Sound Speed Structure Long-term Monitoring in Antarctica by the Deep-sea Automatic Observation Float*

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Abstract:
Indirect observation to convert the sound speed has been carried out as a method of observing the ocean acoustic environment from water temperature and salinity observed in the mooring buoy and ship observations. However, there is a problem in that these have both high initial cost and running cost. Therefore, to address these issues, a study of the wide area ocean sound observation system using the observation data from a marine automatic observation float was performed. To capture in detail the changes in the ocean acoustic environment due to recent climate change, however, it is necessary to observe areas of the deep sea that can not be detected by Argo floats. Also, during the season when the Antarctic Ocean is frozen, continuous observation data of the deep sea cannot be acquired, and water temperature, salinity, and sound speed structure are not clear. As a result, JAMSTEC developed a new profiling float, called the "Deep NINJA" for deep-sea observations. The float was subjected to a yearlong monitoring of the Antarctic Ocean off the Adelie Coast in 2012. For the first time, it succeeded in monitoring long-term the sound speed profile to a depth of 4000 m in the Antarctic Ocean, and was able to capture a seasonal change in the surface area in the freezing and thawing seasons. In addition, by calculating sound speed from these data, simulations were performed assuming low-frequency sonar. The results obtained the ingredient that propagates while repeating a reflection in the extremely small layer of the sea surface neighborhood, and the ingredient that propagates while being reflected near a water depth of 100 m, which changes the sound speed gradient. From this, propagation loss was found to be smaller in winter than summer, and the possibility that a sound wave would propagate to a more distant place was demonstrated. This may affect the long-distance sound wave propagation of the echolocations of passive sonar and marine mammals.

Classification: Sound propagation
Keywords: Antarctic ocean, sound speed structure, wintering, profiling float, underwater robot control

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1. Introduction

To comprehensively understand the influence of oceans on climatic change, ocean acoustic tomography observations and observations using vessels and mooring buoys have been conducted. In ocean acoustic tomography, based on the characteristic that the propagation of sound waves in the sea depends on water temperature, salinity, and pressure, an observation system was developed to analyze these aspects of sound wave propagation and multiple experiments were conducted in the 1990s.\(^1,2\)

In terms of observations using vessels, in the mid-1990s, the World Ocean Circulation Experiment (WOCE)—a large-scale international project—was implemented to acquire detailed data about the entire ocean. In this project, the program that countries most focused on was the WOCE Hydrographic Program (WHP),\(^3\) the purpose of which was to conduct observations “from land to land” and “from sea surface to sea bottom.”\(^3\) Many research institutes and agencies from Japan, including universities that own research vessels as well as the Science and Technology Agency, Fisheries Agency, and Meteorological Agency at the time, participated in this program. Moreover, because it is difficult to conduct continuous temporal observations using vessels, a long-term monitoring network comprising mooring buoys [Tropical Atmosphere Ocean (TAO)/TRIangle Trans-Ocean buoy Network (TRITON)] was constructed as a long-term monitoring method.\(^4\) Furthermore, recently, various oceanographic observation methods have been developed that have enabled the observation of the sea surface using an artificial satellite.

As described above, various platforms have been constructed for capturing environmental changes in the oceans and studies have been conducted to understand the influence of the ocean environment on climate change phenomena, e.g., El Nino and La Nina, and their mechanisms.

In ocean sound communication using underwater sound wave propagation, it is known that the propagation of sound waves varies depending on the sea area and season. However, it is difficult to comprehensively capture such changes, which are due to extremely large timescale phenomena, e.g., global warming, with conventional observation methods. For this reason, as a method to monitor the influence of global-scale long-term climate changes on underwater sound wave propagation, a system to analyze underwater sound environments using the observation data obtained from automatic ocean profiling floats (so-called “Argo floats”) has been developed.\(^5\) Using this system, data can be automatically collected from 3,500 Argo floats deployed in a 300-km mesh under the Argo program,\(^6\) which started in 2000, and converted to sound speed to capture seasonal changes in the global sound speed field. As a result, it was revealed that a sound wave propagation path that passes through a sound channel (sound speed minimum layer), which has been believed to undergo minimum changes in deep-layer regions of the seas at low and mid latitudes, is complicated depending on the season.\(^5\)

However, while the observation depth of Argo floats is 2,000 m, the average water depth of the oceans in the world is approximately 3,800 m, which means many deep-layer regions cannot be observed using Argo floats. Therefore, for those sea areas, statistical data, e.g., LEVITUS,\(^7\) and on-site observation values obtained using research vessels and mooring measuring devices have been used. These observation data have also been used for the simulation of underwater sound wave propagation. Although precise observation at considerable
depths can performed using research vessels, this method cannot be used to conduct continuous temporal observations. Moreover, when conducting observations using vessels, the operational costs are high and there are many associated problems, e.g., worldwide lack of observation vessels. Moreover, it is difficult to conduct observations using vessels in the Arctic and Antarctic regions, which are covered with thick layers of sea ice during winter. Therefore, large amounts of data cannot be obtained, which are continuously obtained during the other parts of the year. Furthermore, the negligible amount of data acquired are mostly of the sea surface area.

To comprehensively capture the changes in the oceanic environment due to global warming and other factors, continuous monitoring of changes in the water temperature and salinity is required in oceanic zones deeper than 2,000 m. For this reason, there is a demand for developing a deep-sea profiling float that enables long-term monitoring at depths greater than those of Argo floats.

Since 2010, the Japan Agency of Marine-Earth Science and Technology (JAMSTEC) and Tsurumi Seiki Co., Ltd. have been engaged in the development of “Deep NINJA,” a deep-ocean profiling float that can automatically observe oceans at depths of up to 4,000 m. Similar to Argo floats, these floats measure water temperature and salinity in the vertical direction while repeatedly diving and floating and send the observation data to a float user through an artificial satellite when floating.

In December 2012, JAMSTEC conducted year-long observations using “Deep NINJA” in the offshore Antarctic Adélie coast and successfully conducted continuous observations (overwintering observation) under the winter sea ice.

Herein, based on the overwintering data of the Antarctic sea, we conduct variability analysis of the oceanic sound environment in the deep ocean zone of the Antarctic sea during the freezing season. This analysis could not be easily conducted using conventional observation methods involving vessels and mooring (secured) buoys. First, we introduce the Deep NINJA observation method and the internal structure of the device used in this method in Section 2. In Section 3, we describe a method for sound speed profiling conversion of the obtained data. In Section 4, we discuss the changes in sound speed over a year in the Antarctic sea. Furthermore, in Section 5, through sound wave propagation simulations, we examine seasonal changes in the sound speed field in the Antarctic sea, which has not been observed conventionally.

2. Overview of Deep NINJA

Oceanic profiling floats, e.g., Argo floats, measure water temperature, salinity, and depth data based on a preset observation program and provide the data to users who have registered the observation data via a communication satellite substantially in real time. “Deep NINJA” has been developed for continuous monitoring of water temperature and salinity changes in oceanic zones deeper than 2,000 m. Figure 1 shows the structure of “Deep NINJA.” The buoyant force is adjusted by ejecting/drawing hydraulic oil into/from an external oil bladder from an internal oil reservoir. The total body length is 210 cm (including the antenna for satellite communication), and the weight in air is approximately 50 kg. The pressure housing is made of an aluminum alloy; there is a compact pump located within to manage the oil for adjusting the buoyancy, and it is equipped with a circuit and lithium battery to control the driving and observation devices. The device dives and floats according to the preset observation sequence, as shown in Fig. 2, and sends observation data to a float user.
via an artificial satellite when the float comes up to the sea surface. As a result, the observable zone has expanded to 90% (volumetric ratio) or more of the entire ocean, including the deep ocean zone that could not be observed with a conventional Argo float.

The observation data are sent to a land station (an operator) in short bursts via Iridium communication satellite. The recorded data include GPS data that indicate the floating location as well as water temperature and salinity at various depths.

Moreover, because the float is capable of bidirectional communication, even after the float expands to the sea, it is possible to change parameters, e.g., the diving/surfacing cycle and observation depth, via the artificial satellite. In addition, as shown in Fig. 3, if sea ice is present above the device, it stops floating using its sea ice detection function. In this case, the observation data are recorded in the internal memory and are transmitted when the device next floats.

3. Surveyed oceanic areas and sound speed conversion

Figure 4 shows the latitudes and longitudes that indicate the track and the floating locations of the float according to the GPS data sent from a float placed offshore the Adélie coast by a JAMSTEC’s research vessel called “Mirai” in December 2012. From this figure, it is evident that the float was drifting in the range of about 1° in the latitude direction and about 7.6° in the longitude direction. Furthermore, the floating positions L–R are substantially aligned in a straight line.

The observation period corresponding to the same Fig. 4 was the freezing season, and it was impossible to receive GPS data. Therefore, floating positions were not known accurately and were determined via their linear interpolations before and after the freezing season.

This time, using the profiles of pressure, water temperature, and salinity observed over a year from December 2012 to December 2013, we estimated the structure of sound speed in the Antarctic sea under sea ice. Vertical profiles of water temperature and salinity are shown in Figs. 5 and 6, respectively.
These results show that the changes in water temperature and salinity are observed mainly at depths shallower than 250 m from the sea surface. Using this result, a sound speed profile for each month was determined at depths of up to 4,000 m, the results of which are shown in Fig. 7.

The sound speed in the sea can be determined as the square root of the ratio of the bulk modulus $K$ to the density $\rho$ of seawater. However, because these values change with water temperature and pressure, the underwater sound speed cannot be easily calculated. Therefore, we determined the underwater sound speed $c$ using a function $f$ of the parameters, including water temperature $T$, salinity $S$, and pressure $P$. Generally, $P$ can be converted to water depth $D$. Additionally, we converted pressure to water depth for the data obtained from the float. Moreover, to determine the sound speed $c$, many experimental equations have been suggested, such as those by Del Grosso, Coppens, and Mackenzie. This time, we used UNESCO, an
equation for measuring the sound speed (Chen and Millero, 1977)\textsuperscript{15,16} and generated a sound speed profile.

As shown in Fig. 7, the sound speed tends to be lower in the shallow water zone, but in zones deeper than 250 m, the sound speed increases as the depth increases and eventually converges into a generally constant sound speed gradient. From this fact, it can be understood that the in-seawater sound speed in the Antarctic sea is most affected by the changes in water temperature and salinity near the sea surface, which is a common characteristic of sound speed profiles in areas with high-latitude water, e.g., Mediterranean Sea.\textsuperscript{17,18} In this ocean area, because the changes in water temperature and salinity are extremely small at depths ≥2,000 m, it can be understood that pressure dominantly influences the sound speed.

On the other hand, the changes in the sound speed can be observed near the sea surface. To observe these changes in detail, we show the sound speed profile for each month at water depths of up to 300 m in Fig. 8.

In this figure, we can confirm a sound speed inverse layer, where the sound speed gradient inverses, near the sea surface at depths of 20–100 m from December 2012 to March 2013. In the low- and mid-latitude oceanic areas, a sound speed inverse layer is formed at water depths of around 1,000 m throughout the year. However, this layer is formed for only a short period during summer. It is different in nature from the sound channel formed throughout the year. Therefore, the sound speed inverse layer is thought to be formed due to seasonal changes.

In the thawing season, the sound speed inverse layer was formed mainly at depths of around 50 m from December 2012 to March 2013, whereas in the freezing season, no significant layer formation was observed.

Typically, in oceanic areas with ice formation, the water temperature is the lowest near the sea surface, so the sound speed is the lowest near the sea surface. Furthermore, the sound speed gradient in winter changes about 15 m/s between the water depths of 50 and 100 m. Therefore, the sound speed changes dramatically in a very shallow and small range. Accordingly, because the state of formation of the sound speed inversion layer is different between the thawing season (summer) and the freezing season (winter) near the sea surface in the ocean area, it can be said that seasonality influences long-distance sound wave propagation near the sea surface. Therefore, there exists a possibility of seasonal changes in the signal level of sound wave propagation.

Moreover, as can be seen in the sound speed profile for January 2013 in Fig. 8, the sound speed drops to approximately 1,443 m/s near a water depth of 70 m and then increases similarly in other months.

However, at depths of 130–200 m, the sound speed decreases again to approximately 1,452 m/s near a depth of 140 m. This may suggest the precipitation of low-temperature water mass. However, because such a pattern is not observed in the months before and after, it can also be considered that this pattern is influenced by coastal flows from...
Antarctica. For details, we need to obtain additional data using floats and analyze these data.

4. Sound speed change during the freezing season

In Fig. 8, a considerable change in in-seawater sound speed can be observed at depths of up to 250m in the sea surface area of the Antarctic sea depending on the season. Therefore, from the viewpoint of comprehensively determining the influence of seasonal changes under the sea ice condition, Fig. 9 shows the change in sound speed in each month at each depth. From this figure, at depths ≥200m, where changes in water temperature and salinity are small, there is no significant seasonal change and the sound speed simply increases as the depth increases. Therefore, it can be understood that the influence of pressure is dominant.

During the freezing period (winter) from July to October, the sound speed was low near the sea surface and constant at approximately 1,440 m/s. On the other hand, in the thawing season (summer) from December 2012 to March 2013, the sound speed increased. As shown in Fig. 10, this can be ascribed to the significant influence of changes in water temperature near the sea surface.

Furthermore, in this figure, while the water temperature is generally constant during the freezing season from July to October, the water temperature near the sea surface changes significantly during the thawing season from December to March. Generally, the in-seawater sound speed is most influenced by this change in water temperature and the sound speed increases as the water temperature increases. Therefore, in Figs. 9 and 10, the sound speed is influenced by the changes in water temperature from March to May and it changes significantly. While the water temperature at depths of around 40 m in March was 1.5°C, it decreased to -1.6°C in May, a temperature change of approximately 3.1°C. Therefore, it is understandable that the sound speed in Fig. 7 also changed significantly in the same season. While the sound speed at a water depth of 0–40m was approximately 1,453 m/s in March, it decreased to approximately 1,440 m/s in May. Accordingly, the sound speed changed by about 13 m/s for the 3.1°C change in temperature over the two months.

In addition, at water depths ≥80m, there is a further significant difference. More specifically, the decrease in water temperature at depths of 0–70m occurs from March to May, whereas the decrease
in water temperature at water depths of 80–100 m occurs in May or later. As the depth is greater, the temperature drop starts later. This influence is observed in the change in sound speed as well. At water depths of 80–100 m, the delay in changes in sound speed is synchronized with the change in water temperature.

Figure 11 shows salinity changes over the same season. In the figure, at a water depth of 0–40 m, from December 2012 to March 2013, salinity was approximately 33.8 psu, which increased gradually from March. Thereafter, around June, which is the beginning of the freezing season, salinity was approximately 34.2 psu. One of reasons for this increase in salinity is considered to be high-salinity seawater produced upon the discharge of salts from the seawater during the freezing season. Accordingly, in the ocean area, ice formation seemed to have started around June.

In contrast, once the salinity of seawater is high, the sound speed increases due to the changes in density. However, for the change near the sea surface during winter in Figs. 9 and 11, while the salinity increased from May to October, the sound
speed was as low as approximately 1,440 m/s. Based on this fact, the influence of changes in water temperature is greater than the influence of seasonal changes in salinity on the changes in sound speed. Even in the Antarctic area, where it is believed that the changes in sound speed are smaller than those in other oceans, the sound speed was influenced by minute changes in the seawater temperature.

5. Sound wave propagation simulation

Based on the sound speed profile obtained from the observation data this time, to visualize the difference in sound wave propagation between the freezing and thawing season in the Antarctic ocean, we conducted a sound wave propagation simulation. Assuming a low-frequency sonar used in an offshore vessel, we set the frequency as 1 kHz, the horizontal propagation distance as 5,000 m, and the sound source depth as 10 m. In terms of simulation methods, the parabolic equation method (PE method) and the sound ray method\(^{20}\) can be used. For obtaining an exact solution in the close range, we employed the normal mode method.\(^{20,21}\) The number of modes calculated was 10–200. Because the propagation distance is short, it is assumed that the sound speed profile does not change in the horizontal direction. Moreover, although a bathymetric map of this ocean area was not prepared because the water was sufficiently deep (≥4,000 m), we assumed that the seabed was flat. In addition, we did not consider sea surface changes occurring due to ocean waves.

This time, to observe the influence of climate changes on sound wave propagation, using the sound speed profiles obtained from January 2013 to December 2013, we conducted a simulation of sound waves. The results are shown in Figs. 12(a)–12(f). In those graphs, the abscissa represents the propagation distance, the ordinate represents the depth, and the color bars represent relative attenuation.

From these results, it can be understood that there is an obvious difference in sound wave propagation between summer and winter in the Antarctic ocean. First, in Figs. 12(a)–12(d), a part of the components of the sound waves transmitted from the sound source submerge to a depth of about 50 m without reflection on the sea surface. The components radiated in the horizontal direction are trapped in the sound speed inversion layer, where the sound speed has a local minimum. Then, they propagate horizontally around the depth while undergoing repeated refraction in the layer. In contrast, from July to October, which is equivalent to winter (freezing season), in the sound waves transmitted from the sound source, we can observe a component that propagates while undergoing repeated refraction in a very narrow layer near the sea surface and a component that propagates horizontally while undergoing repeated refraction between the sea ice surface and near 100-m depth, where the sound speed gradient changes. This fact demonstrated that two sound fields are generated in winter, including a component that propagates with sea ice as an axis and a component that propagates over a relatively wide range of depths of up to 100 m.

Next, in terms of sound pressure distribution, the attenuation is approximately −65 dB near the sound source at 10-m depth in Fig. 12. However, during summer, as shown in Figs. 12(a)–12(c), the attenuation increases to approximately −90 dB near a water depth of 100 m at 5,000 m from the sound source in the horizontal direction. In contrast, at the same point during winter, as shown in Figs. 12(f)–12(j), an attenuation of approximately −80 dB has a wide range, whereas the attenuation
of the area very close to the sea surface is approximately $-70\text{ dB}$. From this result, it appears that a high level of attenuation due to ocean waves occurs because the surface is covered with sea ice and the sound waves reflected by the sea ice surface propagate over long distances. In this simulation, the influences of ocean waves on the sea surface were not considered. Therefore, in the actual ocean area...
during the summer, the component trapped in the sound speed inversion layer could be larger than that reflected by the sea surface. In contrast, in the area wherein the sound pressure level is low (shadow zone), at a point where the horizontal propagation distance is 5,000 m, the depth and the area vary depending on the season. Because observation profiling was done only at one point, we could not determine the regularity. However, this result may suggest that the changes are complex and depend on the season.

In comparison, among the analytical results shown in Figs. 12(b)–12(e), which correspond to the period from February to May, the horizontal propagation of sound waves trapped in the sound speed inversion layer at a water depth of about 50 m is dominant in February and reflection by the sea surface or therearound is dominant in May. Furthermore, in June (Fig. 12(f)), in addition to the component reflected by the sea surface, we can observe signals of approximately −65 dB that propagate horizontally in the narrow area near the sea surface. Therefore, we can infer that sea ice formation starts from April or May and covers the surface in June.

From the above results, we found distinct differences in the propagation path and attenuation between summer and winter in the case of long-distance sound observation in the Antarctic ocean. In particular, in winter, while it is difficult to conduct observations because of the sea ice that covers the surface, the influence of noise from the sea surface is less. Therefore, in summer, the wave reception levels of observation devices, e.g., passive sonar, are better than those in winter and it may be possible to capture faraway sounds. However, the propagation path may change in the future due to global warming, and it may also affect the feeding activity of marine mammals using sound waves.

6. Conclusion

We conducted a one-year long-term observation in the Antarctic sea using the newly developed deep-observation float “Deep NINJA,” which enabled us to conduct observations at water depths of up to 4,000 m. As a result, for the first time in the world, we could successfully conduct deep profiling observations under the sea ice condition during winter. From the pressure, water temperature and salinity profiles obtained from the observations, we analyzed the sound speed profile in the ocean at depths of up to 4,000 m under the sea ice condition during winter in the Antarctic. As a result, we found that water pressure is generally the dominant factor governing the changes in the sound speed because the changes in water temperature and salinity are small at depths of ≥2,000 m, where observations cannot be conducted using Argo floats. In contrast, we found that the water temperature changes due to thawing and freezing are dominant, particularly in the sea surface area. More specifically, we captured the distinct seasonal difference between the freezing and thawing season in the sea surface area. On comprehensively comparing the changes in sound speed between the freezing and thawing season, we found that the sound speed in the sea surface area was affected by water temperature, which changes with the season.

Furthermore, in the shallow area of the Antarctic ocean, because the propagation path and sound pressure level may vary depending on the season, we conducted simulations assuming the use of a 1-kHz low-frequency sonar, which is widely used in vessels. As a result, we found that attenuation was smaller during winter compared to that during summer and that sound can be propagated over long distances, which suggests a possible influence on long-distance sound wave propagation mecha-
nisms, e.g., passive sonar\textsuperscript{22) and} echolocations of marine mammals.\textsuperscript{23,24)}

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