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Karen Walker

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Isotopic evidence for climate change during the Vandal Minimum from *Ariopsis felis* otoliths and *Mercenaria campechiensis* shells, southwest Florida, USA

Ting Wang,[1] Donna Surge[1] and Karen Jo Walker[2]

Abstract

Archaeological evidence from coastal southwest Florida suggests this region and its local inhabitants (the Calusa) were affected by drought and cooling during the Vandal Minimum climate episode (AD 500–800). To test this hypothesis, we reconstructed seasonal-scale climate conditions using stable oxygen and carbon isotope ratios ($\delta^{18}O$ and $\delta^{13}C$) preserved in *Ariopsis felis* otoliths and *Mercenaria campechiensis* shells. Comparing $\delta^{18}O$ records from both species distinguishes between cool versus warm and wet versus dry conditions. $\delta^{18}O$ values from four otoliths indicate cooling of winter temperatures occurred in the early Vandal Minimum (AD 500–600) and late half of the middle Vandal Minimum (AD 650–700). Persistent dry summers punctuated by occasional years with wet summers throughout the Vandal Minimum were detected from $\delta^{18}O$ values of eight archaeological shells. Our climate reconstructions are in good agreement with archaeological observations and with the cool and dry conditions documented in Europe.

Keywords

Ariopsis felis, Calusa, *Mercenaria campechiensis*, oxygen and carbon isotopes, southwest Florida, Vandal Minimum

Introduction

With the present trend of global warming, understanding rapid climate change and the role of human activities in climate change is critically important (Bauer et al., 2003; Bradley and Jones, 1993; Crowley, 2000; Crowley and Lowery, 2000; Free and Robock, 1999; Mann et al., 1995, 1998; Osborn and Briffa, 2006). Abrupt climate change during the late Holocene (i.e. the past 3000 years), has been targeted for investigation because of important events in human history that may further our understanding of human–climate interactions. Several rapid climate episodes during the past 2000 years have been identified, such as the 'Roman Warm Period' (300 BC–AD 500), Vandal Minimum (also known as the 'Dark Age Cold Period') (AD 500–800), 'Medieval Warm Period' (AD 800–1200), and 'Little Ice Age' (AD 1200–1550) (Carbotte et al., 2004; Cronin et al., 2003; Keigwin, 1996; McDermott et al., 2001; Willard et al., 2003; Woodhouse and Overpeck, 1998). Of these episodes, the 'Little Ice Age', 'Medieval Warm Period', and 'Roman Warm Period' have received much attention; however, the Vandal Minimum has not been well studied because of the low resolution of proxy records in previous studies and also relatively small change in climate compared with the 'Medieval Warm Period' and 'Little Ice Age'. To fill this knowledge gap, we deciphered high-resolution climate information preserved in archaeological otoliths (fish 'ear bones') and shells that were deposited during the Vandal Minimum by the local inhabitants of southwest Florida (the Calusa people).

We chose southwest Florida (Figure 1) as our study area because this low-lying, estuarine region is sensitive to climate change and contains abundant biogenic carbonate remains in its archaeological sites (see Surge and Walker, 2005 for a more detailed environmental description). Furthermore, the ancient Calusa people inhabited this area until the mid-eighteenth century with periodic episodes of site abandonment; therefore, this location has important archaeological value for studying human–climate relationships. The archaeological evidence suggests that the climate transition from the 'Roman Warm Period' to the Vandal Minimum resulted in cooler temperatures, a lowered sea level, and drought leading to an increasingly seaward shift in settlement pattern beginning around AD 500–550; ultimately, these environmental changes during the Vandal Minimum likely forced the Calusa people to abandon some sites by AD 750 (Walker, 2000).

Oxygen and carbon isotope ratios ($\delta^{18}O$ and $\delta^{13}C$) of fish otoliths and mollusc shells have been widely used in paleoclimate, paleoecological, and paleoproductivity studies (Fenger et al., 2007; Goewert and Surge, 2008; Ivany et al., 2000; Jones and Quitmyer, 1996; Jones et al., 1989, 1990; Krantz et al., 1987; Surge and Walker, 2005, 2006; Wurster and Patterson, 2001). Archaeological shells and otoliths are particularly interesting

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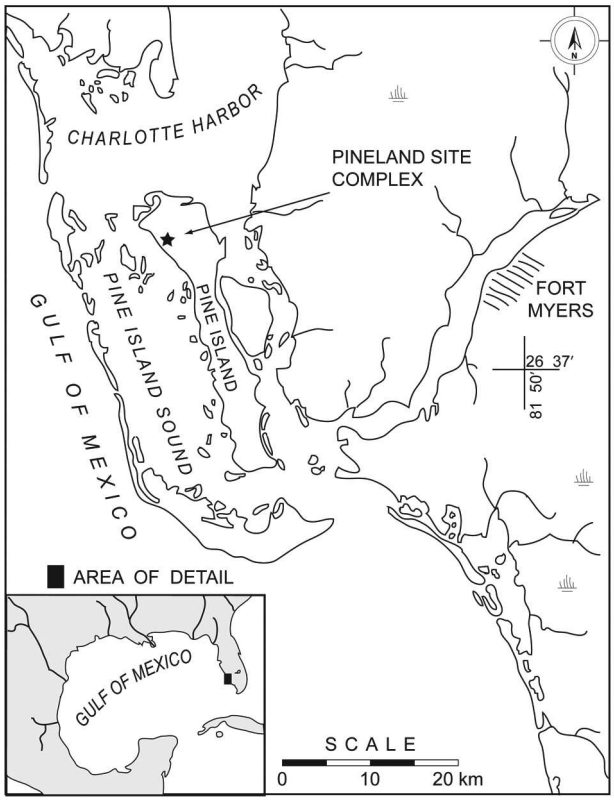

Figure 1. Map of the study area in southwest Florida, USA. A star identifies the major archaeological site 'Pineland Site Complex', which is located on the northwestern shore of Pine Island

because they preserve not only environmental proxy data, but they also contain evidence of human behavior. Therefore, we deciphered climate proxy data from otoliths of the hardhead catfish, *Ariopsis felis*, and shells of the hard clam, *Mercenaria campechiensis*, to answer these questions: did cooling/drought occur in southwest Florida during the Vandal Minimum, if so, how severe were these conditions; and how do the paleoclimate records compare with the archaeological evidence? To answer these questions, we compared: (1) isotopic records of modern and archaeological otoliths/shells; and (2) the reconstructed temperatures between archaeological and modern otoliths.

Ecology of *Ariopsis felis* and *Mercenaria campechiensis*

The fish *Ariopsis felis* inhabits estuaries and coastal lagoons and has a wide geographical range from Cape Cod, Massachusetts, to the Yucatan Peninsula (Muncy and Wingo, 1983). The adults prefer water temperature between 25°C and 36°C (Jones et al., 1978). Therefore, in winter and early spring, adult *A. felis* (~2 years old) live offshore to avoid the cold estuarine water, and in spring they migrate back to inshore estuaries to spawn. Because of their accretionary growth pattern, otoliths contain growth increments separated by prominent growth lines, which represent intervals of slow growth (Wurster and Patterson, 2001). We can estimate the seasonal range of growth temperature and productivity information from the isotope records preserved in otoliths. In the subtropical waters of southwest Florida, *A. felis* lives in normal marine salinity water at depths no deeper than 20 m during winter months (Muncy and Wingo, 1983). This depth range is above the thermocline; therefore, $\delta^{18}O_{otolith}$ values record seasonal temperature variability rather than depth-related temperature changes.

Mercenaria campechiensis inhabits sandy or muddy sand sediment in the intertidal to subtidal zone, and is especially abundant in bays and estuaries (Kraeuter and Castagna, 2001). This species occurs in the warm- to cold-temperate biogeographic provinces from south Florida to southern New Jersey along the Atlantic coast of the United States and along the Gulf of Mexico coast (Arnold et al., 1998; MacKenzie et al., 2002; Merrill and Ropes, 1967). Optimal water temperature and salinity for growth ranges from 15 to 25°C and 20 to 30 psu (practical salinity units), respectively, and growth rate slows below 9°C and above 31°C or below 17 psu (Ansell, 1968; Kraeuter and Castagna, 2001). Their accretionary growth pattern is readily visible in cross-section. In addition to environmental conditions, ontogeny (i.e. age) can affect shell growth rate and the resultant growth patterns (Kraeuter and Castagna, 2001). Dark, translucent growth increments form during intervals of slowed growth, whereas light, opaque growth increments reflect intervals of fast growth. Dark and light increments are observed under reflected light, whereas translucent and opaque increments are observed under transmitted light (see Jones and Quitmyer, 1996 for a detailed discussion of increment nomenclature). Arnold et al. (1991) reported that *M. campechiensis* shells from the Indian River in Florida form dark increments (slow growth) from May to October when the water temperature is above 25°C, and light increments (fast growth) during the remainder of the year. They also observed that growth rate slows with ontogeny after five to six years of age.

Archaeological context

Our study focuses on what is archaeologically known as the Caloosahatchee culture area, where the socio-politically complex Calusa people inhabited the region encompassing Pine Island Sound, Charlotte Harbor, and bays to the south until approximately the mid-eighteenth century (Marquardt and Walker, 2001; Widmer, 1988) (Figure 1). The Calusa were non-agricultural, and their diet consisted mainly of estuarine/marine fish and shellfish supplemented by terrestrial animal and plant foods. Therefore, the rich aquatic resources formed the basis of Calusa subsistence strategy, quite different from the agricultural adaptations typically associated with complex societies (Widmer, 1988).

According to modern fish surveys (Wang and Raney, 1971) and zooarchaeological evidence (Walker, 1992), the Calusa residents collected fish and shellfish along the shallow-water shoreline close to their home settlements. The skeletal remains of the collected aquatic animals accumulated to form middens and mounds usually in stratigraphic succession. These stratigraphic shell middens and mounds have the potential to accurately reflect the paleoenvironmental and paleoecological changes during the late Holocene through identification of the spatial variation in settlement patterns and the temporal variation in animal diversity and abundance (Marquardt and Walker, 2001; Walker, 1992; Walker and Surge, 2006). Our specific source of animal study specimens is the Pineland Site Complex (see Marquardt and Walker, 2001 for a detailed description). Six cultural periods are preserved at this site complex (Walker and Surge, 2006): Caloosahatchee I-late (AD 0–500); Caloosahatchee IIA (AD 500–800); Caloosahatchee IIB (AD 800–1200); Caloosahatchee III (AD 1200–1350); Caloosahatchee IV (AD 1350–1500); and Caloosahatchee V (AD 1500–1750). Our temporal focus is Caloosahatchee

Table 1. Time range of the archaeological shells

Specimen	FLMNH-ANT catalog no.	NOSAMS no.	AMS radiocarbon age, ^{14}C yr BP	δ^{13}C (VPDB ‰)	Cal. yr AD range, (1 sigma)	Chronostratigraphic range (AD)
CIIA-M5	90-3-27	OS-54179	1750 ± 35	0.59	610–680	700–750
CIIA-M2	90-3-53-1/4b	OS-54155	1850 ± 40	0.65	490–610	650–700
CIIA-M1	90-3-54-1/1	N/A	N/A	N/A	N/A	650–700
CIIA-M8	90-3-57-1/1	OS-54182	1740 ± 35	0.61	620–690	600–650
CIIA-M4	95-3-6	OS-54178	1870 ± 30	1.02	480–580	550–600
CIIA-M6	92-24-2	OS-54180	1930 ± 40	0.83	420–540	500–550
CIIA-M7	95-3-31/5	OS-54181	1970 ± 35	0.67	350–470	500–550
CIIA-M9	2003-38-8/2/5	OS-54183	1890 ± 30	0.93	460–560	450–500

IIA, the period which more or less coincides with the cold climate episode documented in Europe, the Vandal Minimum.

Methods

Dating of archaeological specimens

Following the approach of Walker and Surge (2006), our aim was to analyze otolith-shell pairs dating to the Caloosahatchee IIA period (AD 500–800) selected from the Pineland collections housed at the Florida Museum of Natural History (FLMNH). To achieve the best spatial and temporal representation possible for the Vandal Minimum, the archaeological pairs were selected based on their chronostratigraphic contexts (dated by pottery and conventional radiocarbon analyses) from multiple areas of the Pineland Site Complex (Marquardt and Walker, 2001; Walker, 2000; Walker et al., 1995). We identified four otolith-shell pairs (otolith-shell identification numbers: CIIA-A2/CIIA-M2, CIIA-A7/CIIA-M7, CIIA-A8/CIIA-M8, and CIIA-A9/CIIA-M9; see Table 1 for corresponding FLMNH shell catalog numbers) and analyzed an additional four shells (shell identification numbers: CIIA-M1, CIIA-M4, CIIA-M5, and CIIA-M6; Table 1). For this study, shells were dated directly using AMS (accelerator mass spectrometry) at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility, Woods Hole Oceanographic Institute. Measured AMS ^{14}C ages of the archaeological shells were calibrated using MARINE04 of CALIB 5.0.2 and corrected for the global ocean reservoir effect (408 years), local reservoir effect (−5 ± 20 years), and ^{13}C fractionation (Hughen et al., 2004; Stuiver et al., 2005). Finally, combining the stratigraphic order of archaeological proveniences and the conventional radiocarbon dates with calibrated AMS ^{14}C dates, the 50-year archaeological AD time ranges of the specimens were estimated (Table 1).

Microsampling and isotopic analysis

In addition to the archaeological otoliths and shells, we analyzed one modern otolith (specimen identification number: MOD2002 collected on 8 May 2002) and two modern shells (specimen identification numbers: 05PI05 and 05PI17, collected on 8 June 2005) from Pine Island Sound to allow comparison of the Vandal Minimum climate with present-day conditions.

A. felis otoliths (~1 cm in length) were set in an epoxy resin cube to facilitate cutting and polishing. Each otolith was cut along the transverse plane, and shells were cut along the axis of maximum growth. Cross-sections of otoliths and shells were polished until the internal growth lines and increments were clearly visible. Before microsampling, the microstructure of all archaeological otoliths and shells was screened under an Olympus stereomicroscope with a 12.5 megapixel DP71 digital camera to evaluate preservation of original aragonite. If original aragonite was present, we assumed the specimen was not diagenetically altered.

Otoliths were microsampled at 15 to 20 samples per year across the second to sixth years of growth to achieve submonthly resolution. Visible growth increments guided our sampling strategy. For *M. campechiensis* shells, we microsampled only the first 5 years of growth because growth rate slows down after 5 to 6 years of age (Jones and Quitmyer, 1996). Shells were microsampled at 24 to 26 samples per year to achieve fortnightly resolution. The sampling resolution of shells was higher than that of the otoliths because the shells were larger with faster growth rates. Microsampling was performed on a Merchentek micromill fitted with a carbide dental scriber (Brasseler). Each digitized drilling path produced approximately 20 to 40 µg of carbonate powder for isotopic analysis. Oxygen and carbon isotope ratios of carbonate powdered samples were measured using an automated carbonate preparation device (Kiel-III) coupled to a gas-ratio mass spectrometer (Finnigan MAT 252). Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C for 1 h. The isotope ratio measurement was calibrated based on repeated measurements of NBS-19 (National Bureau of Standard) and NBS-18. The precision of the measurements was ±0.1‰ for δ^{18}O (1σ) and ±0.06‰ for δ^{13}C (1σ). The results were reported in per mil units (‰) relative to the VPDB (Vienna Pee Dee Belemnite) standard.

Estimated temperature and precipitation

To reconstruct climate change during the Vandal Minimum, we used two approaches: (1) comparison of δ^{18}O values and estimated temperature between modern and archaeological otoliths to reconstruct winter temperature of the Vandal Minimum; and (2) comparison of δ^{18}O values between modern and archaeological shells to estimate summer precipitation during the Vandal Minimum.

Southwest Florida is characterized by a wet and dry season as suggested by the instrumental records of monthly average air temperature (from 1891 to 2007) and precipitation (from 1931 to 2007) at Fort Myers (www.ncdc.noaa.gov). The coldest average monthly temperature is 17.4 ± 1.7°C, whereas the warmest average monthly temperature is 28.1 ± 0.6°C. Monthly accumulation of rainfall during the wet season (May–October) averages 181 mm/month, whereas the dry season (November–April) averages 50 mm/month. These data indicate that southwest Florida has seasonal changes in temperature and precipitation (wet/dry seasons).

Therefore, deconvoluting these two parameters using oxygen isotope ratios preserved in carbonate hard parts is challenging. However, Surge and Walker (2006) overcame this challenge by using a multitaxa approach. Because of its seasonal migration behavior, *A. felis* can provide winter temperature information because we can constrain the oxygen isotope ratio of water ($\delta^{18}O_w$) to marine seawater values (see ecology section). The $\delta^{18}O_w$ value of seawater in this region is approximately +1‰ (VSMOW) (Surge and Lohmann, 2002). Estimated temperature from oxygen isotope ratios of *A. felis* otoliths ($\delta^{18}O_{otolith}$) was calculated using the procedures outlined by Surge and Walker (2005). Following these previous studies, we used the equilibrium fractionation equation reported by Patterson et al. (1993) to calculate temperature from $\delta^{18}O_{otolith}$ values. We converted $\delta^{18}O$ values of carbonate hard parts from the VSMOW scale to VPDB following Gonfiantini et al. (1995).

M. campechiensis are sessile and inhabit estuarine-marine environments where, in the study area, modern $\delta^{18}O_w$ values vary intra-annually between wet and dry seasons, but may not vary by the same magnitude from one year to the next. This uncertainty in Pine Island Sound makes estimating temperature from oxygen isotope ratios of *M. campechiensis* shells ($\delta^{18}O_{shell}$) difficult. Nevertheless, we can make inferences about summer precipitation by comparing the summer $\delta^{18}O_{shell}$ values between modern and archaeological shells. Because summer temperatures in the study area have low interannual variability as discussed above, the variation of $\delta^{18}O_{shell}$ values is mainly influenced by the seasonal fluctuation of $\delta^{18}O_w$. Therefore, more negative $\delta^{18}O_{shell}$ values suggest more negative $\delta^{18}O_w$ values, which result from increased input of freshwater due to more precipitation

Results

Each archaeological otolith (CIIA-A9, CIIA-A7, CIIA-A8, and CIIA-A2) has a temporal variation of $\delta^{18}O$ values following a sinusoidal trend (Figure 2). The variation of $\delta^{18}O$ values in the modern otolith (MOD2002) range from −3.0‰ to +0.6‰, consistent with the $\delta^{18}O$ range (−3.6‰ to +0.3‰) of the modern otolith reported by Surge and Walker (2005). The temporal variation of $\delta^{13}C$ values recorded in the archaeological otoliths also follows a more or less sinusoidal pattern; however, the pattern is not in phase with $\delta^{18}O$ values (Figure 2). Oxygen isotope ratios of the archaeological shells (CIIA-M9, CIIA-M7, CIIA-M6, CIIA-M4, CIIA-M8, CIIA-M1, CIIA-M2, and CIIA-M5) and modern shells (05PI05, 05PI17) also vary quasi-sinusoidally (Figures 3 and 5). To reconstruct winter climate, we computed the coldest winter temperature recorded in each archaeological otolith using paleothermometry equations by Patterson et al. (1993) (Figure 4). The coldest temperatures are variable within and among otoliths (Figure 4).

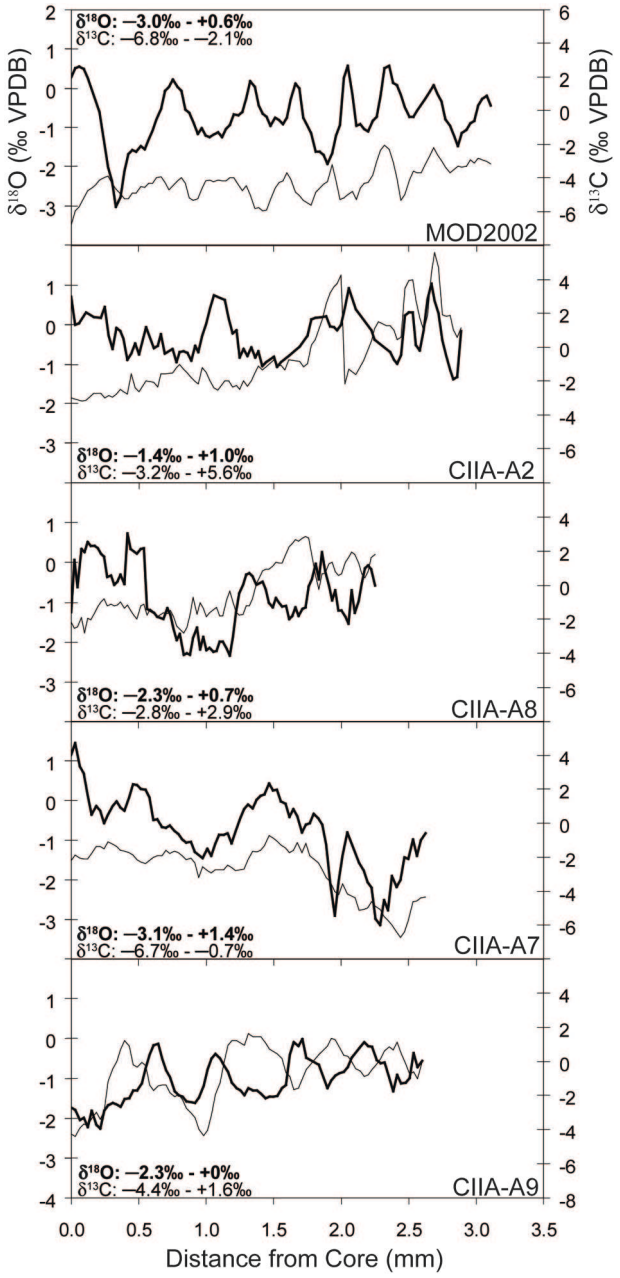

Figure 2. Variation of $\delta^{18}O$ and $\delta^{13}C$ values of archaeological and modern otoliths versus distance from the inner core toward the growing margin (growth direction is from left to right). Thick lines represent $\delta^{18}O$ values and thin lines represent $\delta^{13}C$ values. Ranges of $\delta^{18}O$ and $\delta^{13}C$ values of archaeological and modern otoliths are shown in the figure

Discussion

Isotopic geochemistry of otoliths

Previous studies have shown that otolith carbonate precipitates in oxygen isotope equilibrium with ambient water (Iacumin et al., 1992; Kalish, 1991; Patterson et al., 1993; Thorrold et al., 1997). Kalish (1991) and Iacumin et al. (1992) reported that the $\delta^{18}O$ values of otolith carbonate are close to equilibrium with the ambient water because the incorporation of oxygen isotopes during otolith precipitation is not affected by kinetic/hydration-hydroxylation processes. Consequently, the oxygen isotope ratios of otoliths can serve as a proxy for estimating temperature (±<1°C), provided the $\delta^{18}O_w$ of the surrounding environment is known (Patterson et al., 1993; Thorrold et al., 1997). Surge and Walker (2005) evaluated the $\delta^{18}O$ values of modern *A. felis* otoliths and determined that the fractionation equation by Patterson et al. (1993) is best suited for this species.

In our study, modern and archaeological otoliths record seasonal variation in $\delta^{18}O$ values (Figure 2). The most positive $\delta^{18}O$ values represent winter, whereas the most negative $\delta^{18}O$ values represent summer. Compared with the average winter temperature in the past century (Figure 4), winter temperatures reconstructed from modern otolith MOD2002 are warmer. Winter

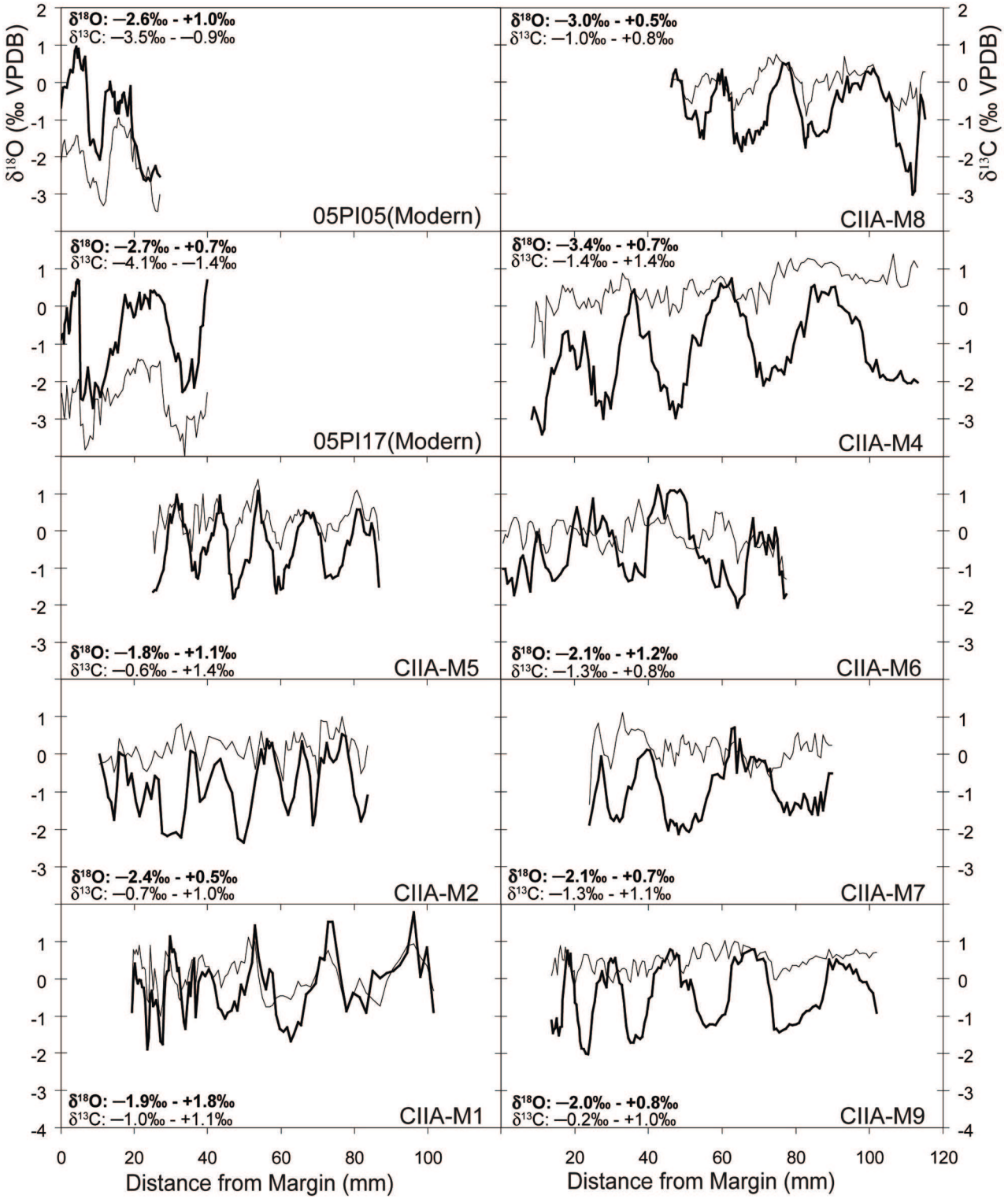

Figure 3. Variation of $\delta^{18}O$ and $\delta^{13}C$ values of archaeological and modern shells versus distance from growth margin (growth direction is from right to left). Thick lines represent $\delta^{18}O$ values and thin lines represent $\delta^{13}C$ values. Ranges of $\delta^{18}O$ and $\delta^{13}C$ values of archaeological and modern shells are shown in the figure

temperatures estimated from archaeological otoliths are no colder than the average twentieth-century winter temperature, except for the first winter of CIIA-A7. This observation implies *A. felis* otoliths may not record the coldest winter temperature.

In addition to seasonal fluctuation, variation in $\delta^{18}O_{otolith}$ values provides ontogenetic information. In the $\delta^{18}O_{otolith}$ profiles with well-defined seasons, there are more $\delta^{18}O_{otolith}$ values recorded in warm intervals than in cold intervals, suggesting growth rate is fast in summer and slows in winter. The dark growth lines in the otoliths, which represent growth cessations, are generally coincident with the most positive $\delta^{18}O$ values, corresponding to winter temperature (Figure 4). Winter growth cessation increases the time averaging during cold months and explains why otoliths may not record the coldest winter temperatures. Patterson et al. (1993) encountered the same pattern in otoliths from freshwater fish. However, this seasonal growth

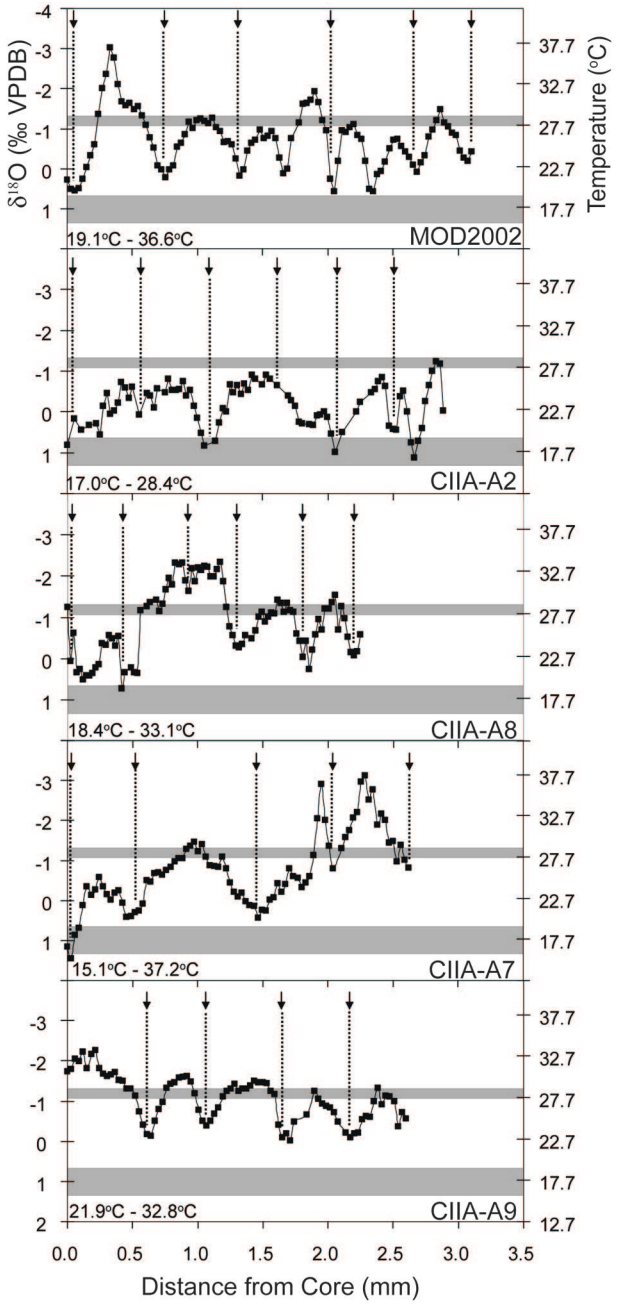

Figure 4. $\delta^{18}O$ values and estimated temperatures of archaeological and modern otoliths versus distance from the inner core toward the growth margin (growth direction is from left to right). The narrow gray bar represents the average summer temperature (28.1 ± 0.6°C) observed at Ft Myers over the past century; the wide gray bar represents the average winter temperature (17.4 ± 1.7°C) for the past century. The ordinate of $\delta^{18}O$ is decreasing upward to coincide with the temperature scale. The temperature ranges of archaeological and modern otoliths are indicated in the figure. Arrows indicate the location of major growth lines

pattern is not obvious in the final two years of MOD2002 and the last year of CIIA-A2, suggesting that growth rate of otoliths is not only determined by temperature, but also affected by biological factors such as food resources or 'old' age.

Unlike the equilibrium isotope effects between temperature and $\delta^{18}O_{otolith}$ values, the equilibrium fractionation of carbon isotopes in biogenic carbonate is easily interrupted by biological activities resulting in vital effects. Carbon isotope disequilibrium is a very common phenomenon and occurs in most biogenic carbonates to varying degrees. McConnaughey (1989) classified the isotopic disequilibria into two primary patterns: kinetic disequilibrium and metabolic disequilibrium. Kinetic disequilibrium is caused by the isotopic discrimination against ^{18}O and ^{13}C during the process of formation and diffusion of HCO_3^-. As a result, biogenic carbonates are depleted in ^{18}O and ^{13}C simultaneously (Kalish, 1991; McConnaughey, 1989; Thorrold et al., 1997; Turner, 1982). Metabolic disequilibrium results from the incorporation of carbon produced by metabolic activities such as respiration. Therefore, it is strongly associated with biological activities and tends to affect principally carbon isotope fractionation without affecting oxygen isotope equilibrium (Kalish, 1991; McConnaughey, 1989; Thorrold et al., 1997).

To evaluate the controls on $\delta^{13}C_{otolith}$ values, Thorrold et al. (1997) raised juvenile *Micropogonias undulatus* in temperature-controlled tanks. They found a statistically significant correlation between temperature and $\Delta^{13}C$, where $\Delta^{13}C$ represented the correction of the otolith $\delta^{13}C$ data for variations in the $\delta^{13}C$ of dissolved inorganic carbon (DIC) in the individual tanks. However, they observed that the $\delta^{13}C_{otolith}$ values were depleted by 5‰ relative to predicted values at 25°C because of a vital effect. They evaluated whether kinetic or metabolic processes controlled this vital effect, and their findings suggest that metabolic, rather than kinetic, isotope effects produced the carbon isotope disequilibrium.

We did not observe evidence of a kinetic isotope effect as described by McConnaughey (1989), which is consistent with the findings of Thorrold et al. (1997). The carbon isotope ratios of *A. felis* otoliths likely result from the combination of $\delta^{13}C_{DIC}$ variation and metabolic isotope effects. The combination of these factors may explain the absence of a seasonal trend in the $\delta^{13}C_{otolith}$ values. Nonetheless, comparison of $\delta^{13}C$ values within and among modern and archaeological otoliths provides informative trends related to ontogenetic change. We observe overall increases in the general trend of $\delta^{13}C_{otolith}$ values from juvenile to adult stages in four of the otoliths (specimens MOD2002, CIIA-A2, CIIA-A8, and CIIA-A9). This finding is similar to the observation by Kalish (1991) that juvenile fish have high metabolic rates and incorporate more light carbon isotopes by consuming food items from lower trophic levels than adult fish. However, variation in $\delta^{13}C_{DIC}$ may also influence $\delta^{13}C_{otolith}$ values; thus, we cannot differentiate between these two effects. Unlike the other otoliths, specimen CIIA-A7 exhibits decreasing $\delta^{13}C_{otolith}$ values, which may be due to the combined effects of metabolism and variation in $\delta^{13}C_{DIC}$. We also observe an overall negative shift in carbon isotope ratios of otoliths from the Vandal Minimum to today. There is a 1.4–3.8‰ difference in average $\delta^{13}C_{otolith}$ values between the archaeological and modern otolith (Table 2). We offer an explanation below after discussing our $\delta^{13}C_{shell}$ results.

Isotopic geochemistry of shells

Earlier studies reported that oxygen isotope ratios in *M. mercenaria* and *M. campechiensis* can be used to reconstruct ambient environmental conditions (Elliot et al., 2003; Surge and Walker, 2006; Surge et al., 2008). However, $\delta^{18}O_w$ of estuarine water is difficult to constrain, but here we use this to our advantage. We used summer $\delta^{18}O_{shell}$ values as a proxy for relative changes in wet season precipitation because interannual summer temperature variability over the last century does not change very much (see methods section). Therefore, based on the comparison of $\delta^{18}O_{shell}$

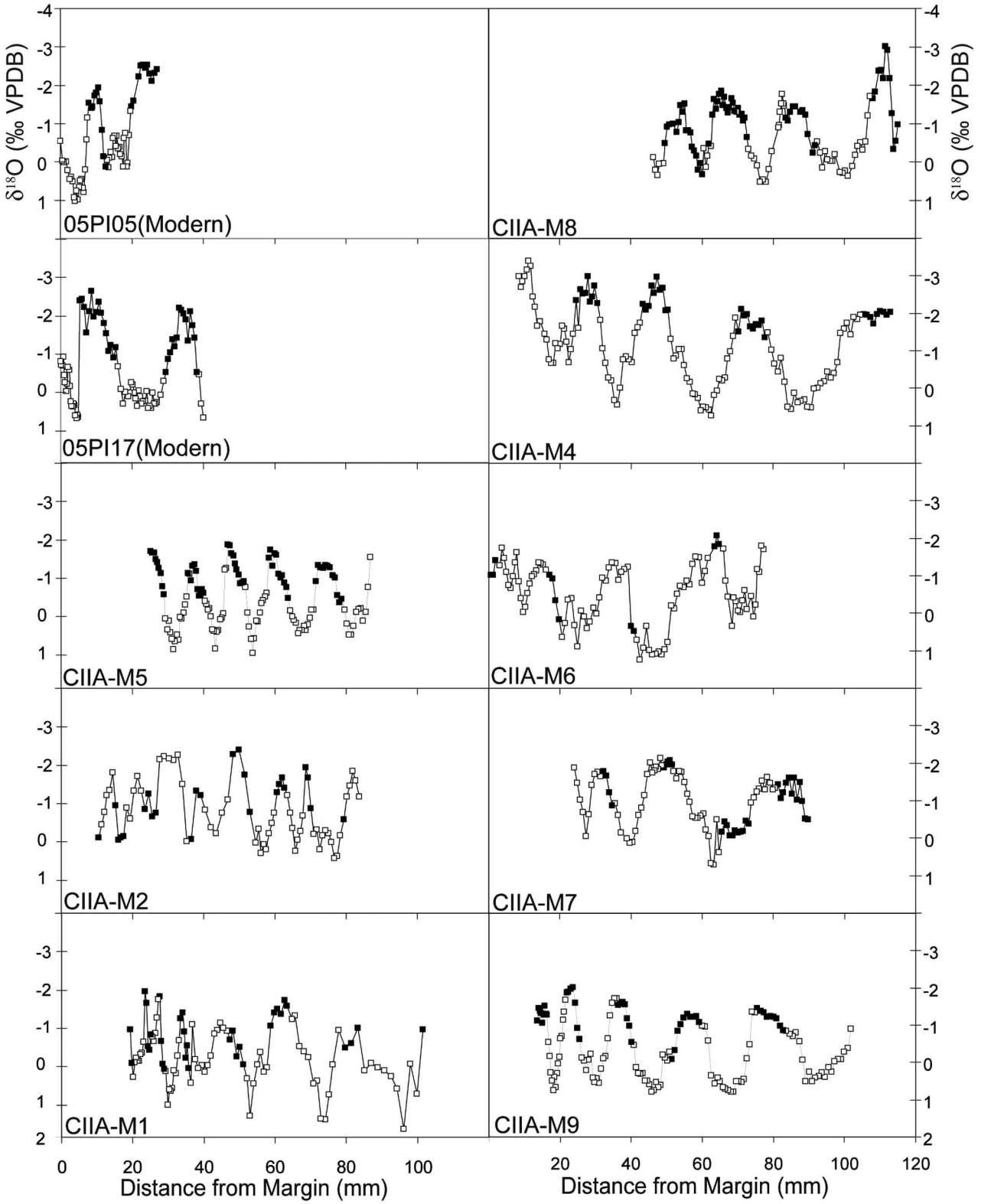

Figure 5. $\delta^{18}O$ values of archaeological and modern shells versus distance from growth margin (growth direction is from right to left). Open squares represent $\delta^{18}O$ values and solid squares indicate the location of dark growth increments

values between modern and archaeological shells, we can evaluate differences in precipitation during the Vandal Minimum relative to today.

Combining oxygen isotope ratios with growth increment analysis (sclerochronology) provides information on seasonal changes between slow and fast shell growth rates. Previous studies reported that *Mercenaria* shells from subtropical latitudes form dark growth increments during the summer reflecting summer growth cessation (Arnold et al., 1998; Elliot et al., 2003; Jones and Quitmyer, 1996; Quitmyer et al., 1997; Surge and Walker, 2006; Surge et al., 2008). In this study, modern shells and most growth years of the archaeological specimens form dark increments that coincide with the most negative oxygen isotope ratios, corresponding to summer months (Figure 5). This

Table 2. Average summer oxygen isotope ratios and carbon isotope ratios of modern and archaeological shells, and average winter temperatures and carbon isotope ratios of modern and archaeological otoliths

Shell specimen	Average $\delta^{18}O_{shell}$ values with standard errors (summer) (VPDB ‰)	$\delta^{13}C_{shell}$ (VPDB ‰)	Otolith specimen	Average temperatures with standard errors (winter) (°C)	$\delta^{13}C_{otolith}$ (VPDB ‰)
05PI05	−2.4 ± 0.3	−2.1 ± 0.7	MOD2002	20.5 ± 0.5	−4.2 ± 0.9
05PI17	−2.5 ± 0.2	−2.5 ± 0.7			
CIIA-M5	−1.5 ± 0.1	0.3 ± 0.4			
CIIA-M2	−2.0 ± 0.2	0.2 ± 0.4	CIIA-A2	17.8 ± 0.3	−0.4 ± 2.2
CIIA-M1	−1.3 ± 0.2	0.1 ± 0.5			
CIIA-M8	−2.0 ± 0.3	−0.1 ± 0.4	CIIA-A8	20.3 ± 1.0	−0.4 ± 1.6
CIIA-M4	−2.5 ± 0.3	0.5 ± 0.5			
CIIA-M6	−1.6 ± 0.2	−0.1 ± 0.4			
CIIA-M7	−1.8 ± 0.2	0.1 ± 0.4	CIIA-A7	18.2 ± 1.6	−2.8 ± 1.5
CIIA-M9	−1.6 ± 0.2	0.5 ± 0.3	CIIA-A9	22.5 ± 0.4	−0.7 ± 1.6

pattern represents summer growth cessation and is consistent with previous studies. However, this correspondence only occurs during the time when the shell growth is mainly controlled by temperature. When shell growth is dominated by biological factors, such as food availability, predation or reproduction, the $\delta^{18}O_{shell}$ values will not show a sinusoidal pattern coinciding with seasonal temperature fluctuation. Instead, the $\delta^{18}O_{shell}$ time series will appear choppy and irregular. In this case, the dark growth increment will not coincide with warm summer season, as we observed in CIIA-M2 (the growth range of 10–40 mm from margin) and CIIA-M1 (the growth range of 20–40 mm from margin) (Figure 5).

Unlike the equilibrium precipitation of $\delta^{18}O_{shell}$ values, carbon isotope ratios of bivalve shells are determined by $\delta^{13}C_{DIC}$ values of the ambient water and metabolic isotope effects. Kinetic effects can be ignored in *M. campechiensis* shells because kinetic effects influence oxygen isotope equilibrium and carbon isotope equilibrium simultaneously (McConnaughey, 1989). As *M. campechiensis* precipitates its shell in oxygen isotope equilibrium with surrounding water, the kinetic effect should be minimal (Gillikin et al., 2007). Understanding the controls on the variation of the carbon isotope time series remains challenging, given that 5 to 35% of the carbon can be metabolically derived (Gillikin et al., 2007). Surge and Walker (2006) also observed that variation of $\delta^{13}C_{shell}$ lacked reproducibility among modern *M. campechiensis* individuals growing during the same time and at the same location near our study area. Because of these complexities in interpreting $\delta^{13}C_{shell}$ of *M. campechiensis*, we cannot explain the temporal change of $\delta^{13}C_{shell}$ observed in the modern shells and archaeological shells. Nonetheless, similar to $\delta^{13}C_{otolith}$, a negative offset (2.0–3.0‰) of $\delta^{13}C_{shell}$ is also observed in the modern shells relative to the archaeological shells (Table 2). Under the assumption that the metabolic isotope effect of shells and otoliths did not change from the Vandal Minimum to present, this negative shift between the archaeological specimens and the modern specimens is mainly attributed to the negative shift of $\delta^{13}C_{DIC}$. Both offsets are close to that observed by Surge et al. (2003) based on $\delta^{13}C$ values recorded in pre-industrial subfossil oyster shells relative modern oyster shells from the Ten Thousand Islands region of southwest Florida. They concluded that the negative shift was derived from the change of freshwater input, the anthropogenic carbon sources (Suess effect), vegetation types C_4 to C_3 plants (Surge et al., 2003), or nutrient inputs from land-use changes. In our study, changes in freshwater input are not likely to be the cause because we would also observe a similar negative offset in $\delta^{18}O$ values between the archaeological and modern specimens. The anthropogenic activities of burning fossil fuels have depleted the $\delta^{13}C$ in the atmosphere and ocean reservoirs because of the uptake of ^{12}C from CO_2 produced by fossil fuels (Bacastow et al., 1996). The above process of ^{13}C depletion is called the Suess effect, which has been detected in sponges, corals, bivalves and other biologic carbonate skeletons (Bohm et al., 2002; Butler et al., 2009; Druffel and Benavides, 1986; Nozaki et al., 1978; Surge et al., 2003). However, the Suess effect can only explain at most a 1–1.5‰ negative shift. Alternatively, a change in vegetation type from terrestrial C_4 plants to C_3 plants or in land-use modification in the watershed may have contributed to the offset; however, more environmental information is required to evaluate these contributions.

Reconstructed temperature and precipitation

In order to reconstruct climate change during the Vandal Minimum, we used two approaches. First, we compared the estimated winter temperatures between archaeological and modern otoliths to evaluate the winter temperature change in the Vandal Minimum. Second, we compared the summer $\delta^{18}O_{shell}$ values between modern and archaeological shells to assess changes in summer precipitation in the Vandal Minimum. We justified this approach based on the observations that the summer temperatures in southwest Florida have low interannual variability; therefore, the variation of $\delta^{18}O_{shell}$ values reflects the fluctuation in $\delta^{18}O_w$ and, hence, summer precipitation.

We observed warming and cooling trends during winter in the archaeological otoliths (Figure 4). As previously stated, winter growth cessation of otoliths increases the time averaging during cold months and may not record the coldest winter temperatures. Therefore, to eliminate the time averaging in otoliths, we compared the estimated winter temperatures from archaeological otoliths with the estimated winter temperatures from modern otoliths, instead of comparing with modern instrumental records. The earliest otolith (CIIA-A9; AD 450–500) records average winter temperature of 22.5 ± 0.4°C, which is about 2°C warmer than the modern otoliths record (20.5 ± 0.5°C) (Table 2). Otolith CIIA-A7 (AD 500–550 records a subsequent cooling of about 4°C (average winter temperature of 18.2 ± 1.6°C), and otolith CIIA-A8 (AD 600–650) records similar winters to today with an average winter temperature of 20.3 ± 1.0°C (Table 2). Another relative cooling is

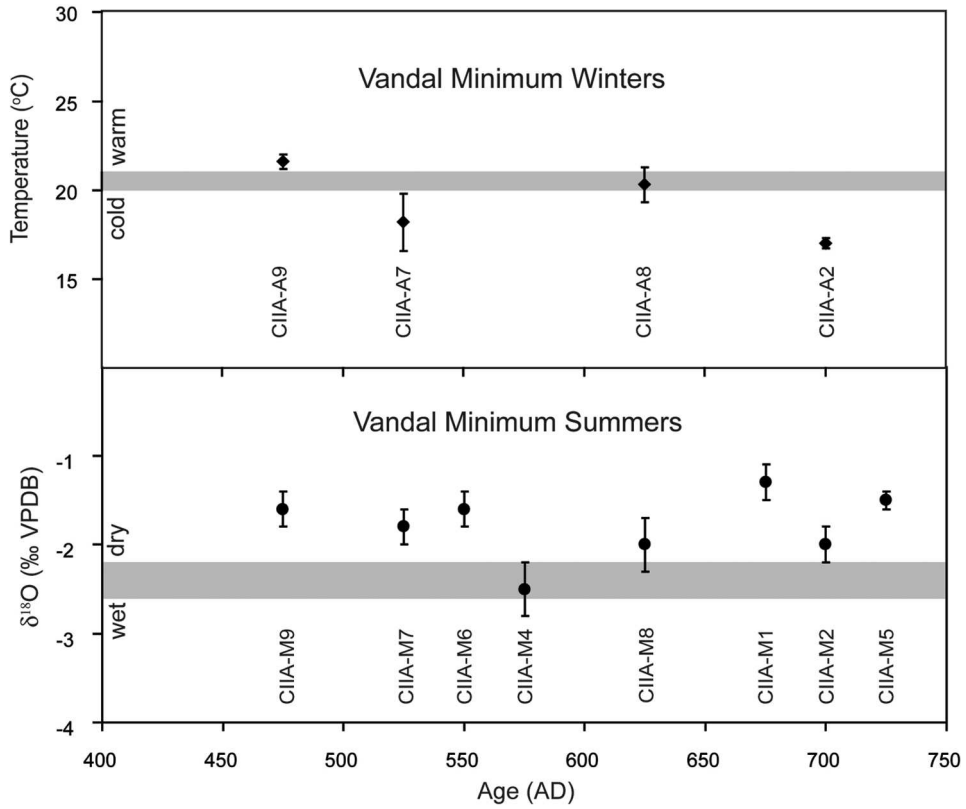

Figure 6. Reconstructed Vandal Minimum (AD 500–750) winters and summers. Diamonds represent winter temperatures with standard errors estimated from otoliths. Circles represent summer $\delta^{18}O$ values of archarological shells with standard errors. The gray bar in the figure of Vandal Minimum winters is the average winter temperature of modern otolith MOD2002 (20.5 ± 0.5°C), and the gray bar in the figure of Vandal Minimum summers is the average summer $\delta^{18}O$ value of modern shells 05PI05 and 05PI17 (−2.4 ± 0.2‰)

recorded in otolith CIIA-A2 (AD 650–700), having an average winter temperature of 17.8 ± 0.3°C, which is as much as 3°C colder than the modern otolith record (Table 2).

We compared the average summer $\delta^{18}O_{shell}$ values between modern and archaeological shells (Table 2). Seven of the archaeological shells (specimens CIIA-M9, CIIA-M7, CIIA-M6, CIIA-M8, CIIA-M1, CIIA-M2, and CIIA-M5) recorded more positive $\delta^{18}O_{shell}$ values than the modern shells, representing more positive $\delta^{18}O_w$ values and drier summers than today (Table 2). Shell CIIA-M1 recorded the driest summers (Table 2). Only the third and the fourth summer from shell CIIA-M4 (the growth range of 0–60 mm from margin) and the first summer from shell CIIA-M8 (the growth range of 100–120 mm from margin) are wetter compared with modern shells (i.e. more negative $\delta^{18}O_{shell}$ values) (Figure 5).

We summarized our findings by plotting estimated winter temperatures and summer $\delta^{18}O_{shell}$ values in chronostratigraphic order (Figure 6). Based on the above observations, we conclude that the winter temperature of the Vandal Minimum has warming and cooling trends relative to today. We detect persistent summer drought conditions during summer months that are observed in most archaeological shells. The fluctuations of winter temperature and summer precipitation generally agree with the archaeological evidence (Marquardt and Walker, 2001; Walker, 2000; Walker et al., 1995). That evidence suggests that the transition from the end of the 'Roman Warm Period' to the beginning of the Vandal Minimum (the time of otolith-shell pair CIIA-M9/CIIA-A9) was the warmest time with high sea level and therefore high-elevation human habitation. The CIIA-M9/CIIA-A9 specimen pair comes from Pineland's Surf Clam Ridge, an elevated sand and midden topographic feature within the site complex. The average winter temperature of otolith CIIA-A9 is indeed the warmest in the Vandal Minimum. The early Vandal Minimum (AD 500–600), the time of CIIA-M7/CIIA-A7, CIIA-M6, and CIIA-M4, is thought to be the first cold episode of the Vandal Minimum at Pineland when many ducks such as the lesser scaup (*Aythya affinis*) migrated far to the south to southwest Florida (in normal winters, most migratory ducks winter in coastal Maryland and the Mississippi Delta region) (Walker, 2000). All four specimens come from Pineland's Old Mound midden, deposits that also contain high relative abundances of duck remains, whether measured by NISP (number of identified specimens) or MNI (minimum number of individuals). The decreasing winter temperatures recorded in otolith CIIA-A7 relative to CIIA-A9 are consistent with the archaeological evidence. Moreover, during the time intervals represented by otolith-shell pair CIIA-A7/CIIA-M7 and shell CIIA-M6, summers were dry with low-elevation human habitation. This observation is supported by the dry summers recorded in shells CIIA-M7 and CIIA-M6. During AD 600–650, the time of CIIA-M8/CIIA-A8, the environment was warmer (fewer migratory ducks) and wetter (high relative abundance of ribbed mussels, *Geukensia demissa*, whose habitat is brackish black-mangrove wetland). The CIIA-M8/CIIA-A8 specimen pair comes from a midden deposit low in Pineland's Brown's Mound Complex, one containing a few duck remains and high numbers of ribbed-mussel shells in its faunal assemblage. During AD 650–700, the time of CIIA-M1 and CIIA-M2/CIIA-A2, a second cooling interval occurred as identified by increased numbers of migratory duck remains and supported by the decreasing winter

temperatures from shells CIIA-A8 to CIIA-A2. During AD 700–750, dry conditions were characterized in midden deposits by a sudden predominance of charred pine fragments, indicating a change in fuelwood use from the preferred intertidal black mangrove to the terrestrial pine (Walker, 2000). A comparison of our data from shell CIIA-M2 with those from CIIA-M5 supports this interpretation. Based on our results and the archaeological evidence, we suggest that climate conditions during the Vandal Minimum in southwest Florida are characterized by cooling during AD 500–600 and AD 650–700 and dry summer conditions during AD 500–600 and AD 650–750. We also infer that the dry summers resulted in a persistent drought coincident with low sea level (Walker et al., 1995). These conditions may have forced the Calusa people to abandon their coastal Pineland residence in southwest Florida for the interval of AD 750 to 850 based on a gap in Pineland's chronostratigraphic record.

Conclusions

Although reconstructing temperature change from the hard-part remains of estuarine molluscs and fish is difficult because of seasonal fluctuation of $\delta^{18}O_w$ in coastal waters, a multitaxa approach has provided an effective way to interpret the $\delta^{18}O$ results. Our study derived temporal shifts in temperature and precipitation during the Vandal Minimum in southwest Florida from the four otolith-shell pairs (CIIA-A/M9, 7, 8, and 2) and another four shells (CIIA-M6, 4, 1, and 5). The reconstructed climate information from $\delta^{18}O$ values confirmed winter cooling and persistent summer drought punctuated by occasional years with wet summers during the Vandal Minimum, and provided insights into the impact of climate change on the Calusa people. Longer and more successive $\delta^{18}O$ records will allow us to better evaluate this mechanism influencing climate patterns of the past.

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