Chapter 8
Acoustic Survey

Kazushi Miyashita

Abstract Hydroacoustic methods are important for marine studies because of their advantages of directness, continuity, and quickness. Acoustic data provide quantitative information from a variety of marine organisms, including not only fishery-target fish species but also nontarget zooplankton, mesopelagic fish, and the sea forest. Characterizing the acoustic environment by discriminating, classifying, and quantifying biological backscatter is promising to better understand ecological processes, such as prey-predator relationships, habitat selection, and biomass estimates, which can help with ecosystem-based fisheries management. This chapter describes how acoustic methods are beneficial for monitoring marine organisms by (1) helping identify and discriminate zooplankton and larval, juvenile, and adult fish based on backscattering strength frequency characteristics and biomass estimates, (2) describing advances in acoustic applications for ecological monitoring, and (3) developing an acoustic monitoring system for "shirasu" (Japanese anchovy post-larvae) fisheries management now in operation. Finally, we provide some perspectives on an acoustic monitoring system for ecosystem-based fisheries management.

Keywords Acoustics · Acoustic monitoring system · Biomass estimation · Ecosystem-based fisheries management · Quantitative echo sounder · SV difference method

8.1 Acoustics in Fisheries Research

Electromagnetic waves—including visible light—are attenuated greatly in water and do not reach great depths. However, acoustic waves reach deeper into water compared to electromagnetic waves. This property allows many marine organisms

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I. Aoki et al. (eds.), *Fish Population Dynamics, Monitoring, and Management*,
Fisheries Science Series, https://doi.org/10.1007/978-4-431-56621-2_8

to use acoustic waves. Whales and dolphins are examples of animals that use acoustic waves as a communication and positioning tool. Killer whales vocalize to communicate with their families, and dolphins use ultrasonic pulses rather than eyesight to locate prey. Many fish use acoustic waves for communication and during reproduction. Thus, the underwater world is the "world of acoustics."

Humans have also used acoustics underwater, particularly in the oceans. For example, submarines use sonar to navigate underwater, and fishermen use sonar and fish finders known as "echo sounders" to detect fish aggregations for an efficient catch. Currently, acoustics is one of the most commonly used technologies in fisheries and marine science research. In this chapter, we introduce the acoustic survey and its application to fisheries research.

Underwater acoustic (hydroacoustic) methods play an important role in marine organism monitoring due to their technical advantages, such as time efficiency, high area coverage, and directness. Therefore, hydroacoustic methods are commonly used worldwide.

Studies on fisheries acoustics began with detecting fish and fish schools using a simple echo sounder. An echo sounder visualizes an echo image termed an "echogram," which allows the acoustics to be used to determine the presence or absence of a fish/school and determine its relative size. The present quality of visual monitors makes use of acoustics more popular than previously. For example, fish finders have become an indispensable tool for recreational and commercial fisherman. As echo sounder applications progressed, fish abundance and biomass estimates using hydroacoustic methods were actively investigated worldwide. Currently, quantitative echo sounders are commonly used to measure fish biomass. A quantitative echo sounder is a piece of scientific equipment based on acoustic theory (Fig. 8.1), in which the accuracy of a biomass estimate is sufficient to quantitatively evaluate a fish stock if calibrated correctly.

8.2 Acoustic Survey Using a Quantitative Echo Sounder

Surveys using both quantitative echo sounders and trawl nets, or the so-called acoustic and trawl survey or acoustic survey, are one of the most popular methods of estimating fish biomass in the field. In this type of survey, researchers use one or more onboard quantitative echo sounders. A combination of 38 and 120 kHz is the most common frequency set-up for an acoustic survey. Many research vessels are equipped with echo sounder systems with multifrequency channels. A low frequency, such as 38 kHz, is used mainly to estimate fish biomass, whereas a high frequency, such as 120 kHz, is used mainly for detecting zooplankton. Species (e.g., fish or zooplankton) can be identified based on the differences in acoustic frequency characteristics between marine organisms (Kang et al. 2002; Miyashita et al. 2004). Notably, there is a limit to species identification using only a quantitative echo sounder. Thus, a scientific echo sounder combined with direct trawl net sampling provides detailed size estimates, helps identify

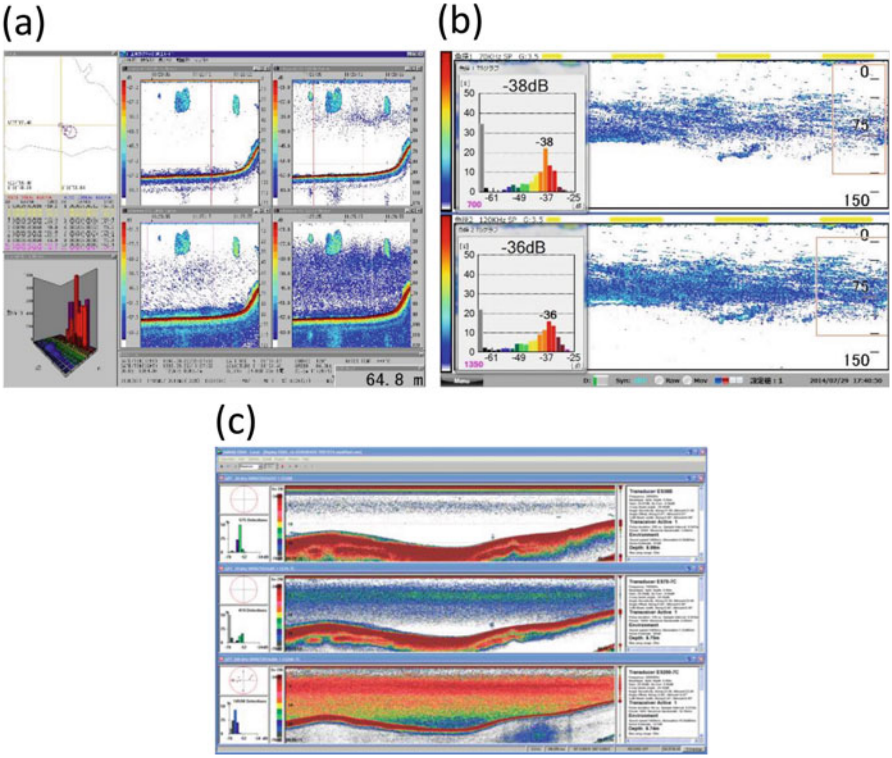


Fig. 8.1 Quantitative echo sounder echograms and operation system. (**a**) Sonic KFC3000 (reproduced from http://www.u-sonic.co.jp/product/kfc-3000.html), (**b**) Sonic KFC6000 (reproduced from http://www.u-sonic.co.jp/product/kfc-6000.html), (**c**) Simrad EK60 (reproduced from https://www.simrad.com/ek60)

species, and is essential for an acoustic survey. Sampling by trawl net is also effective for estimation of fish biomass in an acoustic dead zone, such as near the sea bottom.

8.3 Acoustic Survey Design

Three important points should be considered to conduct an accurate and efficient acoustic survey. First, the researcher must formulate a detailed survey plan. Second, the researcher should have a basic understanding of acoustic reflection characteristics. Third, the researcher must analyze the related error factors.

It is important to formulate a detailed survey plan that includes when (time and time period) and where (survey area) the survey is to be conducted and the desired information about the target organism (e.g., biomass, distribution, or life history). In addition, knowledge of the ecological characteristics around the target organisms is required. For example, if determining the biomass of an adult spawning fish is the aim of an experiment, it is necessary to know their spawning area (horizontal and vertical), season, timing, behavior, and other ecological factors. Then, transect lines with predetermined biological and environmental sampling stations can be set to cover the entire distribution area.

To understand the acoustic reflection characteristics of a target organism, it is important to convert the biological properties of the target into acoustic information. Acoustic reflection (echo) intensity of target organisms varies depending on the shape and size, swimming angle, presence or absence of a swim bladder, and differences in acoustic frequencies.

The presence or absence of a swim bladder facilitates distinguishing of target fish echo intensity. If echo intensity is compared between fish of the same size and shape with and without a swim bladder, the echo intensity of the fish with the swim bladder will be significantly greater than that of the fish without a swim bladder. For example, the echo intensity of Pacific mackerel (*Scomber japonicus*) (swim bladder) (Abe et al. 2010) is much higher than that of Atlantic mackerel (*S. scomber*) (no swim bladder) (Edwards and Armstrong 1983) for fish of the same size and of similar shape.

The swimming angle of a target organism also affects the echo intensity. In general, the echo intensity of the near dorsal aspect of a target organism is highest at all swimming angles. As swimming angle (when the dorsal aspect is 0°) decreases, the echo intensity decreases. Hence, it is essential to be aware of the average swimming angle of each target organism to properly estimate biomass. For example, the swimming angle of walleye pollock (*Gadus chalcogrammus*) differs between adult and young fish (Torisawa et al. 2006). Thus, if walleye pollock biomass is estimated in an area in which both adult and young fish are distributed, biomass must be estimated after the swimming angles have been determined.

It is also important to understand error factors, such as underwater noise, electrical noise, and interference with other acoustic equipment, to conduct an accurate acoustic survey. The presence of such noise can result in overestimation of biomass. In addition, error factors, such as underwater air bubbles, must be considered, particularly during a storm or other intense oceanographic events. If an acoustic survey is conducted during a storm, biomass might be underestimated because of attenuation due to air bubbles. The timing and location of these potential errors must be determined if an accurate acoustic survey is to be conducted.

8.4 Acoustic Species Identification and Discrimination

Species can be identified using differences in frequency characteristics between marine organisms, as mentioned in Sect. 8.2. In general, smaller organisms without a swim bladder (no gas in their body), such as zooplankton, can be identified using differences in frequency characteristics. For example, the echo intensity of *Euphausia pacifica*, a krill species, at 38 kHz is >10 dB lower than that at 120 kHz (Miyashita et al. 1996). The acoustic frequency characteristics of juvenile sand eel (*Ammodytes personatus*), which does not have a swim bladder, are similar to those of *E. pacifica* (Matsukura et al. 2013). In contrast, the echo intensity of adult sand eel at 38 kHz is a few decibels lower than that at 120 kHz (Safruddin et al. 2013), indicating that the acoustic frequency characteristics of sand eel change with life stage. The acoustic frequency characteristics of small pelagic fish also change during their life history. For example, the echo intensity of juvenile Japanese horse mackerel (*Trachurus japonicus*) at 38 kHz is a few decibels higher than that at 120 kHz (Nakamura et al. 2013). In contrast, the echo intensities of adult Japanese horse mackerel at 38 and 120 kHz are very similar. The echo intensities of sardine and anchovy change not only with life stage but also between day and night during their early life history. In addition, their acoustic frequency characteristics differ from those of Japanese horse mackerel.

Post-larvae of Japanese anchovy (*Engraulis japonicus*) and Japanese sardine (*Sardinops melanostictus*) are known as "shirasu" in Japan. The swim bladders of shirasu deflate during the day and inflate at night (Uotani 1973) (Fig. 8.2). As a consequence, the echo intensity of shirasu at 38 kHz is >10 dB lower than that at 120 kHz during the day and a few decibels higher at 38 kHz than that at 120 kHz at night, which is similar to other juvenile fish, such as juvenile horse mackerel (Miyashita 2003). Additionally, the echo intensities of young and adult sardine and anchovy at night are very similar at 38 and 120 kHz. These examples indicate that species can be identified using such biological-acoustic information.

Species have also been identified based on empirical information, such as the fish fauna of a survey area obtained from past surveys or commercial fishing. The distribution patterns and shapes of fish schools on an echogram are also collected during acoustic surveys. Distribution patterns and shapes vary depending on fish species, life stage, season, and other physical and biological factors. In general, adult and young small pelagic fish, such as anchovy and sardine, form large schools at the sea surface to mid-water layers, whereas juveniles tend to form small patchy schools near the sea surface. Adult and young demersal species, such as walleye pollock and

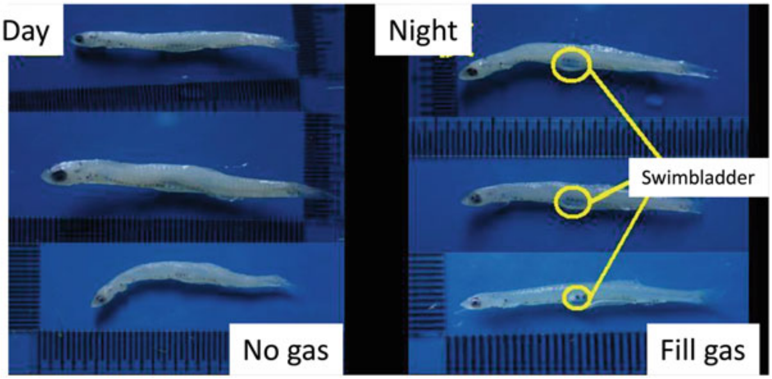


Fig. 8.2 Shirasu with a swim bladder. Left: no gas in swim bladder during day. Right: gas-filled swim bladder at night

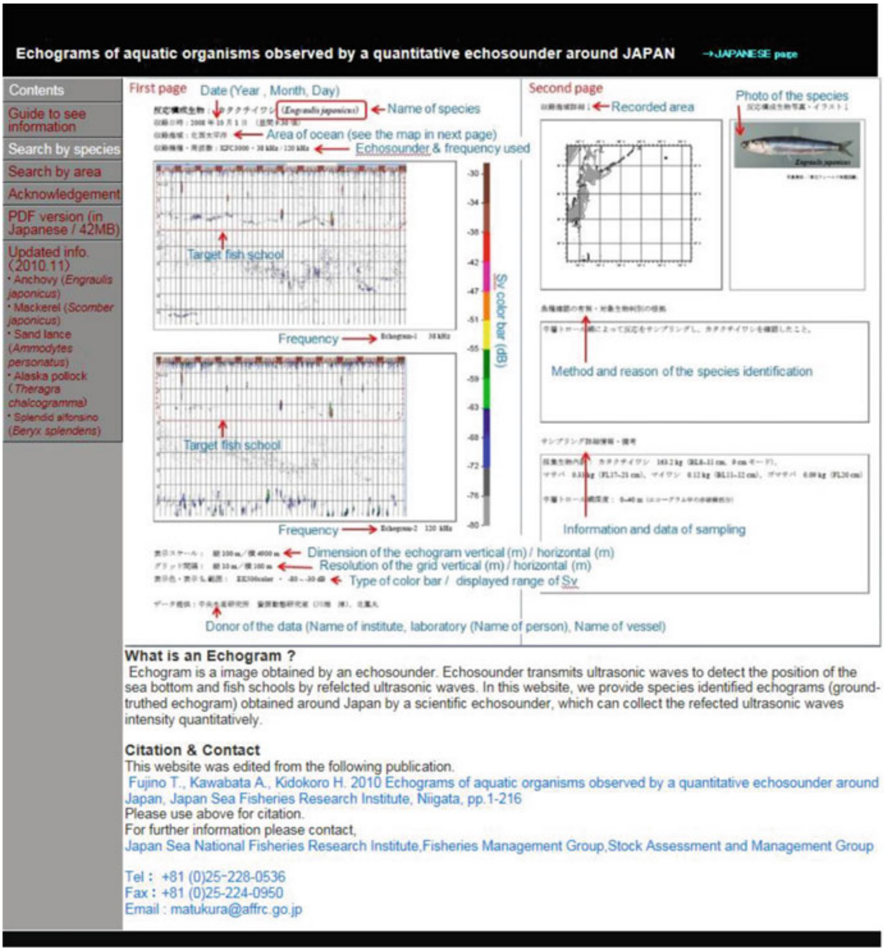
cod, form large aggregations near the sea bottom and in the mid-water layer, whereas juveniles form large aggregations near the sea surface and mid-water layer. The distributions of many marine organisms often change diurnally in the same area, season, and life stage. Mesopelagic lantern fish are the main species in the deep scattering layer (DSL). These fish are distributed in deep water during the day but tend to move to near the surface at night (Yasuma et al. 2010). Krill-like organisms also inhabit the DSL and have the same diurnal vertical distribution patterns as mesopelagic lantern fish.

Planktonic copepods are another component of the DSL. These organisms migrate vertically, following seasonal and diurnal patterns. *Neocalanus* copepods change their vertical distribution depending on season and life stage (Kobari and Ikeda 1999, 2000). Immature adult (CI–CIV) stage *Neocalanus cristatus* are distributed mainly near the surface during spring and summer, whereas mature (CV–CVI) stage *N. cristatus* are distributed mainly in the deepwater layer during fall and winter (Kobari and Ikeda 1999). *Metridia* copepods change their distribution between day and night. For example, *Metridia pacifica* are distributed mainly in deep water during the day and near the sea surface at night (Hattori 1989). The accuracy of species identification and discrimination using acoustic techniques improves depending on distribution characteristics, aggregation shape, and the background biological and ecological characteristics of the organisms detected in a survey area.

Databases that facilitate species identification and estimating biomass in an acoustic survey have been improved. The echogram catalog (Japanese portal site: http://jsnfri.fra.affrc.go.jp/shigen/echocata/; English portal site: http://jsnfri.fra.affrc.go.jp/shigen/echocata/indexEN.html) has been one of the most useful acoustic databases for fisheries researchers (particularly beginners) since 2010 (Fig. 8.3). This database collects echograms of many species obtained during acoustic surveys around Japan and in the northwestern Pacific Ocean. Echo intensity (target strength) data of some important fisheries species are summarized in the echogram catalog. Such databases will continue to improve and will be applied worldwide.

8.5 Advanced Acoustic Applications for Ecological Monitoring

Underwater acoustic technology has been developed, and a variety of acoustic equipment is utilized worldwide. Applications of this technology have extended from traditional fisheries resources surveys to other research fields. In particular, ecological research applications are popular. For example, the behavior and migration patterns of fish schools, prey-predator relationships, habitat selection, and other significant ecological studies have been conducted using acoustic equipment. In 2002, the ICES Symposium on Acoustics in Fisheries and Aquatic Ecology was held and published as a special issue of the *ICES Journal of Marine Science* (Volume



What is an Echogram ?

Echogram is a image obtained by an echosounder. Echosounder transmits ultrasonic waves to detect the position of the sea bottom and fish schools by refelcted ultrasonic waves. In this website, we provide species identified echograms (ground-truthed echogram) obtained around Japan by a scientific echosounder, which can collect the refected ultrasonic waves intensity quantitatively.

Citation & Contact

This website was edited from the following publication.

Fujino T., Kawabata A., Kidokoro H. 2010 Echograms of aquatic organisms observed by a quantitative echosounder around Japan. Japan Sea Fisheries Research Institute, Niigata, pp.1-216

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Fig. 8.3 Portal site for the echogram catalog (Reproduced from http://jsnfri.fra.affrc.go.jp/shigen/echocata/indexEN.html)

60, Issue 3, 2003). Publication of significant acoustic studies in aquatic ecology was a milestone event. In this section, some examples of these acoustic applications in ecology are introduced.

8.5.1 *Spatial Visualization of Prey–Predator Relationships: Walleye Pollock and Zooplankton*

Miyashita et al. (2004) reported that changes in the diurnal vertical distribution of walleye pollock were affected by those of prey organisms, such as zooplankton.

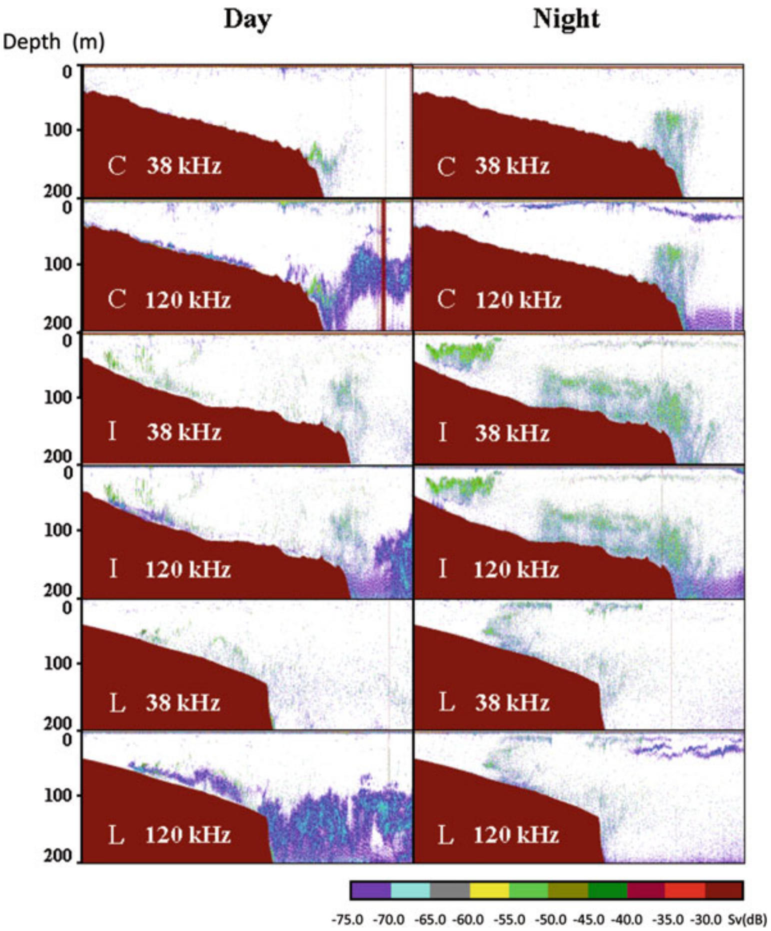

Fig. 8.4 Typical walleye pollock and zooplankton echograms off the Pacific coast of northeastern Hokkaido, Japan, in early summer during day and night. C, I, and L are lines in the eastern, central, and western parts of the survey area (Cited from Miyashita et al. 2004)

Figure 8.4 shows representative walleye pollock and zooplankton echograms taken off the Pacific coast of northeastern Hokkaido in early summer during day and night (Miyashita et al. 2004). The upper panel is the 38 kHz echogram, and the lower panel is that at 120 kHz. The echograms on the left were taken during the day, and those on the right were taken at night. Here, we observed that echoes at 120 kHz were mainly zooplankton, and those at both frequencies were mainly walleye pollock (Miyashita et al. 1997). The differences in the diel distribution patterns of walleye pollock and zooplankton are notable in these figures. Images of diel changes in early summer distribution patterns of zooplankton (prey) and walleye pollock (predator) are shown in Fig. 8.5. Layers of zooplankton were distributed over the continental shelf near the sea bottom during the day, and schools of young walleye pollock were distributed

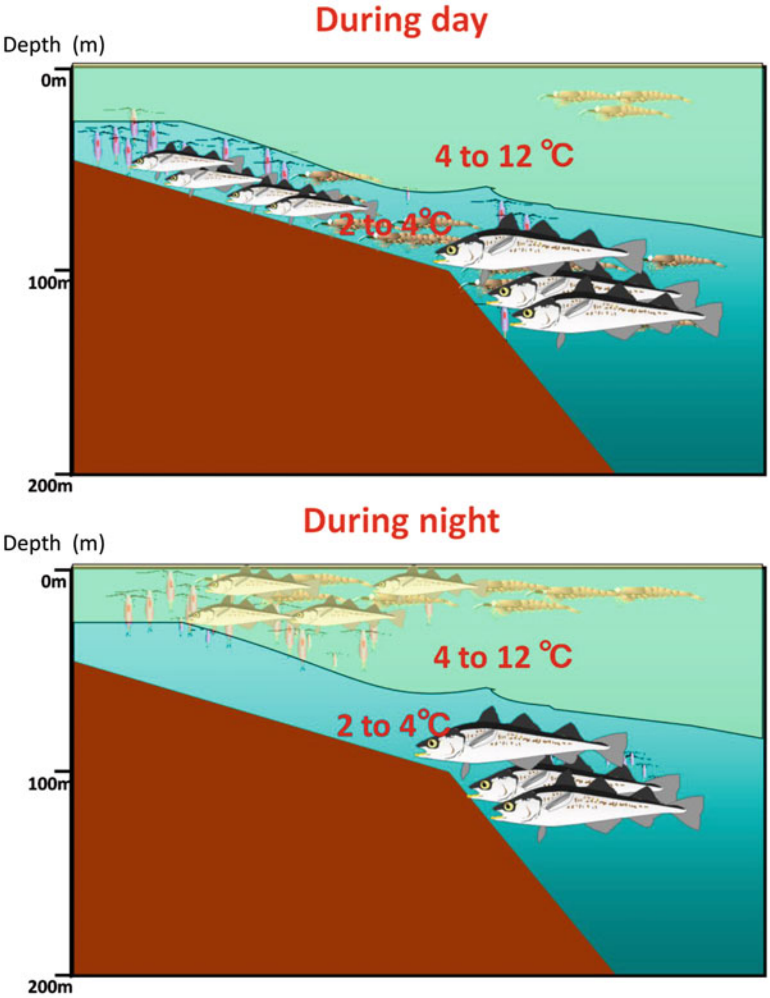

Fig. 8.5 Images of diel changes in zooplankton (prey) and walleye pollock (predator) distribution patterns in early summer off the Pacific coast of northeastern Hokkaido, Japan (Modified from Miyashita 2006)

mainly from mid-water to the sea bottom. However, near and offshore of the continental shelf, the layers of zooplankton were distributed near the sea bottom and mid-water, whereas adult aggregations of walleye pollock were near the sea bottom. The temperature range during the day, when the majority of walleye pollock and zooplankton were found, was 2–6 °C. The layers of zooplankton over the continental shelf tended to move to the sea surface at night, and the schools of young walleye pollock also tended to ascend to the upper layers at night. The layers of zooplankton outside of the continental shelf were distributed mainly near the surface, and adult aggregations of walleye pollock were distributed near the bottom to the mid-water level. The night temperature range at which young walleye pollock and zooplankton were detected was 4–12 °C. In contrast, the temperature range in which adult walleye pollock was present at night was similar to that during the day.

The observations of Miyashita et al. (2004) and Miyashita et al. (1997) show that the diel changes in vertical distribution and movement patterns of young walleye pollock and zooplankton are similar, but that those of adult walleye pollock and zooplankton are different. Miyashita et al. (2004) discussed differences in survival strategies for adult and young walleye pollock. That is, young fish feed during day and night to facilitate their growth, whereas adults feed only during the day to conserve energy for reproduction.

8.5.2 *Spatial Visualization of Differences in Adult and Juvenile Distribution Patterns: Krill*

Tojo et al. (2008) suggested that spatial distribution patterns of *E. pacifica*, which is called Isada krill in Japan, differ north and south of the Subarctic Front (SAF). They detected Isada krill using differences in the characteristics of the two acoustic frequencies (38 kHz and 120 kHz) and MOCNESS trawl information. Then, the spatial distribution characteristics of Isada krill were quantified using a geostatistical method, and the ecological interpretations were made by integrating acoustic echoes, biological information, and environmental data (e.g., temperature and salinity). Figure 8.6 is a conceptual model of the Isada krill distribution estimated using the abovementioned method around the SAF north of the 4 °C isotherm. The Isada krill distribution was more dispersed and extended in the north-south direction than that in the south, where aggregations

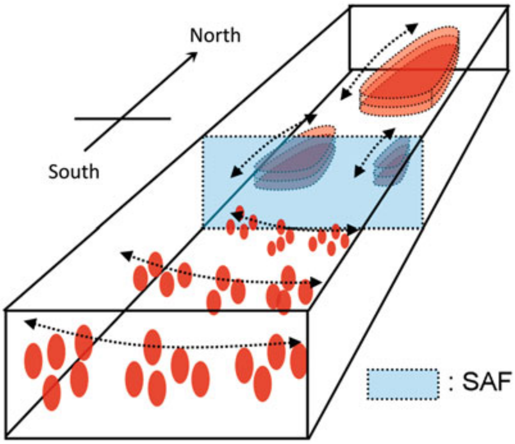

Fig. 8.6 Conceptual model of the Isada krill distribution around the Subarctic Front (SAF). Red circles, Isada krill aggregations; blue rectangle, SAF; dotted arrows, major directional distribution trends (Cited from Tojo et al. 2008).

of various densities were observed. Specimens in the north were mostly juveniles, whereas adults were found mainly in the south. Their results suggest that the Isada krill life history determines their habitat within a given oceanographic and environmental structure.

8.6 Advanced Acoustic Monitoring System: Real-Time *Shirasu* School Mapping System

Small pelagic fish, such as sardine and anchovy, are important fisheries resources worldwide. In Japan, sardine and anchovy of all life stages are caught using various methods. In particular, the so-called shirasu (post-larvae to juvenile stages) are the most economically valuable target resource at all stages, and shirasu fishing is conducted in the coastal waters of southern and eastern parts of Japan. Therefore, it is important to understand the shirasu recruitment mechanisms for resource and fisheries management. It is also necessary to quantitatively determine their abundance simply and quickly for sustainable management. Acoustics is a powerful tool, and an acoustic real-time shirasu monitoring system was introduced to support the shirasu fishery in the western part of Japan.

8.6.1 Shirasu *Fishery and Acoustics*

The most common shirasu fishing method is a trawl net during the day. Shirasu fishermen use a commercial dual-frequency echo sounder (50 and 200 kHz), which is known as a “shirasu echo sounder,” to detect shirasu schools. Figure 8.7 shows a representative echogram recorded by a shirasu echo sounder on shirasu fishing grounds during the day. The left panel shows the 50 kHz echogram, and the right panel shows that at 200 kHz. The shirasu school echoes were detected at the higher frequency (200 kHz) but not the lower frequency (50 kHz). Fishermen detect shirasu schools using differences in the acoustic frequency characteristics and their experience.

Figure 8.8 shows representative echograms recorded by a dual-frequency quantitative echo sounder on shirasu fishing grounds during the day (Miyashita 2006). The upper panel shows the 38 kHz echogram, and the lower panel shows that at 120 kHz. Here, two types of acoustic frequency characteristics were observed. That is, the 120 kHz echoes were only shirasu schools, whereas the 38 and 120 kHz echoes were young and adult anchovy, respectively. The shapes of the young/adult anchovy and shirasu schools were very similar on the 120 kHz echogram, indicating that a dual-frequency quantitative echo sounder is needed to detect a shirasu school.

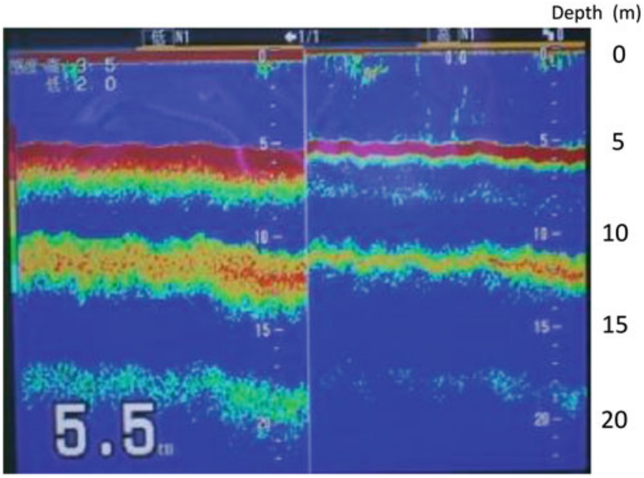

Fig. 8.7 Typical echograms recorded by a shirasu echo sounder on a shirasu fishing ground. Left, 50 kHz; right, 200 kHz

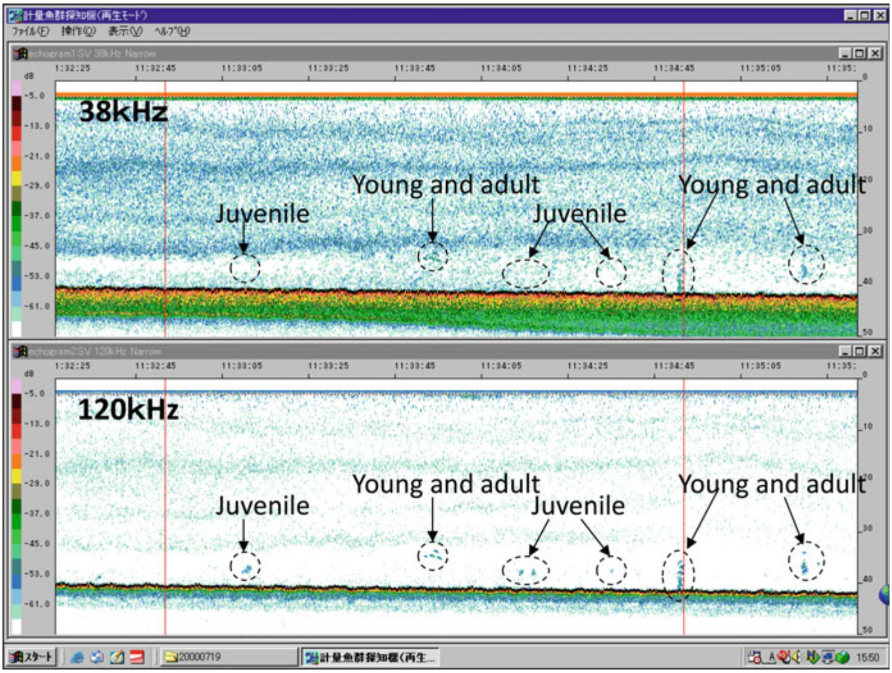

Fig. 8.8 Typical echograms recorded by a dual-frequency quantitative echo sounder on a shirasu fishing ground. Upper, 38 kHz; lower, 120 kHz (Modified from Miyashita 2011a, b)

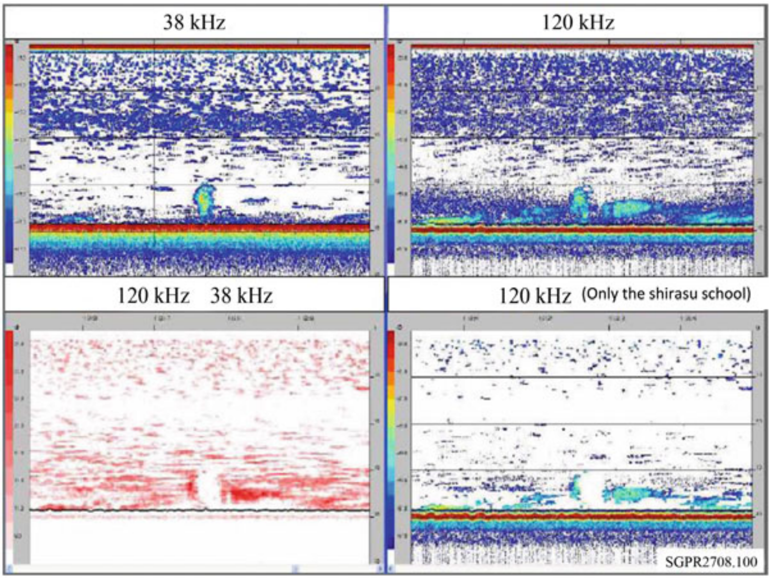

Fig. 8.9 Echograms from the automatic shirasu school discrimination system (Modified from Miyashita 2011a, b)

8.6.2 *Automatic* Shirasu *School Discrimination System*

Figure 8.9 shows echograms of an automatic shirasu school discrimination system. The left side of the upper panel shows the 38 kHz echogram, and the right shows that at 120 kHz. The left side of the lower panel shows the mean volume backscatter strength (MVBS) difference at 38 and 120 kHz (MVBS = 120–38 kHz), and the right shows the 120 kHz echogram of only the shirasu school, which was discriminated using the shirasu acoustic frequency characteristics suggested by Miyashita (2003). These computations were processed automatically.

8.6.3 *Real-Time* Shirasu *School Mapping System*

It is essential to have a shirasu school discrimination system that automatically transfers data from the vessel to land to process during a survey using this type of system. Furthermore, researchers and managers can take a practical approach to fisheries management by integrating additional information, such as environmental data (e.g., temperature, salinity, etc.) from a survey and satellite, automatically using the shirasu school information.

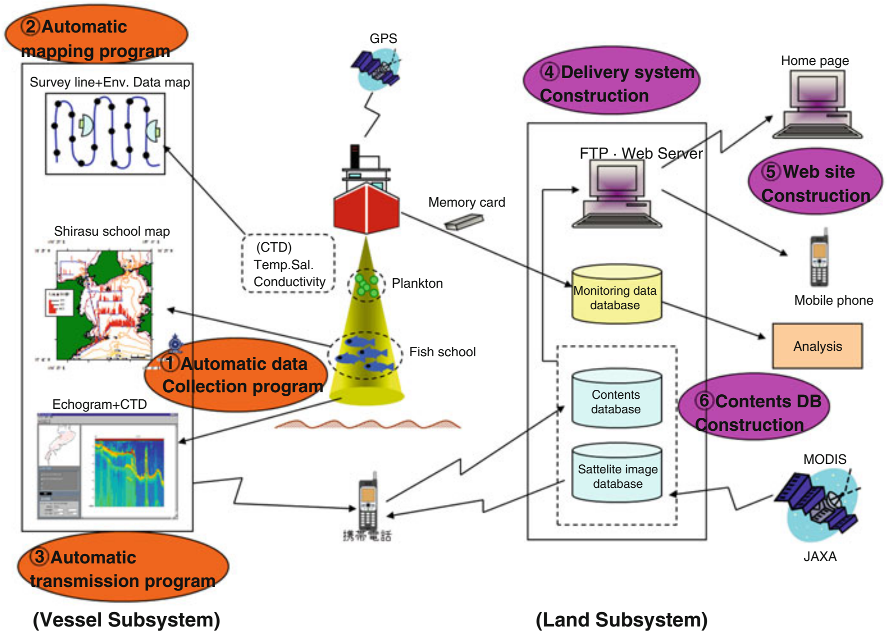

Fig. 8.10 Outline of the real-time shirasu school mapping system (Modified from Miyashita 2011a, b)

Figure 8.10 is an outline of a real-time shirasu school mapping system (Miyashita 2011a, b). This system comprises a research vessel and a land subsystem. Each subsystem is connected to a communication network. Three programs are operated by the research vessel subsystem: (1) automatic collection of shirasu school echo and sea surface temperature data, (2) automatic mapping of the collected data, and (3) automatic transmission of the maps created. The maps of the shirasu schools, echograms, vessel survey lines, and sea surface temperatures are processed. Additionally, there are three programs for transferring the shirasu school maps to the on-land subsystem: (4) content database (processed maps and satellite images), (5) map transport, and (6) an Internet-based interface.

Figure 8.11 shows a view of the portal site from the Internet-based interface for the real-time shirasu school mapping system operated from 2009 to 2013 in the coastal waters of western Japan (areas around Kii Channel and Bungo Channel, http://fishmap.ddo.jp/shirasu/). This portal site was developed using web-based GIS, and the interface can be operated easily by anyone clicking on the area polygons. A mobile site was also developed and is accessed by a hyperlink from the portal site (http://fishmap.ddo.jp/shirasu/mobile/). Shirasu fishermen can monitor the web site on a fishing vessel during the fishing.

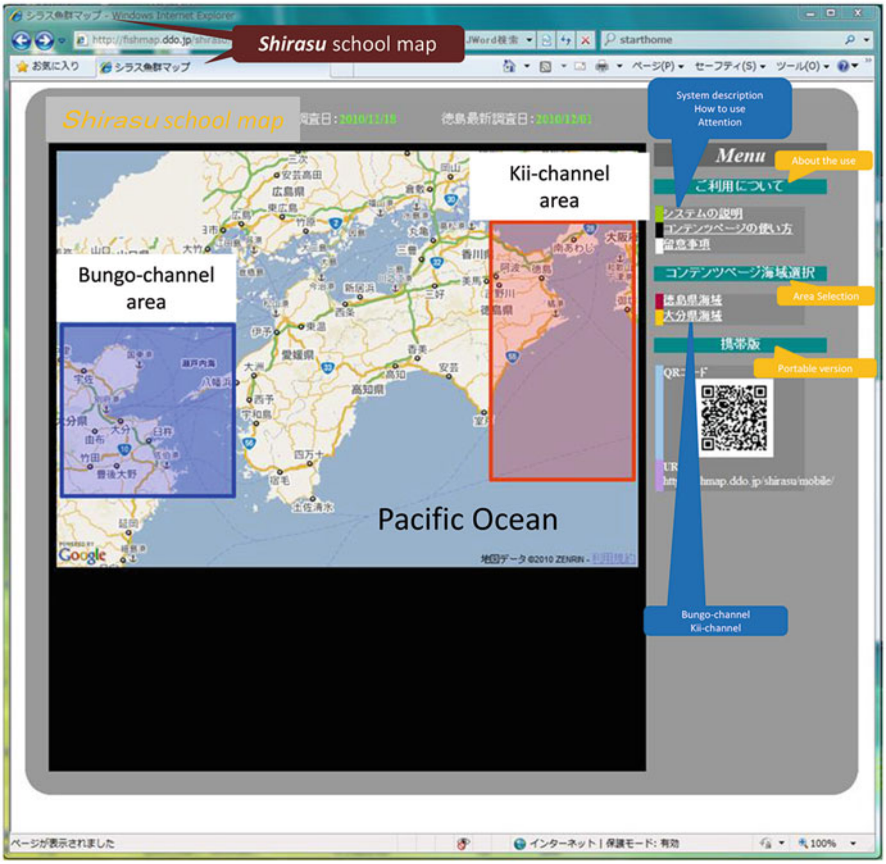

Fig. 8.11 Portal site for the real-time shirasu school mapping system, displayed in Japanese (Modified from Miyashita 2011a, b) http://fishmap.ddo.jp/shirasu/

Figure 8.12 is an example of a shirasu school map obtained from Bungo Channel, Japan. In the upper panel, the estimated individual shirasu densities and the measured sea surface temperatures are displayed using a color classification system on the vessel survey line. Individual shirasu density was estimated using target strength based on Itoh et al. (2011). Furthermore, satellite images, such as those for sea surface temperature or ocean color, can be overlaid with individual shirasu density. Original echograms (38 and 120 kHz) and the shirasu school echogram estimated using the automatic shirasu school discrimination system were also monitored, as shown in the lower panel of Fig. 8.12.

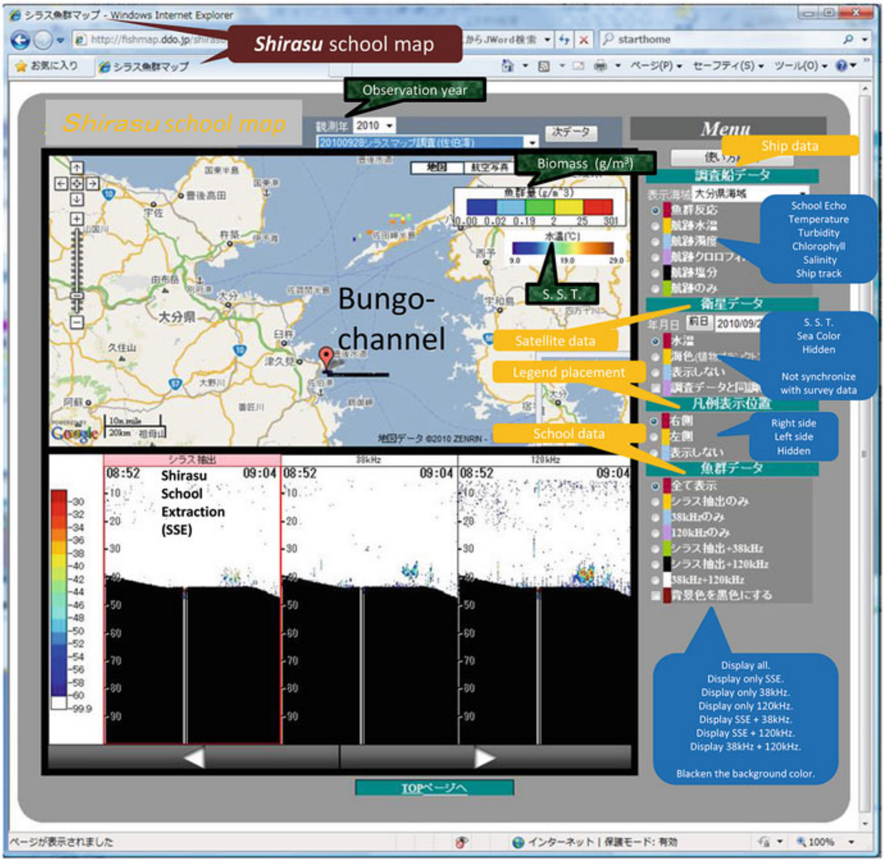

Fig. 8.12 Example of a shirasu school map obtained in the Bungo Channel, displayed in Japanese (Modified from Miyashita 2011a, b)

8.6.4 Applying the Real-Time Shirasu *School Mapping System*

The real-time shirasu school mapping system is one of the first practical applications of an interactive acoustic integrated system in the world. Fish schools were automatically discriminated based on valid theoretical information using a quantitative echo sounder system, and the processed data were shared through the Internet in real time.

This system is being improved through field applications and the comments of fishermen. However, the system relies on the operations of a research vessel in each area. Thus, it is difficult to spatially and temporally estimate many shirasu school distributions. To resolve this time problem, low-cost and compact quantitative echo sounders are expected to be introduced to commercial fishing vessels in the near future. Use of the system by fishermen will facilitate efficient management of fishing. Then, data monitoring using the system will assist researchers and managers in evaluating fisheries resources and taking better decisions.

8.7 Perspectives on an Acoustic Monitoring System for Ecosystem-Based Fisheries Management

Acoustic methods are essential to visualize aquatic organisms. There is no doubt that acoustic applications are the only means of quantifying live underwater resources in situ, particularly dynamic organisms such as small pelagic fish.

However, a few limitations must be overcome for further applications, such as stock assessments of aquatic living resources. For example, the data obtained from an acoustic survey are snapshots in the water column. Imagine that an acoustic survey is conducted continuously for 3 days. The estimated overall biomass from the survey may not be representative of the total biomass. The distributions of marine organisms change rapidly. Therefore, the biomass estimated in a survey is not equal to the actual standing stock. I suggest two means of overcoming this “snapshot” problem. The first would be to establish a continuous acoustic monitoring system, and the second would be to visualize and conceptualize ecological processes around target marine organisms in their ecosystem. Continuous acoustic monitoring surveys for target marine organisms during all seasons, and integration and conceptualization of ecosystem processes, would enable highly accurate estimation of biomass and the variability thereof following correct interpretation of distribution changes. Moreover, an acoustic monitoring system will enhance conceptualization of the ecological processes in marine ecosystems. The information provided will assist quantitative diagnosis of the health status of a marine ecosystem.

A new research field known as “marine acoustic ecology” has developed, as mentioned above (Miyashita 2006). The aims of marine acoustic ecology are to visualize marine organisms in situ and quantify ecological characteristics using acoustics science and technology. In this chapter, various applications of acoustics in ecological research were introduced as marine acoustic ecology. As the field of marine acoustic ecology advances due to a new and quantitative understanding of marine ecosystems, new methods of managing fisheries will be established. Management of fisheries resources using “marine acoustic ecology” (Miyashita 2006) will be recognized as an important part of the novel and (intensively) applied research field of marine ecosystem metrology.

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