Global and Planetary Change 157 (2017) 35–47

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Interannual to decadal variability of summer sea surface temperature in the Sea of Okhotsk recorded in the shell growth history of Stimpson's hard clams (*Mercenaria stimpsoni*)

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ARTICLE INFO

Keywords:
Mercenaria stimpsoni
Sea of Okhotsk
Sclerochronology
Oxygen isotope ratios
Summer seawater temperature
Decadal variability

ABSTRACT

Sclerochronological and shell stable oxygen isotopic analyses were conducted on live-caught specimens of Stimpson's hard clams, *Mercenaria stimpsoni*, from the southern Sea of Okhotsk, off northern Hokkaido, Japan. In this region, the main growing season of this species during early ontogeny (below the age of 12 years) lasts from mid-spring to mid-fall at sea surface temperatures (SST) between approximately 10 and 22 °C. Growth cessation begins between late fall and early spring at SST, below approximately 6 °C; however, shell growth was largely limited to the summer season later in life. Counting of annual increments indicated that this species had a relatively long life span of up to 100 years. Annual shell growth rates were high during early ontogeny and declined abruptly afterwards. Mean standardized shell growth indices (SGIs) of long-lived specimens were positively correlated to the mean summer SSTs near the sampling site and in the coastal waters off northern Hokkaido. The SGI chronology of the longest-lived specimen (99 years old) exhibited periodicities of approximately 10 and 5 years during the calendar years 1920–2011, possibly reflecting the quasi-decadal variability of summer SST in the southern Sea of Okhotsk. These findings indicate that *M. stimpsoni* could serve as an archive to reconstruct past marine climate changes in the Sea of Okhotsk.

1. Introduction

Long-term and annually resolved records of past environmental conditions from different geographic settings provide a reliable basis for predicting future state of the climate system. Of the various organisms that secrete a marginal growing skeleton, bivalve mollusks are best suited to analyze past aquatic environmental changes because (1) they exhibit a broad biogeographic, bathymetric, and environmental distribution ranging from tropical to polar realms, intertidal to deep-sea settings, and freshwater to marine environments; (2) their shells have a high preservation potential as fossils; and (3) they preserve sequences of daily and annual increments in the ventral shell margin and hinge plate (Richardson, 2001; Schöne and Surge, 2012).

In the past two decades, sclerochronological studies, specifically analyses of shell growth patterns, stable isotopes, and trace elements, have been conducted in several long-lived marine bivalve species to reconstruct past environmental conditions such as SST (sea surface temperature), salinity, nutrient sources, and daily light cycles over a wide range of different temporal resolutions ranging from seasons to millennia. Examples include the giant clams, *Hippopus hippopus* and *Tridacna gigas*, from the tropical to subtropical oceans (e.g., Watanabe et al., 2004; Elliot et al., 2009; Aubert et al., 2009; Sano et al., 2012; Hori et al., 2015), *Arctica islandica* (e.g., Witbaard et al., 1997; Schöne et al., 2004; Wanamaker et al., 2008; Butler et al., 2011; Schöne, 2013; Holland et al., 2014), and *Glycymeris glycymeris* (Brocas et al., 2013; Royer et al., 2013) from the northern North Atlantic, as well as *Panopea abrupta* from the Northeast Pacific (Strom et al., 2005; Black et al., 2009). These studies also demonstrated that age-detrended shell growth rate is coupled with decadal climate variabilities, such as the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and El Niño-Southern Oscillations (ENSO).

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http://dx.doi.org/10.1016/j.gloplacha.2017.08.010
Received 3 April 2017; Received in revised form 15 August 2017; Accepted 15 August 2017
Available online 16 August 2017
0921-8181/

In the Sea of Okhotsk, inter-annual and decadal variations in summer SST are well documented by oceanographic observations covering time intervals from 1961 to 1996 (Shatilina, 1996) and 1982 to 2016 (data available from the Meteorological Agency of Japan, Sapporo Regional Headquarters; http://www.jma-net.go.jp/sapporo/kaiyou/engan/data/txt/area102.txt), and statistical analyses of climate data sets covering the time interval of 1951 to 1996 (Minobe and Nakamura, 2004; see Levitus et al., 1998 for the climate data sets). However, climate oscillations in the Sea of Okhotsk before the 1950s have not yet been sufficiently documented because instrumental records are not available.

In this study, we chose a venerid bivalve, *Mercenaria stimpsoni* (Gould), commonly called Stimpson's hard clam, as a model species to analyze the response of annual shell growth rates to environmental changes in the Sea of Okhotsk. This infaunal suspension feeder inhabits the fine sandy substrates of the shallow subtidal zone (5–30 m deep) along the mid- to high-latitude coasts of the Northwest Pacific, Sea of Japan and Sea of Okhotsk (Habe, 1977). The outer shell layer of this species shows a combination of composite prismatic and crossed-lamellar microstructures, whereas the inner layer is composed of homogeneous microstructures, both of which are made of aragonite (Kobayashi, 1971). Previous sclerochronological and stable isotope analyses of shells of live specimens collected from the coasts of eastern South Korea (Khim et al., 1998) and northeast Honshu Island, Japan (Kubota et al., 2017), demonstrated that this species forms periodic annual shell growth patterns with distinct annual growth lines associated with a notch on the outer shell surface. The annual growth lines were formed between late fall and early spring, during which SST dropped below 10 °C. These annual growth lines permitted us to determine the ontogenetic age and shell growth rate of each specimen. Kubota et al. (2017) reported a relatively long life span ranging from 76 to 92 years for the three specimens from Funakoshi Bay, northeast Honshu (sampling location: 39°23.4′N, 141°57.6′E). Hence, long-lived specimens of this species are expected to preserve a long-term record of the past marine environmental conditions in their annual increment sequences, but to date this hypothesis has not been addressed.

Based on combined shell growth patterns and oxygen isotope analyses, we demonstrated here, to our knowledge, for the first time, that the marine climate controls seasonal and inter-annual shell growth patterns of *M. stimpsoni* from the southern Sea of Okhotsk, off northern Hokkaido, Japan. Special reference was given to the response of the shell growth rate to inter-annual and decadal-scale oscillations of summer SST in the region.

2. Study area and oceanographic and environmental settings

The Monbetsu area, northern Hokkaido Island, Japan (Fig. 1A, B), from which the studied material was collected, faces the southern margin of the Sea of Okhotsk in the northwestern arm of the Pacific Ocean. In the northern hemisphere, the Sea of Okhotsk is the southernmost sea with significant ice cover from winter to early spring. The sea is situated on the eastern side of the Far East Russian Siberian coast and surrounded by the Kamchatka Peninsula to the east, Sakhalin Island to the west, Kuril Islands to the southeast, and Hokkaido to the southernmost periphery. Seawater moves through the Sea of Okhotsk in a counterclockwise direction known as the Okhotsk Sea Gyre (Fig. 1A), and there are 12 distinguished boundary currents in the sea (Kim, 2012).

In the study area, SST was measured bimonthly during 1996–2001 and daily during 2002–2009 near the Okhotsk Tower (2 m water depth) by the Okhotsk Sea Ice Museum of Hokkaido. In addition, the Monbetsu Fishermen's Union completed bimonthly measurements during 1996–2001 and daily measurements during 2002–2008 at the Monbetsu Port (4 m water depth). These data were provided by the Environmental and Geological Research Department, Geological Survey of Hokkaido (http://www.hro.or.jp/list/environmental/research/gsh/publication/data/temperature_data/index.html) for 1994–2001 and by the Japan Oceanographic Data Center (http://www.jodc.go.jp/data/coastal/obs_detail_data.htm#hokkaido2a) for 2002–2009. We also obtained monthly salinity data collected in 2008 at the Monbetsu Port by the Monbetsu Fishermen's Union.

Annual variations in SST at the study site were fairly large (20–25 °C), ranging from − 1.9 to 0.0 °C between late January and early March and 13.9–22.8 °C between July and September (Fig. 1C; Table 1). Surface salinity showed clear seasonal variations in the study area; namely, mean monthly value was higher than 33.0 during July to October but suddenly dropped being < 32.0 in December and January (Fig. 1D).

Higher SST and salinity during summer were caused mainly by a stronger flow of the warm and saline Soya Current, a branch of the Tsushima Warm Current moving northeastward along the Sea of Japan off Honshu and Hokkaido Islands (Itoh and Ohshima, 2000). The Soya Current flows along the northern coast of Hokkaido in a southeastern direction. During winter, the Soya current weakens and is replaced by the cold and fresh East Sakhalin Current (ESC) in the southern Sea of Okhotsk off northern Hokkaido, which flows along the eastern coast of Sakhalin before entering the Oyashio Cold Current region of the northern Northwest Pacific (Nakatsuka et al., 2002; Ohshima et al., 2002) (Fig. 1A). Ohshima et al. (2002) reported the current structure, volume transport and tidal currents of ESC analyzed with satellite-tracked drifters.

Abrupt decrease in surface salinity in winter in the study area has also been reported from the southern Sea of Okhotsk coasts and interpreted an indication of the influence of ESC (e.g., Watanabe, 1963; Itoh and Ohshima, 2000).

Oceanographic data of the study area during 1999–2009 showed that the lowest SSTs in winter remained nearly constant between − 1.4 and − 1.9 °C, whereas the highest and mean summer (July–September) SSTs showed quasi-decadal variations and ranged from 18.9 to 22.8 °C and 16.8 to 19.1 °C, respectively (Table 1).

3. Material and methods

3.1. Material

In 2010 and 2012, the Monbetsu Fisheries Cooperatives and the Fisheries Research Department of the Hokkaido Research Organization conducted a marine resource survey on the northeastern coast of Hokkaido, facing the Sea of Okhotsk. Several specimens of *Mercenaria stimpsoni* (Gould) were collected alive during the survey by means of a trawl with a 1.2 m-wide wire-frame opening from the subtidal (3–15 m water depth) fine sandy bottom at two localities off Monbetsu Port, Northern Hokkaido (locality 1 at 143°21′38″E, 44°22′15″N and locality 2 at 143°24′8″E, 44°19′49″N) (Fig. 1B). Of these specimens, eight long-lived individuals (Mon 2012-12, 2012-13, 2012-15, 2012-16, 2012-17, 2012-18, 2012-19, and 2012-20; Table 2) were used in the sclerochronological analyses. In addition, two specimens (Mon 2010-3 and 2010-11; Table 2) were used for stable oxygen isotope analyses. All specimens utilized herein were housed at the University Museum, University of Tokyo (UMUT).

3.2. Methods

3.2.1. Sample preparation

Soon after capture, live-caught specimens of *M. stimpsoni* were frozen and transported to the laboratory. After removal of the soft tissues, one valve of each specimen was coated with epoxy resin (J-B KWIK) and cut along the maximum growth axis using a low speed saw (Buehler Isomet) (Fig. 2). Both halves of the cross-sectioned valves were glued onto glass slides using epoxy resin with the mirroring portions facing upward. The surfaces were then polished with a graded series of carborundum and 1 μm Al_2O_3 powder or diamond suspensions using a Buehler MetaServ 2000 variable-speed grinder–polisher. Half of each