Cluster Analysis of Deep Water Sound Speed Profiles in Indian Ocean

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Abstract. Sound speed profiles in the ocean have a significant impact on the acoustic propagation, thus affecting the sonar detection performance. Sound speed profiles have characteristics of positional and seasonal distribution. In order to guide the sonar detection, use WOA13 dataset, calculate the number of categories of sound speed profiles by hierarchical clustering method, classify sound speed profiles categories and typical sound speed profile structure of various categories in different seasons by fuzzy c-means clustering. It is concluded that there are 7 categories of sound speed profiles in Indian ocean: Antarctic Water category, Antarctic Transition Water category, Sub-Antarctic Transition Water category, Sub-Antarctic Water category, Sub-Tropical Water category, Tropical Divergence Zone category and North Indian Ocean Water category. The distribution area of these categories are generally zonal distribution. Sub-Tropical Water category, Tropical Divergence Zone category and North Indian Ocean Water category have significant seasonal variations. The seasonal variation of other categories are not significant.

1. Introduction

The sound speed profiles in the ocean are important factors affecting the underwater acoustic propagation. The sonar detection distance in different sound speed profiles can reach several times or even hundreds of times. Moreover, there are different distributions of sound speed profiles in different sea, seasons and time. Therefore, it is necessary to study the sound speed profiles. In particular, the classification and distribution characteristics of the sound speed profiles should be studied. According to experience,《Atlas of Bohai sea, Yellow Sea and East China Sea》¹ gave the distribution of sound speed profiles categories in Bohai sea, Yellow Sea and East China Sea, but only in the shallow shelf sea north of the East China Sea. Xiejun et al.² divided the types of sound speed profiles in coastal waters of China into 3 categories and 13 types by sequential cluster analysis, hierarchical cluster and SOFM neural network cluster arithmetic. Zhangxu et al.³ divided the types of sound speed profiles in coastal waters of China into 3 categories and 11 types by fuzzy c-means clustering. The above method mainly classifies the sound speed profiles of Chinese coastal waters. Mandelberg⁴ classified sound speed profiles in the North Atlantic and Northeast Pacific by hierarchical clustering method. The Indian Ocean is an important area, and the division of sound speed profiles in Indian Ocean is not involved. In order to guide the detection and use of sonar in this area, it is necessary to study the categories and distribution of sound speed profiles in Indian Ocean.

In this paper, by using WOA13 dataset, the number of categories of sound speed profiles are calculated by hierarchical clustering method, the categories of sound speed profiles are classified by fuzzy c-means clustering. The distribution regions and typical sound speed profiles of various categories are obtained in different season to provide marine environment support for sonar detection.
and use.

2. Data and methodology

2.1 Data

The data were chosen from WOA13 (World Ocean Atlas 2013) published by the National Oceanographic Data Center (NODC) of the United States. The water temperature and salinity profiles were from observatories, MBT, CTD, DBT, XBT worldwide from 1955 to 2012. Through Levitus objective analysis, the grid data set with horizontal grid of 0.25°×0.25° is obtained. Including annual, seasonal and the monthly average three-dim-ensional field data. The Indian Ocean region is 0°~65°N, 120°~180°E in this paper. The seasonal average temperature and salinity data of the region were selected, and each season included 62400 sets of temperature and salinity profiles respectively. Based on sea temperature, salinity and depth data, the sound speed is calculated by the empirical formula proposed by Mackenzie (1981) [5].

2.2 Sound speed profiles classification method

A typical feature of deep water sound propagation is that when the sound source is located near the sea surface, due to the sound channel, deep water convergence zone exist in most sea areas. Whether there is a convergence zone, mainly determined by water depth, sound speed profiles and seasonal changes. When there is a critical depth, the propagation path of the acoustic is reversed back to the sea surface due to the refraction of the seawater, so that the acoustic avoids contact with the sea floor, the loss of acoustic is small and make acoustic long-distance propagation. According to the statistical analysis of the critical depth of the Indian Ocean, there is no critical depth in most part of Indian Ocean with depth of less than 2000 m in summer. Therefore, in order to study the characteristics of convergence zone in deep water, the deep water in this paper refers to the sea with depth of more than 2000 m.

The Indian Ocean is vast, the surface waters mass include tropical water, subtropical water, sub-antarctic water and antarctic water [6-7], and there are many currents in Indian Ocean. The main currents include the North Equatorial Current, the Equatorial Countercurrent, the South Equatorial Current, and Java Flow, Somali Flow, Zanzibar Flow, Mozambique Flow, Agulhas Flow and Antarctic Circumpolar Flow, etc. The physical properties of seawater vary greatly. Cluster analysis can accurately divide the sound speed profiles category and the area of each category. Typical sound speed profiles of each category can also be obtained. Here, the hierarchical clustering method is used to calculate categories number of sound speed profiles in Indian Ocean, and then the fuzzy c-means clustering is used to classify the distribution area and the sound speed profile central values of every category in Indian Ocean.

The cluster method classifies the samples according to their similarity. The hierarchical clustering method is the most commonly used in oceanography, which is a polymerization process [8]. Let the set of sound speed profiles in a certain season be \( X = \{x_1, x_2, \ldots, x_n\} \), The number of samples is \( n \), \( x_i \) represents the vector of sound speed values in the \( i \)-th profile, make \( n \) samples into one class, marked as 1, 2, ..., \( n \), at this time, the mean of each category is the sample value itself, and the sum of the squares of the intra-class deviation is zero. Then, the sum of the squares of the dispersion between the classes are calculated. The sum of the squares of the dispersion represents the magnitude of the two categories of similarity. According to the degree of similarity, the classes with high similarity are merged first, and then the classes with low similarity are merged. Finally, when the sum of squared deviation reaches 1000, the classification ends. Thus, the sound speed profiles categories are divided into 7 categories in Indian Ocean.

Hierarchical clustering method is straightforward, but when the sample size is large, the computer is taking up too much memory. When analyzing sound speed profiles with 0.25°×0.25°grid in Indian Ocean, the value of \( n \) will be large and the processing speed will be very slow. In addition, the category of sound speed profiles between any two areas is not eidetic but ambiguous. In order to make the regional division result more consistent with the actual situation, fuzzy c-means clustering is
adopted for classification[3].

Let the set of sound speed profiles in a certain season be \( X = \{x_1, x_2, \cdots, x_n\} \). The number of samples is \( n \). \( x_i \) represents the vector of sound speed values in the \( i \)-th profile. In the depth range of 0~2000m, there are 67 layers. Establishing the criterion function based on the Euclidean distance.

\[
J(D,V) = \sum_{j=1}^{n} \sum_{i=1}^{n} (d_{ij}) \|x_j - V_i\|^2 \tag{1}
\]

\( D = (d_{ij})_{p \times n} \) is the membership function of the \( j \) th sample to the \( i \) th class, need to meet \( d_{ij} \in [0,1] \), \( \sum_{i=1}^{p} d_{ij} = 1 \), \( \sum_{j=1}^{n} d_{ij} > 0 \); \( V = \{v_1, v_2, \cdots, v_p\} \), \( v_i \) is the cluster center of class \( i \); \( c \) is the fuzzy degree control constant, here, \( c = 2 \), \( P \) is number of categories. After \( P \) is determined by the hierarchical clustering method, an initial partition matrix \( D_0 \) is given arbitrarily for the samples and the clustering center is initialized, and then \( d_{ij} \) and \( v_j \) iterative calculation is carried out. The expression is,

\[
d_{ij} = \left( \frac{\|v_i - x_j\|}{\|v_k - x_j\|} \right)^{2/c-2} \tag{2}
\]

\[
v_j = \frac{\sum_{i=1}^{n} (d_{ij})^c x_j}{\sum_{j=1}^{n} (d_{ij})^c} \tag{3}
\]

After \( l \) iterations, if the criterion function meets \( J(D^{l-1},V^{l-1}) - J(D^l,V^l) < \epsilon \) , (here, \( \epsilon = 1 \times 10^{-5} \)) the iteration is stopped, the clustering center of each category and the membership value of each sample to each category can be obtained. Then, according to the maximum principle of membership degree, defuzzification is carried out, and fuzzy classification is transformed into deterministic classification. The regional distribution and the central values of the sound speed profiles in different sea are obtained.

3. Categories and characteristics of sound speed profiles

The categories of sound speed profiles are divided into 7 categories in Indian Ocean by cluster analysis, as shown in Fig. 1. Fig. 1a, b, c and d represent the classification results of winter (northern hemisphere), spring, summer and autumn respectively, these season is represented by JFM season, AMJ season, JAS season and OND season respectively. In the figure, white represents the area with water depth less than 2000m, and the color scale value represents the categories of sound speed profiles. It can be seen from the figure that each category has a zonal band distribution feature. This is mainly caused by the difference in water temperature and salinity distribution between the surface and subsurface water. The temperature and salinity distribution of each water mass is also zonal distribution. According to the distribution of surface and subsurface water masses, 7 categories are named from south to north: Antarctic Water category (category 1), Antarctic Transition Water category (category 2), Sub-Antarctic Transition Water category (category 3), Sub-Antarctic Water category (category 4), Sub-Tropical Water category (category 5), Tropical Divergence Zone category (category 6), North Indian Ocean Water category (category 7). There are significant seasonal variation of the category 5~7 area, and other category of seasonal changes are not obvious.

Antarctic Water category (category 1): Located in the water south of the Antarctic Front[6], the latitude range is roughly beyond 55°S. The water temperature is low throughout the year. JFM has the
largest surface sound speed of about 1457 m/s, and the JAS is the smallest, about 1446 m/s, as shown in Fig. 2, the center value of each sound speed profiles category is showed in the figure 2. Fig. 2a, b, c and d represent the central values of each sound speed profiles category in JFM, AMJ, JAS, and AND respectively. "*" in the figure indicates the depth of sound channel axis. Except for the JFM, the sound gradient categories in the rest of the season are positive gradients. There is a seasonal sound cline in JFM, the depth of the sound cline is very shallow, there is no main sound cline, the overall appearance is “seasonal sound cline + shallow sound channel + positive gradient” Structure, the depth of sound channel axis is about 125m.

Fig. 1. Regional division of different seasonal sound speed profiles categories in Indian Ocean

Table 1. Sound channel axis depth of each sound speed profiles category (unit: m)

|     | 1  | 2  | 4  | 5  | 6  | 7  |
|-----|----|----|----|----|----|----|
| JFM | 125| 175| 1150|1250|1150|1400|
| AMG | 0  | 175| 1200|1250|1100|1650|
| JAS | 0  | 0  | 1150|1250|1100|1600|
| OND | 65 | 150| 1150|1250|1100|1550|

Antarctic Transition Water category (category 2): It is mainly influenced by the Antarctic Front. As shown in Fig. 1, the sound speed of each layer in this area is larger than that of the corresponding layer of category 1. Seasonal variation is not significant. The surface sound speed in JFM is the largest, about 1468 m/s, smallest in JAS, about 1459 m/s, as shown in Fig. 2. The vertical structure of sound speed in JFM and AMJ is “sound layer + seasonal sound cline + shallow sound channel + positive gradient”. The depth of sound channel axis is 175 m, as listed in Table 1. The vertical structure of
sound speed in JAS is positive gradient. The vertical structure of sound speed in OND is “negative gradient + shallow sound channel + positive gradient”, and the depth of sound channel axis is about 150 m.

Sub-Antarctic Transition Water category (category 3): It is mainly influenced by the Sub-Antarctic Front. Its coverage is shown in Fig. 1. The surface sound speed in JFM is the largest, about 1485m/s, and that in JAS is the smallest, about 1476m/s, as shown in Fig. 2. The vertical structure of sound speed in JFM presents as “sound layer + seasonal sound cline + deep sound channel + deep sound positive gradient” and the depth of sound channel axis is 650m; the vertical structure of sound speed in AMJ and JAS presents as “sound layer + negative gradient + deep sound channel + deep positive gradient”. The depth of channel axis is about 700m and 650m respectively, and the seasonal sound cline disappears; the vertical structure of sound speed in OND presents as a double sound channel structure. The first layer is a weak sound channel with a depth of about 150 m. The depth of deep sound channel axis remains unchanged at 650 M.

Sub-Antarctic Water category (category 4): It is mainly influenced by the Subtropical Front, its coverage is shown in Fig. 1. The latitude range is between 35˚S~40˚S, which is exactly the same as the Subtropical Front indicated by He Zhigang et al.[9]. The surface sound speed in JMF is the largest, about 1503m/s, and smallest in JAS, about 1494m/s, except for the AMJ, the channel axis depth is 1200m, and the rest of the season is 1150m, as shown in Fig. 2. Sound speed vertical structure is “seasonal sound cline + main sound cline + deep sound channel + deep positive gradient” in JFM;
sound speed vertical structure is “sound layer + main sound cline + deep sound channel + deep positive gradient” in AMJ and JAS, sound layer depth can reach 300m in JAS; sound speed vertical structure is “weak negative gradient + main sound cline + deep sound channel + deep positive gradient” in OND.

Sub-Tropical Water category (category 5): It is mainly located in the subtropical water, the coverage of the area has obvious seasonal changes, mainly in its northern boundary. AMJ is affected by the monsoon, and the northern boundary is at the northernmost point, which is around 15°S, as shown in Fig. 1b. The coverage area is the largest; JFM is at the southernmost point, around 25°S, which is the smallest, as shown in Fig. 1a; the other seasons are between the AMJ and JFM. There is basically no seasonal change in the southern border, roughly around 40°S. Due to sub-tropical convergence, the depth of the sound channel axis is further deepened to approximately 1250 m with no seasonal variation, as shown in Fig. 2. The surface sound speed is the highest in JFM, about 1521 m/s, and smallest in JAS, about 1509 m/s. Sound speed vertical structures are same in AMJ and JAS, both are “sound layer + main sound cline layer + deep sound channel + deep positive gradient”. Sound layer in JAS is deeper than AMJ; Sound speed vertical structure is “main cline layer + deep sound channel + deep positive gradient” in OND, due to the enhancement of solar radiation in JFM, the seasonal sound cline layer is emergence, the vertical structure of sound speed is “seasonal sound cline layer + main sound cline layer + deep sound channel + deep positive gradient”.

Tropical Divergence Zone category (category 6): It is located in the tropical divergence zone, this category of distribution area is greatly affected by the monsoon and tropical divergence zones, with obvious seasonal changes. Due to the influence of the northeast monsoon in the northern Indian Ocean, the tropical divergence zone moved southward, it reached the southernmost tip in JFM, with a distribution region from 14°S to 25°S, as shown in Fig. 1a; it is affected by monsoon and hot salt circulation in AMJ, the divergence zone moves north to the northernmost end, and the distribution region is roughly between 3°S–25°S, as shown in Fig. 1b; other seasonal distributions region between JFM and AMJ. Due to the tropical divergence effect, the sound channel axis depth is reduced, except for the JFM depth is about 1150m, and depth is 1100m in the rest of the season, as shown in Fig. 2. Because the water temperature in the area is high all the year round, there is little seasonal difference in surface sound speed. Surface sound speed is the largest in AMJ, about 1540 m/s, and smallest in JAS, about 1534 m/s. The vertical structure of sound speed is no seasonal variation, which is “shallow sound layer + main sound cline + deep sound channel + deep positive gradient”.

North Indian Ocean Water category (category 7): Its main body is located in the tropical waters of the northern Indian Ocean. Due to the influence of monsoon and tropical convergence, this category of distribution has obvious seasonal changes. It has the largest distribution area in JFM, which is a vast area surrounded by 14°S and surrounding continents, as shown in Fig. 1a; the distribution area is the smallest in AMJ, which is surrounded by 3°S and the surrounding continents, as shown in Fig. 1b; other seasonal distributions are between the JFM and AMJ. Due to the combination of high temperature, high-salt seawater and tropical convergence in the northern Gulf, the depth of the sound channel axis is significantly increased, the shallowest in JFM, about 1400m, and the deepest in AMJ, about 1650m. The depth of sound channel axis is between the two seasons in other seasons, as shown in Fig. 2. Because the water temperature in the area is high all the year round, seasonal difference of surface sound speed is not large. The vertical structure of sound speed is basically the same as that of category 6, but the strength of the main sound cline layer is significantly enhanced, and the depth of the sound channel axis is significantly increased too.

4. Conclusion
Deep water sound speed profiles are classified by hierarchical clustering method and fuzzy c-means clustering method in Indian Ocean. The conclusion is that the deep water sound speed profiles in the Indian Ocean are divided into 7 categories: Antarctic Water category, Antarctic Transition Water category, Sub- Antarctic Transition Water category, Sub-Antarctic Water category, Sub-Tropical Water category, Tropical Divergence Zone category and North Indian Ocean Water category.
Sub-Tropical Water category, Tropical Divergence Zone category and North Indian Ocean Water category have significant seasonal changes, and there are no significant seasonal change in the other categories. The most obvious feature of each category is the change of sound channel axis depth with latitude. From north to south, the change with latitude decreases first, then increases and then decreases, arrived near the surface of the sea at high latitudes (JFM is about 50˚S).

The above 7 categories of sound speed profile in the Indian Ocean will have different effects on underwater acoustic propagation, especially on deep water convergence zone. It is of great significance to master the categories characteristics of sound speed profile for guiding the use of sonar.

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