



## Gulf of Maine shells reveal changes in seawater temperature seasonality during the Medieval Climate Anomaly and the Little Ice Age

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### ABSTRACT

In this study, we use subannually resolved oxygen isotope values of fossil (dead-collected) and modern (live-caught) bivalve shells (*Arctica islandica* L.) from the northwestern Atlantic (Gulf of Maine, USA) to reconstruct past seasonal changes in seawater temperature. Our results indicate decreased seasonal temperature amplitude of about 1.6 °C (or ~21%) during Medieval times (ca. AD 1033–1062) compared to shells from the early Little Ice Age (ca. AD 1321–1391) and during the late 19th century (AD 1864–1886). Additionally, seasonal oxygen isotope data suggest that summers were cooler and winters were warmer in the Gulf of Maine during the 11th century compared to summers and winters in the 14th century and the late 19th century. The inferred decreased seasonality during Medieval times likely resulted from increased stratification of the coastal waters due to warmer seawater temperatures. As seawater cooled during the Little Ice Age, we suggest that increased vertical mixing of the coastal surface waters was a major driving factor for the observed increase in the amplitude of the seasonal seawater temperature cycle.

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### 1. Introduction

Small changes in seasonality can have dramatic and rapid effects on the climate system (Denton et al., 2005), terrestrial and marine ecosystems (e.g., Hinzman et al., 2005; Smetacek and Nicol, 2005), and on the health and stability of human populations (e.g., Barlow et al., 1997; Altizer et al., 2006; Patterson et al., 2010). In the current global warming scenario (IPCC, 2007), records of past climate and seasonality from a variety of locations are needed to place recent global changes into context. Although there is a vast network of annually-resolved, terrestrial-based proxies in the northern hemisphere for the last millennium (NRC, 2006) to study climate change, such records are scarce in the marine realm; this problem exists despite the fact that marine-based data are critical to fully capture recent and past climate change. Thus far, much of the existing annually-resolved, marine-based proxy records, mostly from corals and sclerosponges, are biased to the tropical oceans. To some extent, research in the climatically important mid-to-high-latitude oceans has been hindered by a lack of suitable high-resolution marine archives with annual banding for sclerochronological studies (e.g., Halfar et al., 2008).

In this study we attempt to reconstruct past seasonal dynamics of seawater temperature variations in the Gulf of Maine, USA for intervals of the last millennium. The Gulf of Maine is situated in the northwestern Atlantic located along a hydrographic and faunal transition zone that is sensitive to minor climate shifts (Fig. 1) (e.g., MERCINA, 2001, 2003). The Gulf of Maine is an extremely productive ocean environment that supports a rich and dynamic ecosystem. Because of its geographic location, changes in the strength and/or position of slope water currents (Labrador Current and Gulf Stream) are thought to significantly affect the oceanography (e.g., temperature, salinity, productivity) in the Gulf of Maine (Pickart et al. 1999; MERCINA, 2001; Greene and Pershing, 2001; Conversi et al., 2001; Halfar et al., 2008; Wanamaker et al., 2008a, 2009). To date very few studies have investigated the ocean climate and ecosystem dynamics of the Gulf of Maine beyond the relatively short instrumental period. Of these studies, none have characterized the past seasonality of seawater temperature variability in terms of climate (i.e., 30-yr means). Previously, Wanamaker et al. (2008a) showed a long-term increasing trend in annual  $\delta^{18}\text{O}$  shell values (indicative of 1–2 °C cooling) in the Gulf of Maine during the last millennium using oxygen isotope profiles from *Arctica islandica* shells. In this study, we revisit the work of Wanamaker et al. (2008a) to determine if there were any significant changes in seawater temperature seasonality during the last 1000 years, especially between the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) intervals.

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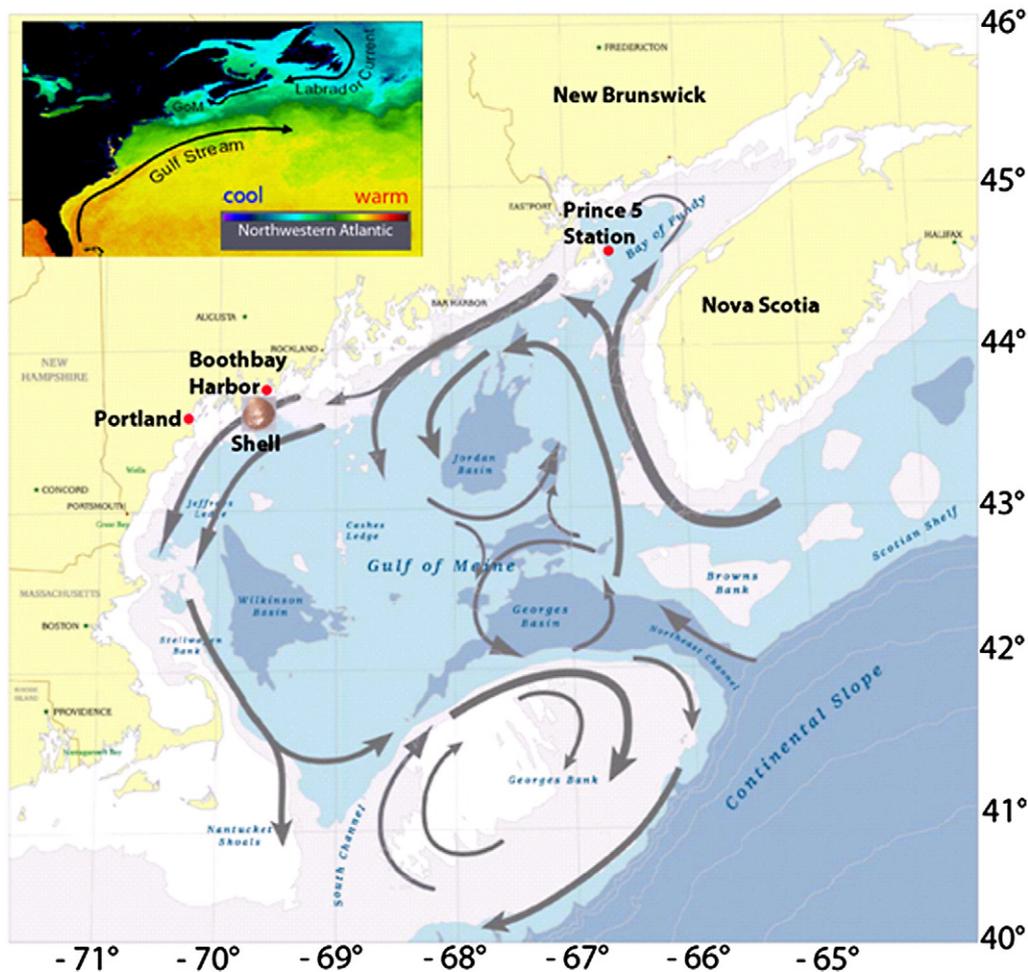


Fig. 1. General summer surface ocean circulation patterns in the Gulf of Maine (modified from Pettigrew et al., 2005). Small red circles represent long-term climate monitoring stations. Large shell symbol represents the shell study location of Wanamaker et al., (2008a). The Prince 5 station is located near the mouth of the Bay of Fundy. Insert panel- General surface ocean temperature patterns in the northwestern Atlantic (adapted from NASA/Goddard Space Flight Center, <http://oceancolor.gsfc.nasa.gov/>).

## 2. Materials and methods

### 2.1. *Arctica islandica* as a marine bioarchive of environmental change

The long-lived bivalve mollusk *A. islandica*, common in the shelf seas of the temperate to sub-polar North Atlantic, has enormous potential as a high-resolution marine archive. This sessile benthic bivalve mollusk is highly suitable for environmental and climate studies because (1) it is extremely long-lived (up to 3–4 centuries; Schöne et al., 2005a; Wanamaker et al., 2008b), (2) it produces annual increments in its shell (Jones, 1980), (3) regional increment series can be cross-dated, demonstrating a common response to environmental forcing(s) (Schöne et al., 2003), (4) fossil shells can be cross-dated and floating shell chronologies can be constructed after radiocarbon dating (Scourse et al., 2006), (5) live-caught shells can be cross-dated with fossil shells to assemble very long, absolutely-dated growth records (Marchitto et al., 2000; Schöne et al., 2003; Butler et al., 2009), (6) master shell chronologies can be created that are as statistically robust as tree ring chronologies (Butler et al., 2009), (7) *A. islandica* is widely distributed in the mid-to-high-latitudes of the North Atlantic throughout the Holocene (Dahlgren et al., 2000), (8) it precipitates its aragonitic shell in oxygen isotope equilibrium with ambient seawater (Weidman et al., 1994; Schöne et al., 2004), and (9) the geochemical signature ( $^{14}\text{C}$ ,  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) from the shell material and master shell-growth chronologies can be used to reconstruct ocean circulation (Wanamaker et al., 2008a), hydrographic changes (Weidman et al.,

1994; Schöne et al., 2005a), carbon cycling (Weidman and Jones, 1993; Butler et al., 2009; also see Butler et al., 2010-this issue, and Schöne et al., 2010-this issue), seasonal changes in seawater temperature (Schöne and Fiebig, 2009), and productivity dynamics (Witbaard et al., 2003; Wanamaker et al., 2009). Additionally, in the Gulf of Maine, it appears that *A. islandica* deposits its shell material throughout most of the year (Wanamaker et al., 2008a); hence *A. islandica* does not exhibit a major shutdown period in this location. Beyond this study, it is also important to note that there is no evidence that *A. islandica* experiences differing lengths of time during growth cessation as a function of ontogeny (see Schöne et al., 2005a).

### 2.2. Shell collection

One specimen of *A. islandica* (SF1) was collected alive in the Western Gulf of Maine, USA ( $43^{\circ} 39' 22.14'' \text{ N}$ ,  $69^{\circ} 48' 6.01'' \text{ W}$ ), in 30 m water depth via the fishing vessel FV Foxy Lady on March 14, 2004 during a Maine Department of Marine Resources dredge survey (Fig. 1). Also, three articulated and well-preserved fossils of *A. islandica* were collected in the Western Gulf of Maine ( $43^{\circ} 41' 13.14'' \text{ N}$ ,  $69^{\circ} 47' 56.34'' \text{ W}$ ) in 38 m water depth via a Rossfelder vibracore (SBVC-9609) and recovered from 48 cm (shell SBVC9609-48), 40 cm (shell SBVC9609-40) and 30 cm (shell SBVC9609-30) core depths, respectively, on September 29, 1996. Because the animals were collected from the same oceanographic setting (location and water depth) within the Western Maine Coastal Current (part of the

Gulf of Maine Coastal Current; see Pettigrew et al., 2005), comparisons among the shell geochemistry to assess changes in seasonality through time is thought to be appropriate.

### 2.3. Shell preparation, stable isotope measurements, and $^{14}\text{C}_{\text{AMS}}$ dating

In preparation for sclerochronological and isotope analyses (see Schöne et al., 2005a), the left valve from each shell was mounted on a plexiglass block, and a quick-drying metal epoxy resin was then applied to the surface (inside and out). Two thick (3 mm) sections of the shell were cut from the valve along the axis of maximum growth, and perpendicular to the annual growth lines with a Buehler Isomet low-speed saw using a 0.3 mm thick diamond wafering blade. Each section was mounted on a glass slide, ground with 800 and 1200 SiC grit, polished with 1 mm  $\text{Al}_2\text{O}_3$  powder and cleaned with dehydrated ethyl alcohol. Further, to resolve annual growth patterns, one polished section from each shell was immersed in Mutvei's solution (Schöne et al., 2005b) for 20 min at 38 °C. The treated shell was immediately rinsed with demineralized water and air-dried. The growth patterns of the etched shell were viewed under a reflected light stereomicroscope (Leica Wild M3Z) and digitized using a Nikon Coolpix 995 camera. Annual growth widths were determined to the nearest 0.01 mm with Scion Image (version 1.63). Measurements were conducted on the outer shell surface.

Carbonate samples were micromilled along annual growth increments from the untreated shell section using methods outlined by Schöne et al. (2005a). Based on 1807 oxygen isotope analyses ( $\delta^{18}\text{O}_c$ ) on the four shells during the specified time intervals, the average number of sub-annual  $\delta^{18}\text{O}_c$  samples per year were: 11 for shell SBVC9609-48 (geochemical sampling began in ontogenetic year 4 to 5;  $N_{\text{total}}=319$ ; range 7–18), 23 for shell SBVC9609-40 (geochemical sampling began in ontogenetic year 1 to 2;  $N_{\text{total}}=697$ ; range 7–71), 15 for shell SBVC9609-30 (geochemical sampling began in ontogenetic year 6 to 7;  $N_{\text{total}}=426$ ; range 7–28), and 15 for shell SF1 (geochemical sampling began in ontogenetic year 1 to 2;  $N_{\text{total}}=365$ ; range 7–41). For this study, the minimum number of carbonate samples per year was seven. Each carbonate sample of aragonite weighed  $\sim 50\ \mu\text{g}$ . The samples were reacted with 99% anhydrous phosphoric acid at 72 °C in an automated carbonate preparation device (Gas Bench II) coupled to a Finnigan MAT-253 continuous-flow mass spectrometer at the University of Frankfurt, Germany. Oxygen isotope ratios of the samples are reported in per mil units (‰) relative to the VPDB (Vienna Pee-Dee Belemnite) carbonate standard based on a NBS-19 calibrated Carrara marble value of  $-1.76\text{‰}$  ( $\delta^{18}\text{O}$ ). Precision of the instrument determined from replicate analyses was  $\pm 0.07\text{‰}$  for  $\delta^{18}\text{O}$ .

To determine the  $^{14}\text{C}$  age of each fossil shell, approximately 8 mg of aragonite powder was milled from the ventral margin and dated by  $^{14}\text{C}_{\text{AMS}}$  (performed by National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institution). Calibrated  $^{14}\text{C}$  ages (cal yr AD) were calculated using Calib 5.01 (Stuiver and Reimer, 1993) and a regional Gulf of Maine marine reservoir effect of  $\Delta R=39\pm 40$  yr (Tanaka et al., 1990). The calendar age assigned to the entire shell resulted from counting the annual growth increments from the ventral margin back to the umbo (Jones, 1980).

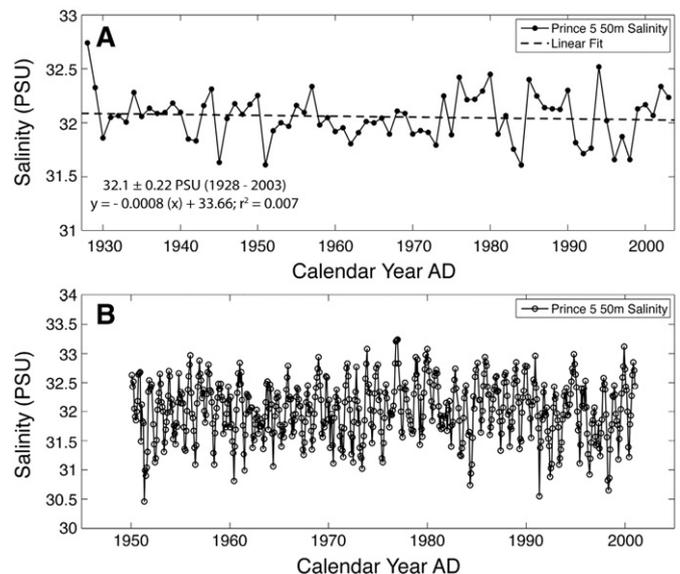
### 2.4. Data normalization and resampling of $\delta^{18}\text{O}_c$

The low-frequency trend in  $\delta^{18}\text{O}_c$  was removed from each shell utilizing a linear model. The best-fit model was used to calculate the trend in the  $\delta^{18}\text{O}_c$  data, which was then subtracted from the raw  $\delta^{18}\text{O}_c$  value establishing a high-frequency (high-pass) time-series. Next, the  $\delta^{18}\text{O}_c$  data were normalized by removing the mean  $\delta^{18}\text{O}_c$  value from each shell. This normalization resulted in shell  $\delta^{18}\text{O}_c$  values with a mean of zero, and allowed the determination of average seasonal maximum (max) and minimum (min)  $\delta^{18}\text{O}_c$  values without low-

frequency variability (interannual to decadal). In order to assess the seasonality of oxygen isotope patterns, we resampled the data within each year with a 7-point cubic spline model (AnalySeries 2.0.4.2; freely available at <http://www.lscce.ipsl.fr/en/software/index.php>) (see Paillard et al., 1996 for a complete description) for each of the four shells (also see Schöne and Fiebig, 2009). Additionally, for select years (e.g., years with 7, 14, 21, or 42 raw samples and easily compared to the 7-point model) we compared the cubic spline resampling protocol with a linear piece-wise model (also using AnalySeries 2.0.4.2), and simple averaging to ensure that the resampling strategy did not influence the amplitude of seasonal seawater temperature cycle throughout ontogeny. A total of 14 yr were compared utilizing shells SBVC9609-48 (7 years; samples per year: 7, 7, 14, 14, 14, 14, 14), SBVC9609-40 (1 year; samples per year: 42), SBVC9609-30 (3 yr; samples per year: 7, 14, 21), and SF1 (3 yr; samples per year: 14, 14, 21). The resampling method used here (7 samples/yr for all four shells) minimizes any biases related to growth rate variability and/or changes in the sampling rates per year through time due to ontogeny. Based on the isotope sampling rate (more samples when the animal is younger; fewer samples when the animal is older; for a review see Goodwin et al., 2003), the 7-point model was a good compromise because it allowed us to produce four intra-annual shell oxygen isotope time-series that were either 30 yr in length (three shells; SBVC9609-48; SBVC9609-40; SBVC9609-30) or at a minimum, 23 yr (one shell; SF1) in length, that still captured the annual seawater temperature cycle. Our goal is to produce climatological means (30 yr) of seasonality that are sampled equivalently (i.e., same number of samples represented) to assess changes in the seasonal seawater temperature cycle. For this study, the number of  $\delta^{18}\text{O}_c$  samples per year considered in the seasonal seawater temperature calculation was seven.

### 2.5. Calculation of scaled seawater temperature seasonality

After resampling the intra-annual data, we subtracted  $\delta^{18}\text{O}_c$  min values from  $\delta^{18}\text{O}_c$  max values for each time interval. The difference between  $\delta^{18}\text{O}_c$  max and  $\delta^{18}\text{O}_c$  min ( $\Delta\delta^{18}\text{O}_c$ ) was used to estimate seasonality using the Grossman and Ku (1986) paleotemperature equation for biogenic aragonite. However, a small modification of their equation was required because they report oxygen isotope



**Fig. 2.** Panel A – Long-term annual 50 m salinity values from Prince 5 station (1928–2003) (see Fig. 1). Panel B – Monthly 50 m salinity values from Prince 5 station (1950–2000). The mean difference in max and min salinity values from 1950 to 2000 was  $1.41\pm 0.33$  PSU.

values of seawater ( $\delta^{18}\text{O}_{\text{water}}$ ) in SMOW  $-0.27\text{‰}$  (see footnote in Dettman et al., 1999). The corrected function is as follows (Eq. (1)):

$$T(^{\circ}\text{C}) = 20.60 - 4.34 \times (\delta^{18}\text{O}_{\text{aragonite}} - (\delta^{18}\text{O}_{\text{water}} - 0.27)). \quad (1)$$

Because of the long-term stability in salinity at 50 m ( $32.1 \text{ PSU} \pm 0.22$ ; see Fig. 2A) from 1928 to 2003 measured at the Prince 5 station (Fig. 1;  $44.93^{\circ}\text{N}$ ,  $66.85^{\circ}\text{W}$ ), and based on the uniformity of max and min salinity values (mean difference =  $1.41 \pm 0.33 \text{ PSU}$ ; derived from monthly data) during the last 50 yr (Fig. 2B), and due to the lack of any paleo-salinity data in the Gulf of Maine, we assumed no changes in interannual max and min oxygen isotopic values of the water ( $\delta^{18}\text{O}_{\text{water}}$ ; related to salinity) in our seawater temperature seasonality calculations. Based on the Houghton and Fairbanks (2001) isotope/salinity mixing line for the Gulf of Maine, and the modern fifty-year standard deviation ( $\pm 0.33 \text{ PSU}$ ) in mean salinity max minus min values (Fig. 2B), a variation of  $\pm 0.19\text{‰}$  in the oxygen isotopic composition of the water is

likely. However, a full discussion of the assumption for using a constant  $\delta^{18}\text{O}_{\text{water}}$  value along with the uncertainties associated with it follows. Thus, Eq. (1) was further modified (Eq. (2)) as we considered only the slope value, which is shown below:

$$\text{Seasonality } T(^{\circ}\text{C}) = 4.34 \times (\Delta\delta^{18}\text{O}_c). \quad (2)$$

Because the 7-point model attenuated the true seasonal cycle in shell  $\delta^{18}\text{O}_c$ , it produced a reduced magnitude in seawater temperature seasonality. To make these calculations more relevant and easier to understand, we scaled the  $\Delta\delta^{18}\text{O}_c$  record from the most recent (live-caught) animal with nearby instrumental records (20–50 m) (Casco Bay and Central Maine Shelf; data from Gulf of Maine Ocean Observing System [GoMOOS]; <http://www.gomoos.org/>). The modern seasonal cycle during the recent decade, derived from monthly mean seawater temperature values, from this region in 35 m water depth is  $7.8 \pm 0.6^{\circ}\text{C}$ . On average, the actual range in seasonal seawater

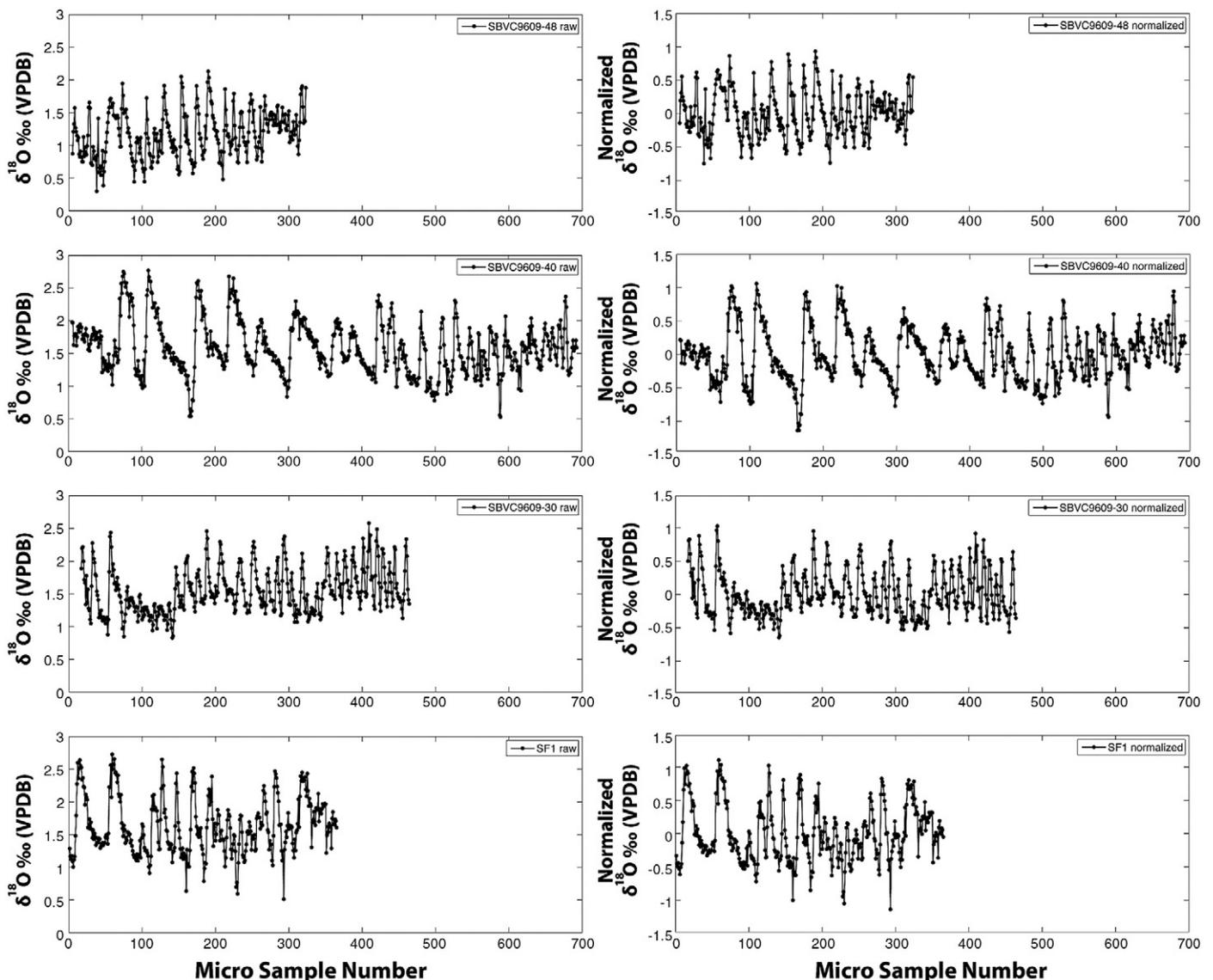
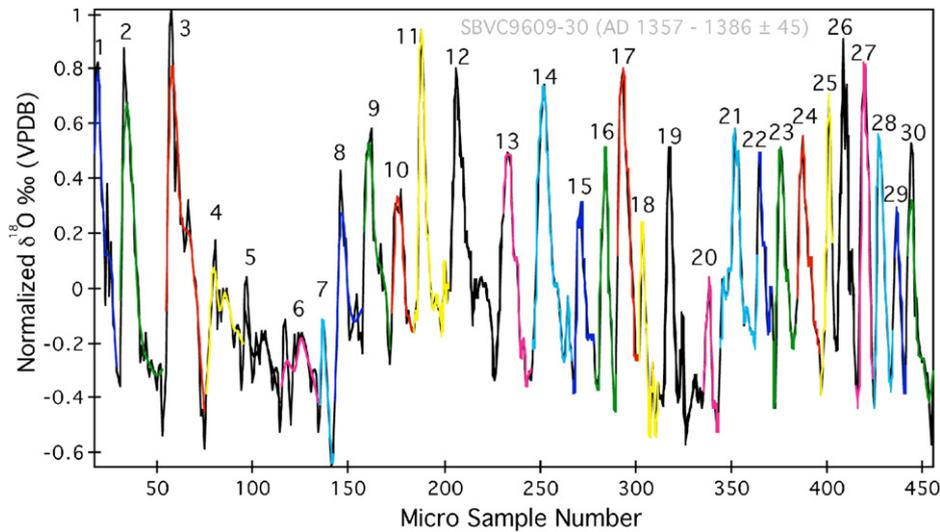


Fig. 3. Raw shell  $\delta^{18}\text{O}_c$  values (left panel) for each of the four shells used in this study are shown. The normalized (see text for description) shell  $\delta^{18}\text{O}_c$  values (right panel) prior to resampling for each of the four shells used in this study are also shown. For ease of comparison, the relative changes in the scales are identical in both the left and right panels.



**Fig. 4.** An example of the 30-year 7-point resampling strategy using AnalySeries 2.0.4.2 (cubic spline model) for shell SBVC9609-30 is shown. The normalized data are shown in black and the resampled data are shown in color. Each year (or annual increment sampled) is numbered (1–30). Each of the four shells used in this study were resampled using this protocol, yielding seven data per year.

temperature was 2.22 times that of the resampled  $\Delta\delta^{18}\text{O}_c$  values. Thus, we used a scaling factor of 2.22 ( $\Delta\delta^{18}\text{O}_c \times 2.22$ ) in Eq. (2) to approximate the modern seasonal seawater temperature cycle where the shells were collected. The modified version of Eq. (2) is shown below (Eq. (3)):

$$\text{Scaled seasonality } T(^{\circ}\text{C}) = 4.34 \times (\Delta\delta^{18}\text{O}_c \times 2.22). \quad (3)$$

### 3. Results

#### 3.1. Sclerochronological measurements

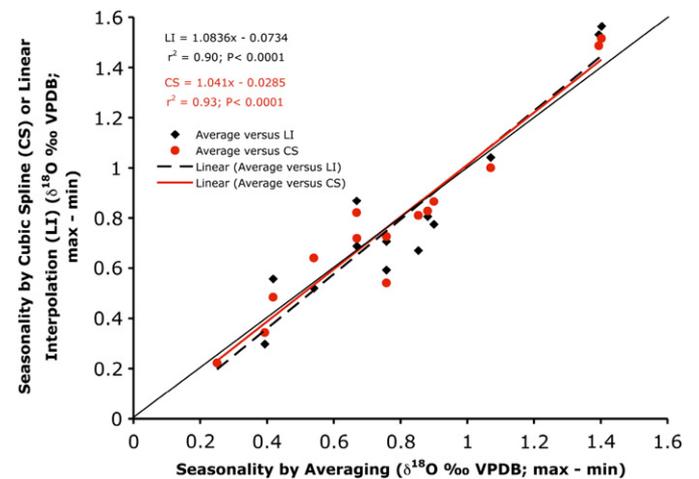
Based on sclerochronological analyses, the modern *A. islandica* shell (shell SF1) was 142 yr old and lived from cal yr AD 1863–2004. The sclerochronological ages based on  $^{14}\text{C}_{\text{AMS}}$  analyses from the dead-collected shells recovered from vibracore SBVC-9609 were AD 1030–1078  $\pm$  78 (48 yr old; shell SBVC9609-48), AD 1320–1355  $\pm$  48 (36 yr old; shell SBVC9609-40), AD 1357–1470  $\pm$  45 (116 yr old; shell SBVC9609-30), respectively.

#### 3.2. Data normalization and resampling of $\delta^{18}\text{O}_c$ data during ontogeny

It should be noted that only the younger portion (first 30–40 ontogenetic years) of the shells were used for the construction of scaled seawater temperature seasonality estimates. Relatively higher growth rates during the first 30–40 yr of life allowed for a minimum of seven samples per year to be obtained from each annual growth increment. The raw and normalized oxygen isotope intra-annual data prior to resampling are shown in Fig. 3 for each of the four shells. An example of the 30-yr resampling strategy using AnalySeries 2.0.4.2 (cubic spline model) for shell SBVC9609-30 is shown in Fig. 4. The methodology illustrated in Fig. 4 was conducted on each of the four shells (not shown) in order to calculate scaled seawater temperature seasonality values. Additionally, a comparison among the three different resampling methods (cubic spline, linear piece-wise interpolation, averaging) is shown in Fig. 5. The correlation between averaging and the cubic spline model was slightly higher ( $r^2 = 0.93$ ;  $p < 0.0001$ ) compared to the correlation between averaging and the linear piece-wise interpolation model ( $r^2 = 0.90$ ;  $p < 0.0001$ ).

#### 3.3. Scaled seawater temperature seasonality estimates during the last millennium

Using a fixed  $\delta^{18}\text{O}_{\text{water}}$  model and Eq. (3), mean-scaled seawater temperature seasonality was  $5.9 \pm 2.2^{\circ}\text{C}$  ( $\Delta\delta^{18}\text{O}_c = 0.61\text{‰}$ ;  $\delta^{18}\text{O}_c$  mean max =  $0.34 \pm 0.27\text{‰}$ ;  $\delta^{18}\text{O}_c$  mean min =  $-0.28 \pm 0.23\text{‰}$ ) from AD 1033–1062  $\pm$  78 (shell SBVC9609-48) (Fig. 6; note the broken scale for Calendar Age AD). Based on  $^{14}\text{C}_{\text{AMS}}$ , this shell broadly falls into the early MCA. From AD 1321–1350  $\pm$  45 (shell SBVC9609-40) (early LIA) the mean-scaled seawater temperature seasonality was  $7.7 \pm 3.6^{\circ}\text{C}$  ( $\Delta\delta^{18}\text{O}_c = 0.80\text{‰}$ ;  $\delta^{18}\text{O}_c$  mean max =  $0.44 \pm 0.31\text{‰}$ ;  $\delta^{18}\text{O}_c$  mean min =  $-0.36 \pm 0.19\text{‰}$ ) (Fig. 6). Also, from AD 1362–1391  $\pm$  45 (shell SBVC9609-30) the mean-scaled seawater temperature seasonality was  $7.0 \pm 2.3^{\circ}\text{C}$  ( $\Delta\delta^{18}\text{O}_c = 0.73\text{‰}$ ;  $\delta^{18}\text{O}_c$  mean max =  $0.40 \pm 0.28\text{‰}$ ;  $\delta^{18}\text{O}_c$  mean min =  $-0.33 \pm 0.12\text{‰}$ ) (Fig. 6). Because the calibrated  $^{14}\text{C}_{\text{AMS}}$  ages for two shells used in this study (1321  $\pm$  45 AD;



**Fig. 5.** A comparison among seasonality estimates using the cubic spline (CS) resampling protocol, a linear piecewise interpolation (LI) model, and simple averaging utilizing AnalySeries 2.0.4.2 is shown. A total of fourteen years were compared using shells SBVC9609-48 (7 years; samples per year: 7, 7, 14, 14, 14, 14, 14), SBVC9609-40 (1 year; samples per year: 42), SBVC9609-30 (3 years; samples per year: 7, 14, 21), and SF1 (3 years; samples per year: 14, 14, 21). The solid black line represents the 1:1 relationship in seasonality for CS and LI versus simple averaging. Both the CS and LI protocol yield a best-fit relationship that is nearly 1:1 with simple averaging.

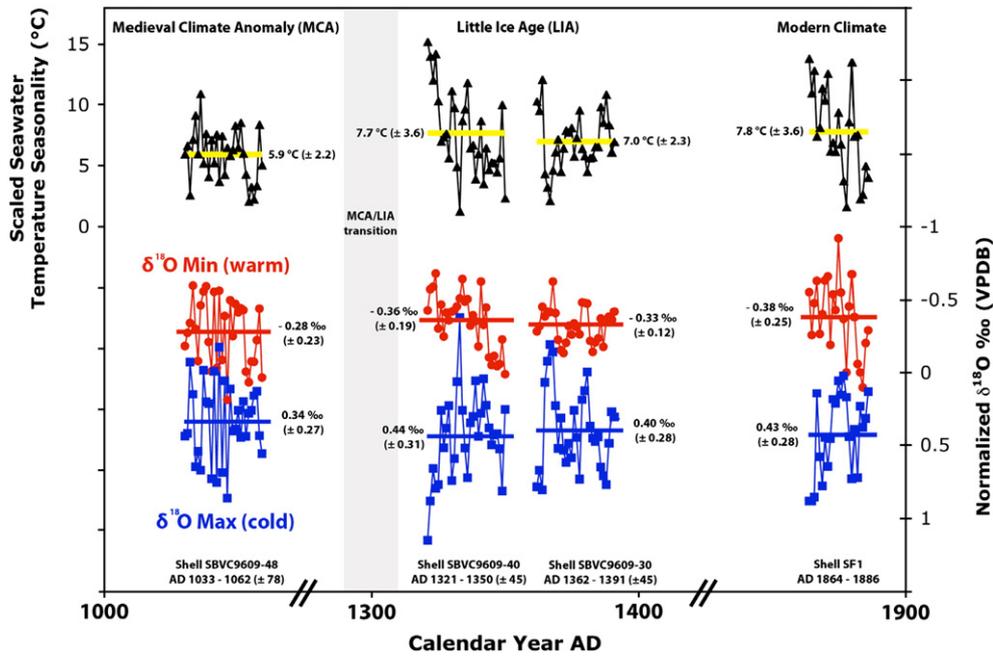


Fig. 6. Estimates of scaled seawater temperature seasonality (black line; solid triangles) for intervals of the last millennium are shown (note the broken scale for calendar year AD). Additionally, the mean-scaled seawater temperature seasonality (yellow line) and standard deviation for each shell are also shown. Normalized max (red line; solid red circles) and normalized min (blue line; solid blue squares) shell  $\delta^{18}O_c$  values and the associated standard deviation are shown. Normalized mean max (heavy solid red line) and normalized mean min (heavy solid blue line) shell  $\delta^{18}O_c$  values are shown.

1357 ± 40 AD) were so close, we used cross-dating techniques to determine if the two shells overlapped. This method yielded no significant correlation in growth histories between the two shells. The modern (live-caught) shell (shell SF1) revealed a mean-scaled seawater temperature seasonality of 7.8 ± 3.6 °C ( $\Delta\delta^{18}O_c = 0.81\text{‰}$ ;  $\delta^{18}O_c$  mean max = 0.43 ± 0.28‰;  $\delta^{18}O_c$  mean min = -0.38 ± 0.25‰) from AD 1864–1886 (Fig. 6).

3.4. Scaled seawater temperature seasonality and mean  $\delta^{18}O_c$  values

The mean-resampled 30-yr  $\delta^{18}O_c$  values for the dead-collected shells were 1.19 ± 0.23‰ (shell SBVC9609-48), 1.60 ± 0.18‰ (shell SBVC9609-40), and 1.54 ± 0.17‰ (shell SBVC9609-30), respectively

(Fig. 7). The mean-resampled 23-yr  $\delta^{18}O_c$  value for the live-caught shell was 1.64 ± 0.21‰ (shell SF1) (Fig. 7).

4. Discussion

4.1. The effects of data normalization and resampling of  $\delta^{18}O_c$  data during ontogeny

The visual impacts of data normalization appear to be minimal as noted in Fig. 3, however this protocol ensured that only high-frequency variations (intra-annual) and not low-frequency variations (in this case – interannual to decadal) were considered in the calculation of scaled seawater temperatures. The effects of resampling the intra-annual data for shell SBVC9609-30 with the cubic spline 7-point model

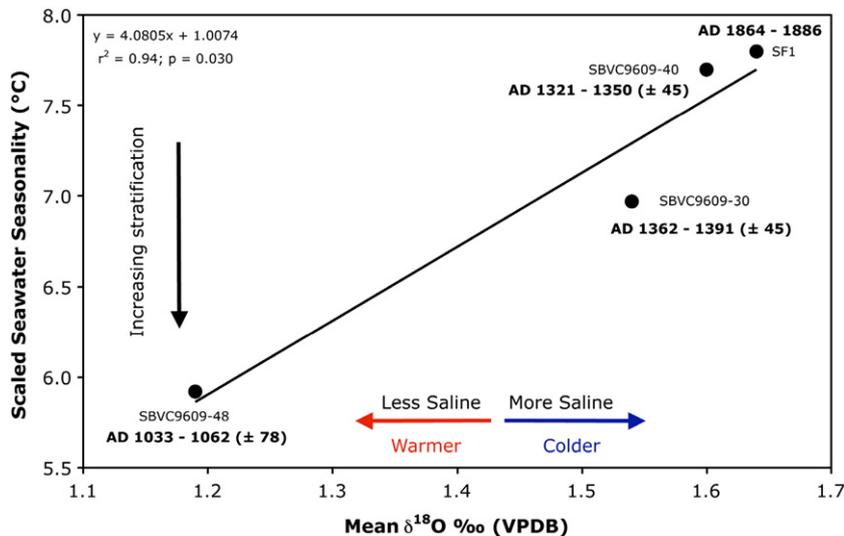


Fig. 7. Mean-resampled shell  $\delta^{18}O_c$  values versus scaled seawater temperature seasonality for each of the four shells used in this study are shown. The time interval (calendar year AD) for each shell used in this study is also noted.

are shown in Fig. 4. It can be clearly seen that the cubic spline 7-point model reduces the seasonal amplitude in early ontogenetic years to match those later in life. However, to ensure that the resampling method used here did not artificially increase or decrease  $\delta^{18}\text{O}_c$  seasonality, we compared a cubic spline model and a linear piece-wise interpolation model with simple averaging (Fig. 5). Resampling using simple averaging is likely the most valid method to ensure that each year is sampled equivalently (i.e., same number of samples represented per year) throughout ontogeny to assess changes in the seasonal seawater temperature cycle. In this study, the minimum number of  $\delta^{18}\text{O}_c$  samples per year was seven, thus all years with more than seven samples were reduced to seven. For example, if there were twenty-one samples in a given year, then an average of three neighboring for all twenty-one samples would yield seven new resampled data. However, if there were twenty samples or twenty-two samples in a given year, then simple averaging will not return exactly seven new data. If this latter case is common, then simple averaging could potentially introduce erroneous seasonality estimates. On the other hand, interpolation methods (noted here using AnalySeries 2.0.4.2) are fast and effective ways to resample unevenly-distributed data. The results shown in Fig. 5 establish that both the cubic spline model and the linear piece-wise interpolation model accurately estimates  $\delta^{18}\text{O}_c$  seasonality as compared to simple averaging. As mentioned earlier, the skill of the cubic spline model was slightly better than the linear piece-wise model. Thus we are confident that the cubic spline resampling model used here is a valid method for reconstructing seasonal  $\delta^{18}\text{O}_c$  values.

#### 4.2. Changes in scaled seawater temperatures during the last millennium

In Fig. 6, we show the changes in scaled seawater temperature seasonality based on  $\Delta\delta^{18}\text{O}_c$  values and Eq. (3) for intervals during the last millennium. The major finding of this study is that there was decreased scaled seawater temperature seasonality during the MCA ( $5.9 \pm 2.2$  °C [shell SBVC9609–48]) as compared to the early LIA ( $7.7 \pm 3.6$  °C [shell SBVC9609–40] and  $7.0 \pm 2.3$  °C [shell SBVC9609–30]) and the late 19th century ( $7.8 \pm 3.6$  °C [shell SF1]). Mean-scaled seawater temperature seasonality for the shells SBVC9609–40, SBVC9609–30, and SF1 was  $7.5$  °C. Thus, compared to the three most recent shells, the MCA shell showed a reduction in scaled seawater temperature seasonality of  $\sim 21\%$  or  $1.6$  °C. Additionally, the shell from the MCA showed the least variability in terms of scaled seawater temperature seasonality (Fig. 6). It is interesting to note that after the MCA/LIA transition at about AD 1300 (e.g., Sicre et al., 2008), there was a large increase in scaled seawater temperature seasonality. Although it is beyond the scope of this study, future work utilizing methods outlined here and the construction of an absolutely-dated master shell chronology (e.g., Butler et al., 2009) during the last millennium might elicit important information about the relationships between rapid climate change events (e.g., MCA/LIA transition) and changes in climatic seasonality.

#### 4.3. Were changes in scaled seawater temperature uniform between the winter and summer seasons?

Was reduced scaled seawater temperature seasonality in the Gulf of Maine during Medieval times the result of warmer winters, cooler summers, or both? The data indicate that both the winter and summer seasons were less severe. In other words, winters were warmer and summers were cooler (Fig. 6). As the last millennium progressed, summers generally became warmer and winters generally became colder, ultimately leading to the highest seasonality values in the late 19th century. Due to a lack of similarly resolved paleo-seasonality records from the Gulf of Maine region, comparison with other proxy reconstructions is hindered. If the scaled seawater temperature seasonality data from the Gulf of Maine region were typical for the North Atlantic region, these data might help explain the increased

human prosperity (e.g., productive farming, expansion in travel and trade, population growth) generally reported during Medieval times in greater Europe (e.g., Fagan, 2008). However, the characterization of Medieval climate outside of Europe is poorly developed. Hence records such as those reported here provide the opportunity to characterize and evaluate both the MCA and the LIA climates from the marine perspective outside of greater Europe.

#### 4.4. Relationship between scaled seawater temperature and mean $\delta^{18}\text{O}_c$ values

We compare the mean-resampled  $\delta^{18}\text{O}_c$  shell values with the scaled seawater temperature seasonality. In general, there is a strong and statistically significant relationship ( $r^2 = 0.94$ ;  $p = 0.03$ ) between inferred seawater temperatures (based on mean-resampled  $\delta^{18}\text{O}_c$  values) and the degree of scaled seawater temperature seasonality (Fig. 7). When seawater temperatures were warmer during the MCA, there was decreased seawater temperature seasonality. As seawater temperatures cooled into the LIA and during the late 19th century, the scaled seawater temperature seasonality increased. This result is interesting and merits further investigation. For example, additional shell samples from a variety of locations within the Gulf of Maine for the last millennium would allow us to test the voracity of the scaled seawater temperature seasonality and mean  $\delta^{18}\text{O}_c$  values. Specifically, contemporaneous shells collected from different regions within the Gulf of Maine Coastal Current (Western Maine Coastal Current [this study] and Eastern Maine Coastal Current; see Pettigrew et al., 2005 for a detailed summary) would allow a direct comparison with respect to seawater temperature seasonality at the regional scale. Previously, Pettigrew et al. (2005) concluded that the connectivity between the Eastern Maine Coastal Current and the Western Maine Coastal Current (near Rockland, see Fig. 1) has been variable in recent years. The degree to which these water masses were connected in the past likely influenced the hydrographic properties (temperature, salinity, degree of stratification) of the “downstream” Western Maine Coastal Current. At this stage, the connectivity of these coastal currents on seawater temperature seasonality in the Western Maine Coastal Current is not well known.

#### 4.5. Stratification dynamics in the Gulf of Maine as a potential mechanism for changes in seawater temperature seasonality

One likely mechanism that would closely link mean-resampled shell  $\delta^{18}\text{O}_c$  values with the degree of seasonality is stratification intensity. The shells used in this study lived in  $\sim 35$  m water depth in the seasonally-stratified coastal waters (Lynch et al., 1997) of the Western Maine Coastal Current. Wanamaker et al. (2008a) reported that annual surface waters near the shell collection site were on average about  $2.2$  °C warmer than the bottom seawater temperatures, which is indicative of a stratified water mass. Stratification intensity is closely related to vertical seawater temperature differences and tidal mixing dynamics (Simpson and Hunter, 1974). Excluding other potential factors (e.g., salinity, wind stress), when seawater temperatures are relatively high at the surface, there would be increased stratification (less vertical mixing) and reduced seasonality. Conversely, relatively cool surface seawater temperatures would facilitate increased vertical mixing of the coastal surface waters, which would ultimately lead to decreased stratification and increased seasonality. Although there are other possible mechanisms that might explain the reduced seawater temperature seasonality during the (inferred warmer) MCA, reduced stratification is perhaps the simplest explanation of the observed trends in the data.

#### 4.6. Uncertainties in scaled seawater temperature estimates using a constant $\delta^{18}\text{O}_{\text{water}}$ value

Wanamaker et al. (2007) demonstrated that paleotemperature estimates can be highly accurate ( $\pm 0.57$  °C) using bivalve shell (*Mytilus*

*edulis*) geochemistry (oxygen isotope ratios). However, to achieve such accuracy in seawater temperature estimates, measurement of the  $\delta^{18}\text{O}_{\text{water}}$  where the bivalves grew is required. It is most often the case in paleoceanography that we do not know the ancient isotopic composition of the water. This unknown parameter ( $\delta^{18}\text{O}_{\text{water}}$ ) greatly limits traditional paleothermometry techniques (also see Wanamaker et al., 2006). In seawater temperature seasonality studies, the absolute value of the ancient  $\delta^{18}\text{O}_{\text{water}}$  is not required, however knowledge of the difference between max and min  $\delta^{18}\text{O}_{\text{water}}$  values is required to achieve highly accurate results. To establish a reasonable range in max/min  $\delta^{18}\text{O}_{\text{water}}$  values (related to salinity), we considered 50 yr (AD 1950–2000) of monthly-resolved salinity data from the Prince 5 station, which is the closest long-term salinity station in the Gulf of Maine (Fig. 1) to the study site. Based on the data in Fig. 2A, we determined that the standard deviation in mean salinity max minus min values was  $\pm 0.33$  PSU (mean = 1.41 PSU). Using the Houghton and Fairbanks (2001) isotope/salinity mixing line for the Gulf of Maine, the likely uncertainty (assuming similar variations in the past) associated with using a constant  $\delta^{18}\text{O}_{\text{water}}$  model is  $\pm 0.19\%$ . Using Eq. (1), and an uncertainty in  $\delta^{18}\text{O}_{\text{water}}$  of  $\pm 0.19\%$ , the associated seawater temperature error is  $\pm 0.82$  °C. This error is relatively small considering the relative differences in scaled seawater temperature seasonality during the last millennium. Hence we are confident that the data presented here represent robust estimates of past seasonal seawater temperature cycles with an uncertainty of less than 1 °C.

## 5. Conclusions and future work

We demonstrate that it is possible to reconstruct past seawater temperature seasonality conditions with the long-lived bivalve *A. islandica*. An advantage of working with long-lived bioarchives is the potential ability to reconstruct sub-annual conditions, such as seasonality, for multiple decades at a time. Although short-lived bioarchives can give insight about seawater temperature at the “ultra” high-resolution scale, these data are most useful in the context of paleo-weather (e.g., Patterson et al., 2010). Bioarchives that can lend insight on the climate-scale (i.e., 30 yr of continuous data at the same resolution) will likely be most useful in addressing recent and past climate change. Although bivalves experience an ontogenetic growth trend, adaptive data sampling methods can be employed to ensure that the data from the shell material is equivalently resolved throughout the sampling period. The 7-point data resampling model (cubic spline) used here (AnalySeries 2.0.4.2) adequately represented an annual seasonal cycle of seawater temperatures once the  $\delta^{18}\text{O}_{\text{C}}$  values were scaled to instrumental records. Although there are several limitations to these data (e.g., assuming a constant  $\delta^{18}\text{O}_{\text{water}}$  value, needing to scale  $\delta^{18}\text{O}_{\text{C}}$  values; shell SF1 had only 23 yr of data instead of 30), the tremendous potential of fossil *A. islandica* shells (and other bioarchives) to reconstruct paleo-seasonality has yet to be explored. This study, and the recent study by Schöne and Fiebig (2009), represent a significant advancement in our understanding of the past ocean climate at the seasonal-scale. The modern and past distribution of *A. islandica* in the North Atlantic region (Dahlgren et al., 2000), and the potential for paleo-seasonality reconstructions at the climate-scale noted here, and by Schöne and Fiebig (2009), further highlight the usefulness of this bioarchive in marine environmental studies. Additional work is required to build a robust multiproxy (e.g., Schöne et al., 2006) representation for seawater temperature seasonality in the Gulf of Maine for the last millennium. Future work should also include other long-lived bioarchives from the region, such as red coralline algae (Halfar et al., 2008) and deepwater corals (Sherwood et al., 2005) that might complement, or supplement, the *A. islandica* records. Although it is beyond the scope of this study, future work should include the integration of archaeological data from shell midden sites (e.g., Sanger, 1996) with “new” high-resolution geochemical data in the Gulf of Maine region to address environ-

mental factors that might have contributed to the settlement patterns and habits of indigenous people.

### 5.1. Main findings of this study

We sampled four *A. islandica* shells from the Gulf of Maine to assess changes in seawater temperature seasonality during intervals of the last millennium. We produced three intra-annual shell  $\delta^{18}\text{O}_{\text{C}}$  time-series that were thirty years (climate-scale) in length, and one that was 23 yr long. The construction of these ultra-high-resolution bivalve records to examine changes in ocean climate outside the tropical oceans is a major advancement in the field of paleoceanography. Our results indicate about a 21% reduction in seawater temperature seasonality during the MCA (ca. AD 1033 to 1062) compared to shells from the LIA interval (ca. AD 1321–1391) and from the late 19th century (AD 1864–1886). During the MCA, winters were warmer and summers were cooler. As the last millennium progressed, summers generally became warmer and winters generally became colder, ultimately leading to the highest seasonality values in the late 19th century. There was a strong relationship between scaled seawater temperature seasonality and mean-resampled  $\delta^{18}\text{O}_{\text{C}}$  values (inferred seawater temperature). We suggest that the decreased seasonality during the MCA resulted from increased stratification of the coastal waters due to warmer seawater temperatures. Conversely, we suggest that as seawater cooled during the LIA and into the late 19th century there was increased vertical mixing of the coastal surface waters and increased seawater temperature seasonality.

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