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Oxygen isotope composition of modern and archaeological otoliths from the estuarine hardhead catfish (*Ariopsis felis*) and their potential to record low-latitude climate change

Donna Surge [a,*], Karen Jo Walker [b]

[a] *University of North Carolina, Department of Geological Sciences, Campus Box 3315, Chapel Hill, NC 27599-3315, United States*
[b] *University of Florida, Florida Museum of Natural History, PO Box 117800, Gainesville, FL 32611-7800, United States*

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Abstract

Shells and otoliths (fish "ear bones") from archaeological deposits of Pine Island, southwest Florida, provide valuable archives of ecological patterns, climate change, and associated human responses. Many remains from these deposits that can be used for climate reconstruction are from estuarine animals. The challenge in using oxygen isotope composition of their carbonate hard parts lies in deconvoluting the effects of temperature and salinity (mixing of fresh- and saltwater, each having different isotopic compositions). Otoliths of the hardhead catfish (*Ariopsis felis*, Linneaus, 1766) may provide a record of winter temperature without the complication of salinity variation because this fish spends winter months in waters of marine to near-marine salinities. Hence, $\delta^{18}O_{WATER}$ can be constrained when employing published temperature equations. Here, we present geochemical data from modern and archaeological otoliths to evaluate whether they preserve winter temperature.

A modern catfish was caught near Pine Island Sound and the otoliths (lapilli) removed. Archaeological otoliths from the 2nd/3rd century AD, falling within the Roman Optimum (RO), and the 13th/14th century AD, falling within the Little Ice Age (LIA), were obtained from the Florida Museum's collections. Oxygen isotope compositions were converted to temperature using published temperature equations and assuming +1‰ for Gulf water. Isotopic compositions for the modern otolith range from −3.55‰ to +0.29‰, the LIA otolith ranges from −3.92‰ to +0.52‰, and the RO otolith ranges from −1.80‰ to +0.84‰. All three otoliths record winter temperature (~20 °C) similar to modern conditions. Calculated summer temperatures for the modern and LIA otoliths (~40 °C) are overestimated and reflect the combined influence of temperature and salinity when catfish inhabit brackish estuarine waters during their reproductive season. In contrast, summer temperature estimates for the RO otolith are similar to modern conditions indicating estuarine water during the summer was close to +1‰. This result

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[*] Corresponding author. Fax: +1 919 9664519.
E-mail address: donna64@unc.edu (D. Surge).

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suggests that seasonal rainfall patterns during the time period represented by the RO otolith were different than today, such that the summer wet season was not prevalent.

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1. Introduction

Coastal habitats are inherently sensitive to climate change. Consequences of climate change in coastal areas include fluctuation in sea level, storm intensity and frequency, beach erosion, the economy of the tourism, seafood industries, etc. Therefore, it is imperative to develop proxies that will allow reconstruction of paleoclimate data to understand how these environmentally sensitive habitats respond to climate change.

Variation in the $\delta^{18}O$ of biogenic carbonate has traditionally been used to reconstruct water temperature or the oxygen isotope composition of ambient water. To do this, one of the parameters (either temperature or $\delta^{18}O_{WATER}$) must be constrained. For example, planktonic foraminifera have been used to reconstruct sea surface temperature because $\delta^{18}O_{WATER}$ can be held constant at marine salinity (Curry and Matthews, 1981; Erez and Honjo, 1981; Spero and Williams, 1988; Spero and Lea, 1993; Zachos et al., 2003; Tian et al., 2004; Flower et al., 2004 and many others). Conversely, benthic foraminifera from the deep ocean have been used to reconstruct changes in the $\delta^{18}O$ of oceans (and, hence, glacial ice volume) because bottom-water temperature of the deep ocean can be held constant (Marchitto and deMenocal, 2003; Skinner et al., 2003; Oerlemans, 2004; Polyak et al., 2004; Tian et al., 2004 and many others). Deciphering environmental changes in salinity and temperature from variations of $\delta^{18}O$ in biogenic carbonate of taxa from coastal habitats is challenging because of the seasonal variation in both temperature and salinity (i.e., mixing of fresh- and saltwater end members, where freshwater tends to have more negative $\delta^{18}O$ values than seawater).

Oxygen isotope analysis of otoliths has been widely used in paleoclimate and paleoecological reconstruction (Mulcahy et al., 1979; Wefer and Berger, 1991; Patterson et al., 1993; Thorrold et al., 1997; Ivany et al., 2000; Wurster and Patterson, 2001; Andrus et al., 2002a; Andrus et al., 2002b; Andrus et al., 2003; Béarez et al., 2003; Grimes et al., 2003). Therefore, variation in $\delta^{18}O$ of otoliths (lapilli) of the hardhead catfish, *Ariopsis felis* (Linneaus, 1766),[1] may provide a powerful means to reconstruct environmental change and ecological behavior. Despite its coastal habitat, we hypothesize that by invoking ecological constraints useful paleoenvironmental information can be deciphered using $\delta^{18}O$ values. Adults spend winter months in waters at or near marine salinity. Thus, winter $\delta^{18}O_{WATER}$ can be constrained. Temperature equations using otolith $\delta^{18}O$ have already been published allowing us to convert $\delta^{18}O_{OTOLITH}$ to estimated winter temperature by assuming a regional $\delta^{18}O_{SEAWATER}$ value. Here, we test the hypothesis that $\delta^{18}O$ values from a modern *A. felis* otolith records winter temperature and overestimates summer temperature when spawning in brackish estuarine waters. We evaluate the utility of archaeological *A. felis* otoliths as archives of climate change.

2. Ecology of *Ariopsis felis*

The family, *Ariidae*, is one of the most abundant fish groups in tropical and subtropical estuaries and coastal lagoons (Yáñez-Arancibia and Lara-Domínguez, 1988). *A. felis* ranges from Atlantic coastal waters from Cape Cod, Massachusetts, to Yucatan, Mexico, and also occurs in coastal waters of the Gulf of Mexico (Muncy and Wingo, 1983). Ariids are not favored sport or culinary fish by modern standards; however, the pre-European people of southwest Florida did appreciate their food value as their skeletal remains are commonly found in Calusa archaeological deposits (Walker, 1992).

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[1] Previously, the genus of the hardhead catfish was designated as *Arius*, but Nelson et al. (2004) have since changed the genus classification to *Ariopsis*.

This catfish is well suited for paleoclimate investigation because of its behavior characteristics. *A. felis* is a bottom-dwelling fish that spends its juvenile and reproductive season (May to September) in the estuary in salinities ranging from 13‰ to 30‰ (Muncy and Wingo, 1983; Yáñez-Arancibia and Lara-Domínguez, 1988). They reach sexual maturity by age 2 and oral gestation behavior is provided by the males (Benson, 1982). At the end of the spawning season, adults often migrate into the Gulf of Mexico to depths no more than 20 m during the winter/early spring (Muncy and Wingo, 1983; Pattillo et al., 1997). Subtropical waters do not vary much in winter temperature over this depth range; thus, change in winter temperature based on $\delta^{18}O_{OTOLITH}$ should record a change in climate, not a change in depth. We note, however, that, in a survey done by Mote Marine Laboratory in the Charlotte Harbor estuary system, Wang and Raney (1971) caught some *A. felis* within “Charlotte Harbor and adjacent waters” during the winter in salinities ranging from 30–36‰. Regardless, their winter behavior allows us to constrain $\delta^{18}O_{WATER}$ during winter months, and thus, test the hypothesis that $\delta^{18}O$ of aragonitic otoliths of *A. felis* can be used to reconstruct environmental, climatic, and ecological changes at seasonal time scales in coastal marine and estuarine habitats.

3. Study area

Coastal southwest Florida is subtropical, transitional between the true tropics and the temperate zone, and has been a tectonically stable region throughout the Late Holocene (Fig. 1). The region is characterized by a low-lying landscape and shallow-water, micro-tidal, inshore estuarine bays. Thus, these estuarine landscapes and ecosystems were and are hypersensitive to variations (especially abrupt ones) in temperature, rainfall, ground-water and sea level, and storm frequency/intensity. Impacts include shifts in salinity gradients resulting in shifts in animal distributions and diversity and changes in population sizes, losses/gains in wetland areas and seagrass flats, flooding/drought, and barrier island and inlet erosion/deposition (Stapor et al., 1991; Peters and Lovejoy, 1992; Ray et al., 1992; Eisma, 1995). By collecting estuarine animals and discarding their remains on the landscape in telling spatial and vertical patterns, the ancient human residents of this dynamic setting were unknowing historical recorders of environmental changes. Such zooarchaeological remains can be robust indicators of paleoecological change, and thus of climate impacts through time (Walker, 1992; Dincauze, 2000). Add interbedded deposits produced by natural forces such as storms and wetland formation, and the record is greatly enhanced, richly documenting relationships between humans and their ever-changing environment (e.g., Stein and Linse, 1993; Walker et al., 1994; Walker et al., 1995; Rapp and Hill, 1998). In the absence of subsidence and uplift forces, southwest Florida’s archaeological sites can and do accurately record impacts of climate change.

Air temperature and precipitation data recorded at Fort Myers, Florida and provided by the National Climate Data Center (http://www.ncdc.noaa.gov) documents variability at seasonal and interannual scales (Figs. 1–3). Average seasonal temperature across the entire century-long data set ranges from 16.9 ± 1.5 °C in the winter to 28.3 ± 0.6 °C during the summer (Fig. 2). Most of the year-to-year fluctuation in temperature occurs during winter months. Because we have limited temporal coverage of water temperature, we compared air and water temperature from a nearby locality (Naples is ~50 km southeast of the study area) to see if air and water values closely track each other and they do (Fig. 4). (Air temperature data was provided by the National Oceanographic and Atmospheric Administration, and water temperature data was courtesy of Rookery Bay National Estuarine Research Reserve, Naples, Florida.) Precipitation also exhibits seasonal and year-to-year variability (Fig. 3). Seasonal rainfall patterns are more or less sinusoidal, reflecting a wet season and a dry season. The wet season begins generally in May and tapers off in October. Rainfall amounts during the wet season can vary from 147 mm/month during very dry years to 514 mm/month in very wet years. The interannual periodicity between very dry and wet rainy seasons is from 4 to 9 years over the last ~70 years, likely reflecting El Niño cycles. Pine Island provides Pine Island Sound with limited freshwater. Most of the freshwater that enters the Sound comes from direct rainfall and

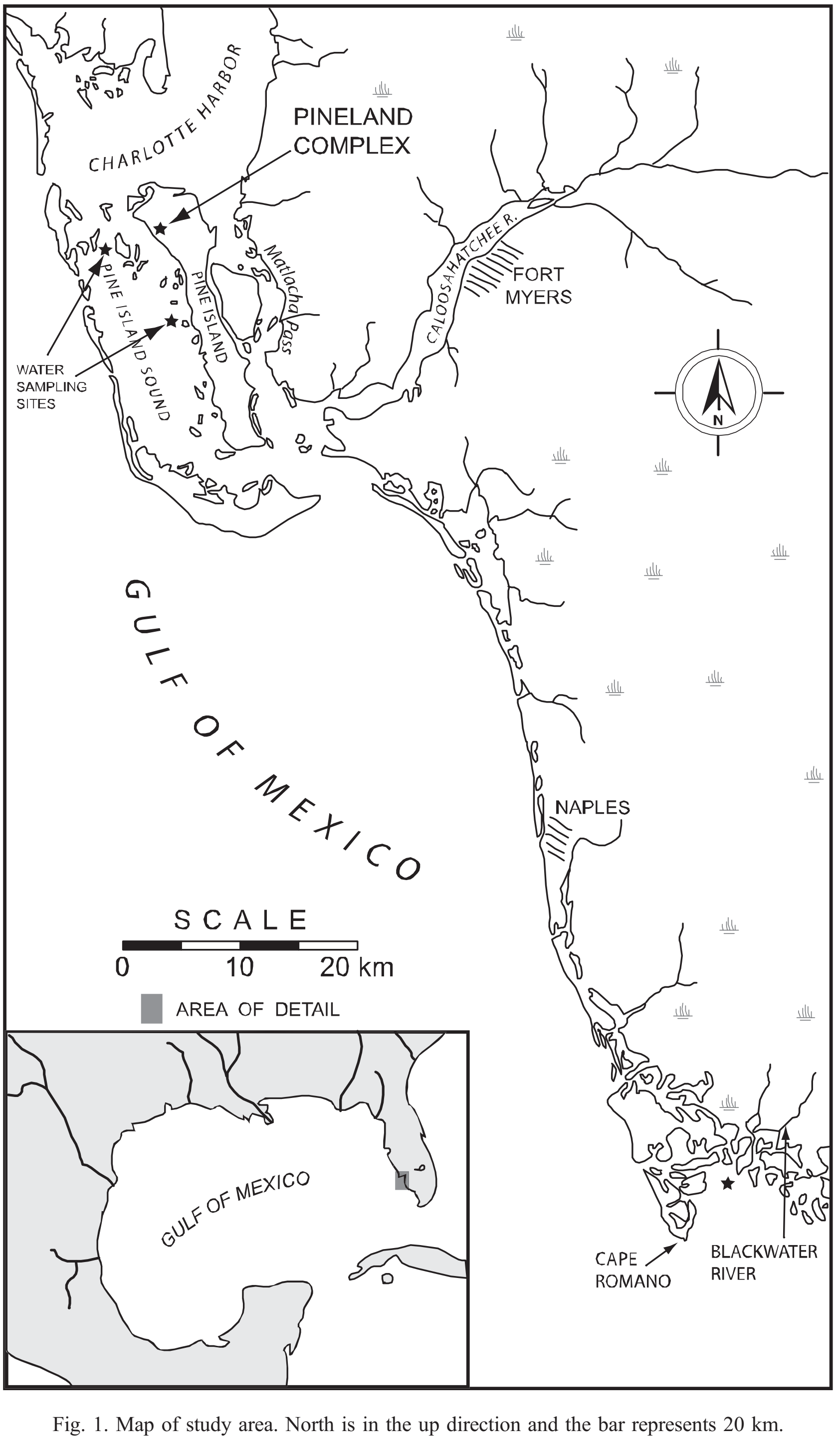

Fig. 1. Map of study area. North is in the up direction and the bar represents 20 km.

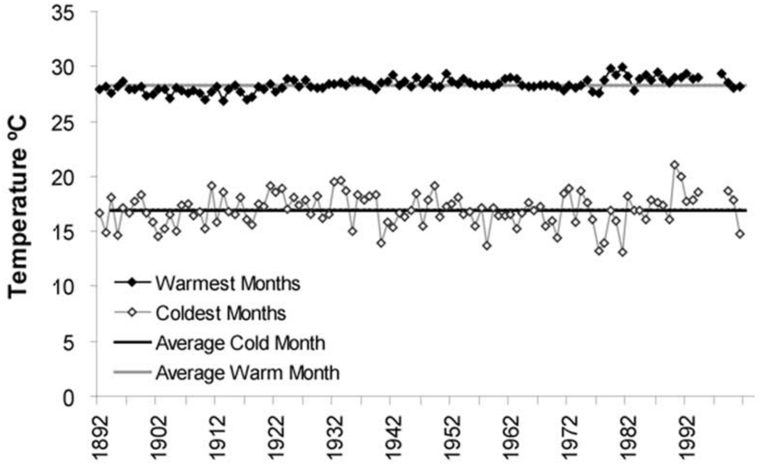

Fig. 2. Annual high (black diamonds) and low (gray diamonds) air temperature (°C) for the last century from Ft. Myers, Florida (based on monthly average temperature courtesy of the National Climate Data Center) from 1892 to 2001. Gray and black horizontal lines represent the average high and low temperatures, respectively, over the entire data set.

runoff from Cape Coral (Rudolph, 2000). Water temperature and salinity in this region are discussed later in this paper.

4. Methods

4.1. Otolith samples

Otoliths of modern and archaeological specimens were obtained from the curated collections of the Florida Museum of Natural History (FLMNH). The modern otolith (FLMNH RRC ZA069) was extracted from a fish caught near Pine Island Sound in December 2001 and measured 10.05 mm from anterior to posterior. The fish itself measured 40.5 cm (total length), 34.5 cm (standard length), and 37.5 cm (fork length). Maximum known size for this species of fish is 61.0 cm (total length; McEachran and Fechhelm, 1998, p. 361). Archaeological specimens from 2nd/3rd century AD (FLMNH EA 0474-0825), falling within the Roman Optimum (RO) climate

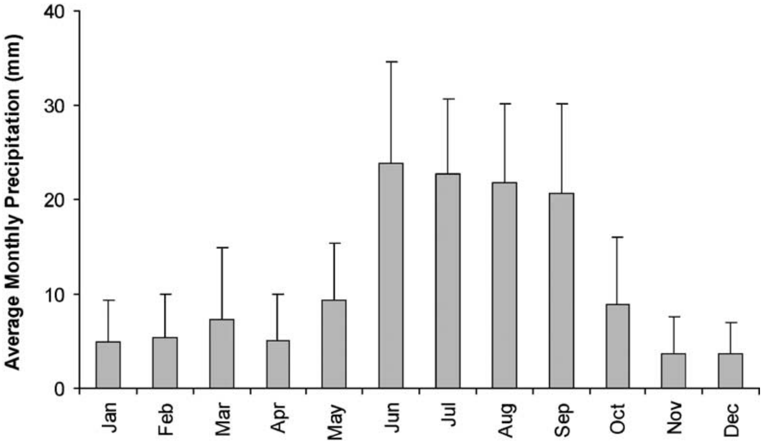

Fig. 3. Average monthly rainfall from Ft. Myers, Florida reflecting wet season and dry season reported in centimeters. Averages calculated from the 1931 to 2001 data set provided by the National Climate Data Center. Lines above gray bars are standard deviations.

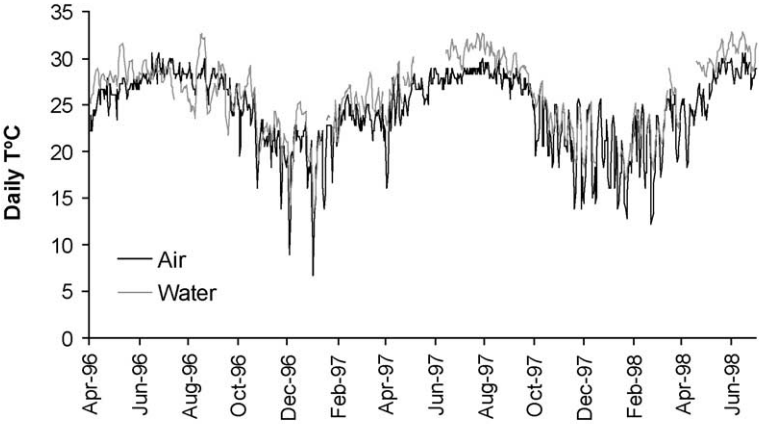

Fig. 4. Comparison of daily air and water temperature (°C) at Ft. Myers and Naples, Florida, respectively. Black line is air temperature and gray line is water temperature.

interval, and from the 13th/14th century AD (FLMNH EA0474-0112), falling within the early Little Ice Age (LIA) climate interval, were excavated from the Pineland Site Complex on the northwest shoreline of Pine Island (Fig. 1). The RO and LIA otoliths measured 10.74 mm and 10.17 mm, respectively, from anterior to posterior.

Archaeological otoliths of adult individuals were identified by comparing them to modern specimens of both *A. felis* and *Bagre marinus*, the two marine catfish that inhabit the region's waters. Although the two species have otoliths that are morphologically similar, they often–but certainly not always, especially in juveniles or in poorly preserved specimens–can be identified based on the angle between the spur and the crest of the dorsal margin (*A. felis* specimens exhibit about a 90° angle; *B. marinus* closer to a 75° angle). Our confidence in this method is bolstered by the fact that many cranial elements of these two catfish can easily be distinguished as belonging to one or the other species and that, typically, the Ariidae cranial specimens from Pineland zooarchaeological samples are composed of 96% to 98% *A. felis* specimens and only 2% to 4% *B. marinus* specimens (deFrance and Walker, in preparation). This reflects the inshore location of Pineland and the fact that *B. marinus* is much more abundant nearer inlets and in the Gulf. Only occasionally were *B. marinus* specimens caught by Pineland's ancient fisherfolk. Overall, Pineland's archaeological fish assemblage supports a focus on inshore exploitation, with little to no evidence for fishing in the Gulf or even in the inlets.

Both otoliths come from midden contexts representing daily refuse of Calusa fisherfolk. The RO otolith is from midden radiocarbon-dated to AD 110–270 (calibrated, 1σ range, Beta-54799). This date is based on a shell specimen of *Mercenaria campechiensis* and was corrected for both global and local geographic reservoir effects and then corrected for δ^{13}C (Stuiver et al., 1993). The LIA otolith is from midden radiocarbon-dated to AD 1270–1330 (calibrated, 1σ range, Beta-39292). This date is based on a shell specimen of *Busycon sinistrum* and was corrected in the same manner. Each date is consistent with its respective midden pottery assemblage (Walker and Marquardt, in preparation).

Otolith specimens were cut along the transverse plane because this surface best revealed incremental growth features and permitted sampling at high resolution (Fig. 5). High-resolution (sub-monthly) sampling was achieved using a Merchentek micromill equipped with a 0.3 mm dental burr. Sampling traverses parallel to incremental growth features were digitized online from a real-time image of an otolith section. Milling began at the first prominent growth band and continued toward the growing edge. Small amounts (20–40 μg) of powdered carbonate were collected from the polished specimen surface. Oxygen isotope composition was analyzed on a Finnigan MAT

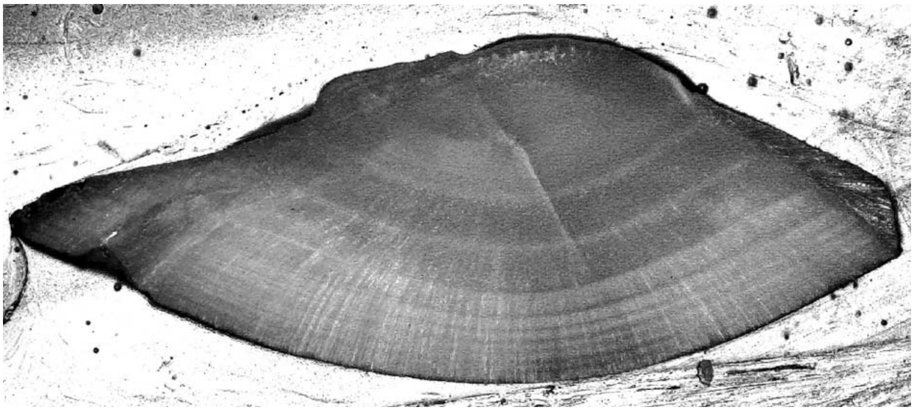

Fig. 5. Photomicrograph of otolith cross section cut across the transverse plane of RO specimen (FLMNH EA 0474–0825). Distance from anterior to posterior is 10.74 mm.

251 mass spectrometer with an automated carbonate reaction system (Kiel Device). Analytical precision was better than 0.1‰. Oxygen isotope ratios were corrected for ^{17}O contribution (Craig, 1957). Values of δ^{18}O are reported in per mil units with respect to the VPDB standard.

4.2. Water properties

Water samples from Pine Island Sound and Charlotte Harbor were collected to characterize seasonal variation in oxygen isotope composition. Temperature in Pine Island Sound was measured from August 5, 2003 to July 1, 2004. Hourly temperature measurements were obtained using StowAway Tidbit underwater temperature loggers (Onset Computer Corporation). Hourly data were converted to daily and weekly averages and are reported in °C. Fifteen milliliters of water for δ^{18}O analysis were collected twice a month from August 4, 2003 to March 15, 2004 at two sites in Pine Island Sound (Fig. 1). Salinity measurements were taken for each sample using a Leica refractometer. Five milliliters of water were analyzed using a Gas Bench II auto-preparation system coupled to a Finnigan Delta Plus/XL. Data were normalized to an internal standard water and absolute δ^{18}O values were normalized to measured values of VSMOW and VSLAP. Standard deviation for repeated measurements of the internal standard was better than 0.1‰ δ^{18}O values are reported with respect to the VSMOW standard.

5. Results and discussion

5.1. Water properties

Water temperature in Pine Island Sound followed a more or less sinusoidal pattern reflecting seasonal variation (Fig. 6). Winter temperature from December to February averaged 18.7 (±2.6) °C, whereas summer temperature (June, July, and August) averaged 30.7 (±1.2) °C. Values of $\delta^{18}O_{WATER}$ ranged from −1.25‰ to +1.70‰ and are described by the following least-squares regression equation ($r^2=0.78$, $p<0.001$, $n=32$):

$$\delta^{18}O_{WATER} = 0.13S - 2.70$$

where S is salinity (Fig. 7). The positive shift from the global marine average (0‰) likely reflects evaporation at low latitudes. The negative departure from the global marine average results from mixing of fresh- and saltwater during the wet season. These seasonal differences have been observed elsewhere in the region (Kirby et al., 1997; Surge and Lohmann, 2002) and will become important when evaluating the utility of $\delta^{18}O_{OTOLITH}$ values as a proxy for ambient environmental conditions.

5.2. Modern otolith

The profile of δ^{18}O values is more or less sinusoidal in the modern otolith (Fig. 8A). Values range from −3.55‰ to +0.29‰. The sinusoidal pattern

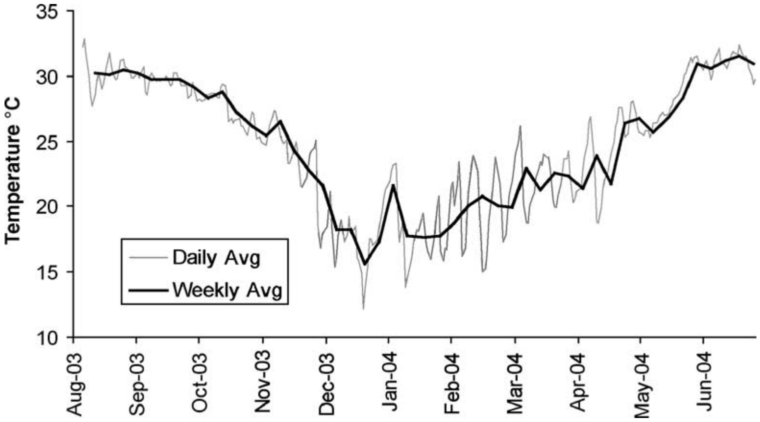

Fig. 6. Water temperature measurements (°C) in Pine Island Sound from August 2003 to July 2004. Gray line is daily averages and black line is weekly averages.

suggests that about 1 year of growth was sampled (assuming most negative value represents warmest season and most positive value represents coldest season recorded).

To test the hypothesis that *A. felis* otoliths record ambient water conditions and seasonal migration patterns, we estimated water temperature from δ^{18}O values of the modern otolith using published temperature equations (Patterson et al., 1993; Thorrold et al., 1997) and compared estimated temperature to measured winter and summer temperatures. We predicted that (i) calculated winter temperature would approximate measured winter values when salinity is near marine and $\delta^{18}O_{WATER}$ is positive; and (ii) summer temperature would be overestimated because *A. felis* spends its reproductive cycle in estuarine waters during the summer wet season, when salinity is brackish and $\delta^{18}O_{WATER}$ values are negative. In addition to evaluating records of environmental conditions and migration patterns, this means of comparison also allowed us to evaluate which temperature equation was better suited for otoliths of *A. felis*.

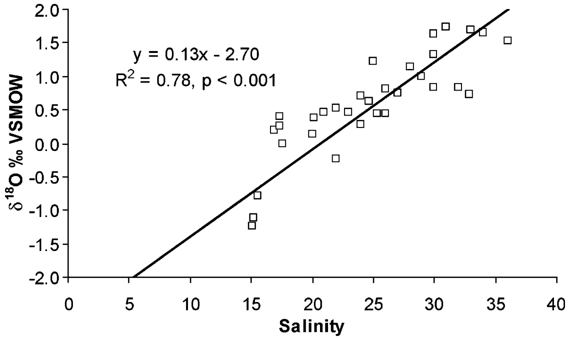

Fig. 7. Mixing relation between $\delta^{18}O_{WATER}$ (‰ VSMOW) and salinity (ppt) from water collected in Charlotte Harbor and Pine Island Sound.

The equation reported by Patterson et al. (1993) is in the form:

$$10^3 \ln\alpha = 18.56\left(10^3 T^{-1}\right) - 33.49 \tag{1}$$

where α is the fractionation factor between water and aragonite, and T is temperature in Kelvin. Thorrold et al. (1997) equation is similar to that published by Patterson et al. (1993) and differs only in intercept:

$$10^3 \ln\alpha = 18.56\left(10^3 T^{-1}\right) - 32.54 \tag{2}$$

The relationship between α and δ is:

$$\alpha = \left(\delta_{\mathrm{ARAGONITE}} + 10^3\right) / \left(\delta_{\mathrm{WATER}} + 10^3\right) \tag{3}$$

and conversion of δ^{18}O values from the VPDB scale to the VSMOW scale was accomplished using the equation by Gonfiantini et al. (1995):

$$\delta_{\mathrm{VPDB}} = 1.03091 * \delta_{\mathrm{VSMOW}} - 30.91$$

Estimated temperature using both equations assumed a regional $\delta^{18}O_{WATER}$ for the saltwater end member is +1‰ based on data from this study (Fig. 7)

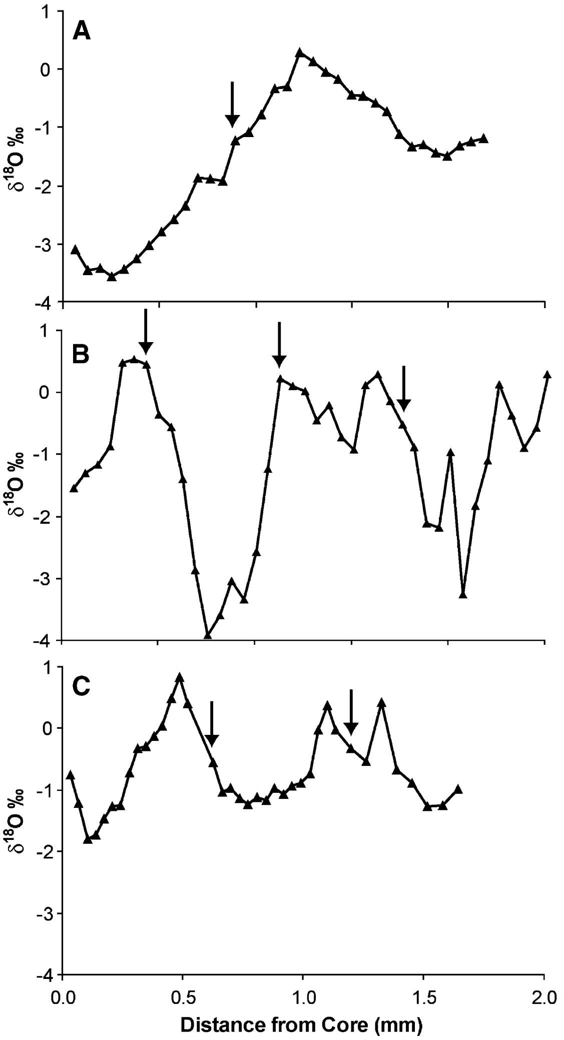

Fig. 8. Variation of δ^{18}O (‰ VPDB) from modern (A), early Little Ice Age (B) and Roman Optimum (RO) otoliths from near the inner core towards the growing edge (from left to right). Arrows indicate location of major growth bands.

and from the literature (Kirby et al., 1998; Surge and Lohmann, 2002).

We compared estimated temperatures to measured summer and winter values (Figs. 2, 6 and 9A). The measured temperature record spans a different time period than the year sampled in the modern otolith. Therefore, based on the air temperature records for Ft. Myers over the last century, we considered estimated temperature to approximate measured values if it was close to the average and within the standard deviation (Fig. 2). We used this restriction to evaluate the two temperature equations.

Temperature calculated using Eq. (1) yields a coldest winter value of 20.44 °C (Fig. 9A). This calculated value is reasonable given measured water and air temperature for this region. Estimated coldest winter temperature using Eq. (2) is 24.92 °C, which is unreasonably high given measured values (Fig. 9A). Therefore, Eq. (1) was used to estimate temperature from $\delta^{18}O_{OTOLITH}$.

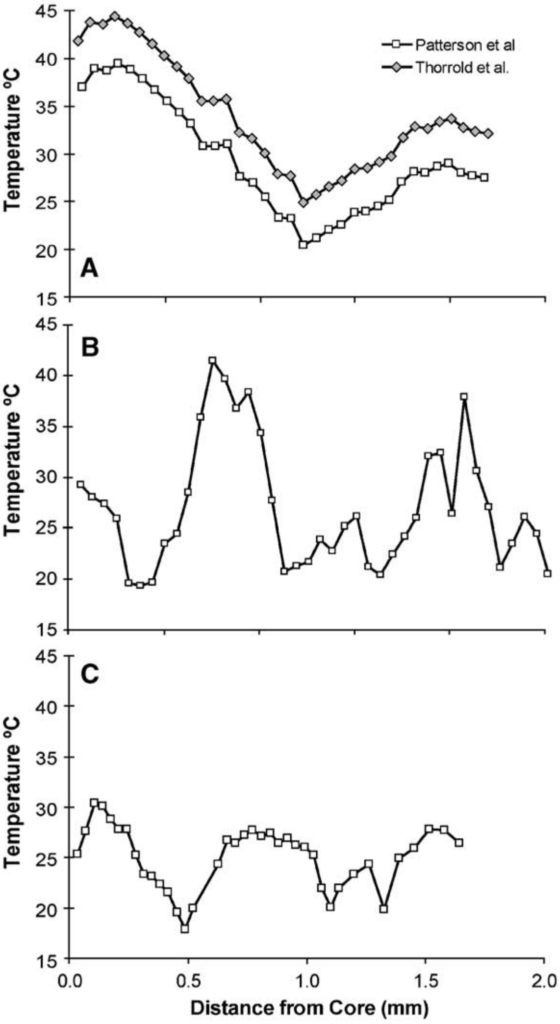

Fig. 9. Estimated temperature (°C) based on $\delta^{18}O_{OTOLITH}$ using the equation by Patterson et al. (1993) (white squares) and the equation by Thorrold et al. (1997) (gray diamonds). (A) Modern otolith, (B) early Little Ice Age otolith, (C) Roman Optimum otolith.

Because *A. felis* have been found not only in the Gulf of Mexico but also in Charlotte Harbor and adjacent waters during the winter in salinities ranging from 30 to 36 ppt (Wang and Raney, 1971), we also evaluated how much error such a range in salinity might introduce into our temperature estimates. Therefore, we calculated the difference in temperature across that range of salinity. We used the δ^{18}O–salinity relationship to calculate $\delta^{18}O_{WATER}$ for each salinity. Estimated temperature varies by a maximum of 3 °C from 30 to 36 ppt. The standard deviation for measured interannual winter temperature variability for the last century is ±1.5 °C. Therefore, our temperature estimates based on $\delta^{18}O_{OTOLITH}$ would be within the expected range for modern conditions and would not affect our conclusions.

Summer temperature based on otolith δ^{18}O is overestimated by almost 10 °C in accordance with our prediction (Fig. 9A). If temperature is re-calculated using a $\delta^{18}O_{WATER}$ value of −1‰ for estuarine water during the wet season, reasonable summer temperature estimates result. Therefore, δ^{18}O of otolith carbonate records summer migration into brackish water during the reproductive season of *A. felis*.

5.3. Archaeological otoliths

Variation in δ^{18}O values of the archaeological otoliths reveal a more jagged sinusoidal pattern relative to the modern otolith (Fig. 9B and C). Values range from −3.92‰ to +0.52‰ in the LIA otolith and from −1.80‰ to +0.84‰ in the RO otolith. Assuming most negative values represent the warmest season and most positive values represent the coldest season, the LIA otolith provided 2.5 years of growth sampled at 2- to 3-week resolution. Two years of growth were sampled in the RO otolith at approximately 3-week resolution. Location of growth bands (arrows in Fig. 8) in all specimens do not consistently correspond to a particular season and, therefore, are likely not useful indicators of age in this species of fish. More detailed sclerochronologic analysis is necessary to confirm this.

Using Eq. (1), δ^{18}O values were converted to estimated temperature (Fig. 9B). Estimated winter temperature for the LIA otolith ranges from 19.33 to 21.18 °C and is similar to modern winter temperature. The RO otolith also records winter temperature similar to modern values, ranging from 17.89 to 20.07 °C (Fig. 9C). As in the modern otolith, summer temperature recorded in the LIA otolith is as high as 41.43 °C, clearly an overestimation (Fig. 9B). Therefore, summer δ^{18}O values record migration of this fish into estuarine waters of brackish salinity. In contrast, summer temperatures estimated from δ^{18}O values of the RO catfish range from 27.67 to 30.44 °C, which is within the range of modern temperature measurements (Fig. 9C). If summer temperature during the 2nd/3rd century AD was in fact similar to today, then this fish must have swum in waters having a δ^{18}O value of about +1‰. This result can be explained by invoking an ecological interpretation or an environmental interpretation.

An ecological explanation requires a change in behavior such that this fish never swam into estuarine waters during the period of time sampled through the otolith. A fundamental change in behavior during its juvenile stage and reproductive season seems unlikely over such a short time interval. Such changes in behavior would more like take place over evolutionary time scales. Therefore, we consider a change in environmental conditions. We suggest that a more likely explanation is that estuarine water during the summer was at near-marine salinity (and, hence, $\delta^{18}O_{WATER}$) during the time period represented by the RO catfish. This interpretation is consistent with zooarchaeological data derived from the midden from which the RO otolith comes. The quantified remains of finfish and shellfish indicate high-salinity conditions in their overall species diversity as well as the unusual presence and/or abundance of high-salinity species (deFrance and Walker, in preparation). If estuarine water in Pine Island Sound was at near-marine salinity during the summer season, then there was a fundamental difference in wet season/dry season rainfall patterns relative to modern conditions in which no summer wet season existed for at least 2 years (the period of time sampled through the otolith) during the time when Pineland's 2nd/3rd-century fisherfolk lived. Using data from additional RO otoliths and from associated RO carbonate shells of other taxa (e.g., *Mercenaria campechiensis*, the southern quahog), we will test in future work whether the summer near-marine estuarine conditions represent a short-term (e.g., interannual drought) or a long-term episode of climate change.

6. Summary and conclusions

Analysis of variation in oxygen isotope composition of modern and archaeological *A. felis* otoliths provides ecological and climate information in subtropical coastal regions. Values of δ^{18}O were converted to temperature using published equations by Patterson et al. (1993) and Thorrold et al. (1997). Based on our results, we determined that the former equation better estimated modern temperature values; therefore, that equation was used for archaeological otoliths in this study. Winter temperature estimates on the modern and archaeological otoliths were similar to measured temperature values of today. Summer temperature estimates from the modern and LIA otoliths were predictably overestimated reflecting modern migration patterns (i.e., spending the summer reproductive season in brackish estuarine waters). Estimates of summer temperature from the RO otolith were similar to modern measurements indicating $\delta^{18}O_{WATER}$ was near marine. This finding suggests that the summer wet season, a prominent feature of today's climate, was not present during the period of time sampled through the RO otolith. High-salinity fauna found in the associated archaeological deposits are consistent with this interpretation. We are undertaking a multi-taxa geochemical approach to further test this hypothesis and to determine, if possible, what time scale is involved.

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