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REVIEW

Holocene records of paleoclimatic and paleoceanographic changes in the western Arctic

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ABSTRACT: Understanding of past climate variability on millennial to decadal scales are of primary importance in order to assess modern processes and predict future climatic events. Past history of Arctic climate changes is currently receiving increasing attention due to the recent phenomena of rapid sea-ice reduction. In this paper, we thoroughly reviewed the Holocene history of spatiotemporal climatic changes in the western Arctic region in order to better understand recent rapid environmental changes occurring in the Pacific sector of the Arctic, and further to discuss critical issues and new perspectives on the western Arctic in terms of paleoclimate researches. Records of temporal and spatial variations in sea-ice extents as well as marine and terrestrial paleoclimatic proxies show a strong asynchronicity between the western and eastern Arctic throughout the Holocene. The reason for this apparent contradiction across the Arctic may be linked to freshwater discharges over the Arctic shelves and the inflow of the Pacific freshwater into the western Arctic Ocean in coupled with a complex interaction between atmospheric and sea-ice dynamics. Special emphasis is placed on a tentative linkage of the late Holocene paleoclimatic events between the Arctic regions and the northwestern Pacific margin, highlighting the notion that climatic events of the northern Pacific Ocean is closely linked to the global climate system through hydrological dynamics in the western Arctic Ocean.

Key words: Holocene, Arctic, sediment, paleoclimate, sea-ice

1. INTRODUCTION AND OVERVIEW

The Arctic has a strong influence on the modern and past global climate system with its unique climatic, hydrographic and geological features (IPCC, 2007; Anderson et al., 2008; Hu et al., 2012). For the last decades, the so-called 'polar amplification', which has the most significant impacts on the Earth climate system in relation to increasing greenhouse gas concentrations, has been recently observed in the Arctic region through changes in sea-ice extent and thickness (e.g., Holland and Bitz, 2003). Such sea-ice variations affect global climate system by regulating surface albedo, heat and moisture fluxes, temperature and salinity structure of the upper water masses and consequently, the global thermohaline circulation (Aagaard and Carmack, 1994; Stein, 2008). Recently, there has been a significant decline in extent of the Arctic sea-ice accompanied with a decrease in thickness and extent of perennial sea-ice and pack ice (Serreze et al., 2007; Stroeve et al., 2007; Comiso et al., 2008; Rothrock et al., 2008).

Interpreting those instabilities in the Arctic sea-ice conditions is of primary importance in order to understand the Arctic's natural variability and response to external forcing over time and space. Marine sediments from the Arctic Ocean have been identified as important and under-exploited paleoclimate archives for obtaining integrated records of natural instabilities of the Arctic sea-ice conditionson millennial to decadal scales. The eastern Arctic Ocean has been well documented from this point of view. However, it has recently become clear that the Pacific sector of the Arctic Ocean play a critical role in modulating global climate system through the Pacific fresh water inputs into the Arctic (Woodgate et al., 2005, 2010; Hu et al., 2010, 2012).

Located in convergence zone between two major current systems of the Arctic surface-water circulation (i.e., the Beaufort gyre and the Transpolar Drift), the western Arctic Ocean is an important region for sea-ice production and its export toward the North Atlantic (Aagaard and Carmack, 1989; Hilmer et al., 1998; Marshall and Schott, 1999; Stein, 2008; Darby et al., 2012). Sea-ice dynamics in the western Arctic are under a complex function, controlled by sea-surface salinity, stratification of water masses and winter cooling, wind circulation systems and their impacts on the spreading of newly formed sea-ice toward the western Arctic Ocean (Laxon et al., 2003). Hydrologic processes in the western Arctic are of particular interest because of the inflow of the less-saline Pacific water into the Arctic *via* the Bering Strait, which consequently affects formation of North Atlantic Deep Water and thus, the global thermohaline circulation (Woodgate et al., 2010; Hu et al., 2012).

Climate variability during the last glacial period shows abrupt millennial-scale shifts, while warm climate of the Holocene was considered to be relatively stable by comparison (Johnsen et al., 1992; Dansgaard et al., 1993). However, paleoclimate records of the northern high latitudes including the Arctic regions reveal abrupt climate perturbations during the Holocene on millennial to centennial time-scales. Those

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Holocene climatic perturbations are suggested to be incurred by changes in intensity of orbitally-controlled insolation as well as other suborbital forcings (i.e., atmospheric and oceanic circulation, solar activity and volcanic eruptions) (Denton and Karlen, 1973; Grove, 1988; CAPE Project Members, 2001; Polyak et al., 2010). In addition, with the recent observation of the anthropogenic greenhouse effect, the need to establish natural Arctic climate variability in the perspective of changes in the Holocene on millennial to decadal scales has notably increased (Stein, 2008; Darby et al., 2012). Although a considerable amount of relevant scientific information about the past climate throughout Arctic and subarctic regions have been generated so far (e.g., Darby et al., 2001, 2012; de Vernal et al., 2005; Woodgate et al., 2010; Hu et al., 2010, 2012), patterns and magnitudes of climatic and oceanographic variability in the Pacific sector of the Arctic during this time period is still in the initial phase of investigation. In this paper, we reviewed the Holocene history of spatio-temporal climatic changes in the western Arctic region in order to; 1) highlight our current understanding of past environmental change and processes in the Pacific sector of the Arctic system, and 2) to discuss critical issues and new perspectives on the Arctic paleoclimate studies that are currently receiving increasing attention.

2. GEOLOGICAL AND OCEANOGRAPHIC SETTINGS OF THE WESTERN ARCTIC

In the Arctic Ocean, the Alpha and Mendeleev ridges (~1,800 km long) are the largest ridge complex, which separate the Amerasian Basin into the Makarov and Canada Basins (Stein, 2008). The Chukchi Borderland that includes the Northwind Ridge and the Chukchi Plateau is a smaller ridge system in the western Arctic Ocean (Fig. 1). The Northwind Abyssal Plain (<3,000 m water depth) divides the Chukchi Borderland into ca. 200 km long Chukchi Rise (<200 m water depth) in the west and the Northwind Ridge in the east (>1,000 m water depth). Underlain by sedimentary rocks, the Chukchi Borderland extends ca. 600 km from the Chukchi continental shelf into the Canada Basin and has a relatively flat ridge crest (generally less than 1000 m water depth) and steep slopes (Jakobsson et al., 2003).

Surrounded by the Eurasian and North American continents, the Arctic Ocean is an enclosed water body that has a strong salt stratification under influence of huge river discharge and relatively fresher Pacific-water inflow (Naidu et al., 2000; de Vernal et al., 2005; Stein, 2008; Woodgate et al., 2010). Based on the distribution of temperature, salinity, and density, the water column structure of the Arc-

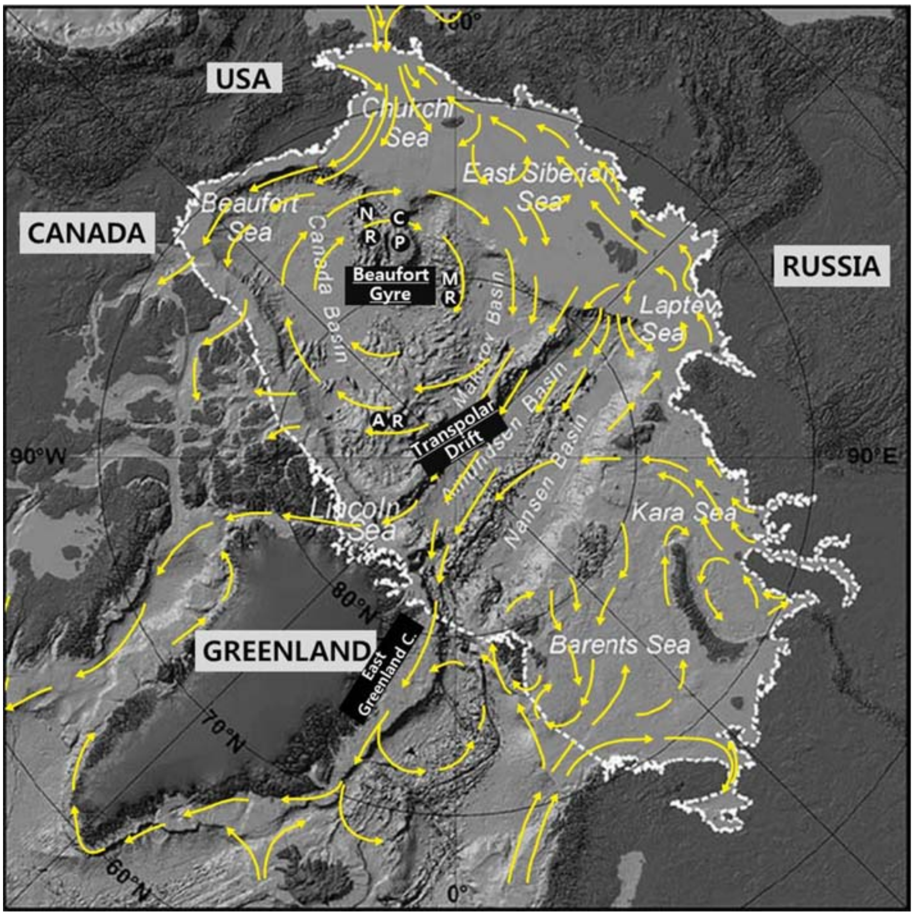

Fig. 1. Map of the Arctic Ocean. Yellow arrows show surface-water circulations (modified from Stein, 2008). Abbreviations used in this figure: AR, Alpha Ridge; MR, Mendeleev Ridge; NR, Northwind Ridge; CP, Chukchi Plateau.

tic Ocean can be divided into three main water masses (Stein, 2008 and references therein): the upper waters, the intermediate waters, and the deep waters. The upper waters are characterized by the polar mixed layer of a cold and very low-saline water mass between 30 and 50 m, and the Arctic halocline of a complex of cold, salt-stratified layers between 30–50 m and ~200 m. The low-salinity surface layer in the Arctic Ocean primarily derives from input of freshwater caused by river discharges as well as sea-ice melting in summer (Aagaard et al., 1981). The intermediate waters, known as the Atlantic Layer, are characterized by more warm and salty water masses below the upper waters occurring between ~200 and 800 m water depth. Below the intermediate waters, the deep waters with relatively high salinities (>34.92‰) exist in the deep basins (>800 m water depth).

The western Arctic Oceanis characterized by a limited ocean exchanges through the shallow Bering Strait (<50 m deep) in comparison to the Atlantic sector. Therefore, subsurface waters within the halocline consist of a mixture of brines released from the shelves during sea-ice formation in winter and water originating from the Pacific and Atlantic oceans. The surface layer (0~200 m) consists of cold (<0 °C) and relatively fresh (30~32‰) polar mixed layer water due to winter Bering Strait inflow and upwelled Atlantic Layer water (Woodgate et al., 2005). A temperature maximum (>0.5 °C) occurs at between 400 and 500 m, where a strong halocline and reversed thermocline separate the polar mixed layer from the underlying Atlantic Layer. The boundary current of the Atlantic-origin water enters to the Chukchi Borderland *via* the Mendeleev Ridge. In the Chukchi Borderland, the Atlantic- and Pacific-dominated water masses are diverted into the interior Arctic Ocean, moving towards the Canada Basin along a continental slope route (Morison et al., 1998; Swift et al., 2005).

The continental shelves of the western Arctic are the most extensive and widest in all of the world oceans (<100 m depth) and sea-ice formation largely occurs due to a huge amount of freshwater discharges into the Arctic Ocean by the Siberian Rivers (Bischof, 2000), which consequently provide a low-salinity surface water into the western Arctic region (Aagaard and Carmack, 1989; Carmack, 2000). The Chukchi Sea is particularly sensitive to sea-ice variations, due to recent warming of surface water and changes in the relative strength and position of the Beaufort Gyre versus the Transpolar Drift that caused more summer ice melting and large sea-ice reductions (e.g., Comiso, 2002). Seasonal durations of sea-ice cover (>50% of sea-ice coverage) in the Chukchi Sea range from 6 to 12 months per year, regulated by atmospheric circulations that determine significant inter-annual fluctuations in the surface coverage and thickness of sea-ice (Cavalieri and Martin, 1994; Roach et al., 1995).

3. HISTORY OF PALEOCEANOGRAPHIC CHANGES IN THE WESTERN ARCTIC DURING THE HOLOCENE

3.1. The Early Holocene (ca. 12,000~6,000 years B.P.)

Spatial and temporal paleoceanographic records of the Arctic region indicate rapid climatic shifts during a transitional period from the last deglaciation to the early Holocene. According to foraminiferal proxy records from the Nordic Seas and western Eurasian Arctic, substantial Atlantic water input to the Arctic Ocean have initiated since ca. 13,000 ^{14}C years B.P. (Lubinski et al., 2001). The advection of the Atlantic water masses over the upper water column in the Arctic Ocean persisted until the early Holocene (Ebbesen et al., 2007; Hald et al., 2007; Ślubowska-Woldengen et al., 2007). A similar timing for minimal ice conditions has been recognized along the margins of the Arctic Ocean, including extensive surface melting records in the Agassiz and Penny ice caps (Fisher et al., 1995, 1998, 2006) and continuous presence of open-water condition along the Canadian coastline recorded in bowhead whale fossils (Dykeand Morris, 1990; Dyke and Savelle, 2001) as well as the retreat of the ice sheet margins in the Canadian channels at around 13,000~11,000 ^{14}C years B.P. (Dyke and Prest, 1987a, b). These events were accompanied by increased discharge of cold sea-ice/icebergs, strongly influencing surface conditions of west and north of Svalbard, the Fram Strait and western Barents Seafrom the earliest Holocene until ca. 10,000~11,000 cal. years B.P. (Ebbesen et al., 2007; Ślubowska-Woldengen et al., 2007).

In the western Arctic, this time interval (notably the early Holocene ~7,800 ^{14}C years B.P.) is remarkable for a occurrence of benthic foraminifera *Cassidulina neoteretis*, an indicator species of modified Atlantic Water/Arctic Intermediate Water (Jennings and Weiner, 1996; Rasmussen et al., 1996) in the Beaufort Sea slope sediments (Andrews and Dunhill, 2004) (Fig. 2a). The rise in the Atlantic water species *C. neoterestis* in the Arctic Ocean during this time interval is also evident in the Eurasian margin sediments of the eastern Arctic region (Duplessy et al., 2001). Overall, these records suggest minimal ice condition during the early Holocene along the Arctic Ocean margins. This may have been caused by changes in water-exchange and circulation systems, which are suggested to be related to an increased northward advection of warm and saline water from the North Atlantic into the Arctic (Kinnard et al., 2011). Notably, records from the Chukchi Shelf sediments (de Vernal et al., 2005) indicate major transitions in coarse silt-sand fraction and sea-ice cover corresponding with the end of the postglacial transgression in the Arcticat ca. 8,000 cal. years B.P. (Fig. 2b). Given that the Arctic shelves was still exposed due to lower eustatic sea-level during the early Holocene, the shelf environment of the western Arctic seems to have been particularly sensitive to sea-ice forma-

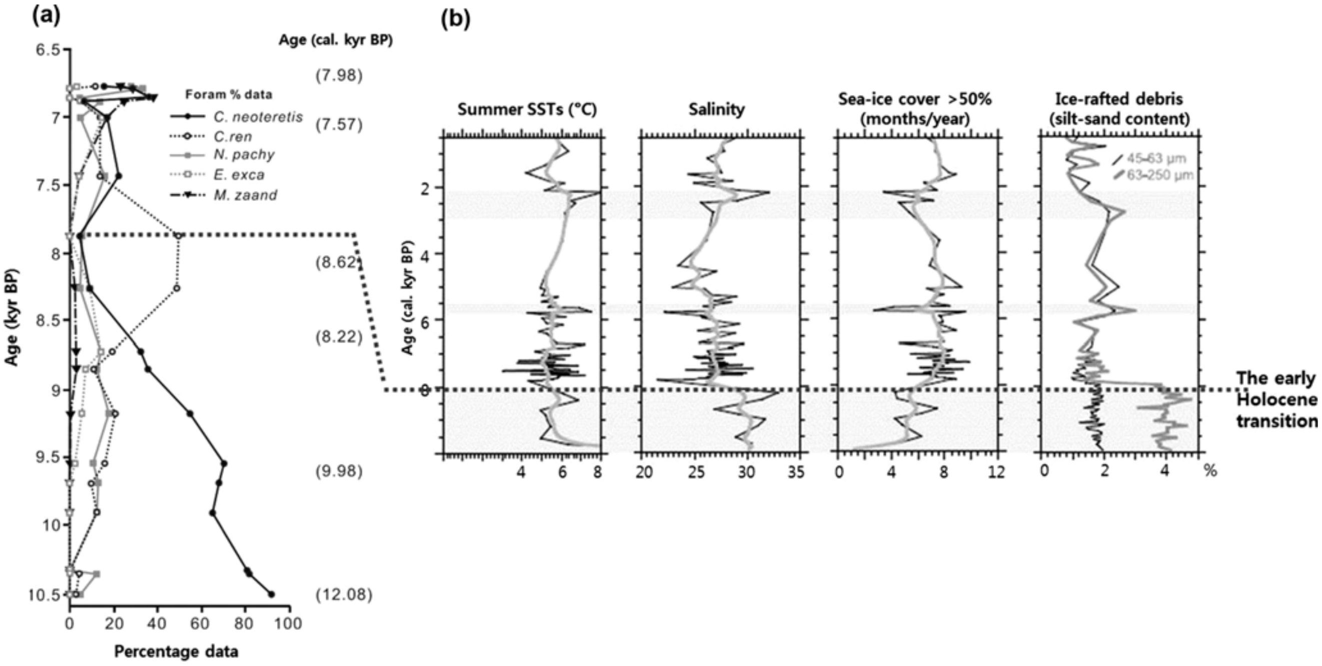

Fig. 2. (a) Down core plots of the main foraminifera species percentage data from the Beaufort Sea slope sediments (from Andrews and Dunhill, 2004). (b) Estimates of sea surface conditions based on dinoflagellate cyst assemblages in sediment cores collected on the edge of the continental shelf of the Chukchi Sea (from de Vernal et al., 2005).

tion and hydrographical conditions owing to its higher sedimentation rates (Bauch et al., 2001). Therefore, such records of transitions in the Chukchi Shelf sediments are possibly associated with a change in the bathymetry and regional physiography caused by the early Holocene rapid sea-level rise rather than a direct response to large-scale climate change (Mason and Jordan, 2002; Polyakova et al., 2005).

In some regions of the western Arctic Ocean, however, the early Holocene minimal ice condition show temporal and spatial disparities.The Holocene sea-ice cover variations of the western Arctic show almost opposite trends to that of the eastern Arctic (de Vernal et al., 2013), which were probably related to changes in regional fresh water input in conjunction with millennial-scale extra-terrestrial cycles (Fisher et al., 2006). For instance, in the Chukchi Sea, a weakening of sea-ice condition occurred only after 9,000 years B.P. (de Vernal et al., 2005; McKay et al., 2008). A particular note is for negative offsets between $\delta^{18}O$ values (*Neogloboquadrina pachyderma* left-coiled foraminifera) and isotopic equilibrium values ($\delta^{18}O$-$CaCO_3$-eq. vs. VPDB inferred from the Goddard Institute sea-water oxygen 18 database; cf. Schmidt et al., 1999) in most of the Holocene sediments from the Chukchi Sea (Hillaire-Marcel et al., 2004), ranging 1‰ (Arctic Seas) ~ –3‰ (Canada Basin). The offset value in the foraminiferal species is suggested to be linked to rates of sea-ice formation and supplies of isotopically light brine to the pycnocline, where the brines are mixed with the North Atlantic Water and thus, export of surface water and sea-ice to the North Atlantic sustain state conditions (Bauch et al., 1997; Hillaire-Marcel et al., 2004). Therefore, the greater offset values in the early Holocene, notably at 9,000~8,000 years B.P., indicate continuous production of sea-ice and isotopically light brines during this time period.

For the Holocene thermal optimum (ca. 9,000~5,000 years B.P.), proxy data from ice cores, pollen, loess, lacustrine sediments, and changes of sea and lake levels in high latitude regions demonstrate generally warmer and wetter climatic conditions (e.g., He et al., 2004 and references therein). Pollen stratigraphy records, for instance, revealed that the summer thermal maximum of a warm/generally moist climate occurred across a wide area of Northern Europe at around 6,000 B.P (Davis et al., 2003). Sea-ice reconstructions based on the sea-ice dwelling ostracode *Acetabulastoma arcticum* from the Mendeleev, Lomonosov and Gakkel Ridges, the Morris Jesup Rise and the Yermak Plateau are also characteristics of minimal sea-ice between 11,000 and 5,000 years B.P. (Cronin et al., 2010). Nevertheless, the duration and amplitude of the Holocene thermal optimum, as well as its onset and end times, tend to be differing in different parts of the Arctic region. In particular, paleoclimate proxy records imply that the Holocene thermal optimum was time-transgressive across the western Arctic region. For instance, during the precession-driven summer insolation anomaly at 12,000~10,000 cal. years B.P., the northwest North America was affected by continuous warming, while the northeast region remained cool conditions (Figs. 3a–d) (Kaufman et al., 2004). This pattern is also evident

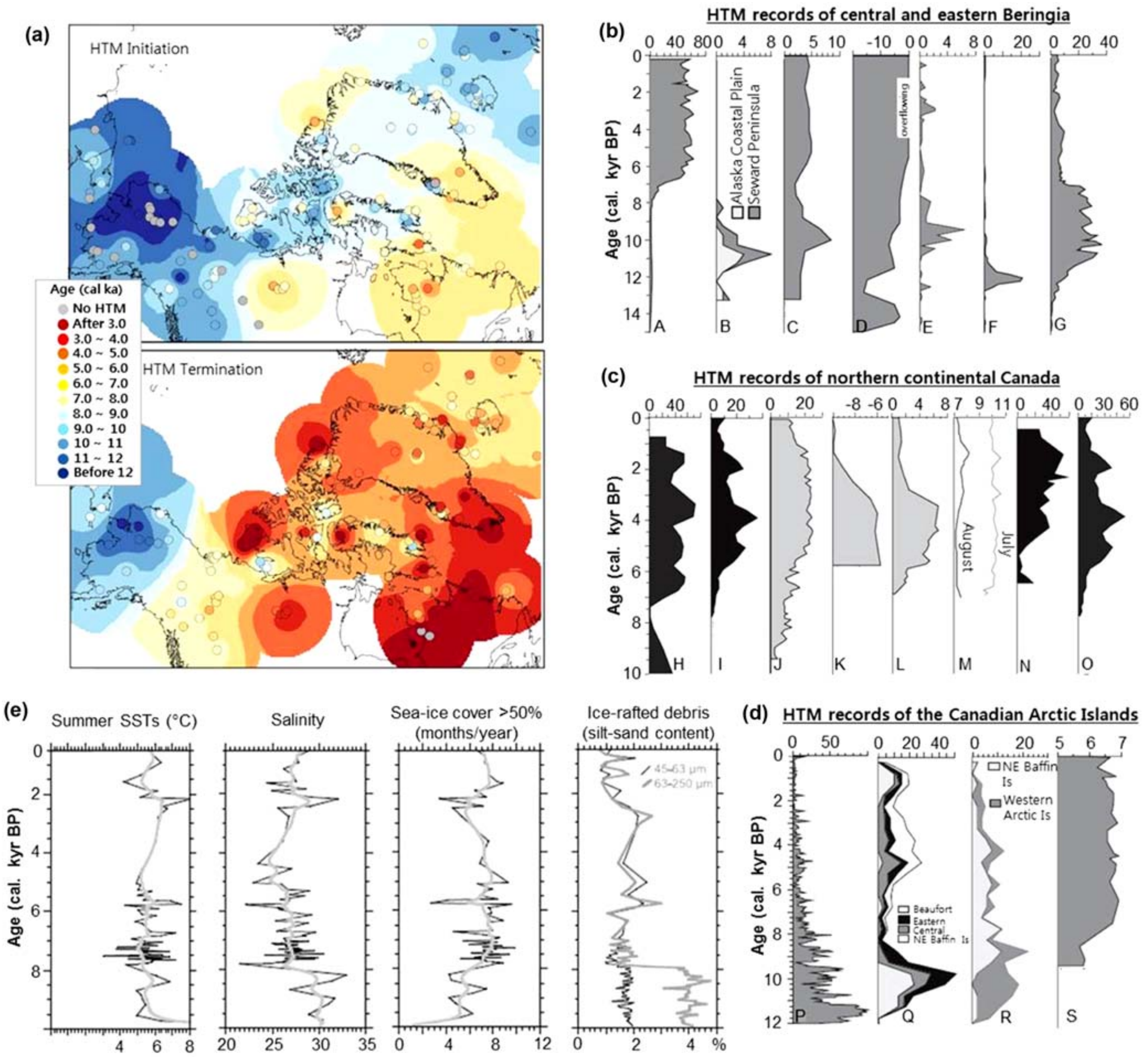

Fig. 3. (a) Spatio-temporal pattern of the Holocene thermal maximum (HTM) in the western Arctic. (b–d) Selected records of the HTM from 'central and eastern Beringia; A - Ptricia Lake *Pinus* (%), B - Extralimital Wood (frequency), C - Farewell Lake Mg/Ca ($\times 10^3$), D - Birch Lake Level (m), E - Idavain Lake *Populus* (%), F - Joe Lake *Populus* (%), G - Sleet Lake *Picea* (%)', 'northern continental Canada; H - Natla Bog (%), I - Toronto Lake (%), J - Lake TK diatom diversity index, K - Isotope inferred MAT (°C), L - Diatom inferred DOC (%), M - Lake LBI temp (°C), N - Lake RAFI (%), O - Ublik Lake (%)' and 'the Canadian Arctic Islands; P - Agassiz Ice Cap melt Layers (%), Q - Bowhead whales ^{14}C ages (frequency %), R - Thermophilic Molluscs ^{14}C ages (frequency %), S - Donald Lake pollen inferred temp (°C)'. Reproduced from Kaufman et al. (2004). (e) Estimates of sea surface conditions based on dinoflagellate cyst assemblages in sediment cores collected on the edge of the continental shelf of the Chukchi Sea (from de Vernal et al., 2005).

in Alaska and northwest Canada, where the Holocene thermal optimum was identified between ca. 11,000 and 9,000 years B.P., about 4,000 years earlier than northeast Canada. The discrepancy in the Holocene thermal optimum warming across the northern American and Canadian continents is suggested to be linked to the residual Laurentide Ice Sheet, which chilled the region through its impact on surface energy balance and ocean circulation (Mitchell et al., 1988; Mitchell, 1990; Kaufman et al., 2004).

In the Chukchi Shelf, however, reconstructed sea-surface condition (i.e., sea-ice cover, sea-surface temperature and sea-surface salinity) records do not exhibit similar signals phased with the spatial asymmetry pattern of the warming in the high-latitude and other western Arctic regions (Fig.

3e). For example, de Vernal et al. (2005) showed extensive sea-ice coverin the Chukchi Shelf area for more than 10 months yr^{-1} during 12,000~6,000 cal. years B.P., consonant with anomalies in the postglacial vegetation records around the western Arctic region (Kaufman et al., 2004). In the study, a particular note is for regional thermal optimum records of minimum sea-ice extent and maximum sea-surface temperature (~12,000 cal. years B.P.), which has also been identified from Bering Sea area such as lakes of the northern Bering Strait area and peat deposits on the Chukchi Shelf (Elias et al., 1992, 1996; Ager, 2003). Possibly this was related to ice-free and relatively warm sea-surface condition, together with largely exposed shelf area during the early postglacial period (de Vernal et al., 2005). It should be noted, however, that isotope data in mesopelagic and benthic foraminifers from the Chukchi Shelf shows subsurface temperature peaks at around 8,000 cal. years B.P., indicating maximum inflow of the North Atlantic water flowed into the Arctic (Hillaire-Marcel et al., 2004). This discrepancy in the Chukchi Shelf records probably indicate that sea-surface and subsurface conditions during the early Holocene were spatially decoupled between the surface water layer and the intermediate North Atlantic water mass. Considering that accuracy of age models varies among sites, and also is affected by several factors (e.g., the type of analyzed material, the origin of its carbon, and sediment reworking), this spatial asynchronicity may have been related to chronological control as previously demonstrated in Kaufman et al. (2004). Particularly at the Arctic region (e.g., central Beringia), accurate dating for sediments from lakes is still difficult due to a paucity of macrofossils (Anderson et al, 2002). Therefore, such spatial variability in the early Holocene thermal optimum records over the western Arctic region requires further investigation by improving age control and developing tools of quantifying paleoclmatic parameters.

3.2. The Mid-Holocene (ca. 6,000~3,000 years B.P.)

For the mid-Holocene, it is well known that a wide area of the northern high latitude were generally warmer than today (e.g., Tarasov et al., 1998; Prentice et al., 2000; Davies et al., 2003; Sundqvist et al., 2010). At 6,000 years B.P., climate model experiments on paleovegetation in circum-Arctic regions showed greater extent of temperate grasslands in the continental interior in response to the simulation of drier conditions during the growing season (Vavrus and Harrison, 2003) (Fig. 4a). Pollen data from Eurasia also indicates considerably warmer conditions during this time, as indicated in northward shifts of the tree line in Fennoscandia (western Europe) and central Siberia (e.g., Taimyr peninsula) (Bigelow et al., 2003). Contrastingly, in Beringia of the western Arctic, the mid-Holocene tundra-forest boundary shows little or no differences when compared with the modern, and even a southward shift of the tree-line limit from the present position. Such asymmetric tendency in spatial distribution of biomes in circum-Arctic regions well corresponds to the mid-Holocene sea-ice dynamics obtained with climate model experiments (cf. Hewitt et al., 2001; Vavrus and Harrison, 2003), which show sea-ice thickness similar to the modern condition in the western Arctic, but reduced sea-ice in the eastern Arctic (Kaufman et al., 2004). Indeed, model experiments with sea-ice dynamics for 6,000 years B.P., sea-ice thickness reduced rapidly in sea-ice divergence zone (e.g., the Eurasian Arctic shelves) and less rapidly in sea-ice convergence zone (Hewitt et al., 2001; Vavrus and Harrison, 2003). In those studies, sea-ice convergence in the western Arctic region at 6,000 years B.P. resulted in minimum change in ice concentration, leading to a low surface-air-temperature anomaly in Alaska and the Canadian Arctic, whereas the eastern sector of the Arctic became significantly warmer (Kaplan et al., 2003; Vavrus and Harrison, 2003).

In addition to sea-ice dynamics, the structure of the upper water column in the western Arctic Ocean indicates that stratification and halocline between the subsurface and surface water layers was significantly weakened after 6,000 years B.P., as shown by reduced gradients of $\delta^{18}O$ isotopic values between small-size and large-size planktonic foraminifer *N. pachyderma* sin (Hillaire-Marcel et al., 2004). A similar timing for this transition has been recognized in the isotopic data ($\delta^{18}O$ and $\delta^{13}C$) of benthic and planktonic foraminifer tests (de Vernal et al., 2005), which indicates the increased sea-surface salinity and reduced sea-ice cover extent after 6,000 years B.P. This is likely to be related to a weakening of halocline and a strengthening of heat transfer from the subsurface to the surface layer of the water column (Fig. 4b). These mid-Holocene oscillations in sea-surface conditions of the western Arctic Ocean, as shown by changes in water mass stratification and vertical mixing of the water column, are suggested to be linked to changes in freshwater discharges to the Arctic Ocean (Andreev et al., 2001; Stein et al., 2004). In order to characterize linkages between those processes, especially which are sensitive to rapid changes, freshwater discharge records in short-term variability (centennial-millennial scale) are particularly relevant. Those records can be achieved primarily by sediments from continental margins that have higher sedimentation rates and thus better time resolution. The most effective types of proxy data to trace all fluctuations of freshwater runoff and sea-surface conditions in the Arctic region include stable-isotope, IRD compositions and palynological records in marine sediments (CAPE Project Members, 2001; Andreev et al., 2003; Polyak et al., 2010).

3.3. The Late Holocene~Present (ca. 3,000 years B.P.~)

During the last decades, a number of high-resolution paleoclimate records revealed that the late Holocene period has climatically unstable patterns, registering millennial to sub-

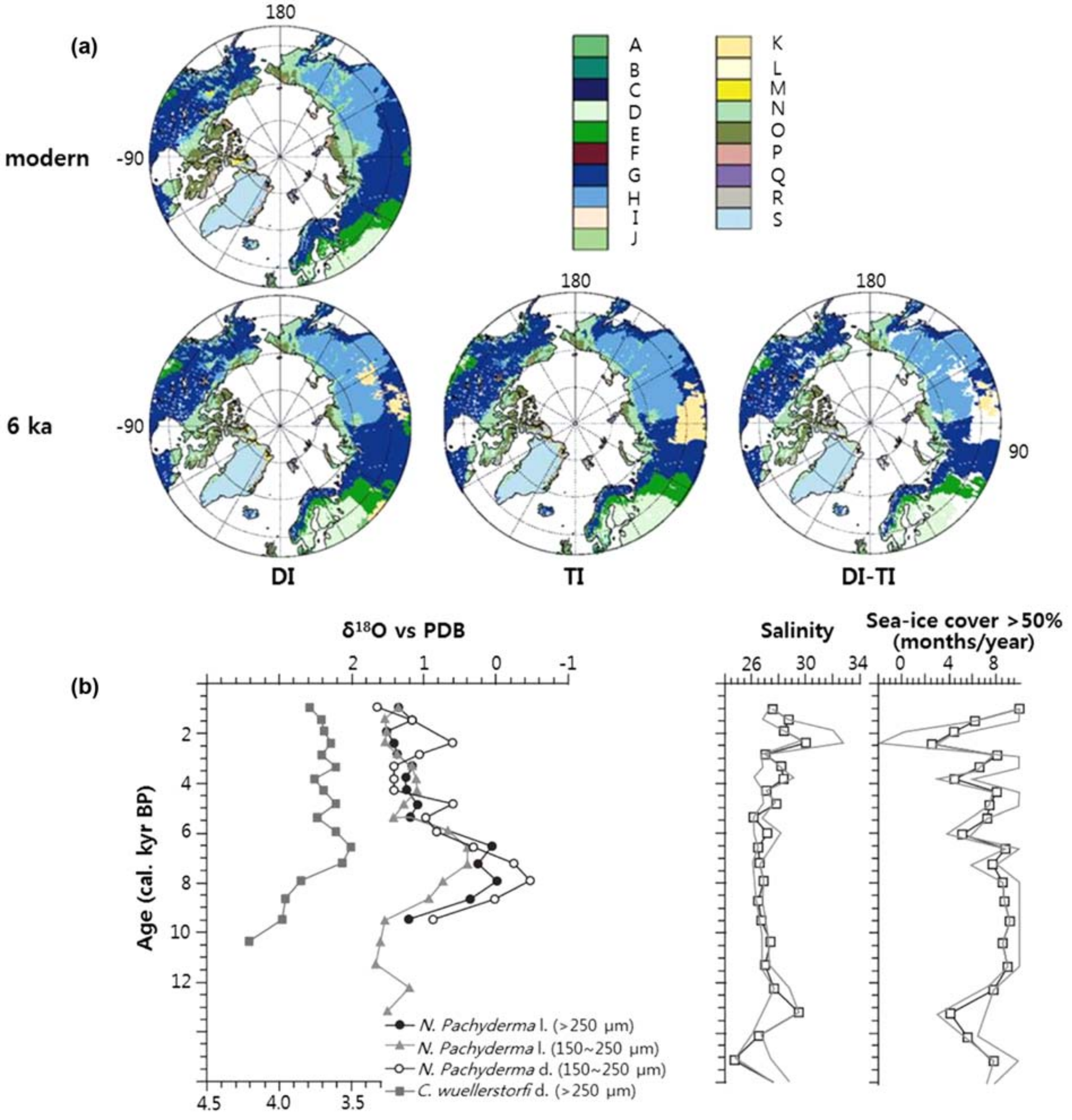

Fig. 4. (a) Major vegetation types (biomes; A - Temperate deciduous broadleaf forest, B - Temperate evergreen needleleaf forest, C - Warm temperate evergreen broadleaf & mixed forest, D - Cool mixed forest, E - Cool evergreen needleleaf forest, F - Cool temperate evergreen needleleaf & mixed forest, G - Cold evergreen needleleaf forest, H - Cold deciduous forest, I - Temperate xerophytic shrub land, J - Temperate deciduous broadleaf savanna, K - Temperate grassland, L - Desert, M - Graminoid and forb tundra, N - Low and high shrub tundra, O - Erect dwarf shrub tundra, P - Prostrate dwarf shrub tundra, Q - Cushion forb tundra, R - Barren, S - Ice) across the Arctic (north of 55°N) as simulated by BIOME4 when driven by modern climatology and the anomalies of the DI and TI simulations (center panels) for 6 ka (from Vavrus and Harrison, 2003). (b) Isotopic data ($\delta^{18}O$ and $\delta^{13}C$) of benthic and planktonic foraminifer shells and estimates of sea surface conditions based on dinocyst assemblages in a sediment core collected on the lower slope of the adjacent Northwind Basin (from de Vernal et al., 2005).

millennial abrupt changes (e.g., Bond et al., 1997; Schilman et al., 2001; Moy et al., 2002). Several climatic proxies indicate that early to mid-Holocene warming trend was not monotonic and was punctuated by abrupt cooling episodes after 6,000~4,000 cal. years B.P. (e.g., Velichko et al., 1997; Korotky et al., 2000; Kawahata et al., 2003). The late Holocene cold condition is characterized by alternations of glacier expansions and retreats, with notable advances in the Neoglaciation (3,300~2,400 cal. years B.P) and the Little Ice Age (LIA; 600~100 cal. years B.P.) (Denton and Karlen, 1973).

Such cooling episodes in the late Holocene have been well imprinted in northern high latitude, especially in the Arctic regions (e.g., Calkin et al., 2001; Jennings et al., 2002; Farmer et al., 2011). According to Jennings et al. (2002), benthic foraminifera, stable isotopes and IRD flux records from the East Greenland shelves point to a transition to colder and lower-salinity conditions began at around 5,000 years B.P. In addition, detrital calcium carbonate flux data shows marked peaks at around 4700 cal. years B.P., concomitant to the onset of Neoglacial cooling in the Renland ice core $\delta^{18}O$ record. After 4700 cal. years B.P., the detrital carbonate flux data exhibits regularity in magnitude and spacing with six peaks and five troughs between 4,700 and 400 cal. years B.P. (Fig. 5a). These oscillations observed in the carbonate flux and sea-salt sodium (Na) flux of Greenland Ice Sheet Project 2 (GISP2) suggest cooling of sea-surface temperature due to increased outflow of polar water and sea-ice in the East Greenland Current, probably resulted from intensive Arctic sea-ice events (Jennings et al., 2002).

In the western Arctic Ocean, records of sea-ice cover variations from the lower slope of the adjacent Northwind Basin show millennial-scale oscillations implying unstable sea-ice conditions during the late Holocene (de Vernal et al., 2005). A particular note is for minimal sea-ice condition in the continental shelf edge of the Chukchi Sea at ca. 3,000~2,000 cal. years B.P., coupled with increased sum-

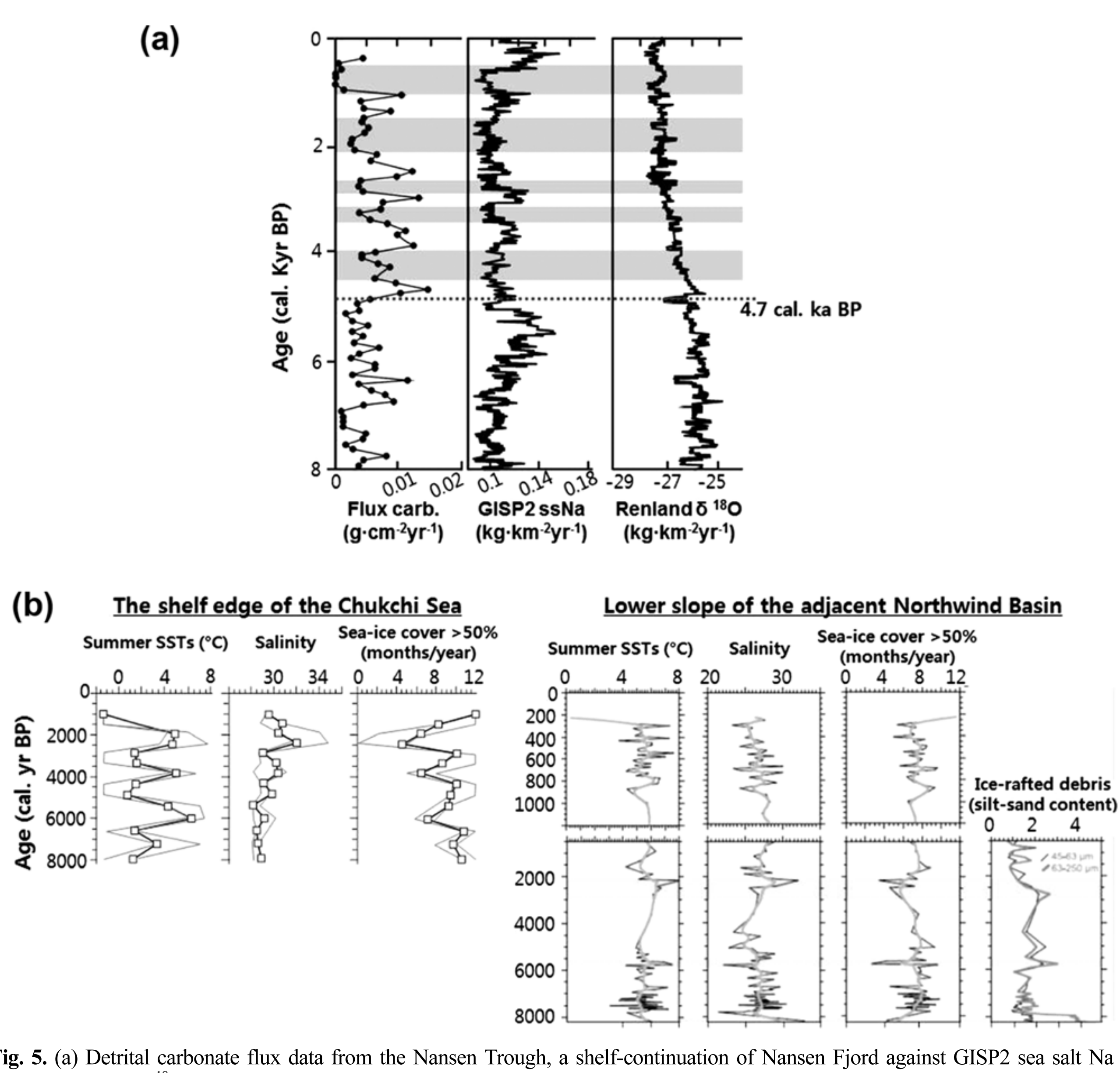

Fig. 5. (a) Detrital carbonate flux data from the Nansen Trough, a shelf-continuation of Nansen Fjord against GISP2 sea salt Na flux and the Renl and $\delta^{18}O$ record (from Jennings et al., 2002). (b) Estimates of sea surface conditions based on dinoflagellate cyst assemblages in sediment cores collected on the edge of the continental shelf of the Chukchi Sea and the lower slope of the adjacent Northwind Basin (from de Vernal et al., 2005).

mer sea-surface temperature and salinity (Fig. 5b). A similar trend has also been recognized in the Canada Basin (Farmer et al., 2011), where foraminiferal $\delta^{18}O$, ostracode Mg/Ca ratios, and dinoflagellate cyst records indicate marked reductions of summer sea-ice coverage at around 3,500 and 1,800 years B.P. These features generally consistent with high inputs of coarse silt and sand fractions to the western Arctic Ocean in relation to enhanced sea-ice rafting and melting at around 6,000 and 2,500 cal. years B.P., indicating warmer conditions and a longer ice-free season (Darby and Bischof, 2004). The enhanced sea-ice rafting and melting events are firstly interpreted to be associated with changes in the main drift (i.e., the transpolar drift) at the sea-ice convergence regulating stratification and vertical mixing of water masses (e.g., Darby and Bischof, 2004). In addition to the main drift, another critical issue in addressing the sea-ice rafting and melting events in the western Arctic region is precipitation and/or freshwater runoff, which influences structure of halocline in the western Arctic (e.g., Kaufman et al., 2004; de Vernal et al., 2005).

With respect to the late-Holocene minimal ice event, one important issue is the present condition of the Arctic sea-ice extent and volume that have been declining rapidly over the last several decades (e.g., Comiso et al., 2008; Stroeve et al., 2008). By means of recent climate model experiments, it is shown that retreat and thinning of the Arctic sea-ice will accelerate and may become seasonally ice-free condition as early as 2040 (Holland et al., 2006; Arzel et al., 2006; Wangand Overland, 2009; Polyak et al., 2010). Continued ice loss will enhance Arctic warming through the ice-albedo feedback mechanism, and changes in ice cover and freshwater flux out of the Arctic Ocean incur various environmental modifications including ocean circulation and weather systems beyond the Arctic through atmospheric and hydrographic regimes (e.g., Seager et al., 2002; Francis et al., 2009). Such changes may have profound influence on the strength of the mid-latitude westerlies and storm tracks, which would in turn modulate the mid- to high-latitude climate system (e.g., Dethloff et al., 2006). Nevertheless, there are many uncertainties remaining in the exact predictions of Arctic's future climate due to complex control factors on these ice reductions. Therefore, more detailed studies of the late Holocene minimal Arctic ice periods are needed for research on modern and future physical processes, from which we can better understand the Arctic's natural climatic variability.

A particular interest is for the Neoglacial interval that began in the mid-Holocene and lasted more than 2,000 years. This event was accompanied by; 1) a marked sea-ice expansion over the East Greenland shelf (Jennings et al., 2002) and the western Arctic Ocean such as Chukchi Sea shelf (de Vernal et al., 2005) and the Canada Basin (Farmer et al., 2011); 2) coastal glacier expansions over the Gulf of Alaska (Calkin et al., 2001); 3) intensely erosive storms along the Chukchi Sea coast (Mason and Barber, 2003); and 4) pronounced cooling events in the western Bering Sea (Razjigaeva et al., 2004). It should be noted that, during this time interval, several proxy records from East Asian marginal seas and northwestern Pacific margin register a major shift in marine-terrestrial paleoenvironments, superimposed on those climatic variations observed in the Arctic regions (Lehmkuhl, 1997; Jin et al., 2004; Ijiri et al., 2005; Xiang et al., 2007; Chung, 2011). Although this trend supports the notion that climatic events of the northern Pacific Ocean are closely linked to the global climate system through hydrological dynamics in the Pacific sector of the Arctic Ocean (Woodgate et al., 2005, 2010; Hu et al., 2010, 2012), the comprehensive interpretation of these records is still hampered by the paucity of high-resolution sedimentary records from the western Arctic region and by the limits of chronological uncertainty, at this time.

For the Medieval Warm Period, which refers to the relatively warm intervals of various magnitudes and at various times between ca. 950 and 1,200 AD (Lamb, 1977), evidences of climate variability in the Arctic region have been indentified in glacier length, marine sediments, speleothems, ice cores, borehole temperatures, tree rings, and archaeology (Miller et al., 2010 and references therein). At around 1000 AD, relatively warm climatic conditions have been reported from the North Atlantic sector of the Arctic including western Greenland (Crowley and Lowery, 2000), the Greenland Ice Sheet summit (Dahl-Jensen et al., 1998), Swedish Lapland (Grudd et al., 2002), northern Siberia (Naurzbaev et al., 2002), Canadian Arctic archipelago (Anderson et al., 2008), and Iceland (Geirsdóttir et al., 2009) (Fig. 6a). In the western Arctic, however, the Medieval warmth is less clearly evidenced comparing to the eastern Arctic, but with some indications of general retreat of glaciers in southeastern Alaska (Wiles et al., 2008) and the wider tree rings in some high-latitude tree-ring records from Asia and North America (D'Arrigo et al., 2006). Meanwhile, at the onset of the Little Ice Age (LIA), paleoclimate proxies around the Arctic show a cooling trend (1,250~1,850 AD) and the coldest interval of the Holocene is registered at 1,500~1,900 AD when the glacier extent reached their Neoglacial maxima (Bradley et al., 2003; Miller et al., 2010). In the Canadian Arctic, glaciers and ice caps began to expand at 1,250~1,300 AD and its expansion were amplified at ca. 1,450 AD (Anderson et al., 2008). Regional sea-ice conditions derived from ocean sediment cores point to marked decrease in sea-ice cover at 1,450~1,620 AD in both of the eastern (the Fram Strait) and western Arctic (Chukchi Sea) (Fig. 6b). Such reduction of Arctic sea-ice coverage during the LIA cooling event may be explained by changes in water-exchange and circulation systems, probably due to an increased northward advection of warm and saline water from the North Atlantic into the Arctic Ocean (Kinnard et al., 2011). On the while, spatial pattern of the LIA cooling seems to be not

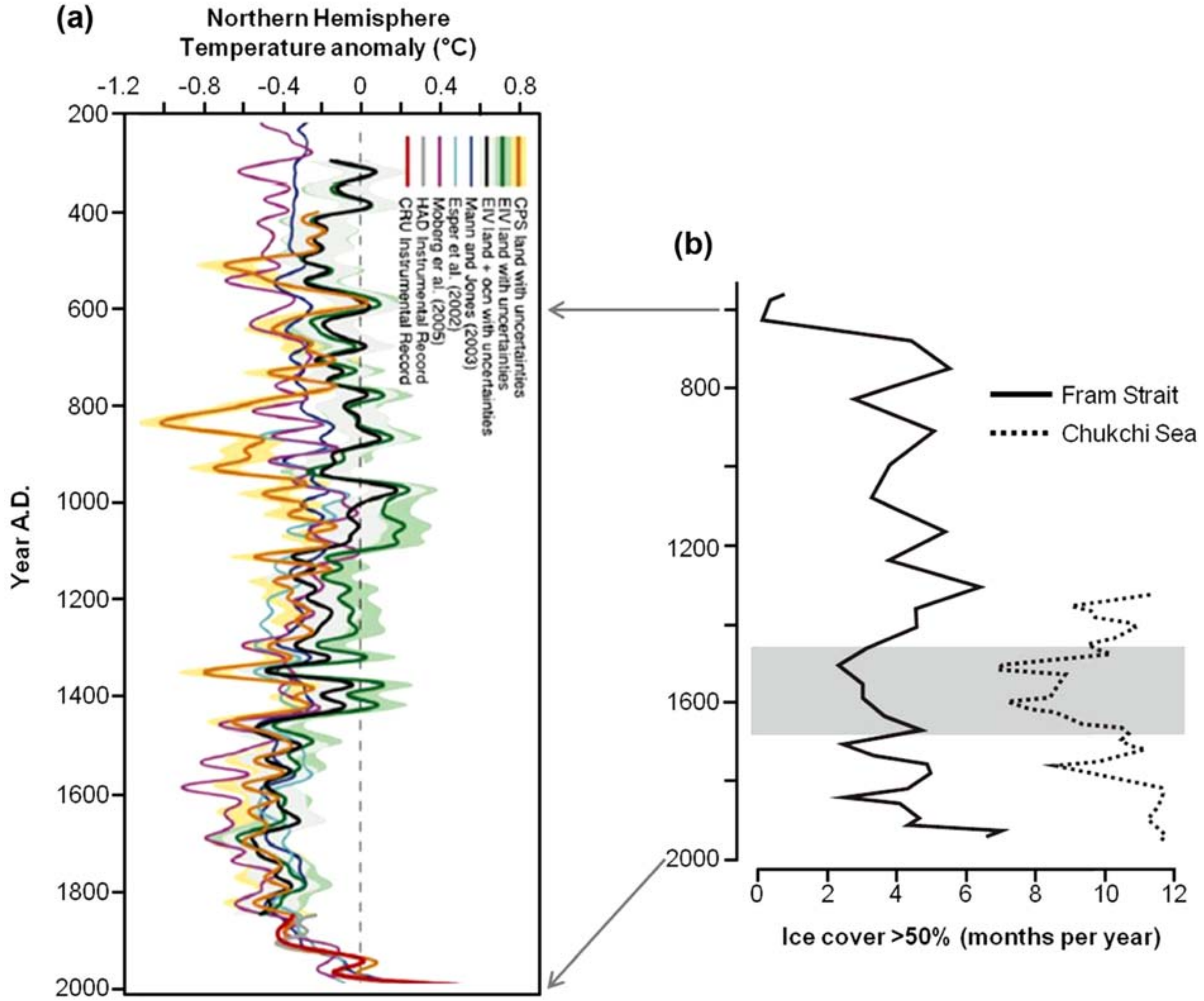

Fig. 6. (a) Updated composite proxy-data reconstruction of Northern Hemisphere temperatures for most of the last 2000 years (from Miller et al., 2010). (b) Comparison between reconstructed late-summer Arctic ice extent and other Arctic sea-ice, climate and oceanic proxy records (from Kinnard et al., 2011).

even across the Arctic, especially some parts of the western Arctic Ocean (e.g., Kaufman et al., 2004), where the cooling trend during the LIA was weaker comparing to the eastern Arctic Ocean (Kaufman et al., 2004). This is probably related to oceanic circulations affected by sea-ice development in the North Atlantic that would have enhanced the LIA cooling in the Atlantic sector of the Arctic (Broecker, 2001; Miller et al., 2005). To provide insight into this process, investigating recent sea-ice cover variations in association with internal coupled ocean–atmosphere–sea-ice dynamics, on inter-annual to decadal time scales, is required.

4. SUMMARY AND CONCLUSIONS

We reviewed Holocene paleoceanographic and paleoclimatic changes in the western Arctic region, and discussed possible forcing mechanisms underlying the spatio-temporal climatic fluctuations. The Holocene history of the Arctic climate variations reflects complex processes and feedbacks between atmosphere, ocean, sea-ice, land surface and biota, involving interactions between surface albedo, marine productivity, ocean-to-atmosphere heat and moisture fluxes. In the early Holocene, sea-surface conditions over the Arctic Ocean such as sea-ice cover are primarily associated with the postglacial sea-level rise that affected the bathymetry and regional physiography. Since then, the Arctic climates show a strong spatial variability throughout the Holocene owing to the particular geography of the Arctic as well as other suborbital forcing such as atmospheric and oceanic circulation and solar activity. For the Holocene minimal sea-ice conditions, a critical issue is not only the temporal and spatial disparities in the western Arctic, but also opposite trends between the western and eastern Arctic. Superimposed on the sea-ice cover variations, the asynchronicity of the marine and terrestrial proxy records between the eastern and western Arctic regions throughout the Holocene implies that atmospheric dynamics play a major role in translating differences in the sea-ice dynamics over the Arctic regions. Furthermore, the eastern and western Arctic regions are strongly influenced by two major oceanic currents (the Atlantic and Pacific water inflows, respectively) that have been evoked as a key factor to explain climatic changes within and far beyond the Arctic regions through water-exchange between the Arctic Ocean and the global ocean. Therefore, investigating the asynchronicity is of pivotal importance in order to elucidate spatially uneven effects over the each sector of the Arctic regions. However, there are still insufficient data to characterize the Holocene asynchronicity in sea-ice dynamics as well as paleovegetation patterns across the Arctic region, particularly in the Pacific sector of the Arctic. Also, in order to interpret in more detail the processes between sea-ice dynamics and marine-terrestrial climatic events during the Holocene, we suggest that investigating paleo-freshwater discharge records in the marginal Arctic seas with increased temporal resolution will offer a wealth of possibilities. Our study also emphasizes a tentative linkage of the late Holocene paleoclimatic events between the Arctic regions and the northwestern Pacific margin, highlighting the notion that climatic events of the northern Pacific Ocean is closely linked to the global climate system through hydrological dynamics in the Pacific sector of the Arctic Ocean. However, precise interpretation is still limited by the absence of comparable data and a paucity of Holocene high-resolution records on both regions. A critical issue on recent climatic changes that requires for further study on the western Arctic paleoceanography is to obtain long marine sediment cores with well preserved climatic records and also to develop tools of quantifying paleoclmatic parameters with well constraint precise age models.

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