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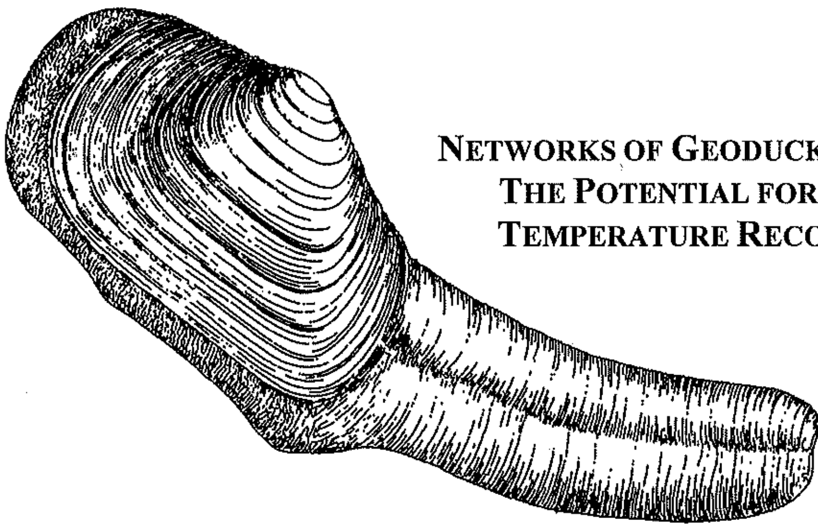

NETWORKS OF GEODUCK CHRONOLOGIES: THE POTENTIAL FOR SEA SURFACE TEMPERATURE RECONSTRUCTIONS

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Abstract

We developed a growth increment chronology from Pacific geoducks at Brady's Beach, a site off the coast of northern British Columbia, Canada. Given that geoducks form annual growth increments akin to tree-rings, we were able to use the dendrochronology technique of crossdating to assign the correct calendar year to each growth increment. From this, we statistically detrended increment measurements in order to isolate the climate signal and create an aggregated master chronology. We compared the final chronology against sea surface temperatures (SST) taken from instrumental records at nine lighthouses found in various locations around the Pacific Northwest. The Brady's Beach chronology did not consistently correlate with monthly or annual SST measurements over time. In order to address these anomalies, potentially influenced by microclimate variations, we examined an additional three geoduck chronologies developed from other sites in British Columbia and Washington, U.S. These chronologies exhibited growth patterns that differed from those found in Brady's Beach, but similarly experienced inconsistencies with SST correlations over time. When geoduck chronologies were averaged in various combinations, however, we found that correlations with lighthouse SST records not only significantly increased, but also remained more consistent. With a more robust chronology network, we were able to develop a high-resolution climate reconstruction for a lighthouse site, predating instrumental records back until 1888.

Introduction

Since the advent of dendrochronology, tree-rings have been widely employed to reconstruct a variety of climactic signals back through time (Stokes and Smiley, 1996). In the early 1900s, Andrew E. Douglass at the University of Arizona discovered that the trees found in within localities around the Southwest shared a level of synchrony among their growth increments (Fritts, 1976). In the arid Southwest, precipitation acted as the limiting factor of growth; dry years would restrict growth across all trees, inducing narrow increments, while years with abundant soil moisture would allow for wide rings. By cross-matching these synchronous, climate induced growth patterns among tree samples, all growth increments can be properly identified and assigned the correct calendar year. This process of "crossdating" allows dendrochronologists to develop highly accurate, annually resolved chronologies suitable for climate reconstructions. With simple ring counting, errors often occur in unclear regions where increments may be overlooked or falsely identified (Stokes and Smiley, 1996).

Through the process of crossdating and other statistical methods of dendrochronology, it is possible to develop a master chronology for a specific locale that can then be related with instrumental records of climate. Since tree-ring data often predates these records, the chronologies can then be used as a proxy to reconstruct climate far into this past. This vastly expanded climate record provides a much broader context in which recent climate changes can be placed, allowing for more accurate analyses and predictions into the future (Mann et al., 1998)

Tree-ring chronologies have been used to reconstruct patterns of terrestrial precipitation or temperature, and some have also proven useful for reconstructing patterns of broad-scale ocean circulation (Black et al., 2005). Trees are often far removed from the marine environment, however, and may not provide the best indicator of oceanic conditions (Kormanyos and Black, 2006). Certain marine organisms, such as bony fish, sharks, whales, corals, and bivalves form annual growth increments akin to those in trees, and analysis of their structure may provide better relationships with ocean climate (Black, in review).

The Geoduck clam (*Panopea abrupta*) is a marine bivalve that is of particular interest for climate reconstructions, as they are long-lived (up to 150 years) and growth forms incrementally as a function of sea surface temperatures (SST) (Orensanz et al., 2004). Years with warmer SST induce wider increments in geoducks, while colder years constrict growth. With the application of crossdating and other tree-ring techniques, geoducks found in the Pacific Northwest from the United States to British Columbia can be used to develop chronologies that immediately reflect patterns of ocean variability (Strom et al., 2004).

Despite the potential for accurate oceanic climate reconstructions on a fine scale, relatively few studies have provided environmental reconstructions from marine organisms (Kormanyos and Black, 2006). In order to address this, several geoduck chronologies have been recently developed from sites off the coast of Canada and the U.S. They strongly relate to SST, faithfully recording the oceanic patterns of the Pacific Decadal Oscillation (PDO), the El Niño Southern Oscillation (ENSO), and the Northern Oscillation Index (NOI) (Black, Boehlert, & Yoklavich, 2005).

Developing an additional geoduck chronology in the Pacific Northwest will help to provide data for further insights on climate. Aside from its individual value, another chronology can also be combined with others in a larger network. This creates more robust climate reconstructions with greater capacity. Further, when combined with tree-ring and other marine chronologies, these geoduck chronologies can yield even higher-resolution reconstructions, ultimately establishing baseline data for evaluating climate in the present and future.

Materials and Methods

Growth increment data for this study was assembled from geoduck specimens that were taken from Brady's Beach, a site in northern British Columbia with no history of geoduck harvesting. Geoduck shells were live-collected in 2003 by the Pacific Biological Research Station of the Department of Fisheries and Oceans Canada. For the purposes of chronology development, growth rings were measured in the chondrophore, a concave surface on the hinge plate used for ligament attachment within the shell. The increment forming properties and internal placement of the chondrophore allows for a more preserved ring structure compared to those on the outer shell surface that are susceptible to erosion in the margins (Kormanyos & Black, 2006).

Technicians at the Department of Fisheries and Oceans Canada processed the geoduck chondrophores using both acetate peels and thin sections. For each geoduck sample, the shell was cut through the center of the chondrophore area using a diamond-blade lapidary saw. After polishing the resulting cut with 800 and 1200-grit sandpaper, respectively, peels were prepared by etching the surface with 2% hydrochloric acid and pressing it against acetate film softened with a drop of acetone. The resulting peel was mounted between two standard microscope slides (Kormanyos & Black, 2006). For thin section preparation, an additional 0.5 mm cut was taken off the exposed center of the chondrophore. The resulting section was mounted on a single microscope slide. In order to best observe the growth increments in the thin sections, we used Mutvei's solution, a stain that clarifies microgrowth structures of biogenic carbonates (Schöne et al., 2005). The solution produces a three-dimensional relief in a stained shading of blue, with growth increments darkly etched and growth lines etch-resistant (Schöne et al., 2005). We created a Mutvei solution based on a scaled down batch of 125 ml 1% acetic acid, 125 ml 25% glutaraldehyde, and approximately 2.5 g alcian blue powder. Geoduck thin sections were submerged in a microscope slide bath filled with the solution, maintained at 37 to 40 °C on a hot plate. After 15 to 20 minutes of immersion under constant stirring, the sections were removed and rinsed under water before being allowed to air-dry.

The set of samples, which included 476 acetate peels and 27 thin sections, were visually crossdated using the list year technique as described by Yamaguchi (Yamaguchi, 1991). Through a MZ9.5 dissecting microscope over transmitted light, the increments of the chondrophore were visible, and synchronous growth patterns were checked for agreement by matching noticeably wide and narrow growth bands across all samples (Fritts, 1976). Calendar years were assigned to these signature increments by beginning at the margin (where the final ring corresponds to 2003, the year of collection) and subsequently moving backwards in time toward the origin. By employing crossdating, if any increments were incorrectly dated, then recorded years would be offset compared to the other samples in the set. Falsely added or missed rings could then be located where the offset begins and readjusted, accordingly.

Of the visually crossdated specimens, 1 thin section and 29 peels were adequately clear. This sample set of 30 was measured and used for constructing the master chronology for the site. By using the dissecting microscope and a Leica DC300 7.2 megapixel camera, two to four overlapping digital images were taken of the chondrophores depending on the magnification levels, which ranged between 25X and 60X. The series of photographs for each sample were tiled using Image-Pro Plus 6.0, resulting in one high-resolution, panoramic representation (Media Cybernetics Inc., Silver Spring, MD). Within Image-Pro, increments were measured by drawing a continuous transect along the axis of maximum growth, starting from the origin and moving toward the margin. The resulting axis crossed each growth increment as perpendicular as possible, and widths were marked off at the start of the growing season as distinguished by the end of the winter line.

With one transect per sample, 30 total geoduck measurements were exported from Image-Pro and analyzed in COFECHA, a computer program in the International Tree-Ring Data Bank Dendrochronology Program Library (ITRDB DPL). Through COFECHA, the data set constructed from Brady's Beach was detrended by fitting each measurement to a 22-year cubic spline. This close fit followed all long-term trends, and dividing each measurement values by the corresponding value predicted by the spline eliminated low-frequency variability. With the removal of the long-term effects, the high-frequency variance could then be compared across samples, with all measurements equally weighted around a mean of one (Grissino-Mayer, 2001). If any of the measurements in the time series contained any remaining autocorrelation, it was removed and each detrended series was then correlated with the average of the rest of the detrended values from the data set. This allowed for a statistical verification of the initial visual crossdating by ensuring that the year-to-year variability was consistent across all samples. Correlations, therefore, were not artificially inflated by the low-frequency variance that is shared among all geoducks, such as with age-related growth declines or long-term oceanic influences. The resulting correlations were provided in overlapping 25-year intervals, so that potential problem areas could be more easily isolated for potential corrections (Grissino-Mayer, 2001).

After crossdating was completed, both statistically in COFECHA and visually, the geoduck measurement set could be compiled into a master chronology for the site. The original measurements taken in Image-Pro were exported and fitted to a negative exponential function for detrending in the ITRDB DPL program, ARSTAN. These rigid negative exponential functions eliminate only age-related growth effects, preserving low-frequency patterns of variability that may be induced by climatic variables, such as the PDO or ENSO (Black, Boehlert, & Yoklavich, 2005).

Detrended measurements were averaged across all samples to construct one master chronology for the Brady's Beach site. The chronology was then compared with monthly and annual SST records spanning 1937 to 2002 from nine different lighthouses along the coast of British Columbia, as provided by the Department of Fisheries and Oceans Canada through the Pacific Region Ocean Sciences Database (Figure 1). In order to find the best associations for robust climate reconstructions, three more chronologies were analyzed in addition to Brady's Beach (BB). The further chronologies were constructed from geoducks in sites at Tree Nob (TN), Bartlett (BA), and Puget Sound (STR) (Figure 2).

Results

A total of 30 geoduck specimens collected from Brady's Beach were used in the construction of the master chronology for the site. Through visual crossdating across all samples, outlier years of substantial growth were identified as 1998, 1992, 1983, and 1935. Conspicuously narrow growth increments were noted as 1976, a triplet of 1969-1967, 1960, 1954, and 1937. There were no missing growth increments in any of the samples, although false checks that closely resembled winter lines were abundant, especially in the stained thin sections of older geoducks. Any of these potentially unclear increments, however, were reasoned to be real or false through crossdating.

After visually crossdating, growth increments were measured in the chrondrophore along the axis of maximum growth. A total of twenty-nine acetate peels and one stained thin section were measured, with one axis per specimen. The resulting 30 measurements were then verified in COFECHA, with an output showing a very strong inter-series correlation of 0.705 and an average mean sensitivity of 0.223. COFECHA did not identify potential errors within any of the provided 25-year intervals, demonstrating that the crossdating was accurate for the site.

From the Brady's Beach site, the longest-lived geoduck was measured from a chondrophore thin section that dated back to 1887. Not all of the specimens dated as far back in time, however, and the final chronology was truncated to span between 1934 and 2001 in order to retain a sample depth of at least eight throughout the series (Figure 3). The master chronology was then correlated with sea surface temperature records for the lighthouse at Amphitrite Point at 48.55N latitude and 125.32W longitude, as it is the closest in location to Brady's Beach out of the stations with long records of SST data. With respect to monthly averages, the Brady's Beach chronology correlated best with SST during March and July, with coefficients of 0.35 and 0.37, respectively (Figure 4). The correlation between the master chronology and Amphitrite Point was 0.20 across the entire time series using the annual average sea surface temperatures. By using a running correlation to analyze the relationship between annual SST and the geoduck chronology over time, the chronology has periods of much higher correlations, such as from the late 1950s to the mid 1960s, which peaked at 0.484 in 1963 (Figure 5). The interval between the late 1970s to the early 1990s had even higher correlations, with a maximum of 0.65 in 1981.

Examining other geoduck chronologies revealed that they also experienced similar inconsistencies over time in correlations between sea surface temperature records from lighthouse data (Figure 6). The previously developed chronology from Tree Nob, a site near Langara lighthouse at 54.15N latitude and 133.03W longitude, correlated very closely with the lighthouse SST records over annual averages across the time series at 0.62. The relationship, however, sharply declined after 1984; if measurements in the Tree Nob chronology are removed after 1984, then the correlation increases to 0.77.

By combining multiple geoduck chronologies, however, it is possible to cancel out these inconsistencies over time and increase the overall correlation with recorded measurements of sea surface temperatures. Relationships to SST provided by combining chronologies proved to be more robust compared to that of any single geoduck chronology. The average of all four chronologies provided the highest correlations for Amphitrite Point at 0.63, Cape St. James at 0.68, and Kains Island at 0.71. The combination of the Bartlett and Puget Sound chronologies provided the highest correlations for Departure Bay at 0.54 and Entrance Island at 0.66. Combining chronologies from the Puget Sound and Tree Nob sites gave the highest correlations for McInnes Island at 0.71, Pine Island at 0.70, Race Rocks at 0.80, and Langara lighthouse at 0.75. These networks provide a relationship that is not only closer with sea surface temperatures, but also more consistent, as illustrated by the combined running correlations compared to the individual chronologies with Langara (Figure 7).

With the highly correlated and consistent chronology networks, it is then possible to develop more accurate climate reconstructions that predate instrumental records. In order to create a reconstruction for the Langara lighthouse measurements, the Tree Nob and Puget Sound chronologies were averaged as this combination provided the highest correlation with SST records. A linear regression between Langara SST and the geoduck chronologies resulted in $R^2 = 0.56$ with $Y = 1.7465(X) + 7.0907$ (Figure 8). This equation allowed for a temperature reconstruction back to 1888, which is the beginning of the combined geoduck chronology. This far predates the lighthouse measurements, which started recording in 1941 (Figure 9).

Discussion

Geoduck chronologies are able to offer high-resolution data sets that closely relate to a variety of indices tracking oceanic variability. By employing the standard techniques from dendrochronology, such as the process of crossdating and application of various statistical methods, it is possible to create very accurate chronologies using geoduck measurements. Each geoduck chronology, by capturing both micro-site variability and broad ocean patterns, shares common features while also uniquely representing its local environment. This allows for climate reconstructions that are increasingly precise with the inclusion of site-specific influences.

However, these micro-site variances also make reconstructions more complicated, as the few available lighthouse stations with instrumental records are often removed in location from the sites where geoducks are collected. Even though the chronology developed from Brady's Beach proved to be highly accurate internally, it did not strongly correlate with SST measurements from any of the nine lighthouses. This may have been caused by the micro-site climate variability of Brady's Beach that was captured within the geoduck chronology, but not in any of the instrumental records from other locations. Even when analyzed on a monthly level opposed to annual averages, the Brady's Beach chronology did not strongly correlate, although certain months did relate better than others. Over time, the chronology did improve in correlation during certain decadal intervals.

This lack of consistency was mirrored by other geoduck chronologies that have been previously constructed. While the Tree Nob and Puget Sound chronologies relate much more strongly to SST records compared to Brady's Beach, they still suffer from periods where correlations drop significantly. For example, both the Tree Nob and Bartlett chronologies had very high correlations with lighthouse records up until the mid-1980s, but quickly lost their SST relationship through the present. During this recent time period, growth increments slowed down and become narrower than what should be expected, given the SST records. Suspiciously, commercial geoduck harvesting on these sites also began the mid-80s, and is still practiced today. Current evidence, however, suggests that harvesting within geoduck populations does not cause any significant negative effect on survivors (Orensanz et al., 2004). Despite this, data from the Tree Nob and Bartlett chronologies initially seemed to indicate that the harvests were actually impacting the remaining geoducks, resulting in a decoupling of the climate relationship.

In order to further study the potential effect of harvesting, the site for Brady's Beach was chosen as it was close in proximity to Bartlett, but otherwise remained unharvested. If the Brady's Beach data set mirrored that of Bartlett, but retained the correlation with SST through to the present, then it would suggest that the effects of harvesting were having an influence, both stunting the geoduck growth and severely limiting their usefulness as a proxy for climate reconstructions. The resulting master chronology from Brady's Beach did not capture the same drop off in correlation with recorded SST after the mid-1980s. However, it generally did not mirror other patterns found in the Tree Nob or Bartlett geoducks. Instead, the Brady's Beach chronology similarly experienced correlation inconsistencies, only during other time periods. Each geoduck chronology was capturing climate from a different perspective that could not entirely be recorded by the instrumental SST measurements from the lighthouses. After comparison between the four available geoduck chronologies, there was no common decline in

SST correlation during periods of harvesting (the Puget Sound chronology actually experienced a significant correlation increase after 1986). Therefore, there is no strong evidence to suggest that harvesting is, in fact, impacting the geoduck growth patterns.

The Brady's Beach chronology did, however, further emphasize the importance of developing chronology networks for the purposes of climate reconstructions. Networks can capture climate from the different perspectives of each site, while also canceling out the anomalies that significantly reduce SST correlations over certain time intervals. As shown with the correlation data across all of the lighthouses, combinations of chronologies provide the strongest, and most consistent, relationship. With the Langara lighthouse, in particular, a network using multiple chronologies was able to significantly raise the correlation with SST, allowing for a more accurate reconstruction that was extended all the way back into the 19th century. The geoduck reconstruction closely tracks the recent warming trend in SST observed in the instrumental records.

Just as networks of geoduck chronologies can capture different perspectives, combinations with networks of other species at an even larger scale can produce more robust reconstructions across ecosystems. Relationships exist between chronologies developed from tree-rings in forests, mussels in streams, rockfishes on the continental shelf, and finally geoducks in the near shore (Black, in review). All of these chronologies link terrestrial, freshwater, and marine ecosystems, allowing for larger networks that can potentially better reconstruct climate from various levels of perspectives, forming a greater context in which climate can be evaluated in the present and into the future.

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Figures and Tables

Figure 1: Instrumental records of monthly and annual sea surface temperature were collected by nine different lighthouses along the coast of British Columbia, as shown by the yellow circles below. The site of the Brady's Beach chronology is designated by the orange geoduck icon.

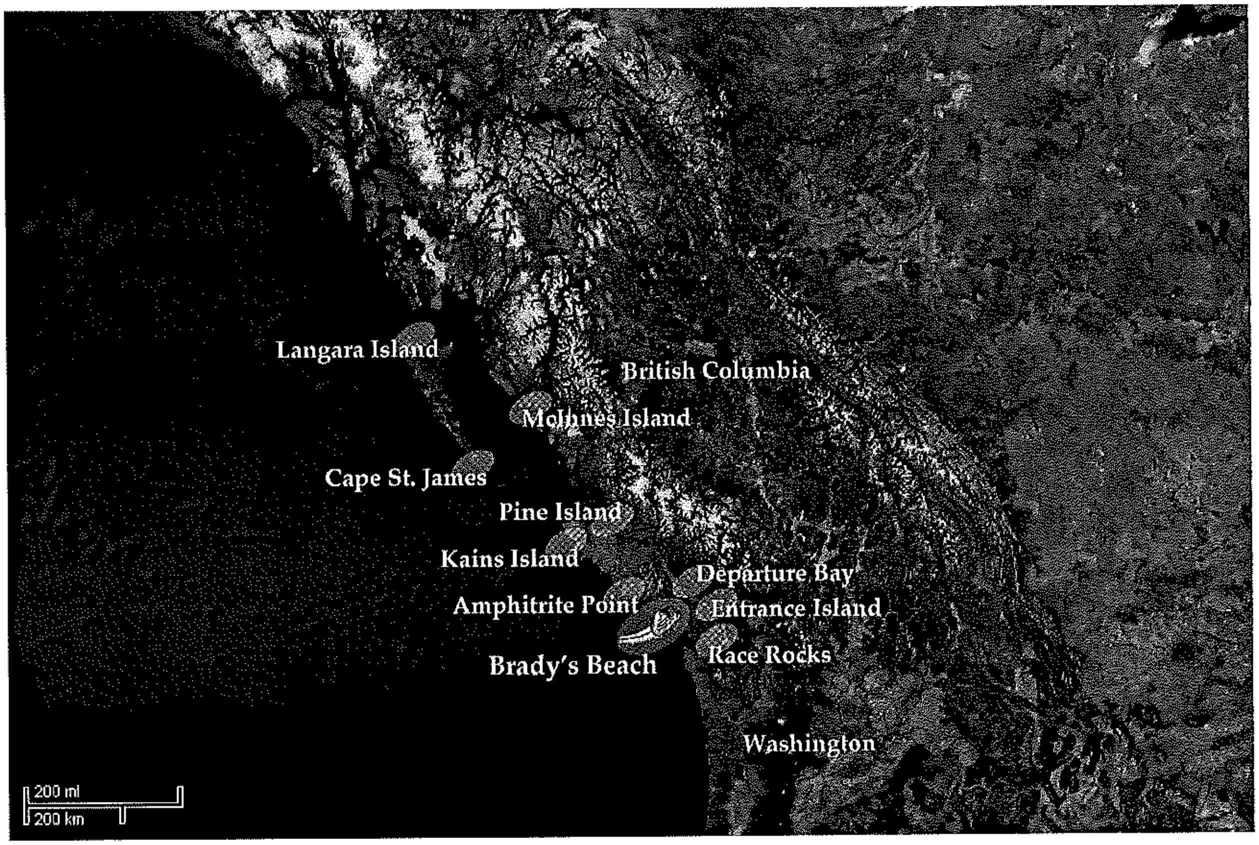

Figure 2: Samples were collected from the sites on the map below (as shown by the orange geoduck icons). Tree Nob, Bartlett, and Brady's Beach are located off the coast of British Columbia, Canada, while the Puget Sound site is in Washington, U.S. The Brady's Beach site remained unharvested commercially.

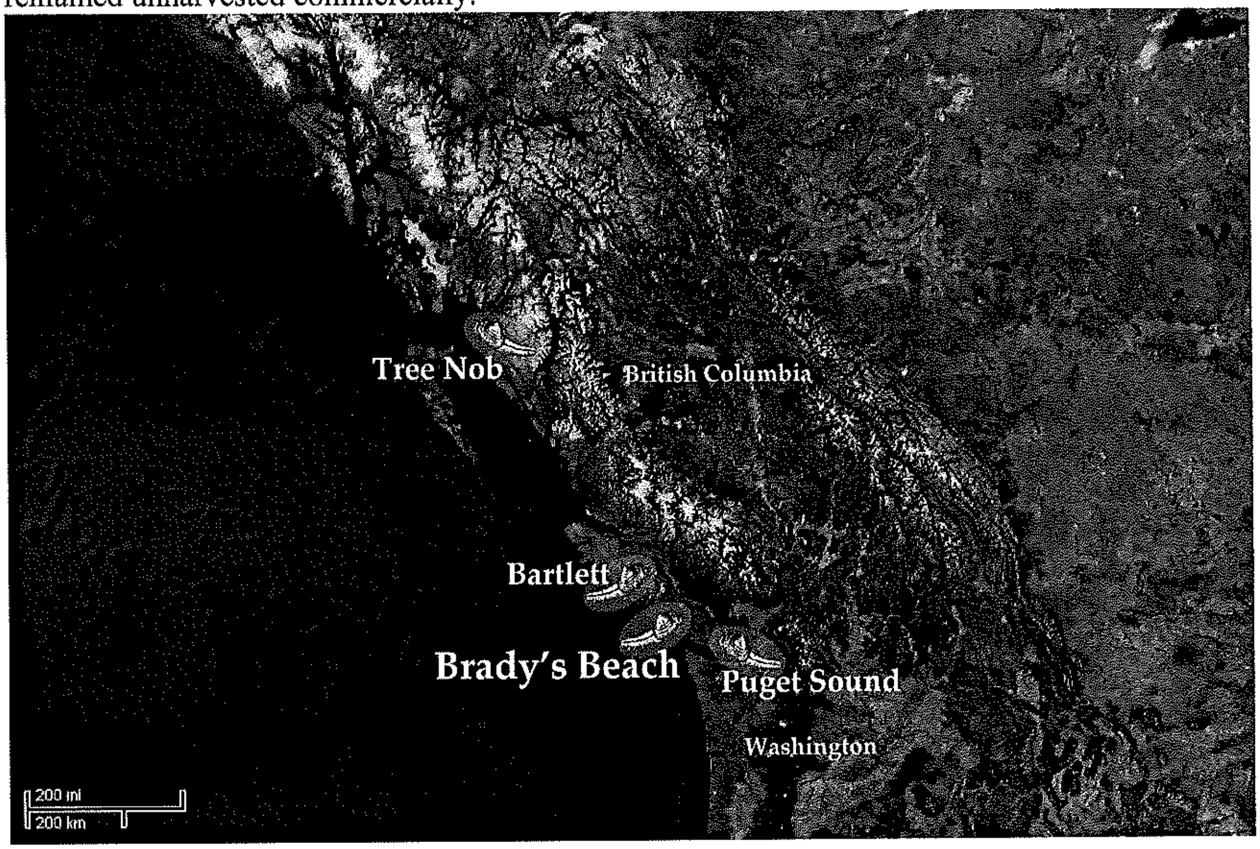

Figure 3: The master chronology for the Brady's Beach site, spanning 1934 to 2001.

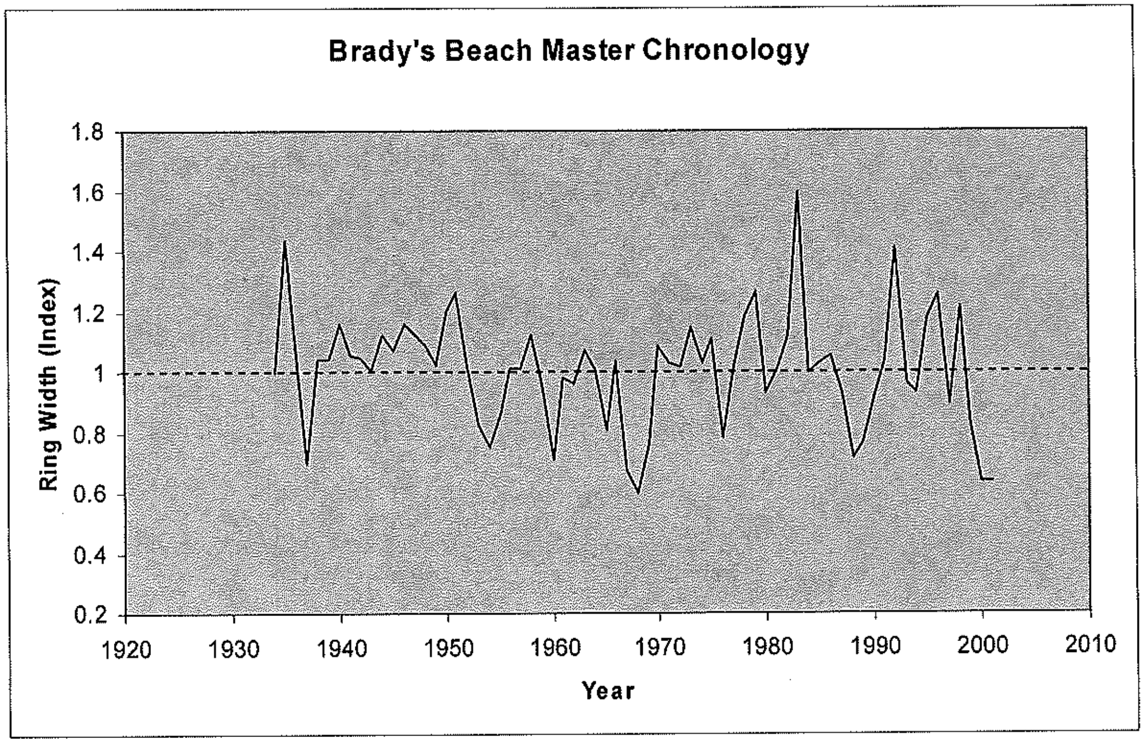

Figure 4: Correlations between the Brady's Beach chronology and averaged monthly SST records from the Amphitrite Point lighthouse.

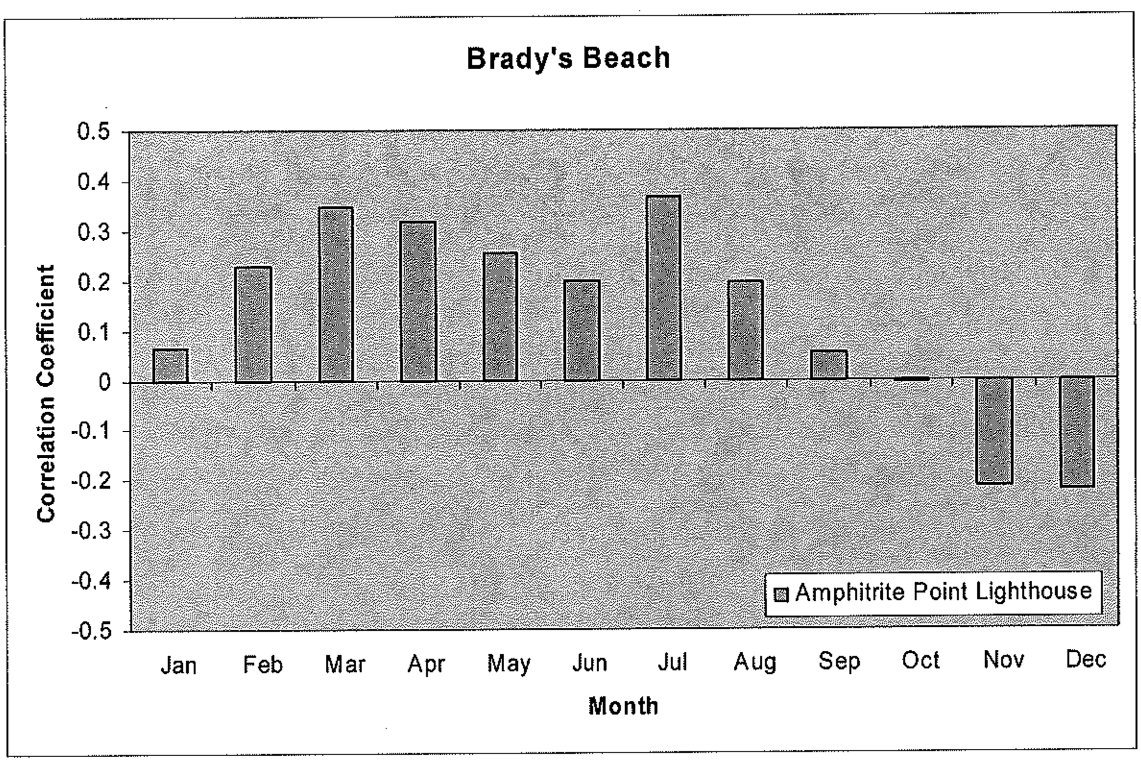

Figure 5: Running correlations between the chronology from Brady's Beach and annual SST records over time from the Amphitrite Point lighthouse.

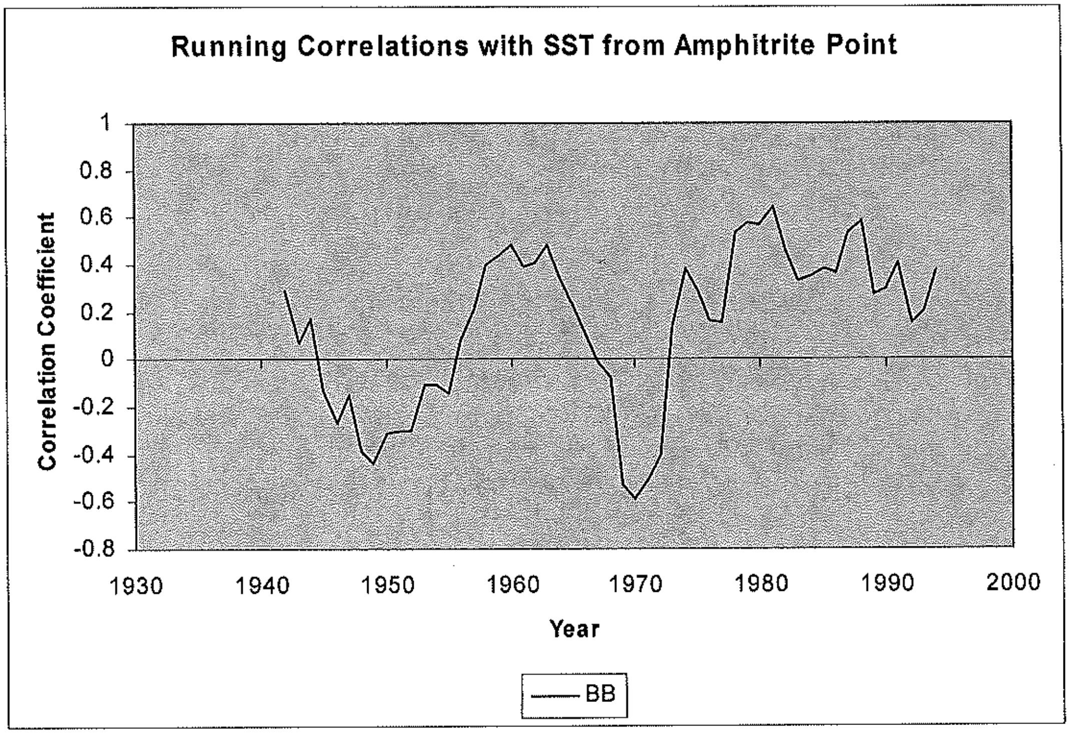

Figure 6: An overlay of the four individual geoduck chronologies. Tree Nob (TN), as shown in yellow dates from 1888 to 2002. Bartlett (BA), as shown in pink, dates from 1937 to 2003. Brady's Beach (BB), as shown in dark blue, dates from 1934 to 2001. Puget Sound (STR), as shown in light blue, dates from 1888 to 1999.

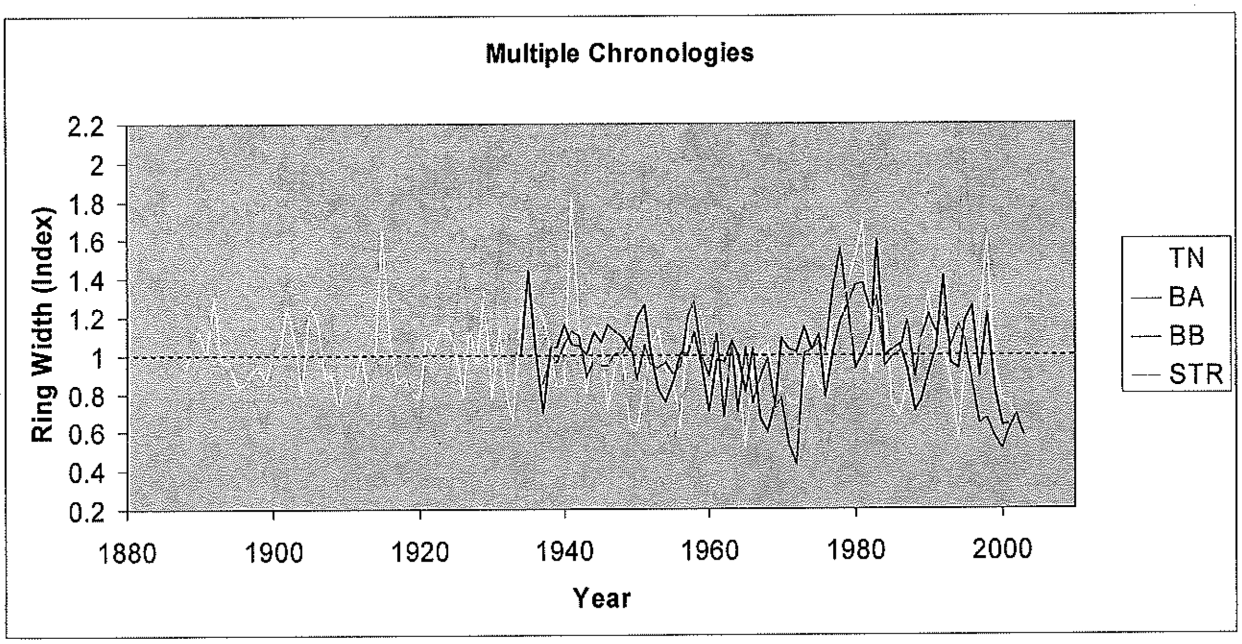

Figure 7: A view of the correlations over time between the individual chronologies and the SST records from the Langara lighthouse. The red line shows the best chronology network combination and its higher, more consistent correlation through the time series.

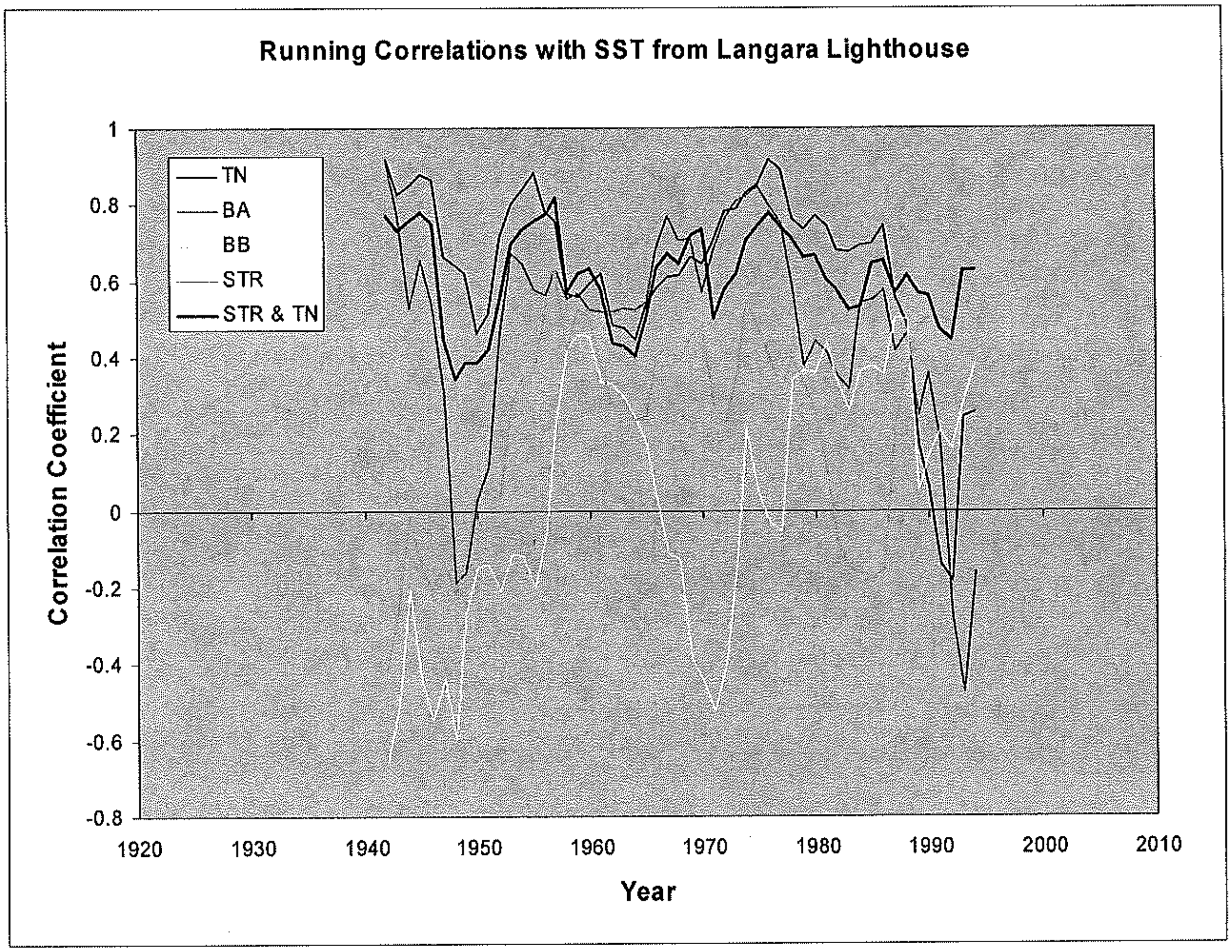

Figure 8: A linear regression between the measurements from the geoduck chronology (combined from the Tree Nob and Puget Sound sites) and the annual SST records from the Langara Lighthouse.

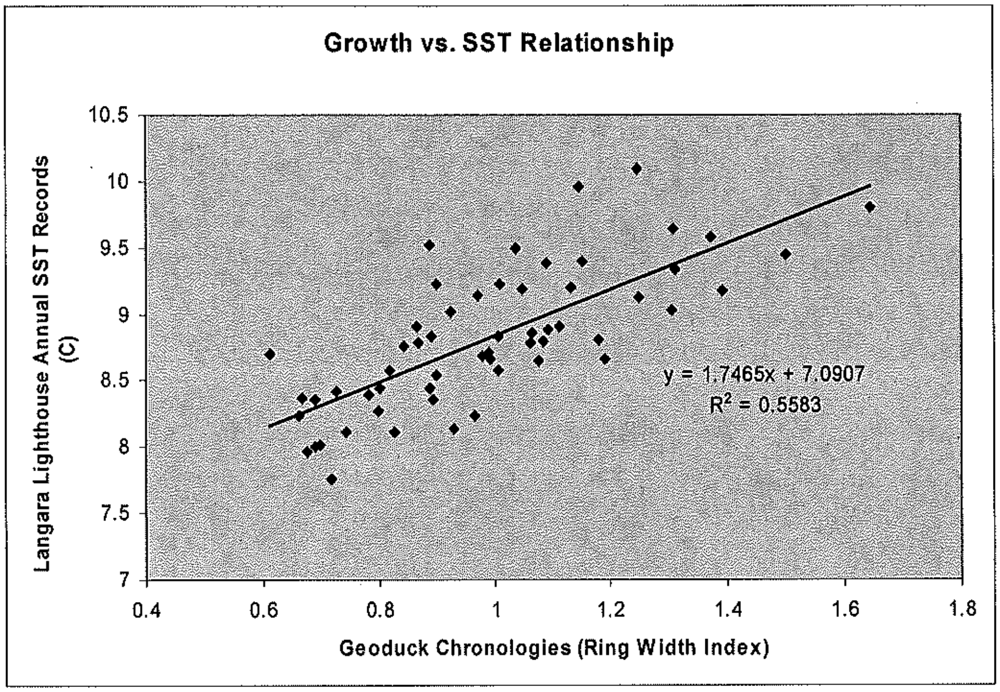

Figure 9: A reconstruction of the annual SST records from the Langara lighthouse. With the network of geoduck chronologies, SST can be predicted back until 1888.