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A sub-surface eddy at inertial current layer in the Canada Basin, Arctic Ocean

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Abstract An Arctic Ocean eddy in sub-surface layer is analyzed in this paper by use of temperature, salinity and current profiles data obtained at an ice camp in the Canada Basin during the second Chinese Arctic Expedition in summer of 2003. In the vertical temperature section, the eddy shows itself as an isolated cold water block at depth of 60 m with a minimum temperature of −1.5℃, about 0.5℃ colder than the ambient water. Isopycnals in the eddy form a pattern of convex, which indicates the eddy is anticyclonic. Although maximum velocity near 0.4 m s^{-1} occurs in the current records observed synchronously, the current pattern is far away from a typical eddy. By further analysis, inertial frequency oscillations with amplitudes comparable with the eddy velocity are found in the sub-surface layer currents. After filter the inertial current and mean current, an axisymmetric current pattern of an eddy with maximum velocity radius of 5 km is obtained. The analysis of the T-S characteristics of the eddy core water and its ambient waters supports the conclusion that the eddy was formed on the Chukchi Shelf and migrated northeastward into the northern Canada Basin.

Key words Eddy, Inertial current, Sub-surface layer, Arctic Ocean.

1 Introduction

General circulation in the basins of the Arctic Ocean is quite weak. The order of magnitude of the surface current is 0.1 m s^{-1} and the current below the surface decreases with depth. However, stronger currents (> 0.3 m s^{-1}) were observed in pycnocline at times. Most of these current anomalies can be identified as Arctic Ocean eddies[1]. The typical radius of Arctic Ocean eddies is 5-10 km, which agrees roughly with the internal Rossby radius of deformation for the Arctic Ocean[2]. Although eddies were usually found in basins of the Arctic Ocean, especially in the Canada Basin and the Beaufort Sea, the anomalous properties in their cores indicate that they are not formed in basins and might migrate from the peripheral regions. Previous researches showed that eddies may shed from coastal currents[3], peripheral currents round curving topography[4] or dense plume outflow at shelf breaks[5]. Thus, eddies might play an import role in transporting the Pacific origin water into the Canada Basin[6,7] and will contribute to the halocline and the nutrient maxima in the Canada Basin[5,8].

Mesoscale eddies in Arctic Ocean were first documented in 1974 by Newton *et al.* (1974)[1]. 6 eddies (2 cyclonic and 4 anticyclonic) were identified utilizing the current, temperature and salinity profile data obtained in the Arctic Ice Dynamics Joint Experiment (AIDJEX) camps (~76°N, 149°W, in 1970 and 1972)[1,9]. More eddies were found in later observations, especially during AIDJEX in 1975 and 1976. Totally 127 eddies were identified utilizing 4 months continuous observation data[5]. Among them, only 3 eddies are cyclonic and have a core deeper than 500 m, 95 eddies are anticyclonic with a core at depth between 50 and 300 m, and the others can not be classified. Five eddies were found during the Arctic Internal Wave Experiment (AIWEX) in 1985. Two of them are anticyclonic cold eddies at depth less than 100 m, another two are cyclonic warm eddies at depth deeper than 200 m[3], and one is a cyclonic eddy with a warm core at depth of 115 m[10]. A US submarine detected a cold eddy at depth between 40 and 400 m[7]. A newly formed anticyclonic cold eddy was found at depth of 160 m near Chukchi slope in September of 2004[8]. According to the reported results, most eddies found in the Canada Basin are anticyclonic and have a core at depth between 50 and 300 m, while cyclonic eddies are deeper.

In spite of their abundance in the Canada Basin, eddies are seldom observed with continuous temperature, salinity and current profile obtained simultaneously due to the sparsity of observations and the randomicity of eddy occurrence. Among the observed eddies listed above, the integrated current pattern and hydrographic structure of the eddy were only obtained from continuous current records at depth of 150 m and a series of hydrographic profiles observed at an ice camp when the camp flowed across the center of the eddy in June of 1972[1]. Although detailed spatial structure of the eddies had been obtained from hydrographic measurements and water samplings for chemical analysis conducted along several sections across the eddy in the eddy observations in 1997 and 2004, the current pattern of the eddies were missed[7,8].

Continuous current profiles and a series of temperature and salinity profiles of the upper ocean were obtained at a 10 days ice camp setup at a floe in the northern Canada Basin during the second Chinese Arctic Expedition in the summer of 2003. The camp happened to go through an eddy. By studying the structure and characteristics of this eddy with the observed data and comparing with the other Arctic Ocean eddies, some special features of this eddy are found, which will be helpful to further understanding of the role and the formation mechanism of the Arctic Ocean eddy.

2 Observations

The oceanographic measurements reported here were made by the Second Chinese National Arctic Research Expedition (CHINARE-2003). The expedition region covered the Chukchi Sea, the Beaufort Sea and the Canada Basin is shown in Fig. 1. CTD measurements were made when the icebreaker *Xuelong* stopped at stations. xCTDs (Expendable CTD) were deployed along the ship track or at the leads of icepacks that were deployed by a helicopter. An icecamp named CNIS7 was setup at a large floe in the Canada Basin on August 23, 2003 (UTC, hereinbelow). The beginning location of the camp is 78°36′N, 146°12′W.

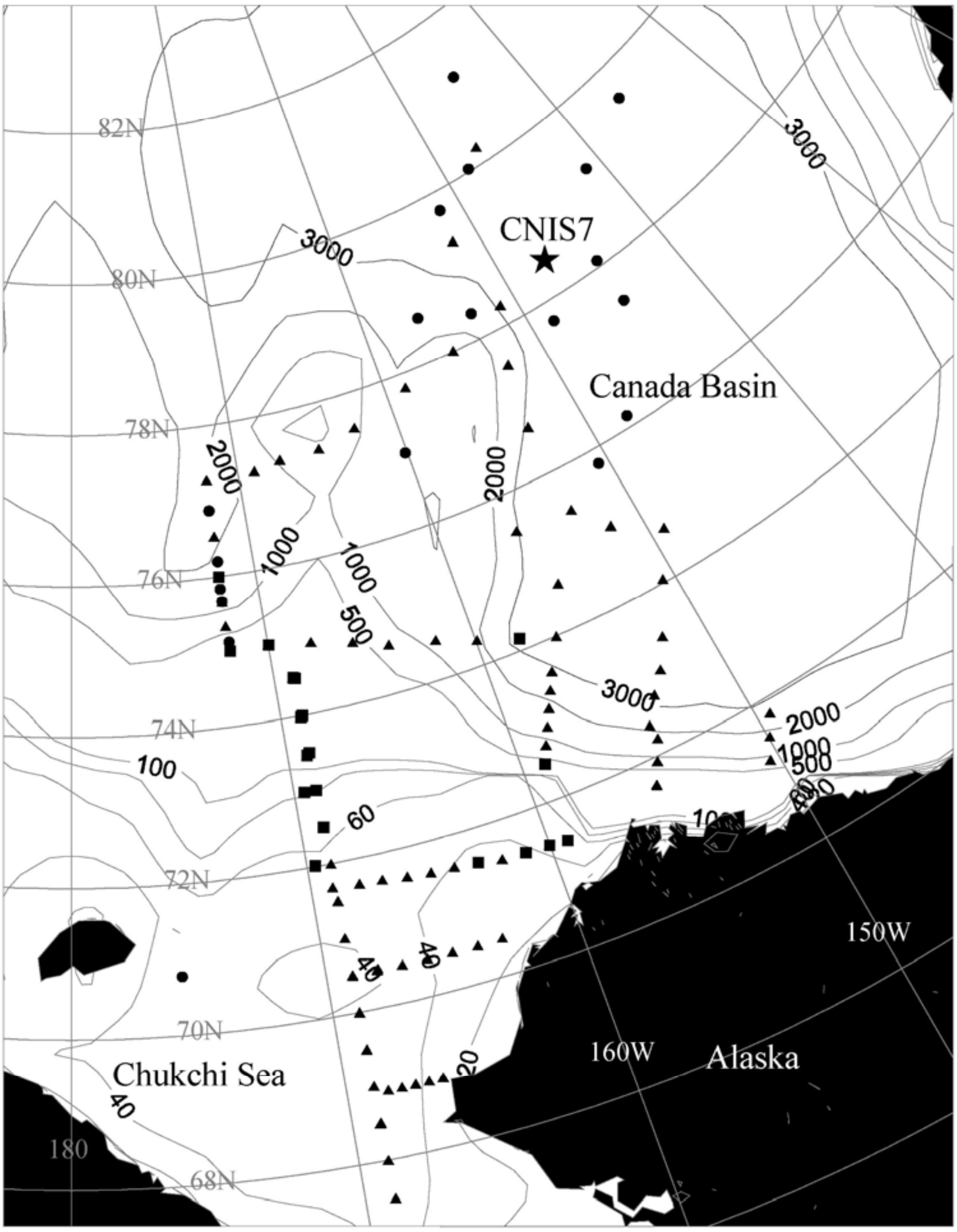


Fig. 1 A map of the observation region of CHINARE-2003. Triangles and dots indicate CTD and xCTD stations of CHINARE-2003 respectively. The squares show the CTD stations at which T-S characteristics similar to the eddy core were found (see section 4). Icecamp CNIS7, at which the eddy was found later, started from one CTD station shown by a star in the Canada Basin on August 23, 2003.

Oceanographic observations bellow the ice floe were conducted through a drilled hole. Currents were measured with an RD Instruments acoustic Doppler current profiler (ADCP) mounted in a hole bellow the 2-m-thick ice. The ADCP was operated at a frequency of 300 kHz, with an effective depth range between 6 m and 64 m, a depth resolution of 2 m, and a sampling interval of 0.5 s. The ADCP started at 8:05 August 29, 2003 at 78°36′N, 146°12′W and worked until 0:05 September 4, except for two breaks of total near 5 hours for taking data from ADCP's memory to a computer on August 31 and September 2. The current directions recorded by ADCP were corrected with the magnetic declination calculated using a program of the NOAA′s National Geophysical Data Center. The magnetic declinations at the location of the first and last ADCP record are 35.0° and 36.3° respectively. For the difference is only 1.3°, 35.7°, a middle value of the magnetic declinations, is used for correction of all ADCP records. Locations and drifts of the camp were recorded every 10 min by a GPS and then were used to convert ADCP data into absolute velocities

(Fig. 2). An FSI Micro-CTD (MCTD) was deployed in the same hole to observe hydrographic profiles between the surface and the depth of 150 m. Totally 10 profiles (Profiles B ~ K, see Fig. 2) were obtained during the observation. After an eddy was identified from

drifted off the eddy.

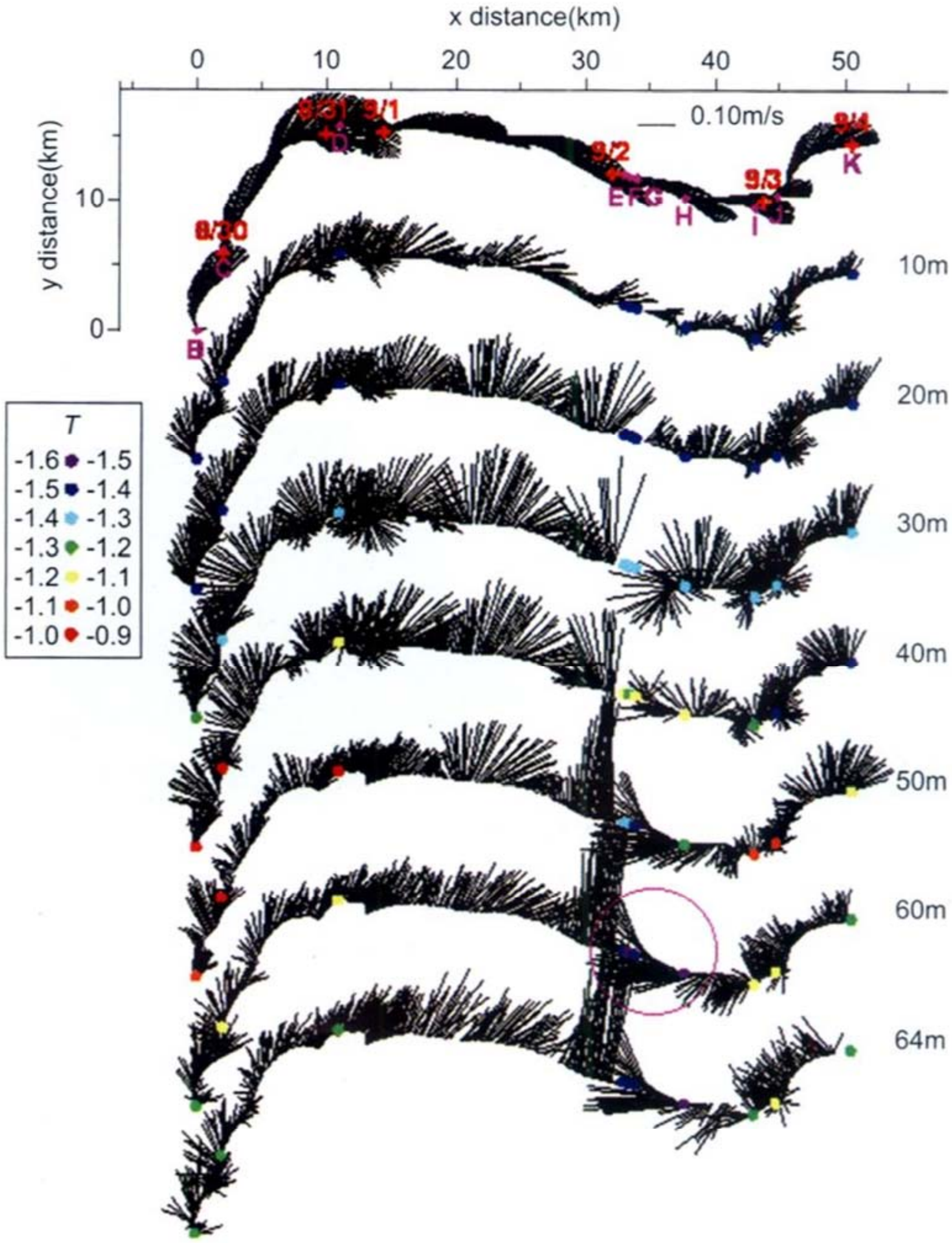


Fig. 2 Vectors of icecamp drift velocity (top) and absolute ocean currents at 7 depths plotted along icecamp drift track. The velocity is 10-min-averaged. The start point is at 8:05 (UTC) on August 29, at the location of 78°35.812′N 146°11.572′W. The red crosses give the date and the purple diamonds give the locations of the MCTD stations (B ~ K). The color-coded dots show the temperature (T, ℃) observed at these stations. A purple circle indicates the position of Eddy CNIS7E that is characterized by the significantly strong currents and T minimum at depth of 60 m.

Integrated information, including drift trace and time of the ice camp, station of MCTD profile, absolute current velocity and temperature at different depth, is presented in Fig. 2. The ice camp drifted northeast at first, then turned to southeast, and finally turn back to northeast, so the ice camp drifted northeast generally. The direction of ice drifting, generally along the tangent of the drift trace, might represent the direction of the surface current. Flows parallel to the surface current are limited in a very thin layer, and the current at layers deeper than 20 m is quite different from the surface current, even almost perpendicular to the surface one at some locations. Enhanced current occurs around the eddy, but the currents at two sides of the eddy are not symmetric. Maximum velocity occurring at depth of 56 m at west of the eddy is 0.37 m s^{-1} with direction of 37°, while the maximum velocity of the same depth at east of the eddy is only 0.24 m s^{-1} with direction of 267°. The difference of the current direction at two sides of the eddy is 130°. This pattern is quite different from a typical axisymmetric eddy current field.

3 Features of the eddy

3.1 *Inertial currents and the elimination of the inertial component*

As shown in Fig. 2, the general circulation in this area is quite weak, and the velocity is only about 0.1 m s^{-1}. Periodical variations can be found in the background currents, which cause the direction and the speed changing obviously. These variations could not be tidal currents because tide in the Arctic Ocean is very weak, especially in the basin deeper than 3800 m. These periodical oscillations could only be inertial currents. If the ADCP records are regarded as a time series, semidiurnal oscillations can be filtered out from the currents outside of the eddy at every depth. Spectrum analyses of this time series result in a dominant period of 11.8 h, which is closed to the local inertial period, $2\pi/f = 12.2$ h, at latitude 78°N, here f is the Coriolis parameter.

Beside the mean circulation, anticyclonic Beaufort Gyre (BG), the inertial currents are the other significant motions in the deep Canada Basin. Inertial motions of sea ice in the Arctic summer, which indeed reflect the same frequency oscillations as that in the surface current, had been detected from icecamp observations[11], Argos ice buoys drifts[12], and RADARSAT images[13]. Doppler sonar observations in the Beaufort Sea[14] also showed an inertial internal wave propagating in the upper ocean. Padman *et al.* (1990)[10] found semidiurnal frequency oscillations in the current meter data outside a cyclonic eddy and speculated that some of the signals within the eddy were also in the same frequency band. These oscillations are also inertial currents. At the depth of 115 m, the typical magnitude was 0.04 m s^{-1}, which was only one tenth of the maximum tangential velocity of the eddy, and such oscillations hardly modified the current structure of the eddy. However, the eddy reported in this paper exists in the subsurface where the magnitude of inertial motions is comparable to that of the maximum tangential velocity of the eddy. The current pattern of the eddy will be changed greatly by the inertial motion. Such kind of eddy has not been seen reported before.

For the amplitude of the inertial current varies with time, and the location of observation and the floe also change continuously, the current records include complicated temporal and spatial variations. It is impossible to eliminate the inertial oscillations directly by data analysis. It can be seen in Fig. 2 that the current fields beside the eddy at depth between 40 and 60 m are quite similar with each other, which indicates that the inertial motion do not change a lot with depth in these layers. Therefore, the inertial component can be eliminated in this way: assume that the current at the layer where is nearest to the eddy but is disturbed slightly by the eddy, for example, the layer at 40 m depth, could represent a background velocity at the depth between 40 and 64 m, consisting of inertial current with amplitude of ~ 0.15 m s^{-1} and the general circulation (BG), ~ 0.1 m s^{-1} with a northeastward direction; this background velocity is subtracted from the current profiles to eliminate the inertial current and the general circulation, and to produce a velocity associated with the eddy as shown in Fig. 3.

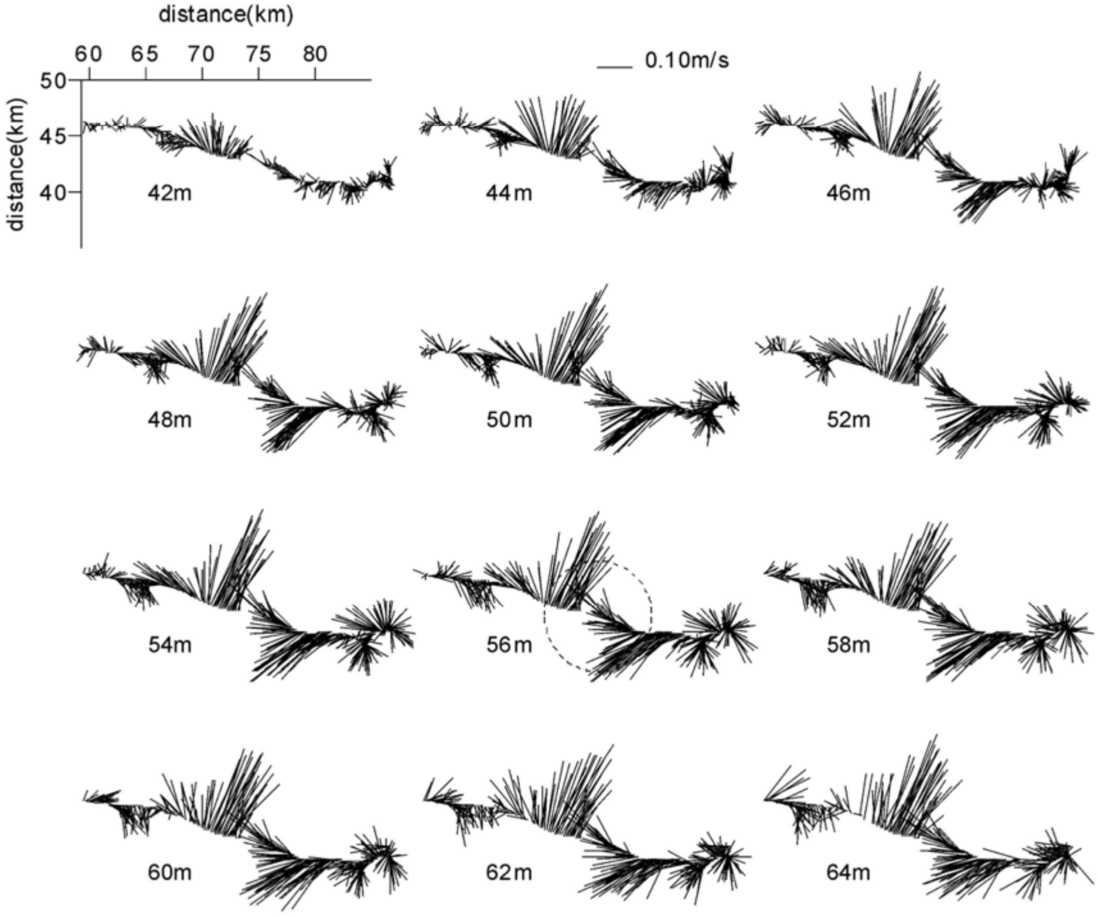


Fig. 3 Vectors of relative velocity referenced to 40m plotted along icecamp drift track. Only the data around the Eddy CNIS7E at depth range of 42~ 60 m are plotted. The dashed circle indicates the eddy radius of 5 km.

3.2 *Current pattern of the eddy*

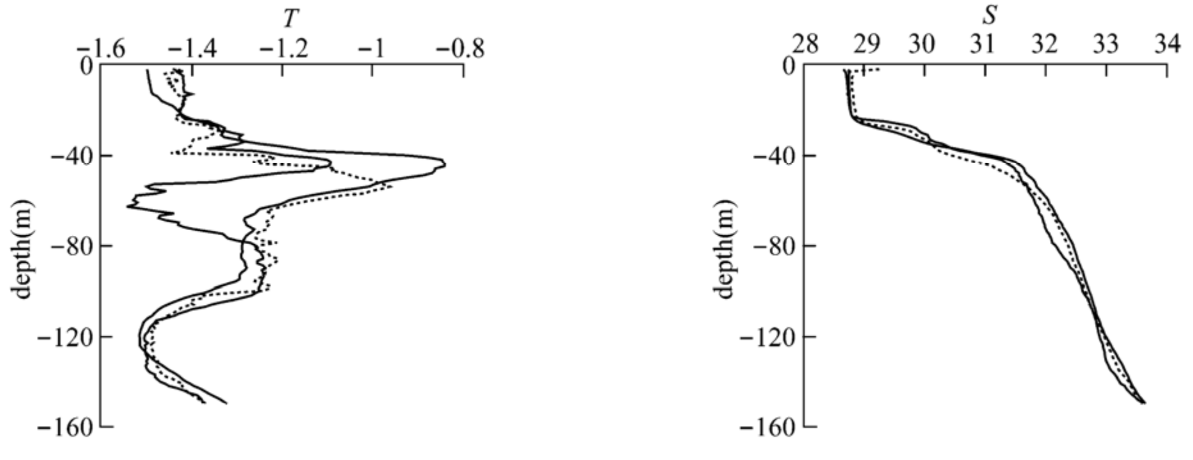
Fig. 3 shows a typical anticyclonic eddy. The drifting floe entered the eddy from west, and left from the eddy after about 24 hours. The current velocity reaches maximum after the floe entering the eddy, and then decreases to zero, and then reaches another maximum with reverse direction, and finally decrease again, which shows a typical current pattern of an Arctic Ocean eddy. Velocity at different layer of the eddy is different, the currents at depth of 56 m are used to define the eddy. There are two maxima at the depth of 56 m, 0.32 m s^{-1} with direction of 24° and 0.23 m s^{-1} with direction of 231° at the west and the east side of the eddy core respectively. The direction difference between the two velocity maxima is 207°, which indicates that the two current vectors are almost reverse.

The drifting trace of the floe within the eddy is approximately a straight line. Although the velocity minimum in the eddy center was not recorded, the current pattern of the eddy, especially the two reverse velocity maxima at two side of the eddy, imply that the drifting trace of floe is quite close to the eddy center. Most ice camps at which ocean eddies were detected flowed the eddy along a chord of the eddies, i. e. did not flowed across the eddy center, so the observed current pattern are asymmetric, which makes it very difficult to calculate the scale features of the eddies. For the eddy reported here, its scale features can be calculated accurately from the drifting trace that coincidently traverses the eddy core.

There are two definitions for an eddy radius, the radius of velocity maximum is the distance between eddy center and point of tangential velocity maximum, and the total eddy radius is the distance from eddy center to the location where the flows associated with eddy disappearing. The former is commonly used, but the later that is normally incurate due to the difficulty of determining the location of eddy flow disappearing. For this eddy, the maximum velocity radius is 5 km and we assume the total radius is about 10 km, which are consistent with the scales of previous eddies scales in the Arctic Ocean.

3.3 Temperature and salinity features of the eddy

Before the ice camp got into the eddy area, all the vertical hydrographic profiles observed at the icecamp and aboard of a boat in this region show a typical profile in the northern BG as described by Steele *et al.* (2004)[6]. As illustrated in Fig. 4, in the temperature profile of Profile C, a maximum (> -0.9℃) at ~ 40 m and a minimum (-1.5℃) at ~ 120 m represent the two cores of Alaskan Coastal Water (ACW, $31 < S < 32$) and winter Bering Sea Water (wBSW, $S = \sim 33.1$), respectively. In-between is the summer Bering Sea Water (sBSW, $32 < S < 33$) with intermediate temperatures. The above three types of waters consist of the Pacific origin halocline water in the Canada Basin[15, 16]. This type of hydrographic structure is common in the Canada Basin, which have been found in the observations in this area in this expedition[15, 16].

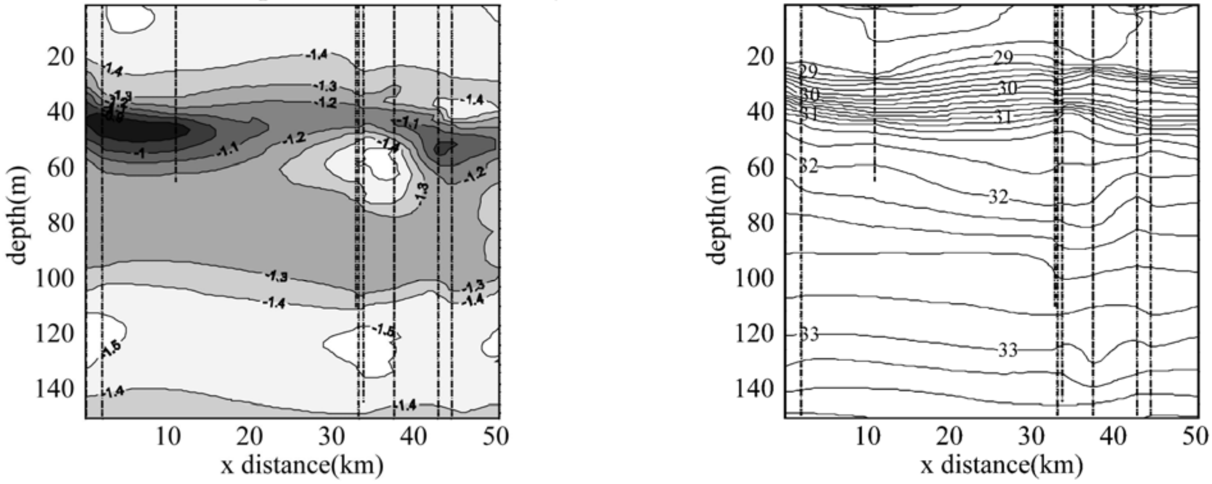


(a) T (℃) (b) S

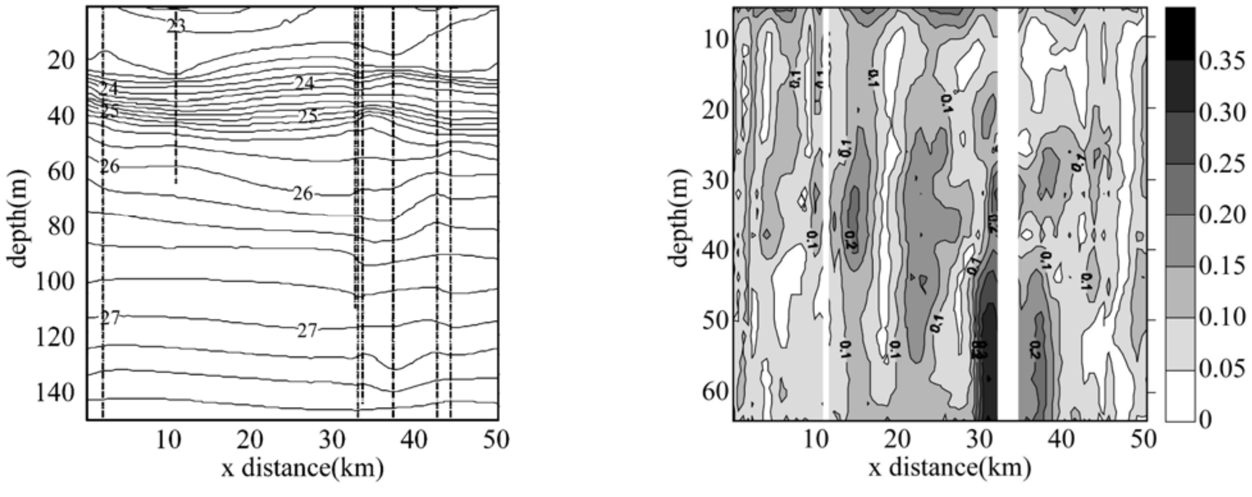
Fig. 4 Temperature (T) and salinity (S) of Profiles C (west of eddy, solid line), H (within eddy, thicker solid line), and I (east of eddy, dashed line).

Profile H, just at the central area of the eddy, shows features quite different from the typical structure presented above. In the temperature profiles within the eddy (Profile H), the eddy is characterized by a minimum temperature less than −1.5℃ at ~ 60 m, and the maximum at ~ 40 m increases to −1.1℃. The maximum of temperature difference occurs at the depth of 54 m, which is 0.5℃ colder at Profile H than at Profile I. The eddy most clearly shows up between 40 m and 80 m at transect of temperature (Fig. 5a) as an isolated cold-water body (Fig. 4a).

Differences can also be found in the salinity profile. Compared to the water east of the eddy (Station I), salinity within the eddy is less than ambient water below 54 m with a difference maximum of 0.23 at the depth of 72 m, and is larger than the ambient at shallower depths with a difference maximum of 0.57 at the depth of 42 m. This salinity feature is similar to another deeper and thicker eddy observed in Beaufort Sea[7].



(a) T, ℃ (b) S



(c) σ_0, kg m^{-3} (d) V, m s^{-1}

Fig. 5 Vertical cross sections of temperature (T), salinity (S), density (σ_0) and absolute speed (V) along x distance. Dotted lines in the first three figures indicate the depth range at which MCTD data were taken and used for plotting these figures (Stations B~K, from left to right). The contours between Station C and E might be inaccurate due to coarse sampling interval. Two blank regions in the last figure are due to the breaks for downloading data from ADCP to a laptop.

A lens type isopycnal pattern is the most reliable criterion to determine sense of rotation of eddy depend on temperature and salinity data. In anticyclonic eddies, isopycnals spread apart near the center like convex lens, while in cyclonic eddies they pinched inward like concave lens. This method is more reliable than using current records obtained on ice camps because the current data might provide misleading information on the rotation of the eddy if the ice camp drifts in a complicated trace[2]. Transect of σ_0 (Fig. 5c) clearly shows the elevation of isopycnals associated with the eddy above 60 m, and the depression of isopycnals below this depth, i.e. the isopycnals spread apart near the eddy center, which indicates the rotation direction of the eddy as anticyclonic. The eddy thickness can be determined from the density distribution. As shown in Fig. 5c, the eddy exists at depth between 40 and 80 m, and isopycnals at depth of 40 and 80 m are almost at horizontal level, which indicates the thickness of this eddy is about 40 m.

4 Comparison with other Arctic Ocean eddies

Arctic Ocean eddies can be anticyclonic or cyclonic: the former normally exist at depth between 50 and 300 m[2] and most of them have cold cores, while most of the later cyclonic eddies are deeper than 200 m and have warm cores at the Atlantic Layer. Furthermore, most eddies observed in the Canada Basin are anticyclonic, for example, 97% of eddies with certain rotation direction detected in 1975~1976 are anticyclonic. So we just compare the eddy reported in this paper with anticyclonic eddies observed in the Canada Basin. Table 1 lists the main features of eddy reported in this paper and some anticyclonic eddies previously observed in the Canada Basin. The speed list in Table 1 with reference depth is calculated from dynamic heights, and the one without reference depth is measured directly.

Table 1 Comparison of anticyclonic eddies observed in the Canada Basin

Date	Heat feature	V_{max} (m s^{-1})	Depth of V_{max}, (m)	Radius, km	Reference
Mar, 1972	cold	0.34	150	6	Newton *et al.* (1974)[1]
1975–1976	Warm	0.58	119	7.5	Manley and Hunkins (1985)[2]
Mar-April, 1985	Cold	0.28/255	100	5	DÀsaro (1988a)[17]
April, 1985	Cold	0.09/100	50~55	2	DÀsaro (1988a)[17]
Sept 1997	Cold	0.22/450	185	10	Muench and Gunn (2000)[7]
Sept, 2003	Cold	0.37	60	5	this paper
Sept, 2004	Cold		160	10	Mathis *et al.* (2007)[8]

Only one of the seven eddies is with warm core. Its speed is quite larger than other one's and is also the maximum velocity recorded in the 14 months measurements. So this eddy is unique. However, advanced analysis is quite difficult due to the lack of detailed information including the observation time.

The cold eddy found in April 1985 at 74°N, 144°W[17] is at depth of 50~55 m that is close to the depth of the eddy observed by us in 2003. Compared with the eddy in 1985, the eddy in 2003 has similar vertical hydrographical features, but is larger and more energetic than the former, which implies that the eddy in 2003 was in a relative younger stage than the former at the time when it was observed. The location difference also supports the above hypothesis. If both of them were formed in Chukchi Shelf and migrated with anticyclonic BG, the eddy in 1985 had to travel a longer route than the eddy in 2003 to reach the location where it was observed.

The other eddies locate at deeper layers. In fact, depths between 100 and 200 m is the layer contains most eddies[2], which is coincident with the hypothesis that eddies come from slope. For the eddy in 2003 locates in a shallower layer that is according to the depth of shelf, the eddy might formed at shelf and do not relate to the denser water sinking at the slope. Layer near depth of 150 m in the Canada Basin is the wBSW that is characterized by the temperature minimum with salinity about 33.1 and density about 26.5 kg m^{-3}[15,16]. This layer is also nutrient maxima layer that is only found in the Canada Basin[18]. Abundant eddies near this layer play an important role in formation of above features[8]. For the depth of 100 m in the Canada Basin is the layer of summer Pacific origin waters (ACW and sBSW) indicated by temperature maxima, the warm feature will be weaken by the intrusive cold eddies. So there should be less eddies in this shallow layer, which is consistent with previous statistical results[2].

5 Discussions on the formation mechanism of the Arctic Ocean eddy

Normally, an eddy core preserves the characteristics of the water in its formation origin area. For example, in the core of an eddy studied by Muench and Gunn (2000)[7], the T minimum closing to freezing point and excess salt implied that it was probably formed in association with a polynya maintaining in winter. The core T-S features (the temperature below −1.5℃ and the salinity near 31.8) of the eddy found in 2003 by the present study is obviously different from the ambient waters. The low temperature in the core of the eddy implies that it is possibly formed during freezing season. However, the temperature minimum in the core is ~0.2℃ higher than the freezing point as shown in Fig. 6. Therefore, it is speculated that some warm waters, for example ACW ($S < 31$) with the greatest possibility, had participated in the formation of this eddy. T-S features obtained at all CTD and xCTD stations of CHINARE-2003 are compared to features of the eddy core. No similar features are found at xCTD stations. The stations with T-S features similar to that of eddy core are found only at the Chukchi Slope as shown in Fig. 1, implying that the eddy likely originated from the Chukchi Shelf.

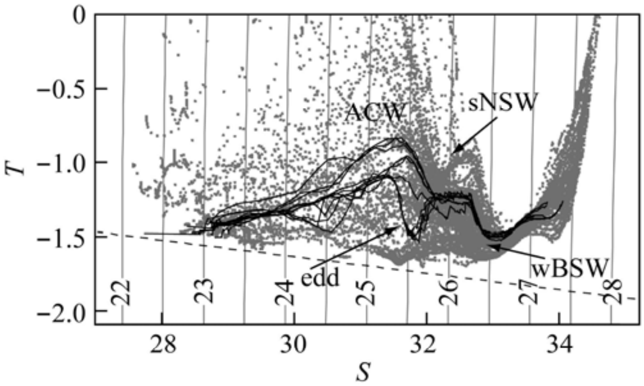


Fig. 6 T-S diagram of MCTD data observed at the icecamp. 1-m-depth-interval MCTD data of a profile are connected in a solid line. All CTD and xCTD data with 1 m depth interval of CHINARE-2003 are also plotted in light gray points for comparisons. The freezing point line (dashed line) and σ_t (Unit: kg m^{-3}) contours (gray line) are also shown for reference.

Previous studies indicate that the Arctic Ocean eddy is a unique mesoscale ocean eddy with faster rotation speed and longer life. The eddy we found in 2003 should had experienced a long drifting, if it formed near the Chukchi slope. At lest, the drifting distance is 750 km and the eddy's life is 80 days if the translation speed of the eddy is 0.1 m s^{-1}. This eddy was detected at the northwest of BG, so it is possible for it to drift from west of Barrow Point to the northern Canada Basin with mean circulations of enhanced BG when Arctic Oscillation (AO) state was negative in 2003[6,19]. How the Arctic Ocean eddy conserve its energy in a long time translation is still a puzzle.

6 Conclusions

A unique ocean eddy was observed at an ice camp near 78°36′N, 146°12′W during the Chinese Arctic Expedition in 2003. With 6 days observed current, temperature and salinity data, the structure and pattern of the eddy are analyzed, the parameters of the eddy are calculated, and the comparison with previous observed eddies are presented in this paper.

All observations for the eddy were conducted at a drifting ice floe. Measured temperature and salinity data show the abnormal features in the eddy that indicate the existence and possible origin of the eddy. The isopycnals around the eddy show themselves as convex lens, which confirms that the rotation sense of the eddy is anticyclonic. The current records of the eddy show an assembled current field of a mesoscale eddy and inertial currents. The current pattern of the eddy is given by eliminating inertial currents and mean circulation with the current records at a reference layer. For the drifting trace of the ice camp is closed to the eddy center, reliable scale parameters have been obtained.

By above analysis, the eddy is about 40 m thick, locates at the depth between 40 m and 80 m, with a cold core of −1.5℃ at ~60 m. Its radius of maximum velocity is 5 km and total radius is supposed about 10 km, which is similar to the scale of previously observed Arctic Ocean eddies.

Water in the eddy is quite different from ambient waters. Depending on analysis of data in the whole expedition region, eddy is thought to originate from the Chukchi shelf, and the Alaskan Coastal Water originating from the Pacific Ocean might involve in the formation of the eddy, which indicate the important role of eddy on the transporting the Pacific origin water into the Canada Basin.

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