Available online at www.sciencedirect.com

SCIENCE DIRECT®

Quaternary International 150 (2006) 3–11

Developing oxygen isotope proxies from archaeological sources for the study of Late Holocene human–climate interactions in coastal southwest Florida

Karen J. Walker[a], Donna Surge[b,*]

[a]*Florida Museum of Natural History, University of Florida, P.O. Box 117800, Gainesville, FL 32611-7800, USA*
[b]*Department of Geological Sciences, University of North Carolina, CB #3315, 225 Mitchell Hall, Chapel Hill, NC 27599-3315, USA*

Abstract

Oxygen isotopes ($\delta^{18}O$) derived from archaeological *Mercenaria campechiensis* shells and *Ariopsis felis* otoliths potentially provide low-latitude paleoclimate data for studying Late Holocene human–climate interactions in coastal southwest Florida. Specimens analyzed come from the Pineland site complex. Deposits record abrupt and subtle environmental changes appearing to have been climate-related and to have impacted the sedentary human residents. One archaeological shell-otolith set dates to 2nd/3rd century A.D. within the Roman Optimum (RO) climatic episode. A second set dates to 13th/14th century A.D. within the Little Ice Age (LIA). A modern shell-otolith set was analyzed for comparison. $\delta^{18}O_{ARAGONITE}$ of modern and LIA shells suggest similar seasonal conditions. RO shell is ~1‰ more positive during summer, suggesting higher estuarine salinity than in modern and LIA times. Modern and LIA otoliths also have similar $\delta^{18}O_{ARAGONITE}$. Estimated Winter temperatures are within measured instrument records. Summer temperatures are overestimated reflecting Summer migration into less-saline water. Estimated Summer temperatures for RO otolith are similar to today's, suggesting elevated estuarine salinity and diminished rainy season, consistent with similar aged zooarchaeological assemblages. Comparisons of two taxa aid in interpreting archaeological $\delta^{18}O$ data; however, early results are mixed with expected profiles for RO specimens and unexpected profiles for LIA specimens.

1. Introduction

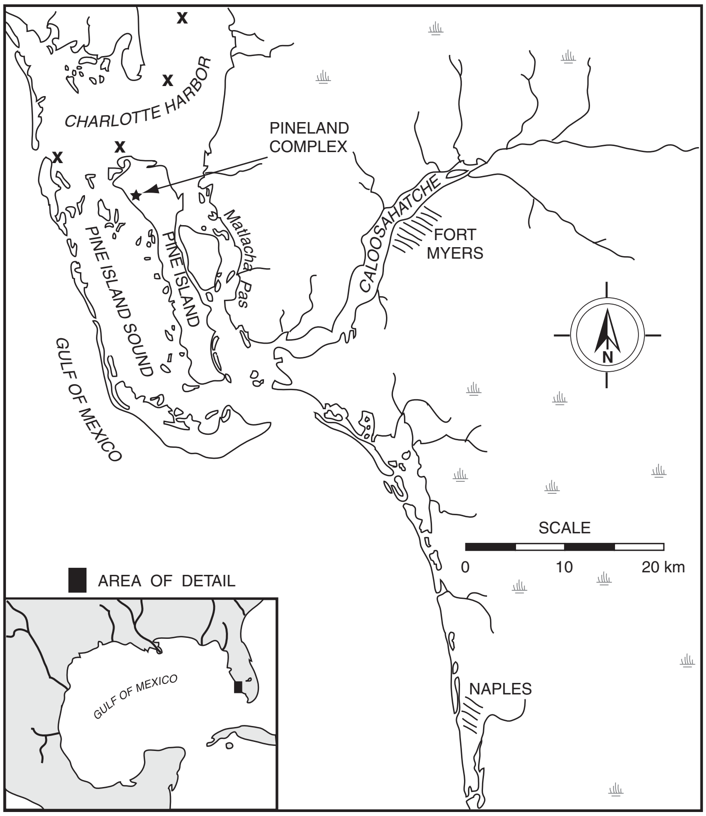
The Charlotte Harbor/Pine Island Sound (CH/PIS) area of coastal southwest Florida (Fig. 1) is potentially an ideal region to study relationships between low-latitude climate change and human societies during the Late Holocene. The region is subtropical, transitional between the true tropics and the temperate zone and has been tectonically stable (Emery and Aubrey, 1991; Fairbridge, 1992) throughout the Late Holocene. The region is characterized by low-lying, mangrove-fringed landscapes and shallow-water, micro-tidal, inshore estuarine bays with abundant and diverse shellfish and fish (Wang and Raney, 1971; Estevez et al., 1984). This environment, with its bounty of aquatic foods, has supported ancient, sedentary human populations for many centuries (Widmer, 1988; Walker, 1992; Marquardt, 1996). However, the very attributes of this region that made it so attractive to human settlement also made both the environment and its human residents hypersensitive to climatic variations, both abrupt and subtle. Research at the region's archaeological sites increasingly demonstrates that they contain records of regional environmental change (Walker et al., 1994, 1995), and patterns are emerging that point to broader climatic trends as major explanatory factors (e.g., Walker, 2000).

Above, we indicate that coastal southwest Florida was *potentially* an ideal location for Late Holocene human–climate studies. What the region lacks are conventional proxy sources for high-resolution, paleoclimate data for the Late Holocene. For example, lakes appropriate for extracting productive sediment cores likely do not exist in subtropical South Florida (Mark Brenner, personal communication). There are, however, several recent climate records from areas not too far afield that include Late

---

*Corresponding author. Fax: +1 919 924 2490.
E-mail addresses: kwalker@flmnh.ufl.edu (K.J. Walker), donna64@unc.edu (D. Surge).

1040-6182/$ - see front matter © 2006 Elsevier Ltd and INQUA. All rights reserved.
doi:10.1016/j.quaint.2006.01.022



Pineland Complex Archaeological Periods	**AD**	**Generalized Cultural & Environmental Correlations**
	1750	
Caloosahatchee V		1710 Abandonment Demise of Calusa European Invasion
	1500	
Caloosahatchee III/IV		Major Calusa Center Low Sea Level ***Little Ice Age*** "Classic" Calusa
	1200	
Caloosahatchee IIB		Rise of Calusa Society High Sea Level/Storms ***Medieval Warm Period*** 950 Resettlement
	800	
Caloosahatchee IIA		750 Abandonment Low Sea Level/Drought ***Vandal Minimum*** 550 Resettlement
	500	
Caloosahatchee I-late		400 Abandonment? High Sea Level/Storms ***Roman Optimum*** 0-400 Settlement
	0	

Fig. 1. Generalized chronology for the Pineland Site Complex and its map location marked by a star within the Charlotte Harbor/Pine Island Sound estuarine system. An "x" identifies water sampling sites. The names Roman Optimum (RO), Vandal Minimum (VM), Medieval Warm Period (MWP) and Little Ice Age (LIA) are used here informally to acknowledge correlations of climate episodes that are broad scale but not necessarily worldwide.

Holocene paleoclimate data. On the western side of the Gulf of Mexico, lake-sediment cores have produced several long Holocene records for the Yucatán Peninsula (Curtis et al., 1996; Hodell et al., 2001; Brenner et al., 2002). Sediments from a Haitian lake provide a long record of Caribbean climate variability (Hodell et al., 1991; Hodell et al., 2000), and an ocean sediment core from the Sargasso Sea provides a record of regional sea-surface temperatures (Keigwin, 1996). Most recently, sediment cores from the Straits of Florida provide paleoclimate data (Lund and Curry, 2004). Although these areas surround South Florida, their records may not be entirely relevant for southwest Florida's land–sea interface in terms of human–climate history.

What coastal southwest Florida does have, however, are multitudes of well-preserved molluscan and fish remains, archived in the region's Late Holocene archaeological deposits. These are the remains of foods collected by the Calusa people and their predecessors who once populated the region. Assemblages of these animal remains, expressed in terms of representative taxa and varying abundances, are proxies of what was available in the local aquatic environment. Some remains, due to their incremental growth structures, also have the potential to produce oxygen isotope ($\delta^{18}O$) proxies for climate information. Here, we present early results in our efforts to identify and develop geochemical records for these archived remains for use as paleoclimate proxies in southwest Florida.

Shells of the southern quahog clam, *Mercenaria campechiensis*, and otoliths of the hardhead catfish, *Ariopsis felis*, are two promising sources of $\delta^{18}O$ proxies, and both are plentiful in area archaeological deposits (Walker, 1992). Moreover, if shell and otolith specimens are selected from tightly controlled, extensive vertical and horizontal stratigraphic contexts, then their individual $\delta^{18}O$ profiles can provide the building blocks for long sequences of proxy paleoclimate data directly relevant to the human residents who originally collected the clams and catfish.

In addition, we chose *M. campechiensis* because $\delta^{18}O$ values of their shells (and those of the closely related *M. mercenaria*) have been used in numerous climate, ecological and archaeological studies of seasonality (Jones et al., 1989; Jones and Allmon, 1995; Jones and Quitmyer, 1996; Stecher III et al., 1996; Quitmyer et al., 1997; Elliot et al., 2003; Surge and Walker, in press). We chose *A. felis* because its ecology makes this species a suitable recorder of climate change (Muncy and Wingo, 1983; Yáñez-Arancibia and Lara-Domínguez, 1988; Andrus et al., 2002; Béarez et al., 2003; Surge and Walker, 2006) and because published temperature equations for $\delta^{18}O$ values of their otoliths already exist (Patterson et al., 1993; Thorrold et al., 1997).

2. Archaeological contexts

2.1. Pineland site complex

For this study, we selected archaeological specimens of each species from two contrasting temporal contexts within the Pineland site complex (hereafter "Pineland"). Pineland is a major archaeological site on the northwestern shore of Pine Island, a large island centrally situated within the CH/PIS estuarine system (Fig. 1). Pineland overlooks the northern part of PIS and its extensive, very shallow (<1 m) seagrass meadows were the primary fishing and shellfishing focus of the site's ancient residents. Today's high elevation of Pineland (9 m amsl) is entirely artificial, the result of 17 centuries (Fig. 1) of midden and house-floor deposits that culminated in a pair of massive mound complexes, separated by a human-engineered, navigable canal. Multiple seasons of excavations at Pineland have provided extensive sequences of artifact, zooarchaeological and other samples (Walker et al., 1995; Walker, 2000; Marquardt and Walker, 2001). Results indicate that residency was year-round through the centuries with one and possibly two hiatuses in occupation, prior to the site's final abandonment, ca. A.D. 1710 (Fig. 1). Temporal variation—at a scale of 50–100 yr—in spatial patterning of deposits at Pineland seems to have been due, in part, to environmental change, as do variations in kinds and abundances of animal remains through time.

A total of 50 radiocarbon dates (Beta Analytic, Inc., Miami) and extensive pottery analyses have allowed for tightly controlled temporal contexts at Pineland. Most of the dates are based on marine shell. The two contexts chosen for the present study are Caloosahatchee I-Late and Caloosahatchee IV corresponding to the RO and LIA climatic episodes, respectively (Fig. 1). The associated general time ranges and specific radiocarbon date ranges that appear below are based on or are dates corrected for both global and local geographic reservoir effects, corrected for δ^{13}C, and then calibrated (Stuiver et al., 1993). One-sigma ranges (instead of the standard two) are used here with confidence as a result of the extensive, tightly controlled, well-dated Pineland contexts.

2.2. Pineland's Caloosahatchee I-Late

Pineland was first occupied by humans during the first century A.D. and occupation intensified during A.D. 100–400 as represented by expansive blankets of middens conforming to a dynamic shoreline. This time span, A.D. 0–400, falls within the Caloosahatchee I-Late cultural period (Fig. 1). Based on differences in midden content and their intra-site location at Pineland, the I-Late period can be divided into three subperiods. The first, Caloosahatchee I-Late-a (A.D. 0–100), is characterized by middens that are dominated with eastern oyster (*Crassostrea virginica*) shell and were deposited on dry ground but today are partially beneath mean sea level. Vertebrate remains, including fishes, are not very abundant. Both food and non-food remains indicate low molluscan and fish diversity. In an estuarine setting, low diversity indicates low-to-mid salinities (Wells, 1961). In support of this interpretation, the ratio of an associate, high-salinity oyster, *Ostreola equestris* (crested oyster), to the low-to-mid salinity oyster, *C. virginica* is low in the middens.

For the subsequent subperiod of A.D. 100–200, the Caloosahatchee I-Late-b middens record a much greater collecting emphasis on estuarine/marine gastropods, indicating increased molluscan (both food and non-food taxa) and fish diversity and higher salinity waters. Fish remains are much more abundant than the previous subperiod. Today, these middens partially lie below mean sea level—slightly seaward of the I-Late-a middens—having been deposited directly in the intertidal zone, perhaps a result of people living in piled structures over the water. One *M. campechiensis* shell (FLMNH ANT92-28-16) and one *A. felis* otolith (FLMNH EA0474-0825) were selected from this context for our present isotopic study. Specifically, they came from the lowest level of the lowest stratum (Stratum 10) of the midden at Old Mound (within the Pineland site complex indicated on Fig. 1), radiocarbon-dated to A.D. 110–270 (Beta-54799, 1-sigma range, *M. campechiensis* shell) probably dating to the earlier part of that range. These specimens are especially well preserved due to the waterlogged, anaerobic nature of the midden deposit.

In contrast to the lowlying middens of I-Late-a and I-Late-b, the A.D. 200–400 Caloosahatchee I-Late-c middens are at higher elevations, landward of the shoreline and high-tide zones. The middens are dominated by marine gastropod shells and indicate high diversity and high salinity. The I-Late-c occupation may have co-occurred with an inundation that flooded the more low-lying, earlier habitation area and its associated middens. The inundation was at least in part generated by a high-intensity storm, as documented by a stratum of sand with washed-in remains of surf clams (many articulated shells), pen shells, sea urchin, sea turtle, bottlenose dolphin and tropical monk seal (Walker et al., 1995). Radiocarbon dates and stratigraphic position place the storm in the 4th century A.D. (Caloosahatchee I-Late-c). This single storm may be representative of a longer-term period of regional storminess; this is supported by documented storm washover deposits of similar age sandwiched between middens on Sanibel Island in the southern part of PIS (Walker et al., 1994). Overlying the I-Late-a and -b middens and storm deposit at Pineland, a black-mangrove wetland developed, indicated by a sandy sediment containing articulated ribbed mussels (*Geukensia demissa*), some in life position. By A.D. 400, Pineland may have been temporarily abandoned.

In sum, the Caloosahatchee I-Late midden pattern varies through time, characterized by abrupt changes: (a) first, lowlying (but dry), shoreline middens are dominated by *C. virginica* shells suggesting adjacent low-to-mid salinity waters; (b) then intertidal shoreline middens (the context of our shell and otolith specimens), dominated by marine gastropods, suggest higher-salinity waters; and (c) then middens (coeval with a storm deposit) shift to landward, higher elevations (suggesting higher water levels and increased storminess) and are again dominated by marine gastropods. These variations in settlement and subsistence patterns are hypothesized to have been linked to variations in mean sea level (Walker et al., 1995). Higher water levels and storminess in PIS for about this time are supported by Tanner's (1991) Gulf of Mexico sea-level curve, Stapor et al.'s (1991) southwest Florida beach-ridge seriation and by an abrupt transgression documented farther North in the central Gulf coast region (Goodbred et al., 1998) and in northwest Florida (Walker et al., 1995). At a much broader scale, this Caloosahatchee I-Late period of A.D. 0–400 correlates with the latter part of a warm climate episode known as the Roman Optimum (RO) which ranged from ca. 500 B.C. to A.D. 300. This RO time span was itself characterized by smaller scale variation.

2.3. *Pineland's Caloosahatchee IV*

In great contrast to the Caloosahatchee I-Late period at Pineland, people living during the A.D. 1350–1550 span of time, known as Caloosahatchee IV (Fig. 1), built their homes on high, steep-sided midden mounds. Zooarchaeological remains from this time show a subtle decrease in molluscan and fish diversity and lowered water salinity compared to the latter part of the I-Late (b and c subperiods) and to the IIB periods (Fig. 1). A period of economic stability, if not abundance, is evidenced by a more complex site layout incorporating an engineered canal (Luer, 1989), increased long-distance trade (Austin et al., 2000) and an elaboration of pottery styles. This was the era that set the stage for a politically powerful Calusa society that gained control of all South Florida by the late 16th century. One *M. campechiensis* shell (FLMNH ANT90-7-10a) and one *A. felis* otolith (FLMNH EA0474-0112) were selected from this context. Specifically, they came from a stratum near the crest of Brown's Complex Mound 2 (within the Pineland site complex indicated on Fig. 1). A radiocarbon date of A.D. 1270–1330 (Beta-39292, 1-sigma range, *Busycon sinistrum* shell) comes from below the stratum. Although the deposits here are well-drained, these two specimens are nonetheless well preserved due to the overall density of molluscan shell and fish bone in the deposit, providing a protective carbonate matrix.

A more stable (i.e., less erratic change, less stormy) environmental context for the Caloosahatchee IV period is supported by Tanner's (1991) Gulf of Mexico sea-level curve and Stapor et al.'s (1991) southwest Florida beach-ridge seriation. Both studies suggest a lowered sea level for the period, and redeposition on previously eroded barrier islands. Pineland's Caloosahatchee IV period falls within the broader, cool climate episode, known as the Little Ice Age (LIA).

3. Geochemical methods

3.1. *Water measurements*

Water samples were collected along a salinity gradient in CH from near the Gulf of Mexico to the mouth of the Peace River upstream (Fig. 1). To capture seasonal differences in mixing between fresh- and saltwater end members, samples were collected in June 2002, October 2002, March 2003, July 2003 and October 2003. Salinity measurements were taken at 2 m below the water surface with a hand-held Hydrolab Quatra data logger. Water samples were collected using a horizontal point sampler (Aquatic Instruments) and stored in 15 ml Nalgene plastic bottles. water (5 ml) was analyzed for δ^{18}O on 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.

3.2. *Shell and otolith measurements*

M. campechiensis was collected alive in October 2002 in PIS adjacent to Pineland (Fig. 1). The *A. felis* specimen was caught by rod and reel near PIS in December 2001. Both individuals were frozen immediately upon return to the Florida Museum of Natural History's (FLMNH) Randell Research Center in Pineland. The *M. campechiensis* specimen (BOK1-1) was subsequently thawed, eviscerated, and the shells cleaned and dried in preparation for cross-sectioning along the plane of maximum growth from umbo to commissure. The exposed cross-section was polished to enhance visibility of annual growth bands (Fig. 2A). Both otoliths (lapilli) were removed from the *A. felis* skeleton (FLMNH RRC ZA069) after maceration of the soft tissue. One of the lapilli was cut and polished along the transverse plane to reveal growth banding (Fig. 2B). Growth bands in *A. felis* otoliths do not appear to be annual (Surge and Walker, 2006). Microsampling of shells and otoliths was achieved using a Merchantek micromilling system equipped with a 0.3 mm dental burr. Digitizing growth bands from a real-time image allowed high-resolution micromilling of exceedingly small (20–50 μg) carbonate samples. Archaeological shells and otoliths were cut, polished and microsampled in the same manner. After roasting in vacuo for 1 h at 200 °C, the samples of carbonate powder were analyzed for oxygen isotope composition on a Finnigan MAT 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

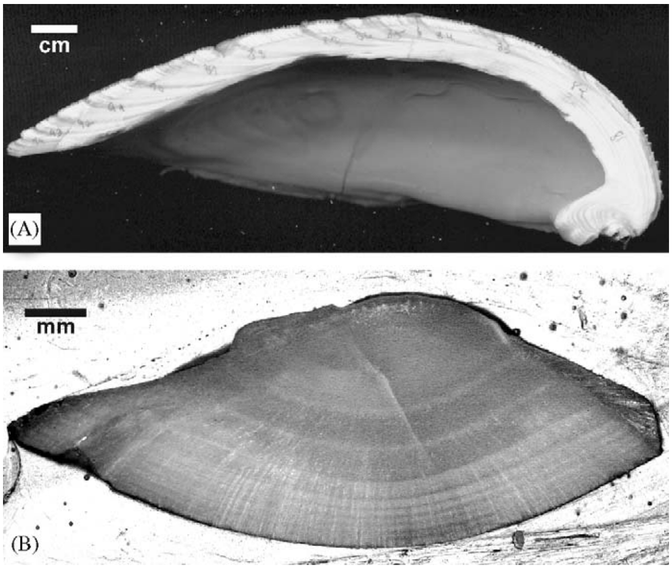


Fig. 2. Cross-sections of modern shell and RO otolith. (A) Photograph illustrating annual growth lines in quahog clam shell cut parallel to maximum axis of growth from umbo (right) to commissure (left); Bar = 1 cm. (B) Photomicrograph illustrating growth features in hardhead catfish otolith (lapilli) cut along the transverse plain; Bar = 1 mm.

(Craig, 1957). Values of δ^{18}O are reported in per mil units (‰) relative to the VPDB standard.

4. Results

4.1. Environmental records

Instrumental data recorded over the last century at Fort Myers (provided by the National Climate Data Center, http://www.ncdc.noaa.gov) show that interannual temperature variation is greatest during winters based on standard deviations of monthly averages from 1891 to 2002 (Fig. 3). January is the coldest month of the year (mean = 18.08 °C, standard deviation = 1.99, $n = 110$) and August the warmest month (mean = 28.20 °C, standard deviation = 0.58, $n = 111$). Monthly cumulative averages of precipitation from 1931 to 2002 illustrate the rainy season extending from May through October. However, the rainy season has atrophied over the last decade and now lasts only from about July to September, perhaps due in part to the channelization of the landscape by extensive canal systems. Based on monthly cumulative averages of this ~70 yr record, June is the wettest month of the year (mean = 23.74 cm, standard deviation = 10.86, $n = 66$) and December the driest (mean = 3.61 cm, standard deviation = 3.42, $n = 65$). The onset of the Summer rainy season results in a decrease of estuarine salinity and more negative $\delta^{18}O_{\mathrm{WATER}}$ values in the CH estuary as demonstrated by water samples taken along a salinity gradient (Fig. 4). Estuarine salinity and $\delta^{18}O_{\mathrm{WATER}}$ approach low-latitude marine values (35 psu and +1‰ VSMOW, respectively) during the dry season.

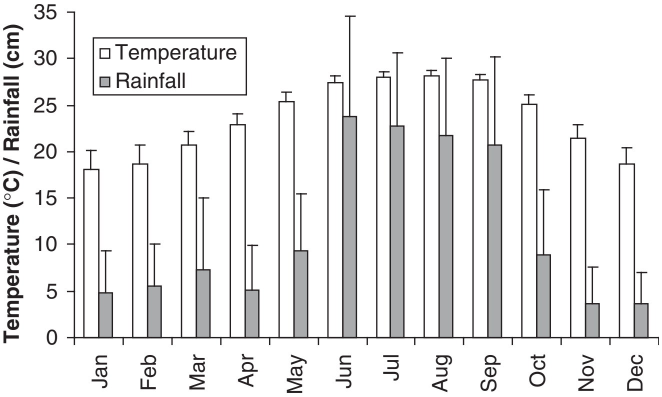


Fig. 3. Bar graph of average monthly temperature (°C) based on 1891 to 2002 data set (white bars) and of average monthly cumulative precipitation (cm) based on 1931 to 2002 data set (gray bars) measured at Fort Myers, Florida by the National Oceanographic and Atmospheric Administration. Vertical lines above bars are standard deviations.

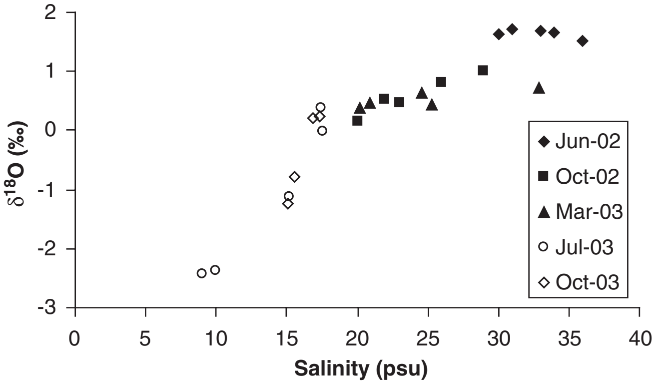


Fig. 4. Cross-plot of salinity (psu) and δ^{18}O (‰ VSMOW) of water collected along a five-site transect in Charlotte Harbor estuary. White and black symbols are data from wet and dry months, respectively. Samples were collected in June 2002 (black diamonds), October 2002 (black squares), March 2003 (black triangles), July 2003 (white circles) and October 2003 (white diamonds).

4.2. Shell and otolith records

All specimens contained Pristine aragonite; therefore, we assume original isotopic composition is preserved. The oxygen isotope composition of the modern and archaeological shells varies in a quasi-sinusoidal pattern (Fig. 5). Shell isotopic composition ranges from −2.40‰ to +2.10‰ (modern), from −2.16‰ to +1.19‰ (LIA) and from −1.28‰ to +1.53‰ (RO). The most positive δ^{18}O values, corresponding to Winter months, are variable within and among shells and show a steady decrease with increasing age in the LIA shell. The most negative δ^{18}O values, corresponding to Summer months, are similar in the modern and LIA shells, but are ~1‰ more positive in the RO shell.

The modern and archaeological otolith δ^{18}O also varies quasi-sinusoidally (Fig. 6), but the profiles are more jagged than those of shell δ^{18}O. Otolith δ^{18}O values range from −3.55‰ to +0.29‰ (modern), from −0.92‰ to +0.52‰

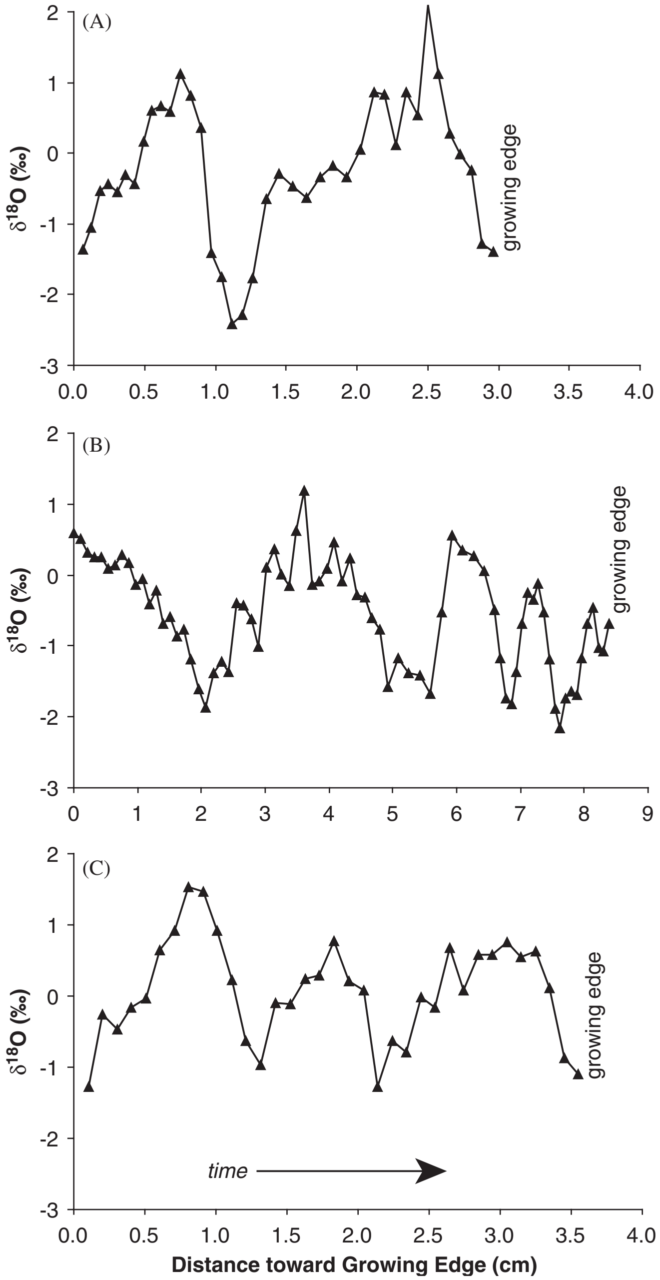


Fig. 5. Cross-plot of shell $\delta^{18}O$ (‰ VPDB) variation with distance (cm) toward growing edge (time proceeds toward right). (A) Modern shell. (B) LIA shell. (C) RO shell. *Note*: *x*-axis for LIA shell (B) is different than that of the modern (A) and RO (C) shells, representing a greater distance sampled.

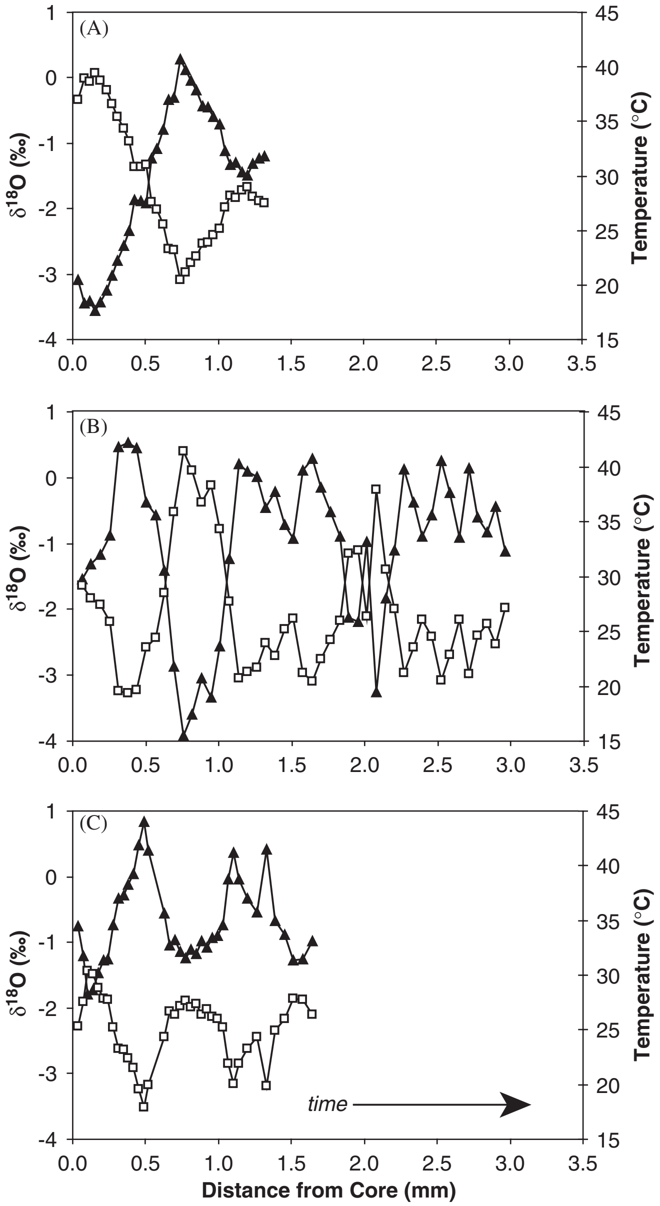


Fig. 6. Cross-plot of otolith $\delta^{18}O$ (‰ VPDB) variation (black triangles) and estimated temperature (°C; white squares) relative to distance (mm) from core (time proceeds toward right). (A) Modern otolith. (B) LIA otolith. (C) RO otolith.

(LIA) and from −0.80‰ to +0.84‰ (RO). As with the shell data, the most negative summer $\delta^{18}O$ values are similar in the modern and LIA otoliths, but are almost ~2‰ more positive in the RO otolith.

5. Discussion

5.1. Geochemistry of shells and otoliths

Results from a recent study suggest that aragonitic shells of *M. campechiensis* are precipitated in isotopic equilibrium with ambient water (Surge and Walker, in press). However, its sedentary nature and ecological preference for salinities between 20 and 30 psu (Kraeuter and Castagna, 2001) make deciphering shell $\delta^{18}O$ in terms of temperature and salinity difficult. Nonetheless, qualitative comparisons can be made among shells to evaluate relative differences in environmental conditions. Variability in the most positive $\delta^{18}O$ values should reflect interannual variation in Winter temperatures as this part of the year coincides with lower precipitation and near-marine to marine salinities (33–36 psu), assuming the dry season also occurred during the Winter in the past. Based on the interannual variation in the most positive $\delta^{18}O$ values of the modern specimen, estimated Winter temperature differs between the years represented by at most 5.5 °C (assuming equilibrium precipitation and similar salinity). This difference in annual Winter temperature is slightly above the standard deviation (±1.99 °C) of annual Winter temperatures for the last century (Fig. 3), but is still reasonable given modern temperature ranges. If Winter salinity was not the same among years and ranged from 33–36 psu, the effect on temperature estimates across this salinity range would be at most 1.16 °C (assuming a shift of 0.2‰/°C and the $\delta^{18}O_{WATER}$-salinity relationship of Surge and Walker, 2006). In comparison, Winter $\delta^{18}O$ values recorded closest to the umbo of the LIA shell are similar to the modern shell, but decrease steadily with age as does the distance between valleys on the profile of isotopic composition. This decrease in $\delta^{18}O$ with age may result from increased time averaging due to slower growth rates in the older part of the shell and has been observed elsewhere (Stecher III et al., 1996). Winter values for the RO shell are similar to the modern shell.

The most negative $\delta^{18}O$ values are similar in the modern and LIA shells, suggesting that modern and LIA summer environmental conditions were similar. In contrast, the most negative $\delta^{18}O$ value in the RO shell is ~1‰ more positive than that of modern and LIA shells. This offset reflects either a difference in temperature, salinity or a combination of both. It is unlikely that the ~1‰ offset is solely due to temperature because this would imply that Summer temperature during the RO was ~4 °C colder, which is unreasonable for such a low latitude. Moreover, based on modern instrument records, interannual summer temperature does not vary by more than half a degree or so. Therefore, a more likely explanation is that summer salinity was higher during the RO.

Records of $\delta^{18}O$ values from otoliths allow us to test this hypothesis. Published temperature equations allowed us to convert otolith $\delta^{18}O$ values to estimated temperature (Patterson et al., 1993; Thorrold et al., 1997). We previously determined that the equation reported by Patterson et al. (1993) more faithfully estimates temperature from $\delta^{18}O$ of *A. felis* otoliths than the temperature equation reported by Thorrold et al. (1997) (Surge and Walker, 2006). We assumed a regional $\delta^{18}O_{WATER}$ value for the saltwater end member of +1‰ based on data from this study (Fig. 4) and from the literature (Kirby et al., 1998; Surge and Lohmann, 2002). Estimated Winter temperature is 20°C in the modern otolith well within the range of modern instrument records. Winter temperature estimated from both archaeological specimens are also within the range of modern values (LIA: 19–21 °C; RO: 18–20 °C). As predicted, Summer values in the modern otolith are overestimated by ~10 °C likely reflecting migration into brackish estuarine water during the reproductive season. If $\delta^{18}O_{WATER}$ of −1‰ is assumed to represent Summer estuarine values, then estimated temperature from the modern otolith falls within the expected range of modern instrument records. Values of $\delta^{18}O$ from the LIA otolith also reflect migration into brackish estuarine water as temperatures are also overestimated by ~10 °C. Unlike the modern and LIA otoliths, the RO otolith estimates of Summer temperature are within the range of measured instrument records, suggesting that this fish swam in water that was +1‰. It is unlikely that this fish changed its behavior by not swimming into the estuary during the reproductive season. Therefore, we conclude that estuarine water was at a higher salinity than present conditions implying a suspension of the Summer rainy season. This conclusion is consistent with the RO shell $\delta^{18}O$ data and zooarchaeological evidence summarized above.

5.2. *Archaeology*

Neither the zooarchaeological assemblages nor the single, analyzed shell and otolith specimens of the Caloosahatchee I-Late-b period (A.D. 100–200) from Pineland suggest that temperatures during this portion of the RO in southwest Florida were especially warm compared to 20th-century records. Given that much of the 20th century has experienced warming temperatures, perhaps this result is not surprising. The I-Late-b zooarchaeological assemblages, however, do suggest that estuarine salinity may have been higher than previous (Caloosahatchee I-Late-a) and later (Caloosahatchee IIA) periods, and together the shell and otolith $\delta^{18}O$ results also suggest a higher salinity compared to today. The chronological, stratigraphic and zooarchaeological position of the I-Late-b deposits is such that they may represent a transitional stage toward rising water levels, increasing salinity and increasing storm activity, all of which seems to have culminated in the I-Late-c subperiod. The impacts of this portion of the RO—Pineland's I-Late period—seem to have been severe in southwest Florida, not only due to catastrophic storms of I-Late-c, but perhaps also, more generally (I-Late-a through -c), due to abrupt rates of change. At Pineland, adjustments in both settlement and subsistence patterns were made in response to environmental changes, but they undoubtably disrupted the lives of residents.

Neither the zooarchaeological assemblages nor the single, analyzed shell and otolith specimens of the Caloosahatchee IV period from Pineland suggest that temperatures of the LIA in southwest Florida were especially cool, which is in contrast to the findings of Lund and Curry (2004) for this time period in the Florida Straits and of Keigwin (1996) in the Sargasso Sea. There is, however, the suggestion of a slightly lowered salinity in the assemblages compared to Caloosahatchee I-Late b and c subperiods and the previous cultural period, IIB (Fig. 1), which is also in contrast to findings of Lund and Curry (2004). However, at Pineland and elsewhere in the region, there is an absence of storm evidence for the LIA, which is consistent with cooler sea surface temperatures. In this case, at least slightly cooler temperatures may have prevailed overall. It is possible that the single, analyzed shell–otolith pair did not capture the prevailing conditions of southwest Florida during the LIA; thus, analysis of multiple pairs are needed to adequately reconstruct climate at this scale.

While the LIA in northern latitudes is often linked to detrimental cultural impacts (e.g., McGovern, 1994), slightly cooler and more importantly, *consistently* cooler temperatures in subtropical Florida may have been culturally beneficial. Combined with an absence of destructive storms, such a scenario may have meant a stable environment ideal for the development of cultural complexity in a society that already benefited from a year-round, abundance of aquatic foods.

6. Conclusion

This paper presents early results of research aimed at developing isotopic proxies for climate data derived from archaeological sources, specifically from shells of *M. campechiensis* and otoliths of *A. felis*. We conclude that a multi-taxa approach provides a better understanding of how to interpret the $\delta^{18}O$ records in terms of the combined effect of temperature and salinity on carbonate shell under estuarine conditions. Interpreting $\delta^{18}O$ results, in the context of climate change, based on so few archaeological specimens, as we have done in this paper, has one obvious flaw. It is the inability to confidently move beyond the timescale of the lifetime, in this case, of the *M. campechiensis* or *A. felis* individuals, to a longer-term scale. But with the addition of many more specimens and the continuation of a multi-taxa strategy, building sequences of records should be a viable approach to testing hypotheses of climate change and its role in cultural change in Calusa society.

Acknowledgments

John Worth, Diane Mahr, and Sydney Cosselman of the FLMNH's Randell Research Center at Pineland provided the modern otolith for this study. The FLMNH provided the archaeological shells and otoliths which were excavated under the direction of KJW and William Marquardt. Thanks to Capt. Pat Hagle and a volunteer who wishes to remain anonymous for assisting with water sampling. Many thanks to Lora Wingate at the Stable Isotope Laboratory at the University of Michigan and to Scott Carpenter at the Stable Isotope Laboratory at the University of Iowa for analyzing the carbonate powders and to Germán Mora and Shikha Sharma at the Stable Isotope Laboratory at Iowa State University for analyzing the water samples. Thanks to Moses Langley for microsampling and photographing the otoliths and to Samantha Owens for microsampling the shells. Partial support for this research was provided by the National Science Foundation (Award #0318152 to DS and Award #0317578 to KJW) and by the American Chemical Society's Petroleum Research Fund (Award #39318-G2 to DS). We appreciate review comments by Helene Jousse, Bernd Schöne and Eric Ekdahl, all of which led to improvements of this paper.

References

Andrus, C.F.T., Crowe, D.E., Romanek, C.S., 2002. Oxygen isotope record of the 1997–1998 El Niño in Peruvian Sea catfish (*Galeichthys peruvianus*) otoliths. Paleoceanography 17 (4), 1508–1511.

Austin, R.J., Farquhar, R.M., Walker, K.J., 2000. Isotope analysis of galena from prehistoric archaeological sites in South Florida. Florida Scientist 2, 123–131.

Béarez, P., DeVries, T.J., Ortlieb, L., 2003. Comment on "Otolith ^{TM18}O record of mid-Holocene sea surface temperatures in Peru". Science 299, 203a.

Brenner, M., Rosenmeier, M.F., Hodell, D.A., Curtis, J.H., 2002. Paleolimnology of the Maya lowlands: long-term perspectives on interactions among climate, environment, and humans. Ancient Mesoamerica 13, 141–157.

Craig, H., 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. Geochimica et Cosmochimica Acta 12, 133–149.

Curtis, J.H., Hodell, D.A., Brenner, M., 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. Quaternary Research 46, 37–47.

Elliot, M., deMenocal, P.B., Linsley, B.K., Howe, S.S., 2003. Environmental controls on the stable isotopic composition of *Mercenaria mercenaria*: potential application to paleoenvironmental studies. Geochemistry Geophysics Geosystems 4 (7), 1–16.

Emery, K.O., Aubrey, D.G., 1991. Sea Levels, Land Levels, and Tide Gauges. Springer, New York.

Estevez, E.D., Miller, J.E., Morris, J., 1984. Charlotte Harbor estuarine ecosystem complex and the Peace River. A Review of Scientific Information. Mote Marine Laboratory, Sarasota, Florida.

Fairbridge, R.W., 1992. Holocene marine coastal evolution of the United States. In: Quaternary Coasts of the United States: Marine and Lucustrine systems. SEPM Special Publication No. 48. Society of Sedimentary Geology, pp. 9–19.

Goodbred Jr., S.L., Wright, E.E., Hine, A.C., 1998. Sea-level change and storm-surge deposition in a Late Holocene Florida salt marsh. Journal of Sedimentary Research 68 (2), 240–252.

Hodell, D.A., Brenner, M., Curtis, J.H., 2000. Climate change in the northern American tropics and subtropics since the last Ice Age: implications for environment and culture. In: Lentz, D.L. (Ed.), Imperfect Balance: Landscape Transformations in the Precolumbian Americas. Columbia University Press, New York, pp. 13–38.

Hodell, D.A., Brenner, M., Curtis, J.H., Guilderson, T., 2001. Solar forcing of drought frequency in the Maya lowlands. Science 292, 1367–1370.

Hodell, D.A., Curtis, J.H., Higuera-Gundy, A., Brenner, M., Jones, G.A., Binford, M.W., Dorsey, K.T., 1991. Reconstruction of Caribbean climate change over the past 10,500 years. Nature 352, 790–793.

Jones, D.S., Allmon, W.D., 1995. Records of upwelling, seasonality and growth in stable-isotope profiles of Pliocene mollusk shells from Florida. Lethaia 28, 61–74.

Jones, D.S., Arthur, M.A., Allard, D.J., 1989. Sclerochronological records of temperature and growth from shells of *Mercenaria mercenaria* from Narragansett Bay, Rhode Island. Marine Biology 102, 225–234.

Jones, D.S., Quitmyer, I.R., 1996. Marking time with bivalve shells: oxygen isotopes and season of annual increment formation. Palaios 11 (4), 340–346.

Keigwin, L.D., 1996. The Little Ice Age and medieval warm period in the Sargasso Sea. Science 274, 1504–1508.

Kirby, M.X., Soniat, T.M., Spero, H.J., 1998. Stable isotope sclerochronology of Pleistocene and recent oyster shells (*Crassostrea virginica*). Palaios 13 (6), 560–569.

Kraeuter, J.N., Castagna, M. (Eds.), 2001. Biology of the hard clam. Developments in Aquaculture and Fisheries Science, vol. 31. Elsevier, New York, 751pp.

Luer, G.M., 1989. Calusa canals in southwestern Florida: routes of tribute and exchange. The Florida Anthropologist 42, 89–130.

Lund, D.C., Curry, W.B., 2004. Late Holocene variability in Florida Current surface density: patterns and possible causes. Paleoceanography 19, 1–17.

Marquardt, W.H., 1996. Four discoveries: environmental archaeology in southwest Florida. In: Reitz, E.J., Newsom, L.A., Scudder, S.J. (Eds.), Case Studies in Environmental Archaeology. Plenum Press, New York, London, pp. 17–32.

Marquardt, W.H., Walker, K.J., 2001. Pineland: a coastal wet site in southwest Florida. In: Purdy, B. (Ed.), Enduring Records: The Environmental and Cultural Heritage of Wetlands. Oxbow Books, Oxford.

McGovern, T.H., 1994. Management for extinction in Norse Greenland. In: Crumley, C. (Ed.), Historical Ecology. School of American Research Press, Santa Fe, NM.

Muncy, R.J., Wingo, W.M., 1983. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Gulf of Mexico): Sea Catfish and Gafftopsail Catfish. United States Fish and Wildlife Service, Slidell, LA, 17pp.

Patterson, W.P., Smith, G.R., Lohmann, K.C., 1993. Continental paleothermometry and seasonality using the isotopic composition of aragonitic otoliths of freshwater fishes. In: Swart, P.K., Lohmann, K.C., McKenzie, J., Savin, S. (Eds.), Climate Change in Continental Isotopic Records. American Geophysical Union, Washington, DC, pp. 191–215.

Quitmyer, I.R., Jones, D.S., Arnold, W.S., 1997. The sclerochronology of hard clams, *Mercenaria* spp, from the South-eastern USA: a method of elucidating the zooarchaeological records of seasonal resource procurement and seasonality in prehistoric shell middens. Journal of Archaeological Science, 24, 825–840.

Stapor Jr., F.W., Mathews, T.D., Lindfors-Kearns, F.E., 1991. Barrier-island progradation and Holocene sea-level history in southwest Florida. Journal of Coastal Research 7 (3), 815–838.

Stecher III, H.A., Krantz, D.E., Lord III, C.J., Luther III, G.W., Bock, K.W., 1996. Profiles of strontium and barium in *Mercenaria mercenaria* and *Spisula solidissima* shells. Geochimica et Cosmochimica Acta 60 (18), 3445–3456.

Stuiver, M., Long, A., Kra, R.S., Devine, J.M., 1993. Calibration-1993. Radiocarbon 35 (1).

Surge, D., Walker, K.J., 2006. Oxygen isotope composition of modern and archaeological otoliths from the estuarine hardhead catfish (*Ariopsis felis*) and their potential to record low-latitude climate change. Palaeogeography, Palaeoclimatology, Palaeoecology 228, 179–191.

Surge, D., Walker, K.J., in press. Geochemical variation in microstructural shell layers of the southern quahog (*Mercenaria campechiensis*): implications for reconstructing seasonality. Palaeogeography, Palaeoclimatology, Palaeoecology, in press.

Surge, D.M., Lohmann, K.C., 2002. Temporal and spatial differences in salinity and water chemistry in SW Florida estuaries: effects of human-impacted watersheds. Estuaries 25 (3), 393–408.

Tanner, W.F., 1991. The "Gulf of Mexico" Late Holocene sea level curve and river delta history. Gulf Coast Association of Geological Societies, Transactions 41, 583–589.

Thorrold, S.R., Campana, S.E., Jones, C.M., Swart, P.K., 1997. Factors determining $^{\mathrm{TM}13}$C and δ^{18}O fractionation in aragonitic otoliths of marine fish. Geochimica et Cosmochimica Acta 61 (14), 2909–2919.

Walker, K.J., 1992. The zooarchaeology of Charlotte Harbor's prehistoric maritime adaptation: spatial and temporal perspectives. In: Marquardt, W.H. (Ed.), Culture and Environment in the Domain of the Calusa. Institute of Archaeology and Paleoenvironmental Studies, Monograph 1. University of Florida, Gainesville, pp. 265–366.

Walker, K.J., 2000. A cooling episode in southwest Florida during the sixth and seventh centuries A.D. In: Gunn, J. (Ed.), The Years Without Summer: Tracing A.D. 536 and its Aftermath. BAR International Series 872. Archaeopress, Oxford, pp. 119–127.

Walker, K.J., Stapor, J.F.W., Marquardt, W.H., 1994. Episodic sea levels and human occupation at southwest Florida's Wightman site. The Florida Anthropologist 47 (2), 161–179.

Walker, K.J., Stapor, J. F. W., Marquardt, W.H., 1995. Archaeological evidence for a 1750–1450 BP higher-than-present sea level along Florida's Gulf coast. Journal of Coastal Research Special Issue No. 17: Holocene Cyclic Pulses and Sedimentation pp. 205–218.

Wang, J.C.S., Raney, E.C., 1971. Distribution and fluctuations in the fish fauna of the Charlotte Harbor estuary, Florida. Charlotte Harbor Estuarine Studies, New City Island, Sarasota, Florida.

Wells, H.W., 1961. The fauna of oyster beds, with special reference to the salinity factor. Ecological Monographs 31 (3), 239–266.

Widmer, R.J., 1988. The Evolution of the Calusa: A Nonagricultural Chiefdom on the Southwest Florida Coast. The University of Alabama Press, Tuscaloosa.

Yáñez-Arancibia, A., Lara-Domínguez, A.L., 1988. Ecology of three sea catfishes (Ariidae) in a tropical coastal ecosystem—southern Gulf of Mexico. Marine Ecology—Progress Series 49, 215–230.