· **Article** · **Advances in Polar Science**

doi:10.3724/SP.J.1085.2011.00153 September 2011 Vol.22 No.3 153–164

Summer freshwater content variability of the upper ocean in the Canada Basin during recent sea ice rapid retreat

GUO GuiJun[1,2], SHI JiuXin[1,2*], ZHAO JinPing[1,2], JIAO YuTian[1,2] & XU Dong[1,2]

[1] College of Physical and Environmental Oceanography, Ocean University of China, Qingdao 266100, China;

[2] Key Laboratory of Physical Oceanography, Ministry of Education, Qingdao 266003, China

Received August 2, 2011; accepted August 24, 2011

Abstract Freshwater content (*FWC*) in the Arctic Ocean has changed rapidly in recent years, in response to significant decreases in sea ice extent. Research on freshwater content variability in the Canada Basin, the main storage area of fresh water is very important to understand the input-output freshwater in the Arctic Ocean. The *FWC* in the Canada Basin was calculated using data from the Chinese National Arctic Research Expeditions of 2003 and 2008, and from expeditions of the Canadian icebreaker Louis S. St-Laurent (LSSL) from 2004 to 2007. Results show that the upper ocean in the Canada Basin became continuously fresher from 2003 to 2008, except during 2006. The *FWC* increased at a rate of more than 1 $\mathrm{m \cdot a^{-1}}$, and the maximum increase, 7 m, was in the central basin compared between 2003 and 2008. Variability of the *FWC* was almost entirely limited to the layer above the winter Bering Sea Water (wBSW), below which the *FWC* remained around 3 m during the study period. Contributors to the *FWC* increase are generally considered to be net precipitation, runoff changes, Pacific water inflow through the Bering Strait, sea ice extent, and the Arctic Oscillation(AO). However, we determined that the first three contributors did not have apparent impact on the *FWC* changes. Therefore, this paper focuses on analysis of the latter two factors and the results indicate that they were the major contributors to the *FWC* variability in the basin.

Keywords **Freshwater content, Canada Basin, sea ice, Arctic Oscillation(AO)**

Citation: Guo G J, Shi J X, Zhao J P, et al. Summer freshwater content variability of the upper ocean in the Canada Basin during recent sea ice rapid retreat. Adv Polar Sci, 2011, 22: 153–164, doi: 10.3724/SP.J.1085.2011.00153

0 Introduction

The Arctic Ocean (Figure 1) is one of the major source regions for surface waters of the subpolar Atlantic Ocean, where deep convection caused by weak stratification is the main force of ocean circulation and thermodynamics[1]. Sea ice export is one of the primary ways by which the Arctic Ocean provides freshwater to the Atlantic Ocean. Mauritzen and Häkkine[2] stated that the thermohaline circulation in the North Atlantic might be strengthened by 10%–20% in response to a decline of the ice outflow of 800 $\mathrm{km^3}$. Freshwater content (*FWC*) variability has therefore aroused great attention. Previous research has shown that among river runoff, net precipitation (precipitation minus evaporation), sea ice melting/freezing and wind-driven circulation each has some influence on the *FWC* changes in the Arctic Ocean[3–8]. Using a vast collection of observational data, Polyakov et al.[9] studied the *FWC* changes in the Arctic Ocean over the past 100 years. They obtained *FWC* spatial distributions by using linear interpolation and analyzed the influencing factors with their respective contributions to the *FWC* variability. They

---

*Corresponding author(email: shijiuxin@ouc.edu.cn)

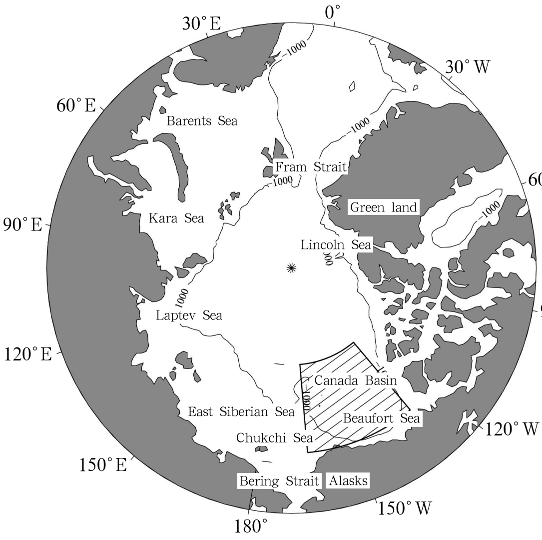

Figure 1 Map of the Arctic Ocean and study area (inset).

concluded that the central Arctic Ocean became increasingly saltier over the twentieth century, with a rate of freshwater loss of 239±270 km^3 per decade[9]. Since the late twentieth century, however, dramatic changes of the Arctic atmosphere-ice-ocean system, including rapid sea ice retreat, has occurred because of the global warming, resulting in a fact that the Arctic Ocean became correspondingly fresher[10]. Potential causes for the *FWC* anomalies include precipitation larger than evaporation, runoff changes, Pacific water inflow through the Bering Strait, sea ice melting/freezing and freshwater export. The first three mechanisms are considered too weak to cause significant *FWC* variability, leaving the last two factors as probable causes[3−9]. Aagaard and Carmack's estimates suggested that the freshwater storage in the Arctic Ocean was approximately 80 000 km^3 (relative to the salinity 34.8)[3]. Of this, the Canada Basin (Figure 1) contained 45 800 km^3, representing about 60% of the total Arctic Ocean storage[3]. This large proportion gives import to research on the *FWC* variability in the Canada Basin, toward an understanding of freshwater changes in the Arctic Ocean.

The Bering Strait is the only ocean gateway between the Pacific and Arctic Oceans. Pacific water flows into the Chukchi Sea through the Bering Strait, then gathers into a polar basin across the slope[11]. Although the Bering Strait inflow is the major freshwater source for the Arctic Ocean, previous studies have shown that its annual variability was not sufficient to significantly influence *FWC* changes[12]. The Pacific water inflow forms the Arctic halocline below the fresher surface water (SW), which is crucial for maintaining the low temperature character of the SW[13]. Most Pacific water is stored in the Canada Basin and forms three distinct water masses with varying temperature and salinity after entering the Arctic Ocean. These three are Alaskan Coastal Water (ACW), summer Bering Sea Water (sBSW) and winter Bering Sea Water (wBSW). These water masses have two types of vertical structure in the Canada Basin: along the exterior of the Transpolar Drift Stream influenced by the Pacific water, the wBSW underlies the sBSW; in the southern Canada Basin, the wBSW underlies the ACW[14]. A typical temperature and salinity profile in the southern Canada Basin is shown in Figure 2. In this figure, the top 50 m layer in the Arctic Ocean is defined as SW, where the temperature is nearly constant and salinity is less than 30; below the SW is the Pacific halocline water, defined by a temperature near the freezing point within the salinity range 30< S <34, where the ACW is above the wBSW. Under the Pacific halocline water lies intermediate Atlantic Water (AW), which has a salinity higher than 34[15]. Freshwater changes take place mainly in the upper Arctic Ocean water masses above the AW, and the depth changes of the AW do not affect the *FWC*. Thus, we take the mean salinity of intermediate AW, 34.8, as the reference salinity, on which the *FWC* is calculated[9]. The water masses above the AW, influenced by the Pacific water, can be divided into two parts by the wBSW. First, the water in the lower layer below the wBSW originates from the Bering Sea and the Chukchi Sea shelves, which has a constant temperature and salinity in winter[16]. In contrast, the waters in the layer above the wBSW containing summer Pacific water and sea ice melt water is the most variable region within the Arctic Ocean. Therefore, we define the upper ocean as the layer above the wBSW by a temperature minimum with salinity less than 33.1, upon which we paid considerable emphasis in our paper.

In the late 1980s, the upper part of the Arctic Ocean began to become fresher in response to decreasing sea ice volume[17−18]. Meanwhile, export of multiyear ice from the ocean began to accelerate[19−20]. Since the mid-1990s, sea ice extent has drastically decreased and continued to reach new record lows[21−23]. Satellite data indicates that sea ice extent in the summer Arctic Ocean has declined by 11.5% per decade since 1979 and, in

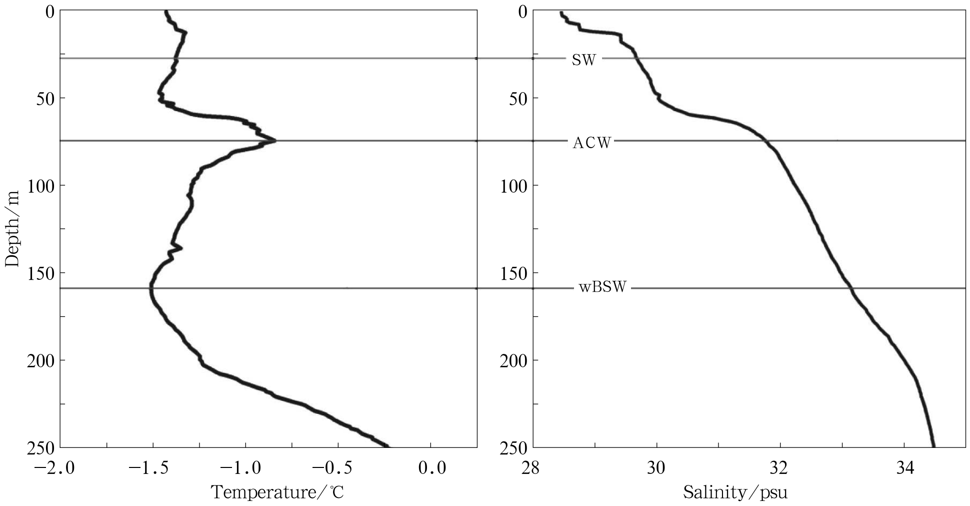

Figure 2 Temperature and salinity profiles in southern Canada Basin (based on Station LSS042 of the Canadian LSSL cruise of 2005, marked with yellow symbol in Figure 3).

August, 2007, it broke all the previous records. In 2008 and 2010, the September minimum extents were the second and the third lowest in the satellite record[24]. Combined with decreases in extent, the age of sea ice in the central Arctic basin has also dramatically changed since the mid-1980s. In 1987, 57% of the ice pack was at least 5 years old, and a quarter of that ice was at least 9 years old. By 2007, however, only 7 percent of the ice pack was at least 5 years old, and virtually none was at least 9 years old[25]. Sea ice melt in the Arctic Ocean occurred mainly in the Canada Basin, lowering salinity and increasing freshwater in the upper ocean.

Changes of the *FWC* in the Arctic Ocean have been left untouched till the discussion provided by Proshutinsky et al.[26]. They suggested that changes of *FWC* storage in the anticyclonic Beaufort Gyre (BG) could potentially be much larger than those due to variations of river runoff and ice export events, and were tied to the decadal mode of ocean circulation variations, the Arctic Oscillation (AO)[26]. The BG is a wind-driven gyre bounded by latitudes 70.5°N and 80.5°N, and longitudes 170°W and 130°W[27]; it is a basic surface circulation pattern and is well within our study area (Figure 1). During the negative phase of the AO, an anticyclonic atmosphere circulation with high pressure induces substantial mass transport in the ocean toward the center of the anticyclonic gyre. Such continuous volume transport generates a downward velocity (Ekman pumping). In this case, the Canada Basin accumulates freshwater. In contrast, when the positive phase of the AO is dominant, the Canada Basin releases freshwater under cyclonic wind forcing. Water released from the basin flows into the Atlantic Ocean through the Fram Strait, reducing freshwater in the upper ocean of the basin[26]. Proshutinsky et al.[26] investigated the *FWC* storage in the BG and found a fact that interannual changes in the *FWC* during 2003–2007 were characterized by a strong positive trend in this region, with a maximum of approximately 1.5 $\mathrm{m \cdot a^{-1}}$ in the central basin. One of the major causes for this was the anticyclonic atmosphere circulation, which aggravated the mixing due to the Ekman pumping. In response, the *FWC* in the Canada Basin increased significantly[28]. Considering that wind forcing is limited and its influence on sea water would be weakened by ice cover, water mixing should be confined to the upper ocean. We thus emphasized our analysis mainly on the *FWC* of the upper ocean, i.e., the layer with salinity lower than 33.1, to investigate its variability in the Arctic Ocean.

In the new century, more accessible observational data in the Canada Basin facilitates study of *FWC* changes in the upper ocean. We analyzed CTD data from the Chinese and Canadian expeditions, to investigate the *FWC* variability and its influences for 2003–2008 in the Canada Basin.

1 Data sources and methods

1.1 Data sources

We calculated the *FWC* in the water column of the upper ocean in the Canada Basin by comparing salinity vs. depth with reference salinity. The hydrographic data that we analyzed came from CTD data obtained during the 2nd and 3rd Chinese National Arctic Research Expeditions in 2003 and 2008 (the 2nd CHINARE–Artic, the 3rd CHINARE–Artic), and expeditions of the Canada icebreaker Louis S. St-Laurent (LSSL) in the Canada Basin, from 2004 to 2007. Hydrographic stations used in this study are shown in Figure 3. Data from the Chinese expeditions were collected mainly in the western basin, whereas stations of LSSL's cruises covered most of the basin. Although the number of stations was limited and distribution of those exhibited large gaps owing to observational conditions in the Arctic Ocean, those profile data were adequate to analyze upper ocean *FWC* variability in the basin.

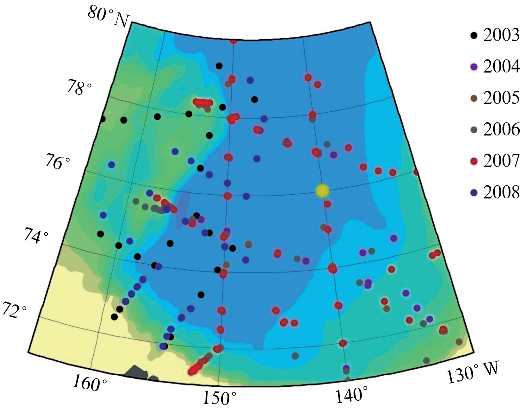

Figure 3 Hydrographic stations of Chinese National Arctic Research Expeditions in 2003 and 2008 and Canadian LSSL cruises in the Canada Basin for 2003–2007.

We also analyzed monthly mean sea ice concentration obtained from the National Snow and Ice Data Center (NSIDC). This product was created with resolution 25×25 km^2 using satellite passive microwave data from the Special Sensor Microwave/Imager (SSM/I). Monthly mean AO index data since January 1950 used in our analysis were from NOAA/CPC, constructed by projecting daily 1 000 mb height anomalies poleward of 20°N onto the loading pattern of the AO, which is defined as the leading mode of Empirical Orthogonal Function (EOF) analysis of monthly mean 1 000 mb height during 1979–2000.

1.2 Freshwater content calculation

The *FWC* (m) within a horizontal unit area in the ocean is calculated as

$$FWC = \int_{z_1}^{z_2} \frac{S_{\text{ref}} - S(z)}{S_{\text{ref}}} dz \qquad (1)$$

where S is water salinity at depth z and S_{ref} is the reference salinity[29]. Here we took the mean salinity of the AW as S_{ref}, namely S_{ref}=34.8. z_1 and z_2 are the upper and lower boundaries of the layer, respectively, within which the *FWC* is calculated. Thus, the *FWC* is a measure of how much freshwater volume is in the ocean column bounded by z_1 and z_2. While the upper ocean *FWC* was calculated, z_1=0 and z_2 was the depth of the upper ocean's bottom boundary, i.e., the depth of the 33.1 isohaline. When we calculated the *FWC* below the wBSW, we took the depth of the 33.1 isohaline as z_1 and the depth of reference salinity (34.8) isohaline as z_2.

Based on observational data from the Chinese expeditions and the Canadian LSSL cruises, we calculated the *FWC* of the two layers bounded by the wBSW. Figures 4 and 5 show its distribution and variability in the Canada Basin during 2003–2008. To aid understanding of *FWC* changes in the upper ocean, the depth of the 33.1 isohaline is shown in Figure 6.

2 Results and discussion

2.1 Freshwater content variability

Although an accurate total freshwater volume in the Canada Basin was unavailable for lack of observational stations, the profiles we obtained are satisfactory for showing the tendency of the *FWC* variability in the basin.

Calculations on the observational data show that for the period 2003–2008, the *FWC* below the wBSW remained roughly constant, 3 m in the southern basin and 2.5 m in the north (Figures 4a–4e). There was an exception in 2008, however, when the *FWC* below the wBSW exhibited a mild increase (Figure 4f). Our conclusion is that the *FWC* changes were generally limited to the upper ocean, because liquid freshwater obtained from the sea ice melt and BG accumulation do not usually influence water masses to depth below the wBSW. We believe that the mild *FWC* increase below the wBSW in the southern basin in 2008 was related to a combination of rapid decline of sea ice extent (Figure 7f) and a strong dominance of the AO negative phase. We will discuss this in detail in section 2.2.2.

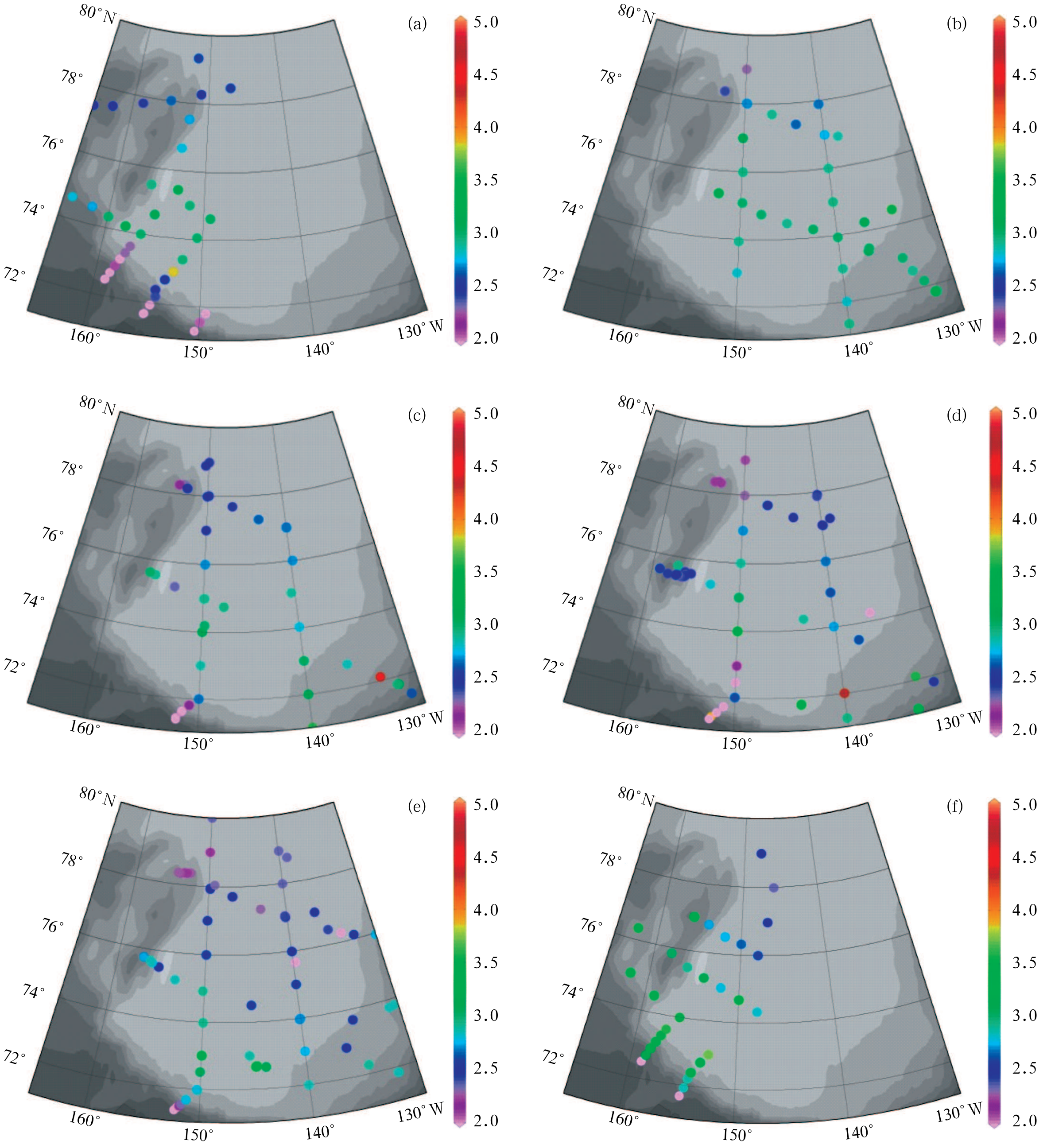

Figure 4 Freshwater content for 2003–2008 in the layer below wBSW in the Canada Basin (m). a. 2003; b. 2004; c. 2005; d. 2006; e. 2007; f. 2008.

McPhee et al.[10] confirmed that the FWC in the southeast Canada Basin in 2008 had increased by as much as 11 m, 60% greater than the climatological mean from 1950 to 2000. Our calculations suggested that the FWC variability took place primarily in the upper ocean. Figure 5 shows the magnitude of freshwater at each station in the basin. During 2003–2008, the FWC in the basin exhibited an apparent increasing trend, 1 m·a^{-1}, except for the year 2006. In the central basin, the FWC increased rapidly from less than 17 m in 2003 to 22 m in 2008, showing that the upper ocean had become much fresher. In the early part of this period, the FWC increase was relatively mild (Figures 5a, 5b). However, the FWC in 2005 increased by approximately 2 m in most areas, except for the southeast basin, where the decline of sea ice extent temporarily halted (Figure 5c). There was an overall decrease in FWC in 2006 (Figure 5d), but thereafter, rapid growth in FWC broke out and in 2008,

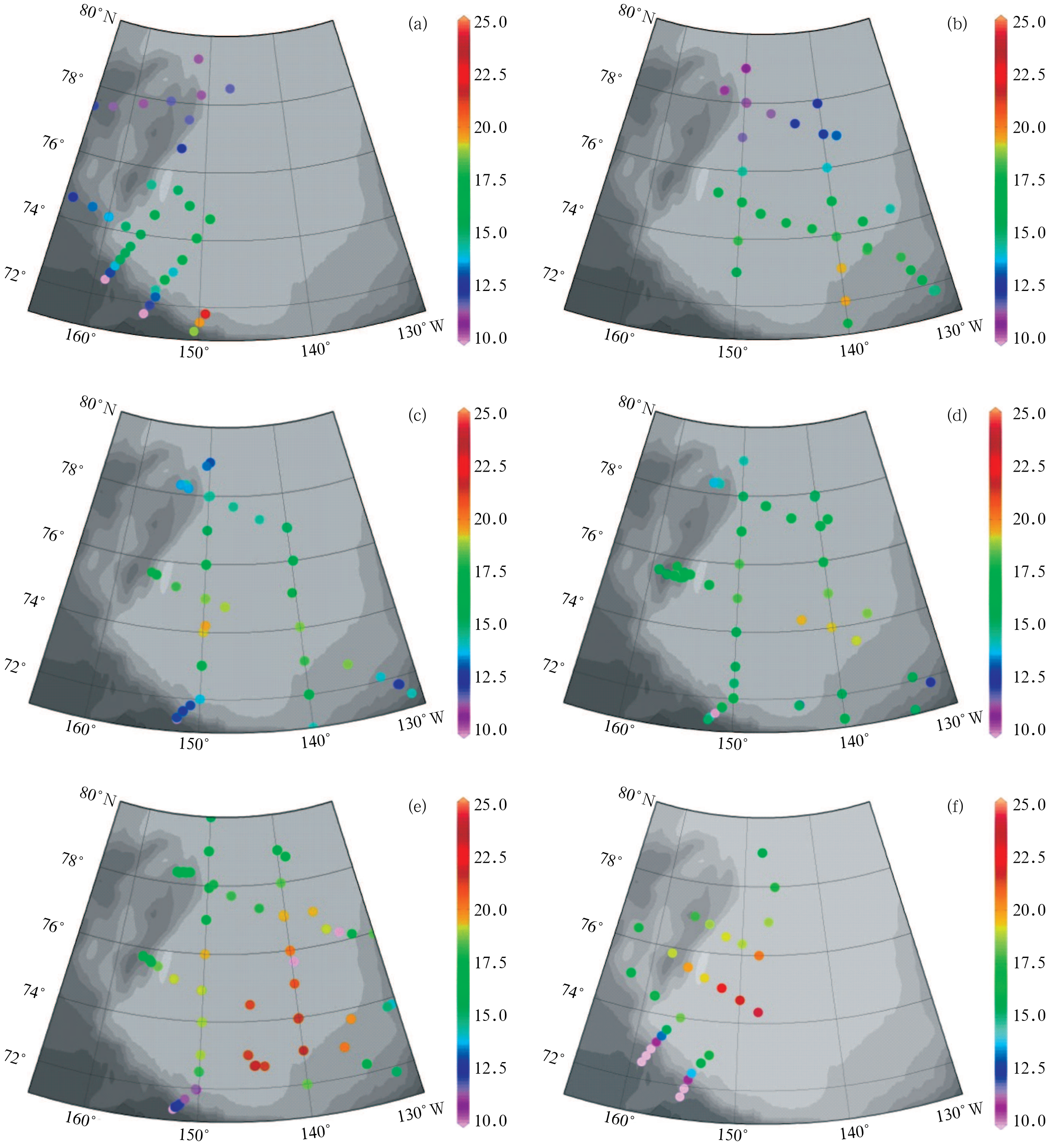

Figure 5 Freshwater content for 2003–2008 in the upper layer of the Canada Basin (m). a. 2003; b. 2004; c. 2005; d. 2006; e. 2007; f. 2008.

the absolute maximum *FWC* increase, 3 m, was reached in the south central region (Figure 5f). Another conclusion from Figure 5 is that freshwater stored in the southern Canada Basin, especially in the southeast, was much greater than that in the northern area. The Bering Strait inflow was the key contributor to the imbalanced distribution because oceanic heat flux through the strait would melt large amounts of sea ice in the southern basin[12]. Sea ice melt produced a great deal of freshwater, making the *FWC* in the south much higher than that in the north.

Salinity in the upper ocean clearly changed in response to the *FWC* variability. Thus we showed the spatial distribution of the bottom depth of the upper ocean in the Canada Basin (the depth of 33.1 isohaline) in Figure 6, to reveal indirectly the changes in *FWC* of the upper ocean. This figure demonstrates that, coincident with the increasing tendency of *FWC*, base depth of the upper ocean also showed large changes with significant positive trends during 2003–2008. In 2003, the base depth of the upper ocean was generally less than 160 m. Thereafter, thickness of the upper ocean increased by approximately 10 m·a^{-1} in the south except for the year 2006, and it reached 200 m in the central basin in 2008. The reason for this rapid increase was that the freshening upper ocean in the Canada Basin transported substantial freshwater downward through Ekman pumping[10], which lowered sea water salinity below the surface water. As stated previously, the exceptional case of 2006 was related to the pause in the decrease of sea ice extent (Figure 7d), which caused salinity of the upper ocean to increase slightly.

2.2 Causes of the FWC variability in 2003–2008

What were the key factors contributing to the strong positive trend in the FWC observed in 2003–2008? Considering freshwater sources, there are such contributors having an impact on FWC as net precipitation, runoff

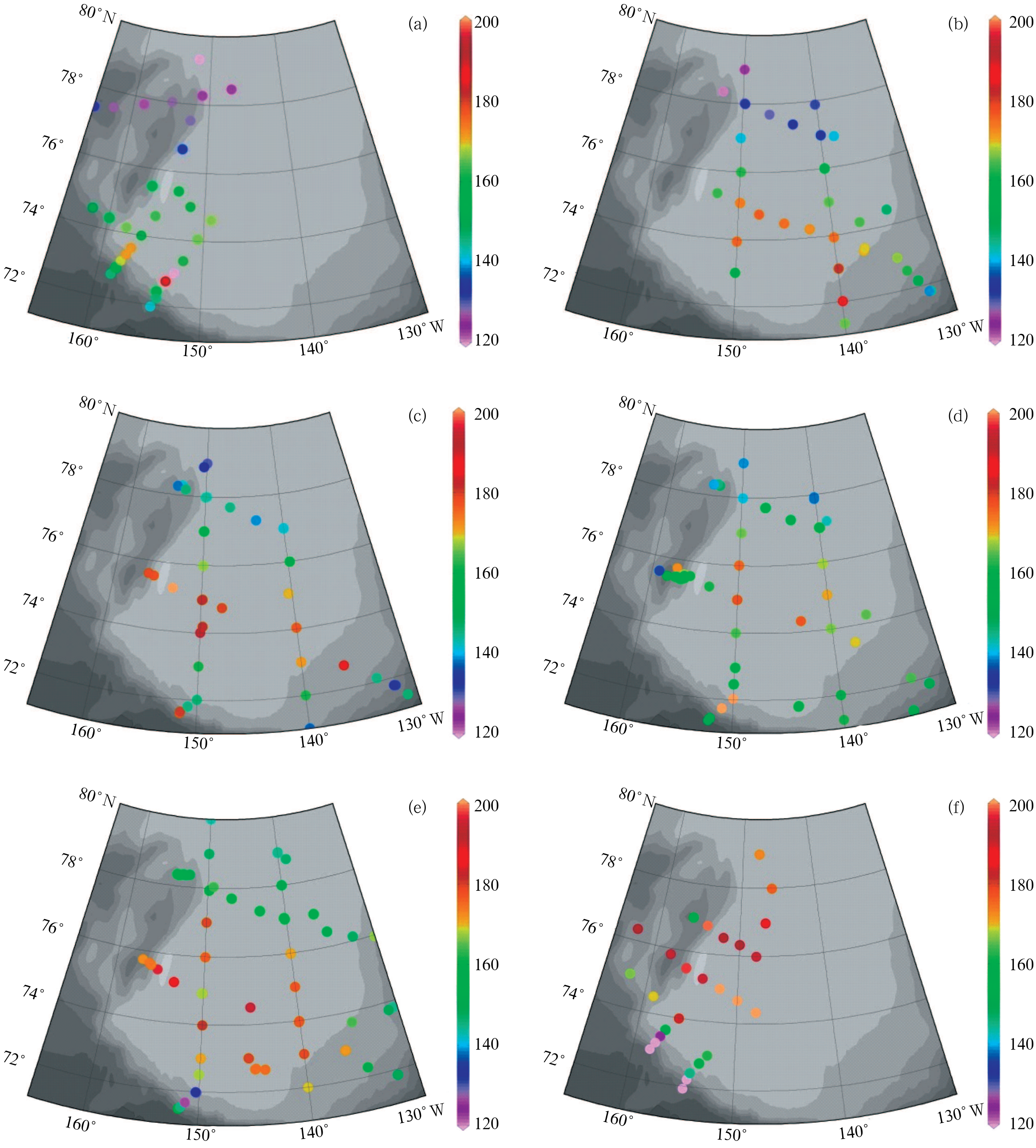

Figure 6 The depth of the interface of S=33.1 in the Canada Basin for 2003–2008. a. 2003; b. 2004; c. 2005; d. 2006; e. 2007; f. 2008.

changes, Bering Strait inflow and sea ice melting/freezing. When freshwater transport and distribution are taken into account, oceanic circulation also has an influence on the FWC variability. Due to lack of current observational data, we explored the impact of the AO index, which is closely related to oceanic circulation.

The Bering Strait inflow is the major source of freshwater in the Arctic Ocean. The annual mean transport through the strait is 0.8 Sv, equivalent to 25 000 km^3 of the Pacific water flowing into the Arctic[12]. As long-term mean salinity of the inflow is generally near 32.5[3], the freshwater volume contained in the imported Pacific water is around 1 600 km^3. No statistically significant change has been found in the annual mean volume transport, in spite of its great magnitude. During 2003–2008, the difference between the maximum and minimum of the inflow transport was less than 0.2 Sv[12], therefore the maximum magnitude of annual change in imported freshwater was approximately 400 km^3, which was too small to account for FWC variability in the Canada Basin. According to NCEP/NCAR reanalysis data, long-term variation of the net precipitation over the Arctic Ocean was around 10%, ranging from –200 km^3 to +200 km^3. These values are so small compared with the magnitude of the FWC changes, measured in thousands of cubic kilometers[9], that the net precipitation should be neglected in our FWC anomaly analysis. In addition, we also neglected the influence of river runoff changes on the FWC variability. This decision is supported by the figures of Aagaard and Carmack[3], who demonstrated that the total runoff from the major rivers entering the Arctic Ocean was about 3 800 $\text{km}^3\cdot\text{a}^{-1}$, with an annual change varying from –200 km^3 to +200 km^3. Furthermore, the Mackenzie is the largest river emptying into the Canada Basin, and its annual mean runoff is only about 340 km^3, with an interannual variability 5%–20%[3].

Thus we can determine that the impacts of Bering Strait inflow, net precipitation and runoff are too small to cause the observed FWC variability. The only remaining candidate responsible for the rapid increase in FWC seems to be sea ice melt. Indeed, the sea ice volume anomalies range from –2 500 km^3 to +2 500 km^3, which would surely have a significant impact on changes in upper ocean freshwater storage[5]. However, as McPhee et al.[10] suggested, an 11 m change of the Arctic Ocean FWC would require nearly 17 m of net sea ice melt. We therefore conclude that sea ice melt alone could not bring about such a large FWC increase (almost 5 m during 2003–2008). There must be other factors carrying important effects on the FWC variability. Proshutinsky et al.[28] showed that the FWC variability in the BG region was closely linked to the atmospheric pressure. During a dominant negative AO index, high pressure in the atmosphere above the sea surface would induce increase in FWC, and vice versa[28]. Therefore, the atmospheric conditions and the corresponding oceanic circulation variability were also important contributors to FWC changes in the upper ocean of the Canada Basin during 2003–2008.

2.2.1 Sea ice retreat

We explored the influence of changes in sea ice extent on the upper ocean FWC in the Canada Basin. With accelerated global warming, sea ice in the Arctic Ocean has retreated dramatically since the 1990s, frequently breaking records of minimum extents. The changes in sea ice volume ranges from –2 500 km^3 to +2 500 km^3, which closely parallel the FWC changes in the Arctic Ocean[9].

The increasing Bering Strait oceanic heat flux is one of the main causes of the ice retreat in the Arctic Ocean. Consequently, the ice retreat occurs predominantly in the region influenced by this inflow. Heat flux increased from 2001 to a maximum in 2007, 5×10^{20}–6×10^{20} $\text{J}\cdot\text{a}^{-1}$, which was twice the 2001 heat flux and enough to melt a third of the total seasonal Arctic sea ice melt of 2007[12]. In response to increasing heat transport, sea ice extent diminished significantly in 2003–2008. This accelerated sea ice retreat enhanced consequently the upper ocean FWC in the Canada Basin. This process was especially pronounced in 2007 and 2008, when sea ice extent reached a record low for summer (Figures 7e, 7f), causing the upper ocean FWC to be substantially higher than that in previous years. The anomalous increase in the sea ice extent (Figure 7d) is a plausible explanation for the overall FWC decrease of 2006. However, Figures 7a and 7c demonstrate that the upper ocean freshwater anomalies and sea ice volume anomalies were not in phase in 2003 and 2005. We attribute this lack of uniformity to the fact that the AO projected differently on the upper ocean in these two years, as explained in the next section.

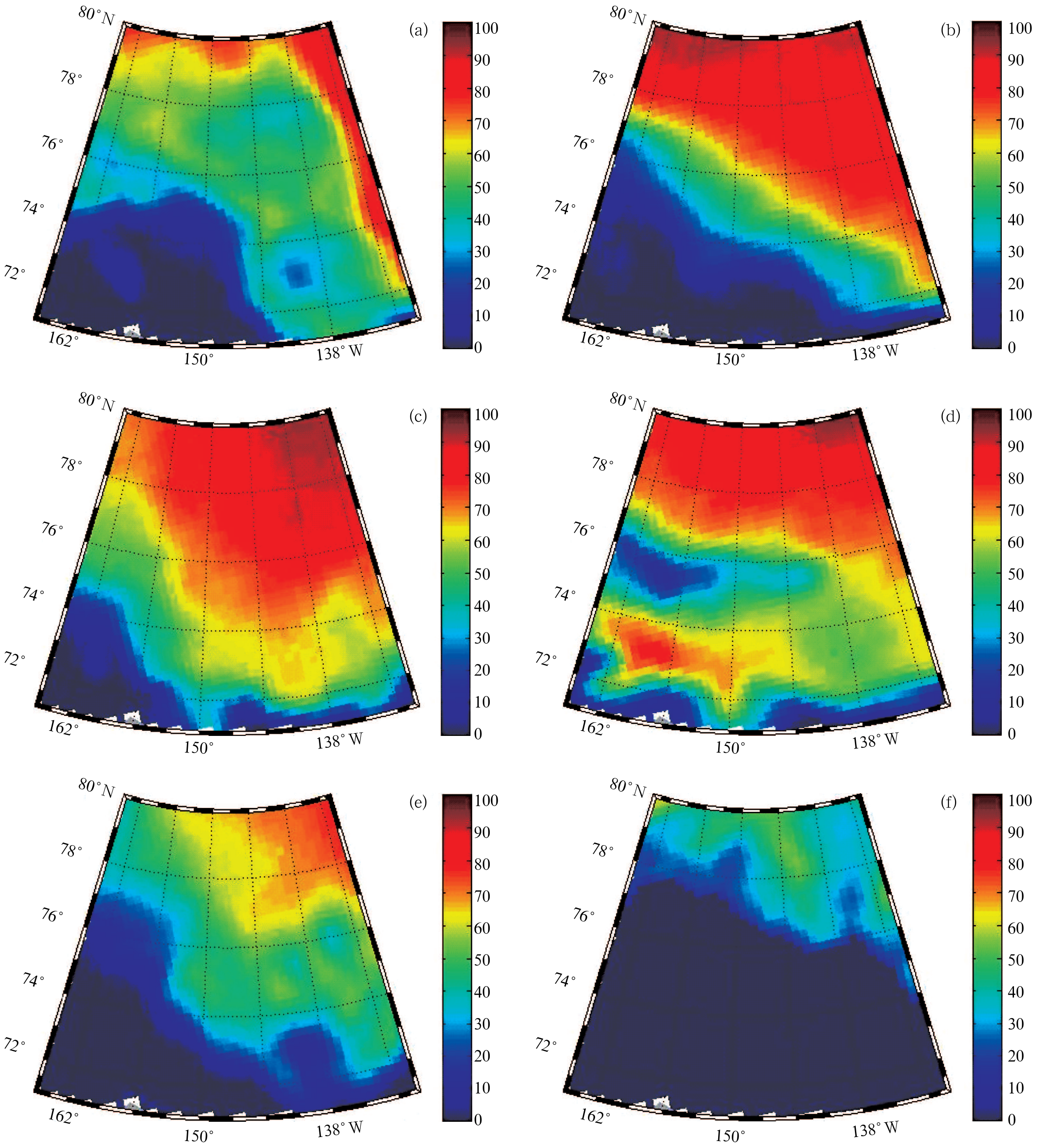

Figure 7 Sea ice concentration for 2003–2008. a. 2003; b. 2004; c. 2005; d. 2006; e. 2007; f. 2008.

2.2.2 Arctic oscillation changes

Proshutinsky et al.[4] proposed a mechanism for the accumulation and release of freshwater in the Arctic Ocean that is centered on the BG, and is related to the temporal variability of its freshwater content. The amount of freshwater calculated relative to the salinity 34.8 in the Canada Basin was about 45 000 km^3, which was 10–15 times larger than the total annual river runoff to the Arctic Ocean, and at least twice larger than the amount of fresh water stored in the sea ice[3]. With Proshutinsky's mechanism, the FWC annual changes are closely associated with freshwater transport caused by atmospheric conditions.

The AO has alternated between positive and negative phases, with no particular periodicity. Starting in the 1970s, the oscillation tended to remain in the positive phase, causing lower than normal Arctic air pressure.

Polyakov et al.[9] found that over the twentieth century the central Arctic Ocean became increasingly saltier with a freshwater loss rate of 239±270 km^3 per decade. In the new century, however, the negative phase of the AO started to dominate (Figure 8) and inducing Arctic atmospheric conditions opposite to those of the positive phase. According to the hypothesis of Proshutinsky et al, the Canada Basin releases freshwater during the positive phase and hence the upper ocean FWC in 2003 was less than normal, despite the relatively heavy sea ice melt. Alternatively, in 2005, a dominant negative phase of the AO caused persistent freshwater accumulation in the basin, which even offset the impact of reduced sea ice melt. However, the AO index returned to a positive phase in 2006 and, coupled with less sea ice melt, this produced a slight FWC decline in most of the area. In 2007, the sea ice cover reached a record low, and the impact of sea ice melt was too great to be offset by the positive phase of the AO. As a result, the FWC exhibited a significant increase in the basin. A strong negative phase of the AO in 2008 generated substantial mass transport of fresher surface water toward the center of the anticyclonic gyre, resulting in downward freshwater motion via Ekman pumping. In the same year, the sea ice extent was the second lowest ever. The combination of these two factors brought about the maximum FWC in the Canada Basin. In addition, due to the strong Ekman pumping induced by anticyclonic circulation during the negative phase of the AO, freshwater accumulated in the upper ocean affected the stable water below the wBSW through strong mixing, causing an abnormal increase in FWC in these layers.

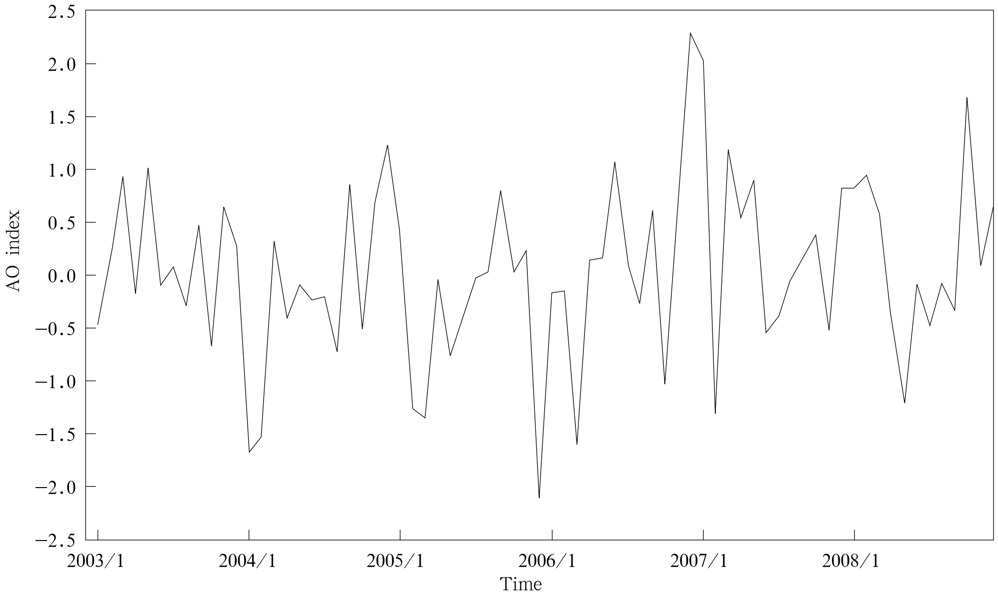

Figure 8 AO index time series for 2003–2008.

3 Summary

We analyzed inter-annual variability of the FWC of the upper ocean in the Canada Basin, based on data from the 2nd and 3rd CHINARE-Arctic of 2003 and 2008 and the Canadian LSSL cruises from 2004 to 2007. We also examined major contributors to the FWC variability in the upper ocean, such as sea ice concentration and AO changes. We also touched briefly on the impact of Bering Strait inflow, net precipitation and river runoff on the FWC variability. In summary, we conclude the following. In 2003–2008, the FWC of the upper ocean in the Canada Basin increased significantly except in 2006, reflecting a tendency toward rapid freshening. The FWC increased by more than 1 m·a^{-1} in the southern basin. In the exceptional year of 2006, FWC in the basin exhibited an overall decrease, but there was a slight increase in the southeast.

Given their small magnitudes and annual variations, Bering Strait inflow, net precipitation and river runoff have little apparent impact on the FWC variability.

Our analysis shows that rapid sea ice melt, caused by global warming, was one of the major contributors to the FWC increase over the study period. In 2007 and 2008, the sea ice extent reached record lows. In response, the upper ocean FWC in these two years was higher than that in previous years.

AO variability was another major control on the upper ocean FWC in the Canada Basin. During the positive phase of the AO, the Canada Basin released freshwater under cyclonic wind forcing, and vice versa. A weakening of the dominant positive phase of the AO, beginning with the 21st century, induced the freshwater increase in the basin. In 2003, the freshwater release caused by positive phase of the AO offset the impact of a relatively large sea ice melt. In contrast, a freshwater increase triggered by a rapid sea ice retreat in 2007 was too strong to be offset by the effect of the dominant positive phase of the AO.

Acknowledgments The authors wish to thank the 2nd and 3rd CHINARE-Arctic and the Canadian LSSL JOIS cruises from 2004 to 2007 for providing CTD data for our analysis. We are also grateful to the National Snow and Ice Data Center (NSIDC) for sea ice concentration data, and to NOAA/CPC for AO index data. This work was supported by the National Natural Science Foundation of China (Grant nos. 40631006, 40976111) and the China's Program for New Century Excellent Talents in University (Grant no. NCET-10-0720).

References

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

2 Mauritzen C, Häkkinen S. Influence of the sea ice on the thermohaline circulation in the North Atlantic Ocean. Geophys Res Lett, 1997, 24: 3257–3260

3 Aagaard K, Carmack E C. The role of sea ice and other fresh water in the Arctic circulation. Geophys Res, 1989, 94(14): 485–498

4 Proshutinsky A, Bourke R H, McLaughlin F A. The role of the Beaufort Gyre in Arctic climate variability: Seasonal to decadal climate scales. Geophys Res Lett, 2002, 29, 2100, doi:10.1029/2002GL015847

5 Häkkinen S, Proshutinsky A. Freshwater content variability in the Arctic Ocean. Geophys Res, 2004, 109, C03051, doi: 10.1029/2003JC001940

6 Swift J H, Aagaard K, Timokhov L, et al. Long term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set. Geophys Res, 2005, 110, C03012, doi:10.1029/2004JC002312

7 Peterson B, McClelland J, Holmes M, et al. Acceleration of the Arctic and Subarctic freshwater cycle. Science, 2006, 313, 1061–1066

8 Steele M, Ermold W. Steric sea level change in the Northern Seas. J Climate, 2007, 20:403–417

9 Polyakov I V, Alexeev V A, Belchansky G I, et al. Arctic Ocean Freshwater Changes over the Past 100 Yeas and Their Causes. J Climate, 2007, 21:364–384

10 McPhee M G, Proshutinsky A, Morison J H, et al. Rapid change in freshwater content of the Arctic Ocean. Geophys Res Lett, 2009, 36, L10602, doi:10.1029/ 2009GL 037525

11 Swift J H, Jones E P, Aagaard K, et a1. Waters of the Makarov and Canada basins. DeepSea Res, Part II,1997, 44, 1503–1529

12 Woodgate R A, Weingartner T, Lindsay R. The 2007 Bering Strait oceanic heat flux and anomalous Arctic sea-ice retreat, Geophys Res Lett, 2010, 37, L01602, doi:10.1029/2009GL 041621

13 Guay C K, Falkner K K. Barium as a tracer of Arctic halocline and river watersDeepSea Res, Part II, 1997, 44,1543–1569

14 Shi J X, Zhao J P, Jiao Y T, et al. Pacific inflow and its links with abnormal variations in the Arctic Ocean (In Chinese with English abstract). Chin J Polar Res, 2004, 16(3): 253–260

15 Shi J X, Zhao J P. Advances in Studies on the Arctic Halocline (In Chinese with English abstract). Adv Earth Sci, 2003,18(3): 351–357

16 Shi J X, Cao Y, Zhao J P, et al. Distribution of Pacific-origin water in the region of the Chukchi Plateau in the Arctic Ocean in the summer of 2003. Acta Oceanol Sin, 2005, 24(6): 12–14

17 Smith D M. Recent increase in the length of the melt season of perennial arctic sea ice. Geophys Res Lett,1998,25: 655–658

18 Belchansky G I, Douglas D C, Platonov N G. Duration of the Arctic sea ice melt season: Regional and interannual variability, 1979–2001. J Climate, 2004, 17: 67–80

19 Rigor I G, Wallace J M. Variation in the age of Arctic sea-ice and summer sea-ice extent. Geophys Res Lett, 2004, 31, L09401, doi:10.1029/2004GL019492

20 Belchansky G I, Douglas D C, Platonov N G. Spatial and temporal variations in the age structure of Arctic sea ice. Geophys Res Lett, 2005, 32, L18504, doi:10.1029/2005 GL023976

21 Belchansky G I, Douglas D C, Platonov N G. Fluctuating Arctic Sea Ice Thickness Changes Estimated by an In Situ Learned and Empirically Forced Neural Network Model. J Climate, 2008, 21: 716–729

22 Serreze M C, Maslanik J A, Scambos T A, et al. A record minimum arctic sea ice extent and area in 2002. Geophys Res Lett, 2003, 30, 1110, doi:10.1029/2002GL016406

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

24 NSDIC. Weather and feedbacks lead to third-lowest extent. 2010. http://nsidc.org/arcticseaicenews/2010/100410.html

25 NSDIC. Global Sea Ice Extent and Concentration:What sensors on satellites are telling us about sea ice. 2010. http://nsidc.org/sotc/sea_ice.html

26 Proshutinsky A Y, Johnson M A. Two circulation regimes of the wind-driven Arctic Ocean. J Geophys Res, 1997, 102 (C6): 12493–12514

27 Krishfield R, Proshutinsky A. Freshwater Content in the Beaufort Gyre: Data from Observations, Russian Climatology and Models. 2004. http://www.whoi.edu/beaufortgyre/pdfs/FWC_BG_draft.pdf

28 Proshutinsky A, Krishfield R, Timmermans M L, et al. Beaufort Gyre freshwater reservoir: State and variability from observations, J Geophys Res, 2009, 14, C00A10, doi:10.1029/2008JC005104

29 Carmack E, McLaughlin F, Yamamoto-Kawai M, et al. Freshwater storage in the Northern Ocean and the special role of the Beaufort Gyre, in Arctic Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate, edited by R. R. Dickson et al., New York: Springer, 2008: 145–169