doi:10.3724/SP.J.1085.2011.00281 December 2011 Vol.22 No.4 281–292

Progress of Chinese research in Arctic physical oceanography during 2007–2010

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Received November 16, 2011; accepted December 21, 2011

Abstract As a part of the National Report of China for the International Association for Physical Science of Ocean (IAPSO), the main research results of Chinese scientists in Arctic physical oceanography during 2007–2010 are reviewed in this paper. This period overlaps with the International Polar Year (IPY), which is a catalyst for nations to emphasize activities and research in the polar regions. The Arctic also experienced a rapid change in sea ice, ocean, and climate during this time. China launched two Arctic cruises with the R/V *XUE LONG* icebreaker, in 2008 and 2010, which provided more opportunities for Chinese scientists to investigate the Arctic Ocean and its change. During this period, Chinese scientists participated in more than ten other cruises with international collaborations. The main research covered in this paper includes the upper ocean characteristic, ocean and sea ice optics, kinematics of sea ice and the Arctic impact on global climate change. The progress in sea ice optics, the observation technologies and Arctic Oscillation are especially remarkable.

Keywords **Arctic Ocean, sea ice, physical oceanography, optics**

Citation: Cao Y, Zhao J P. Progress of Chinese research in Arctic physical oceanography during 2007–2010. Adv Polar Sci, 2011, 22: 281–292, doi: 10.3724/SP.J.1085.2011.00281

0 Introduction

The fourth International Polar Year (4th IPY) was a great opportunity for Arctic scientists, and from 2007–2010 there were more observation cruises and international collaborations. The scientific activities and research results of physical oceanography in China are introduced in this report.

In 2007, the Chinese government approved "The China Program for the International Polar Year 2007–2008", including the activities in both the Arctic and the Antarctic. Two cruises to the Arctic Ocean were planned in this project. The other part of the project in the Arctic was the promotion of research at the Chinese Arctic Yellow River Station, located in the Svalbard Islands. The expeditions in the Arctic Ocean were carried out in the summers of 2008 and 2010 respectively. The plan also supports scientists to participate in international cooperation and collaborative studies.

In 2008, the scientific goal of the third Chinese National Arctic Research Expedition targeted "Rapid Change on the Arctic Climate and Environment". The expedition regions included the Bering Sea, the Chukchi Sea, the Beaufort Sea, the Canada Basin and the Chukchi plateau. The expeditions including research on physical oceanography and ocean optics in the context of ocean physics were carried out. Two sets of subsurface buoys were deployed concurrently to study the coupled variations between the sea-ice-air in the Arctic, the changes of the Arctic Ocean responding to the sea ice, the influence of the climate in China responding to the variation of the

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Arctic, etc. In 2010, the goal of the fourth Chinese National Arctic Research Expedition was "Rapid Changes of the Arctic Sea Ice and the Response of the Marine Ecosystem in the Arctic Ocean". The physical oceanography and the optics expedition regions were the same as the last expedition with more northward sampling reaching to 87°N. A series of observations at the North Pole were carried out supported by a helicopter.

Chinese scientists also participated in expeditions with international cooperation. Eight expeditions included three cruises of the USCG icebreaker *Healy* (2007, 2008 and 2009), one cruise of the Canada LSSL icebreaker (2009), three legs of the Canadian icebreaker, Amundsen (2007, 2008a, b), and one cruise supported by an aircraft on the sea ice around the northern slope of Canada.

Most Arctic expeditions mentioned above took place in summer. Due to its extreme dark and cold, there were rare opportunities to the Arctic in winter. During the 4th IPY, the "Circum Polar Flaw Leads (CFL)" program was carried out by Canada. Scientists from the Ocean University of China attended two legs in winters and one leg in summer. Observations of physical oceanography and several experiments for the sea ice optics were implemented during these expeditions.

Chinese studies of physical oceanography emphasized the physical structure of the ocean response to variations in the sea ice, especially the studies of the structure and energy distribution of the upper ocean. The "Rapid Arctic Sea Ice Retreat and the Associated Climate and Ecological Effects" as a major topic was proposed for inclusion in the 4th IPY.

Based on the observation data obtained from the previous Arctic expeditions, a series of results were acquired by Chinese scientists on the Arctic Ocean sea ice and climate. The studies focused on the temporal and spatial variations of the upper ocean and the sea ice, the sea ice optics and the ocean optics, the core region of the Arctic Oscillation, etc. These studies established the basis of the physical oceanography of the Arctic and enhanced understanding of the relationship between the climate and the ocean in the Arctic.

1 The upper ocean of the Arctic

In summer, melting of the sea ice causes the sea surface water to become fresher. More solar radiation penetrating through the ice heats the seawater. Concurrently, the heat absorbed by the upper ocean accelerates sea ice melting, which forms a positive heat feedback mechanism from the upper ocean to the sea ice in the Arctic. The results obtained by Chinese scientists on the upper ocean of the Arctic are summarized as followed.

1.1 Near surface temperature maximum

Zhao et al.[1] found that there was a temperature maximum water layer near the sea surface in the summer marginal ice zone of the Chukchi Sea by using the CTD data collected by the first Chinese National Arctic Research Expedition in 1999. The water layer was named Subsurface Warm Water and the depth of the temperature maximum peak was observed about 20 m. Jackson et al.[2] renamed it the near surface temperature maximum (NSTM). The formation mechanism of the NSTM was heating by solar radiation and cooling by the overlying sea ice[1]. The NSTM usually occurs in ice-covered water, but sometimes might occur in the open water[3]. The results from the CTD data collected in the Beaufort Sea, Chukchi Sea and the Canada Basin from 1993 to 2008 showed that the NSTM often occurred in the open water of the shelf and the marginal ice zone before 2004 and the temperature maxima were high. After 2004, the sites where the NSTM occur were increasingly extensive, covering most of the Canada Basin (Figure 1).

Corresponding to the obvious decline of sea ice and less ice concentration during this period, more solar radiation penetrates the sea ice and is absorbed by the near surface water[3]. The depth of the NSTM, the maximum temperature and their temporal variation are related to the halocline determined by the fresher ice melt water and the vertical turbulent diffusivity. Zhang et al.[4] calculated the vertical distributions of the turbulent diffusivity using the temperature, salinity and the current profile data in the Canada Basin (74°N–78°N, 144°W–164°W) obtained from the Chinese Arctic Research Expedition cruise of summer 2003. The results showed that the vertical distributions were somewhat consistent at different sampling sites, which were larger 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 formation of the NSTM is related not only solar radiation heating and surface cooling, but also stratification. Chen et al.[5] studied the NSTM using a thermodynamic column model coupled with a sea ice model and an upper ocean model. The results verified that solar radiation is the dominant energy source and the thin ice and the leads are the main energy channels of incoming solar radiation. Long-wave solar radiation flux, air temperature, and atmospheric humidity played important roles in determining the relative intensity of the NSTMs.

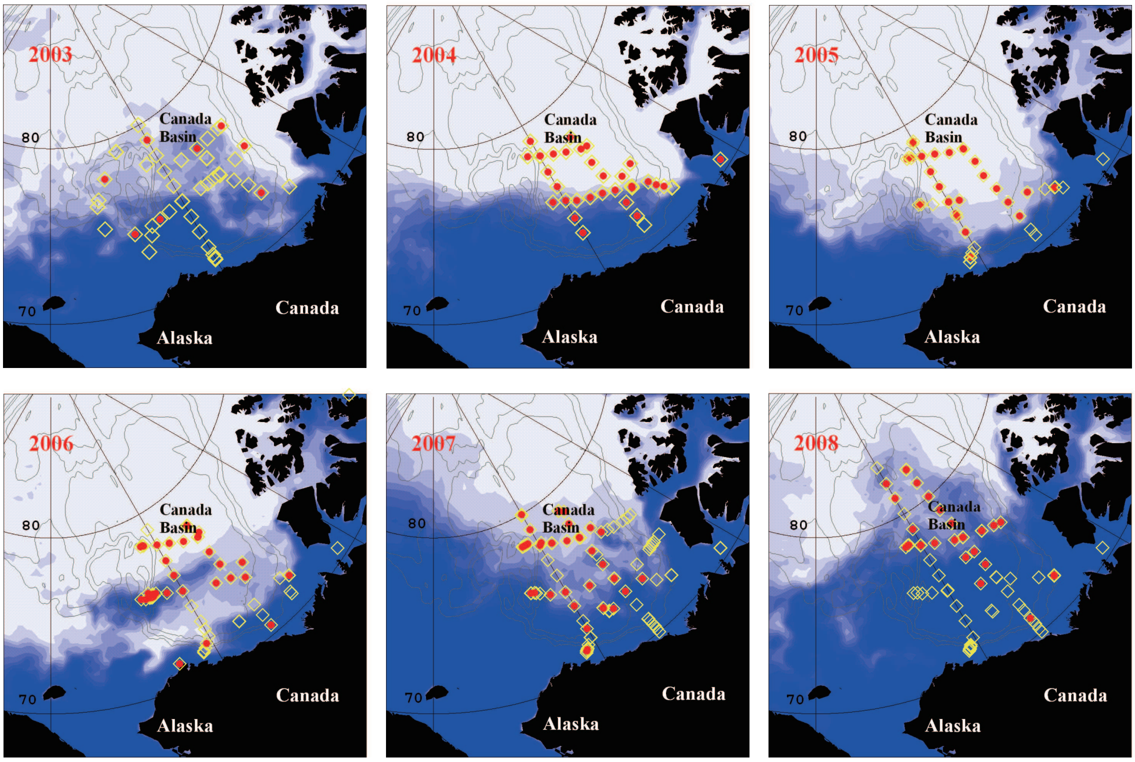

Figure 1 Spatial distribution of NSTM from 2003–2008. Locations of the CTD are expressed by yellow squares and the locations with NSTMs are expressed by red dots. The filed isolines are the averaged ice concentration in August.

1.2 Water mass structure during the ice melting period

The R/V *XUE LONG* icebreaker entered the Chukchi Sea on July 14, 1999 for its first Arctic cruise. Then sea ice was so heavy that the vessel was seriously delayed. In the following four days, the ship struggled to find northward access around the Herald Shoal, and deployed CTDs and took water samples there. Zhao et al.[6] used the data and analyzed the ocean structure of the Chukchi Sea around the Herald Shoal. Aside from temperature and salinity, nutrients and chlorophyll *a* were also recorded to study the water structure. The results showed that there were two water masses that existed in this region. One was the Anadyr Water (AW) that entered in winter or spring with lower temperatures and higher salinity and silicate. The other was the Bering Shelf Water (BSW) entering the Chukchi sea in summer with higher temperatures, lower salinity and silicate. The dividing line between the two water masses was consistent with the margin of the ice edge. During the ice melting process, the AW retreated northward with the ice edge, and was replaced by the BSW. The northward tongues of water with low salinity and low silicate represented the main gateways of the northward currents.

1.3 Water properties and convection under the sea ice in winter

The convection under the sea ice without solar heating is studied in winter at the Amundsen Gulf by Li et al.[7]. The data were from the Circumpolar Flaw Leads System Study (CFL) project during the time of polar night from November 2007 to the end of January 2008. It was the first time for Chinese scientists to take part in a winter cruise in the Arctic. The structure of the sea ice and its temporal variation were studied. The vertical convective mixed layer was formed and deepened in winter in this region. The thickness of the mixed layer varied from meters to tens of meters. No static instability was found, i. e., the density of the water in the mixed layer was lower than that of the water below. The convection was caused by a continually released saline drops. The temperature of the water in the mixed layer was almost at the freezing point, which was the result of the convection by ice formation. Below the mixed layer, there was a warmer layer, but the temperature decreased with time during winter. The cooling of the warmer layer was considered by the energy exchange with the overlying water in the mixed layer. According to the results, the thickness of the mixed layer decreased in late winter and the salinity of this layer increased. The study also analyzed the temperature and salinity data from 3 stations, which are roughly at the same position, and found that the salinity of the mixed layer increased and the temperature of the warm layer decreased during the observation period.

1.4 Polynyas in the Bering Sea

Polynya is an area inside sea ice with open water or very thin ice in polar regions. In winter, a lot of latent polynyas appear regularly on the shelf of the Northern Bering Sea. They made great contributions to the local ecological system and the Arctic halocline. The Los Alamos Sea Ice Model (CICE) with a horizontal resolution of 6.37 km had been implemented to simulate a year round sea-ice growth and decay starting on November 1, 2002 in the Bering Sea[8]. The total sea ice area from the model results and one from AMSRE/Aqua satellite observations had good consistency. Their correlation coefficient of daily mean of total sea ice area was 0.97. Model results showed that polynyas in southern domains of east-west coasts were formed by means of the southward movements of sea ice, which were mainly forced by offshore northeast winds.

Fu et al.[9] studied variations of temperature and salinity in seawater under sea ice using hydrologic data collected from polynyas south of the St. Lawrence Island during March of 2008 and 2009. The results indicated that the high-salinity water found during the cruises of 2008 and 2009 was due to the formation of polynyas. The salinity observed in 2008 was higher than in 2009 as a result of higher salt production in 2008. The spatial distributions of high-salinity cores differed between the two cruises. In March 2008, a southeastward flow was formed under the persistent northerly wind in the observation region, which transported the high-salinity water produced by the polynyas to the southeast. A similar flow, however, did not exist in March 2009 because the northerly wind over the study area was interrupted by a southerly wind. Accordingly, the polynyas and the high-salinity water produced by them existed for a short time. As a result, the high-salinity water in 2009 did not spread very far, and stayed within the polynyas. In addition, during the 2009 cruise, two stages of observations in the polynyas showed the core of high-salinity water was shifted to the southwest of St. Lawrence Island. This result suggested that a southwestward flow might have existed in the area at the onset of the northerly wind, which was consistent with the alongshore and/or offshore flows caused by the northerly wind.

1.5 Structure of a subsurface eddy

An Arctic Ocean eddy in the subsurface layer was analyzed by Shi et al.[10] with temperature, salinity and current profile data obtained at an ice camp in the Canada Basin during the second Chinese National Arctic Expedition in summer of 2003. In the vertical temperature section, the eddy showed itself as an isolated cold water block at the depth of 60 m with a minimum temperature of 1.5℃ that was –0.5℃ colder than the ambient water. Isopycnals in the eddy formed a pattern of convex currents, which indicated the eddy is anticyclonic. Although a maximum velocity near 0.4 $m \cdot s^{-1}$ occurred in the current records observed synchronously, the current pattern is far from a typical eddy. Upon further analysis, inertial frequency oscillations with amplitudes comparable with the eddy velocity were found in the subsurface layer currents (Figure 2). After removing the inertial current and mean current, an axial symmetric current pattern of an eddy with a maximum velocity radius of 5 km is obtained. The analysis of the T-S characteristics of the eddy core water and its ambient waters supported the conclusion that the eddy was formed on the Chukchi Shelf and migrated northeastward into the northern Canada Basin. It was possible for the eddy to drift from west of Barrow Point to the northern Canada Basin with a mean circulation of an enhanced Beaufort Gyre (BG) when the Arctic Oscillation (AO) state was negative in 2003, but how the Arctic Ocean eddy conserves its energy over a long time translation is still in doubt.

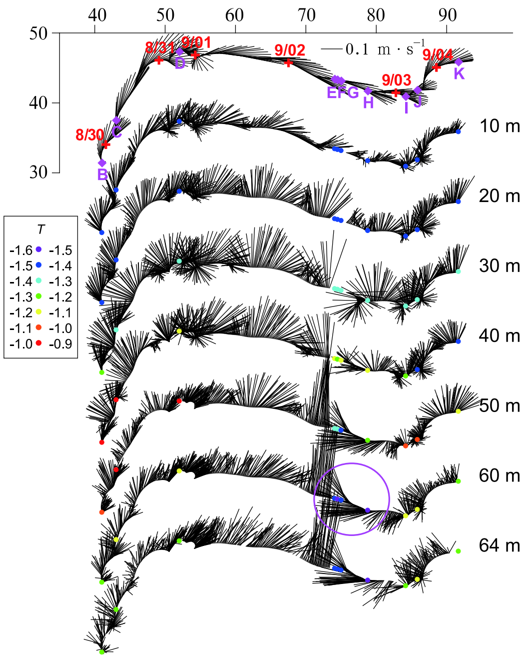

Figure 2 Vectors of ice camp drift velocity (top) and absolute current velocity at 7 depths plotted along ice camp drift tracks.

1.6 Observation technology for physical oceanography

During the second and third Chinese National Arctic Research Expeditions in 2003 and 2008, mooring systems were deployed in the Bering Strait and the Chuckchi Sea. The technical design and deployment processes related to mooring systems in the polar region were discussed[11]. Selection of observation stations and layers, the design of mooring systems and the deployment steps were presented in their studies, which is a precious experience for anchored systems deployment in low temperature and ice covered areas.

A newly developed profiler with an automatic winch was applied for deploying CTDs down to 1 000 m from an ice hole on the ice covered ocean[12]. The profiler was mounted on the ice camp and observed more than 100 profilers in 2008. It is a useful tool together with an ADCP for capturing subsurface eddies on a drifting pack ice.

2 Ocean optics in the Arctic

Besides CTD and LADCP profiling, ocean optics and sea ice optics were the main observations during the third Chinese National Arctic Research Expedition in 2008. It was the first time for Chinese scientists to collect ocean optics data and 80 optical profiles were acquired. In addition, there was a series of other cruises for sea ice optics observation in the Bering Sea, Beaufort Sea, and the Canadian Basin in cooperation with Canadian and American scientists in 2007, 2008 and 2009. These efforts greatly expanded physical oceanographic observations and data acquisition. The downwelling irradiance at the sea surface are measured during the marine optical observation with a much higher sampling rate of 0.2 s, which is beneficial for studying the high frequency variations in the irradiance record[13]. The data obtained in the Bering Sea of spring 2007 were used to analyze the main factors causing high frequency variation in the irradiance. The influences of clouds, fog and sea waves on the irradiance were distinguishable. The variations in irradiance from clouds usually have lower frequencies and higher amplitude, whereas those caused by fog express complex variations with higher amplitude and varying periods from several to a hundred seconds. The complexity was useful for distinguishing fog influence from that of clouds. Under clear skies, the steady incident solar radiation was reflected at the sea surface, modulated by the wave oscillation and then scattered from the particles in the air to the instrument collector. The sea wave signal appeared in the irradiance record with a short period and low amplitude, distinct from the influence of clouds and fog. The influence of clouds, fog and waves on irradiance was analyzed and calculated, which is valuable for understanding the irradiance and the corresponding variation in the underwater record.

Photosynthetically available radiation (PAR) is an important bio-optical parameter related to marine primary production. PAR is usually measured by a broadband sensor and can also be calculated by multispectral data. When the PAR is calculated by multispectral data in Polar regions, there are four possible error sources. Because the wavelengths of multispectral instruments are usually chosen to avoid the main absorption zones of the atmosphere, PAR could be overestimated. However, both PARs calculated by hyperspectral and multispectral data are consistent and give an error value of less than 1%. Using the proposed fitting function, Zhao et al.[14] calculated PAR using multispectral data and showed it has the same accuracy as that of hyperspectral data. In order to calculate the attenuation rate of PAR under the sea surface, the value for PAR_0 just under the surface must be obtained. A proposed approach to calculate PAR_0 uses the best fit of the irradiance profile of 1–5 m with a constant attenuation coefficient. It is demonstrated by observations over time at the same location that the attenuation coefficient of PAR is independent of the radiation intensity. The PAR attenuation coefficient is slightly different under sea ice, because the light spectrum is changed by selective absorption through sea ice. Therefore, the inclusion of data from under sea ice will impact the attenuation of PAR and result in altered PAR values. Using the results of this study, PAR can be calculated reliably with multispectral data (Figure 3).

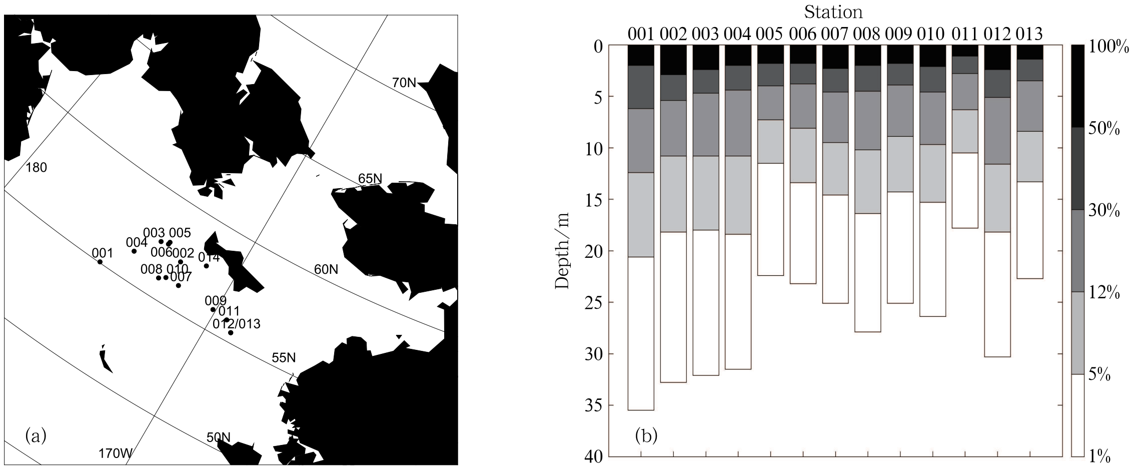

Figure 3 PAR attenuation depth. (a) 13 stations in the the Beijing Sea in 2008; (b) the depth of PAR attenuation to 50%, 30%, 12%, 5%, 1%.

3 Sea ice optics

Sea ice is an important component of the climate system. Sea ice is known as an indicator of climate change, because of its sensitivity to changing conditions. Over the past decade, Arctic sea ice extent and thickness have shown a rapidly decreasing trend. In summer 2007, Arctic sea ice coverage reached its lowest level since the beginning of the satellite data record. There are increasingly complex research questions that come up in the air-sea-ice coupled process with the rapid reduction of the Arctic sea ice. Sea ice needs to absorb enough energy to melt and short-wave solar radiation is the main source of energy, so sea ice optics is the key to studying the sea ice and solar radiation. Starting in 2006, a number of observations and studies on sea ice optics were carried out by the scientists of the Ocean University of China. Data of sea ice optics in the Arctic Ocean were obtained from more than 10 research cruises.

3.1 Light lateral scattering in the sea ice

A winter optical experiment using an artificial lamp was conducted in the Amundsen Bay, Arctic Ocean from November 2007 to January 2008. The radiation field emitted from an artificial lamp was measured and the optimized experimental protocol was discussed by Zhao et al.[15]. It demonstrated that the minimum size of the lamp is determined by both the field of view (FOV) of the optical instrument and the measuring distance from the lamp. Problems that might influence the experimental results, such as instability, spatial non-uniformity, light divergence, effect of lamp temperature, etc., often occurred using a simple lamp. The experiment indicated that reliable results could be obtained only when the optical measurement is coordinated with the radiation field of an artificial lamp. The measured radiation properties of the lamp were used to minimize measuring error in field experiments.

As the artificial lamp experiment was our first attempt in the Arctic Ocean, the experience given by this study is a valuable reference for correlative studies. A measurement method was proposed and applied whereby a recording instrument was buried in the sea ice and an artificial lamp was moved across the instrument[16]. With the exception of blue and red lights, the attenuation coefficient changed little with wavelength, but changed considerably with depth. The vertical decrease of the attenuation coefficient was correlated with salinity: The greater the salinity, the greater the attenuation coefficient. A clear linear relationship between salinity and the lateral attenuation coefficient (R^2=0.939) exists to address the close correlation of the attenuation of the lateral propagation light (LPL) with scattering from the salt water.

3.2 Solar radiation absorbed by the sea ice

Based on the optical data for transmission radiation through sea ice in the Arctic winter of 2007, the transmission of solar radiation under conditions with very low solar altitude was studied[17]. The basic feature of the solar radiation was that the light with shorter wavelengths was significantly reduced to form a two-peak spectral structure. The reflection was lower than in summer because of the thin snow-covered ice, allowing a higher ratio of heat to enter the sea ice. The reflection of the ice in longer wavelengths decreased and more light with longer wavelengths entered the sea ice. Wavelengths of 490 nm were dominant, which meant longer wavelengths were primarily absorbed by the sea ice. Although the light penetrating the sea ice was quite weak, the sea ice obtained more heat by the absorption of longer wavelength light, which would delay the freezing of the sea ice.

The solar energy absorbed by the pack ice in the central Arctic was studied by Zhao et al.[18] based on the optical observations of the third Chinese National Arctic Expedition on an ice camp during the period of August 21–27, 2008 (Figure 4). The transmission, albedo, and the absorption rates of the sea ice and their variation with ice thickness were calculated from the observed data. On average, the absorption rate of sea ice for shortwave solar radiation was about 16%, and about 77% of the incident energy was reflected back to the space. A three-day optical observation was conducted to determine the amount of arriving solar radiation. Although the solar radiation arriving at the upper atmosphere was still strong in August, the atmosphere caused a reduction of about 57%, as the coverage of cloud and fog caused absorption of the shortwave radiation. Therefore, the heat flux absorbed by sea ice was only 10.2 W·m^{-2}, corresponding to melting 2.6 mm ice per day or 1 m of ice within 380 d. The weak heat flux did not provide sufficient heat to melt the sea ice, and the pack ice still covered the central Arctic Ocean even though the ice coverage was nearly at a minimum for the whole Arctic. The results also indicated that some other factors could cause the increased melting of the pack ice, such as a decrease in clouds and fog, the total melting of the snow layer, a reduction in ice thickness, and an increase of the ponds which could especially endanger the permanent pack ice. In the future, it would be possible for the sea ice in the central Arctic to collapse if more heat is absorbed under conditions different from those of the summer of 2008.

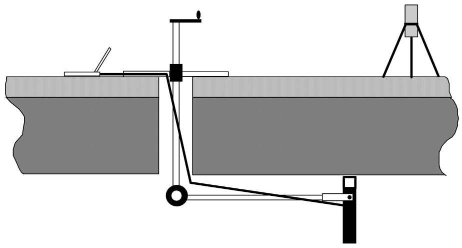

Figure 4 Sketch for sea ice observation system.

3.3 Optical properties of snow on the sea ice

From November 2007 to February 2008, a series of optical measurements of light transmission in the snow on the ice were carried out in the Amundsen Gulf of the North Polar Region. Li et al.[19] have studied the optical extinction properties of artificial light between 313–875 nm in the snow of the polar night. The results confirmed that the radiant intensity was attenuated exponentially with increasing snow thickness, and that the snow attenuation was greater than that of ice. On the basis of the observation results with different snow thicknesses, the optical extinction coefficients in the snow can be calculated. The results showed that the spectral extinction coefficients within 465–625 nm were minima, and were almost constant with the mean value of 20 m^{-1}. When the light wavelength is out of this range, the extinction coefficients increase abruptly, and can even exceed 30 m^{-1}. According to the observation results, the effect of snow density on the optical extinction properties differs with variations in light wavelength: The longer the wavelength, the greater the effect of snow density.

4 Kinematics of the sea ice

Sea ice is an important factor affecting the climate in the northern hemisphere. In recent years, the sea ice extent and the sea ice thickness have been continuously decreasing. These changes range from moderate to severe. The variation of Arctic sea ice depends not only on the internal processes of the Arctic, but also on the ocean processes of the sub-polar regions, such as warm water intrusion from the Pacific and the Atlantic Oceans. Runoff is also an important factor influencing the Arctic sea ice. The previous studies on the Arctic sea ice are mainly morphological using numerical models and studying the temporal variation of the sea ice in different regions.

4.1 Vertical melting process of the sea ice

By describing the thermodynamic and kinetic parameters of the sea ice, the mathematical representation of sea ice behavior can be provided by the climate forecasting models. The physical basis and the parameters of the program to simulate the Arctic sea ice are also based on these values. The kinetic parameters of the sea ice can be divided into the sea ice concentration, the sea ice thickness, the ice surface roughness and the ice motion[20]. Based on the field data on sea ice physical processes obtained during the second Chinese National Arctic Research Expedition in the summer of 2003, the sea ice dynamic characteristics were analyzed and the parameters expressing these characteristics were given. When the ice floe moved toward the Northeast, the rotation angle increased gradually with a maximum of 37.8°, and when the floe moved toward the Southeast, its rotation angle decreased. The oscillation period of the floe was 12.45 h, consistent with that of the inertia current at the same latitude, which showed the contribution of the inertia current to the ice floe movement. The feedback mechanism of the snow/ice albedo is affected by the relative intensities of solar radiation reflection, absorption and transmission by the open water and the snow/ice, which is important in increasing polar warming. The Arctic sea ice plays a critical role in the feedback mechanism. Currently, a diversity of sea ice albedo parameterizations are used in climate system models and standalone sea ice models, ranging from simple to complex. Yang et al.[21] reviewed previous studies on the evaluations of the snow/ice albedo parameterizations, and discussed some problems of the satellite-derived surface albedo for the ice-covered ocean. They put forward some issues related to further developments of the albedo parameterizations as the climate warms, including melt ponds and leads. The thermodynamic mechanism of a system involving a floe and a small lead in the Arctic Ocean was observed during the ice-camp period in the third Chinese National Arctic Research Expedition from 20 to 28 August, 2008[22]. The field measurements included surface air temperature above the floe, albedo of the lead, seawater temperature in the lead and under the floe, and the lateral and bottom mass balance of the floe. The results showed that the surface of the lead was frozen completely by 23 August. The albedo of the thin ice-covered lead from 320–950 nm was 0.46, the vertical seawater-temperature gradient in the lead, as well as the seawater temperatures both in the lead and under the floe decreased gradually, while the oceanic heat under the ice maintained a low level.

4.2 Variation of the sea ice cover

The sea ice has obvious seasonal variation[23–24] and lag response properties[25]. The seasonal variation of the sea ice in the Arctic can be simply described as melting in spring and freezing in autumn, which also can be divided into five phases by using the sea ice concentration and extent: A dense ice phase, the slope of cracking phase, the westward melting phase, the full melting phase and the freezing phase. The beginning dates for these phases vary in different regions and years; the minima and the corresponding dates of the sea ice extent are also variable. Though the Arctic sea ice has been decreasing continuously in recent years, there are annual variations of the sea ice in different regions. Zhu et al.[26] indicated that the sea ice extent in the Chukchi Sea varied from light (1997)– heavy (2000–2001)–light (2002–2005). The ice melt duration correlated well with the ice condition: In a light ice year, the melting begins earlier and freezes later. The minimum sea ice cover appeared in late September to early October each year, but varied considerably in extent: 4% in the light ice years and more than 50% in the heavy ice years. Satellite remote sensing data indicated that there was heavy sea ice in the East Siberian Sea in 1997–2001, while there was light sea ice in this region in 2002–2005[27]. Using a moving-t abrupt test and wavelet analysis, abrupt changes in the ice extent (1953–2004) in the Bering and Chukchi Seas were found independently in the late 1970s. The results showed that there were abrupt changes in the mean values in the Bering Sea and a frequency shift in the Chukchi Sea[28]. There are many factors that influence variations in the Arctic sea ice, such as air temperature, air pressure, wind and other changes. The anomalies of the large-scale circulation, the heat carried by the Pacific inflow and the increasing of the long-wave radiation by greenhouse gases may also cause variations in the sea ice[25−29]. The variation of the global climate is deeply responsive to changes in the Arctic sea ice[30−31].

4.3 Distribution and variation of sea ice in the Northwest Passage

The "Northwest Passage" refers to the passage from the Atlantic to the Pacific through Canadian Archipelago. In recent years, rapid warming of the Arctic made passage navigation possible. The satellite data from the National Snow and Ice Data Center showed that there was usually floe ice in the western Banks Island, and that the McClintock and Parry Channels were covered by multi-year ice until 2006. In 2007, the southern route of the Northwest Passage appeared ice-free for the first time. It is necessary to study the ice situation by using high-resolution satellite data. Su et al.[32] studied the characters in variation of the sea ice concentration around the passage using the AMSR-E sea ice concentration product with a resolution of 6.25 km from 2002 to 2008, which was the highest resolution data available for sea ice concentration. By analyzing melting period, ice-free period, slight-ice period, ice-free days, as well as some details of the variation and distribution of the sea ice in the main ice choke points along the passages, the results showed that the southern route was easier to navigate than the northern one (Figure 5). Sea ice often began to melt near the place where a polynya and the Circumpolar Flaw Lead occurred. For each route, the time of the existence of the ice choke point displayed a decreasing trend, while ice-free and slight-ice days showed an increasing trend. The spatial distribution of the sea ice in the research region and its mechanism were discussed and an index which named ice-free or slight-ice days along the whole route was set to estimate navigation extent.

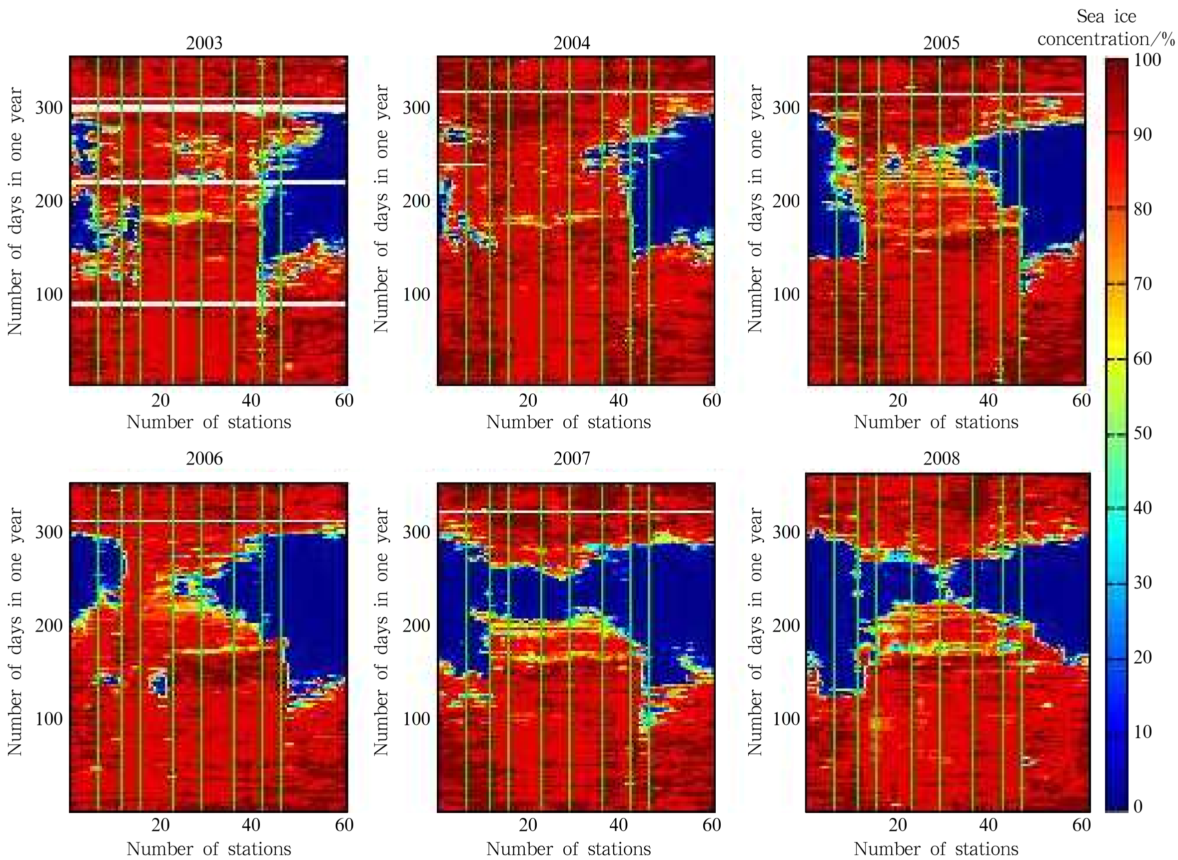

Figure 5 Daily sea ice concentration: Temporal and spatial ice distribution in the Northwest Passage.

5 Arctic impact on global climate change

Arctic Oscillation (AO) is defined by the first mode of Empirical Orthogonal Function (EOF) of the Sea Level Pressure (SLP) north of 20°N, and the time coefficient of EOF-1 is defined as the Arctic Oscillation Index (AOI). It has been used as a representative atmospheric circulation index to express climate change in the Northern Hemisphere (NH). Compared with the pattern of the annular circulation mode of the lower stratosphere in the Southern Hemisphere, which has been extensively documented, AO is in essence the annular mode of the lower stratosphere in the NH. The Arctic region has experienced obvious climatological warming during the past decades at a rate which is nearly twice that of the global average. Most climatological indicators show a linear trend with Arctic warming. The notable ones include the decline of the perennial ice coverage at a rate of 9% per decade, and the thinning of the ice draft for more than a meter from two to four decades to the 1990s. However, AO behaves differently from such regularities, instead, a seesaw-like oscillation is dominant.

5.1 Core region of the Arctic Oscillation

AO displays a pattern in which the SLP at the polar and middle latitudes in the NH fluctuates between positive and negative phases. It has been used as a representative atmospheric circulation index to express climate change. The Arctic region is experiencing significant climate warming, with many climatic factors reflected by linear trends, most notably the reduction of sea ice extent and sea ice thickness decrease. But the change of AO is different, it remains oscillations between positive and negative phases. By calculating the correlation coefficients of AO Index with all the gridded SLPs, Zhao et al.[33] revealed a special region named the Arctic Oscillation Core Region (AOCR), where the Running Correlation Coefficients (RCC) between averaged SLP in the AOCR and the AO index are all negative. The averaged SLP of this region correlated significantly with the AO index (correlation coefficient –0.97). The correlations between SLPs and the AO index outside of the AOCR were weaker than those inside. The events that occurred in different years were indicated by the peaks of RCC, which expressed the maximum scope of the non-AO events. The RCCs between the AOI and all the gridded SLPs north of 20°N were calculated, and the results showed that most of the points in the Arctic were impacted by some events other than the AO, and that the non-AO events distributed themselves in different locations. By examining the spatial distribution, the extents of impact by these events were mapped by lines in Figure 6. These events occurred in 1954, 1955, 1962, 1971, 1982/83, 1995, 1996/97, 1998 and 1999. A comparison of these events and the El Niño Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO) indices suggests that the events in 1982/83 and 1998 are probably associated with the ENSO processes. Events centered in other years are likely connected with the PDO, which reached their minima in the years of 1950, 1955, 1962 and 1971. The results in this study provide an alternative insight to look at the mechanism of the variation of AO.

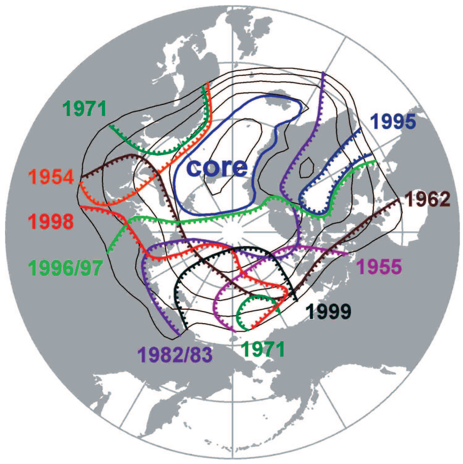

Figure 6 Impacted events in the Arctic in 1950–2002. The region marked with 'Core' is the Arctic Oscillation Core Region (AOCR). Several strong processes influenced the area outside of the AOCR.

5.2 Spatial variation of the arctic oscillation

Zhao et al.[34] defined the spatial variation of the AO as the temporal variation of the ensemble of grids with varying SLP consistent with the AO index over a certain time span. The region of the ensemble is called AO-dominant region, identified by the RCC of the gridded SLP with the AO index. The positive and negative AO-dominant regions show that the SLP oscillated between the polar and mid-latitude regions or between the land and the ocean. Along the Atlantic-Pacific Section, the North Atlantic Oscillation exists as a stationary seesaw-like dipole, while on the Pacific side the oscillation is intermittent with lower intensity and a swinging boundary. The long-term spatial variation of the AO with three stages is clearly identified by the relative area of the SLP anomaly regions. A positive SLP anomaly area dominated before 1970, showing the state before the effects of global warming. A negative SLP anomaly area dominated from 1971–1995, indicating the effect of global warming before the Arctic warming being apparent. Since 1996 both positive and negative SLP anomaly areas are small, possibly caused by the sea-ice retreat during the Arctic warming.

6 Discussion

In the last four years, the studies of the Arctic physical oceanography of China have been closely linked with the 4th IPY, and focused on the rapid changes of the Arctic sea ice and the variation of the ocean and the climate corresponding to the sea ice change. Faced with many scientific issues, we participated in many field expeditions to study the variation in sea ice, ocean and atmospheric processes.

Cruises during the period of polar night are rare in the Arctic Ocean. It was the first time that Chinese scientists were able to attend a winter expedition. The structure of the winter mixed layer and its temporal variations were studied with physical oceanography data under the sea ice in winter. During the same cruise, an experiment using an artificial lamp was the first attempt in the Arctic Ocean, and the experience given by this study is a valuable reference for the correlative studies of sea ice optics.

Observation technology, automatic continuous profiler technology, satellite remote sensing technology, and numerical modeling are developed in China. The ability to acquire more data and numerical forecasts and modeling are enhanced by these technologies.

Corresponding to the normal temporal variation of AO, the study of the spatial variation of AO was undertaken in a novel way. The averaged SLP of the AOCR correlates significantly with the AO index, which indicated that the averaged SLP of the AOCR may substitute for AO. It was the first time that the physical definition of AO index was explained.

A considerable progress in Arctic physical oceanography is achieved by means of China's effort and international cooperation. Acknowledge to all the people and projects those provide the precious supports to Chinese scientists. After the IPY, China will set up a special polar research project, which will promote and enhance Arctic science in China.

Acknowledgments This study is supported by the National Department Public Benefit Research Foundation (Grant no. 201105022) and the National Natural Science Foundation of China (Grant nos. 40876006, 40976111).

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