Study on diel migration of zooplankton in the Arctic surrounding seas during summer season based on mathematical statistics

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Abstract. Marine zooplankton have diel vertical migration behavior and play a key role in the transport of surface organic compounds to the deep ocean, which is of great significance in studying marine climate change. In this research, the manual visual interpretation method was used to preprocess the biological backscattering intensity data of acoustic Doppler current profiler (ADCP) during the eighth Arctic expedition. Results showed that the extracted vertical migration trajectory was in good agreement with the variation of backscattering intensity data. The amount of zooplankton in the Arctic Ocean is significantly lower than that in the North Pacific and the North Atlantic, and sea ice cover has a significant effect on the diel vertical migration of zooplankton. Characteristics of zooplankton distribution in the North Atlantic Ocean were analyzed based on mathematical statistical methods. The results also prove that the backscattering intensity of -90dB can distinguish scattering layer and water, and that of -78dB can distinguish general scatters and zooplankton. There are two significant concentrations of zooplankton in the Atlantic Ocean which were located at the surface and at depths of 350-450 m, respectively.

Keywords: Mathematical Statistics; Acoustic Doppler Current Profiler; Marine Zooplankton; Diel Vertical Migration.

1. Introduction

Suspending in the water layer and often moving with the current, marine plankton is widely distributed as the most important biological group in the marine ecosystem with abundant varieties. In the marine food web, zooplankton that controls primary productivity by feeding on phytoplankton are preyed on by animals of higher trophic class such as fish, shrimp, whale, seabirds, etc. As secondary producers, marine plankton affects the resources of fish and other marine animals [1] with its community structure, population dynamics, and species diversity. Moreover, marine zooplankton acts as a “biological pump” in the transfer and transportation of atmospheric CO2 to the deep sea [2-3], which is vital to the regulation mechanism of global climate change and the research on global CO_2 sea-air exchange. The key link of marine ecosystem dynamics is the biological and ecological process of plankton [4], so the study related to zooplankton has become one of the core contents of marine ecological research [5].

Many marine zooplankton is habitual to the diel vertical migration (DVM), which is common in marine and freshwater ecosystems. In the past 20 years, it is generally believed that zooplankton eats phytoplankton on the surface at night, and after sinking to the deep layer during the day, their respiration metabolism, excrement, and predation by higher trophic animals all enable them imperative to transport organic carbon from the upper layer to the deep layer [6-7]. On the one hand, their vertical migration acts as a biological carbon pump to help transfer the fixed carbon from the upper ocean to the deep sea, which is key to carbon transportation to the deep sea, contributing to atmospheric CO_2 concentration and global change [8-9]. On the other hand, it not only maintains the energy demand of deep-sea zooplankton and planktonic bacteria by transferring carbon flux, but also stabilizes the planktonic ecosystem in the middle layer of the ocean [10]. The dynamic distribution of zooplankton is based on its behavioral ecology. In addition to the vertical distribution of zooplankton, DVM also affects its horizontal distribution and life characteristics. The research on zooplankton’s DVM has been an integral part of population dynamics.

The technical means of deep-sea planktonic ecology research are mainly divided into plankton trawling, optical survey equipment, acoustic survey equipment, and sediment trap [11]. Due to the limitation of traditional biological trawl sampling, many researchers in recent years began to use acoustics to obtain abundance and distribution data of marine animals such as zooplankton and fish [5], so as to analyze the temporospatial changes of zooplankton's vertical movement in different sea areas [12-13]. ADCP is a basic equipment for physical ocean surveys [14] and a new current measuring equipment developed in the early 1980s. It adopts the principle of acoustic Doppler to measure the frequency shift information of scattering signals from a stratified water medium. Besides, the vector synthesis method is utilized to obtain the vertical profile velocity of ocean current, that is, the vertical profile distribution of current. The scatters used by ADCP are mainly zooplankton and suspended particulate matter in seawater, so it can study the abundance and distribution of zooplankton with different particle sizes in seawater.

Vessel-mounted ADCP is fixed at the bottom of the research ship, which is equipped with four transducers both as transmitters and receivers, with each forming a certain included angle against the axis of ADCP [15]. The transducer emits sound waves at a fixed frequency and then listens to the sound waves scattered by the sound scatterer in the water body. When the motion direction of particles approaches the transducer, the echo frequency heard by the transducer is higher than that of the emitted wave, and vice versa. This frequency change caused by the sound scatterer motion is called an acoustic Doppler frequency shift. According to the Doppler frequency shift of the reflected signal, the moving velocity of particulate matter along the direction of the acoustic beam is calculated. Moreover, the absolute ship speed is calculated by using a bottom pulse or global positioning system (GPS) based on the positioning information before and after epochs. The difference between the two vectors is the velocity vector to be measured.

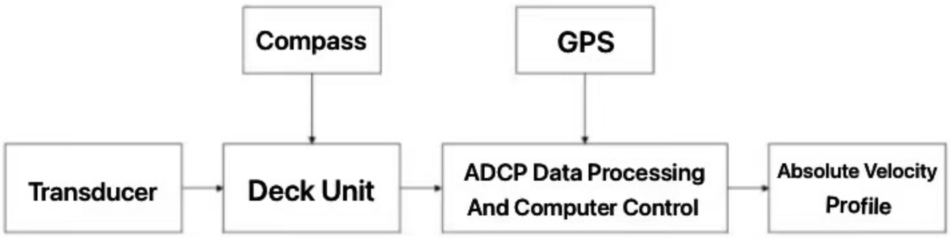


Figure 1. ADCP Hardware and Data Acquisition Flow Chart of Xue Long Vessel-Mounted ADCP

In 2017, the team of China's eighth Arctic expedition for the first time crossed the Central Channel of the Arctic Ocean, tried the Northwest Channel, and investigated the Arctic Ocean, which provided valuable data for research on the changing ecological environment of the Arctic Ocean. Tongji University, one of the authors' universities, has been conducting scientific research on the North and South Poles and guiding the science popularization and innovation for middle school students in the long term. Inspired by the self-propositional science popularization and innovation in the State Key Laboratory of Pollution Control and Resource of Tongji University, this project uses the ADCP data obtained from the eighth Arctic expedition. At the same time, distribution characteristics and DVM laws of zooplankton in the Arctic Ocean were investigated based on mathematical statistics methods. This study reveals the DVM trajectory and distribution characteristics of zooplankton in the Arctic Ocean in summer. The Arctic Ocean is the study area located in the northernmost part of the earth surrounded by Canada, Alaska, Russia, Norway, Iceland, and Greenland. It is connected with the Pacific Ocean through the narrow Bering Strait and the Atlantic Ocean through the Greenland Sea and many straits. As global warming worsens, glaciers in the Arctic are melting rapidly, so the research on zooplankton living in the Arctic Ocean has been a trend.

To analyze efficient statistics of ADCP data based on Python and extract key information on zooplankton's DVM trajectory, this study explores spatial distribution characteristics and differences of zooplankton in the Arctic Ocean in summer and establishes corresponding mathematical models.

2. Research Method and Process

2.1 Research Route and Data Sources

According to Figure 2, the research route of this paper is mainly as follows. 1) Literature and data: Emphasis is laid on learning professional knowledge such as marine plankton, the principle of zooplankton's DVM and ADCP observation through literature, so as to understand the geographical scope, climate change, and ecological environment of the Arctic Ocean; Applying for ADCP data for research from the National Polar Science Data Center; 2) Identify the trajectory of zooplankton's DVM and analyze the spatial distribution law in the Arctic Ocean; identify the zooplankton distribution area and analyze its vertical distribution law in Arctic Ocean.

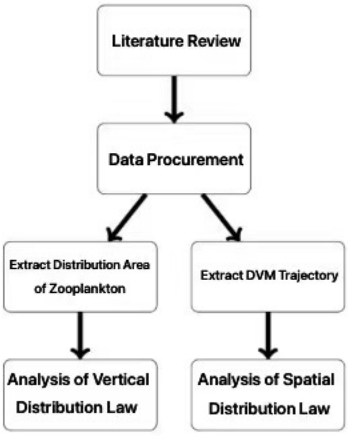


Figure 2. Research Route

The data used in this study come from the National Polar Science Data Center, which is obtained by OceanSurvey 38K, the ADCP observation instrument loaded on the Xue Long polar research vessel. Its maximum observation depth is 2348m with 100 observation layers. The depth of each layer is about 24m and the vessel-mounted observation frequency is 20 minutes per time. Starting with observation on July 20, 2017, and ending on October 7, 2017, this instrument provided no observation data from August 29 to September 7 with 70 days of valid data.

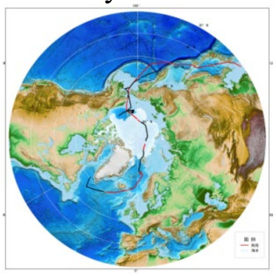


Figure 3. Track Map of China's Eighth Arctic Expedition

The data used in this study is that of biological backscattering intensity calculated from the echo intensity data observed by ADCP, which is in MAT format of Matlab, including track data and backscattering intensity data.

2.2 Research Methodology

2.2.1 Mathematical Methods

Based on mathematical statistical methods, this study aims to process ADCP biological backscatter intensity data and identify the DVM trajectory of marine plankton as well as zooplankton distribution area, so as to analyze the distribution law of zooplankton. The theoretical methods used in this paper are as follows:

Coordinate system transformation: Based on the coordinate transformation principle, the image coordinates obtained by manual visual interpretation are transformed into time-depth coordinates of ADCP data.

Histogram, cumulative histogram, and isoline: Histogram and cumulative histogram are used to view and analyze the distribution characteristics of biological backscattering intensity. They can determine the statistical eigenvalue of backscattering intensity and the threshold of image segmentation. The spatial distribution characteristics of biological backscattering intensity can be analyzed by the isoline method to prove and determine the image segmentation value.

Variance and threshold segmentation: The accuracy of the plankton distribution area is extracted by variance analysis; the zooplankton distribution area is automatically extracted by the threshold segmentation method.

Grouping statistics: According to different depths of water layers, the average and the variance of the backscattering intensity of each water layer are calculated.

2.2.1 Software Tools

In this study, Python programming and QGIS, a geographic information software, are used.

Python programming is mainly used for data analysis and processing. Xarray module is to read and process ADCP acoustic backscattering intensity data before transforming between image coordinates and time coordinates. Pandas module is to carry out statistical analysis of data. Geopandas module and matplotlib module are used to route data reading and mapping respectively.

2) QGIS is mainly used to visually interpret the trajectory of zooplankton's DVM.

3. Research Results

3.1 Identification and Characteristic Analysis of Diel Vertical Migration Trajectory

3.1.1 Manual Visual Interpretation

Recognizing the zooplankton's DVM trajectory is fundamental to analyzing their migration law. Although researchers have proposed many methods of migration trajectory extraction, they are complex in calculation and lack general software support, which is hard to popularize. To quickly identify their migration trajectory, the manual visual interpretation method that is common in remote sensing is used. The interpretation process is as follows:

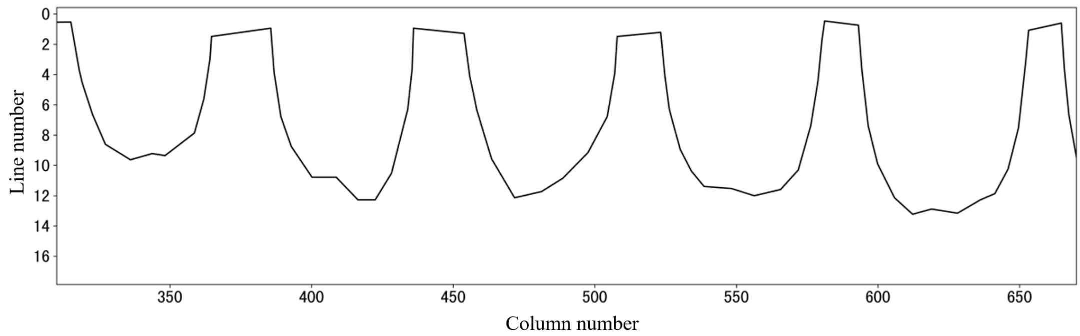
Data preprocessing and conversion: Because plankton are mainly distributed in the true and weak light layers within 1000 meters from the sea surface to underwater, the original acoustic backscatter intensity data is cut and only the data within 1000 meters of water depth is reserved for analysis. ADCP biological backscatter intensity data is converted into image data, which can be read by QGIS. The backscatter intensity data before conversion adopts a time-depth coordinate system, with the vertical axis and horizontal axis representing the water depth and observation time respectively. The converted image adopts an image coordinate system, with abscissa representing the number of image columns and ordinate representing that of the image row.

Visual interpretation: The open source QGIS is used for manual visual interpretation and the data of DVM trajectory after interpretation are saved in the format of shapefile.

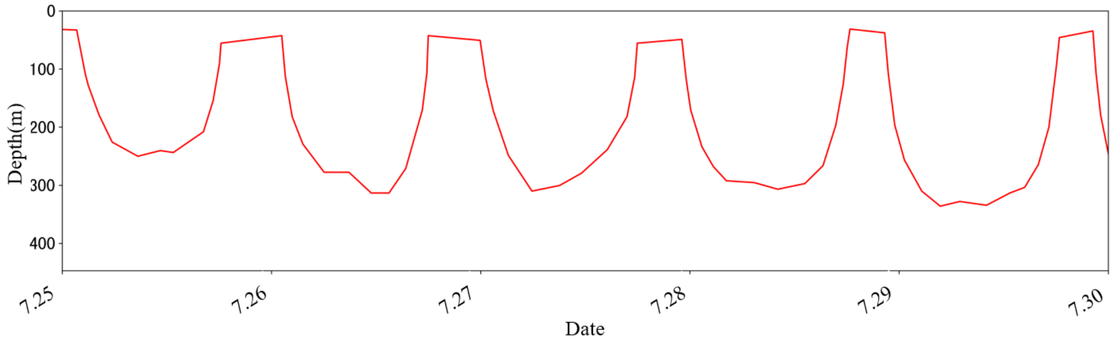
Coordinate transformation: After the manual visual interpretation, the image coordinates are transformed into time series coordinates of biological backscattering intensity data by the coordinate transformation method, with the coordinate transformation formula shown below:

$$Time = t_0 + 0.01389 \cdot column,\ \ Depth = d_0 + 23.96 \cdot row\ , \tag{1}$$

where t_0 represents the starting time of observation; 0.01389 is the interval time of ADCP vessel-mounted observation (20 minutes) with the decimal unit; $column$ is the number of image columns; d_0 represents the starting depth with a value of 16m; 23.96 represents each layer depth of ADCP; row is the number of image rows. Figure 4 shows the vertical migration track of zooplankton before and after a coordinate transformation.



(a) Before the Transformation of Coordinate System



(b) After the Transformation of the Coordinate System

Figure 4. Coordinate Transformation

Result verification: According to Figure 5., the data obtained by manual visual interpretation is superimposed and displayed with the original biological backscattering intensity image to judge the accuracy of manual interpretation.

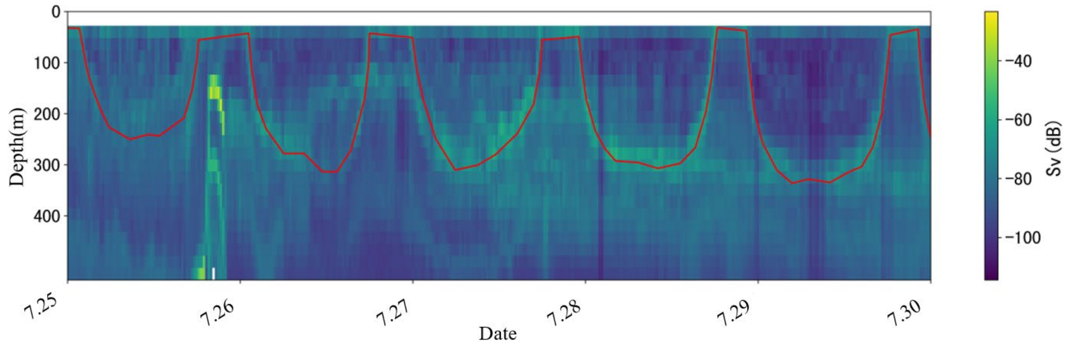
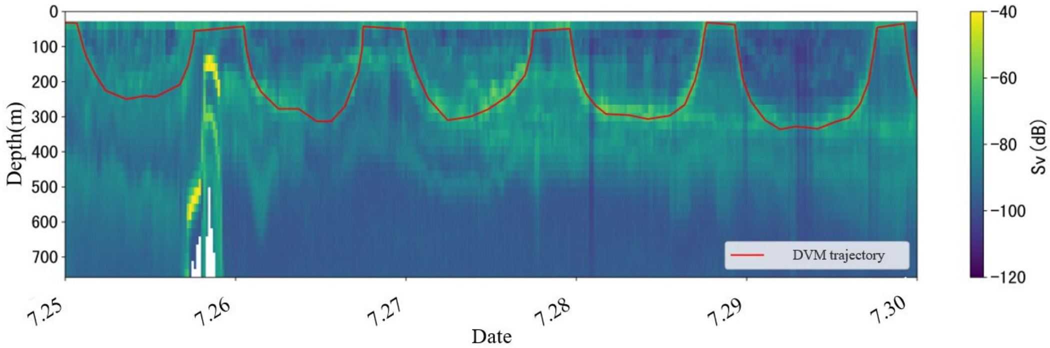


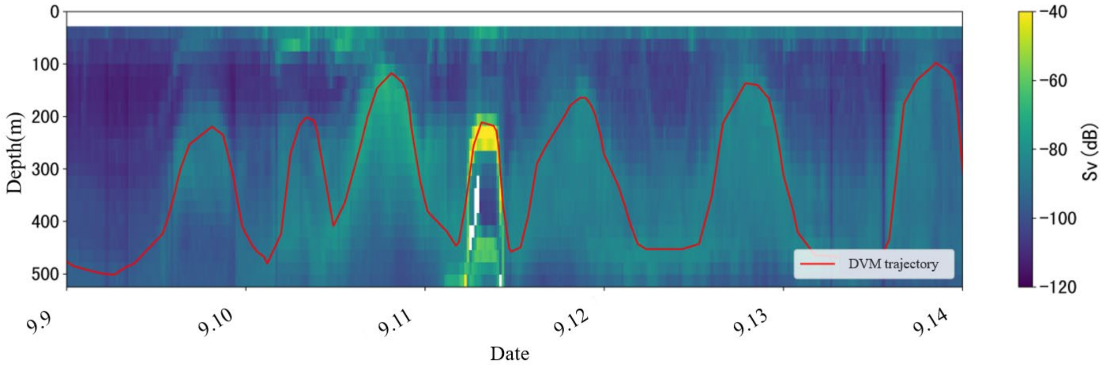
Figure 5. DVM Trajectory of Zooplankton After Superimposing Images

3.1.2 Analysis of Spatial Distribution Characteristics

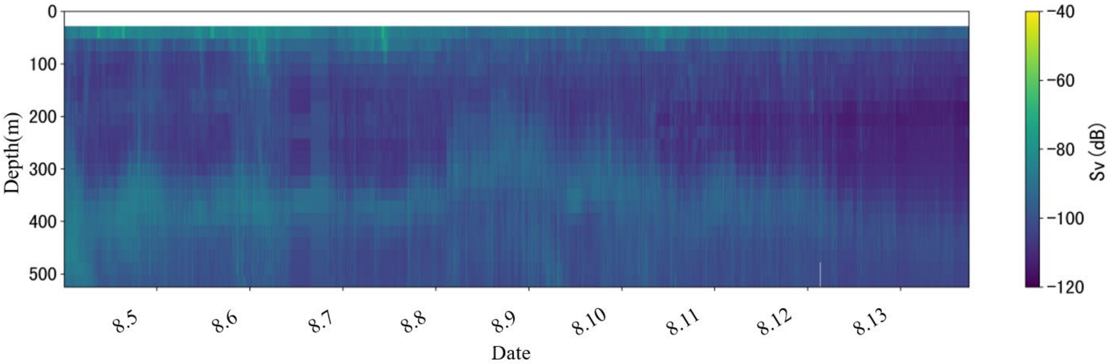
China's eighth Arctic expedition has passed the North Pacific Ocean, Arctic Ocean, and North Atlantic Ocean. The backscattering intensity of organisms and the DVM trajectory of zooplankton in these waters are shown in Figure 6.



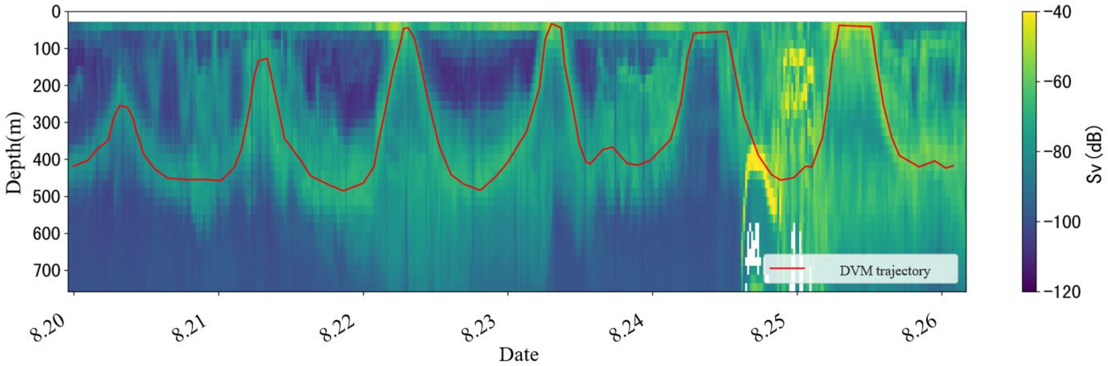
(a) North Pacific Ocean



(b) Ice-Free Areas of the Arctic Ocean



(c) Sea Ice Cover in the Arctic Ocean



(d) North Atlantic Waters

Figure 6. DVM Trajectory of Zooplankton

According to the backscattering intensity data and the DVM trajectory of zooplankton, the zooplankton in the North Pacific Ocean, the Arctic Ocean, and the North Atlantic Ocean have these characteristics:

North Pacific Ocean: The distribution layer and DVM of zooplankton can be found in the North Pacific Ocean. Some sea areas have vertical migration at two depths. However, due to the influence of seabed topography, no DVM characteristics were observed in the waters of the Strait.

Arctic Ocean: The amount of marine zooplankton in the Arctic Ocean is less than that in other sea areas with lower backscattering intensity. In the sea ice-covered area, the backscattering intensity decreased significantly and the distribution range of the scattering layer was also small almost without DVM. In the ice-free area, there is no obvious DVM of zooplankton in July but the data in September have such characteristics, which may be related to the diurnal motion in the Arctic. Due to the influence of light, the DVM of zooplankton is weakened.

North Atlantic Ocean: The North Atlantic Ocean is a traditional fishing area in the world with rich marine fishery resources, which is also proven by the artificial interpretation results. In the North Atlantic, the backscattering intensity increases, the scattering layer is distributed in a wide range, and the DVM characteristics of zooplankton are very obvious. With the decreasing latitude, the zooplankton stays on the sea surface for a longer time.

3.2 Identification and Characteristic Analysis of Zooplankton Distribution Area

3.2.1 Typical Study Area

The marine zooplankton in the North Atlantic Ocean has typical DVM characteristics, which is suitable for developing automatic extraction algorithms of zooplankton distribution areas. The observation data from July 20th to July 22nd are selected, and their geographical range is 58 ~ 66 degrees north latitude and 0 ~ 10 degrees east longitude.

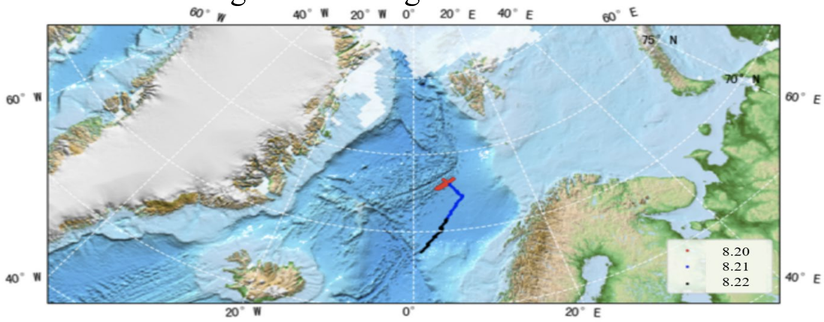


Figure 7. Scope Map of Typical Study Area

3.2.2 Distribution Characteristics Analysis of Biological Backscattering Intensity

ADCP in works will emit sound waves with a fixed frequency, which will produce backscattering signals in water propagation when encountering scatterers such as suspended particles. The backscattering intensity is an index reflecting scatterers' scattering ability, which is proportional to the logarithm of suspended solids concentration. The greater the suspended solids concentration, the greater the backscattering intensity. Thus, scattering layers in water can be extracted by this principle.

The factors affecting the scattering intensity of the water body include plankton, chlorophyll, turbidity, temperature gradient, and ice debris produced by sea ice disintegration. Usually, plankton particles are larger than other suspended solids and the backscattering intensity is greater. Besides, zooplankton has DVM changing at different seawater depths with time. Thus, the zooplankton distribution area can be extracted via the backshooting intensity as shown in Figure 8.

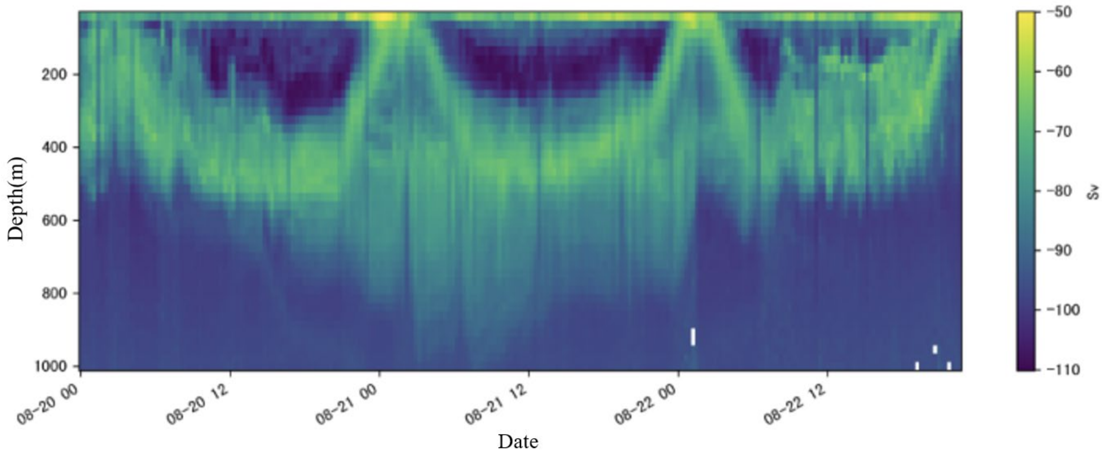


Figure. 8 Backscattering Intensity Diagram

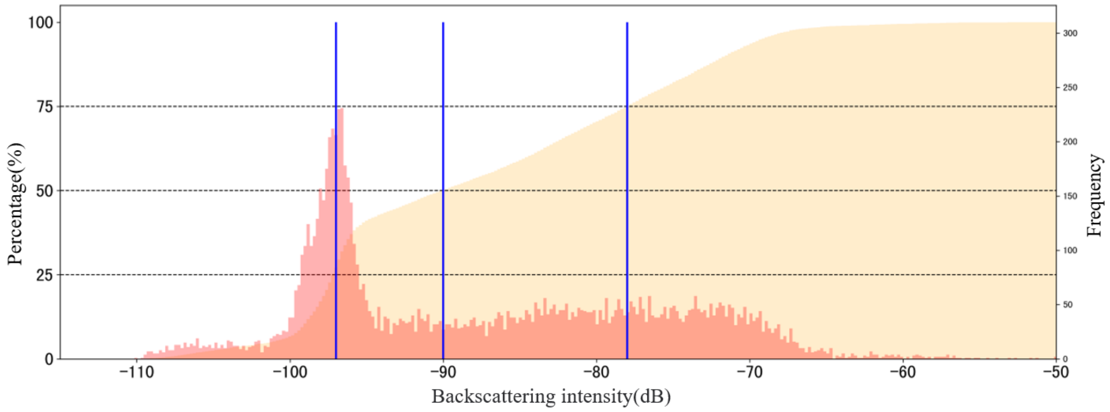


Figure 9. Backscattering Intensity Histogram

As for water bodies' distribution characteristics of backscattering intensity, the histogram and cumulative histogram are used to make statistics on backscattering intensity. Based on Figure 9., the backscattering intensity is mainly between -110db and -70db, 25% of pixels are less than -97dB, 50% and 75% of pixels are less than -90dB and -78dB respectively.

As a smooth curve formed by points with equal quantity and index value of the cartographic object, isoline reflects the spatial structure characteristics of the cartographic object. According to Figure 10, it is found that -90dB can distinguish the scattering layer from the water body and -78dB can distinguish general scatterers from plankton.

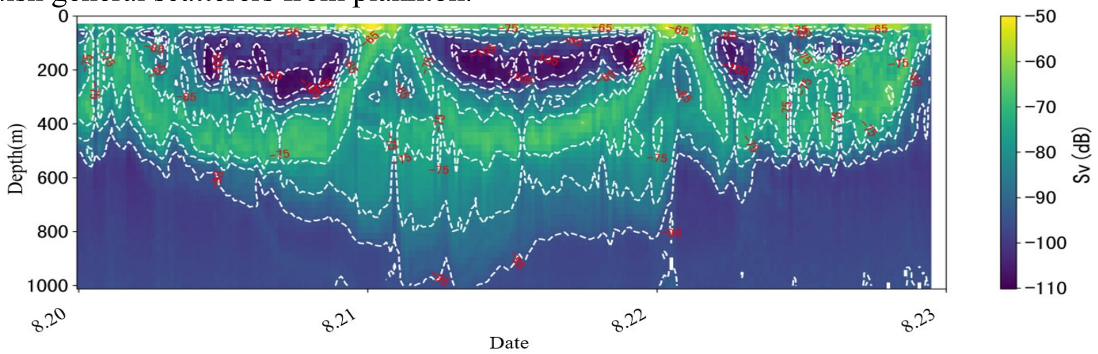


Figure 10. Isoline Distribution of Backscattering Intensity

3.2.3 Image Segmentation

Threshold segmentation is a region-based image segmentation technology, whose principle is to divide image pixels into several classes, suitable for images with different gray levels of target and background. As one of the most common traditional methods, it is the most basic and widely used in image segmentation because of its simple implementation, low computation, and stable performance. The function f of image threshold segmentation method is as follows:

$$f(Sv_i) = \begin{cases} Sv_i, & Sv_i > t, \\ 0, & Sv_i < t, \end{cases} \quad i = 1, \ldots, n, \tag{2}$$

where $Sv = (Sv_1, Sv_2, \ldots, Sv_n)^T$ is the backscattering intensity and t is the image threshold. In the operation, we use the where function syntax xr.where (condition, x, y) of Xarray to segment the image, with -97dB and -78dB taken as thresholds respectively. The extraction of the zooplankton distribution areas is as follows:

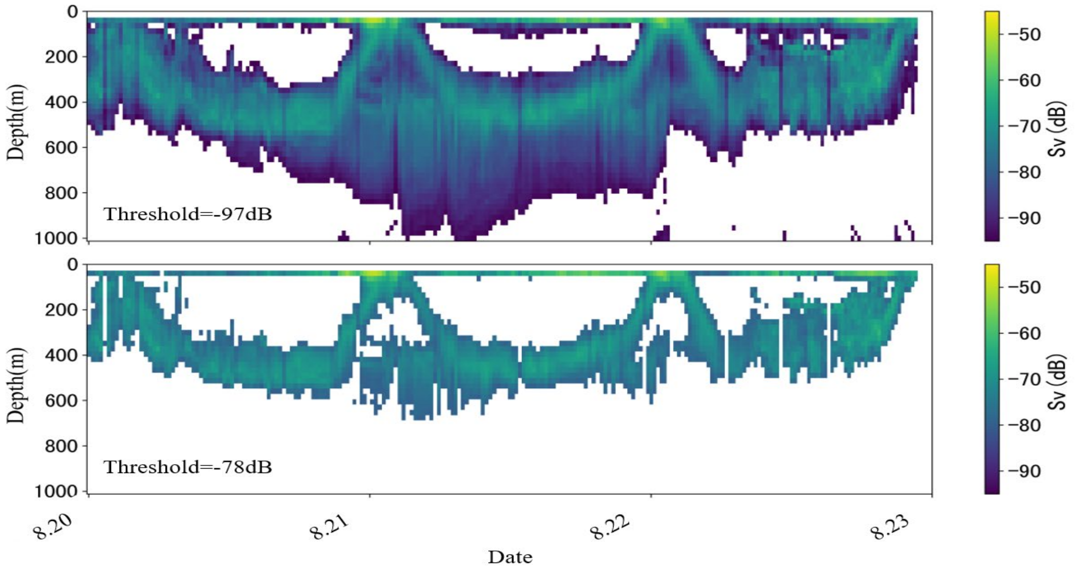


Figure 11. Distribution Map of Zooplankton Extracted by Threshold Segmentation Method

3.2.4 Accuracy Analysis

Variance is a measure of the dispersion degree of random variables or a data group, which can make statistics on the backscattering intensity of all identified distribution areas of the scattering layer and zooplankton with vertical migration characteristics. According to Figure 12, the backscattering intensity variance of scattering layer distribution areas extracted with a threshold of -97dB is large and its distribution is uneven at different seawater depths. The closer it is to sea level, the greater the variance, which indicates that more substances exist in the seawater scattering layer with great scattering difference. The backscatter intensity variance of the plankton distribution area that has diurnal vertical migration characteristics extracted with a threshold of -78dB is small, so is the difference in various water depths, which indicates that the material composition is relatively uniform.

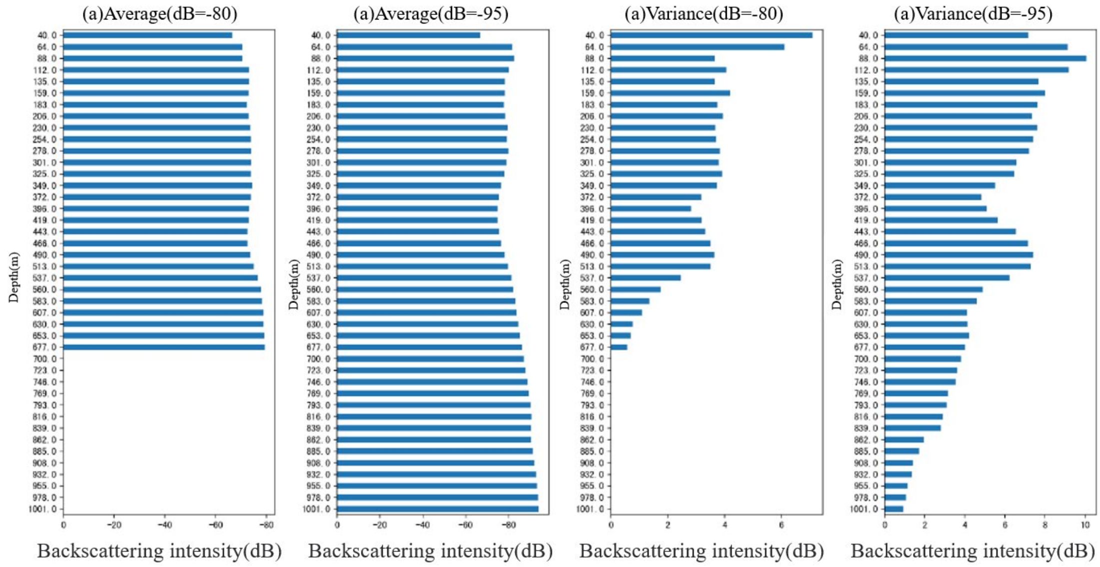


Figure 12. Layered Distribution of Backscattering Intensity

3.2.5 Analysis of Vertical Distribution Characteristics

To analyze the distribution characteristics of marine plankton at different depths of seawater, the backscattering intensity was grouped according to various depths and the total backscattering intensity of each water layer was calculated respectively. The statistical methods are as follows:

$$f(depth) = \begin{cases} \sum_{i=1}^{n} Sv(d_1)_i, & depth = d_1, \\ \sum_{i=1}^{n} Sv(d_2)_i, & depth = d_2, \\ \vdots & \\ \sum_{i=1}^{n} Sv(d_k)_i, & depth = d_k, \end{cases} \tag{3}$$

where $i \in \{1, \dots, n\}$ represents ADCP observation times. As for each $j \in \{1, \dots, k\}$, the vector $Sv(d_j) = \left(Sv(d_j)_1, Sv(d_j)_2, \dots, Sv(d_j)_n\right)^T$ represents the backscattering intensity related to depth d_j. $depth$ represents seawater depth, with $d_1, d_2, \dots, d_k$ as the specific depth. In the actual calculation, Pandas' groupby function is used and the daily statistical results are as follows.

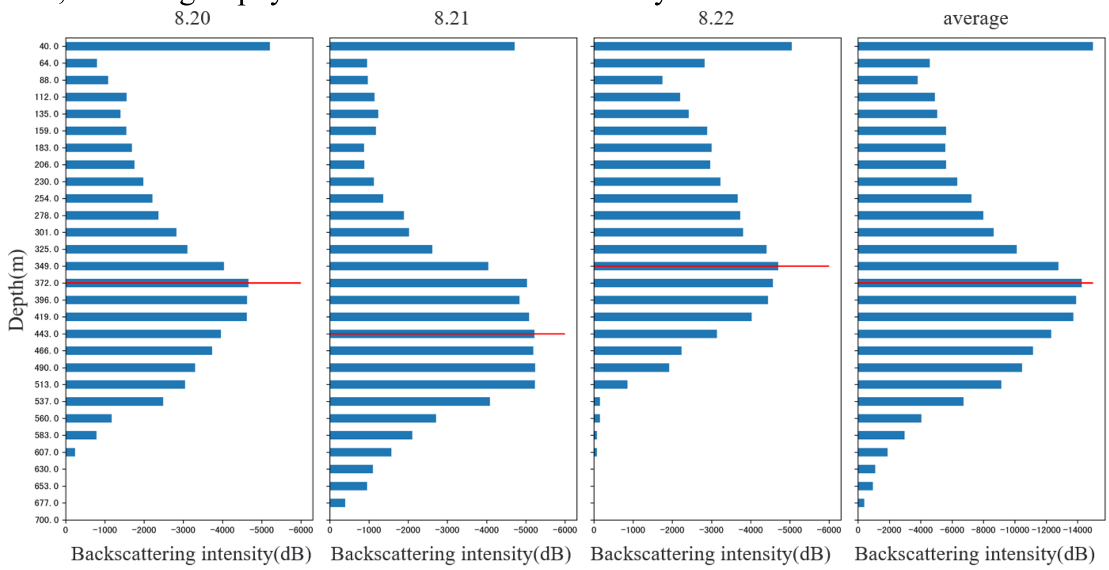


Figure 13. Stratified Distribution Map of Zooplankton

According to the results of statistical analysis, zooplankton are mainly distributed within 700 meters of water depth, and the degree of aggregation varies with water depth. There are two significant aggregation areas, one of which is located on the seawater surface, and the other is located within 350-450 meters of water depth. The depth of the underwater gathering area divides in various sea areas, such as 372 meters on August 20th, 443 meters on August 21st, and 349 meters on August 22nd. The average distribution depth is 372 meters.

4. Conclusion and Analysis

According to the data analysis results, we summarize the conclusions.

1) The plankton in the Arctic Ocean is obviously less than that in the North Pacific and the North Atlantic. In addition, the scattering layer in the water body covered by sea ice is limited without zooplankton's DVM. There is vertical migration in the non-ice area, but it may be affected by the daylight and the vertical migration in July is not obvious.

2) The backscattering intensity of zooplankton is different from that of other suspended solids, and the distribution area of zooplankton with diurnal migration characteristics can be automatically extracted by a threshold method. Specifically, the threshold value of suspended solids is about -97dB and that of zooplankton is about -78dB.

3) The zooplankton mainly distributes within 700 meters of water depth and the degree of aggregation varies with water depths. There are two significant aggregation areas, one of which is located at the seawater surface, and the other is at a depth of 350-450 meters.

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