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Progress in Chinese research on water masses and circulation in the Arctic and subarctic ocean

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Abstract The Arctic Ocean and Arctic sea ice have undergone a series of rapid changes. Oceanographic surveying has become one of the key missions of the Chinese National Arctic Research Expeditions since 1999. Using the data obtained in these surveys and from other sources, Chinese researchers have carried out a series of studies in the field of Arctic physical oceanography. The Near Sea-surface Temperature Maximum, freshwater content and heat flux in different regions of the Arctic have drawn wide attention from Chinese researchers. Arctic circulation is changing with the decline of sea ice, which is also influencing the structure and distribution of water masses. Studies have also focused on these issues. In this paper, the main results of research on water masses, currents, the structure of the upper ocean and other major hydrological phenomena over the past two decades are summarized.

Keywords **Arctic Ocean, physical oceanography, upper ocean, water mass, current**

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1 Introduction

Over the past decades, the Arctic climate has been subject to dramatic change. Warming, decline of sea ice and climate upheaval in the Arctic have had major impacts on climate both within China and globally (Liu et al., 2012; Wu et al., 2016; Zou et al., 2017). Open water is the decisive factor in the absorption, transport and storage of solar radiation; therefore, oceanic forcing is an important process in Arctic warming (Polyakov et al., 2010; Tomas et al., 2016). Variations in the freshwater content, Pacific inflow and heat flux influence the structure and heat balance of the upper ocean in the Arctic. Changes in the oceanic circulation in the Arctic are taking place with rapid changes in the sea ice. The decline of sea ice makes the sea-ice structure of the Arctic Ocean increasingly fragile (Maslanik et al., 2007; Lindsay et al., 2009); meanwhile, the sea-ice drift speed is accelerating (Pfirman et al., 2004; Hakkinen et al., 2008; Rampal et al., 2009). Understanding the relationship between the changes in the upper-ocean currents and the changes in sea ice is important to understand the change in the Arctic. All these issues have aroused great interest in Chinese researchers.

Since the first Chinese National Arctic Research Expedition (CHINARE-Arctic) in 1999, China has carried out seven national Arctic surveys. The first CHINARE-Arctic was designed to study the impacts of the exchange between the Arctic Ocean and the North Pacific on the circulation of the North Pacific (Chen, 2000), after which the second CHINARE-Arctic in 2003 aimed to elucidate the influence of the water-exchange process between the Bering Sea and the Arctic Ocean (Zhang, 2004). The third CHINARE-Arctic was an important scientific expedition during the International Polar Year (IPY) 2007–2008. The aim of this expedition was to study upper-ocean processes and their climatic and ecological effects, the Arctic circumpolar boundary current in the Canada Basin, the

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Arctic Ocean optical structure and the ocean heating mechanism (Zhang, 2009). Since 2008, China has organized an Arctic scientific expedition every 2 years. Observations of the ocean dynamic process were more extensive, and included currents and turbulence. Notably, the research vessel *Xuelong* first passed through the Arctic Northeast Passage and into the Atlantic sector in the fifth CHINARE-Arctic, and successfully deployed a large sea–air coupling buoy in the Nordic Seas.

Chinese researchers are trying to solve the scientific issues of the Arctic through research and international cooperation. Physical oceanography surveys have focused on the Bering Sea, the Chukchi Sea and the Canada Basin, and included ship-based observation, mooring observation and buoys. Using the data obtained in these surveys, Chinese researchers have undertaken a series of studies in the field of Arctic physical oceanography. Significant progress has been achieved in studies of water masses, the thermocline, fronts, currents, ice/sea optics and numerical modeling. Studies of the characteristics and the variation of the upper ocean, water masses and currents in the Arctic Ocean are summarized in this paper.

2 Study of the structure and heat balance of the upper ocean

2.1 Near Sea-surface Temperature Maximum

The thermal structure of seawater under the ice cover is an important factor influencing Arctic climate. Most studies of the upper ocean have focused on the shallow temperature maximum (STM). Recently, another temperature maximum has been frequently observed in the Canada Basin, especially after 2003. Zhao et al. (2003) were the first to examine this temperature maximum using the observations from the first CHINARE-Arctic. A temperature maximum near the sea surface in the summer marginal ice zone was observed in 1999. This water was named the Subsurface Warm Water and the temperature maximum peak was observed at a depth of about 20 m. Jackson et al. (2010) renamed this phenomenon as the “Near Sea-surface Temperature Maximum” (NSTM).

A series of studies on NSTM have been carried out since then (Wang and Zhao, 2004; Cao et al., 2010; Chen and Zhao, 2010; Zhao and Cao, 2011; Cao and Zhao, 2011a, 2011b; Cao et al., 2011). The formation mechanism of NSTM is heating by solar radiation and cooling of the sea surface (Zhao et al., 2003; Wang and Zhao, 2004). The result from the Conductivity–Temperature–Depth (CTD) data collected in the Beaufort Sea, Chukchi Sea and Canada Basin from 1993 to 2014 showed that NSTM often appeared in the open water of the shelf and marginal ice zone before 2004; during this period, the temperature maxima were relatively high. The NSTM has occurred more and more extensively since 2004, nearly covering the whole of the Canada Basin (Figure 1) (Zhao and Cao, 2011). This phenomenon can be attributed to massive melting of sea ice in these years. More solar radiation penetrating the sea ice is absorbed by the near-surface water as the sea-ice concentration decreases (Cao et al., 2010). The depth, temperature peaks and temporal variability of the NSTM are related to the halocline, which is determined by the ice-melt water and vertical turbulent diffusivity. The vertical distribution of vertical turbulent diffusivity was calculated using data collected during the second CHINARE-Arctic in summer 2003 (Zhang et al., 2007). The distribution was consistent in some respects, being higher both at the surface and at a depth of 60 m and smaller in the middle layer, especially at the depth of the halocline. Therefore, the NSTM requires not only solar radiation heating and surface cooling, but also stratification. A thermodynamic-column model coupled to a sea-ice model and an upper-ocean model was used to study the NSTM (Chen and Zhao, 2010). The results verified that solar radiation is the dominant energy source in formation of the NSTM, but that long-wave flux, and sensible and latent heat fluxes also play important roles in determining its relative intensity.

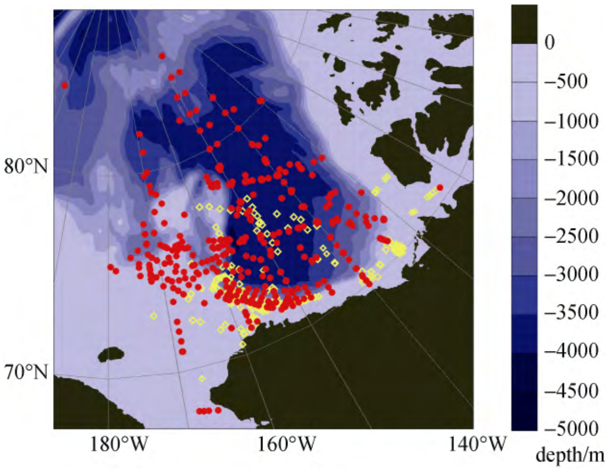

Figure 1 Locations of NSTM from CTD observations obtained from 1993 to 2014 (yellow diamonds mark NSTM before 2002; red dots mark NSTM after 2003).

2.2 Freshwater content in the Canada Basin

The freshwater content (FWC) of the Arctic Ocean has changed rapidly in recent years in response to the significant decrease in the extent of sea ice. It is important to estimate the freshwater content of the Canada Basin, because the region is the main storage area of the Arctic Ocean (Aagaard and Carmack, 1989). The FWC in the Canada Basin was calculated using data obtained from the CHINARE-Arctic of 2003 and 2008 and from expeditions of the Canadian icebreaker *Louis S. St-Laurent* from 2004 to 2007 (Guo et al., 2011). Results show that changes in the FWC were almost entirely limited to the layer above the winter Bering Sea Water at around 3 m, below which the FWC remained constant during the study period. In 2006, there was only a slight increase of FWC in the southeast Canada Basin, while the FWC in the rest of the basin exhibited a decrease. Furthermore, the upper ocean in the Canada Basin became continuously fresher from 2003 to 2008. The average rate of increase of FWC in the Canada Basin is equivalent to more than 1 $m \cdot a^{-1}$ of ice melt, and the greatest increase in FWC, a difference of 7 m between 2008 and 2003, appeared in the central basin. Rapid sea-ice melting and Arctic Oscillation (AO) variability are two major contributors to the FWC increase.

2.3 Heat balance of the upper ocean

In the context of rapid changes in the Arctic sea ice, the seawater heat content has experienced significant changes. Changes in the heat content of the upper ocean (top 200 m) in the Canada Basin were studied using the hydrological data collected in the 2003 and 2008 CHINARE-Arctic (Zhong and Zhao, 2011). That study revealed the overall variation of the upper-ocean heat content. A catastrophic reduction of sea-ice cover in the Canada Basin was evident in 2008 compared to 2003, suggesting that more fresh water was input to the upper ocean, which modified the seawater properties. The study demonstrated that the dramatic reduction in sea ice would result in two changes: widespread warming in the upper ocean and a substantial increase in the depth of Pacific inflow water to the basin. Observations show that the melting of sea ice in 2008 increased the freshwater content of the upper ocean, and therefore the salinity (and thus the density) of the whole water column decreased.

In the marginal ice zone (MIZ), shortwave radiation may heat sea water and melt sea ice. In addition, shortwave radiation returns to the atmosphere in the form of long-wave radiation. Based on the surface data of the interfaces between atmosphere, ocean and sea ice from the first CHINARE-Arctic in 1999, the heat flux and the relative contribution of sensible heat, latent heat and radiant flux in the MIZ were calculated; in addition, information from aeronautical digital images was used to quantify the thermal contribution of the ocean to the atmosphere (Shi et al., 2002). The daily average solar shortwave radiation in summer is at least one order of magnitude higher than the sensible heat and latent heat flux and is the decisive factor giving rise to the increasing seawater temperature and sea-ice melting. In the Arctic, the sensible heat and latent heat flux are smaller in summer because of the small temperature difference between the sea and the air. The thermal contribution of the ocean to the atmosphere is mainly determined by long-wave radiation.

2.4 Multiyear variation of the heat flux in the Nordic Seas

The Nordic Seas (the Greenland Sea, the Iceland Sea and the Norwegian Sea, also known as the GIN Sea) are the main connection between the North Atlantic and the Arctic Ocean. A series of studies on the water masses, convection, sea ice and heat flux have been carried out in the Nordic Seas (Shao and Zhao, 2014; Zhao and Drinkwater, 2014). The Nordic Seas are a key area of the North Atlantic Oscillation/Arctic Oscillation (NAO/AO) (Hurrell, 1995; Thompson and Wallace, 1998) and thus play an important role in the climate system. The NAO is significantly related to changes in the system wind temperature anomaly, latent and sensible heat flux and changes in the sea surface temperature (Cayan, 1992; Kawamura, 1994). The differences between the heat fluxes in various basins of the Nordic Seas were studied to determine the regional variation of the relationship between sea and air in the Nordic Seas (Zhao and Drinkwater, 2014). Heat exchange in the Nordic Seas depends on solar shortwave radiation in summer, and long-wave radiation, sensible heat and latent heat flux from the ocean in winter. The contribution of the Nordic Seas to the AO is mainly caused by the sensible heat and latent heat release from the Greenland Sea. The upwelling airflow through the Icelandic low-pressure zone affects the cloud cover in the Icelandic low region which affects solar radiation and atmospheric circulation.

3 Water-mass characteristics

3.1 Water masses in the Bering Sea

The Bering Sea, Chukchi Sea and Canada Basin are the key areas for the Chinese Arctic scientific expeditions. Since the first CHINARE-Arctic in 1999, Chinese scientists have conducted a series of comprehensive studies of the marine environment and water structures of these seas (Tang et al., 2001; Shi et al., 2002; Gao et al., 2002, 2003a, 2004; Zhao et al., 2006; Wang and Zhao 2011; Zhao et al., 2015; Liu et al., 2016a, 2016b).

Research in China on the Bering Sea began from the first CHINARE-Arctic in 1999. Using the data collected by this expedition, the water masses in the Bering Sea and Chukchi Sea were analyzed. The distribution of temperature and salinity in these two areas has obvious regional differences: the temperature of the Chukchi Sea is generally lower than that of the Bering Sea. There are three water masses in the Bering Sea, which are Bering Sea upper-layer water, Bering Sea intermediate water and Bering Sea deep water; the Chukchi Sea contains two main water masses that are derived from Bering Sea water and polar water (Tang et al., 2001).

On the central Bering Sea shelf, there are four main water masses that occur in the following order from the slope to the coast of Alaska: Bering Slope Current Water; Mixed Water; Bering Shelf Water and Alaska Coastal Water. Using high-resolution CTD data obtained between 1982 and 2008, the properties and inter-annual variation of the summer cold water on the northern shelf of the Bering Sea were studied (Wang and Zhao, 2011). Two different physical parameters, the lowest temperature at the edge and the lowest temperature in the core, were defined to investigate the inter-annual variation of this cold water. In the years 1989, 1994, 2002, 2003, 2004 and 2005, the lowest temperature on the edge was warmer than the long-term average: these years are called warm years. Using the CTD data obtained by the second to sixth CHINARE-Arctic, the classification and inter-annual variation of water masses on the central and northern Bering Sea shelf were analyzed (Liu et al., 2016a, 2016b). The results indicate that both regions exhibit some similarities and differences in their hydrological features. The two regions have the same water source and similar water-mass classification, but spatial-temporal features in temperature and salinity are different in each region. The response to climate change is synchronized in both regions.

3.2 Water masses on the Mendeleev Ridge

Few observations of optical properties have been obtained in the Arctic Ocean (Pegau, 2002). To investigate the attenuation of incident solar radiation, optical properties were studied using irradiance profiles measured during the Korean summer Arctic Ocean cruise of 2012 (Zhao et al., 2015). The attenuation properties were categorized into three types, from which the cyclonically re-circulated branch of shelf water passing over the Chukchi Abyssal Plain could be identified. Both the optical attenuation properties and the physical features of the water indicated the existence of two subsurface water masses: one is cold shelf water that is well mixed with river water and transported to the east by a subsurface current along the East Siberian Slope; the other is warmer water from the Pacific with lower nutrient content that is transported to the northwest along the northern margin of the study region.

3.3 Water masses in the Nordic Seas

Based on observations obtained during the fifth CHINARE-Arctic in 2012, the Hydrobase 2.0 dataset and the WOD13 database, the properties and distribution of water masses in the Nordic Seas were identified and the evolution of cooling convection was studied (Wang et al., 2015a, 2015b). Arctic Intermediate Water, Basin Deep Water, Arctic Deep Water and Basin Bottom Water (from shallowest to deepest) are present in all the three deep basins. In the central Greenland Basin (GB), the potential temperature of deep water was nearly 0.3°C warmer than the value of −1.3°C observed in the 1970s, implying an increase in heat content in the deep layer. The most obvious and earliest warming occurred in the GB which shows a consistent accelerating trend between depths of 2000 and 3500 m (Wang et al., 2015b). This process may take at least two months, thus leaving less time for the subsequent deep-reaching convection. The Nordic Seas are now becoming a heat reservoir for the northern hemisphere and the impacts of such change on the Arctic climate are worthy of further study. As weakening of the deep-reaching convection continues, the abyssal Nordic Seas are playing the role of a heat reservoir in the subarctic region, which may trigger a positive feedback of deep-sea warming in both the Arctic Ocean and the Nordic Seas (Wang et al., 2015b).

3.4 Variability of Arctic Intermediate Water

The water-mass characteristics of Arctic Intermediate Water (AIW) are linked to the Arctic Circumpolar Boundary Current (Rudels et al., 1999), which reflects the evolution of the Arctic system over many years and reflects the conversion of the aquifer in the Arctic. Warming of Arctic Intermediate Water has been an important phenomenon in the Arctic since the 1990s (Dickson et al., 2000). The extended range and the eastern edge of Arctic intermediate water were studied using the sections data obtained during CHINARE-Arctic (Zhong and Zhao, 2014).

The core layer of AIW in the Arctic Ocean (at depths of about 150–900 m) originates in the North Atlantic. This water can be called Atlantic Water. Variation in AIW affects both the properties of water in the Arctic Ocean and global ocean meridional overturning. Chinese scientists have focused on studying the anomalous warming of AIW and have made significant progress (Zhao et al., 2005; Li et al., 2012; Zhong and Zhao, 2014): the propagation process of the AIW warming signal in the Canada Basin was elucidated (Li et al., 2012). Before 1993, the warming signal of AIW first intruded into the Chukchi Abyssal Plain of the Canada Basin. Subsequently, the warming signal continued to spread southward and eastward to the central Canada Abyssal Plain. By 2006, almost all of the Canada Basin was covered by warming water and the 0.5°C isotherm had retreated to the eastern Beaufort Sea, which means that the thermal conditions have changed greatly in the Canada Basin. The depth of the AIW core changed from 400–410 m before 2007 to about 470 m after 2007 (Figure 2). The deepened AIW core is a result of the Beaufort Gyre (BG) spin-up when the temperature of AIW was relatively stable.

3.5 The double-diffusive staircase

The double-diffusive staircase structure in the water column was investigated using CTD profile data obtained from the third CHINARE-Arctic. Double-diffusive mixing is a widespread phenomenon in the Canada Basin (Zhao and Zhao, 2011). The double diffusive-staircase has been observed in the central Canada Basin and Mendeleyev Ridge. The distribution of the double-diffusive staircase exhibits significant spatial differences. Based on data from moored profilers, ice-tethered profilers and microstructure profilers, the heat flux across the staircases was analyzed (Song et al., 2014). The difference in heat flux between the upper and lower interfaces was correlated with the heat

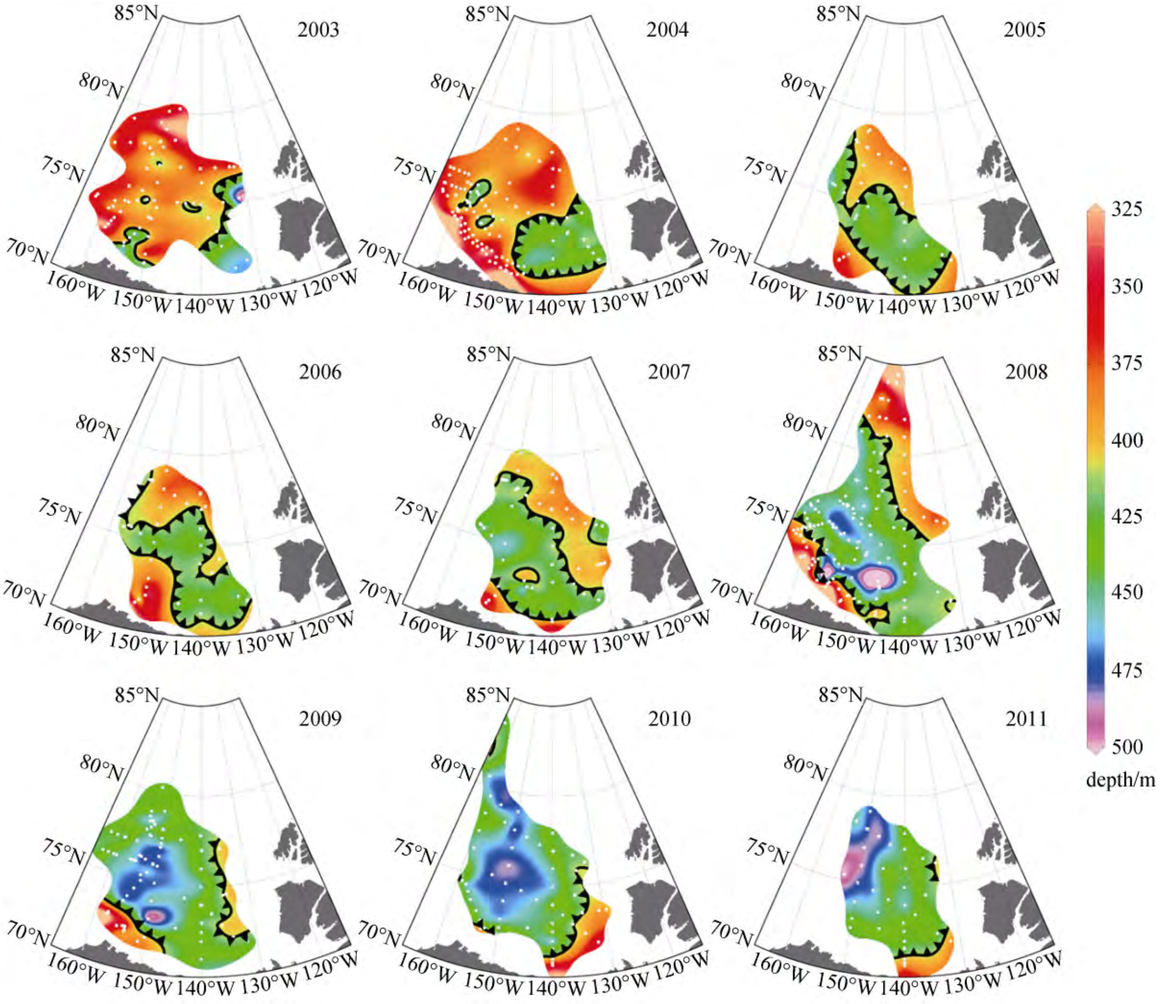

Figure 2 Expansion of the area where AIW deepening occurred (Zhong et al., 2015). The white dots indicate the locations at which CTD data were collected. The irregular black line marks the 410-m isoline, with the triangles pointing toward the deeper AIW core depth.

variation of the mixed layer. The potential temperature of the staircases is affected by the adjacent water masses and by the formation and decay of the adjacent staircases (Qu et al., 2015). There is heat transfer from AIW to the overlying staircases and Lower Halocline Water (LHW). The variations of the depth of these staircases and of AIW are determined by the LHW. Adjacent staircases show almost the same trend of potential temperature.

4 Arctic Ocean currents

4.1 Current in the Bering Strait in summer

The Bering Strait is the only channel connecting the Pacific Ocean and the Arctic Ocean. The properties of Pacific inflow into the Arctic Ocean (Roach et al., 1995), and its distribution (Steele et al., 2004), have changed greatly. The Pacific water through the strait is mainly driven by the meridional sea-level slope; the inter-annual variability of this water has great influence on the Arctic Ocean (Shi et al., 2004). From CTD data observed in the Bering Sea during the first CHINARE-Arctic, the width, speed and flux of the current over the slope of the east Bering Sea were calculated (Gao et al., 2003b). The Bering Slope Current strengthened west-northward in summer 1999. Simple Ocean Data Assimilation data were applied to calculate the monthly mean volume transport through Bering Strait (Zhang and Su, 2012). The sea-surface height in the northern Bering Strait is negatively correlated with the volume transport of the Bering Strait on an inter-annual scale. Further study revealed that the Ekman transport anomaly could be responsible for forging the link between the sea-surface height and the volume flux of the Bering Strait. The sea-level pressure (SLP) anomaly could explain the relationship between the Bering Strait volume transport and the Ekman transport, pumping rate and upper-layer water properties, and thus link the Bering Strait volume flux in summer with large-scale atmospheric circulation.

4.2 Tidal current in the Chukchi Sea

The characteristics of currents in the Bering Strait and the

Chukchi Sea were analyzed based on data collected at two mooring stations during the second CHINARE-Arctic in 2003 (Li et al., 2005). The tidal currents of the principal diurnal and semidiurnal ellipses rotate clockwise in the upper layer. During the cruise, the current was found to exhibit significant semi-monthly oscillations at the two mooring stations. In addition, spectral analyses showed that the air pressure gradient and wind stress display semi-monthly oscillations. Using current-profile data obtained by a shallow mooring deployed in the central channel of the Chukchi Sea during the third CHINARE-Arctic in 2008, the distribution of residual current was studied (Wang et al., 2011). The residual current was quite different in its direction and magnitude vertically and the surface residual current was strongly influenced by the surface wind.

During the second CHINARE-Arctic, a ten-day continuous observation ice station (CNIS7) was set up on the ice in the northern Canada Basin, and continuous ocean currents were observed in both the upper and lower ocean. The drifting ice station happened to pass above a sea vortex and captured its flow, temperature and salt structure (Shi et al., 2007). The vortex movement of the residual current changed over time, but clearly behaved as an anti-cyclone and drove sea ice from the west side of the vortex into the vortex interior about 24 h after the vortex: these are typical flow characteristics of an Arctic Ocean vortex.

4.3 Variation of the BG

The BG spun up in the last decade, which was an important factor in regulating the variation of the upper ocean (Giles et al., 2012). The heat and freshwater content of the upper ocean increased gradually in the Canada Basin, and so did the momentum input. Both the geostrophic wind curl and freshwater content could contribute to the spin-up of the BG. However, even though there was no change in the wind field, increasing freshwater alone could result in spin-up of the BG. It is difficult for the Pacific Water to flow into the central basin as the BG spins up: the maximum temperature of the Pacific Summer Water (PSW) experienced a dramatic decrease inside the BG in 2005 and 2009 as the result of a change in the PSW flow pathway (Zhong et al., 2015). Enhancement of Ekman pumping contributes to the deepening of the Pacific Winter Water by piling up more freshwater. This dynamic change in the water column also contributed to the deepening of the Atlantic Water core after 2007(Zhong et al., 2015). Ekman pumping decreased significantly in 2012 (indicating a spin-down of the BG) and the direction of Ekman transport turned to the north, which favored the release of freshwater that had resided in the basin for years.

4.4 Atlantic meridional overturning circulation

The Atlantic meridional overturning circulation is an important part of the global ocean circulation system. This circulation transfers large amounts of heat from the tropics to the high latitudes of the North Atlantic, forming one of the major heat sources in the northern hemisphere. Macdonald and Wunsch (1996) argued that half of the heat transfer to the polar regions by the ocean–atmosphere system is provided by oceanic overturning circulation, and changes in the intensity of this circulation is crucial to the northern hemisphere climate pattern. In the Greenland Sea, the convection induced by cabbeling is an important type of convection. The possible effects of various water masses from different regions of the Arctic Ocean on cabbeling convection in the Greenland Sea were discussed (Shi and Zhao, 2012). The results showed that greater temperature gradient and weaker stratification would be conducive to stronger convection. In the Greenland Sea all the water masses involved in the cabbeling convection ultimately originate from the Atlantic Ocean. Some of these masses are Atlantic Water re-circulating in the Greenland Sea; the others are Atlantic Water from the Arctic Ocean where they experience re-circulation and subduction. The water masses from the Pacific Ocean that cross the Arctic Ocean into the Nordic Seas, however, are not involved in isopycnal cabbeling convection because of their low density.

4.5 Arctic Circumpolar Boundary Current

The Arctic Circumpolar Boundary Current (ACBC), a circulation around the earth’s axis of rotation, reveals the flow route of Atlantic water in the Arctic Ocean (Rudels et al., 1999). Considering the ACBC as a whole system is quite important in understanding the basin-scale circulation in the Arctic Ocean, which in turn is useful in studying mass and energy balance, ventilation in deep water and mixing between water masses (Zhao and Shi, 2004). Studies of the ACBC shed light on the connection between ocean phenomena and physical processes. As the Arctic ring boundary flow is essentially a compensatory flow, it is bound to be affected by the atmospheric circulation of the Arctic. In the last few years, the Arctic’s climate system has undergone significant changes, and these are bound to have had an unavoidable impact on the Arctic ring boundary flow. Monthly-mean sea-ice motion vectors and SLP for the period 1979–2006 were investigated to examine the spatial and temporal changes of Arctic sea-ice drift (Wang and Zhao, 2012). From the distinct differences in the ice velocity field as well as in the distribution of SLP, there are four primary sea-ice drift types in the Arctic Ocean: Beaufort Gyre + Transpolar Drift; Anticyclonic Drift; Cyclonic Drift and Double Gyre Drift (Figure 3). These four types account for 81% of the total, and exhibit distinct seasonal variations. The annual occurrence times of the Anticyclonic Drift and the Cyclonic Drift are closely correlated with the yearly-mean AO.

5 Conclusion

Since the first CHINARE-Arctic in 1999, there have been

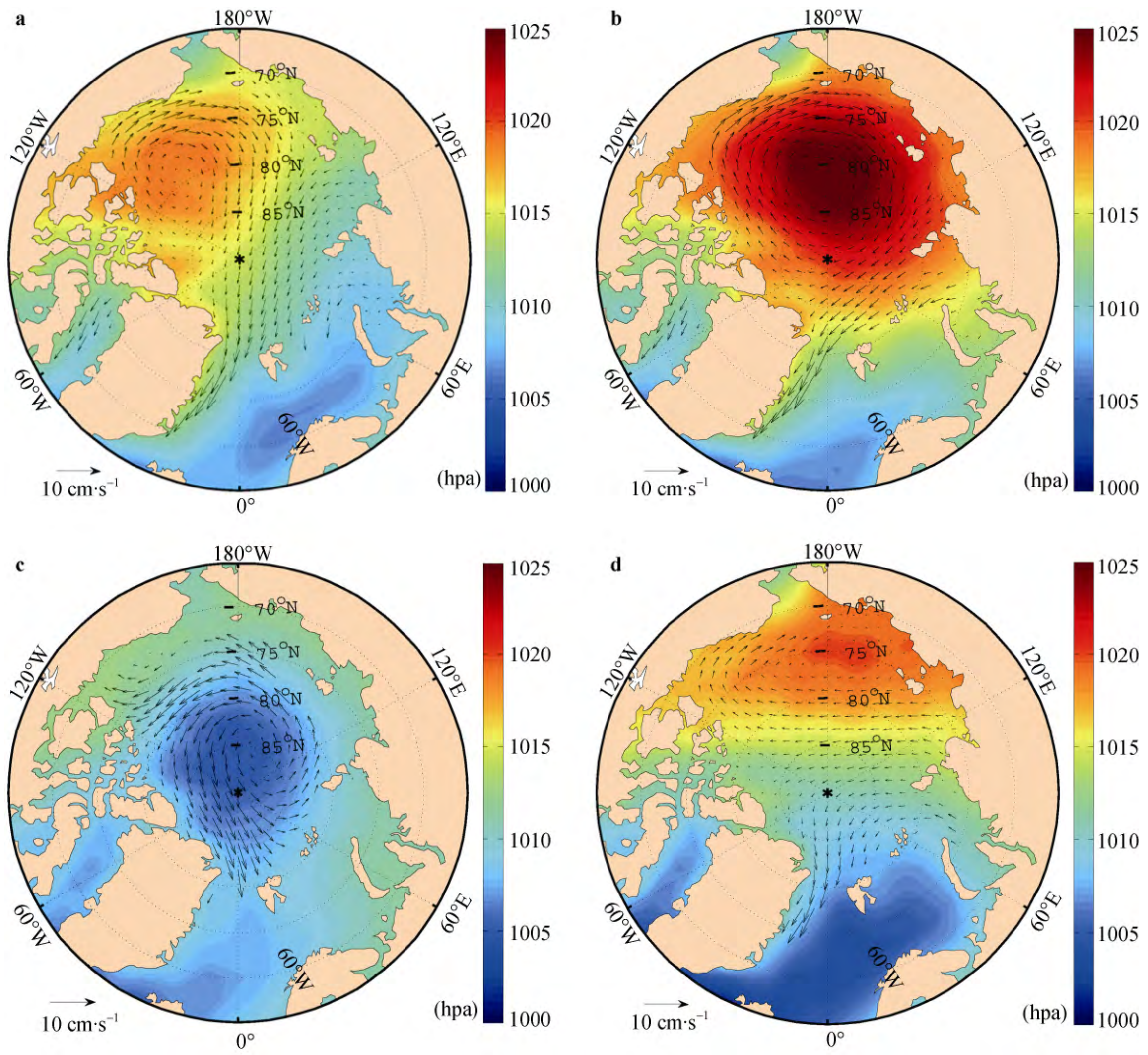

Figure 3 Distributions of typical sea-ice drift velocities (arrows) and SLP fields (Wang and Zhao, 2012). **a**, Beaufort Gyre + Transpolar Drift; **b** Anticyclonic Drift; **c**, Cyclonic Drift; **d**, Double Gyre Drift.

nearly two decades of Arctic research in China. Studies of Arctic physical oceanography in China were promoted during the IPY 2007–2008. Since then, sea-ice retreat has increased. The main topics of China's Arctic studies were focused on rapid changes in the Arctic sea ice and the variations in the ocean and atmosphere corresponding to these changes. The major achievements summarized in this paper include better understanding of the temperature, salinity, and density structure of water masses, the heat balance of the upper ocean through the air–ice–sea interface, and variations in the surface and intermediate circulation.

For oceanic variations, heat fluxes through sea ice and open water were calculated seasonally and regionally. The NSTM was first revealed in 2003, and its long-term variation was tracked. The functions of the NSTM in energy storage and climate adjustment are discussed in detail. The isopycnal deepening in the Canada Basin was revealed, and the dynamics of freshwater accumulation were summarized. The change of the surface circulation was studied in detail. The eastward current along the slope of the East Siberian Sea was identified, and its function in freshwater transportation was noted. These contributions from research in China provide a prominent basis for study of Arctic sea ice, atmosphere and the ecological environment. On the basis of the previous studies, further research will be carried out, such as on the influence of the export of Arctic freshwater on the circulation of the North Atlantic, the Arctic Ocean Circulation Transformation and its climate effects, the influence of inflows from the North Atlantic and North Pacific on the water masses in the Arctic, the heat flux process of the upper ocean, and the heat release of AIW.

A series of polar projects encouraged research on the Arctic and promoted progress in Arctic science cooperation. Arctic studies in China have become part of international efforts in Arctic science through extensive international cooperation.

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