

# Advances in Chinese Arctic and subarctic research in marine biology and ecology with emphasis on the Pacific Arctic sector

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**Abstract** The Arctic is one of the most sensitive regions that respond through feedback to global climate changes. Climatic, hydrological and ecological changes in the Arctic are clear evidence of global warming. In 2012 and 2014, the 5th and 6th Chinese National Arctic Research Expeditions undertook studies in the Bering Sea, the Arctic Ocean (including the Chukchi Sea), and the Norwegian Sea. These studies provided us with a better understanding of the marine biology and ecology in the Arctic and subarctic regions, particularly in the Pacific Arctic sector. Rapid changes observed in the Arctic environment include the shrinking of cold-water masses in the Bering Sea in the summer, and elevated water temperatures promoting phytoplankton blooms, leading to an increase in phytoplankton transferred to higher trophic levels. As a result, the transfer efficiency of organic matter toward the bottom weakened, leading to a reduction in benthic biomass. This is consistent with expectations that the overall carbon and energy flux will ultimately switch from the dominant mode of sea ice–algae–benthos to one of phytoplankton–zooplankton. Influenced by Pacific water inflow, fluvial runoff and melting sea ice, the Chukchi Sea exhibited different responses to various environmental changes. Interactions between water masses led to other interannual ecological shifts. With the increase in sea ice melt and sunlight in the central region of the Arctic Ocean, the relative abundance of heterotrophic bacteria is expected to increase, and play a vital role in the Arctic microbial loop.

**Keywords** Arctic region, climate changes, chlorophyll, plankton, benthos, microbe, food chain

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## 1 Introduction

The Arctic is among the most sensitive regions of the Earth in its response and feedback to rapid global climate changes (Yu, 2011; Zhang et al., 2011). Continuous observations and

studies over the past three decades have shown that the Arctic climate is experiencing rapid changes (Post et al., 2013). For example, over the past 150 years, the average temperature in the Arctic has been rising two to three times faster than the global average temperature (Solomon, 2007). The most conspicuous consequence of global warming in the Arctic Ocean is the ongoing reduction of the volume and spatial extent of sea ice (Chen et al., 2013). The seasonal shrinkage

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of sea ice coverage approaches 45000 km<sup>2</sup> per year in winter, and by the middle of the century, summer sea ice in the Arctic Ocean may disappear completely (Box and Cohen, 2006). Thickness and distribution of Arctic sea ice directly impacts the dynamics of local marine communities. With the loss of sea ice, the Arctic marine ecosystem is changing, resulting in changes to the distribution of fishery resources (Qu et al., 2011). In addition, exploitation of oil and gas, nearshore pollutant discharge, shipping, ocean acidification, overfishing, and tourism all have negative impacts on the vulnerable ecological balance of the Arctic ecosystem. Exploitation and utilization of Arctic marine resources have drawn attention worldwide. The Arctic region continues to face severe challenges due to the rapid changes in its climate and ecosystem.

Climatic, hydrological and ecological variations in Arctic waters show clear evidence of global warming. Therefore, the Arctic region could act as an accurate indicator of global changes (Lin and Song, 2016). Comprehensive multidisciplinary studies on Arctic marine biology and ecology could help us understand better the structure, function and spatiotemporal patterns of the Arctic marine ecosystem. Studies are also needed to shed light on the influences that physical, chemical and biological processes have on the polar ecosystem, along with the underlying response and feedback mechanisms. Finally, it is necessary to establish a baseline for the evaluation of the potential of Arctic marine biological resources, and develop appropriate management and planning procedures.

In contrast to some developed countries, including the eight countries that have territory in the Arctic Circle, China is a relative newcomer to scientific research, particularly in marine biology and ecology of the Arctic and subarctic regions. However, marine biology and ecology have always been key interests in China's investigations of the Arctic region, and much progress has been made in our understanding of these systems. In this paper, we report on advances in Chinese Arctic research in marine biology and ecology based on progress made during the 5th and 6th Chinese National Arctic Research Expeditions (CHINAREs) and other data from Arctic scientific investigations conducted by Chinese researchers. By providing a comprehensive overview of different biological communities in the Arctic region, including bacteria, pico- and nanoplankton, sympagic organisms, zooplankton and benthos, along with distribution of chlorophyll *a* (chl *a*), we draw a basic picture of how Arctic ecosystems are responding to rapid climate change, and establish a baseline for further studies on the regulatory mechanisms of the Arctic ecosystem.

## 2 A brief introduction of the 5th and 6th CHINAREs

The 5th CHINARE took place from 2 July to 27 September 2012. Research in marine biology and ecology involved 107 sampling stations in the Sea of Okhotsk, the Bering Sea, the Arctic Ocean (including the Chukchi Sea) and the

Norwegian Sea (Figure 1). In the Bering Sea, there were 40 stations, including four transects designated BL, BS, BM and BN. In the Arctic Ocean, there were 45 stations, including four transects designated R (SR), M, C0 and CC. In the Norwegian Sea, there were 21 stations, including two transects designated BB and AT.

The 6th CHINARE took place from 7 July to 24 September 2014. Research in marine biology and ecology involved 95 stations in the Sea of Okhotsk, the Bering Sea, and the Arctic Ocean (including the Chukchi Sea) (Figure 2). In the Bering Sea, there were 37 stations, including three transects designated B, BS and NB. In the Arctic Ocean, there were 57 stations, including five transects designated R, C, C0, CC and S0.

## 3 Chlorophyll *a*

In the Bering and Norwegian seas, chlorophyll *a* concentration was low and picophytoplankton dominated phytoplankton biomass. This may be attributed to the dominance of nutrient-poor oceanic water. In the Bering Sea, differences were observed between shelf and basin areas to the west and to the east of 180°E. In the basin area west of 180°E, in the epipelagic layer, there was a high concentration of chlorophyll, mostly contributed by picophytoplankton; in the shelf area east of 180°E, there was a subsurface chlorophyll maximum (SCM), mostly contributed by net phytoplankton (Le et al., 2014). These variations in size-fractionated chlorophyll contributions indicated environmental constraints on phytoplankton in the Bering Sea, with constraints increasing in prominence with depth.

In the Chukchi Sea, net phytoplankton was the largest contributor to biomass and productivity. At some stations, contribution from net phytoplankton was an order of magnitude higher than that from other stations, suggesting that net phytoplankton may be the foundation of the abundant biological resources in this region. Compared with pico- and nanophytoplankton, however, the presence of net phytoplankton was more dependent on environmental conditions. High net phytoplankton concentrations were found only in specific layers, such as the bottom of the euphotic layer. Because of the shallow depth of the Chukchi Sea, euphotic zone depth could reach the bottom or near-bottom layer. High net phytoplankton concentrations at depth suggests that rich nutrients and sufficient illumination may be present in the bottom layer (Lin and Song, 2016). Therefore, high chlorophyll concentrations in the near-bottom layer may be explained by the sinking of net phytoplankton, from the low-nutrient surface layer, to depths where nutrients exist in sufficient quantities. As the location of net phytoplankton may change with variations in environmental conditions, primary production in the Chukchi Sea could be vulnerable to climate change. The main contributors to chlorophyll were net phytoplankton, followed by pico- and nanophytoplankton.

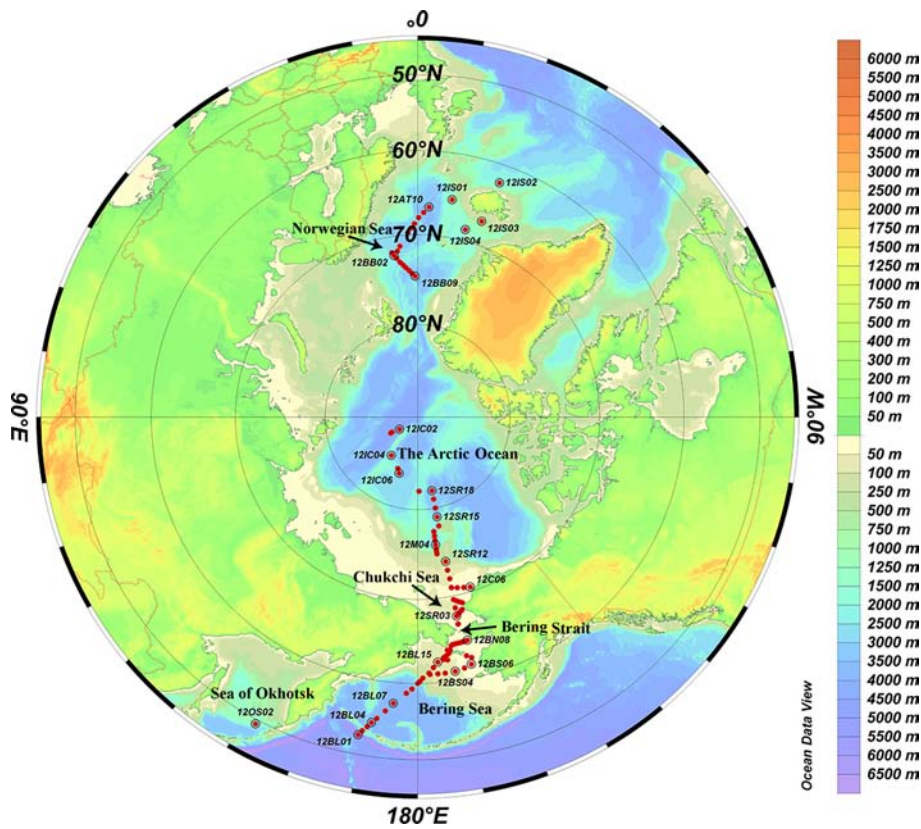


Figure 1 Map of sampling stations of marine biology and ecology during 5th CHINARE.

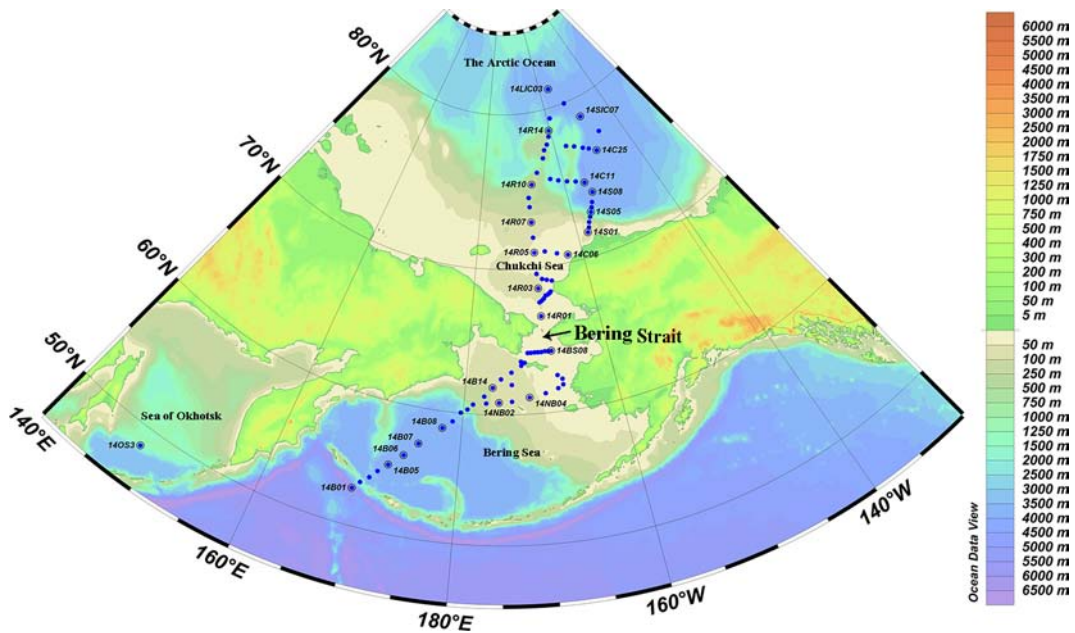


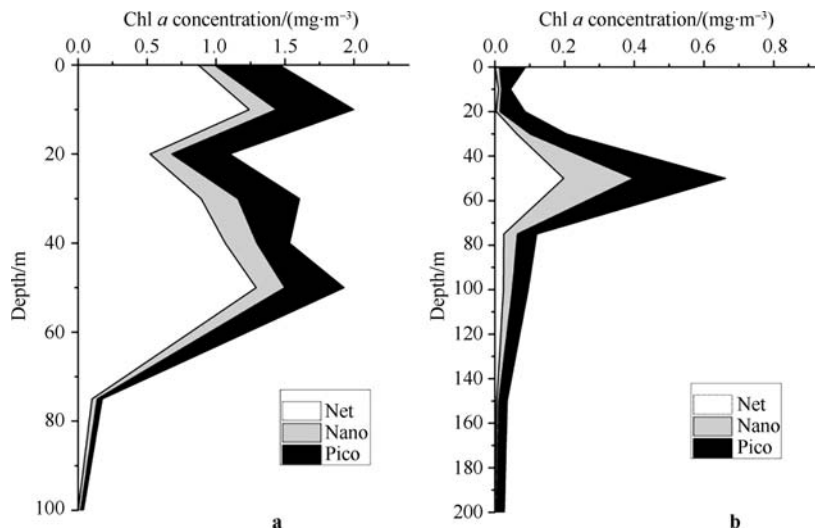
Figure 2 Map of sampling stations of marine biology and ecology during 6th CHINARE.

Ecological partitioning was also found in the Chukchi Sea. On the southern shelf (south of 75°N), chlorophyll concentration was high and was mostly contributed by net phytoplankton. High chlorophyll concentrations were found in all layers and a stable SCM layer was absent (Figure 3). This could be a result of a phytoplankton bloom—an Arctic

food pulse—that led to net phytoplankton growth; the subsequent sinking of net phytoplankton would lead to high concentrations of chlorophyll in all layers. In the area where the euphotic layer was deep and the mixing layer was shallow, nutrients were replenished rapidly, and would stimulate a phytoplankton bloom; organic matter produced

by phytoplankton in the epipelagic layer would move toward the bottom, contributing significantly to the high biomass of the benthos, potentially playing an important role in the benthic ecosystem. In the northern basin, constrained by poor nutrients and paucity of illumination induced by the sea ice cover, phytoplankton biomass was low. It was almost an order of magnitude lower than phytoplankton biomass measured in areas south of 75°N.

Vertical distribution of chlorophyll was stable, and the SCM layer was found around the depth of 50 m (Figure 3). This indicated that nutrient distribution, which is controlled by the mixing layer, had a predominant effect on chlorophyll distribution. Picophytoplankton was the largest contributor to total phytoplankton biomass. Further analysis is needed to determine if illumination or nutrients was the principal limiting factor (Lin and Song, 2016).



**Figure 3** Vertical distribution of size-fractionated chl *a* in distinct areas of the Chukchi Sea in summer of 2012. **a**, Shelf area; **b**, Abyssal area.

We examined a possible scenario in which phytoplankton in the Norwegian Sea is influenced by a mesoscale gyre. In a cyclonic gyre, upwelling at the center moves nutrients from the depths to the surface and downwelling prevents nutrients from reaching the bottom. This results in phytoplankton blooms near the surface and decline of phytoplankton biomass near the bottom. While the observed chlorophyll distribution was consistent with this scenario, primary production did not match it completely. We concluded that interpretation of carbon fixation and primary production was complicated by large variations in illumination and hydrology over the investigation area, which spanned 10 degrees of latitude (Lin and Song, 2016).

## 4 Pico- and nanoplankton communities

### 4.1 Prokaryotes

#### 4.1.1 Bacteria

Bacterial abundance exhibited a declining pattern along the Bering Sea–Chukchi Sea–central Arctic transect. In the Bering Sea, maximum abundance was found adjacent to the Bering Strait, in waters influenced by Bering shelf water. Thus, in contrast to Anadyr water and Alaska coastal water (ACW), Bering shelf water had the strongest positive effect on abundance. In the Chukchi Sea, maximum abundance was found in the bottom layer. This could have resulted

from the incapability of nutrient-poor water in the epipelagic layer to support high abundance, as Bering shelf water would have lost most of its nutrients before flowing into the Chukchi Sea; meanwhile, under the influence of resuspension, nutrients in the sediments may have been released into the water, supporting bacterial growth. Abundance was lower in the northernmost Arctic than in the southern sampling areas. Maximum abundance was found at depths of 20 to 40 m rather than in the epipelagic layer, indicating that sea ice meltwater enhanced stratification and impeded incorporation of bottom nutrients into the epipelagic layer, resulting in lower abundance (Lin and Song, 2016).

Compared with the results of the 5th CHINARE, data collected during the 6th CHINARE showed a westward expansion of the area of high abundance in the Bering Sea, indicating the expansion of ACW. In the Chukchi Sea, abundance distribution remained mostly unchanged. However, abundance was lower in 2014 than in 2012. Similar trends were observed in the central Arctic between 2012 and 2014 (Lin and Song, 2016).

#### 4.1.2 *Synechococcus*

*Synechococcus* abundance was highest in the Bering Sea, but lowest in the Chukchi Sea. The *Synechococcus* distribution observed along transect M and in the 30-m layer at the northern stations SR14 and SR15 may also be associated with enhanced ACW. *Synechococcus* in the

Arctic Ocean is thought to have originated from fluvial runoff or ACW. Therefore, regardless of its origin, the occurrence of *synechococcus* at high latitudes can be considered as an ecological effect of rapid changes in the Arctic region, and this new taxon could have a profound influence on the Arctic ecosystem (Lin and Song, 2016).

Abundance was significantly higher in 2014 than in 2012. *Synechococcus* was most abundant in the Bering Sea, particularly in the Bering Strait. In the Chukchi Sea, maximum abundance was observed on the central continental shelf in 2012. However, in 2014, abundant populations were found in the Bering Strait and at the edge of the northern shelf (Lin and Song, 2016).

## 4.2 Eukaryotic pico- and nanophytoplankton

### 4.2.1 Abundance

At below  $5 \text{ cells} \cdot \mu\text{L}^{-1}$ , picoeukaryote abundance in the epipelagic layer was low. In the Bering Sea, high abundance was observed in the deep Bering basin and along the Alaskan coast. On the Bering continental slope and shelf, abundance was found to be below  $1 \text{ cells} \cdot \mu\text{L}^{-1}$ , except along transect CC, where influence of ACW is strong. Abundance in the epipelagic layer was between 1 and  $4 \text{ cells} \cdot \mu\text{L}^{-1}$ , indicating that growth was favored by the conditions of high temperature, low salt and low nutrients present in ACW.

### 4.2.2 Community structure and pigment constitution

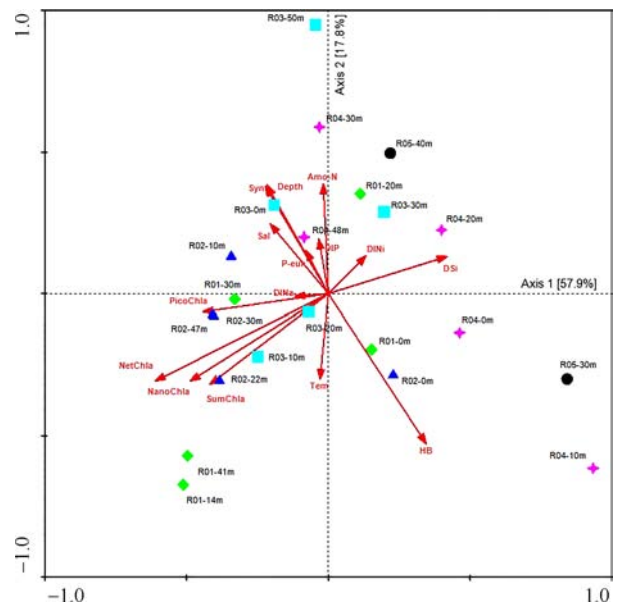
High phytoplankton abundance was found in the Bering and Chukchi seas. Diatoms were predominant, and their dominance increased with latitude. *Pavlova gyrans* and prasinophytes were also dominant in picophytoplankton and nanophytoplankton, respectively.

Chl *a* and fucoxanthin (Fuco) were the main photosynthetic pigments in the Bering Strait, and their concentrations decreased with latitude. Chl *a* and Fuco were also abundant in the Chukchi Sea.

## 4.3 Response to environmental changes

The dominant pico- and nanoeukaryotes in the Chukchi Sea were *Micromonas*, *Poterioochromonas*, *Chaetoceros*, *Gyrodinium*, *Cryptococcus* and *Cryothecomonas*. Factors that had the strongest influence on community composition and distribution were Chl *a* and silicate concentrations (Figure 4), followed by heterotrophic bacteria. Other nutrients, temperature and salinity had little influence. The Chukchi Sea is typically an area with high biomass and high productivity, where diatom blooms are common. Diatom blooms are associated with high silicate and Chl *a* concentrations; therefore, we concluded that community composition and distribution were mainly regulated by diatom blooms.

Sea ice meltwater and freshwater supply from land have continued to increase. As seawater temperature continues to rise and salinity continues to decline, dominance of nutrient-

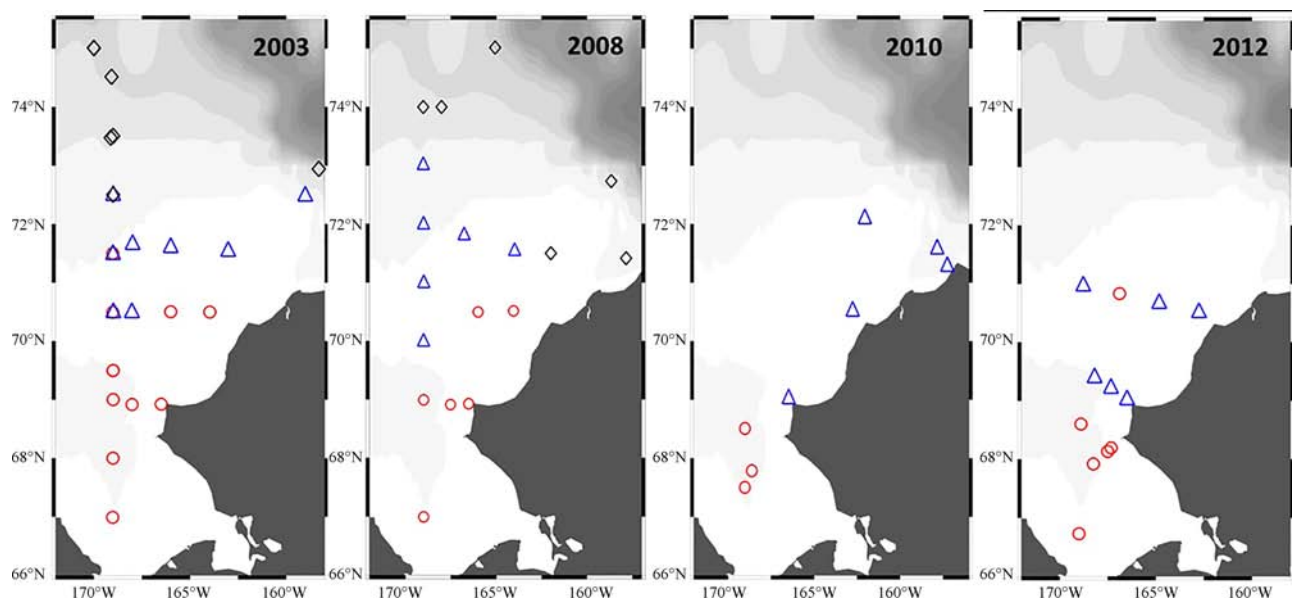


**Figure 4** Canonical correlation analysis (CCA) ordination plots showing the relationships between relative abundance of pico-eukaryotes and environmental factors, among which included dissolved silicate (DSi), dissolved inorganic nitrite (DINi), heterotrophic bacteria (HB), *synechococcus* (Syn), pico-eukaryotes (P-euk), dissolved inorganic nitrate (DINa), picochlorophyll (PicoChla), netchlorophyll (NetChla), sum chlorophyll (SumChla), temperature (Tem), salinity (Sal). Squares, rhombuses, triangles, circles and stars represent sampling stations that belong to different sectors, the names next to these geometrical shapes are captions for sampling stations and sampling depths.

limited picophytoplankton will become more obvious. Taxa in the picoplanktonic community with smaller cells will likely become more competitive, and *synechococcus* may replace picophytoplankton to become the new dominant taxon in some waters. In the central Arctic, chlorophytes have replaced diatoms to become the predominant taxa. As nutrient limitations become more widespread, competition between heterotrophic bacteria and eukaryotic autotrophs may become more significant.

## 5 Zooplankton community

From planktonic composition and abundance data collected in the Chukchi Sea during the 2nd to the 5th CHINAREs, we identified three geographically isolated zooplankton communities (Figure 5). The southern community was found in the southernmost part of the Chukchi Sea and along the Alaskan coast, where water depth was less than 50 m. The central shelf community was located on the shelf of the Chukchi Sea between  $70^{\circ}\text{N}$  and  $73^{\circ}\text{N}$ , where water depth was between 50 and 100 m. The northern slope community was found on the northern continental slope of the Chukchi Sea, where water depth was greater than 100 m (Xu et al., 2016a).



**Figure 5** Geographical distribution of zooplanktonic communities in the Chukchi Sea during the 2nd—5th CHINAREs, red circle is a symbol for southern community, blue triangle is a symbol for central continental shelf community, black rhombus is a symbol for northern continental slope community.

## 5.1 Geographical distribution

Zooplankton abundance in the western Arctic Ocean was high on the shelf and low in the basin, with average abundance on the shelf being an order of magnitude greater than that in the basin. On the slope, total abundance dropped dramatically, suggesting the presence of a clear boundary between shelf and deep-sea communities. Copepods were predominant in the basin, while copepods and barnacle larvae dominated the shelf community.

## 5.2 Interannual variation

Zooplankton communities in the northern Chukchi Sea were dominated by copepods. Community structure exhibited interannual variations, with copepod abundance increasing significantly following sea ice retreat. A different situation was observed in the southern and central shelf communities. In the southern and central shelf communities, interannual variations in total abundance were higher than those observed in the northern Chukchi Sea, but they were decoupled from sea ice coverage; in addition, copepod abundance showed an increasing pattern, while the abundance of barnacle larvae varied substantially. High abundance of planktonic larvae with benthic origins is the most prominent feature of the zooplankton community in the Chukchi Sea. Our studies found a negative correlation between meroplankton and holoplankton, with high abundance of planktonic larvae of benthic organisms, such as barnacles, being associated with low abundance of planktonic taxa, such as copepods. Our finding will be of interest for predicting responses of the Arctic shelf ecosystem to the retreat of sea ice.

## 5.3 Vertical distribution

In the Canada and Makarov Basins and the Chukchi Abyssal Plain, high concentrations of zooplankton were found in the epipelagic layer while low concentrations were found in the deep layer. Herbivorous taxa, such as *Oithona similis*, *Calanus glacialis* and *Calanus hyperboreus*, were abundant, and congregated in layers above 200 m. In layers below 200 m, omnivorous taxa, such as *Microcalanus pygmaeus*, *Metridia longa* and *Oncaea* spp., were abundant proportionally, although individual abundance declined significantly. Community composition was similar in the three investigated areas, but zooplankton abundance at low-latitude stations in the Canada Basin was far higher than that at other stations. The main difference between the vertical distribution in the Makarov Basin and that in the Chukchi Abyssal Plain was found in the layer between 500 and 1 000 m. At this depth, abundance was between 22.7 and 92.6 ind. $\cdot$ m<sup>-3</sup> in the Makarov Basin, but only 1.6 ind. $\cdot$ m<sup>-3</sup> in the Chukchi Abyssal Plain. The observed geographical difference suggests heterogeneity in the function of the biological pump. We concluded that this was induced by the high density of *C. hyperboreus*, as this species begins feeding before ice melt in spring, and consequently reduces downward flux of organic matter from ice algae (Xu et al., 2016b).

## 6 Sea ice community

### 6.1 Surface melt pond community

Biomass in melt ponds on sea ice was low. Heterotrophic taxa were the predominant group, with bacteria accounting

for 55% of the total biomass, and heterotrophic flagellates and autotrophic taxa contributing 36% and 9% to the total biomass, respectively.

Flagellates with cell size between 10 and 20  $\mu\text{m}$  constituted 59% of the biomass of all heterotrophic flagellates. Picoflagellates (5–10  $\mu\text{m}$ ) were predominant among autotrophic flagellates, accounting for 77% of autotrophic flagellate biomass. *Fragilaria* (>20  $\mu\text{m}$ ) was dominant among the diatoms in melt ponds of the central Arctic Ocean (Lin and Song, 2016)

## 6.2 Sympagic community

With an average value of 105.85  $\text{mg C}\cdot\text{m}^{-2}$ , biomass of summer sea ice in the central Arctic Ocean was low. Bacteria were the main group, followed by diatoms. Both groups are of great importance to the Arctic sea ice food chain. A flagellate bloom, with a biomass of 329.6  $\mu\text{g C}\cdot\text{L}^{-1}$ , was present at the bottom of the ice floe at station IC02. It could have been a result of ice melt and specific nutrient conditions. The ecological roles of flagellate blooms should be highlighted. Heterotrophic groups were predominant, suggesting that they may play an important role in the food chain of the Arctic marine ecosystem (Lin and Song, 2016).

## 6.3 Under-ice water column community

Total biomass in the water column under sea ice was low. Bacteria were the main group (64%), followed by flagellates (18%), and algae were low in proportion. The major food source of heterotrophic taxa was bacterioplankton, which suggests the significant role the microbial loop plays in the Arctic food chain.

Biomass of heterotrophic flagellates (10–20  $\mu\text{m}$ ) and autotrophic flagellates (2–5  $\mu\text{m}$ ) were high, with the former accounting for 47% of total biomass of all taxa in the water column. The highest and second highest abundances of diatoms were found in the cell size classes of >50  $\mu\text{m}$  and 20–50  $\mu\text{m}$ , respectively. Diatoms with small cells dominated the central Arctic Ocean. Biomass of ciliates with small cells (>20  $\mu\text{m}$ ) was high, accounting for 80% of total ciliate biomass of ciliates, although the proportion of ciliates in the water column community was low (Lin and Song, 2016).

# 7 Benthic community

## 7.1 Macrobenthos

We have identified 440 macrobenthic species belonging to 114 phyla from sediments collected from the 1st to the 6th CHINAREs. The dominant taxa were annelids (194 species), accounting for 44.1% of all species, mollusks (93 species), and arthropods (85 species). In addition, 3 poriferans, 15 cnidarians, 4 nemertean, 1 priapulid, 7 sipunculans, 1 echinuran, 2 bryozoans, 2 brachiopods, 22 echinoderms, 1 hemichordate, and 8 chordates were identified.

Macrobenthos in Arctic waters were composed mostly

of cold-water boreal species, *i.e.*, eurythermal immigrants, but only a few indigenous Arctic species (Wang et al., 2014b). This is different from the situation in the Southern Ocean where endemic species dominate. The predominant species in Arctic waters were *Maldane sarsi*, *Scoloplos armiger*, *Nephtys caeca*, *Heteromastus filiformis*, and *Scoletoma fragilis* (Annelida); *Golfingia margaritacea* (Sipuncula); *Macoma calcarea*, *Ennucula tenuis*, and *Musculus discors* (Mollusca); *Harpiniopsis vadicularis*, and *Chionoecetes opilio* (Arthropoda); and *Ophiura sarsii*, *Echinarachnius parma*, and *Ctenodiscus crispatus* (Echinodermata).

Bray-Curtis cluster analysis indicated low similarity between macrobenthic communities at most stations. Communities were complex, highly diverse and spatially heterogeneous (Wang et al., 2014b). The Arctic region is characterized by its young geological age, an unstable environment with continuous periodic oscillations and undeveloped biogeographic isolation; thus, relatively robust species exchange occurs between the Arctic region and other northern seawaters (Piepenburg, 2005), and accounts for the diverse and patchily distributed community structure found in the benthos (Wang et al., 2014b).

Biomass analysis of the continental shelf, slope and deep basin areas of the Bering Sea indicated that high macrofaunal density and biomass existed along the slope and the shelf edge, forming the Bering Sea Green Belt (Wang et al., 2014a). Biomass on the shelf of the Chukchi Sea was high, particularly in the southern and northeastern parts of the Chukchi Sea (near Barrow Canyon), but decreased sharply along a shelf–slope–basin transect (Lin et al., 2016). Warm and nutrient-rich water from the Pacific and strong pelagic–benthic coupling were believed to be the crucial factors that determined Arctic benthic community and biomass (Grebmeier et al., 2006).

## 7.2 Meiobenthos

Fourteen meiofauna groups were identified from samples collected from the 1st to the 6th CHINAREs. They included Nematoda, Copepoda, Polychaeta, Oligochaeta, Kinorhyncha, Acari, Cumacea, Ostracoda, Nauplius, Bivalvia, Tanaidacea, Isopoda, Tardigrada and undetermined taxa. Results from all CHINAREs exhibited a clear partitioning between shelf and basin. High meiofaunal abundance and meiobenthic biomass were found on the shelves of the Bering and Chukchi seas, while low abundance were recorded in the Bering Sea basin, the deep sea, and the high latitude waters of the Arctic Ocean (Lin et al., 2014b; Huang et al., 2016).

Results from all CHINAREs indicated that abundance was the most significant difference between meiobenthic communities. In most years, the average measured abundance was around 2600  $\text{ind}\cdot(10\text{ cm})^{-2}$ , while a lower value was measured in the Chukchi Sea during the 5th CHINARE. Abundance gradually decreased along the Bering Sea shelf–Bering Sea basin–Arctic Ocean transect.

Variations in group numbers and diversity also showed a similar pattern.

Previous studies regarding meiobenthos have mainly focused on the Beaufort and Laptev seas and the Canada Basin, while studies focused on our investigation areas—the Bering and Chukchi seas and the Bering Strait—remain scarce. In contrast to previous studies, results from CHINAREs showed that, in deep waters, abundance varied little with location, and communities comprised only a few groups; in shallow shelf waters, abundance was higher than that found in most other waters, including the nearshore waters of China, indicating that the continental shelf waters included in our studies have abundant meiobenthic populations.

### 7.3 Demersal fishes

During the demersal fish investigations from the 4th to the 6th CHINARE, 67 fish species belonging to 9 orders, as well as 2 elasmobranchs and 65 teleosts, were recorded. *Hippoglossoides robustus* and *Gymnocanthus tricuspis* were the most abundant and widely distributed species. Species composition was closely related to water depth. Species composition in the shallow shelf water of the Chukchi Sea resembled that of the Bering Sea.

The southern part of the Bering Sea is connected to the Pacific Ocean, and water exchange between them is clear and unblocked. The southern part of the Chukchi Sea is connected to the Bering Sea through the Bering Strait, and thus its hydrological characteristics are strongly influenced by Pacific water. The northern part of the Chukchi Sea is deeply influenced by the low temperatures of sea ice, and is connected to the North Atlantic waters through Fram Strait and the Canadian Archipelago. Therefore, fish species compositions of the Bering and Chukchi seas share features of both the North Pacific and Arctic oceans, but they are also associated with the fish fauna of the North Atlantic Ocean, thereby forming a unique composition.

We observed some fish beyond their previously recorded ranges. This phenomenon indicated that some indigenous fishes that had previously been restricted to the North Pacific or Arctic–North Atlantic waters were dispersing and altering their traditional ranges due to environmental and climatic changes (Lin et al., 2014a).

## 8 Responses of the Arctic marine ecosystem to rapid climate changes

During our investigations, we observed that cold-water masses in the Bering Sea began to shrink in the summer, and the elevated water temperatures promoted phytoplankton blooms. Zooplankton food intake increased, weakening the transfer efficiency of organic matter toward the bottom, reducing benthic biomass (He and Zhang, 2012). Nutrients were consumed by phytoplankton, leading to an extensive nutrient-poor area along the shelf. With continued

rapid climate change, the overall carbon cycling and energy flux may switch from the dominant mode of sea ice–algae–benthos to one of phytoplankton–zooplankton (Piepenburg, 2005).

Influenced by Pacific water inflow, fluvial runoff, and melting sea ice, we also observed that the Chukchi Sea exhibited different responses to various environmental changes. Water masses with heterogeneous properties led to interannual variations in ecological elements, such as fluctuations in community composition in the southern and central shelf zooplankton communities, and fluctuations in the abundance and biomass of zoobenthos. With continued rapid climate change, phytoplankton cell size may also decrease (Yu, 2016).

As sea ice melts in the central Arctic Ocean, sunlight and relative abundance of heterotrophic bacteria increase, and will play a vital role in the Arctic microbial loop (He et al., 2011). Water mass structure is the principal factor determining the growth and distribution of the bacterioplankton community in the newly ice-free waters in the Arctic. We observed that the relative proportions of Pacific and Atlantic water inflows shaped nutrient structure, affected phytoplankton growth and cell size, altered dissolved organic matter import, and determined the growth and distribution of the bacterioplankton community. Finally, we noted that variations in zooplankton composition in the epipelagic layer contributed to a reduction in organic matter vertical flux, which resulted in low zooplankton abundance in the mesopelagic layer.

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