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Oxygen isotopic composition and its application to the study of tracing oceanographical process in Bering Sea and Chukchi Sea

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Abstract In this paper, the ^{18}O distribution of surface water from the central sea areas of the Bering Sea and the Chukchi Sea was studied. The $\delta^{18}O$ value of surface water from the Bering Sea is averagely $-0.5‰$; the $\delta^{18}O$ contents of the Chukchi Sea are distributionally lower in northeast and higher in southwest; the $\delta^{18}O$ value at the margin of Canadian Basin is $-2.8‰$, and averagely $-0.8‰$ in the southern area of the Chukchi Sea. The $\delta^{18}O$ vertical distribution in some deep water stations from the Chukchi Sea and the Bering Sea is also studied. In the southern margin of Canadian Basin, the $\delta^{18}O$ value is $-2‰$ - $-3‰$ for surface layer and rises to 0 at 100 m depth layer. In the Bering Sea, the $\delta^{18}O$ is about $-0.5‰$ for surface layer and increases to 0 at the depth of 300 m. The NO tracer can reflect obviously three water masses vertically distributed in the central Bering Sea: the upper Bering water mass, the middle Bering water mass and the deep Pacific water mass. The distributive ranges of NO and temperature for the various water masses are $T < 7℃$, $NO > 780$ μmol/dm^3 and $T \geqslant 7℃$, $NO > 650$ μmol/dm^3 for upper Bering water mass, $T < 4℃$, $550 < NO < 780$ μmol/dm^3 for middle Bering water mass, and $T < 4℃$, $330 < NO < 550$ μmol/dm^3 for deep Pacific water mass. It is found from $\delta^{18}O$ - S relation diagram and $\delta^{18}O$ vertical profiles that the $\delta^{18}O$ is about $+0.3‰$ from halocline layer till sea bottom. Its isotopic characteristics are the same as the Atlantic water, showing that the sea water comes from the north Atlantic. The freshwater end-member of the Chukchi Sea in the survey period is also explored.

Key words Chukchi Sea, Bering Sea, ^{18}O, water masses, sea-ice melting water.

1 Introduction

^{18}O in marine environment plays an important role in oceanographical study. As a stable isotope of oxygen, ^{18}O together with hydrogen atoms constitutes water molecule $H_2{}^{18}O$ and moves with a large amount of H_2O molecules in seawater. So that $\delta^{18}O$ becomes an ideal tracer for the movement of the waters and has been widely applied (Bjork 1987; Cooper *et al*. 1997; Ostlund and Hut 1984; Craig and Gordon 1965a, 1965b; Vetshteyn *et al*. 1974; O'neil 1968; Bjork 1990; Van Donk and Mathieu 1969). In the last two decades, the studies on tracing oceanographical process have been in great progress in China and the studied sea area involved the Pacific Ocean, Indian Ocean, Atlantic Ocean and Southern Ocean (Li and Kang 1988; Wu 1988; Zhou *et al*. 1989; Lin *et al*. 1996; Li and Hong 1991; Hong *et al*. 1993, 1994; Huang *et* *al*. 1996a, 1996b, 1996c, 1996d; Wei *et al*. 1996; Cai 1999[*]; Zeng *et al*.[**]). *The Chinese researchers carry out relatively few studies on* ^{18}O in seawater and sea-ice from Arctic Ocean as well as in land-surface runoff running into Arctic Ocean. In this paper, ^{18}O distribution in seawater from the Chukchi Sea and Bering Sea and its application are preliminarily studied.

2 Sample collection and analysis

Fig.1 shows the hydrological survey stations in the Bering Sea and the Chukchi Sea during the first Arctic Expedition of China. Circles around the station locations show the ^{18}O analyzing stations. Among them, ^{18}O vertical distributions were determined on the stations of B1-1(31), B2-1(32) and B4-1(40) in the Bering Sea and P5(89) and P6(90) in the Chukchi Sea. Seawater samples were collected using a standard CTD Rosette system after standard layers. The water sample collected from each layer was filled in 60 ml polythene bottle, ridding air bubble, covered by bottle top, sealed with wax and placed upside down to prevent leakage or not to contact with air.

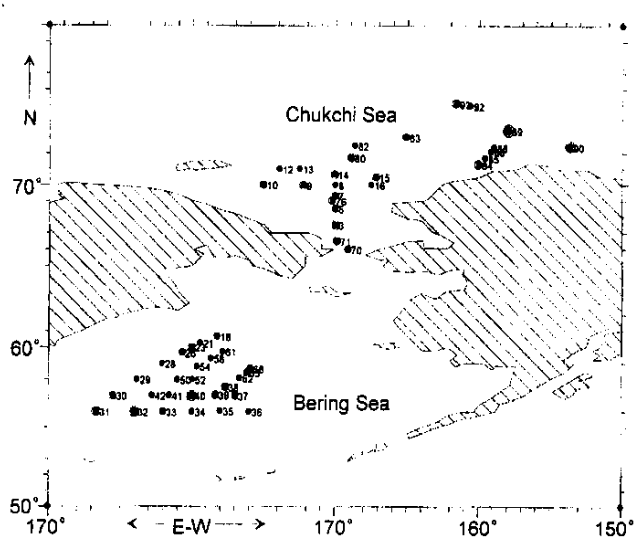

Fig.1. Station locations during 1st Arctic Scientific Expedition of China.

For ^{18}O analysis, H_2O-CO_2 equilibrium method was used to transform water samples (Zeng *et al*.)[*] and the $\delta^{18}O$ value of the sample was determined with VG-SIRA-24 gas isotopic mass spectrometer. The water samples of the national first-class standard materials, GBW 04401 and GBW 04404 were transformed simultaneously for relative determination to give the $\delta^{18}O$ value rel-

* Cai PH(1999): Isotopic trace study of oceanographical process in Nansha sea area and Southern Ocean. A doctoral thesis, Xiamen University, 79 – 136.

** Zeng XZ, Yin MD, Zeng WY, Huo XJ, Wu SY, Shi CT, Yao JD, Chen QY: Tracer studies on seawater ^{18}O, NO distributive characteristics and oceanographical process in Prydz Bay, Antarctica.

ative to VSMOW. The analyzed accuracy was within ±0.1%. The definition of $\delta^{18}O$ in sample is expressed as:

$$\delta^{18}O = [\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{SMOW}} - 1] \times 1000$$

The unit is ‰; the error value is the standard deviation of parallel samples.

3 Results and discussion

3.1. Horizontal distributions of $\delta^{18}O$ in surface water from the central Bering Sea area and Chukchi Sea

Fig.2 shows the ^{18}O distribution in the studied sea area during the first Arctic Expedition of China.

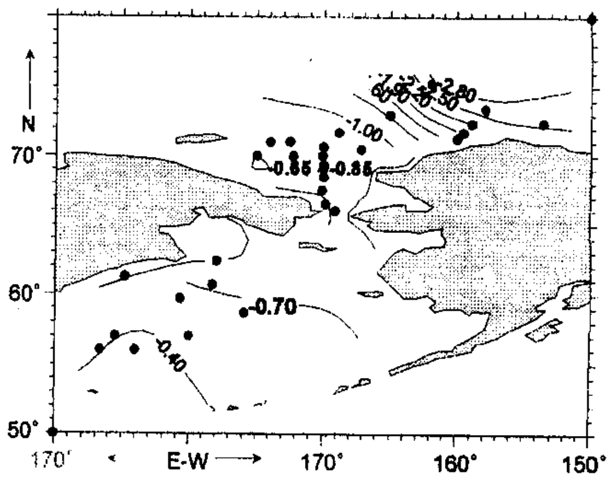

Fig.2. Horizontal distributions of ^{18}O of surface water in the Bering and Chukchi Seas.

1) For the surface seawater from the studied sea area, the highest ^{18}O content the samples is from the central sea area of Bering Sea, with $\delta^{18}O$ between −0.4‰ − −0.6‰, averagely −0.5‰. In the whole survey sea area, the ^{18}O distribution is relatively even. Along the west coast of the Bering Sea, the $\delta^{18}O$ value decreases because of the effect of land-surface runoff, reaching −1‰, even −1.39‰ for a sample collected in investigated period. The $\delta^{18}O$ value for a station from the southern mouth of the Bering Strait is −0.5‰.

2) Because the sampling in the Chukchi Sea is basically taken following the investigated line, not according to the arrange spots in sea areas, the distribution of the surface ^{18}O is roughly estimated. The ^{18}O contents, distributionally, are lower in the northeast and higher in the southwest on the whole. For the three stations from the margin of Canadian Basin, P5, P6 and P7 (93), the $\delta^{18}O$ values are all lower than −2.0‰, averagely −2.8‰, Among them, P7 is the station with lowest $\delta^{18}O$ content in the survey, reaching −3.18‰. From the three stations southwestwards, $\delta^{18}O$ values increase, reaching about −1‰ on the line along the stations of

7300(83) and 7111(84). From station P7142(80) 72°N to the station on the southern mouth of the Bering Strait, $\delta^{18}O$ values varies from −1.00‰ to −0.48‰, averagely (−0.76 ± 0.16)‰. But for the two stations, J7(26) and J8(28) at 70°N, the $\delta^{18}O$ values are much higher than those of the eastern stations.

3.2 *Vertical distributions of $\delta^{18}O$ in sea water from Bering and Chukchi Seas*

Fig.3 shows the distributions of $\delta^{18}O$ of several deep water stations from the Chukchi Sea (P5, P6) and Bering Sea (B1-1, B2-1 and B4-1). For the southern margin of Canadian Basin, the vertical distributions of ^{18}O indicate that the $\delta^{18}O$ value is −2‰ ~ −3‰ for surface water and rises to 0 at the depth of 100 m. The $\delta^{18}O$ value ≥0.3‰ for the waters below halocline (below 100 m), showing that its waters has a source from North Atlantic Ocean with $\delta^{18}O$ of (0.3 ± 0.1)‰ and salinity of 34.92. The vertical distributions of ^{18}O in the Bering Sea indicate that the $\delta^{18}O$ is about −0.5‰ for surface water and increases with the depth, up to 0 at 300 m deep.

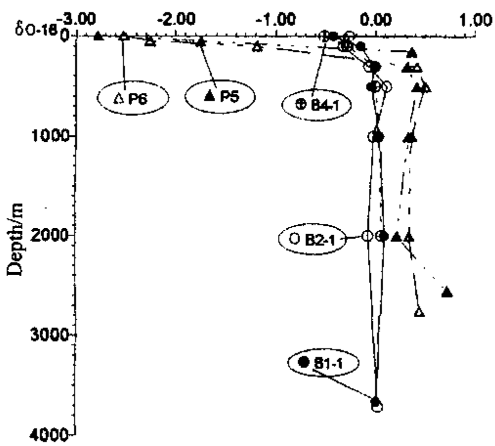

Fig.3. Vertical distribution of $\delta^{18}O$ at some stations in the Bering Sea and Chukchi Sea.

3.3 *NO-T relation of seawater in the Bering Sea*

The NO tracer can reflect obviously three water masses vertically distributed in the central Bering Sea, i.e. the upper Bering water mass, the middle Bering water mass and the deep Pacific water mass (See Fig.4). The distributive ranges of NO and temperature for the various water masses are T < 7℃, NO > 780 $\mu mol/dm^3$ and T ≥ 7℃, NO > 650 $\mu mol/dm^3$ for upper Bering water mass, T < 4℃, 550 < NO < 780 $\mu mol/dm^3$ for middle Bering water mass, and T < 4℃, 330 < NO < 550 $\mu mol/dm^3$ for deep Pacific water mass.

3.4 *$\delta^{18}O$-S relations of surface water from the Bering and Chukchi Seas*

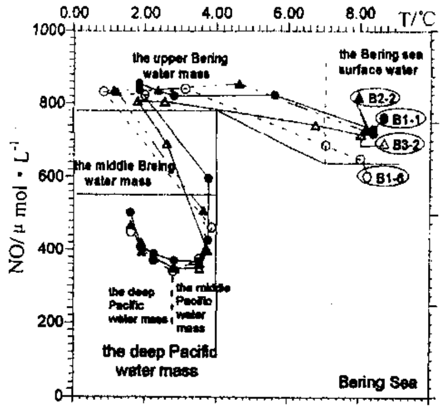

Fig.4 NO-T diagram of some stations in the Bering Sea.

Fig.5 shows the relations of $\delta^{18}O$ and S on surface water from the Bering and Chukchi Seas.

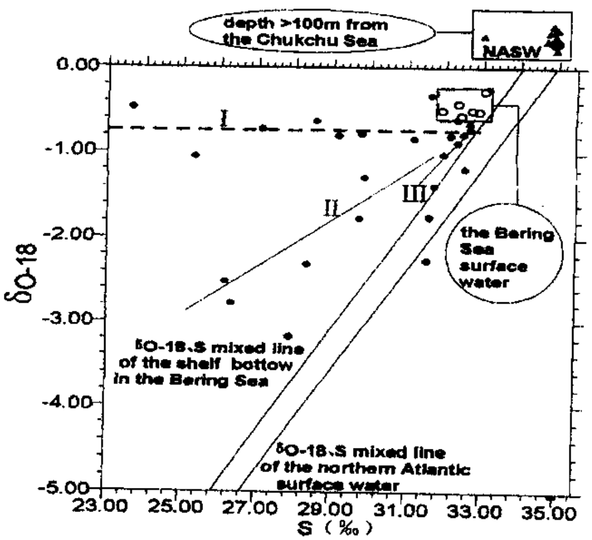

Fig.5. Relation of $\delta^{18}O$ – S in surface water from the Bering Sea and Chukchi Sea.

The $\delta^{18}O$ values of the $\delta^{18}O$ – S spots in seawater of various stations from the central sea area of the Bering Sea are concentratedly within –0.4‰ and –0.6‰ and S is within a rather small range of 32‰ – 33‰. The $\delta^{18}O$ value of Anadyr seawater is between –0.4‰ – –0.6‰, S is more than 32.5‰, the same as the $\delta^{18}O$ value and salinity of surface water from the central Bering Sea. Most $\delta^{18}O$-S spots in seawater of the stations from the Chukchi Sea are distributed along two intersecting straight lines. The $\delta^{18}O$ value on the horizontal line I is –0.

76‰. The $\delta^{18}O$ value of the spots distributed along the line is about −0.76‰, while the salinity is varies greatly ranging, from 23‰ to 32.5‰. Those spots along the horizontal line are the stations in the region of 69°N − 72°N and 175°W − 165°W, i.e. the sea area east of the Wrangell I.

The spots are scattered along the straight line Ⅱ, representing the stations from the sea area west and north of Cape Barrow. There is a huge anticyclonic eddy in the Canadian Basin, and the stations P5, P6 and P7 are just located on the southern margin of the eddy, in which $\delta^{18}O$ values of surface water are −2.52‰ − 3.28‰, S are between 26 − 28. The simulated extending line of straight line Ⅱ intersects with straight line I, the intersection point is at $\delta^{18}O$ of −0.76‰ and S of 32.5‰.

There are some spots distributed along a short straight line Ⅲ, representing all the stations from the Bering Strait northwards along 170°W till 70°N. The starting point of the line Ⅲ is the same as the intersection point of the lines I and Ⅱ, The $\delta^{18}O$ value decreases with the salinity lowering, but its $\delta^{18}O$ and S values have no great difference from those of Anadyr seawater. It shows that they are formed from denaturation of the seawater entering the Chukchi Sea through the Bering Strait.

NASW shows an end-point of northern Atlantic water, with $\delta^{18}O$ of (0.3 ± 0.1)% and salinity of 34.92. The spots near NASW are the $\delta^{18}O$-S spots of seawater of the layers below halocline layer of stations P5 and P6, which isotopic characteristics are the same as the Atlantic water, showing that the seawater below halocline layer of the stations P5 and P6 comes from northern Atlantic.

3.5 Freshwater end-member

One of the $\delta^{18}O$ isotopic methods to identify water mass is to compare the $\delta^{18}O$ values of freshwater end-member of the water masses, because the $\delta^{18}O$ values of freshwater end-member of various water masses are always different from each other. The method to calculate the $\delta^{18}O$ value of fresh end-member of a water mass is to establish the $\delta^{18}O$-S regression equation, $\delta^{18}O = mS + b$. when $S = 0$, transecting distance b of ^{18}O will be the $\delta^{18}O$ value of freshwater end-member. Besides the identification of water mass, the freshwater end-member method is also used to study the proportion of freshwaters in the seawater. If two freshwater end-members with different oxygen isotope exist in the seawater, the proportion of the two freshwater end-members can be evaluated.

It is reported (Cooper *et al*. 1997) that the $\delta^{18}O$ value of freshwater end-member of the bottom water from the continental shelf of the Bering Sea is −21.1‰, which is the same as the $\delta^{18}O$ weighted average of the precipitation on the inland around the Arctic Ocean, and also close to the $\delta^{18}O$ weighted average, −22 of the water of the Yukon River which is the greatest river entering into the Bering sea. It indicates that the shelf bottom water of the Bering Sea contains basically no melting water of sea-ice.

The $\delta^{18}O$ value of freshwater end-member of the seawater deeper than −150 m in the Bering Sea is −17.4‰ (Cooper *et al*. 1997) and that of upper layer water (shallower than −1000 m) of northern Pacific is about −18‰ (Craig and Gorden 1965). Both two values are much close to each other and consistent with the $\delta^{18}O$ weighted average of the atmospheric precipitation, showing that the upper water of northern Pacific and the seawater deeper than −150 m in the Bering Sea contain no melting water of sea-ice.

The $\delta^{18}O$ of freshwater end-member of surface water from the Bering Sea continental shelf is −19.1‰, higher than that of bottom water, resulting from the adding of the sea-ice melting water (Cooper *et al*. 1997). If taking −21‰ as the isotopic composition of the freshwater sourced from atmosphere (including land-surface runoff, rain, snow etc.) and the $\delta^{18}O$ value of sea-ice melting water is −2‰ − −3‰, the proportion of sea-ice melting water is 11% − 16% in the whole freshwater composition.

That is to say, for the seawater entering into the Arctic Ocean through the Bering Strait, the $\delta^{18}O$ value of freshwater end-member is −19.1‰ − −21‰.

The $\delta^{18}O$-S spots of the deep water in the northern Atlantic are just on the mixing line of its surface water (Craig and Gordon 1965), so that the northern Atlantic water has the same $\delta^{18}O$ value of freshwater end-member, −21‰. The Chukchi Sea have two main freshwater sources, just like the Arctic Ocean, i.e. the land-surface runoff and sea-ice melting water converging into the Arctic Ocean. The $\delta^{18}O$ values of the both freshwater differ considerably. The $\delta^{18}O$ values of the land-surface runoff is about −21‰.

In view of this, for the seawater entering into the Arctic Ocean whether from land-surface runoff or from the northern Atlantic and the Bering sea, the $\delta^{18}O$ values of their freshwater end-members are all about −21‰.

For the $\delta^{18}O$ value of sea ice, various values are accepted by various authors (Cooper *et al*. 1997; Ostlund and Hut 1984). In the paper, the medium value −2.5‰ of −2‰ − −3‰ is taken as its $\delta^{18}O$ value. If other $\delta^{18}O$ values are accepted, they would differ in diverging amounts, which would not affect the study on the distribution.

It is shown from the above analyses that there are two freshwater end-members with various ^{18}O isotopic compositions in the Chukchi Sea. One is the freshwater end-member with $\delta^{18}O$ value of −21‰, namely the freshwater end-member from the atmosphere, including the land-surface runoff and river water entering into the Chukchi Sea, the rain and snow on the sea surface, the sea water from the Bering sea, and maybe the seawater from the Atlantic. But for the seawater from the Atlantic, the isotopic fractionation happens in the part above the halocline layer because of the reformation after the forming and melting of sea ice. Another freshwater end-member with various $\delta^{18}O$ value is sea- ice melting water, which is produced on the sea surface with the $\delta^{18}O$ value obviously higher than that of the freshwater end-member coming from the atmosphere. From the really determined $\delta^{18}O$ value of the freshwater end-member of sea water, the $\delta^{18}O$ values of the sea ice and the freshwater end-member from atmosphere, and the proportion of sea ice in the freshwater composition, P_i, can be calculated.

$$P_i = \frac{\delta^{18}O_a - \delta^{18}O_m}{\delta^{18}O_a - \delta^{18}O_i} \times 100\% \quad \text{or} \quad P_i = \frac{21 + \delta^{18}O_m}{21 + \delta^{18}O_i} \times 100\% \qquad (1)$$

In the equation (1), P_i: proportion of sea-ice melting water in freshwater composition; $\delta^{18}O_a$: $\delta^{18}O$ value of freshwater end-member from atmosphere; $\delta^{18}O_i$: $\delta^{18}O$ value of sea ice; $\delta^{18}O_m$: really determined $\delta^{18}O$ value of freshwater end-member of sea water.

After regression treatment to the $\delta^{18}O$-S spots near the straight lines Ⅲ and Ⅱ, the following equations can be obtained.

$$\text{Line Ⅲ}: \delta^{18}O(‰) = 0.4182S(‰) - 14.39 \quad (r = 0.875,\ n = 7) \qquad (2)$$

Line Ⅱ: $\delta^{18}O(‰) = 0.3567S(‰) - 12.29$ ($r = 0.938$, $n = 12$) (3)

Average of Chukchi Sea (continental shelf):

$\delta^{18}O(‰) = 0.2844\ S(‰) - 9.844$ ($r = 0.74$, $n = 17$) (4)

From the equations (1), (2), (3) and (4), the proportion of sea-ice melting water in freshwater component for the surface sea water from each sea area of the Chukchi sea can be estimated: 32% – 37% for the sea area from the Bering Strait northwards till 69°N; 43% – 48% for the sea area west and north of Cope Barrow; 60% for the average of the continental shelf of the Chukchi Sea.

The P_i of surface seawater from the continental shelf area of the Chukchi Sea is 60%, which means that the surface seawater from the sea area east of the Wrangell I. must be more than 60%. On the $\delta^{18}O$-S relation diagram, the straight line I is close to the horizontal line, reflecting the sea area is just in a ice-melting state. The samples from this sea area were collected during the first sailing into the Chukchi sea northwards to 70°N, and were mostly the seawater among the floating ice because the northward sea area had been frozen over. And then the water samples collected must be that of sea ice just melting. The salinity of the samples is 23 – 32 with a rather great variation range, but the $\delta^{18}O$ values are about $-0.76‰$, which is consistent with $d\delta^{18}O/dS$ of seawater tending to 0 when icing and melting.

It is seen from the P_i for various sea areas from the continental shelf region of the Chukchi Sea, the proportion of sea-ice melting water in the freshwater composition in the surface sea water increases with the increasing of latitude. If considering that the proportion of melting water in surface water from the continental shelf of the Bering Sea is 11% – 16% (Cooper), the above-mentioned tendency would be clearer. The tendency is the same as the result of Cooper who thought that the tendency of the $\delta^{18}O$ value of freshwater end-member tending to positive value is consistent with the increasing of the effect of sea-ice malting water from south to north.

4 Conclusion

The studies on the ^{18}O distributive characteristics of surface water from the Chukchi Sea and the Bering sea show that the $\delta^{18}O$ value of the surface seawater in all the surveyed sea area decreases gradually with the increase of latitude, which is consistent with the ^{18}O distribution in the global surface seawater, but the ^{18}O distributions in various sea areas show its own $\delta^{18}O$ characters.

The vertical distribution of ^{18}O shows that the $\delta^{18}O$ value is $\geqslant 0.3‰$ for the water below halocline layer deeper than -100 m in the Chukchi Sea, indicating that the water body originates from the north Atlantic. For the Bering sea, the $\delta^{18}O$ value increases with the deepening of water and the $\delta^{18}O$ value below -300 m is basically 0.

The $\delta^{18}O$ values of the freshwater end-member of the surface water from various sea regions in the Chukchi Sea differs from each other. The $\delta^{18}O$ value of freshwater end-member from the Bering strait northwards to 69°N is $-14.39‰$, and is $-12.29‰$ for the sea area west and north of Cape Barrow. The proportions of sea-ice melting water in freshwater composition is 32% – 37% and 43% – 48%, respectively. It is over 60% for the sea area east of Wrangell I., and averagely 60% for the continental shelf region of the Chukchi Sea.

The $\delta^{18}O$ value of freshwater end-member shows a tendency of tending to positive value with the increase of latitude, and the proportion of the sea ice melting water in the freshwater composition also shows increasing tendency.

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