North Pacific climate recorded in growth rings of geoduck clams: A new tool for paleoenvironmental reconstruction

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[1] To better understand North Pacific climate variability at interannual to interdecadal scales, we have developed a new tool for paleoenvironmental reconstruction. We show that growth rings in long-lived geoduck clams (*Panopea abrupta*) can provide high quality, annually resolved records of sea-surface temperature (SST). We used shell samples from the Strait of Juan de Fuca, in Washington State, to extend the coastal SST record back to 1877. The spatial correlation pattern between the growth index and gridded SSTs bears a strong resemblance to the leading pattern of interdecadal global SST variations and underscores the remarkable long-distance coherence evident among coastal SST records in the northeast Pacific. Our results also indicate that the 1990s was the warmest decade in this region since at least the 1850s. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 4299 Oceanography: General: General or miscellaneous. **Citation:** Strom, A., R. C. Francis, N. J. Mantua, E. L. Miles, and D. L. Peterson (2004), North Pacific climate recorded in growth rings of geoduck clams: A new tool for paleoenvironmental reconstruction, *Geophys. Res. Lett.*, *31*, L06206, doi:10.1029/2004GL019440.

1. Introduction

[2] It is now widely recognized that climatic shifts over the past century have had substantial impacts on marine ecosystems throughout the North Pacific basin [*Francis and Hare*, 1994; *Mantua et al.*, 1997; *McGowan et al.*, 1998]. Coherent patterns of variability have also been noted between North Pacific SST series and indices of atmospheric circulation, accumulation of CO_2 in the atmosphere, and global air temperatures [*Chavez et al.*, 2003]. The underlying physical processes driving this variability are poorly understood, and instrumental SST records are too short to establish robust causal links or make predictions about the longer-term behavior of climatic patterns evident only in 20th century records.

[3] Given the lack of instrumental data, a number of proxy SST records have been developed in recent years. These have been derived mostly from tree-rings and tropical corals, primarily because annual banding in each allows for the precise dating control needed to resolve interannual to interdecadal climatic variability. Neither proxy is ideal for reconstructing North Pacific SST, however. Tree growth is primarily a response to terrestrial, not marine conditions, and coral records represent mostly a tropical climate signal. What has been missing until now is a marine equivalent of tree rings to bridge existing gaps in coverage and provide annually resolved proxy SST records for extratropical regions.

[4] Geoduck (goo'e-duk) clams were first identified as potential climate proxies by *Noakes and Campbell* [1992], based on several key characteristics. They are long-lived, commonly reaching 100 to 160 years of age; they deposit annual growth rings in the shell each winter [*Shaul and Goodwin*, 1982]; and rates of shell growth in some areas are correlated to temperature [*Noakes and Campbell*, 1992]. Shells grow rapidly in both length and thickness for the first 10 to 15 years. Afterwards, the increase in shell length nearly ceases, though shells continue to grow thicker and heavier at a gradually slowing rate. Geoducks are found from southern California to Kodiak, Alaska (Figure 1), at depths ranging from low intertidal to 100 meters [*Coan et al.*, 2000]. They are abundant from Puget Sound to SE Alaska, and due to the existence of a large commercial dive fishery, shell samples are widely available. Accumulations of subfossil shells can be found in benthic sediments, and offer the potential to considerably extend growth chronologies through the use of crossdating techniques [*Cook and Kairiukstis*, 1990]. Despite the recognized potential of geoduck clams as climate proxies, we are unaware of any sustained efforts over the past decade to develop chronologies suitable for climate reconstruction.

[5] Growth experiments indicate that shell accretion in a number of marine bivalves is strongly related to temperature. For northern latitude species, this relationship is commonly linear and positive from 1°C to 12°C and then gradually flattens, becoming negative above 20–25°C [*Cerrato*, 2000; *Storr et al.*, 1982; *Witbaard et al.*, 1997]. Though shell growth varies with temperature, it never completely ceases, even under starvation conditions and at temperatures down to 1°C. As temperatures rise, rates of shell growth remain correlated to oxygen consumption. This holds true even when food is limited and tissue growth is negative [*Cerrato*, 2000]. Consequently, *Cerrato* [2000] proposed that increment widths were an integrated measure of metabolic activity over time. Above

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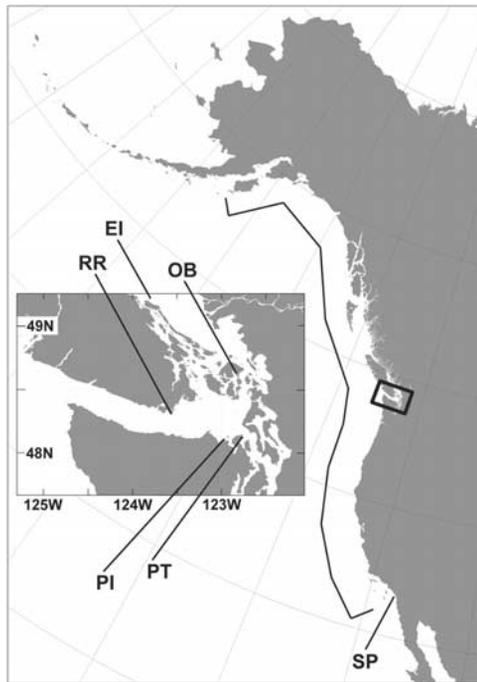[4]USDA Forest Service, Pacific Northwest Research Station, Seattle, Washington, USA.

Figure 1. Range of geoducks in North America. The inset shows the Protection Island sample site (PI). Locations with continuous SST records include Race Rocks (RR), Entrance Island (EI), and Scripps Pier (SP). AT records were obtained from Port Townsend (PT) and Olga Bay (OB).

threshold levels, food availability may influence shell growth by stimulating filter-feeding activity [*Witbaard et al.*, 1997]. Higher than normal temperatures during periods such as the spring phytoplankton bloom may therefore have a disproportionately large impact on cumulative shell growth [*Witbaard et al.*, 1997]. It is also possible that a climate-induced change towards earlier onset of spring would extend the window for optimum shell growth to occur.

[6] Both food density and temperature appears to limit growth of geoduck shells. Under controlled conditions, we found that one-year-old geoducks kept at elevated temperatures ($15–16°C$), and supplied with a continuous flow of food-rich water (45 k cells/ml), grew significantly faster (p = 0.0037) than other treatment groups in which either food or temperature was restricted ($10–11°C$ and 15 k cells/ml) [*Strom*, 2003]. There is some indication, however, that food may not be a major limiting factor at our sample site. *Robinson and Ware* [1999] estimated that diatom abundance near the western entrance to the Strait of Juan de Fuca declined by approximately 30% during the 1990s. This coincided with the highest rates of shell accretion in 155 years, and SSTs well above normal. The data on food abundance for this area are sparse, and the results of *Robinson and Ware* [1999] should be used with caution, but if rates of shell growth in geoducks are stimulated by temperature to the same extent as other northern marine bivalves, it would be reasonable to expect a positive, linear relationship between temperature and growth within the $≈7–13°C$ annual range that prevails where our shells were obtained. Further studies will clearly be needed, however, to understand the phys-

iological and environmental mechanisms controlling shell growth.

2. Data and Analysis

[7] We have developed a ring-width index from geoduck shells obtained near Protection Island in the Strait of Juan de Fuca (Figure 1). These geoducks had originally been harvested for other purposes, such as stock assessment, biotoxin testing, or personal use by tribal fishers. Protection Island is located in an area of strong currents, intense tidal mixing, relatively cold bottom temperatures [*Mackas and Harrison*, 1997] and slower rates of shell growth than at other geoduck habitats in the Puget Sound area [*Hoffmann et al.*, 2000]. The geoducks were harvested at depths ranging from 8–20 meters. Due to tidal mixing, temperatures at this depth, measured just north of Protection Island [*Newton et al.*, 1998], correspond closely to SST records from the Race Rocks lighthouse, located approximately 46 km to the northwest.

[8] The growth index was compared to SST data from Entrance Island, British Columbia, and Scripps Pier in southern California, and was used to reconstruct the Race Rocks SST record. The Race Rocks (1921–1999) and Entrance Island (1937–1999) data are available from Fisheries and Oceans, Canada, at http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/sst/default_e.htm. The Scripps Pier data are available at http://www-mlrg.ucsd.edu/shoresta/. We also compared the growth index to air temperature (AT) data from Port Townsend (1896–1999), and Olga Bay (1890–1999) in Washington State. These data are available from the U.S. Historical Climatology Network at http://cdiac.esd.ornl.gov/epubs/ndp019/ndp019.html.

[9] Growth data were obtained by extracting thin-sections from the hinge area of each shell. We then measured ring-widths from digitized images of the sections. At least three sections were cut from each shell to assure adequate replication in measuring ring-widths and dating the annuli. We processed the measurement series using conventional dendrochronology techniques. Series were standardized using a modified negative exponential curve [*Cook and Kairiukstis*, 1990], which effectively modeled the age-related growth trend. Annual growth indices were computed as the ratio of actual to modeled growth. A detailed description of methods is available in *Strom* [2003]. Growth data are available from the World Data Center for Paleoclimatology at http://www.ngdc.noaa.gov/paleo/paleo.html.

[10] We found that shell growth at Protection Island correlated best with Mar–Oct SST. This is consistent with *Shaul and Goodwin* [1982] who demonstrated that the annual growth line in geoducks is deposited during winter, between November and February, and that negligible shell growth occurs during these months. We found no evidence of significant lagged relationships between temperature and growth. The correlation between mean Mar–Oct Race Rocks SST, and mean geoduck growth for the period 1921–1998 (r = 0.66) was significant at the 99% level. This is comparable to correlations obtained from high quality tree-ring chronologies, and suggested that the growth index was suitable to be used for climate reconstruction. The subsample signal strength (SSS) criterion [*Cook and Kairiukstis*, 1990] indicated that portions of
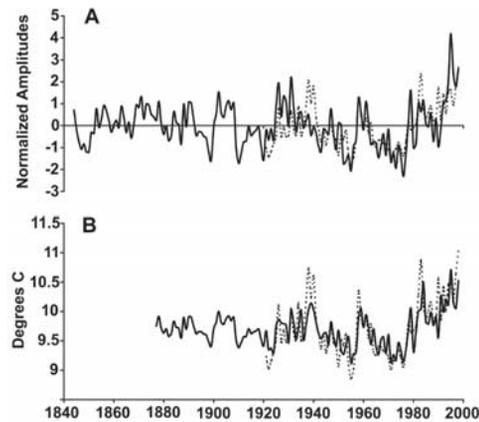
Figure 2. (A) The geoduck growth index (black line, 1844–1998), and the Mar–Oct Race Rocks SST record (dotted line, 1921–1998). (B) The reconstructed Mar–Oct Race Rocks SST record (black line, 1877–1998) and the instrumental Mar–Oct Race Rocks SST record (dotted line, 1921–1998).
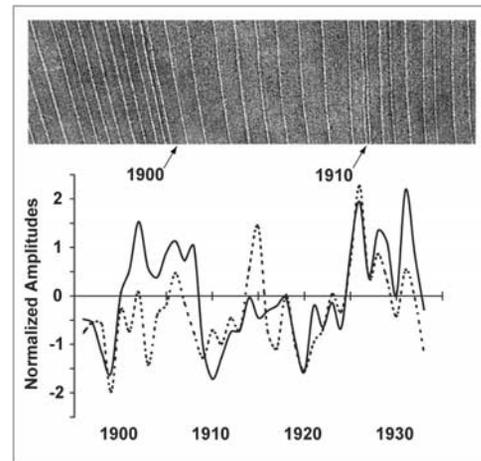

Figure 3. Local AT records versus ring-widths. The top panel shows an SEM micrograph of the ring structure from a 163-year-old geoduck. Abrupt changes in shell growth rates occurred in 1900 and 1910. The bottom panel shows the growth index (black line) and mean Mar–Oct ATs from Port Townsend and Olga Bay (dotted line) between 1896 and 1933.

the index derived from at least 6 shells retained sufficient signal (SSS > 0.85) to be useful. This provided a statistically acceptable chronology from 1877 to 1998, with sample depth ranging from 6 to 23 shells. We used an autoregressive model calibrated over the 1921–1998 period to reconstruct the Mar–Oct Race Rocks SST record. We then confirmed our estimates for the reconstructed portion using an alternative method in which persistence was first removed from both the SST and growth series and then built back into the model following calibration [*Meko*, 1981].

3. Results and Discussion

[11] The reconstruction explained 57% of the variance in the instrumental record over the 1921–1998 period (Figure 2). For the period prior to 1921, both models produced nearly identical results. We verified the reconstruction using 'leave-one-out' cross validation [*Blasing et al.*, 1981], and three standard measures of the common variance [*Cook and Kairiukstis*, 1990]. These included the Reduction of Error (RE = 0.55), the Pearson coefficient (r = 0.75, p < 0.01), and the sign test (+62, −16, p < 0.01). No significance test is available for RE. We obtained additional verification of our results by correlation tests of the reconstructed series with instrumental Mar–Oct SST records from Entrance Island, British Columbia (1937–1998, r = 0.61, p < 0.01), and Scripps Pier in La Jolla, California (1917–1998, r = 0.58, p < 0.01). The correlation with Scripps SST illustrates the remarkable long-distance coherence evident in ocean temperature records along the west coast of North America [*McGowan et al.*, 1998]. The raw growth index also tracks local trends in AT. Figure 3 shows coherent trends in geoduck growth and AT going back to 1896.

[12] A global representation of correlations between the raw geoduck growth index and March–October gridded SSTs is shown in Figure 4a. The correlation pattern bears a striking resemblance to the leading pattern of interdecadal global SST variations [*Zhang et al.*, 1997], and is essentially the canonical PDO pattern in the North Pacific [*Mantua et*

al., 1997]. Correlations are positive in a narrow band along the Pacific coast of the Americas and in the tropical Indian Ocean and central Pacific, and negative in the extratropical central and western North Pacific.

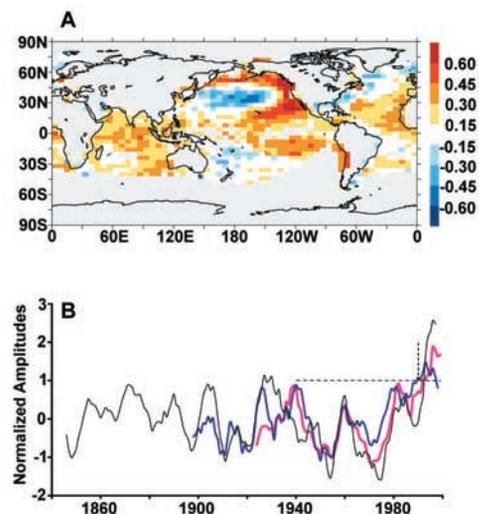[13] Another remarkable feature of the growth chronology are the exceptionally high values recorded in the 1990s.

Figure 4. Correlation coefficients (A) between the geoduck growth index and gridded Mar–Oct average SSTs for the 1950–1997 period, derived from COADS SST, aggregated into 4° latitude by 6° longitude grid squares. Locations with missing data are shaded in grey. Comparison (B) between the growth index (black line), mean AT from Olga Bay and Port Townsend (blue line) and Race Rocks SST (red line). Time-series were computed from annual values as five-year centered means. The horizontal dashed line indicates normalized amplitudes one standard deviation above the historical mean. The vertical dashed line denotes 1990.

Mean ring-widths reached extreme peaks during this period, and above normal temperatures appear to be the principal cause. During the 1990s, a number of marine organisms responded in a manner consistent with a sharp upward trend in upper ocean temperatures. Zooplankton data from just outside the western entrance to the Strait of Juan de Fuca show that the "normal" fauna were replaced by "southerly" species more common to the offshore waters of the central and northern California coast [*Mackas et al.*, 2001]. Pacific sardine (*Sardinops sagax*) returned to British Columbia waters after a 50-year absence [*Hargreaves et al.*, 1994], piscivorous seabirds bred earlier in the spring than previously recorded, and the timing of the spring zooplankton biomass maximum advanced by 6–8 weeks [*Bertram et al.*, 2001]. Increased temperatures were accompanied by increased stratification, reduced upwelling, and lower nutrient content in offshore surface waters [*Mackas et al.*, 2001]. Both AT and SST records obtained from the Protection Island vicinity show that the 1990s was the warmest decade in the historical record. Temperature spikes of relatively short duration (2–3 years) occurred on several earlier occasions, but during the 1990s, measurements of AT (Port Townsend and Olga Bay) and SST (Race Rocks) computed as 5-year centered averages (Figure 4b) attained higher levels than ever before, and persisted above those levels for most of the decade.

4. Conclusions

[14]   As evidence has accumulated in recent years that the Pacific Ocean plays an important role in regulating global climate, considerable effort has been directed to developing new proxy SST records. We have demonstrated that growth rings in geoduck clams, when obtained from sites where temperature controls rates of shell accretion, can provide high quality proxy records of ocean temperature. Chronologies spanning a broad latitudinal range can be developed at a moderate cost, and could be used in conjunction with other paleo-climate proxies to improve SST and related climatic reconstructions. We anticipate that a growing archive of accurately dated shell material will provide new avenues for unraveling the mysteries of historical climatic variability.

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