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Warming and depth convergence of the Arctic Intermediate Water in the Canada Basin during 1985–2006

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Abstract
The warming of the Arctic Intermediate Water (AIW) is studied based on the analyses of hydrographic observations in the Canada Basin of the Arctic Ocean during 1985–2006. It is shown that how the anomalously warm AIW spreads in the Canada Basin during the observation time through the analysis of the AIW temperature spatial distribution in different periods. The results indicate that by 2006, the entire Canada Basin has almost been covered by the warming AIW. In order to study interannual variability of the AIW in the Canada Basin, the Canada Basin is divided into five regions according to the bottom topography. From the interannual variation of AIW temperature in each region, it is shown that a cooling period follows after the warming event in upstream regions. At the Chukchi Abyssal Plain and Chukchi Plateau, upstream of the Arctic Circumpolar Boundary Current (ACBC) in the Canada Basin, the AIW temperature reached maximum and then started to fall respectively in 2000 and 2002. However, the AIW in the Canada Abyssal Plain and Beaufort Sea continues to warm monotonically until the year 2006. Furthermore, it is revealed that there is convergence of the AIW depth in the five different regions of the Canada Basin when the AIW warming occurs during observation time. The difference of AIW depth between the five regions of the Canada Basin is getting smaller and smaller, all approaching 410 m in recent years. The results show that depth convergence is related to the variation of AIW potential density in the Canada Basin.

Key words: Arctic Intermediate Water, Canada Basin, warming, interannual variation, convergence of AIW depth

1 Introduction

There are three significantly different water masses in the Arctic Ocean (Swift and Aagaard, 1981; Aagaard et al., 1985): The surface or arctic water with low temperature and low salinity (0–200 m), the Arctic Intermediate Water (AIW) with high temperature and relatively higher salinity (200–900 m), and the deep or bottom water with relatively low temperature but high salinity (900 m to the bottom). Originating from the Atlantic Ocean, the AIW is also called the Atlantic water. After entering the Arctic Ocean through the Fram Strait and the Barents Sea, the Atlantic surface water promptly gets colder and heavier, and then sinks under the surface to become the AIW. The AIW continues to flow eastward along the Eurasian slope, and finally spreads over the whole Arctic Ocean to form the cyclonic circulation known as the Arctic Circumpolar Boundary Current (ACBC) (Rudels et al., 1999; Karcher et al., 2003). The AIW is between the surface water and the deep water, with salinity ranging from 34.8 to 35.1, temperature from 0 to 3℃, and potential density (we represent potential density by potential density anomaly in this paper, i.e., sigma-t, just like other reference paper) from 27.900 kg/m^3 to 32.785 kg/m^3 (Schlichtholz and Houssais, 2002).The strong halocline under the surface water restrains energy exchange between the surface water and the AIW, which keeps the AIW high-temperature properties in vertical direction. Carrying massive heat, the AIW is the most important energy source for the intermediate water and the deep water in the Arctic Ocean, and largely determines the energy balance of the Arctic Ocean. The AIW variation influences not only the

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properties of water in the Arctic Ocean, but also the global ocean thermohaline overturning.

Since the 1970s, great changes related to global warming have taken place in the Arctic Ocean (Deser et al., 2000; Stroeve et al., 2005; Yang et al. 2010). After the early 1990s, the anomalously warming phenomenon of the AIW is continually observed in the various seas of the Arctic Ocean (Dickson et al., 2000; Steele et al., 2004). The anomalous warming of the AIW was first observed in the Nansen Basin in 1990 (Quadfasel et al., 1991; Quadfasel et al., 1993). Thereafter, the warming AIW was observed downstream of ACBC in succession, such as the Amundsen Basin, the Makarov Basin and the Mendeleev Ridge (Carmack et al., 1995; Carmack et al., 1997; Swift et al., 1997; Steele and Boyd, 1998; Morison et al., 1998). By the late 1990s, the warming AIW has flown through the Mendeleev Ridge into the Chukchi Plateau, south of the Canada Basin. The Chinese arctic research expedition in 1999 shows that the AIW temperature in some area of the Chukchi Plateau is higher than 1℃, far exceeding the historical average of 0.5℃ (Zhao et al., 2003). Observations from the USA CBL cruise in 2002 show that the warming AIW covered all over the Chukchi Plateau (Woodgate et al., 2007). Shimada et al. (2004) show that the warming AIW penetrated into the Canada Basin starting from 1996 to 1998, and then spread to the Canada Ambyssal Plain in 2002. Although the magnitude of the AIW warming is smaller as compared with that in the atmosphere, the significance of the AIW warming would play an important role as heat capacity of ocean is 3000 folders greater than that of atmosphere. The warming AIW can influence upper water and ice by altering the vertical heat transport, thereby impacting the arctic climate (Zhang and Steel, 2007).

The previous studies of the AIW warming are mostly confined to one cruise result, therefore it is difficult to set up a basis for the better representation of the interannual variability of the AIW warming, not mentioning the differences among the different seas of the Arctic Ocean during the events. In addition, the study of the AIW warming in the Canada Basin is less than that in the Eurasian Basin as the warming starts later in the Canada Basin. It is also unclear about the variations of other properties (such as salinity and its residing depth) of the AIW during the warming, although the variations of the properties are also critical to the heat diffusion. The objective of this paper is therefore to study the interannual variation characteristics of the AIW in the different seas of the Canada Basin based on in-situ hydrographic observations in the Canada Basin, to discuss the expansion process of the AIW warming in the Canada Basin as well as to unravel variation mechanism for the AIW salinity and its corresponding depth during the AIW warming.

2 Data and methods

The primary datasets used in this study are the hydrographic observations collected during 1985–2006 in the Canada Basin, and most are collected by CTD and XCTD. The main sources of observation datasets include the Canadian LSSL dataset, the Mirai atlas from Japan, the SCICEX and WOD05 from America. The LSSL dataset consists of these cruises: AOS-1994 (Carmack et al., 1997), LSSL-1997(McLaughlin et al., 2004) and LSSL03-06 (Proshutinsky et al., 2002). The Mirai dataset is released by the Japan Agency for Marine-Earth Science and Technology for the Arctic Ocean. In this paper, we choose Mirai CTD data collected in 1999, 2000, 2002 and 2004 in the Arctic Ocean. The SCICEX is a 5 a program (1995–1999) funded by U.S. Navy using a nuclear-powered submarine for unclassified science cruises to the Arctic Ocean (Edwards and Coakley, 2003). We append the data to include the experimental voyage in 1993 and the successor expedition in 2000. WOD05 (World Ocean Database 2005) is released by the National Oceanographic Data Center of the USA (Boyer et al., 2006). We choose the CTD data observed in the Canada Basin from 1985 to 2006. Although the accuracy of temperature and salinity is different since the different datasets were collected using different instruments, the temperature accuracy of all the instruments reaches ±0.02℃, and conductivity accuracy is higher than ±0.03 mS/cm. This is enough for the purpose of studying the AIW warming. Additional data utilized in this paper include the expedition cruise as follows: ODEN-1991, SHEBA-1997/1998, CBL-2002 (Woodgate et al., 2007) and CHINARE-2003 (Zhang, 2004).

The study region is the mid-southern Canada Basin between 180°–120°W, 70°–80°N (Fig. 1). With the characteristics of high temperature and salinity, the AIW contains a layer with maximum temperature in the vertical direction, which is usually referred to as the intermediate water core (IWC) (Carmack et al., 1997; Polyakov et al., 2004). In this study, the thermohaline conditions of the IWC are used as the AIW physical characteristics, and the corresponding vertical locations are highlighted to represent the depth of the AIW. The interannual variability of the AIW can then be investigated on the basis of the properties of the IWC, i.e., the IWC temperature, salinity and depth. As the depth of the IWC in the Canada Basin is overall between 300 m and 500 m, we choose the data with the observational depth of more than 500 m from the above mentioned datasets. Overall, 1110 CTD/XCTD stations meet the limiting conditions (Fig. 1).

For the selected stations that meet the criteria, there is no long time series at fixed CTD station near the study time. Meanwhile, the ACBC is significantly modified by the bathymetry, making the thermohaline distribution of the AIW reshaped by bottom topography (Grotefendt et al., 1998; Woodgate et al., 2007). Here we divide the Canada Basin into five regions based on topography features, namely, from west to east: the Chukchi Abyssal Plain, the Chukchi Plateau, the Canada Abyssal Plain, the Chukchi/Beaufort Slope and the Beaufort Sea (Fig. 2). The interannual variabilities of the AIW in each region are then studied accordingly.

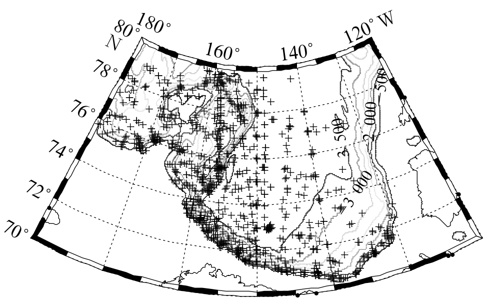

Fig.1. Spatial distribution of the observation stations in the Canada Basin used in this study. "+" sign denotes observation sites, and the water depth is plotted using ETOPO5.

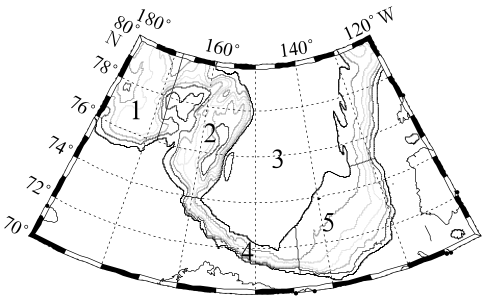

Fig.2. The five divided regions in the southern Canada Basin, namely, from west to east: the Chukchi Abyssal Plain (1), the Chukchi Plateau (2), the Canada Abyssal Plain (3), the Chukchi/Beaufort Slope (4) and the Beaufort Sea (5).

3 Warming of the AIW in the Canada Basin

3.1 *Spatial distribution of the warming AIW during the different period*

In order to study the spatial propagation of the AIW warming signal in the whole Canada Basin since the 1990s, we have divided all the observations into four temporal periods to describe the spatial distributions of the IWC temperature in each period. The four periods are: 1985–1990, 1991–1995, 1996–2000 and 2001–2006. The spatial distributions of the IWC temperature in different periods are shown in Fig. 3.

Climatology shows that the IWC temperature is generally lower than 0.5°C in the southern Canada Basin (Treshnikov and Baranov, 1972; Treshnikov, 1977; Zhao et al., 2003). As such, we choose 0.5°C as the warming standard in the Canada Basin. During 1985–1990 (Fig. 3a), all the observational sites are within the Chukchi/Beaufort Slope and the Beaufort Sea, and the IWC temperature is between 0.4°C and 0.5°C, indicating that the AIW during this period is still in the cool stage in this region. But it is unknown whether the AIW temperature in the west Canada Basin is warming or not, as there are no data in this region during 1985–1990. By 1995 (Fig. 3b), the IWC temperature of the above region is still lower than 0.5°C, and there is also observation in the Chukchi Abyssal Plain and the Chukchi Plateau where the IWC temperature has been more than 0.5°C and reached 0.9°C at most. Even in the Canada Abyssal Plain near the Chukchi Plateau, the IWC is also higher than 0.5°C. Figure 3b indicates that the warming AIW signal covered almost the Chukchi Plateau in 1995 and there was an obvious warming tongue intruding into the northern Canada Abyssal Plain from the northern tip of the Chukchi Plateau. In the upstream of ACBC in the Canada Basin, the Chukchi Abyssal Plain, the IWC temperature of all the observations was even higher than 0.7°C, indicating that the AIW temperature was about 0.2°C higher than the climatology [see in Fig. 2b in Grotefendt et al. (1998), Carmack et al. (1995)]. Figure 3c shows the spatial distribution of the IWC temperature during 1996–2000. In contrast to the previous period, the warming signal continued to spread southward and eastward, and

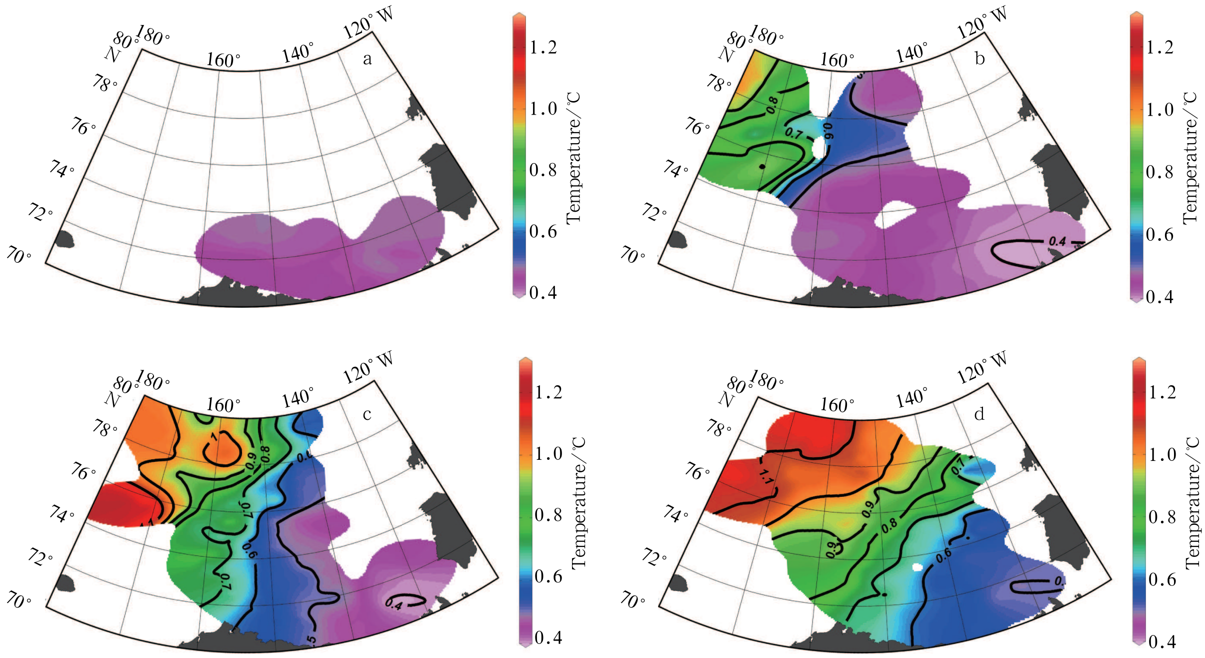

Fig.3. Spatial distributions of the IWC temperature at different periods. The periods for a, b, c and d are 1985–1990, 1991–1995, 1996–2000 and 2001–2006, respectively.

the 0.5℃ isotherm was driven to near 145°W in the middle of the Canada Abyssal Plain, meaning that the boundary of the AIW warming reached here in 2000. At the east of the 145°W, The simultaneous AIW temperature in the Canada Abyssal Plain and the Beaufort Sea was still in cool stage with temperature lower than 0.5℃. In the Chukchi Abyssal Plain, the AIW temperature kept rising and reached more than 1.1℃ at most with warming extreme of 0.3℃ compared with the previous period. The AIW temperature in all the Chukchi Plateau was more than 0.8℃ and the maximum temperature was higher than 1.0℃ in the northern plateau. In 2001–2006 (Fig. 3d), the 0.5℃ isotherm was quickly driven eastward to the eastern Beaufort Sea near the Amundsen Gulf, which indicates that almost all the Canada Basin was covered by the AIW with the temperature of more than 0.5℃. It is realized (Figs 3a–c) that the AIW temperature in the Beaufort Sea was about 0.4℃ before 2000, and it is warmer at least 0.1℃ by 2006, and this indicates that AIW thermal properties changed greatly in the entire Canada Basin. At the upstream of the ACBC, the AIW with over 1℃ continued to spread eastward to the northern tip of the Chukchi Plateau, and the AIW temperature was higher than 0.9℃ in the all Chukchi Plateau. In the meantime, the AIW temperature continued to increase in the Canada Abyssal Plain, the Chukchi/Beaufort Slope and the Beaufort Sea. All these analyses indicate that the warming AIW started to spread into the Canada Basin in the early 1990s. By 1995, the warming signal of the AIW covered the Chukchi Plateau and passed 160°W longitudinal line at the northern Chukchi Plateau; by 2000, the warming signal reached the mid Canada Abyssal Plain (150°–140°W); In 2006, even the Beaufort Sea started to be covered by the warming AIW and the thermal condition greatly changed in the Canada Basin.

3.2 *Interannual variability of the AIW in the different regions of the Canada Basin*

In order to study the AIW warming process, we calculate mean IWC temperature at each of the five regions in different years (Fig. 2). Figure 4 shows the time series of IWC temperature in five regions. The star marks represent the observed IWC temperature, and dashed line is the spatial average of all observed IWC temperature in this region in corresponding year. The time length of the IWC temperature in the five regions in Fig. 4 is different. It is relatively shorter in the Chukchi Abyssal Plain, with observations between 1993 and 2004 (Fig. 4a). The 8 a observations show that there are two phases for the AIW temperature changes in the Chukchi Abyssal Plain in the observation time, warming period during 1993–2000, and

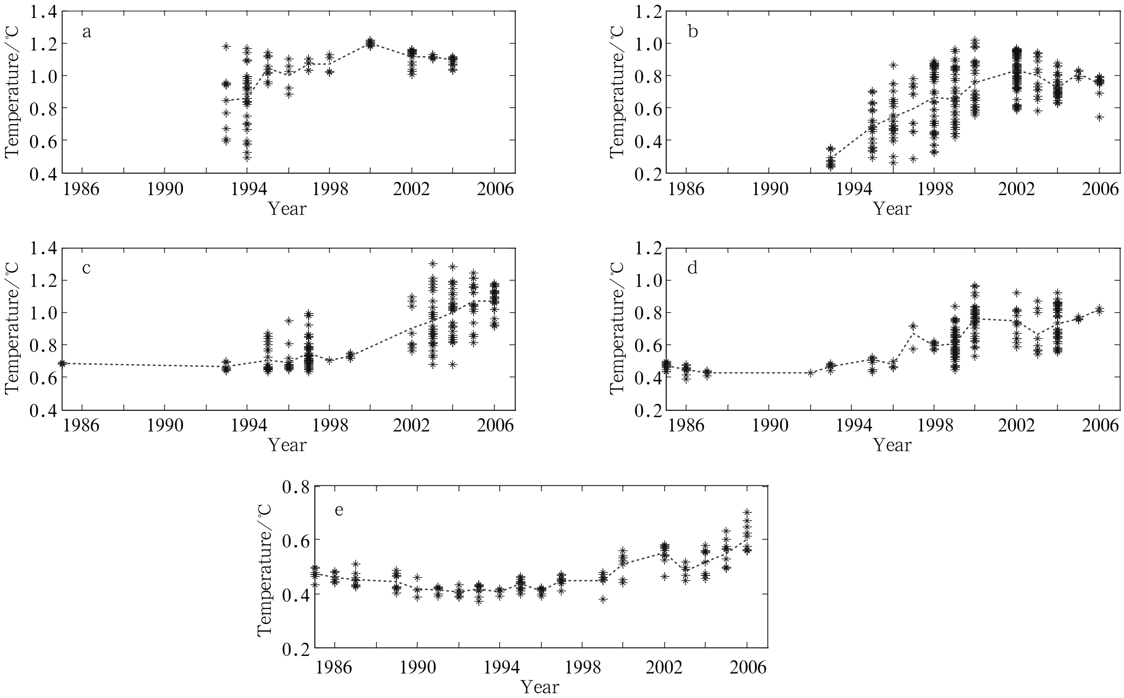

Fig.4. Time series of IWC temperature in the five regions of the Canada Basin. The star marks are the IWC temperature in one observational region in corresponding year and the dashed line represents the averaged IWC temperature over all the observations that year in each region.

cooling period after 2000. In 1993, the mean value of IWC temperature over all the stations in this region is 0.85℃, clearly higher than historical climatology 0.5℃ (Treshnikov, 1977), indicating that the AIW warming in fact started before 1993 in this region. This is consistent with the results of Carmack et al. (1995) and Grotefendt et al. (1998). After 1993, the AIW temperature continued to rise, and reached to the maximum of 1.2℃ in 2000. Then it was followed by a slow AIW temperature decrease. The AIW temperature in this region dropped to 1.1℃ in 2004. In the Chukchi Plateau, the AIW temperature underwent two similar stages: a warming stage and a cooling stage (Fig. 4b). But the switching time from the warming stage to the cooling stage lagged Chukchi Abyssal Plain by 2 a. In 1993, the mean IWC temperature in this region was about 0.5℃, and rose rapidly to more than 0.7℃ after 1995, reached a maximum of ca. 1℃ in 2002, and then dropped to 0.95℃ in 2006. This indicates that the AIW in the Chukchi Plateau warms later and lower than the Chukchi Abyssal Plain. Both variations in the Chukchi Abyssal Plain and the Chukchi Plateau show that, after its warming lasts about 10 a, the AIW warming starting from early the 1990s has slowed down recently, and even they go into one cooling stage after 2000 and 2002 respectively in the Chukchi Abyssal Plain and the Chukchi Plateau. In the Chukchi Abyssal Plain and the Chukchi Plateau, the warming period has already finished, and the cooling period is still yet under development.

In the Canada Abyssal Plain, the Chukchi/Beaufort Slope and the Beaufort Sea, there are different significant changes in the AIW warming compared with that in the Chukchi Abyssal Plain and the Chukchi Plateau (Fig. 4). During the observational time, the AIW in these regions experienced two different stages: a relatively cold stage and a warming stage. The earliest observation in the Canada Abyssal Plain is in 1985, and the mean value of the AIW temperature is 0.49℃. By 1999, the AIW mean temperature was still lower than 0.55℃, indicating it was in cold stage in the Canada Abyssal Plain from 1985 to 1999. However, the AIW temperature was already more than 0.70℃ in 2002, and reached 0.87℃ in 2005–2006, which shows that the warming AIW went through the Chukchi Plateau and started to enter this region. In the Chukchi/Beaufort Slope, it fluctuated within the range of 0.4–0.5℃ in 1985–1996, and increased to more than 0.6℃ after 1997. In 2006, the AIW was still in warming stage with a highest value of 0.8℃ during observation time. The Beaufort Sea where the AIW arrived the latest in the southern Canada Basin is the region with most continuous observations compared with others (Fig. 4e), with 19 a observations in 1985–2006. There are also cold period and warming period in this region, although the cold period is much longer than the warming period. The cold period before 2000 had an IWC temperature lower than 0.5℃. The IWC temperature exceeded 0.5℃ after 2000, even reaching 0.6℃ in 2006. This also indicates that the AIW temperature in the Beaufort Sea is lowest in the Canada Basin and starts to warm in the latest.

In comparing the mean IWC temperature of the five regions (Fig. 5a), we find difference between them during the AIW warming. The mean IWC temperature values over 1993–2004 for the five regions are 1.04, 0.83, 0.60, 0.62 and 0.46℃, respectively. Except that the temperature in the Canada Abyssal Plain and Chukchi/Beaufort Slope is close, the differences among regions are distinct. Such a difference also represents the sequential spreading of the AIW in the Canada Basin. Based on the above analysis, the timing for AIW warming in the five regions of the Canada Basin is prior to 1993, 1995, 1999–2002, 1997 and 2000, respectively. The time when AIW temperature reached maximum was 2000 and 2002 in the Chukchi Abyssal Plain and the Chukchi Plateau. Therefore, the sequential order of the AIW warming is the Chukchi Abyssal Plain, the Chukchi Plateau, the Canada Basin and the Chukchi/Beaufort slope, followed by the Beaufort Sea.

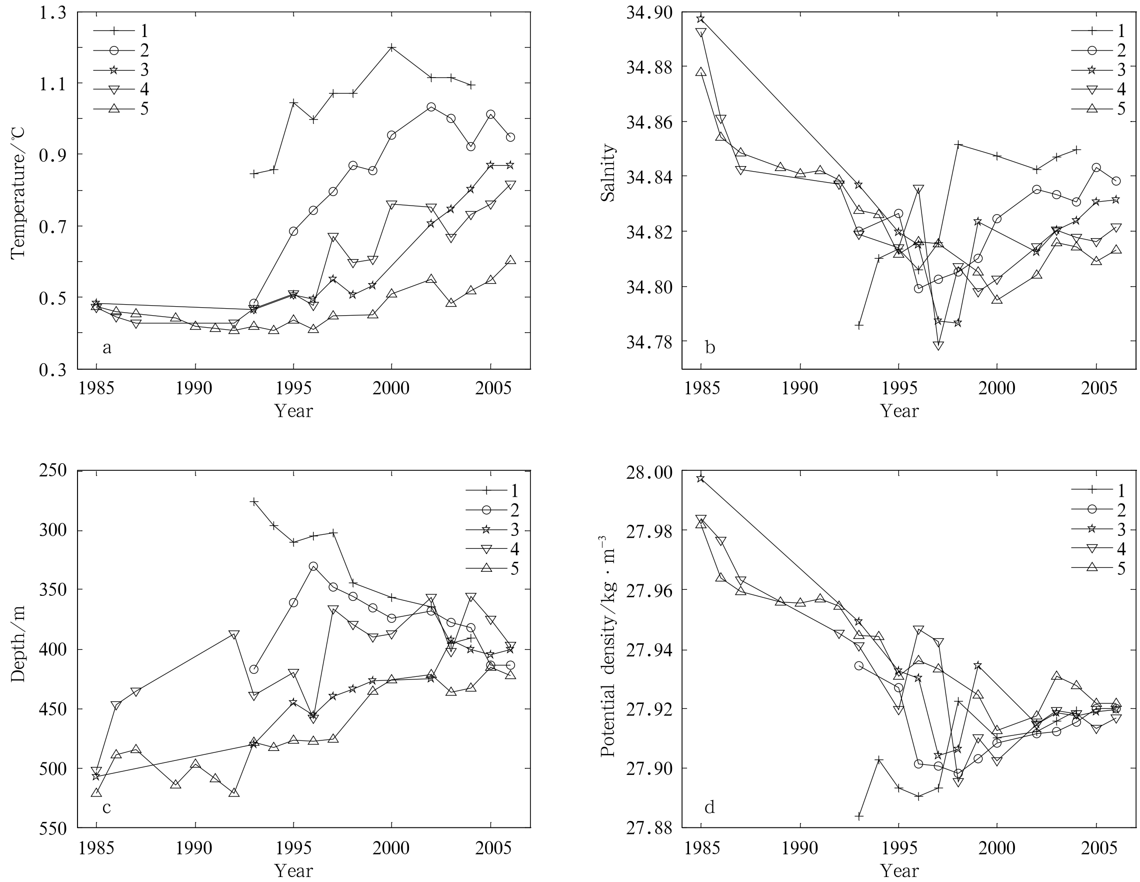

Fig.5. Evolution of IWC temperature (a), salinity (b), depth (c) and potential density (d) in five regions of the Canada Basin.

4 The depth convergence of the AIW in the Canada Basin

Although the AIW warming phenomenon was discovered earlier, it is still not yet clear how other physical properties of the AIW (such as salinity and depth) evolves when warming occurs. For this purpose, we also calculated the variation trend of the IWC salinity and the corresponding depth in five regions of the Canada Basin (Figs 5b–c). Figure 5b shows that the interannual variability of the IWC salinity is obviously different from that of the IWC temperature. Overall, the AIW salinity of five regions experiences two periods during the observation time. Prior to the late 1990s, the salinity is generally in a decreasing trend, which is most remarkable in the Canada Abyssal Plain, Chukchi/Beaufort Slope and Beaufort Sea; after that, the AIW salinity increases in most regions, although the salinity by 2006 is still lower than 1995. It is the period with salinity increasing from 2000 to 2005 for all the regions of the Canada Basin, and the mean IWC salinity values in five regions were as follow: 34.85, 34.83, 34.82, 34.82 and 34.81, which indicates that the IWC salinity decreased from west to east in this period. At the same time, the salinity increments in the five regions are respectively 0.06, 0.04, 0.04, 0.04 and 0.02 from 2000 to 2005, which indicates that the salinity increment of the AIW in the upstream is slightly higher than that in the downstream of the ACBC. In the Chukchi Abyssal Plain, the IWC salinity shows upward trend in overall in 1993–2004. Whereas in the Chukchi Plateau, the IWC salinity decreases before 1996, then it increases from 34.80 to 34.84 in 10 a between 1996 and 2006. In the Canada Abyssal Plain and Chukchi/Beaufort Slope, the IWC salinity decreases from 34.90 to below 34.79 from 1985 to 1997, and then increases to more than 34.82 in 2006. In the Beaufort Sea, the IWC salinity reached the minimum in 2000.

Polyakov et al. (2004) and Mclaughlin et al. (2005) indicated that the AIW warming in the Canada Basin was possibly accompanied by IWC depth shallowing. If that is the case, it would have significant impact on the vertical heat transfer, and even affect the melting process of surface sea ice (Zhang and Steele, 2007). Figure 5c shows the interannual variation curve of the IWC depth in five regions of the Canada Basin. The variation of the IWC depth is obviously different from temperature and salinity, and there is only one phase with shoaling or deepening in each region of the Canada Basin. The result also reveals that the IWC depth in the Canada Basin is shallow in west and deep in east in general. This is obvious before the AIW warming, and the IWC depth is from about 275 m in the Chukchi Abyssal Plain to 478 m in the Beaufort Sea in 1993, and the difference in the IWC depth between the two regions is about 200 m. It is proposed that the spatial distribution property of the IWC depth is related to AIW temperature cooling and density increasing during AIW flowing in the Arctic Ocean. As the AIW temperature decreases and density increases, the AIW temperature peak deepens accordingly, so the IWC depth of the ACBC downstream is deeper than that of the ACBC upstream. However, as shown in Fig. 5c, the spatial difference in the IWC depth between the west and east of the Canada Basin is gradually reducing. The IWC depth of the western regions (the Chukchi Abyssal Plain and the Chukchi Plateau) is continuously deepened in the observations time, but that of the east (the Canada Abyssal Plain, the Chukchi/Beaufort Slope and the Beaufort Sea) is continuously shallower. Polyakov et al. (2004) and Mclaughlin et al. (2005) indicate that the IWC depth shallow when the AIW warming is mainly in the Canada Abyssal Plain and southern region, so the results here are consistent with their results in the western Canada Basin, furthermore we give the interannual variation in detail compared with their one depth difference between two times. But the interannual variation of the IWC depth in the Chukchi Abyssal Plain and Chukchi Plateau show that the AIW warming is not surely companied by the IWC depth shallowing. The different trends of the IWC depth variation leading to the IWC depths of all regions are generally inclining to 410 m, which we named the phenomenon of AIW depth convergence. In 1993, the maximum of IWC depth difference between different regions of the Canada Basin is 200 m, but it reduces to 50 m in 2006. In the Chukchi Abyssal Plain and the Chukchi Plateau of the ACBC upstream, the IWC depth deepened year after year. However, in the Canada Abyssal Plain, the Chukchi/Beaufort Slope and the Beaufort Sea, the IWC depth became shallower than before, and these two different trends led to the decrease of the IWC depth difference.

What leads to the spatial difference of the IWC depth in the different regions of the Canada Basin to disappear? In Fig. 5d, it is found that the spatial difference of the IWC potential density in different regions is decreasing during the observation time. In 1993, the differences of potential density among regions are higher than 0.06 kg/m^3, but it is smaller than 0.01 kg/m^3 in 2006, and all of the potential density is inclining to 27.92 kg/m^3.This variation trend of the IWC potential density may make the IWC depth to develop to the same layer.

5 Conclusions and discussion

Ever since the occurrence of the AIW warming in the early 1990s, the warming signal has propagated eastward from the Eurasian Basin with the ACBC flowing, finally has extended to the Canada Basin near the Pacific Ocean, and the warming has been still developing nowadays. In this paper, the 22 a observations in 1985–2006 are analyzed to study the AIW warming in the Canada Basin and regional difference of the AIW warming. The results are summarized as follows.

(1) On the basis of the spatial distribution of the IWC temperature in different periods, we indicate the AIW warming signal propagation process in the Canada Basin. Before 1993, the warming signal of the AIW first intruded into the Chukchi Abyssal Plain of the Canada Basin. In 1995, the warming signal spread to the east of 160°W and covered most of the Chukchi Plateau. In 2000, the warming signal continued to spread southward and eastward to the mid Canada Abyssal Plain (150°–140°W). By 2006, all the Canada Basin has been almost covered by the warming water and the 0.5℃ isotherm has been driven to the east of the Beaufort Sea, which means that the thermal condition has changed greatly in the Canada Basin.

(2)The interannual variability of the AIW temperature in five regions of the Canada Basin is studied. It is found that the warming AIW propagates from west to east and with two process of strongly and weakly warming. In the Chukchi Abyssal Plain and Chukchi Plateau, the AIW first started to warm before 1993, and reached the maximum temperature in 2000 and 2002 respectively, then started to decrease in these regions. In the downstream of the ACBC, the Canada Abyssal Plain, the Chukchi/Beaufort Slope and the Beaufort Sea, the AIW is warming latter than the upstream, so it is always in the period of warming before 2006. At the same time of the AIW warming, the IWC salinity in the Canada Basin experienced two periods with a decrease and an increase. In 1985–1997, the IWC salinity decreased from 34.90 to 34.79, and then increased afterward to more than 34.82 in 2006.

(3) Before the AIW warming in the Canada Basin, the IWC depth is shallower in the west and deep in the east, from about 200 m in the west to 500 m in the east. However, in the AIW warming, the IWC depth in different regions of the Canada Basin gradually converged to the same depth, i.e., 410 m. The potential density of different regions inclines to 27.92 kg/m^3 during the observation time, driving the IWC to develop to the same layer. Except potential density, the upper water properties should also affect the IWC depth variation, but this needs further study and discussion.

References

Aagaard K, Swift J H, Carmack E C. 1985. Thermohaline circulation in the arctic mediterranean seas. Journal of Geophysical Research, 90: 4833–4846

Boyer T P, Antonov J I, Garcia H E, et al. 2006. World Ocean Database 2005. In: Levitus S, ed. NOAA Atlas NESDIS 60. Washington, D C: U.S. Government Printing Office, 190

Carmack E C, Aagaard K, Swift J H, et al. 1997. Changes in temperature and tracer distributions within the Arctic Ocean: Results from the 1994 Arctic Ocean section. Deep Sea Research: part II, 44: 1487–1502

Carmack E C, Macdonald R W, Perkin R G, et al. 1995. Evidence for warming of Atlantic water in the southern Canadian Basin of the Arctic Ocean: results from the Larsen-93 expedition. Geophysical Research Letter, 22: 1061–1064

Deser C, Walsh J E, Timlin M S. 2000. Arctic Sea Ice Variability in the Context of Recent Atmospheric Circulation Trends. Journal Climate, 13: 617–633

Dickson R R, Osborn T J, Hurrell J W, et al. 2000. The Arctic Ocean response to the North Atlantic Oscillation. Journal Climate, 13: 2671–2696

Edwards M H, Coakley B J. 2003. SCICEX investigations of the Arctic Ocean System. Chemie der Erde, 63(4): 281–328

Grotefendt K, Logemann K, Quadfasel D, et al. 1998. Is the Arctic Ocean warming. Journal of Geophysical Research, 103: 27679–27687

Karcher M J, Gerdes R, Kauker F, et al. 2003. Arctic warming: evolution and spreading of the 1990s warm event in the Nordic seas and the Arctic Ocean. Journal Geophysical Research, 108(C2): 3034, doi:10.1029/2001JC001265

McLaughlin F A, Carmack E C, Macdonald R W, et al. 2004. The joint roles of Pacific and Atlantic-origin waters in the Canada Basin, 1997–1998. Deep Sea Research: part I, 51: 107–128

McLaughlin F, Shimada K, Carmack E, et al. 2005. The hydrography of the southern Canada Basin, 2002. Polar Biology, 28: 182–189

Morison J, Steele M, Anderson R, 1998. Hydrography of the upper Arctic Ocean measured from the nuclear submarine USS Pargo. Deep Sea Research: part I, 45: 15–38

Polyakov I V, Alekseev G V, Timokhov L A, et al. 2004. Variability of the intermediate Atlantic Water of the Arctic Ocean over the last 100 years. Journal of Climate, 17(23): 4485–4497

Proshutinsky A, Bourke R H, McLaughlin F A. 2002. The role of the Beaufort Gyre in Arctic climate variability: Seasonal to decadal climate scales. Geophysical Research Letters, 29(23): 2100, doi:10.1029/2002GL015847

Quadfasel D, Sy A, Rudels B. 1993. A ship of opportunity section to the North Pole: upper ocean temperature observations. Deep Sea Research: part I, 40: 777–789

Quadfasel D, Sy A, Wells D, et al. 1991. Warming in the Arctic. Nature, 350: 385

Rudels B, Friedrich H J, Quadfasel D R. 1999. The Arctic Circumpolar Boundary Current. Deep Sea Research: part II, 46: 1023–1062

Schlichtholz P, Houssais M. 2002. An overview of the $\theta-S$ correlations in Fram Strait based on the MIZEX 84 data. Oceanologia, 44: 243–272

Shimada K, McLaughlin F, Carmack E, et al. 2004. Penetration of the 1990s warm temperature anomaly of Atlantic Water in the Canada Basin. Geophysical Research Letters, 31: L20301, doi:10.1029/2004GL020860

Steele M, Boyd T. 1998. Retreat of the cold halocline layer in the Arctic Ocean. Journal of Geophysical Research, 103: 10419–10435

Steele M, Morison J, Ermold W, et al. 2004. Circulation of summer Pacific halocline water in the Arctic Ocean. Journal Geophysical Research, 109: C02027, doi:10.1029/2003JC002009

Stroeve J C, Serreze M C, Fetterer F, et al. 2005. Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. Geophysical Research Letter, 32: L04501, doi: 10.1029/2004GL021810

Swift J H, Aagaard K. 1981. Seasonal transitions and water mass formation in the Iceland and Greenland seas. Deep Sea Research: part I, 28: 1107–1129

Swift J H, Jones E P, Aagaard K, et al. 1997. Waters of the Makarov and Canada Basins. Deep Sea Research: Part II, 44: 1503–1529

Treshnikov A F. 1977. Water masses of the Arctic Basin. In: Dunbar M J ed. Polar Oceans. Calgary: The Arctic Institute of North America, 17–31

Treshnikov A F, Baranov G I. 1972. Structure of the Arctic Water Circulation (in Russian). Leningrad: Gidrometeoizdat

Woodgate R A, Aagaard K, Swift J H, et al. 2007. Atlantic water circulation over the Mendeleev Ridge and Chukchi Borderland from thermohaline intrusions and water mass properties. Journal of Geophysical Research, 112: C02005, doi:10.1029/2005JC003416

Yang Xiaoyi, Fyfe John C, Gregory M. 2010. The role of poleward energy transport in Arctic temperature evolution. Geophysical Research Letters, 37: L14803, doi:10.1029/2010GL043934

Zhang Zhanhai. 2004. The reports of 2003 Chinese Arctic Research Expedition. Beijing: China Ocean Press, 7502760687

Zhang Jinglun, Steele M. 2007. The effect of vertical mixing on the Atlantic Water layer circulation in the Arctic Ocean. Journal of Geophysical Research, 112: C04S04, doi:10.1029/2006JC003732

Zhao Jinping, Gao Guoping, Jiao Yutian. 2003. Warming in Arctic intermediate and deep waters around Chukchi Plateau and its adjacent regions in 1999. Science in China: Series D-Earth Sciences, 35: 1312–1320