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Climatic change and its relationship with human society in northern Japan since the mid-Holocene - Quantitative reconstruction of atmospheric and sea surface temperature -

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Abstract

For the prediction for future climate, it is required to enhance our understanding of the Holocene climatic change. By estimating paleo-temperature, we attempted to examine the relationship between climatic changes and human activities in northern Japan. The alkenone SSTs showed a variation of 8.7 °C (14.5 °C to 23.2 °C). Jomon people living around Funka Bay were more dependent on marine products than in Honshu due to cooler climatic conditions. There are two Hypsithermal environments at Funka Bay around 4.6 cal. kyr BP and 1.2 cal. kyr BP. Sea levels for the last 7 kyrs have been controlled mainly by local/regional tectonic vertical movement. Therefore, the highstand never always corresponded to Hypsithermal environments. More than one driving forcing, rather than one, may control climatic/environmental change. The 4.2ka event in northern Japan could be characterized by cooling by a few degrees by the combination of reduced ESAM and El Niño mode. Another notable cooling event occurred in 1.0-0.8 cal. kyr BP due to the La Niña condition and reduced solar activities, which means that the Japanese archipelago never experienced Medieval Warm Event: instead, there was a Medieval Cold Event in Japan. The Okhotsk culture in Hokkaido prospered only under the Hypsithermal condition during the 5th - 9th centuries and subsequently it declined and was incorporated into the Satsumon culture under the cooler environmental conditions. For the Yayoi-era (2.9 cal. kyr BP-) and the following periods, our results are consistent with the previous results from Hiroshima Bay, western Japan, that cold periods (6th - 7th century BC, 3rd century BC, 6th century AD, 10th -12h century AD and 16th century AD) coincided with major shifts in social systems in Japan.

Introduction

Background

The Holocene is an important period because of the worldwide dispersal of the human species and its consequences. Notable changes during this period include the development of major civilizations and dramatic shifts toward urban lifeways through to the present (e.g., Weiss et al., 1993; Stanley et al., 2003; Habu, 2004). Currently some anthropogenic activities have significant direct or indirect influences on the environments on a global scale, including global warming, desertification, ocean acidification, pollution, and deforestation (e.g., Kawahata et al., 2019). It is required for us to understand natural processes more deeply in order to predict future climatic changes by distinguishing anthropogenic climatic/environmental change from non-anthropogneic variability.

The oldest evidence for a prosperous hunter- fisher–gatherer culture known as the Jomon culture is dated to approximately 16.5 cal. kyr BP, around which the world's earliest known stone arrowheads and pottery were produced in northern Japan during the coldest episode. The Jomon period continued through to 2.9 cal. kyr BP (ca. 2.3 cal. kyr BP in northeastern Japan) (e.g., Fujio et al., 2005; Taniguchi, 2006; Habu, 2008). Jomon archaeological sites in the northern Tohoku region and Hokkaido of Japan provide a unique testimony to a prehistoric culture that left sedentary settlements based on hunting, fishing and gathering (http://jomon-japan.jp/en/) (Figs. 1a, 1b). Among these, Ofune, Kakinoshima, Irie-Takasago, and Kitakogane sites in Hokkaido are located near Funka Bay (e.g., settlements, shell middens, and wetlands). Scholars suggest that these sites were associated with affluent societies with advanced technologies and rich spiritual elements even though they never relied on rice cultivation or the domestication of other cereals. One of the most famous and well-studied mid-Holocene Jomon archaeological sites is the Sannai-Maruyama site in northern Japan, the occupation of which started at 5.9 ± 0.1 cal. kyr BP just after the eruption of Towada volcano at 6.0 cal. kyr BP. The size of the settlement, 24 hectares, is extraordinarily large. The occupation of this settlement ended at regional/global 4.2ka event with a sudden cooling by 2.0 °C (Habu, 2004; 2008; Kawahata et al., 2009b; Kariya et al., 2016). The site remained uninhabited until the 9 - 10th century AD (http://sannaimaruyama.pref.aomori.jp/english/) of the early warm Heian Period (Fig. 1b). At 4.2 cal. kyr BP, major civilizations in other parts of the world, including the North Mesopotamian Civilization, the Old Kingdom in Egypt, and the Yangtze River Civilization, also declined (Weiss et al., 1993; Parker et al., 2006, Stanley et al., 2003; Riel, 2008, Zhang, 2013).

The practice of an intensive rice agriculture in paddy fields were introduced at around 2.9 cal. kyr BP by immigrants from the Asian continent under the notable cold climate/environment (Wang et al., 2011). The introduction of metallurgy (bronze and iron) for mirrors and weapons are dated just after this period. These changes were followed by a significant population increase. People lived in permanent farming

villages, accumulated wealth through land ownership and the storage of grain with society more stratified and complex. Based upon the reconstructed SSTs in Hiroshima Bay, western Japan, Kawahata et al. (2017b) argued that the beginning and collapse of aristocratic politics corresponded to notable cold periods. i.e., there is a positive correlation between the prosperity of the early state and climate.

Turning eyes to Europe, for later historic periods, the Roman Warm Period (RWP, 50–400 AD), the Medieval Warm Period (MWP, ca. 950–1250 AD [1000–1400 AD in certain areas]), the Dark Ages Cold Period (AD 500–900) and the Little Ice Age (LIA, ca. 1600–1850 AD [1350–1850 in certain areas]) have received much attention from climatic and historical points of view (e.g., Yan et al., 2011). The RWP and MWP are often called the Roman and Medieval climatic optima respectively, both of which proposed to have been the period of unusually warm weather in Europe and the North Atlantic (e.g., Mann et al., 2009). The time range of, and the affected areas by, MWP are still open to debate. Bradley et al. (2003) concluded that the warmest MWP atmospheric temperatures (ATs) were not synchronous around the globe based upon compiled lines of evidence. On the other hand, LIA was often identified in the regional/global scale. According to the IPCC Assessment Report (2001), it is suggested that LIA is represented as a modest cooling in the Northern Hemisphere and that it was largely an independent regional climate change rather than a globally-synchronous increased glaciation. Although it has been reported that climatic events could be triggers to transform a society, until now, most of the reconstructed temperature data are qualitative or semi-quantitative (e.g., deMenocal, 2001; Haug et al., 2003). In order to understand a causal relationship between climate/environmental and social changes, quantitative reconstruction of paleo-temperature is required.

Problematic

The mid-latitude zone of the northwestern North Pacific is a sensitive area in terms of the regional and global climate change. The northern westerly wind, which is overlying this region, meanders between warm and cold air mass and brings the continental material such as eolian dust (Fig. 1a) (e.g., Kawahata et al., 2000). Also the Kuroshio Current and its branches, Tsushima and Tsugaru Currents, carry heat energy from low latitude to warm up this region, while the Oyashio Current flows from the northern North Pacific to cool down the coasts of Hokkaido and Tohoku regions (e.g., Takei et al., 2002; Sagawa et al., 2014; Horikawa et al., 2015). The oscillation in cooling/warming could be controlled by climate modes, such as the El Niño–Southern Oscillation (ENSO), the Asian Monsoon System and other atmosphere-ocean interactions (e.g., Yamamoto, 2009; He et al., 2015; Tada et al., 2016a, b). In addition, other factors such as solar activity, insolation, and sea level change also influence climatic/environmental change. Previous studies indicate that the temperature fluctuations cannot be explained by a single cause but rather by more

than one external and internal driver of climate variability. It is crucial to understand which factors could play a more important role in SST events in the Holocene.

Objective

Coastal sediments collected from bays provide a special advantage to present quantitative estimates of summer AT based upon the high correlation between AT and sea surface temperature (SST) (Kawahata et al., 2017a, b). In this study, we reconstruct paleo- alkenone SSTs quantitatively with a high time resolution in northern Japan by collecting sediments from semi-closed Funka Bay (Fig. 1a, 1b). This paper evaluates the processes behind climatic/environmental change, especially events since the mid-Holocene and discusses the ecodynamics between climatic/environmental changes and human activities in Hokkaido, including the lives of Jomon and Okhotsk peoples in relation to the subsequent development of the Ainu culture.

Study areas and materials

Study area

Funka (Uchiura) Bay, 30 km in diameter and over 90 m in depth, is located between Hakodate and Muroran Cities in southern Hokkaido (Fig. 1a, 1b). The surface sediments are composed mainly of mud, sometimes of sand, along the shallow coast in semi-enclosed bay. The term "Funka" in Japanese means volcanic eruptions because several active volcanoes such as Mt. Hokkaido Komagatake, Mt. Usu, Mt. Showa-shinzan, Mt. Yotei, and Mt. Tarumae are located around the bay. In particular, Mt. Komagatake, which is 1,131 m above the sea level, is an active andesitic strato-volcano. Its major eruption was recorded at 1640 AD with volcanic debris of 2.9 km^3 after roughly 5,000 years of dormancy (Katsuki et al., 1989; Geological Survey of Japan, 2017). Subsequently, three additional smaller eruptions occurred in 1694 AD (0.36 km^3), 1856 AD (0.21 km^3) and 1929 AD (0.34 km^3).

SSTs in the bay are influenced by the two major ocean currents, the Tsugaru and Oyashio Currents. The warm Tsugaru Current reaches the bay from the southeast and makes a left-hand (anticlockwise) turn mainly in the summer while the cold Oyashio Current flows into the bay from the northeast and shows a right-hand (clockwise) flow in the other seasons (http://www.fsc.hokudai.ac.jp/muroran/lab.html). The Tsugaru Current shows higher salinity and lower nutrient concentration, while the Oyashio Current is famous for lower salinity and higher nutrients.

Muroran City (42°19′ N, 140°58′ E) is the largest city around Funka Bay (Fig. 1a, 1b). Japan Meteorological Institute (2015) provides a monthly record of meteorological parameters such as AT, rainfall, and others between 1981 and 2010, which show definite seasonality. The annual rainfall is 1,185

mm (https://weather.time-j.net/Stations/JP/muroran). Although the annual mean AT is 8.6°C, August and January are the warmest and coldest months, respectively. The maximum, average and minimum monthly-mean ATs in August are 23.4, 20.5, 18.5°C respectively, while those in January are 0.3, -2.0 and -4.2°C. During the same period, Muroran Marine Station of Hokkaido University provided a monthly record of SSTs (http://www.fsc.hokudai.ac.jp/muroran/english/). The maximum and minimum monthly-mean SSTs were 20.1°C (August) and 3.5°C (February), respectively. The monthly AT and SST are particularly well correlated during summer (June through September). (AT = 0.7899xSST +4.26; r = 0.89, p = 0.001).

Without large rivers that flow into the bay, the salinity and SST in the bay increased and decreased versus depth, resulting in steep gradient of water density (Miyake et al., 1977). The annual rainfall and duration of insolation are 1,185 mm year^{-1} and 1,725 h year^{-1}, respectively. The wind is generally 3.5 m s^{-1} in summer and 6.0 m s^{-1} in winter. Wind direction is the east-northeast in summer and the west-northeast in the other seasons.

Sediment samples

A total length of 731cm of core St. 5 was collected at a distance of only 7.8 km from the coast and at a water depth of 64 m at 42°23'59.377" N; 140°24' in Funka Bay during the research program by Geological Survey of Hokkaido in 2010 (Fig. 1a). Based upon seismic survey, the 20 m thick surface sediments were not disturbed, which demonstrates that the sedimentary particles have been deposited continuously (Hokkaido Research Organization, National Institute of Advanced Industrial Science and Technology, 2011). The sediments were generally composed of dark olive homogeneous mud with ash layers in shallow depths.

Analytical Procedures

The core description and the analysis of magnetic susceptibility (MS) were carried out just before collecting samples, which enabled us to identify ash layers.

A total weight of <12 mg of plants and molluscan shells was selected for accelerator mass spectrometry (AMS) radiocarbon dating at the Beta Analytic in USA (Table 1). The detailed procedures used are described at their web site of http://www.radiocarbon.com.

Sediment samples were dried and crushed into fine powder in the laboratory. The alkenone analytical procedures used are described in Minoshima et al. (2007) and Kawahata et al. (2009a). The targeted organic materials were extracted with an accelerated solvent extractor (ASE-200, Dionex, California, USA) and an automatic solid-phase extraction system (Rapid Trace SPE Workstation, Zymark, UK) from 3 g of the powdered samples. The C37 alkenone fraction was analyzed by capillary gas chromatography with a

Hewlett Packard 6890 series gas chromatograph equipped with an on-column injector, an Agilent HP-5ms fused silica column (60m×0.25mm), and a flame ionization detector. Several procedural blanks, which were analyzed in parallel with the sample analyses, showed no C37 alkenone contamination. The analytical error for $U^{K'}_{37}$ (defined as [37:2]/{[37:2] + [37:3]}) was ± 0.0060 based on the results of five replicate analyses. As pointed out by Villanueva and Grimalt (1997), irreversible adsorption of C37:3 on the chromatographic column is often a major source of error when the total amount of C37 alkenone injected into the system for analysis is <5 ng. Therefore, the error should be minimized in this study because >5 ng was used in each injection.

In this study, SSTs were calculated by assuming a linear relationship between SST and C37 alkenone unsaturation and using the empirical equation reported by Prahl et al. (1988): $U^{K'}_{37} = 0.034\ T\ (°C) + 0.039$. Therefore, the estimated alkenone SST has error of 0.2°C at its best.

Results

Age model

The thick ash layer at 46 cm depth can be identified by visual inspection and magnetic susceptibility profiles, which contains pyroxene and plagioclase as phenocrysts and white color glass with rough surface (Miyazono and Nishina, 2007) (Fig. 2). It can be estimated to originate from the large Komagatake eruption at 1640AD (Ko-d) after the dormant period over 5000 years (Geological Survey of Japan, 2017) because the other volcanic products from subsequent eruptions, such as Komagatake (Ko-c1, Ko-c2), Tarumae (Ta-a, Ta-b) and Usu (Us-1663), have not accumulated in Funka Bay (Nakamura, 2016), Small increase of magnetic susceptibility at 66cm may be compared with the unknown Tsunami deposit just below Ko-d, which is identified in the wide area of southern Hokkaido (Nakanishi and Okamura, 2019).

The ^{14}C dating results from plant and shell samples are shown in Table 1. They were converted to calendar ages using the Oxcal ver. 4.2.4 software (Ramsey and Lee, 2013) with the Intcal 13 and Marine 13 datasets (Reimer et al., 2013). In the case of marine shells, a regional specific reservoir (ΔR) correction of 34 ± 12 years reported in the southern Hokkaido was incorporated into the calculation (Yoneda et al., 2007). Based on these calibration methods, the age of the plant collected from a depth of 700 cm was in good agreement with the age of the shell collected from the depth of 702 cm (Table 1a). This confirms that our age model is reasonably accurate. In the age model construction for the Core St.5, 9 samples were datable because biogenic carbonates were unfortunately dissolved in the organic-rich coastal sediments in spite of the best effort to conduct ^{14}C analysis for all the plant and molluscan shell samples. We excluded three data of #8, #10 and #12 because they were broken and degraded pieces. Extremely strong positive correlation between the adopted ^{14}C ages and those recovered depths ($r^2 = 0.997$) suggests that Core St. 5 provides continuous and constant environmental records since 6700 yr BP. The Ko-d tephra originated

from the Komagatake 1640 eruption was also used as an age control horizon because it completely matches this regression line. On the other hand, the top 30 cm section provides rough estimate of the age determination because of loose and soft sediment with much water and then our discussion is focused on the sediments below the Ko-d tephra (up to 1640AD) (Table 1, Fig. 2). The ages of sediments for alkenone analysis were calculated assuming a constant sedimentation rate between the age control horizons. The mean sedimentation rate was 108 cm kyr^{-1}, which was consistent with those obtained in Mutsu, Tokyo and Hiroshima Bays (Table 1b; Kawahata et al., 2009b; 2017b, Kajita et al. 2020).

C37 alkenone SST

The SST was reconstructed based upon the analysis of C37 alkenone. The major alkenone-producing coccolithophorid was *Emiliania huxleyi* in this area under both the Tsugaru and Oyashio currents (Hagino et al., 2005; Kawahata et al., 2017a; Kawahata, 2019). The major production period of *E. huxleyi* has been observed in satellite images in summer (June – August) (Takahashi et al., 1995), which is confirmed by the sediment trap experiment at Site MD01-2409 (41°33.8', 141°52.0'E) under the influences by the Tsugaru current (Fig. 1a) (Kawahata et al., 2009a). A global core-top calibration from 370 sites between 60°S and 60°N in the Pacific, Atlantic, and Indian Oceans by Müller et al. (1998) is within the error limits of the widely used *E. huxleyi* culture calibration of Prahl et al. (1988).

The mean alkenone SST in surface-top soft sediments was 21.7 °C, which is nearly the same as the summer (August) SST range (17.7-21.0 °C, mean value of 19.7 °C) during the last 30 years. Since the AT is highly correlated with the SST, as is observed in Mutsu Bay and off Shimokita, the mean monthly AT is almost comparable to the monthly SST around 20 °C in Funka Bay at the modern condition (Kawahata et al., 2009b; Kawahata et al., 2017a).

The alkenone SSTs varied from 14.5 °C to 23.2 °C with a mean value of 18.6 °C (Fig. 3a). They peaked in 6.4, 4.6, 1.2 cal. kyr BP and the present day. Broad maxima occurred in 5.7-4.3 and 2.9-2.1 cal. kyr BP. Large temperature falls occurred in 6.1-5.9, 4.2-4.1, 3.0, 2.0 and 0.8 cal. kyr BP. The results are consistent with the occurrence of a molluscan assemblage including warm water species such as *Meretrix lusoria, Mactra veneriformis, Umbonium moniliferum* and others, which occurred in 5.0-4.0 and 2.4-2.3 cal. kyr BP in southern Hokkaido (Akamatsu et al., 1995; Kito et al., 1998).

Mutsu Bay, which is located on the opposite bank of the straits, showed no definite long-term warming trend of SSTs (ATs) in summer (Figs. 1 and 3a), probably due to a slight difference of the current channel and intensity across the Tsugaru Strait. However, Funka Bay was colder than Mutsu Bay because of higher latitude by 1°30’ and an appreciable influence by the Oyashio Current (Fig. 1a). Also both bays showed low-frequency oscillations of ATs (SSTs) in the millennial-scale to sub-millennial-scale with maxima around 6.4 and 4.6 cal. kyr BP and minima around 5.8 and 4.1 cal. kyr BP respectively (Fig. 3a).

Atmospheric temperature

Temperature is one of the most important parameters for environmental changes. At modern state, the monthly AT and SST are well correlated during summer in semi-enclosed Japanese Bays and coastal areas (e.g., Kawahata 2017a, b) (Fig. 1a). In particular, in Mutsu Bay, both monthly AT and SST are the same from March to August (http://www.mutsuwanbuoy.jp/observation/). Therefore, summer AT can be quantitatively reconstructed because alkenone production occurs primarily in early summer off northern Japan (Yamamoto et al., 2007; Kawahata et al., 2009a). If the correlation between the monthly AT and SST has been valid for the last several thousand years, the ATs around Funka Bay can be calculated to be 16.9°C, 18.5°C, 20.1°C and 21.6°C in the cases of SSTs of 16°C, 18°C, 20°C and 22°C respectively. The difference between the ATs and SSTs is so small around 18°C (Fig. 3a). The estimated ATs varied from 15.7 °C to 22.6 °C with a mean value of 19.0 °C.

Discussion

Consistency of alkenone SST with bivalve assemblage in Jomon sites

There are 5 Jomon sites with shell middens around Funka Bay: the Usu 6 site, Kitakogane middens B and C, Wakkaoi midden A, Etomo midden, and Takasago midden C. The distance among these sites are 36 km or less. Bivalves assemblages at each shell midden were different, depending on the marine ecosystems that were affected by time-series coastal environmental change (Aono, 2017).

Crassostrea gigas accounted for more than 80% of shells at the Usu 6 site (middle Initial to early Early Jomon) without fish and sea and terrestrial animals. This implies that the site occupants focused their subsistence activities primarily on *Crassostrea gigas* from autumn to spring as a result of their intentional choice (Aono, 2017). On the other hand, Kitakogane midden B of the early Early Jomon, which seems to have been occupied throughout the year, is characterized by the predominance of *Meretrix lusoria*, which prefers to inhabit in warm environments (Aono, 2013). In the late Early Jomon, *Macridiscus melanges* accounted for 58.3% while *Crassostrea gigas, Mytilus coruscus, and Venerupis philippinarum* were approximately 10% each, at Kitakogane midden C (6.0-5.6 cal. kyr BP). Similar characteristics are observed at the Wakkaoi midden. At the bottom layer of Kitakogane midden C, *Meretrix lusoria* are present. This indicates that the climate cooled down from the early to late Early Jomon (6.2-5.8 cal. kyr, BP). As a result, the percentage of *Meretrix lusoria* decreased to only 0.2%.

There were no large shell middens around Funka Bay during the warm environmental period of 5.7-4.5 cal. kyr BP (Early Jomon - late Middle Jomon). The possibility for the loss of shell midden by the costal erosion due to higher sea level (Fig. 3f) is unlikely, because Jomon people around Funka Bay tended to leave shell middens at relatively higher locations (generally, more than 7m above sea level) and because shell middens tended to decrease under the warmer environmental condition in Hokkaido. *Mya arenaria*

oonogai and *Venerupis philippinarum*, which are proxies for cool environments, accounted for 41.5% and 33.1% respectively in 3.98-3.90 cal. kyr BP at the Etomo midden (early Late Jomon). At Takasago midden C (early Late Jomon), the ratios of *Venerupis philippinarum, Mytilus coruscus,* and *Littorina brevicula* were 77.7%, 4.9%, and 14% respectively.

In summary, from the middle Early Jomon through to early Late Jomon, the dominant shell species changed as follows: *Crassostrea gigas* (late Initial Jomon) → *Meretrix lusoria* (early Early Jomon)→ *Macridiscus melanges* (late Early Jomon) → *Crassostrea gigas* (late Early Jomon) → No occurrence of shell middens probably due to warm environments (early to mid/late Middle Jomon) → *Mya arenaria oonogai* (early Late Jomon) and*Venerupis philippinarum* (early Late Jomon). This suggests that the dominant species of bivalve assemblages changed from cool species through warm species to cool species again. This fluctuation trend is consistent with the change in alkenone SST from 6.70 to 3.90 cal. kyr BP.

Mid-Holocene Hypsithermal environments and its relationship with sea level highstand

Orbital variations have often governed insolation changes, which primarily forced the Holocene Thermal Maximum (HTM), called often as the Hypsithermal period, at high latitude. Precessional culmination occurred in 12–10 ka with total annual insolation of 1Wm^{-2} higher than the present at 60^{o}N, which brought HTM in the northwest North America, in 12-9 ka. The local summer temperature was on average 1.6 ± 0.8°C higher than the present. On the other hand, northeastern North America experienced delayed warming peak by 4,000 years due to the cooling by the residual Laurentide Ice Sheet. The early Holocene warming was associated with sea level rise by melting of ice sheet (Kaufman et al., 2004). The linkage between temperature and sea level change is also reported from Hiroshima Bay, located in the Seto Inland Sea. The SST reconstructed by shallow water sediments generally decreased before 7.0 cal. kyr BP in response to a decline in insolation and the sea-level rise. A lower sea level could promote warming in the shallower water column. After the sea level was stabilized, even when insolation continued to decrease, the mean temperature fluctuated little (Kawahata et al., 2017b). Although transgression generally works as a warming factor because albedo is higher on the sea than on the land at the regional/global scale, the timing of sea-level highstand is compared with that at the Mid-Holocene Hypsithermal environments in this study.

In the case of Funka Bay, insolation change could not have played an important role in SST change because the long-term SSTs' trend seemed to have a reverse profile to the summer insolation. It gradually declined from the middle to the late Holocene in the Northern Hemisphere (Berger, 1978) (Fig. 3b). The eustatic sea level data suggest that meltwater contributions from the major North American and European ice sheets largely ceased by 7.0 cal. kyr BP, after which the rate of sea level rise slowed down at the global scale, leaving prominent ice sheets only in Greenland, Iceland, and Antarctica (Lambeck and Chappell, 2001) (Fig. 3f). Continuing melting of the Antarctic ice sheet might have lasted until 4.0 cal. kyr BP

(Yokoyama et al., 2012). In the case of Japan, located away from major ice-loading effects, regional/local sea level changes have been caused by either tectonic or isostatic causes (Fig. 3f).

Based upon the topography with the distribution of shell middens, it is known that the lowland in Kanto of eastern Japan was flooded by seawater in 6.5-5.5 cal. kyr BP. This was the period when *Corbicula japonica* lived in brackish water more than 100 km away from the present-day shoreline and both corals and warm bivalves occurred at temperatures about 2°C higher than the present (Fig. 1a) (Matsushima, 2006). Tanabe et al. (2012) reconstructed detailed time-series sea level change in this area, where the sea level rose rapidly in the deglaciation period and slowly reached its highest in 7.4-4.5 cal. kyr BP by +4.0m relative to the modern level (Tanabe et al., 2012) (Fig. 3f). On the other hand, the high precision field surveys demonstrated a broad maximum of the sea level (up to +1.3m) at eastern Hokkaido (Akkeshi Bay), northern Japan, in 6.0~4.0 cal. kyr BP (Shigeno et al., 2013) (Figs. 1a, 3f). However, the alkenone SSTs peaked in 4.7-4.3 cal. kyr BP in Funka Bay and 4.9-4.2 cal. kyr BP in Mutsu Bay (Kawahata et al., 2009b) (Fig. 3a). Therefore, it is suggested that the Mid-Holocene Hypsithermal environment was associated with high stand of sea level in eastern and northern Japan in a broad frame but not in exactly the same time (Figs. 1a, 1b, 3f).

This warming period confirmed in Mutsu and Funka Bays in northern Japan can be associated with a broad increase in sunspot numbers (Fig. 3a, 3c). The numbers estimated from variations in tree ring $\Delta^{14}C$ generally provide a good proxy for solar radiation (Fig. 3e). When sunspot numbers increase, the sun is brighter and the solar output increases (Usoskin et al. 2007). Lower levels of solar radiation could be related to a significant climatic cooling (Timmreck et al., 2009). Therefore, the Mid-Holocene warm climate could be partly attributed to the enhanced solar activity. However, another factor is required because solar radiation alone is too small to explain such warm environments during this period.

The Japanese archipelago has been influenced by the East Asian Summer Monsoon (EASM). According to a simulation study, the EASM was significantly enhanced during the mid-Holocene and characterized by increased southerly winds in eastern China (Liu et al. 2014). Nagashima et al. (2013) analyzed spatial variations in EASM precipitation to evaluate the westerly jet path over East Asia during the Holocene (Fig. 3d). They found that the contribution of dust from the Mongolian Gobi Desert relative to that from the Taklimakan Desert showed millennial-scale to multi-millennial-scale broad minima at 6.0–4.6 cal. kyr BP, which could be attributed to the earlier seasonal northward progression of the westerly jet. This was associated with the westerly jet shifted northward earlier in the year, resulting in earlier northward migration of the EASM rain-band with heat energy (Fig. 3d). Therefore, it is suggested that the Mid-Holocene Hypsithermal in eastern and northern Japan could be affected mainly by enhanced EASM and solar activity.

Regarding the sea level change, detailed field surveys conducted off the shores of Shimokita and Matsushima, northern Honshu, indicated that the sea level rose to +0.7~+2.1m at about 4.0~3.5 cal. kyr BP (Fujimoto, 1990; Yokoyama et al., 2012). Strictly speaking, these lines of evidence demonstrated that the timing of sea-level highstand have differed from place to place in eastern and northern Japan. Sea level for the last 7 kyrs have been controlled mainly by local/regional tectonic vertical movement while Hypsithermal environments could have been influenced by EASM and solar activity in Japan.

4.2ka event in Funka Bay

The 4.2 ka event is famous for a mid/low-latitude aridification event at the boundary between the mid-Holocene, Northgrippian, and the late-Holocene, Meghalayan (Mayewski et al., 2004; Staubwasser and Weiss, 2006; Walker et al., 2012) but its forcing mechanism remains less obvious than is the case with that at 8.2 ka event. In Funka Bay, alkenone SSTs (ATs) showed definite cooling by 2-3°C at this event. Kawahata (2019) discussed the climatic mechanism behind the event based upon the environmental factors in Mutsu Bay, and concluded that southward shift of the westerly jet, in association with a weakened East Asian Summer Monsoon, could cause a relatively cool climate.

ENSO, one of the most important climate phenomena on the Earth, fluctuated largely during the Holocene (e.g., Wu and Liu, 2004; Wang et al., 2005; Hu et al., 2008). The Southern Oscillation Index (SOI) is a proxy for an ENSO event, with negative and positive values corresponding to an El Niño and La Niña episodes, respectively. Although the Japanese islands face western North Pacific, they have received significant influences by a coupled ocean–atmosphere climate phenomenon in the tropical Pacific. In general, during an El Niño episode, the Pacific high is weakened, with reduced atmospheric pressure in the vicinity of Japan. This result in an enhanced Okhotsk high, which tends to be accompanied by a cold and cloudy/rainy summer in Japan (Meteorological Agency of Japan, 2014). In the case of La Niña episodes, the effect is reversal.

The ENSO cycles from 20.0 cal. kyr BP to the present were semi-quantitatively reconstructed in spite of low precision (Rein et al., 2005). The weak El Niño condition was rather stable throughout the mid-Holocene period (8.0 – 5.2 cal. kyr BP), which was followed by a major shift to stronger El Niño activities from 5.2 to 3.6 cal. kyr BP. This change from the La Niña to El Niño conditions might have been responsible for the large decline of AT from 4.5 to 4.1 cal. kyr BP. At 4.2ka event, the onset of aridification coincided with a 1–2°C cooling of North Atlantic surface waters (Bond et al., 1997), which could bring cooling of tropical ‘deep’ waters in the tropical Pacific. It has cooled sufficiently to switch-on the El Niño -like condition (Sun, 2000). This condition could weaken the Asian monsoon across 4.1 ka BP (Fisher et al., 2008). At least the 4.2ka event in northern Japan could be characterized by cooling by a few degrees by the combination of reduced ESAM and El Niño mode.

Late Holocene Hypsithermal environment and a Medieval Cool Event in Japan

Another Hypsithermal environment occurred at 1.2 cal. kyr BP in the late Holocene with a maximum temperature of 23.2 °C, comparable with that observed at Mutsu Bay (Figs. 1 and 3a). After that, the SSTs rapidly decreased and showed a large minimum in Funka Bay. This indicates that the Japanese archipelago never experienced the Medieval Warm Event but a Medieval Cool Event, which have already reported from both Hiroshima and Tokyo Bays (Kawahata et al., 2017b; Kajita et al., 2018). In the case of the Mid-Holocene Hypsithermal environment, EASM could have played an important role in transporting heat energy from the lower to higher latitudes in the western Pacific. Although similar situation could have occurred in 3.5–1.5 cal. kyr BP, ESR Intensity, average summer insolation and sunspot number never showed sharp peaks at 1.2 cal. kyr BP, at the SST maximum in Funka Bay (Nagashima et al., 2013) (Fig. 3b, 3c, 3d).

Recently, proxy-based reconstructions of the SOI on a multi-decadal scale became available for the last 2 kyrs (Fig. 3e). As mentioned before, the Japanese archipelago tends to have cooler and hotter summer at El Niño and La Niña conditions, respectively. La Niña condition and its corresponding SST in Funka Bay peaked at 1.20 cal. kyr BP. After that, both SOI and alkenone SST rapidly decreased to El Niño conditions and down to 18.6°C in 300 years. This SST fluctuation between 1.4 and 0.9 cal. kyr BP can be verified by historical documents in and around the ancient capital city of Kyoto, western central Japan (Ishii, 2002).

In contrast to Japan, Europe tends to have warm summer at El Niño condition (https://www.data.jma.go.jp/gmd/cpd/data/elnino/learning/tenkou/sekai1.html). The warm summer prevailed in 1.95-1.55 and 0.95-0.60 cal. kyr BP. The former period appreciably corresponded to the Roma Warm Period (1.90-1.55 cal. kyr BP) and the latter to the Medieval Warm Period (0.95-0.65 cal. kyr BP) (Mann et al., 2009; Büntgen et al., 2016). In contrast, La Niña condition corresponded to the Dark Ages Cold Period (1.45-1.05 cal. kyr BP) and the LIA (0.55-0.10 cal. kyr BP) (Büntgen et al., 2016). Therefore, it is suggested that the SOI and AT co-varied in Europe. As pointed by the IPCC Assessment Reports (2001, 2007), Bradley et al. (2003) and Mann et al. (2009), it is suggested that the warmest medieval ATs might have been local/regional, not synchronous around the globe. Reduced solar activities (the Oort Minimum) during a part of the period of 0.94-0.87 cal. kyr BP could partially contribute to a decrease in temperature during this period, too.

Volcanic forcing is often pointed as an important factor in sudden cooling events. By compiling a historical weather description for 1670–1985AD in northern Japan, a meteorologist Kondo (2000) reported that damage to crops from cold weather occurred 39 times and that 24 of these events were related to large volcanic eruptions within and outside Japan. However, alkenone SST in Ko-d tephra originating from Mt.

Komagatake at 1640 AD never resulted in cooling episodes but rather it led to enhanced SSTs (Figs 2 and 3a). The reduced temperature of 1.0-0.7 cal. kyr BP could be attributed to the Little Ice Age.

Implications for the relationships between AT and human activities

Prosperity of the Okhotsk culture in warm climate in Hokkaido

The Okhotsk culture was a coastal fishing and hunting-gathering culture in the Sea of Okhotsk area dated to the 3^{th} -13^{th} centuries AD. In Hokkaido, Okhotsk archaeological sites are dated to the 5^{th}–9^{th} centuries. The Hokkaido Okhotsk sites was contemporaneous with Epi- Jomon (3^{th} century BC-7^{th} century AD) and Satsumon (7^{th} - 12^{th} century AD) sites in the other areas of Hokkaido, but characteristics of these cultures are distinct from each other. Scholars suggest that the bear rituals of the historic Ainu culture originated from the Okhotsk culture. Recent studies on genetic analysis suggest that to major ancestral groups for the historic Ainu people were Jomon and Okhotsk peoples (Adachi et al. 2011;Adachi et al. 2012; Takigawa 2012; Shinoda 2015; Sakitani, 2018).

Okhotsk subsistence strategy has traditionally been classified as a specialized system of marine resource gathering. Carbon and nitrogen stable isotope analysis of skeletal remains from Okhotsk culture sites indicates that the relative contribution of marine protein was more than 60% (e.g., whale, seal, salmon) (Naito et al., 2010). However, archaeological data also indicate that their diet was complemented by terrestrial mammals (e.g., domestic pigs, deer, and rabbits) and grains, including barley.

The alkenone SSTs around Funka Bay increased from 18.4°C at 89AD, peaked at 23.2°C in 759AD and decreased 17.4°C at 1080AD. It is striking that the warm period overlaps with the prosperity of the Okhotsk culture in Hokkaido from the 5^{th} to the 9^{th} centuries, which corresponds to the most Hypsithermal period for the last 2000 years. Today, the Sea of Okhotsk is known for its abundant ice floe formation at the lowest latitude in the world. Cold air from Siberia in winter forms sea ice in the northwestern Sea of Okhotsk. As the ice forms, it expels salt into the deeper layers. This heavy water promotes vertical mixing of coastal water, upwelling of nutrients to the surface, enhancing spring bloom, and bringing abundant sea life. It supports a strong food chain: phytoplankton bloom nourished zooplanktons such as krill, which are the diet of small fishes and shells. They are eaten by large fish, seal, and birds. Therefore, the Sea of Okhotsk is one of the world's richest areas in terms of biological resources.

When the climate cools down, the ice floes cover sea surface for a longer period, which prevents people from fishing in the coastal region. In addition, farming, including livestock-farming, becomes more difficult to be operated. The Amur River, the world's tenth longest river (4,350km) with the catchment area of $2.05x10^6$ km^2, is so nourishing that its basin is home to a variety of large predatory fish. Lower AT tends to reduce vapor pressure of water to bring less rainfall, to decline terrestrial weathering and to reduce nutrients supply from river to the coastal region. At those times, these effects could deteriorate fishing and hunting. The most prosperous period of the Okhotsk culture could have been blessed with the security of

balanced food supplies from both marine and terrestrial environments. Therefore, it is likely that the Okhotsk culture prospered only under the warm climatic condition and that the culture was eventually absorbed by the Satsumon culture.

Predominance of marine products as a diet of Jomon people around Funka Bay

Alkenone temperature data demonstrated that the Jomon people in Funka Bay in Hokkaido experienced colder climate than those at the Sannai-Maruyama site in Aomori Prefecture, the largest Jomon settlement (5.9 to 4.3 cal. kyr BP) (Fig. 3a). Marine products, such as fish and shellfish, must have been abundant while the productivity of terrestrial food declined during the colder phase. It is well known that the colder surface ocean generally promotes marine productivity due to more nutrient supply to the surface ocean by vertical mixing (e.g., Kawahata et al., 2009a). As such, modern Funka Bay provides rich fishing grounds, including those for scallop farming. The Tsugaru and Oyashio Currents enter the bay clockwise in summer and counterclockwise in winter respectively. In accordance with ocean currents, whales and seals move seasonally. Carbon and nitrogen isotopic analyses of proteins extracted from Jomon skeletal remains at Kitakogane, Usu, and Irie–Takasago around Funka Bay demonstrated that the diet consisted primarily of marine fish (including anadromous fish such as salmon), marine bottom fish (e.g., flounder, flatfish) and large marine animals (https://jomon-japan.jp/jomon-sites/ofune/). Jomon residents of this area were more dependent on marine products than Jomon people in Honshu, where two thirds of their nutrition came from terrestrial harvests such as plants, including nuts, and terrestrial animals (e.g., Minagawa et al., 2006). This difference in the dietary trend is basically consistent with the colder climate around Funka Bay than in Honshu.

Implications for human societies in Japan after 3.0 cal. kyr BP

The mid-latitudes are important areas for the development of early complex societies and civilizations (e.g., Fan, 2009; Hodell et al., 2001). Our research is focused on climatic change back through to 3 cal. kyr BP, around which a major wave of migration started from Continental Asia to the Japanese archipelago (Fig. 4). Early societies on the Japanese islands in the last 3.0 kyr can be divided broadly into 6 phases: 1) the Jomon period (before the 10th-5th century BC),. 2) the Yayoi period (10th-5th century BC– ca. 250 AD), when paddy-rice cultivation and other new technologies were introduced together with waves of many immigrants from continental Asia, followed by rapid social stratification (Sato, 2001, 2002; Kawase, 2006; Kono, 2006), 3) the Kofun period (ca. 250–592 AD), the period of early state formation under the strong influences of continental immigrants during and after the 5th century AD, primarily from the Korean Peninsula (Miyamoto, 2009), 4) the Yamato State and Aristocracy period (592–1185 AD), which was the era of centralized states, with many continental immigrants during the 6th – 8th centuries, many of whom were from China (Seki, 2009) 5) the Feudal period (1185–1868 AD), when *samurai,* the warrior class, were

in charge of political power, and 6) the Modern period (1868 AD to the present) (e.g., Kono, 2006). The SSTs reconstructed at Hiroshima Bay suggest that notable cold periods appeared to coincide with major shifts in social systems in Japan (Kawahata et al., 2017a).

The minimal SSTs at Hiroshima Bay generally responded to those at Funka Bay: 6th - 7th century BC, 3rd century BC, 6th century AD, 10th -12h century AD and 16th century AD (Fig. 4). The first cold period corresponded to the gradual transition from the Jomon to the Yayoi periods in western Japan. The cold episode at the 3rd century BC might correspond roughly to the boundary from the Early to the Middle Yayoi period, during which the use of bronze and iron artifacts became more common. The cold event of the 3rd century seems to match the beginning of the Kofun period but the age precision for the 2nd - 3rd centuries is not enough. The Yamato State was established and flourished with increased agricultural production in the improved climatic condition, but its political power declined at the time of the cold conditions (Watanabe, 2009). A major cooling episode coincided with the decline of the Yamato state's political power, and it was eventually replaced by the military-based *samurai* shogunate systems.

As pointed in Kawahata et al. (2017a, b), it is likely that the minima in SSTs (ATs) played an important role in serving as an impetus for societal changes. While this possibility has been discussed in several studies (e.g., deMenocal, 2001; Haug et al., 2003), we do not know the precise mechanisms behind the social upheavals discussed above. Economic and sociocultural factors, including agricultural food production, forestry, fishery and other economic activities, as well as political factors such as military occupation and the development of social hierarchy and classes, must also have played significant roles. In order to understand these processes, quantitative data of other climate parameters, such as rainfall, humidity, and cloudiness, will be helpful.

Conclusions

This paper aimed to enhance our understanding of the Holocene climatic change and to examine the relationship between climatic changes and the human activity in the Holocene in northern Japan, including Hokkaido.

1) The SSTs (ATs) in Funka Bay in Hokkaido, northern Japan, ranged from 14.5°C (15.7°C) to 23.2°C (22.6°C) with the difference of 8.7°C (6.9°C). Major maximal SSTs (ATs) were observed around 4.6, 1.2 cal. kyr BP and the present day.
2) Since the SSTs (ATs) observed in Funka Bay were generally lower than those in northern Honshu, the results are consistent with archaeological data that the Hokkaido Jomon people were more dependent on marine resources than those in Honshu.
3) Two Hypsithermal episodes were identified around Funka Bay. The 1st Hypsithermal condition generally corresponded to the warm period of 5.9-4.2 cal. kyr BP in Mutsu Bay in Aomori Prefecture, where the Sannai Maruyama settlement flourished. After this warm period, northern

Japan experienced the 4.2ka event, a large-scale cooling climate by a few degrees, which was caused by the combination of reduced ESAM and El Niño mode.

4) The 2^{nd} Hypsithermal condition of the 5^{th} – 9^{th} centuries AD could have provided a favorable condition for the Okhotsk culture to prosper along the cost of the Okhotsk Sea in Hokkaido. A notable cooling event occurred around 1.0 cal. kyr BP due to La Niña condition and reduced solar activities. As reported in Hiroshima and Tokyo Bays, the Japanese archipelago never experienced the Medieval Warm Event, but instead the presence of a Medieval Cold Event was identified.

Abbreviations

SST: sea surface temperatures; AT: atmospheric temperature; EASM: East Asian Summer Monsoon.

Declarations

• Ethics approval and consent to participate

There is no part on human participants, human data or human tissue in this manuscript. Also this manuscript does not report on or involve the use of any animal or human data or tissue.

• Consent for publication

There is no other individual person’s data in any form (including individual details, images or videos).

This manuscript does not contain any individual personal data.

• Competing interests

HK has no competing interest.

• Availability of data and materials

Data and Materials were collected by Kenji Nishina, analyzed by Hodaka Kawahata under his scientific funds.

But, If some would like to share HK’s samples, Please contact author for data requests.”

• Authors' information

No special information for HK.

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• Authors' contributions

HK proposed and designed the study. K Nishina collected the sedimentary core. Y Hatta, H Kajita, Y Ota analyzed alkenone. A Yoshida, T Aono and J Habu contributed the discussion on the Jomon period.

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Figure captions

Figure 1(a). Map of the western North Pacific and Japan Sea near the Japanese Islands. The paths of the Kuroshio, Tsushima, Tsugaru and Oyashio Currents are also shown. The location of the cores from St. 5, Site MD01-2409 (41°34' N, 141°52' E), Site MD01-2412 (44°32' N, 145°00' E), PC02 site (41°00' N, 140 °46' E) and of the sediment trap position at Site MD01-2409 (Kuroyanagi et al., 2006; Kawahata et al., 2009a, 2009b). (b) Major Jomon site locations: Ofune (Earth to Middle Jomon), Kakinoshima Site (Initial to Late Jomon), Kitakogane (Early Jomon) and Irie–Takasago (Early to Finanl Jomon), Odai-Yamamao I Site (Incipient Jomon), and Sannai-Maruyama (Early-Middle Jomon), Jomon periods for 14,200 years are classified into six sub-periods: Incipient (16.5-11.55 cal. kyr BP), Initial (11.55-6.95 cal. kyr BP), Early (6.95-5.47 cal. kyr BP), Middle (5.47-4.42 cal. kyr BP), Late (4.42-3.22 cal. kyr BP), and Final (3.22-2.90 cal. kyr BP) (Habu, 2004; Sekine, 2014; Kawahata et al., 2017a).

Figure 2. Schematic representation of the visually observed lithology and magnetic susceptibility (MS) of core St. 5, with calendar ages. Dating was determined using AMS ^{14}C dating of plants and molluscan shells. All ^{14}C ages were calibrated to calendar ages and it was assumed no difference of ΔR because Funka Bay is more isolated from open ocean than Tsugaru Strait. The sediments were precipitated at very constant rate (r^2 = 0.997 between depth and age) from the bottom to 46 cm depth (Ko-d tephra originating from the Komagatake at 1640 AD). The ages above the Ko volcanic ash are approximate.

Figure 3. Time series records of (a) C37 alkenone SSTs (ATs) at St. 5 (solid circle) and SSTs and SSTs (ATs) at PC02 site (line) in Mutsu Bay (solid square) (Kawahata et al., 2009b), (b) The summer and winter daily insolation at 55°N in the Northern Hemisphere for the last 8,000 years (W m^{-2}) (Berger, 1978), (c) sunspot number (Usoskin et al., 2007), (d) ESR intensity of fine silt-sized quartz particles in Japan Sea sediments with vertical shading showing negative peaks (Nagashima et al., 2013), which is a proxy for the latitudinal shift of Westerly Jet stream, related to latitudinal shift of East Asian Monsoon, (e) $\delta^{18}O$ of the Dongge and Hulu Cave stalagmites as a proxy for the intensity of the Far Eastern Asian Summer Monsoon (Dykoski et al., 2005), (f) Southern Oscillation Index (SOI)-like index for the last 2 kyr (Yan et al., 2011) and lithic down-core variation off Peru as a proxy for SOI in 2-8 cal kyr BP (Rein et al., 2005), (g) global sea level change (bold line: Tanabe et al., 2012; dotted line: Shigeno et al., 2013;

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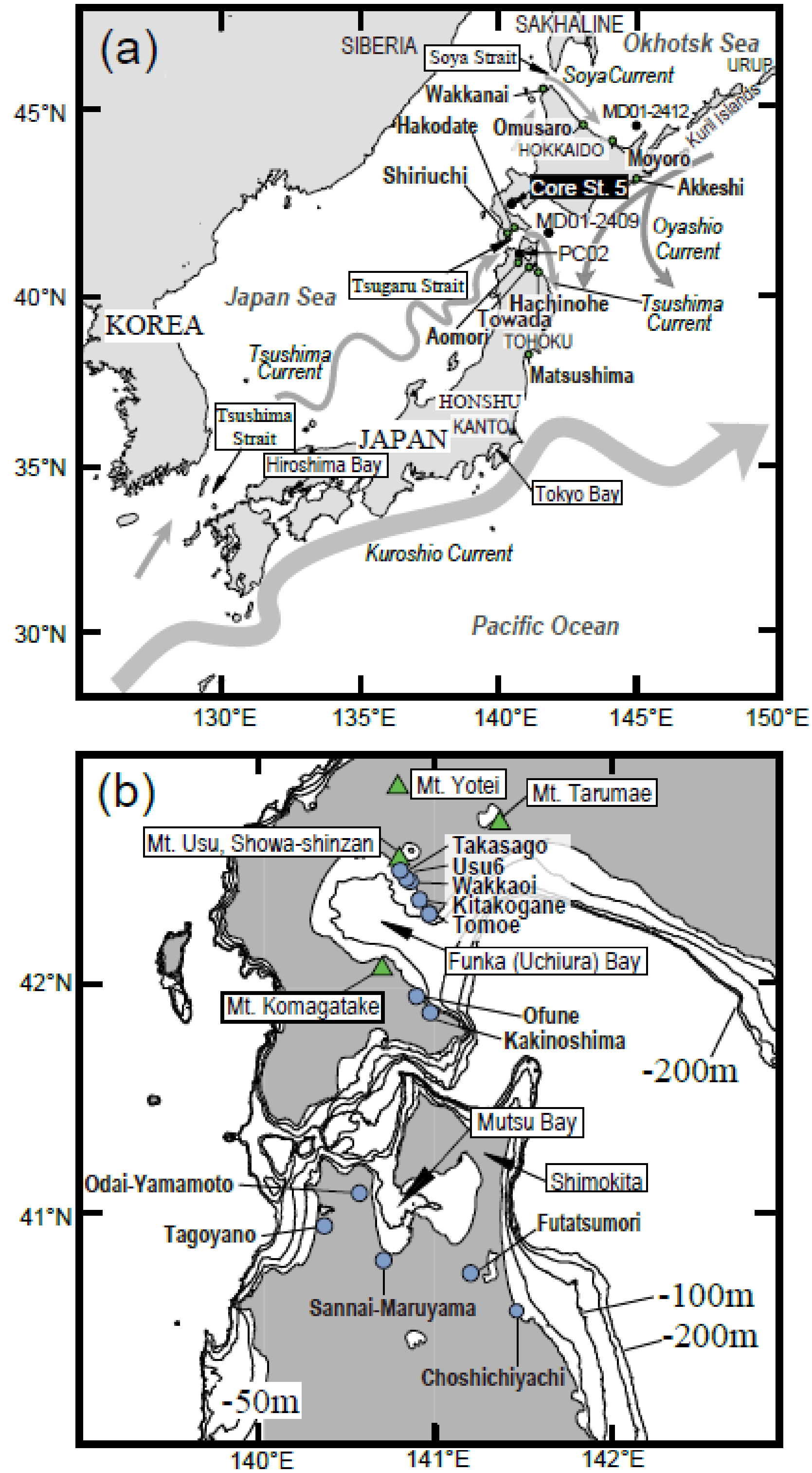
Figure 4. Time series of alkenone sea surface temperature (SST) and atmospheric temperature (AT) during the last 3,000 years in Hiroshima (a, circle) and Funka (b, solid square) Bays. The gray color area, after 1640AD, in Funka Bay indicated that the age of the SSTs (ATs) data is approximate. Upper column shows each period with broad category of social system. The life style in ancient society in Japan is classified broadly into six groups. Three main immigration intervals are also plotted. Italic characters, representing volcanic eruption, show possible causes. Upper solid triangles represent possible volcanic eruption. Especially the large eruption in 1258 AD was identified in Ice cores and sediments but the source is mysterious (Emile-Geay et al., 2008). Gray curves in 1000 BC–400 BC, in 600–1400 AD and in 1750–1850 AD represent C_{37} alkenone SSTs in Yellow Sea (Wang et al., 2011), qualitative AT estimate from the historical documents (Ishii, 2002; Yoshino, 2009a, b) and semi-quantitative AT estimate from the historical documents (Kondo, 1987), respectively. All famines shown here represent a widespread scarcity of food, caused by cold climate. Three severe famines in Medieval times include Yowa (1180AD), Kangi (1230 AD) and Kansho (1460 AD) while four severe famines in northern Japan in Edo period include Kanei (1642–43 AD), Horeki (1755-57), Tenmei (1782–87 AD), and Tenpo (1833–39 AD). Middle column shows periods of culture in Hokkaido: Ainu (modern-13^{th} century), Satsumon (13^{th} -7^{th} century), Post- Jomon (7^{th} AD – 3^{th}BC century) and Jomon (before 3^{th} century). An arrow in Figure (b) shows Okhotsk culture in Hokkaido in 5^{th} - 9^{th} centuries. Arrows on the bottom represent Roman Warm Period (RWP, 50–400 AD), Medieval Warm Period (MWP, ca. 950–1250 AD [sometimes 1000–1400]), Dark Ages Cold Period (AD 500–900) and Little Ice Age (LIA, ca. 1600–1850 AD [sometimes 1350–1850]) have received much attention (e.g., Yan et al., 2011

Figure 1

Figures



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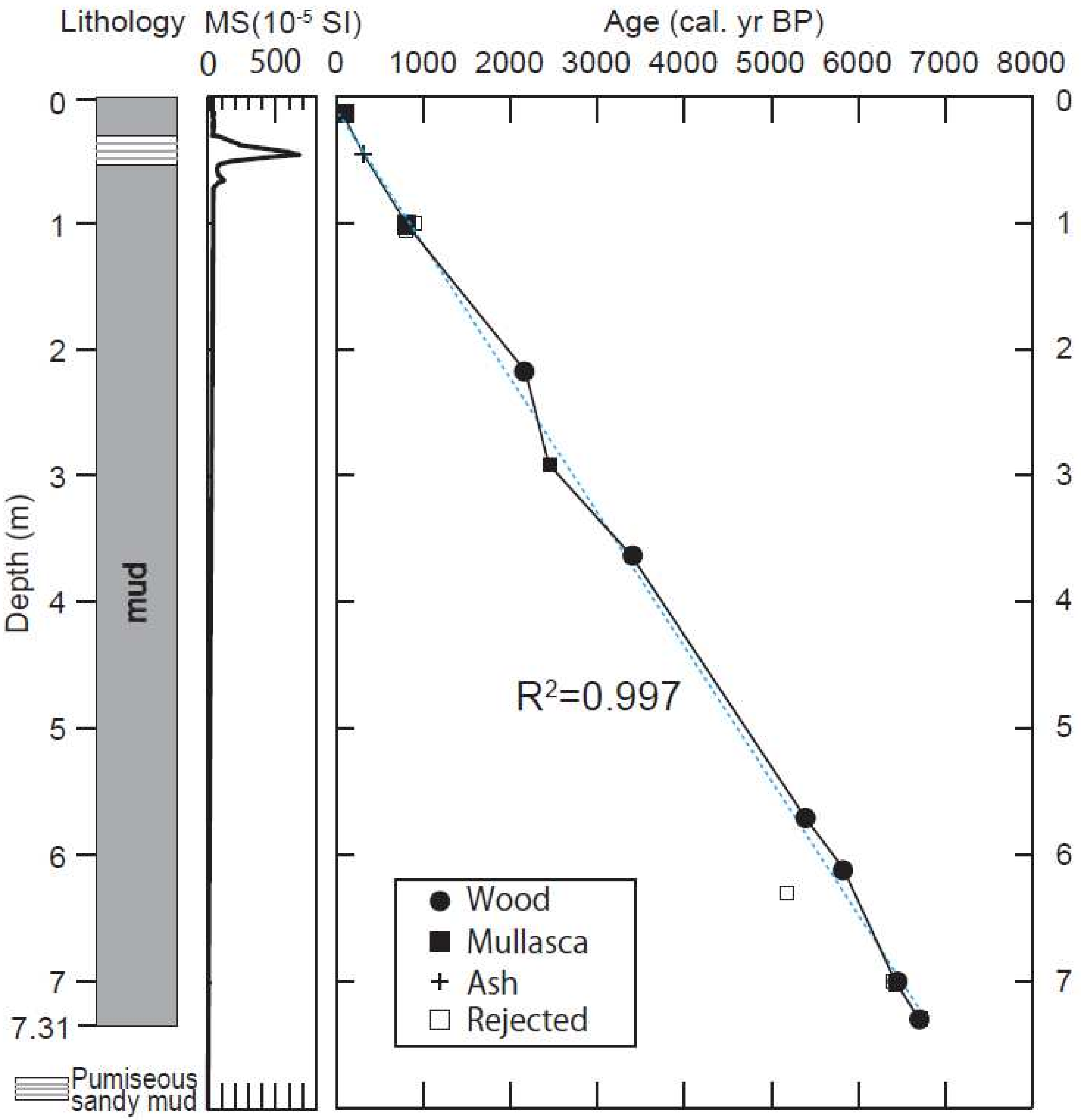

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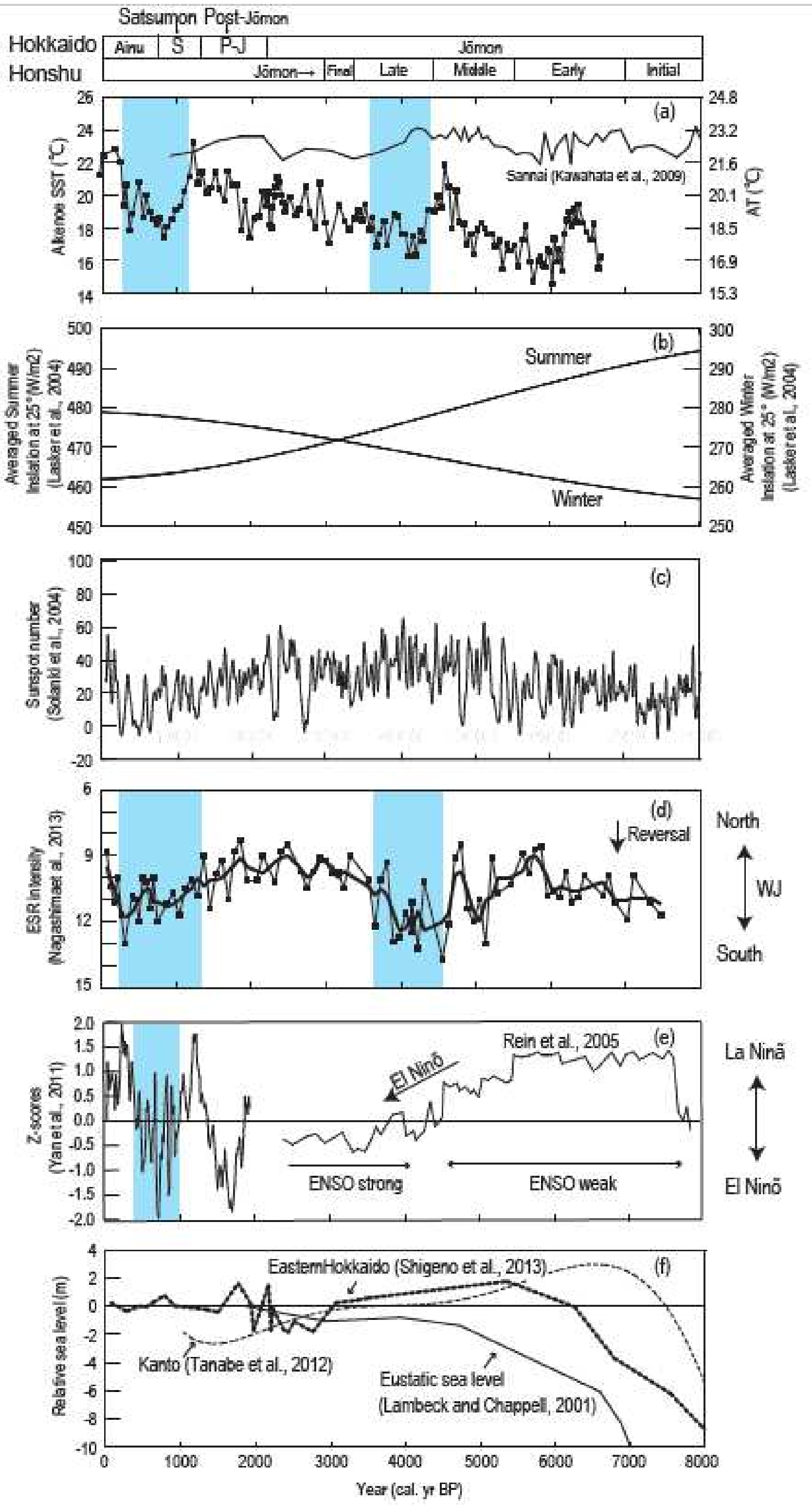

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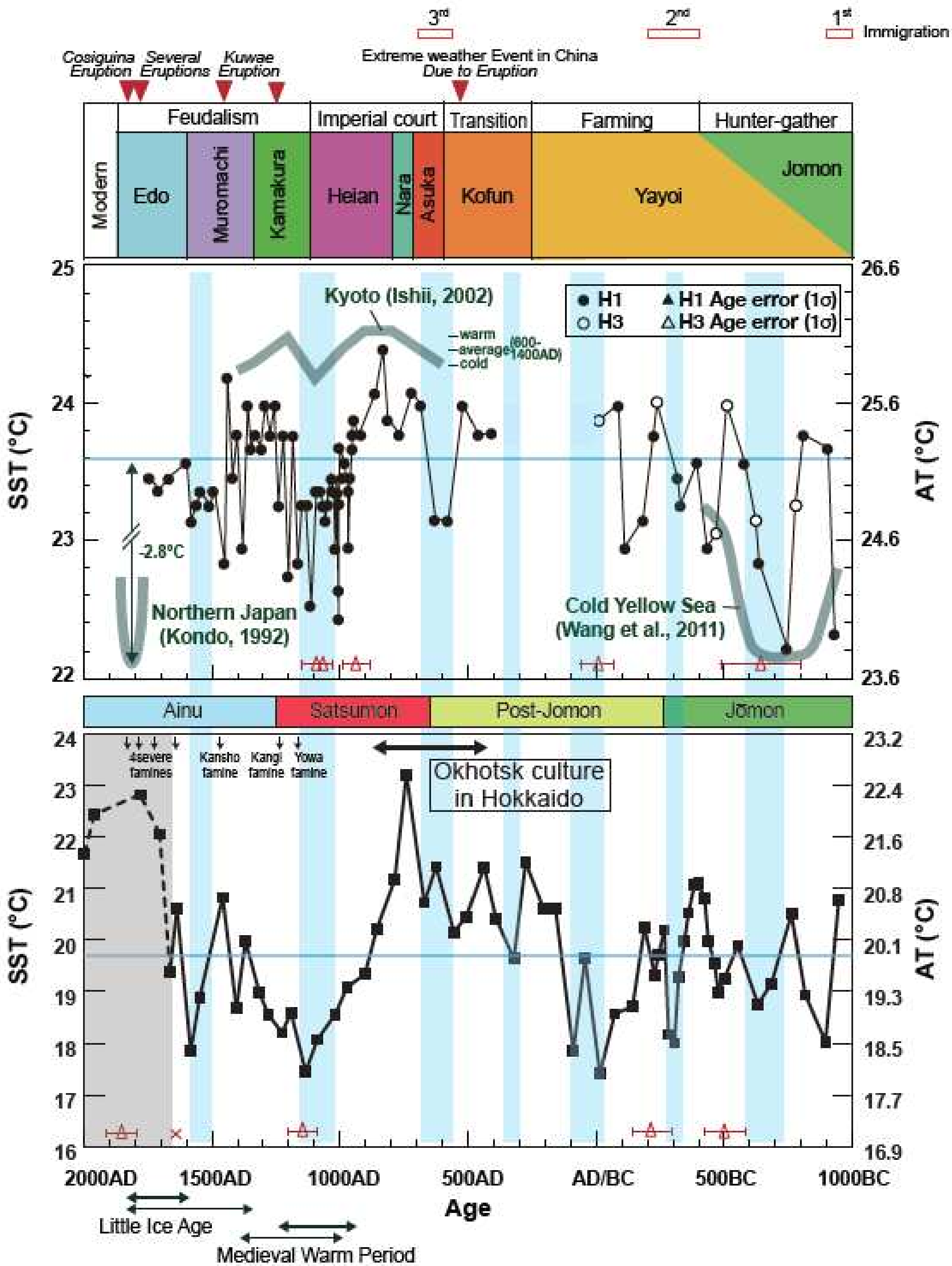

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