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Holocene climate change and anthropogenic activity records in Svalbard: a unique perspective based on Chinese research from Ny-Ålesund

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Abstract Climate change in the Arctic region is more rapid than that in other areas owing to Arctic amplification. To better understand climate change and the driving mechanisms, long-term historical reconstructions throughout the Holocene and high-resolution records of the past few hundred years are required. Intense anthropogenic activities in the Arctic have had a great impact on the local environment. Here, we review the Holocene climate change record, responses of the ecosystems to climate change, and the anthropogenic impacts on the environment based mainly on Chinese research from Ny-Ålesund. Climate reconstruction studies from Svalbard have revealed several cold episodes during the Holocene, which are consistent with ice rafting events in the North Atlantic region and glacier activity from Greenland, Iceland, and Svalbard. The ecosystem also showed corresponding responses to climate change, especially during the late Holocene. Over recent decades, anthropogenic activities have caused serious pollution and deterioration to the local environment in Svalbard in areas frequented by people. Greater environmental protection is therefore needed to reduce the anthropogenic impacts on the local environment.

Keywords **Arctic, climate change, ecology, anthropogenic activity**

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1 Introduction

The Arctic has undergone significant changes in the recent past (Birks et al., 2004a; Cohen et al., 2014). Rapid warming of the Arctic (Overpeck et al., 1997; Jones and Birks, 2004), especially since the mid-19th century, has led to a decrease in the extent of sea ice and snow cover (Stroeve et al., 2007; Comiso et al., 2008), retreat of glaciers (Straneo and Heimbach, 2013), and degradation of the permafrost (Lawrence et al., 2008), which may also generate several positive feedbacks to amplify climate change in the Arctic (Curry et al.,1996; Cohen et al., 2014). Recent research has shown that the Arctic region is warming at twice the global average, a phenomenon known as Arctic amplification (Cohen et al., 2014). Furthermore, the frequent extreme weather events in the mid-latitudes may be related to Arctic amplification across the Northern Hemisphere (Cohen et al., 2014). To fully understand these changes, we must answer questions such as how rapidly did the climate change in the past, did such phenomena occur during the historical period, and what is the driving mechanism of climate change in the Arctic?

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Holocene climate is generally thought to have been relatively stable. However, evidence from North Atlantic sediments indicates that several cold episodes occurred in the Holocene with a cycle of approximately 1470 ± 500 years (Bond et al., 1997). Early Holocene climate oscillations were also observed in three Greenland ice cores (Rasmussen et al., 2007). Larsen et al. (2012) presented a record of glacier activity and environmental change from Iceland to study Holocene climate evolution in the North Atlantic. Bjune (2005) reconstructed the Holocene vegetation history and tree-line changes in Norway using pollen and plant macrofossils in lake sediments. Large numbers of climate proxies, such as ice cores (Johnsen et al., 2001; Rasmussen et al., 2007; Steffensen et al., 2008), glacier variations (Miller et al., 2005; Larsen et al., 2012), biological proxies (Bjune, 2005; Jiang et al., 2011; Alsos et al., 2016), and sediments (Bond et al., 2001; Kaplan et al., 2002; Kaufman, 2009), have been used to investigate Holocene climate change in the Arctic. The Svalbard archipelago is located near the interface of the warm Atlantic and the cold Arctic waters, and is sensitive to climate change (Werner et al., 2016). However, climate change records from Svalbard are still very rare.

Rapid climate change and intense anthropogenic activities over recent decades have caused a series of environmental issues in Svalbard. Although there are still many problems in the study of atmospheric contamination owing to high background values and site-specific characteristics (Birks et al., 2004a), the local mining industries and coal-fired power stations during the 20th century and the rapid development of tourism in recent years have caused pollution and deterioration of the local environment in areas on Svalbard frequented by people (Birks et al.,2004b; Rose et al., 2004; Madsen et al., 2009; Eckhardt et al., 2013). Therefore, investigating the pollution status of Svalbard is required to better understand the anthropogenic impacts on the environment.

In this paper, we review the Holocene climate change in Svalbard, especially in Ny-Ålesund, and discuss the ecological responses to climate change. We also investigate the pollution status in Ny-Ålesund and the anthropogenic impacts to the environment, and highlight the need to enhance environmental protection awareness in Svalbard.

2 Regional setting

Svalbard (76°–81°N, 10°–35°E) is a High Arctic archipelago located between the Barents and the Greenland seas (Figure 1). Svalbard is 657 km north of the Norwegian mainland, halfway to the North Pole. It is the most northerly settled land in the world and the total land area is approximately 63000 km^2. Spitsbergen is the largest island of Svalbard with an area of over 39000 km^2. Up to 60% of the land area is permanently covered by ice and glaciers, and the largest ice-free areas are in the central and western parts (Hisdal, 1998). Along western Svalbard, an arm of the Gulf Stream, the Norwegian Current, flows northwards to create the northernmost area of open water in the Arctic. These currents, coupled with high cyclonic activity, produce a polar maritime climate along the western regions (Birks et al., 2004b). In contrast, eastern Svalbard is influenced by cold currents from the north (Hisdal, 1998).

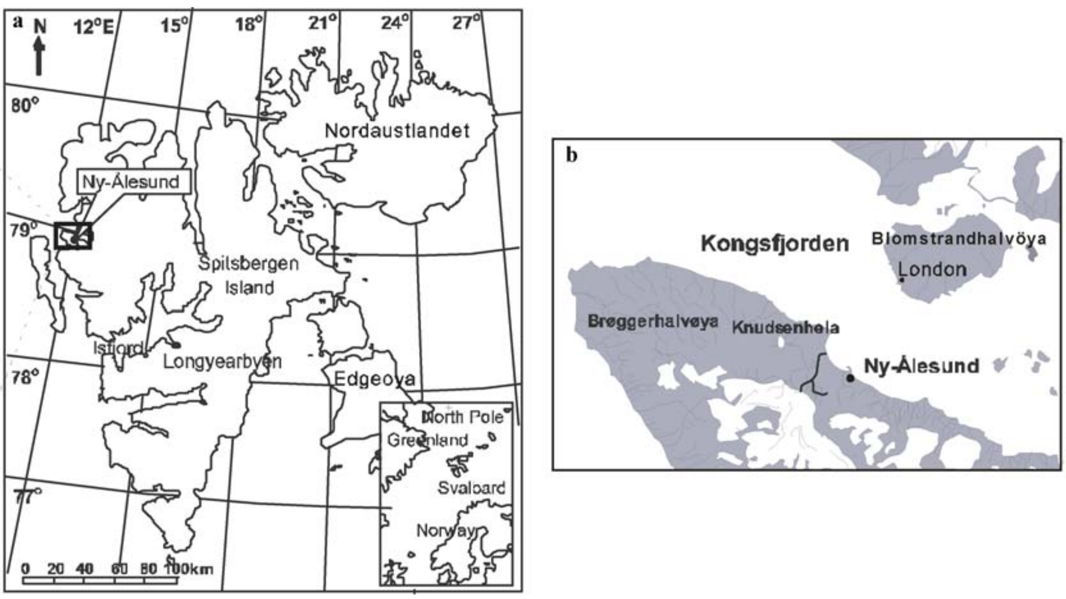

Figure 1 Map of the study area. Locations of Svalbard (**a**); and Ny-Ålesund and Blomstrandhalvöya Island (**b**).

The mean annual air temperature recorded from the meteorological station in Ny-Ålesund was –5.2°C between 1981 and 2010 (Førland et al., 2011), approximately 6–7°C warmer than eastern Greenland at the corresponding latitude. Summers are relatively mild; for example, the mean summer air temperature in Ny-Ålesund (1981–2010) was 3.8°C (Førland et al., 2011). The annual mean precipitation is approximately 400 mm along the western coast, gradually decreasing to

200–300 mm toward the inland areas (Hisdal, 1998).

There is a great diversity of vegetation in Svalbard including 742 lichen species (Øvstedal et al., 2009), 373 bryophyte species (Zhang et al., 2015), and 184 vascular plant species (Alsos et al., 2017). In addition, ~1100 types of known terrestrial and freshwater invertebrate fauna are found in Svalbard (Coulson, 2007). The vegetation of western Svalbard lies largely within the northern Arctic-tundra and Arctic polar desert zones with some middle Arctic-tundra vegetation in the inner-fjord areas (Birks et al., 2004b). Detailed descriptions of the climate, geology, and the vegetation of Svalbard are provided in Birks et al. (2004b).

3 Holocene climate change records

The Late Weichselian Barents ice sheet covered most of Svalbard with its adjacent margins during the Last Glacial Maximum (Landvik et al., 1998). The Barents ice sheet may have begun to deglaciate as early as 15000 BP (Elverhøi et al., 1993) and no later than 13310 ± 110 BP according to radiocarbon dates from a mollusk (Vorren et al., 1988). The ice sheet retreated to the western coast of Spitsbergen around 12500 BP (Lehman et al., 1992; Mangerud et al., 1992; Forman et al., 2004) and the Svalbard Archipelago gradually appeared. However, there are few Holocene paleoclimate reconstructions from Svalbard so far. Watanabe et al. (2001) reconstructed the temperature records for the past six hundred years using ice cores (Austfonna and Vestfonna) from the Svalbard archipelago. Recent environmental change and atmospheric contamination have been investigated using lake sediments (Jones and Birks, 2004; Birks et al., 2004a, 2004b; Betts-Piper et al., 2004; Brooks and Birks, 2004). However, the time scale of these studies is short and insufficient for long-term climate change research. Holocene glacier variability has been reconstructed from glacier-fed lake sediment (van der Bilt et al., 2015). Alsos et al. (2016) reconstructed past vegetation and species diversity from Skartjørna lake sediment and assessed the resilience of Arctic flora to Holocene climate change. However, other Holocene climate records from Svalbard are rare. A major reason for this is that the glaciers during the Holocene were at their maximum during the Little Ice Age and destroyed large quantities of lacustrine sediment sequences. Therefore, did any proxy material survive the movement of the glaciers?

In 2005, Sun et al. (2005) found a well-preserved paleo-notch sediment sequence in Fildes Peninsula, Antarctica, which provided reliable proxy material to study the paleoclimate and the paleoenvironment. Similarly, Yuan et al. (2011) collected a well-preserved paleo-notch sediment sequence (Yn) in Ny-Ålesund and found a large number of mollusk shell fragments in the sediment profile. They performed AMS ^{14}C dating, and stable oxygen and carbon isotope analyses on the shell fragments. The reservoir- corrected radiocarbon ages of all the shell fragments averaged 9400 BP and the reconstructed paleotemperature using aragonite oxygen isotope showed that the environmental temperature ranged from −0.52 to 4.78°C, about 1°C warmer than today (Figure 2). The reconstructed sea surface temperature (SST) in western Svalbard showed an abrupt decrease of ~2°C around 9400 BP (Hald et al., 2007). Thus, the mortality of mollusks may have been caused by an abrupt cooling event around 9400 BP. The ^{14}C production rate (Oeschger et al.,1975) and the ^{10}Be flux (Yiou et al.,1997) indicate that solar irradiation weakened around 9400 BP (Figure 3). The North Atlantic climate became colder at ~9400 BP, characterized by the increase of hematite-stained grains and Icelandic glass, and a decrease in the $\delta^{18}O$ of *Neogloboquadrina pachyderma* (d) in the deep-sea sediment (Bond et al., 2001) (Figure 3). This sudden cooling event, which was also reported by a number of studies (Bradbury et al., 1993; Bond et al., 1997; Björck et al., 2001), was likely caused by declining solar irradiation, weakened thermohaline circulation, and abrupt decreased SST (Yuan et al., 2011).

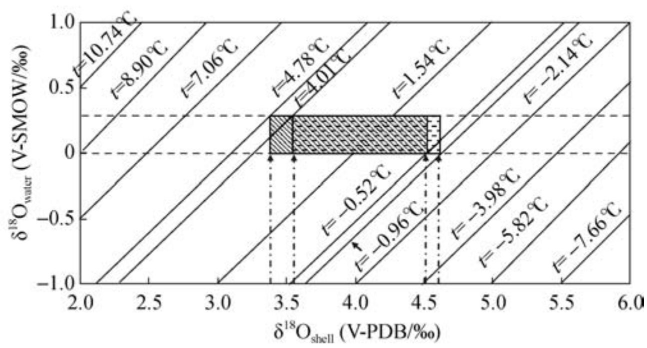

Figure 2 $\delta^{18}O$ values of the fossil shells in the paleo-notch sediment, the modern shells, and the reconstructed paleotemperatures (fossil shells ranged from −0.52 to 4.78°C, while modern shells ranged from −0.96 to 4.01°C) (Yuan et al., 2011).

In addition, Yang et al. (2017) found an undisturbed paleo- notch sediment sequence (LDP) on Blomstrandhalvöya Island (Figure 1), about 5 km to the north of Ny-Ålesund, and reconstructed mid- to late Holocene climate change in this area. Multiple weathering indices were determined, and the variation profiles of TOC and TN were similar to those of weathering indices, which indicated four cold and four warm periods in the study area. The cold climate conditions at ~5600 BP marked the termination of the Holocene thermal maximum (Larsen et al., 2012). The recorded cold periods during 4100–4500 BP and 2500–3000 BP were in good agreement with the increase of hematite-stained grains in deep sea sediment and glacier advance in the Arctic region (Figure 4). An abrupt shift to colder conditions was also recorded in Svalbard (Balascio et al., 2016) and Greenland (Balascio et al., 2015). Thus, the reconstructed climate conditions in Blomstrandhalvöya Island are consistent with ice rafting events in the North Atlantic region (Bond et al., 1997) and glacier activity in Greenland, Iceland, and Svalbard (Larsen et al., 2012; van der Bilt et al., 2015; Balascio et al., 2015) (Figure 4).

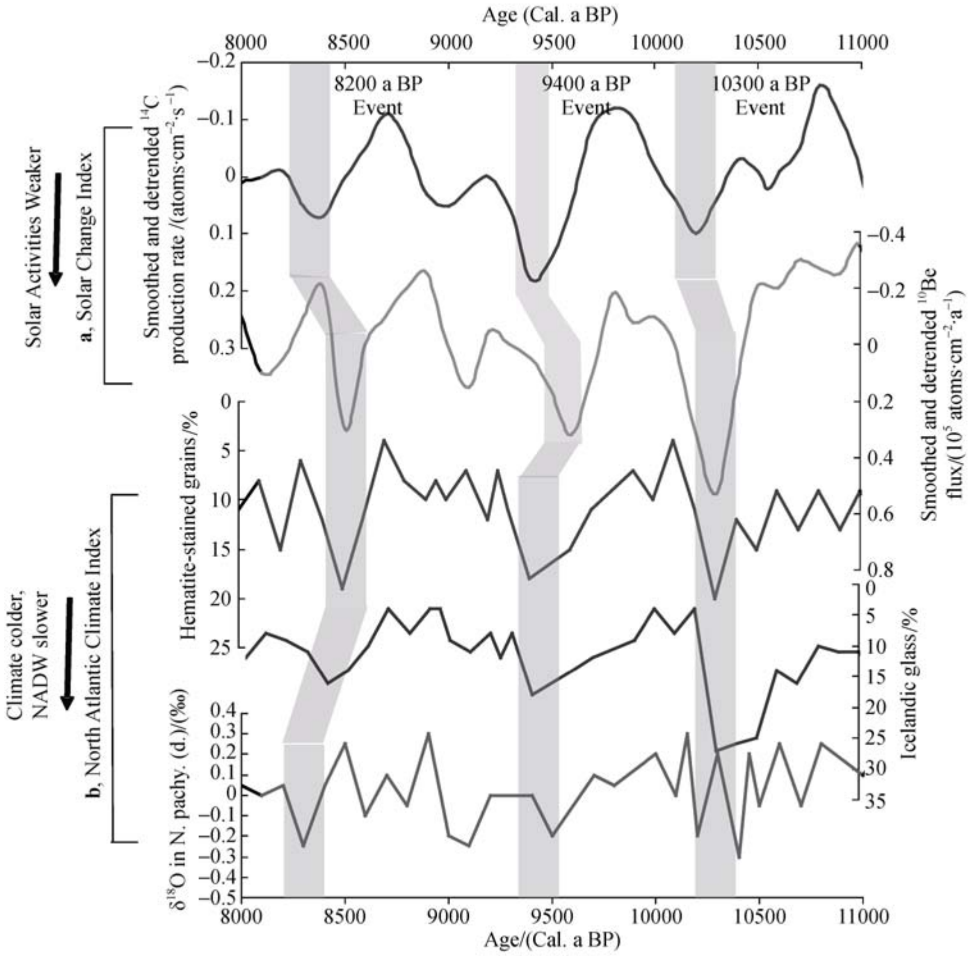

Figure 3 High-resolution climate records from 11000 to 8000 BP (Yuan et al., 2011). The shaded areas indicate the cooling events around 8200, 9400, and 10300 BP. **a**, ^{14}C record from tree rings corrected for marine and terrestrial reservoir effects (Oeschger et al., 1975), and ^{10}Be record from Greenland ice cores converted to a ^{10}Be flux (Yiou et al., 1997), which are regarded as solar activity proxies; **b**, The North Atlantic Climate Index, including hematite-stained grains, Icelandic glass, and the planktonic $\delta^{18}O$ from *Neogloboquadrina pachyderma* (d) of VM29-191 in the eastern North Atlantic (Bond et al., 2001).

The late Holocene and recent climate change were also reconstructed from a lake sediment record from Ny-Ålesund (Jiang et al., 2011) on the basis of multi-proxy analyses on sediment pigments, mineral magnetic susceptibility, various sediment quality (i.e., organic matter content, $CaCO_3$ content, and carbon and nitrogen isotopes), and diatom composition (Figure 5). All the proxies recorded the cold period from AD 1420 to 1850, corresponding to the Little Ice Age, and the cold conditions caused a decline in lake primary productivity. During the 20th century, the increase in sediment pigment, diatom population, and TOC content indicate the recent climate warming and increase in precipitation at Ny-Ålesund.

Holocene climate has been traditionally thought as relatively stable. However, research from North Atlantic deep water cores showed abrupt shifts in the Holocene climate (Bond et al., 1997). Evidence from paleo-notch and lacustrine sediments also indicate that Ny-Ålesund experienced significant climate change throughout the Holocene (Jiang et al., 2011; Yuan et al., 2011; Yang et al., 2017) and that the reconstructed climate change is consistent with the climate records from other areas of the Arctic (Bond et al., 1997; Larsen et al., 2012; van der Bilt et al., 2015; Balascio et al., 2015).

4 Ecological responses to climate change

The special environment in the Arctic makes the ecosystem sensitive to climate change. Therefore, changes in the ecosystem could be an ideal proxy to reflect climate change. Many studies of vegetation history have been performed in the Arctic. Jiang et al. (2011) studied multiple biological proxies to investigate the ecological responses to climate change (Figure 5). The lake primary productivity decreased during the Little Ice Age owing to the cold climate, which was unfavorable for the growth of lake algae. The warm climate after about AD 1890 led to the rapid growth of lake algae, and enhanced lake primary productivity. The Holocene

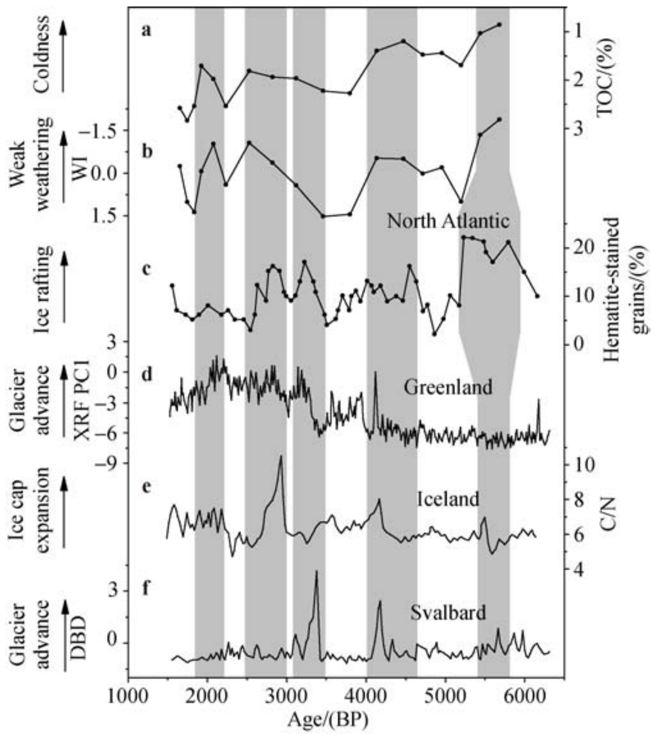

Figure 4 Paleoclimatic records from the North Atlantic region during the mid- to late Holocene (Yang et al., 2017). **a**, Climate change inferred from the TOC content in paleo-notch sediment sequence LDP (Yang et al., 2017); **b**, Standardized weathering history proxy of Svalbard (Yang et al., 2017); **c**, Variations of Hematite-stained grains from a North Atlantic deep sea sediment core as a proxy for ice rafting events (Bond et al., 2001); **d**, XRF PC1 data from Kulusuk Lake sediment in Greenland, a proxy for Kulusuk glacier movement (Balascio et al., 2015); **e**, The carbon-nitrogen ratio from Hvítárvatn Lake sediment in Iceland interpreted to indicate the size of the Langjökull ice cap (Larsen et al., 2012); **f**, Dry Bulk Density (DBD) changes in the lake sediment in Svalbard interpreted to reflect past variations in glacier movement (van der Bilt et al., 2015).

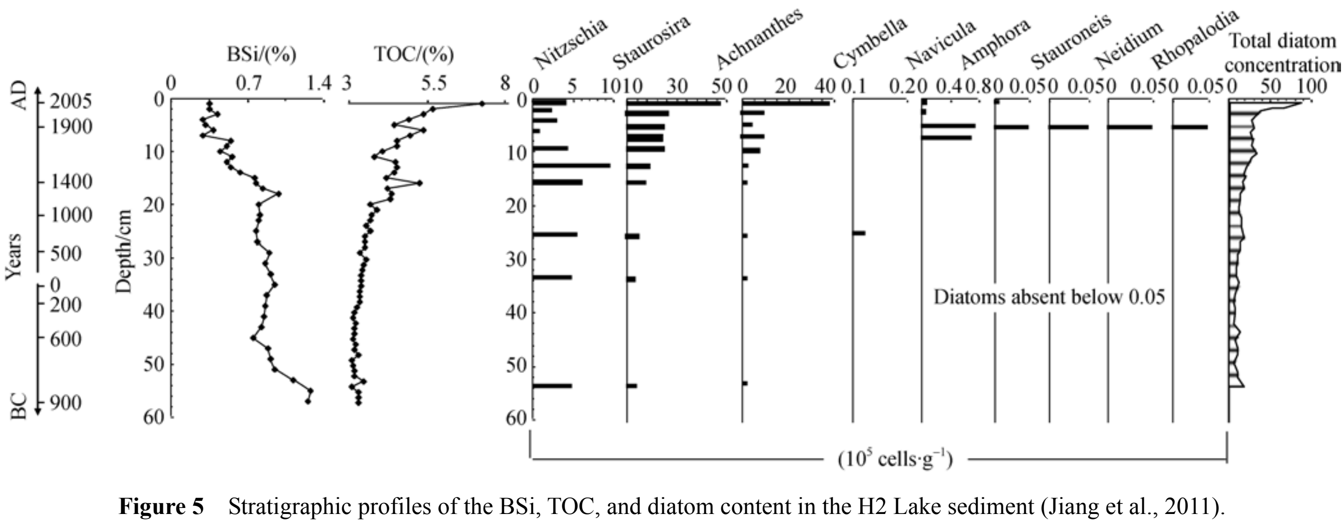

Figure 5 Stratigraphic profiles of the BSi, TOC, and diatom content in the H2 Lake sediment (Jiang et al., 2011).

vegetation history was reconstructed based on plant macrofossils from Skardtjørna, an Arctic lake (Birks, 1991), and the vegetation history showed synchronous responses to climate change. These findings were further confirmed by the sedimentary ancient DNA results (Alsos et al., 2016). Past vegetation from the inner fjords of the Svalbard has been studied based on macro- and micro-fossils to track its response to climate change (Bernardová and Košnar, 2012). The occurrence of *Salix herbacea x polaris*, a taxon that requires warm conditions, was correlated with the Holocene thermal optimum (8000 to 4000 BP), consistent with Birks (1991). Previous research on the vegetation history of Svalbard has mainly involved pollen, diatoms, and plant macrofossils (Birks,1991; Jiang et al., 2011; Bernardová and Košnar, 2012). In recent years, sedimentary ancient DNA has been used widely in vegetation reconstruction (Alsos et al., 2016).

Although many studies have been performed to reconstruct the vegetation history of the Arctic, research concerning the ecology of marine animals, such as sea birds or mollusks, have rarely been reported. The growth of shallow-marine mollusks may be affected by factors, such as ambient water temperature (Kennish and Olsson, 1975), food availability (Sato, 1997), and the influx of meltwater (salinity change) (Schöne et al., 2005). Water temperature and food availability are the main controlling factors for shell growth (Sato, 1999). The food source of the mollusk is mainly derived from meltwater and the die-off of the mollusks around 9400 BP was likely caused by the abrupt decrease in temperature and influx of meltwater (causing the sharp reduction in food availability) (Yuan et al., 2011) during the cooling event.

The ecosystems in the border zone of land and sea are unique in the Arctic (Stempniewicz et al., 2007). The terrestrial ecosystems in the Arctic are usually deficient in nutrients, which are characterized by low biomass and primary production, while marine animals, such as seabirds, can transport nutrients and energy from sea to land (Stempniewicz et al., 2007; Huang et al., 2014). Blais et al. (2005) first proposed that seabirds are the main bio-vector of marine-derived nutrients and contaminants to land. Seabirds in the Arctic therefore play a significant role in biogeochemical cycling. Wagner and Melles (2001) reconstructed a Holocene seabird record from a lake sediment core in East Greenland. The biogeochemical evidence indicated a high abundance of seabirds between 7500 and 1900, from 1000 to 500, and since 100 BP. The disappearance of most seabirds at ~1900 BP was likely caused by climate deterioration (Wagner and Melles, 2001). Seabirds returned between 1000–500 BP, indicating a warm climate during the medieval period. During the Little Ice Age, the seabirds almost completely disappeared. The seabird populations in East Greenland are therefore sensitive to climate change (Wagner and Melles, 2001). However, few studies exist on the ecological history of seabirds in Svalbard. The age of the base of the paleo-notch sediment Yn was 9400 BP based on radiocarbon dating of two mollusk shell fragments (Yuan et al., 2010). The organic material in the sediment was mainly derived from seabird guano according to the $\delta^{13}C_{org}$-C/N plot and $\delta^{14}N_{org}$ characteristics (Figure 6), which indicated that seabirds had colonized Ny-Ålesund, Svalbard ~9400 years ago (Yuan et al., 2010). This study was the first report on seabird occupation on Ny-Ålesund. However, there is no further data on the seabird population after the colonization of Ny-Ålesund. Therefore, future research is required to investigate the ecological history of seabirds and its response to climate change in Svalbard.

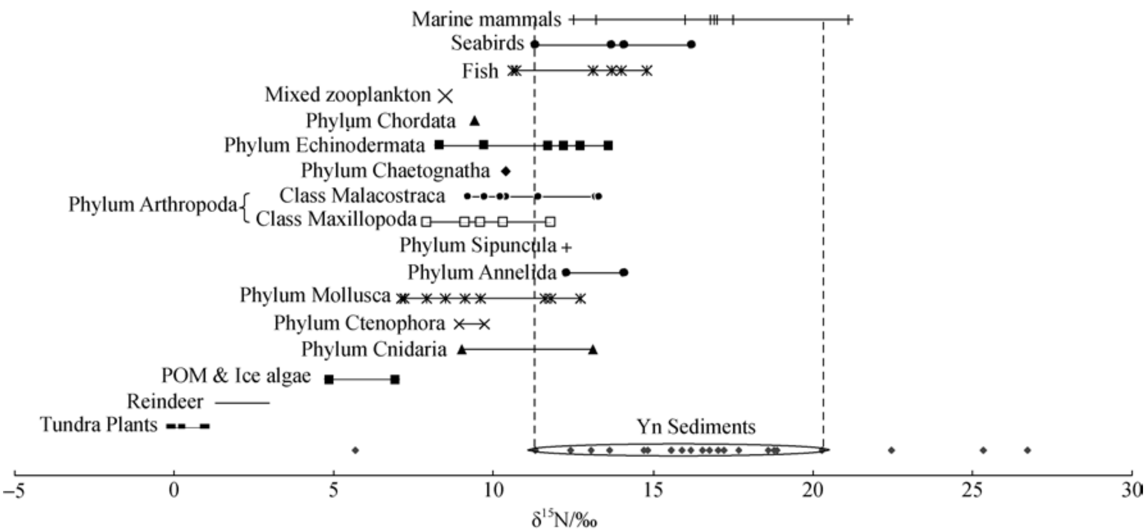

Figure 6 Range of $\delta^{15}N$ variability of different trophic levels in the Arctic marine ecosystem (Yuan et al., 2010). The solid squares at the bottom represent the $\delta^{15}N$ values of the paleo-notch (Yn) sediments.

5 Anthropogenic impacts on the environment

Since the Spitsbergen was first discovered in 1596, anthropogenic activities have intensified. The English trading Muscovy Company began to hunt seal, walrus, and whale in the 17th century, soon followed by the Dutch. The hunting activities peaked around the 1630s. Russia built year-round habitations in the 18th century and their hunting activities peaked at the end of the 18th century. The population of whales in this area decreased rapidly and the whaling industry ended in the 19th century (Hisdal, 1998; Birks et al., 2004b). In the 20th century, the main activity in Svalbard was coal mining by Norway and Russia. The Norwegian mines were centered at western Svalbard, Longyearbyen, Ny-Ålesund, and Sveagruva; while Russian mining areas were in Barentsburg, Grumantbyen, and Pyramiden. The coal-fired power stations generated large amounts of pollutants in the Isfjord area for at least 40 years (Rose et al., 2004), and a gas-oil powered station in Ny-Ålesund became the local pollution source (Beine et al., 1996). In addition, the rapid development of tourism in this area has had a substantial influence on the local environment (Madsen et al., 2009; Eckhardt et al., 2013). Evidence from Svalbard lake sediments indicates that atmospheric contamination results from a combination of local and remote sources (Rose et al., 2004; AMAP, 2009). The assessment of the pollution status of Svalbard is important.

Paleoenvironmental records can be used to track the anthropogenic contamination history through long-range transport. The distributions of Hg and MeHg (Jiang et al., 2011), and historical records of Pb pollution (Liu et al., 2012) were reconstructed from the H2 lake sediments from Ny-Ålesund (Figure 7). The Hg and Pb concentrations caused by anthropogenic contamination began to increase around AD 1400, experienced a large increase since the Industrial Revolution, and peaked in the 1960–1970s. Increased Hg and Pb concentrations from AD 1400 and the further development of the industrial era were mainly caused by the anthropogenic contamination through long-range atmospheric transport. However, the peak values of Hg in recent decades were likely caused by the increased algal scavenging process (Jiang et al., 2011). The anthropogenic Pb peaked between the 1960s and 1970s owing to the heavy use of leaded gasoline during that period. Most of the Pb pollution was transported from western Europe and Russia according to the excess Pb isotope ratios (Liu et al., 2012).

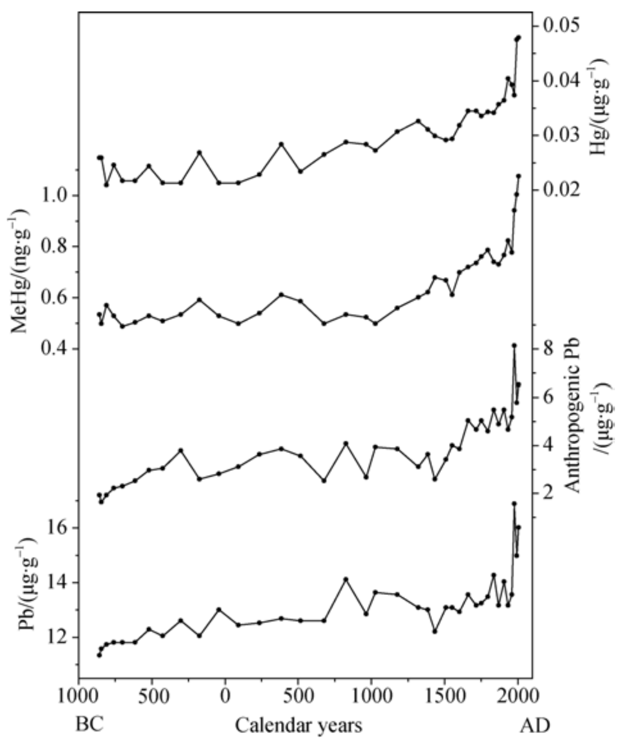

Figure 7 Temporal changes in the Hg and MeHg concentrations (Jiang et al., 2011), Pb, and anthropogenic Pb concentrations (Liu et al., 2012) in the H2 Lake sediments from Ny-Ålesund, Svalbard.

In recent decades, coal mining and intense anthropogenic activities have had a great impact on the local environment. Multiple tundra plants and soil samples in Ny-Ålesund were analyzed for heavy metal elements (Hg, Pb, Cd, Cu, Zn, Ni, Fe, Mn, As, and Se), and S and TOC content, with the pollution found to originate from coal mining activities (Wang et al., 2007). The local tundra plant *Dicranum angustum* had a substantial and selective enrichment of these heavy metals, and could therefore be a good bio-indicator for heavy metal pollution in Ny-Ålesund (Wang et al., 2007). Sun et al. (2010) analyzed antimony (Sb) concentrations in the soil, moss, and sediment samples from Ny-Ålesund. The Sb concentrations of the soil and moss samples near the coal mine were higher than those far away from the coal mining activities; while the Sb concentrations in the upper part of the sediment profile were at a high level that may have been related to anthropogenic activities, such as coal mining and gas burning. Analysis of Sb in multiple topsoil and moss samples in Ny-Ålesund also indicated that the distribution of Sb in this area was partially related to traffic and historical mining activities (Jia et al., 2012). However, the maximum Sb concentration was caused by anthropogenic activities (Jia et al., 2012) (Figure 8).

6 Conclusion

This review summarizes the Holocene climate change record, ecological responses to climate change, and anthropogenic impacts on the environment based mainly on Chinese research in Ny-Ålesund. The major points are:

(1) The Holocene climate in Svalbard experienced several cold episodes, which is consistent with ice rafting events in the North Atlantic region and glacier activity from Greenland, Iceland, and Svalbard. After the 20th century, the climate has continued to warm.

(2) The biomass and primary production in an Arctic lake had a positive response to climate change, and the die-off of mollusks around 9400 BP was likely caused by the sudden cooling event at that time. Evidence has shown that seabirds colonized Ny-Ålesund, Svalbard at ~9400 years ago. This is the first report on seabird occupation on Ny-Ålesund, and thus future research is required to investigate the ecological history of seabirds and its response to climate change in Svalbard.

(3) The contamination in Svalbard is a combination of both local and remote sources. Anthropogenic contamination began to increase around AD 1400, and most of the pollution was transported from western Europe and Russia. However, coal mining, a power station, and intense anthropogenic activities in recent decades have caused serious pollution around inhabited regions in Ny-Ålesund.

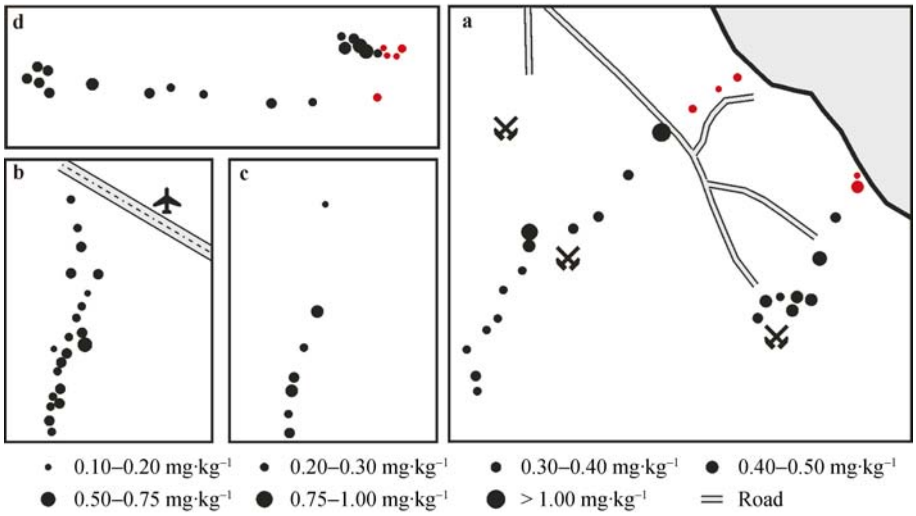

Figure 8 Sb distribution in topsoils in Ny-Ålesund (Jia et al., 2012). The larger the solid circle, the higher the Sb distribution.

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