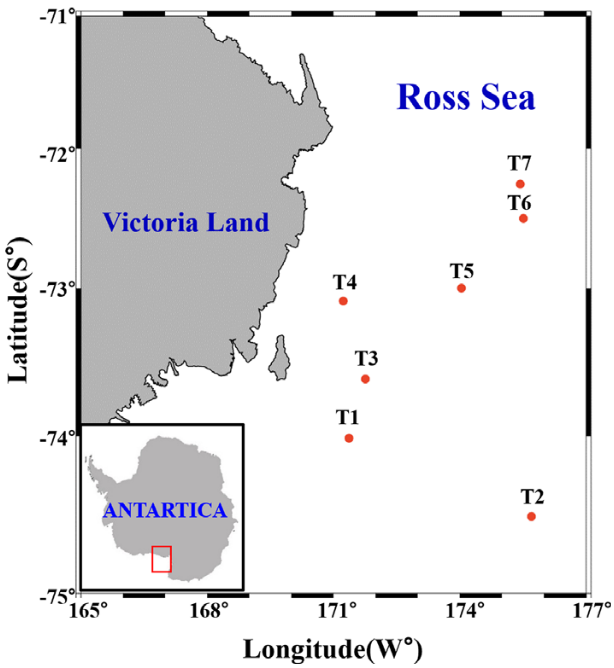

Fig. 1. The collection location of Antarctic krill for the measurement of swimming orientation

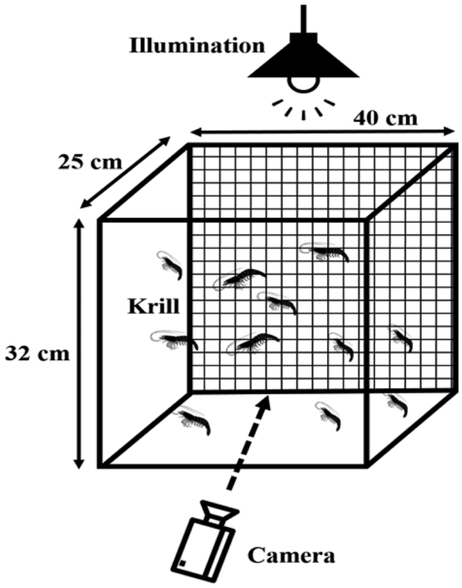

Fig. 2. Experimental water tank used for the photographing method for the swimming orientation measurement and image system

could swim freely in the tank, and lighting was installed to determine whether the level of illuminance drives any change in their swimming behavior. The light source used in the experiment was a white LED lamp with 450 nm wavelength, and the color temperature was 4000 degrees Kelvin (K). The experiment was undertaken at 5 different levels of illuminance, i.e., 216 lx, 36.25 lx, 23.98 lx, 12.58 lx, and 0.025 lx. Five different levels of illuminance were applied to the measurement, and an illuminance meter (T-10, Konica Minolta Sensing Co., Ltd., Korea) was used to measure the illuminance after the experiment. The illuminance meter used had a measuring range of 0.01–299,900 lx. The illuminance was measured after the experiment using the illuminance meter. The tank was filled with seawater at a water temperature of approximately

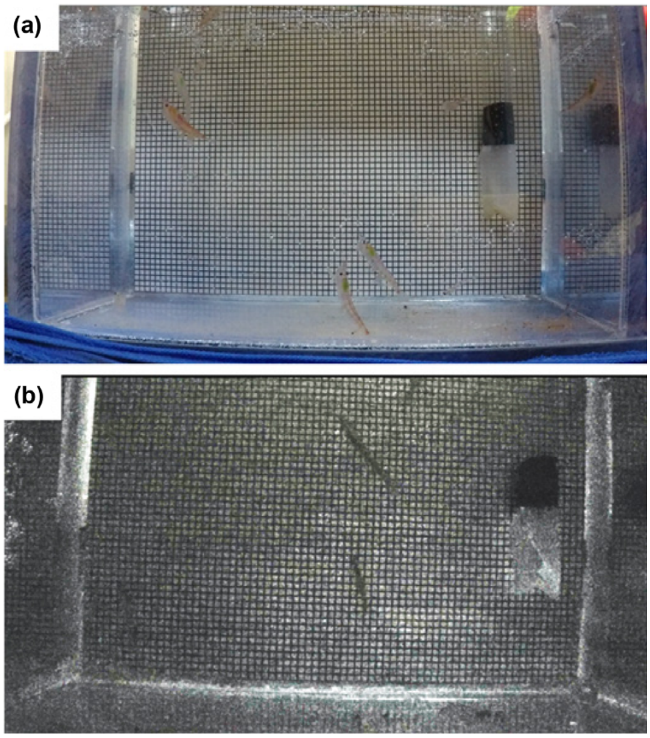

Fig. 3. Video data stored in the swimming orientation measurement water tank at the brightest (a) and darkest (b) illuminance

5°C, 20 Antarctic krill individuals were put into the tank, and their behavioral characteristics were studied (Fig. 3).

Digitization of Antarctic krill length

Since acoustic scattering models approximate the contour shape of a target animal into a cylindrical object, a detailed set of coordinates for the contour shape must be obtained. In order to quantify the contour shape of the Antarctic krill, 20 individuals were randomly selected among the collected krill samples and were grouped by size, then placed on a scaled fish measuring board, and a photograph was taken

Krill	AT : 57 mm
	Body width : 9 mm

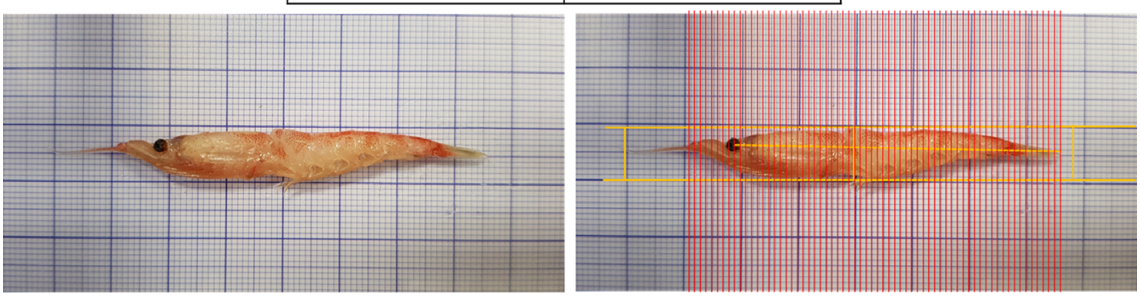

Fig. 4. Example of digitizer used to quantify the contour shape of Antarctic krill

from above using a digital camera. Images sampled with the digital camera were digitized by 0.1 mm interval to obtain the coordinates of the contour shape, using a digitizer program (GetData Graph Digitizer, Shareit, Germany). The image distortion was maintained to less than 0.05 mm in the x-axis and 0.1 mm in the y-axis, and obtained coordinates were averaged to determine the generic contour shape of an Antarctic krill (Fig. 4).

A method of analyzing swimming orientation by illuminance levels

The photographs were taken using a single camera (Gopro4, Gopro Co., Ltd., USA) at the resolution of 1920 × 1080 pixels for the given 5 levels of illuminance. In order to determine the swimming orientation of Antarctic krill, the video recordings of the water tank were replayed and stored in a computer using a video capture board. Image sampling rate was set to 0.5 frame/sec; images were captured using an image capture program; images captured from video recordings using a capture board were transformed into jpeg formatted files for analysis; and the recorded images were edited using an editing software (Adobe Photoshop Ver. 12, Adobe Systems Incorporated, USA). Behavioral characteristics of Antarctic krill were analyzed under each illuminance level, and corresponding swimming orientation was determined using a software program (Image J, Java, USA) (Fig. 5). Image J software, capable of displaying continuous images, was used to assign each sample's center of the eye to the telson on an x-y coordinates plane and to automatically determine the swimming orientation of Antarctic krill. Any image with an overlap between krill individuals or sample with distortion in its orientation were excluded from the measurement. The end of the telson was defined as the origin of the coordinate axes (0, 0), an angle made by a head up orientation was considered a positive value, and that made by a head down orientation was considered a negative value.

Studying acoustic scattering properties using an acoustic model

Small organisms like zooplankton, krill species, and neomysis species, small fish whose swim bladder has not been developed, and jellyfish whose body contour is difficult to determine have weak backscattering properties, so that measuring backscattering strength on site can be an extremely difficult task. In this case, the DWBA (Distorted Wave Born Approximation) model and SDWBA (Stochastic distorted Wave Born Approximation) model, the high-frequency models capable of describing the animal in detail, can be used to estimate the backscattering strength of such animals. This study utilized the GetData Graph Digitizer program to determine the body contours of 20 Antarctic krill individuals by their size. Then the SDWBA model, a method of estimating acoustic scattering properties by approximating animal contour shape discretized into fine cylindrical sections, was used to estimate the backscattering strength. The DWBA-modeled acoustic scattering amplitude f_{bs} can be obtained from the following equation (Stanton et al., 1996; McGehee et al., 1998):

$$f_{bs_j}(\phi) = \frac{k_1}{4}\int_{\vec{r}_{pos}}^{0} a_j(\gamma_k-\gamma_p)e^{-i2\vec{k}_1\cdot\vec{r}_{pos}}\frac{J_1(2k_2\cos\beta_{tilt})}{\cos\beta_{tilt}}|d\vec{r}_{pos}| \quad (1)$$

where k = wave number ($k = 2\pi/\lambda$), λ = wavelength (c/f), c = wave speed (m/sec), f = frequency (Hz), the lower subscript 1 = the medium of seawater, a = radius of the cylindrical section, $\gamma_k = \left(\frac{\rho_1 c_1^2}{\rho_2 c_2^2}\right)$ related to the compressibility, $\gamma_p = (\rho_2$ -

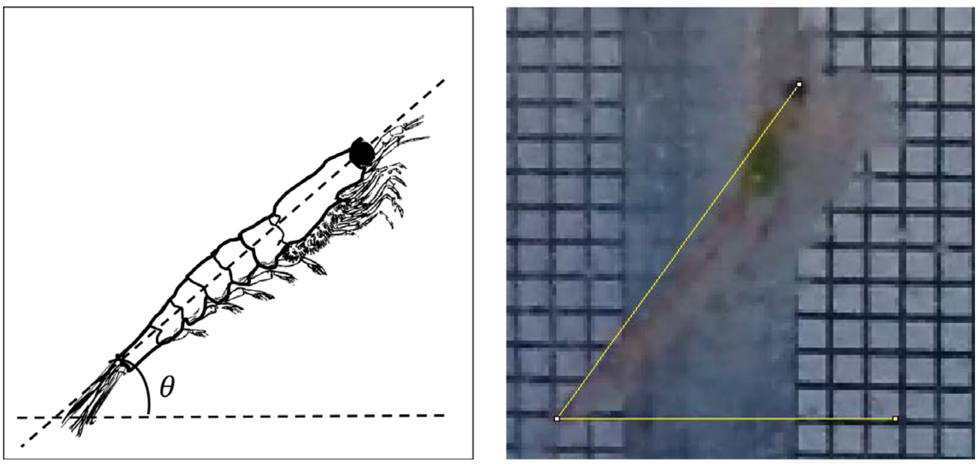

Fig. 5. The tilt angle measurement for the swimming orientation of Antarctic krill and the digitizing program used in the measurement

$\rho_1)/\rho_2$ with ρ the mass density, J_1 = the type 1 Bessel function, β_{tilt} = the angle between the incident wave and the cylindrical axis, $\vec{r}_{pos}$ = the position vector (x, y, z) of the center of mass when digitizing Antarctic krill. The relationship between the scattering amplitude and the TS value the study aims to determine can be described by the following equation:

$$TS = 10\log(|f_{bs}|^2) \qquad (2)$$

The SDWBA model is a modification of the DWBA model, describing an animal body contour using a statistical approach. The SDWBA model probabilistically provides TS estimates for all direction angles based on the assumption that scattering factors accompany a number of sources of variability. The SDWBA function for the angle of incidence Φ is obtained by summing the components f_{bs} calculated for each of the N cylinders with a different random phase φ_j.

$$f_{bs}(\Phi) = \sum_{j=1}^{N}(f_{bs}(\Phi))_j \cdot \exp(i\varphi_j) \qquad (3)$$

The phase variability of each cylinder j along the body is selected based on Gaussian distribution centered in 0 and standard deviation. The backscattering cross section σ_{bs} is obtained by averaging over multiple realisations of the ensemble of phase φ_j with fixed standard deviation sd_φ, and the TS at specific angle of incidence Φ is obtained by the following equation:

$$TS(\Phi) = 10\log_{10}\sigma_{bs}(\Phi) = 10\log_{10}\langle|f_{bs}(\Phi)|^2\rangle_\varphi \qquad (4)$$

In order to determine the TS of Antarctic krill using a theoretical acoustic scattering model, estimates for the parameters such as the krill's body contour, size, internal density contrast, sound speed contrast, and swimming orientation must be obtained. When measuring the total length of Antarctic krill samples, the 'Discovery' method (Siegel 2016), the standard measure endorsed by CCAMLR, was used to measure the total length in mm, from the Anterior margin of the eye to the tip of the telson excluding the terminal spine; the range of the length measurements made on 20 krill individuals was 28.0–67.0 mm. The parameters, density contrast (1.0357 kg/m^3) and sound speed contrast (1.0279 m/s) were determined based on Demer and Conti (2003), and sound velocity was set to 1,456m/s. For the basic parameterization, the number of cylinders (14), krill length (38.35 mm), and fatness coefficient (40%) were determined referring to McGehee et al. (1998). For the operational parameterization, frequencies were set to 38 kHz and 120 kHz, incidence angles from -90° to 90°, and stochastic realization to 100 in order to obtain a statistical average.

This study firstly applied the swimming orientations of the 5 illuminance levels as a parameter of the previous study (McGehee et al. 1998) and obtained the TS estimates to make comparisons with those of the previous studies for the frequencies 38 kHz and 120 kHz; secondly, using the obtained swimming orientation, the TS of the 20 krill having different lengths was estimated to analyze the TS trend as the krill length changes. Thirdly, this study fed the digitized representation of krill contour shape into the SDWBA model as a parameter, determined the averaged TS for each krill length measurement of the 20 samples using a mean swimming orientation, and calculated the range of the frequency difference of the two frequencies, 38 kHz and 120 kHz.

3. Results

The analysis result on the swimming orientation and behavior at given illuminance levels

The frequency distribution of swimming orientation measurements of Antarctic krill at given illuminance levels is presented in Fig. 6. Illuminance was categorized into 5 levels. The horizontal axis represents the swimming orientation and the vertical axis represents the frequency. N represents the number of data points, Avg. is the averaged swimming orientation, and S.D. is standard deviation. Also, the red solid line represents the normal distribution of the swimming orientation obtained from the averaged swimming orientation and standard deviation.

The analysis of the distribution of orientations of Antarctic krill at given illuminance levels has shown that, at the brightest illuminance, 216.00 lx, 2,324 individuals of krill were measured in the stored images, averaged swimming orientation was 53.12°, and standard deviation was 21.47. At 36.25 lx, a total of 1,444 individuals' swimming orientation was measured; averaged swimming orientation was 45.28°; and standard deviation was 23.00. At 23.98 lx, a total of 1,391 individuals were measured; averaged swimming orientation was 48.27°; and standard deviation was 23.08. At 12.58 lx, 1,194 individuals' swimming orientation was measured; averaged swimming orientation was 45.97°; and standard deviation was 23.03. With the lowest illuminant level, 0.02 lx, 1,442 individuals' swimming orientation was measured; averaged swimming orientation was 46.17°; and standard deviation was 19.95.

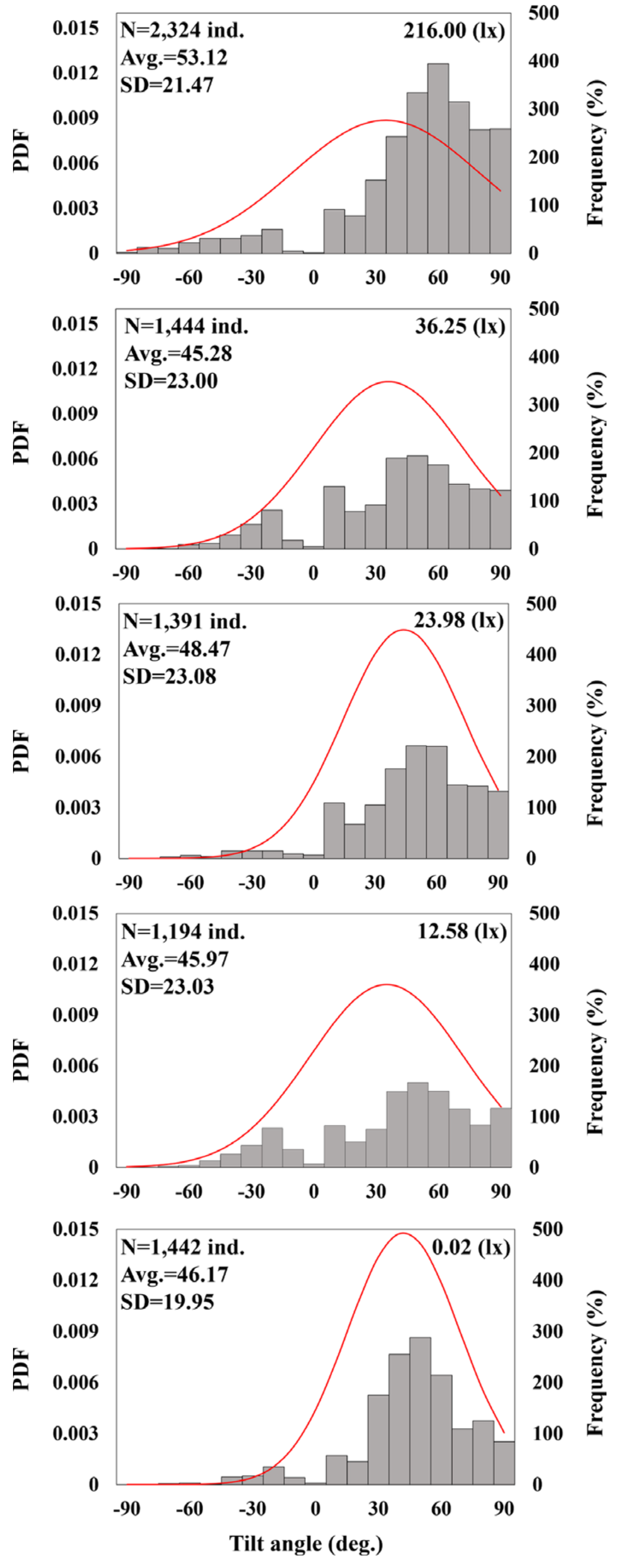

Fig. 6. Frequency distribution of swimming orientation measurement by the illumination of Antarctic krill. The probability density function (PDF) is a function whose integral is calculated to find probabilities associated with a continuous random variable in statistics

To summarize the analyzed results, krill were shown to swim at 47° in general. Although inconsistent, larger tilt angles of around 60° were observed at the brightest illuminance, and stable swimming orientation were observed at the lowest illuminant level.

Analysis result of the contour shape digitization

The result of the shape digitization is illustrated in Fig. 7. A digitizer program was used to obtain the x and y coordinates of the contour shapes of the 20 randomly selected Antarctic krill individuals. The x axis represents the digitized value of the krill length, and y axis represents the center point of the dorsal and ventral coordinates. The measurements of krill shape ranged from 28 mm to 67 mm, and shape coordinates of all 20 individuals were determined. For krill with 28 mm in length, a maximum of 26.00 mm of coordinates was digitized, and the average y value was 3.02 mm with higher values notable on the tail side. For 30 mm of krill length, the digitized length was 26.83 mm, and the average y value was 4.18 mm with higher values being observed on the head side. For 33 mm of krill length, the digitized length and average y value were 30.95 mm and 3.91 mm, with higher values evident on the head side. For krill with 44 mm in length, the maximum digitized length was 38.61 mm, and the average y value was 5.42 mm, presenting a head up shape. For the lengths 43 mm and 45 mm, the digitized lengths and average y values were respectively 39.95 mm and 14.03 mm and 39.55 mm and 11.34 mm, showing a head up and tail down shape. There were samples of length 45 mm, 51 mm, and 54 mm whose digitized lengths were identical to each other but each with a different type of contour shape. For the krill length of 55 mm, a maximum length of 46.55 mm was measured, and the average y value was 5.86 with higher values being observed on the tail side. For the krill length of 56 mm, the maximum length measured was 53.31 mm, and the average y value was 5.38 with higher values on the head side. For the krill length of 58 mm, 61 mm, 62 mm, and 67 mm, higher values were observed on both head and tail side. Digitizing the contour shapes of 20 krill individuals with differing lengths provided length coordinates ranging from 26.00 mm to 66.24 mm, each of which had varying krill width coordinates from head to tail.

Acoustic scattering properties by swimming orientation

The trend of the TS inferred from the SDWBA model based on the distribution of swimming orientation of Antarctic krill is illustrated in Fig. 8. The horizontal axis represents the

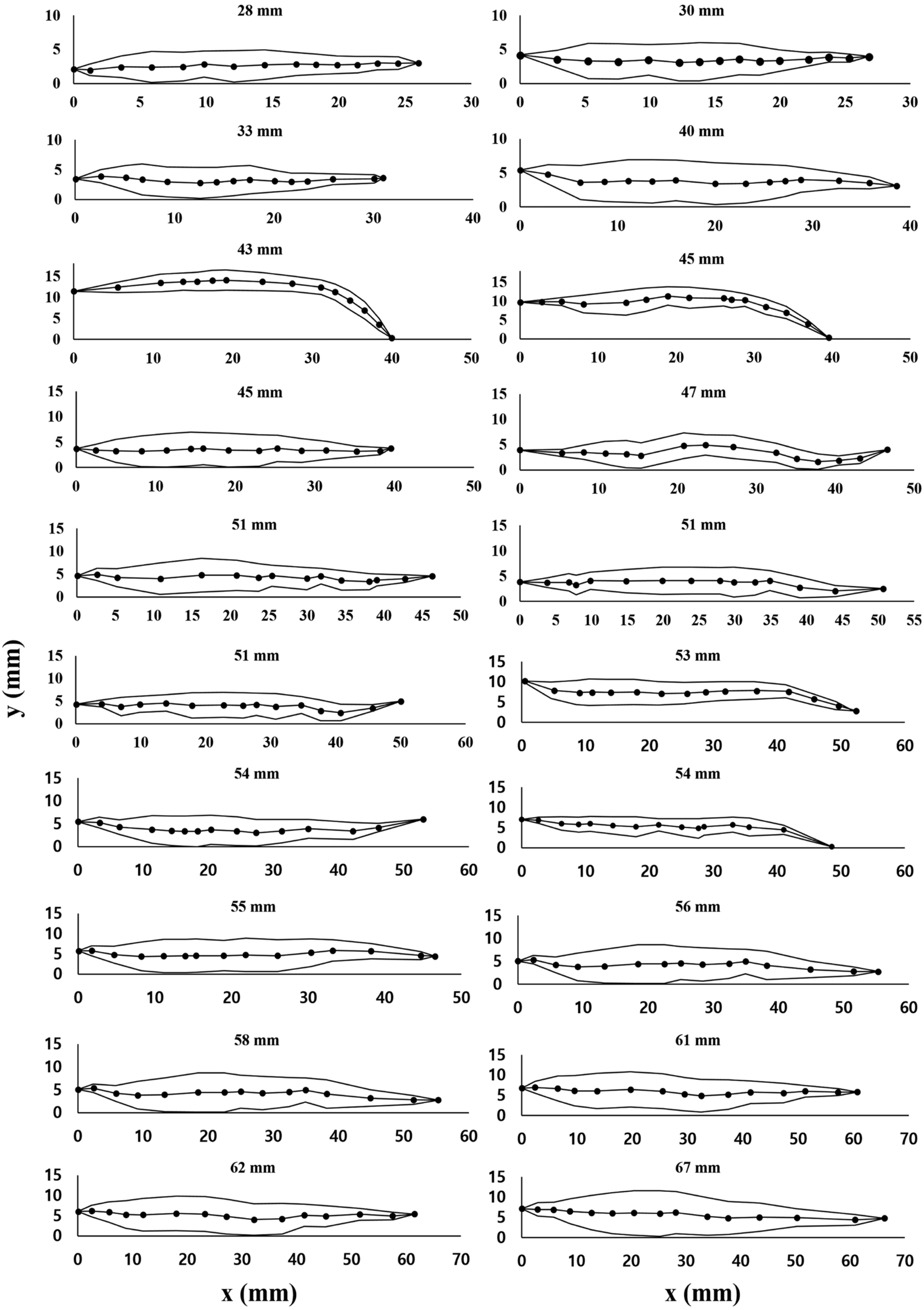

Fig. 7. The digitized results of body shapes of Antarctic krill

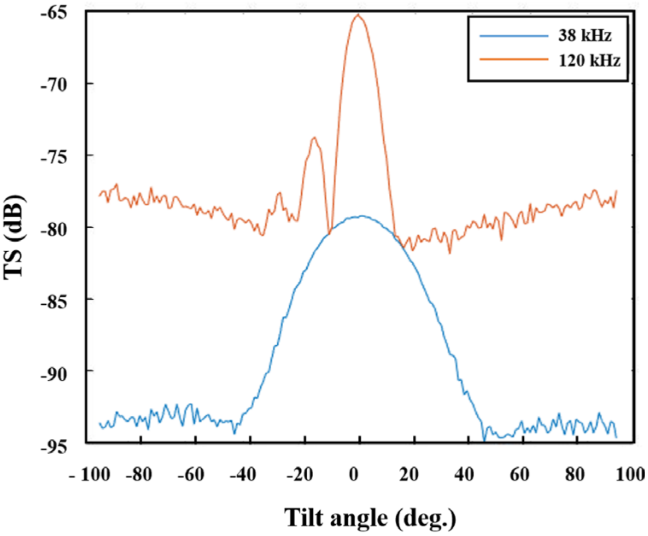

Fig. 8. The target strength estimation of Antarctic krill measurement by SDWBA models according to swimming orientation. The blue line represents 38 kHz, and the red line represents 120 kHz

swimming orientation of Antarctic krill (deg.), the vertical axis represents the TS (dB), the blue line represents 38 kHz, and the red line represents 120 kHz. The distribution of swimming orientation was in the range of -90° to 90°. The maximum TS value estimated by the SDWBA model was observed when the swimming orientation was at the horizontal 0° and decreased as the angle tilted.

The TS based on the distribution of orientation measured at given illuminance levels was determined using the SDWBA model at frequencies 38 kHz and 120 kHz (Table 1). Standard AT length of 38.35 mm and fatness coefficient of 40% presented in McGehee et al. (1998) were used for the estimation. When the default swimming orientation 11.0° and standard deviation 4.0° was applied to the SDWBA model, the TS was -80.64 dB at 38 kHz and -74.09 dB at 120 kHz, which were similar to the values in Calise and Skaret (2011). With the distribution N[53.1°,21.4°] obtained under the brightest illuminance level 216.0 lx, the TS was -89.27 dB at 38 kHz and -77.93 dB at 120 kHz. TS calculated based on 36.25 lx was -87.23 dB at 38 kHz and -76.85 dB at 120 kHz, and TS obtained based on 23.98 lx was -87.80 dB at 38 kHz and -77.18 dB at 120 kHz. The values were -87.37 dB and -76.94 dB for 12.58 lx, and under the lowest illuminant level 0.02 lx, TS was -88.22 dB at 38 kHz and -77.60 dB at 120 kHz. For the brightest illuminance level 216 lx, the TS at 38 kHz had the lowest dB levels among its counterparts, while the TS at 120 kHz, i.e., -76.85 dB obtained from orientation of 45.2°, was the highest among its counterparts. Changes in TS values with orientation angle were more prominent at 120 kHz; measurement of more diverse angles of orientations may be required in order to predict average TS values at higher frequencies.

Quantified SDWBA model and averaged target strength

This study applied the digitized coordinates of krill contour shapes as values of a model parameter and obtained the averaged TS estimates at frequencies 38 kHz and 120 kHz as described in Figs. 9 and 10. The horizontal axis represents the swimming orientation, the vertical axis represents the TS, and solid lines represent the TS values for each krill length size in the range 28 mm to 67 mm at 38 kHz and 120 kHz. The maximum TS values for frequencies 38 kHz and 120 kHz were both observed when the swimming orientation was at 0° and decreased as the angle tilted. Also, small individuals had less impact with regard to change of orientation on TS, while large individuals had a greater impact with regard to change of orientation.

At 38 kHz, the impact regarding the change of orientation on TS was not significant for krill individuals that were 28 mm, 30 mm, and 33 mm in length, although it was observed for individuals that were 40 mm in length or greater, indicating that small individuals have a weak average TS at 38 kHz. At 120 kHz, TS estimates of krill individuals with lengths up to 43 mm revealed low values less than around -70 dB, but the TS values increased as krill length increased. For krill individuals that were 43 mm, 45 mm, 47 mm, and 54 mm in length, null

Table 1. Averaged target strength at 38 and 120 kHz measured by the SDWBA model according to the swimming angle of each illumination

L (mm)	fts(%)	Lux (lx)	N (deg.)	Average TS_{38kHz}	Average TS_{120kHz}
38.35	40	-	11.0°, 4.0°	-80.64	-74.09
		216.00	53.1°, 21.4°	-89.27	-77.93
		36.25	45.2°, 23.0°	-87.23	-76.85
		23.98	48.1°, 23.0°	-87.80	-77.18
		12.58	45.9°, 23.0°	-87.37	-76.94
		0.02	46.1°, 19.9°	-88.22	-77.60

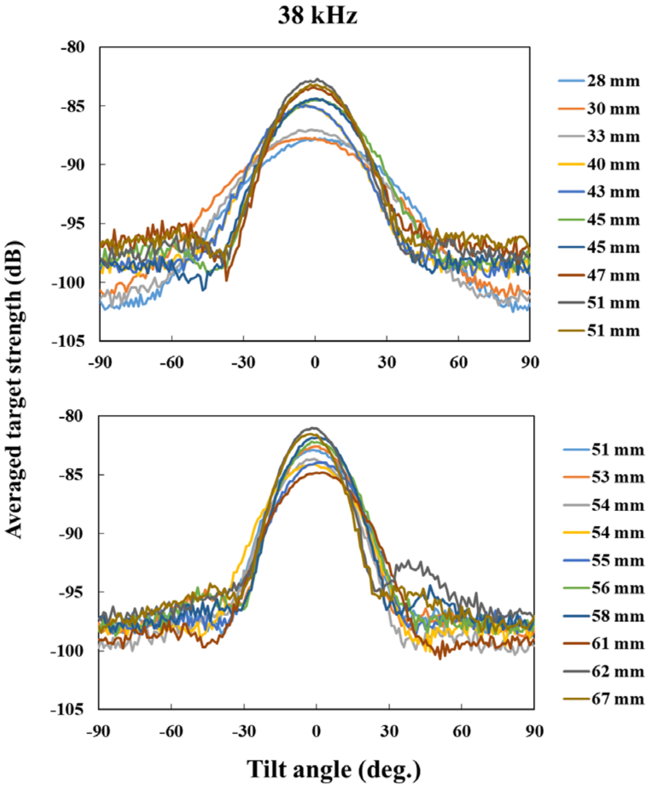

Fig. 9. The averaged target strength at 38 kHz according to the swimming angle was applied to the SDWBA model by digitizing data of body length

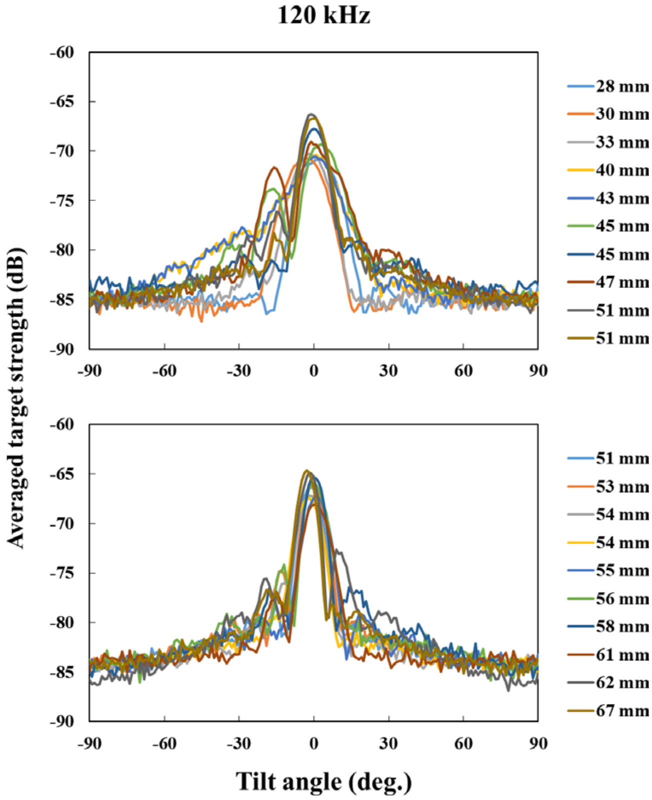

Fig. 10. The averaged target strength at 120 kHz according to the swimming angle was applied to the SDWBA model by digitizing data of body length

values often occurred in both frequencies 38 kHz and 120 kHz, and this appears to have resulted from erroneous digitized shapes caused by severely bent tail or twisted body. For krill individuals that were 45 mm, 51 mm, and 54 mm in length, whose digitized lengths were identical, TS estimates showed a similar trend to the change of swimming orientation, except for the case of 45 mm at 120 kHz when a null value occurred. Higher averaged TS values were observed at both frequencies 38 kHz and 120 kHz when the swimming orientation was at 0°, and the larger the krill length was the greater the observed averaged TS value was.

Averaged target strength by krill length and swimming orientation using the SDWBA model

This study measured the length and swimming orientation of Antarctic krill; estimated the averaged TS at 38 kHz and 120 kHz using the SDWBA model based on the obtained length and orientation; and determined the range of frequency difference by krill length (Fig. 11). When the default swimming orientation 11.0° and standard deviation 4.0° was applied to the SDWBA model, the averaged TS of krill with the smallest length, 28 mm, was -87.89 dB at 38 kHz and -76.92 dB at 120 kHz. For the length of 67 mm, the averaged TS was -70.15 dB at 38 kHz and -70.09 dB at 120 kHz. The range of frequency difference between 28 mm and 67 mm was 0.06–10.97 dB.

When the swimming orientation and standard deviation obtained under the brightest illuminance level of this study was applied, i.e., 53.1° and 21.4°, the averaged TS of krill with 28 mm in length was -95.12 dB at 38 kHz and -85.29 dB at 120 kHz. For the length of 67 mm, the averaged TS was -78.54 dB at 38 kHz and -73.32 dB at 120 kHz. The range of frequency difference was 5.21–9.82 dB. When the swimming orientation and standard deviation obtained under the second brightest illuminance level was applied, i.e., 45.2° and 23.0°, the averaged TS of krill with 28 mm in length was -93.26 dB at 38 kHz and -81.51 dB at 120 kHz. For the length of 67 mm, the averaged TS was -76.50 dB at 38 kHz and -73.22 dB at 120 kHz, and the range of frequency difference was 3.28–11.74 dB. When the swimming orientation and standard

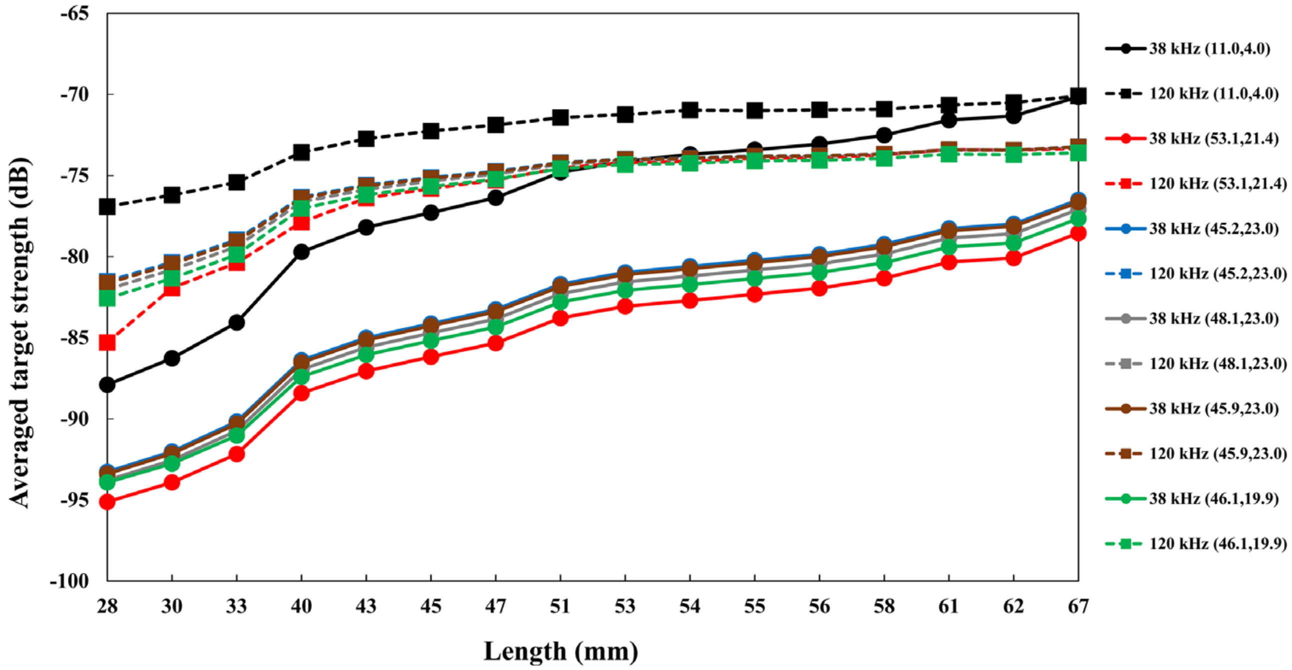

Fig. 11. Averaged target strength of the Antarctic krill by body size and swimming orientation using the SDWBA model

deviation obtained under the 3rd illuminance level was applied, i.e., 48.1° and 23.0°, the averaged TS of krill with 28 mm in length was -93.78 dB at 38 kHz and -82.01 dB at 120 kHz. For the length of 67 mm, the averaged TS was -77.08 dB at 38 kHz and -73.24 dB at 120 kHz, and the range of frequency difference was 3.83-11.76 dB. When the distribution N[45.9°, 23.0°] was applied, the averaged TS of krill with 28 mm in length was -93.39 dB at 38 kHz and -81.64 dB at 120 kHz. For the length of 67 mm, the averaged TS was -76.64 dB at 38 kHz and -73.22 dB at 120 kHz. The range of frequency difference between 28 mm and 67 mm was 3.4–11.75 dB. When the distribution N[46.1°,19.9°], obtained under the 5th illuminance level, was applied, the averaged TS of krill with 28 mm in length was -93.91 dB at 38 kHz and -82.57 dB at 120 kHz. For the length of 67 mm, the averaged TS was -77.65 dB at 38 kHz and -73.60 dB at 120 kHz. The range of frequency difference between 28 mm and 67 mm was 4.05–11.34 dB. In all of the swimming orientations, the smaller the krill size was the lower the averaged TS value was; likewise, the larger the krill size was the higher the averaged TS value was. The result indicated that swimming orientation impacted greatly on the range of frequency difference of Antarctic krill (Table 2).

4. Discussion

There have been biomass and acoustic estimates of Antarctic krill and other zooplanktons reported by many researchers (Greenlaw 1979; Holliday et al. 1989; Inagaki et al. 1992; Peter and Charles 1994). However, Antarctic krill, zooplankton, and other small living organisms, due to their small size, have very small acoustic scattering energy, and the targets are aggregated at high densities such that it is difficult to distinguish single individuals (Miyashita et al. 1996). Because of this reason, ecological information such as the target organism's swimming orientation and swimming behavior is required in order to make an accurate biomass estimation.

This study measured swimming orientation for 5 levels of illuminance, namely, N[53.1, 21.4] at the brightest illuminance 216.00 lx, N[45.2, 23.0] at 36.25 lx, N[48.1, 23.0] at 23.98 lx, N[45.9, 23.0] at 12.58 lx, and N[46.1, 19.9] at the lowest illuminant level 0.02 lx. At all 4 levels of illuminance except when the illuminance was the brightest, the swimming orientation was approximately 46° with a standard deviation of 22°. Strand and Hamner (1990), who conducted a study on the visual stimuli, reported that Antarctic krill often exhibit abnormal behavior due to an abrupt change in light intensity, cease schooling, and show an abnormal swimming

Table 2. Averaged target strength measured by the SDWBA model according to swimming orientation of body length

L(mm)	N [11.0°, 4.0°]		N [53.1°, 21.4°]		N [45.2°, 23.0°]	
	$TS_{38\,kHz}$ (dB)	$TS_{120\,kHz}$ (dB)	$TS_{38\,kHz}$ (dB)	$TS_{120\,kHz}$ (dB)	$TS_{38\,kHz}$ (dB)	$TS_{120\,kHz}$ (dB)
28	-87.89	-76.92	-95.12	-85.29	-93.26	-81.51
30	-86.26	-76.20	-93.92	-81.92	-92.01	-80.34
33	-84.06	-75.42	-92.17	-80.37	-90.17	-78.95
40	-79.71	-73.57	-88.42	-77.86	-86.38	-76.33
43	-78.19	-72.73	-87.06	-76.39	-85.00	-75.58
45	-77.29	-72.25	-86.17	-75.80	-84.12	-75.12
47	-76.37	-71.88	-85.33	-75.27	-83.25	-74.74
51	-74.80	-71.43	-83.78	-74.53	-81.69	-74.20
53	-74.12	-71.23	-83.06	-74.21	-80.97	-73.98
54	-73.69	-70.97	-82.70	-74.12	-80.60	-73.92
55	-73.41	-70.99	-82.32	-73.93	-80.22	-73.80
56	-73.06	-70.95	-81.93	-73.90	-79.85	-73.77
58	-72.51	-70.90	-81.33	-73.71	-79.24	-73.67
61	-71.58	-70.66	-80.33	-73.40	-78.26	-73.42
62	-71.32	-70.50	-80.08	-73.43	-77.98	-73.44
67	-70.15	-70.09	-78.54	-73.32	-76.50	-73.22
L (mm)	N [48.1°, 23.0°]		N [45.9°, 23.0°]		N [46.1°, 19.9°]	
	TS_{38kHz} (dB)	$TS_{120\,kHz}$ (dB)	$TS_{38\,kHz}$ (dB)	$TS_{120\,kHz}$ (dB)	$TS_{38\,kHz}$ (dB)	$TS_{120\,kHz}$ (dB)
28	-93.78	-82.01	-93.39	-81.64	-93.91	-82.57
30	-92.56	-80.81	-92.14	-80.46	-92.76	-81.33
33	-90.73	-79.37	-90.30	-79.05	-91.03	-79.87
40	-86.96	-76.62	-86.52	-76.40	-87.40	-77.02
43	-85.58	-75.86	-85.14	-75.64	-86.05	-76.19
45	-84.70	-75.33	-84.26	-75.18	-85.18	-75.68
47	-83.84	-74.91	-83.40	-74.78	-84.33	-75.23
51	-82.28	-74.30	-81.83	-74.23	-82.80	-74.57
53	-81.56	-74.05	-81.11	-74.00	-82.08	-74.32
54	-81.19	-73.98	-80.74	-73.94	-81.72	-74.24
55	-80.82	-73.83	-80.37	-73.81	-81.35	-74.09
56	-80.44	-73.80	-80.00	-73.78	-80.97	-74.05
58	-79.83	-73.67	-79.38	-73.67	-80.37	-73.94
61	-78.85	-73.40	-78.40	-73.42	-79.40	-73.68
62	-78.58	-73.42	-78.13	-73.44	-79.14	-73.71
67	-77.08	-73.24	-76.64	-73.22	-77.65	-73.60

behavior until they acclimate to the new light level. In this study, the illuminance of the experimental water tank was measured using an illuminance meter after the camera-recording experiment was conducted; the impact of luminous intensity on krill was not thoroughly considered; and a limited number of illuminance levels was applied to the experiment.

The results on the distribution of krill orientation includes Kils (1981) distribution N[45.3, 30.4] and Endo (1993) distribution N[45.6, 19.6], both observations made in an aquarium, and Chu et al. (1993) distribution inferred by the DWBA model from duel-frequency 38 and 120 kHz. There are also Demer and Conti (2005), which obtained N[15, 5] using an SDWBA model, and Conti and Demer (2006), whose parameters have been referred to in the SDWBA model in this study, which obtained N[11, 4].

Miyashita et al. (1996) obtained N[30.4, 19.9] from video observation of orientation of neomysis spp. in a small aquarium; the distributions of Northern krill orientation, N[53.8, 64.2], N[-9.8, 34.1], and N[0, 30], have been obtained through in situ observation with an underwater camera (Kristensen and

Dalen 1986); and Cochrane et al. (1991) used N[5, 5] in the cylinder model to estimate volume backscattering at 50 kHz and 200 kHz. As we have seen, there are a number of studies on swimming orientation, but these results show a diverse range of swimming orientation and standard deviation. Furthermore, different krill species have been used in the studies to obtain the results. Therefore, it is not only important to collect ecological information that matches the purpose of study but also to obtain detailed results on swimming orientation. As for the target species of this study, Antarctic krill, more field observations on swimming orientation are needed as changes in its swimming orientation impact greatly on the TS estimates. Meanwhile, this study analyzed the range of difference for only two frequencies - 38 kHz and 120 kHz. In that context, future studies on Antarctic krill should involve studying the swimming orientation and behavior based on a wider option of frequencies. It was also estimated that the discrepancy with the in-situ frequency difference values was due to the significant changes observed in the TS as the krill's swimming orientation changes.

This study used the SDWBA model and provided TS estimates of Antarctic krill based on their swimming orientation. However, when calculating TS values with an acoustic model, the target animal's swimming orientation must be entered as a parameter. The parameter values applied in this study refers to Calise and Skaret (2011), which are length parameter values of Antarctic krill measured by McGehee et al. (1998). However, this study assumed a 40% increase in fatness, because the krill measured in McGehee et al. (1998) had been starved for six months, which Demer and Conti (2004) also claimed to take into account. Also, mature females and males have been reported to have differences in length, and Endo (1993) reported that mature females with swollen cephalothorax demonstrated larger tilt angles than did males.

Since the ranges of the volume scattering strength and averaged TS for a given frequency window have a strong relationship to krill length, and there are seasonal variabilities of krill length frequencies, differences of mean S_v for a given window tend to get smaller as the krill length increases (Fielding et al. 2011). This study also observed changes in the mean TS values according to differing krill lengths. Meanwhile, collecting sufficient length measurements of juvenile krill samples was not feasible, as a commercial trawl net was used to sample the Antarctic krill species for this study and species smaller than the mesh size could have escaped from the net, and adult krill were targeted during the season in which this study was conducted. Therefore, future research should involve using a zooplankton sampling net, which will improve the credibility of research and enable more accurate species identification.

Acknowledgements

This research was supported by the 'Ecosystem Structure and Function of Marine Protected Area (MPA) in Antarctica' project (PM19060),funded by the Ministry of Oceans and Fisheries (20170336), Korea and was partially supported by the National Institute of Fisheries Science (R2020031), Korea. We are grateful to an editor and anonymous reviewers for their insightful comments that greatly helped to clarify and refine the paper, and we wish to thank Mr Geunchang Park for analysis support.

References

Calise L, Skaret G (2011) Sensitivity investigation of the SDWBA Antarctic krill target strength model to fatness, material contrasts and orientation. CCAMLR Sci **18**:97–122

CCAMLR (2003) Twenty-second Meeting of the Scientific Committee, Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Hobart, 27–31 Oct 2003, SC-CAMLR-XXII. http://ccamlr.org/en/sc-camlr-xxii Accessed 11 Nov 2019

CCAMLR (2019) Report of the Meeting of the Subgroup on Acoustic Survey and Analysis Methods. In: Thirty-eighth Meeting of the Scientific Committee, Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Bergen, 26–30 Aug 2019, SC-CAMLR-38/06. https://www.ccamlr.org/en/sc-camlr-38 Accessed 12 Nov 2019

Chu D, Foote KG, Stanton TK (1993) Further analysis of target strength measurements of Antarctic krill at 38 and 120 kHz: Comparison with deformed cylinder model and inference of orientation distribution. J Acoust Soc Am **93**:2985–2988. doi:10.1121/1.405818

Cochrane NA, Sameoto D, Herman AW, Neilson J (1991) Multiple-frequency acoustic backscattering and zooplankton aggregations in the inner Scotian Shelf basins. Can J Fish Aquat Sci **48**:340–355. doi:10.1139/f91046

Conti SG, Demer DA (2006) Improved parameterization of the SDWBA for estimating krill target strength. ICES J Mar Sci **63**:928–935. doi:10.1016/j.icesjms.2006.02.007

Demer DA, Conti SG (2003) Validation of the stochastic distorted-wave Born approximation model with broad bandwidth total target strength measurements of Antarctic krill. ICES J Mar Sci **60**:625–635. doi:10.1016/S1054-3139(03)00063-8

Demer DA, Conti SG (2004) Erratum - Validation of the stochastic distorted-wave Born approximation model with broad bandwidth total target strength measurements of Antarctic krill. ICES J Mar Sci **61**:155–156. doi:10.1016/j.icesjms.2003.12.002

Demer DA, Conti SG (2005) New target-strength model indicates more krill in the Southern Ocean. ICES J Mar Sci **62**:25–32. doi:10.1016/j.icesjms.2004.07.027

Endo Y (1993) Orientation of Antarctic krill in an aquarium. Nippon Suisan Gakk 59:465–468. doi:10.2331/suisan.59.465

Everson I, Watkins JL, Bone DG, Foote KG (1990) Implications of a new acoustic target strength for abundance estimates of Antarctic krill. Nature **345**:338–340. doi:10.1038/345338a0

Everson I (2000) Distribution and standing, The Southern Ocean. In: Everson I (ed) Krill biology, ecology and fisheries. Blackwell Science, Oxford, pp 63–79

Fielding S, Watkins J, Cossio A, Reiss C, Watters G, Calise L, Ramm D (2011) The ASAM 2010 assessment of krill biomass for Area 48 from the Scotia Sea CCAMLR 2000 synoptic survey. In: Working Group on Ecosystem Monitoring and Management, Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Busan, 11–22 Jul 2011, WG-EMM-11/20. https://www.ccamlr.org/en/wg-emm-11 Accessed 11 Aug 2019

Foote KG, Everson I, Bone DG, Watkins JL (1990) Target strengths of Antarctic krill. J Acoust Soc Am **87**:16–24. doi:10.1121/1.399282

Furusawa M, Miyanohanna Y, Ariji M, Sawada Y (1994) Prediction of krill target strength by liquid prolate spheroid model. Fish Sci **60**:261–265. doi:10.2331/fishsci.60.261

Greenlaw CF (1979) Acoustical estimation of zooplankton populations 1. Limnol Oceanogr **24**: 226–242. doi:10.4319/Io.1979.24.2.0226

Greenpeace (2018) Licence to Krill: The little-known world of Antarctic fishing. Greenpeace International, 35 p. https://www.greenpeace.org/archive-korea/Global/korea/publications/reports/oceans/2018/license_to_krill/license_to_krill_2.pdf Accessed 25 Aug 2019

Hewitt RP, Demer DA (1996) Lateral target strength of Antarctic krill. ICES J Mar Sci **53**:297–302. doi:10.1006/jmsc.1996.0038

Holliday DV, Pieper RE, Greenlaw CF, Dawson JK (1998) Acoustical sensing of small-scale vertical structures in zooplankton assemblages. Oceanography **11**:18–23

Inagaki T, Aoki I, Ishii T (1992) Acoustic estimation of plankton biomass. In: Proceedings of the PORSEC 1992 in Okinawa: Conference for Pacific Ocean Environments and Probing, Scientific Organizing Committee of PORSEC, 25–31 Aug 1992, Okinawa, pp 916–921

Kang D, Hwang D, Kim S (1999) Biomass and distribution of Antarctic krill, *Euphausia superba*, in the northern part of the South Shetland Islands, Antarctic Ocean. Korean J Fish Aquat Sci **32**:737–747 (in Korean)

Kils U (1981) Swimming behavior, swimming performance and energy balance of Antarctic krill *Euphausia superba*. Biomass Sci Ser **3**:1–121

Kristensen Å, Dalen J (1986) Acoustic estimation of size distribution and abundance of zooplankton. J Acoust Soc Am **80**:601–611. doi:10.1121/1.394055

Lee K, Bae BS, Kim IO, Yoon WD (2010) Measurement of swimming speed of giant jellyfish *Nemopilema nomurai* using acoustics and visualization analysis. Fish Sci **76**:893–899. doi:10.1007/s12562-010-0294-7 (in Korean)

MacLennan DN, MacKenzie IG (1988) Precision of acoustic fish stock estimates. Can J Fish Aquat Sci **45**:605–616. doi:10.1139/f88074

MacLennan DN, Simmonds EJ (2013) Fisheries acoustics, Vol. 5. Springer Science & Business Media, 326 p

McGehee DE, O'Driscoll RL, Traykovski LM (1998) Effects of orientation on acoustic scattering from Antarctic krill at 120 kHz. Deep-Sea Res Pt II **45**:1273–1294. doi:10.1016/S0967-0645(98)00036-8

Miyashita K, Aoki I, Inagaki T (1996) Swimming behaviour and target strength of isada krill (*Euphausia pacifica*). ICES J Mar Sci **53**:303–308. doi:10.1006/jmsc.1996.0039

Peter H, Charles H (1994) The use of high frequency acoustics in the study of zooplankton spatial and temporal patterns. Proc NIPR Symp Polar Biol **7**:133–157

Siegel V (2016) Biology and ecology of Antarctic krill. Springer, Cham, 441 p

Stanton TK, Chu D, Wiebe PH (1996) Acoustic scattering characteristics of several zooplankton groups. ICES J Mar Sci **53**:289–295. doi:10.1006/jmsc.1996.0037

Strand SW, Hamner WM (1990) Schooling behavior of Antarctic krill (*Euphausia superba*) in laboratory aquaria: reactions to chemical and visual stimuli. Mar Biol **106**:355–359. doi:10.1007/BF01344312