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Coralline alga reveals first marine record of subarctic North Pacific climate change

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[1] While recent changes in subarctic North Pacific climate had dramatic effects on ecosystems and fishery yields, past climate dynamics and teleconnection patterns are poorly understood due to the absence of century-long high-resolution marine records. We present the first 117-year long annually resolved marine climate history from the western Bering Sea/Aleutian Island region using information contained in the calcitic skeleton of the long-lived crustose coralline red alga *Clathromorphum nereostratum*, a previously unused climate archive. The skeletal δ^{18}O-time series indicates significant warming and/or freshening of surface waters after the middle of the 20th century. Furthermore, the time series is spatiotemporally correlated with Pacific Decadal Oscillation (PDO) and tropical El Niño-Southern Oscillation (ENSO) indices. Even though the western Bering Sea/Aleutian Island region is believed to be outside the area of significant marine response to ENSO, we propose that an ENSO signal is transmitted via the Alaskan Stream from the Eastern North Pacific, a region of known ENSO teleconnections. **Citation:** Halfar, J., R. Steneck, B. Schöne, G. W. K. Moore, M. Joachimski, A. Kronz, J. Fietzke, and J. Estes (2007), Coralline alga reveals first marine record of subarctic North Pacific climate change, *Geophys. Res. Lett.*, *34*, L07702, doi:10.1029/2006GL028811.

[2] The subarctic North Pacific - Bering Sea climate has been undergoing major changes which purportedly threaten the world's largest fisheries and endanger unique ecosystems between Siberia and Alaska [*Grebmeier et al.*, 2006; *Overland and Stabeno*, 2004]. Instrumental temperature records indicate two regime shifts during the mid 1970's and late 1990's [*Volkov and van Aken*, 2005] were followed by major ecosystem reorganizations [*deYoung et al.*, 2004; *Francis et al.*, 1998]. However, in the absence of reliable century-long oceanographic records, long-term climate dynamics and teleconnection patterns in this region are poorly understood [*MacDonald and Case*, 2005]. Thus, it remains unclear whether recent changes are unique or recurrent events. In order reconstruct past climate evolution we collected a 5-cm thick live crust of the shallow water coralline red alga *Clathromorphum nereostratum* in August 2004 at Attu Island (52°47N; 173°10E) in the western Bering Sea/Aleutian Island region (Figure 1). This region is influenced by the east-west flowing Alaskan Stream, i.e. the swift and narrow western boundary current of the cyclonic eastern subarctic gyre located just south of the Alaska Peninsula and Aleutian Islands [*Reed and Stabeno*, 1994]. The Alaskan Stream originates in the Gulf of Alaska and enters through Aleutian Island passes into the Bering Sea where it is the dominant source of relatively warm, fresh and nutrient-rich water [*Reed and Stabeno*, 1994]. While *C. nereostratum* has only been described from the central and western North Pacific and Bering Sea region [*Lebednik*, 1976], coralline red algae grow in shallow marine settings of all climate zones. Coralline red algal skeletons form by accretion of high-Mg calcite mainly during the summer months. In the dark winter months and at temperatures below 5°C, skeletal growth of *C. nereostratum* slows or ceases entirely so that the summer-winter transition forms a distinct growth line. This assumption is based (1) on aquaculture studies that indicated a slowdown or halt in growth at low light intensities and/or low temperatures in a coralline red algae of the same genus (*C. circumscriptum*) [*Adey*, 1970]. (2) Highest correlations of isotope data were found when correlated to averaged June–November monthly sea surface temperatures (SSTs). During these months SSTs exceed 5°C in the region studied. The regular pattern of summer growth increments and winter growth lines enables a precise calendar dating of each portion of the hard tissue. Vertical growth is not influenced by an ontogenetic, asymptotic growth trend common to other marine biota frequently used as mid- and high-latitude climate archives such as bivalve mollusks [*Schöne et al.*, 2003]. Vertical accretion rates averaged 350 μm per year in the studied samples (ranging between 190 and 650 μm per year). A specimen collected alive at Attu Island was U/Th-dated at 850 ± 28 years cal BP, making *C. nereostratum* one of the longest-lived marine organisms. The age model for the 117-year old alga presented here is based on counting of annual growth increments, and confirmed by multi-collector inductively coupled plasma mass spectrometer derived U/Th ages [*Fietzke et al.*, 2005], which precisely match the number of annual increments (Table 1). Carbonate for δ^{18}O measurements was taken at subannual resolution by micromilling. Each milling step perpendicular to the direction of growth measured 60 μm (Figure 1). Depending on annual

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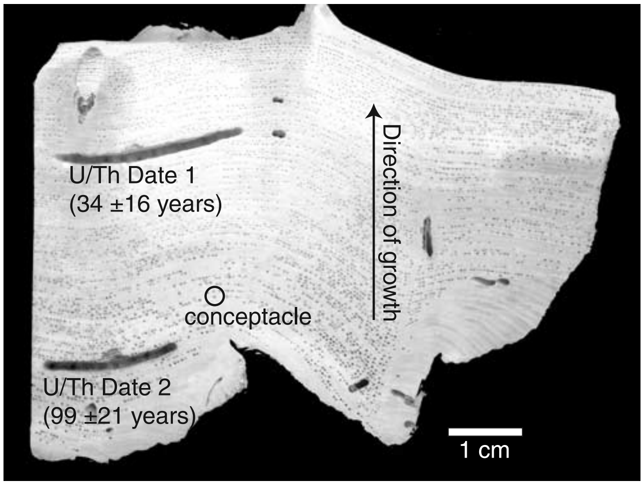

Figure 1. Polished surface of *Clathromorphum nereostratum*. Growth increment pattern can be recognized in this image by annually formed uncalcified reproductive structures (conceptacles) that appear as dark spots. Carbonate for U/Th dating was removed parallel to growth lines marked in the figure.

growth interval widths three to ten samples were obtained within an individual annual growth increment. Here, we calculated annual arithmetic averages (=growing season averages) from subannual δ^{18}O values and compared these data to growth increment widths. Subannual δ^{18}O cycles have previously been shown to reflect local SST variations in coralline red algae [*Halfar et al.*, 2000].

[3] Annually resolved and decadally smoothed δ^{18}O anomalies of the Attu Island red algal record (negative anomaly = warmer and/or less saline conditions) for the period 1886–2003 indicated negative intervals between 1893–1912, 1927–1945 and 1977–2001 (Figure 2). An overall warming or freshening trend after around 1940–1960 was significant at the 95% level (Figures 2 and 3). A multi-taper power spectrum of the δ^{18}O-time series shows significant spectral power at interannual (2.25, 2, and 4 years), decadal (10 years) and multidecadal (~60 years) frequencies [*Ghil et al.*, 2002] (Figure 4). In the absence of multidecadal SST data from oceanographic moorings, uninterrupted and reliable instrumental SST observations of the greater Attu Island region were only available for the period of 1960 to 2003 from the ERSST data set (ERSST.v2 [*Smith and Reynolds*, 2004]; selected grid 50–55°N, 170–175°E). Annually averaged δ^{18}O values and $\mathrm{ERSSTs}_{\mathrm{Jun-Nov}}$ are negatively correlated ($r = -0.46$, $p < 0.0015$) (Table 2). Although this correlation is significant, $\mathrm{ERSST}_{\mathrm{Jun-Nov}}$ data only explain 21% of the variance of the δ^{18}O time series. This is partly attributed to the coarse spatial resolution of the ERSST data (resolution 5 × 5°) in comparison to the Attu Island record, which is located within the influence of the western end of the Alaskan Stream. The latter can be as narrow as 30 km [*Chen and Firing*, 2006] and create local SST conditions which differ from the surrounding northernmost Pacific.

[4] In order to evaluate large-scale SST variability in the Pacific Ocean, the red algal proxy data were compared to the instrumentally derived $\mathrm{PDO}_{\mathrm{June-Nov}}$ index covering the period of 1900–2003 [*Mantua et al.*, 1997]. Both series compare well to each other and exhibit a weak, but significant ($p = <0.001$) correlation of $r = -0.34$ (Figure 2 and Table 2). In addition, a decadal signal is apparent from the power spectrum (Figure 4). The algal time series tracks $\mathrm{PDO}_{\mathrm{June-Nov}}$ most closely during positive $\mathrm{PDO}_{\mathrm{June-Nov}}$ phases, whereas during negative $\mathrm{PDO}_{\mathrm{June-Nov}}$ intervals correspondence is somewhat lower (Figure 2). Both the instrumental and the Attu proxy data suggest that the PDO shifted toward a negative or more variable state since 1997 [*MacDonald and Case*, 2005] (Figure 2). Furthermore, the Attu record indicates a pronounced negative PDO phase terminated at around 1893. This shift was also recorded by a tree-ring record from the western Pacific Kurile Islands [*Jacoby et al.*, 2004], but is not exhibited by tree-ring chronologies focusing on the northeastern Pacific [*Gedalof et al.*, 2002]. In fact, a pronounced incoherence of the PDO during the 19th century was observed in reconstructions from different localities [*Gedalof et al.*, 2002]. This finding was attributed to changes in the spatial pattern of sea level pressure over the Pacific. In addition to decadal-scale variability a multidecadal signal present in the record (~60 years (Figure 4)) supports earlier reports on a 50–70 year oscillation affecting climate and fish stocks in the North Pacific [*Chao et al.*, 2000; *Minobe*, 1997].

[5] Anomalously cold SSTs in the central subarctic North Pacific coincide with unusually warm SSTs along the west coast of the Americas during positive PDO phases [*Mantua and Hare*, 2002]. Surprisingly, δ^{18}O values from the central subarctic North Pacific Attu Island proxy time series correlate negatively to those of the northeastern Pacific PDO state, rather than the expected positive correlation (Figures 2

Table 1. U/Th Results Obtained From *C. Nereostratum*, Attu Island, Alaska[a]

	Age, years	Weight, mg	U^{238}, ppm	Th^{232}, ppb	Th^{230}, ppt
Sample 1	**34 ± 16**	226.2	0.4153 ± 0.0005	0.291 ± 0.003	0.0034 ± 0.0011
Sample 2	**99 ± 21**	113.6	0.5380 ± 0.0008	0.275 ± 0.003	0.0102 ± 0.0019

	Th^{230}/Th^{232}, dpm/dpm	U^{238}/Th^{232}, dpm/dpm	Th^{230}/U^{238}, dpm/dpm	$Th^{230}_{\mathrm{excess}}/U^{238}$, dpm/dpm	U^{234}/U^{238}, dpm/dpm
Sample 1	2.2 ± 0.7	4419 ± 49	0.00050 ± 0.00016	0.00036 ± 0.00017	1.1448 ± 0.0019
Sample 2	6.9 ± 1.3	6053 ± 59	0.00114 ± 0.00021	0.00104 ± 0.00022	1.1446 ± 0.0025

[a] See Figure 1 for sampling transects and *Fietzke et al.* [2005] for methodology. Diagenetic alteration of samples can be excluded for a number of reasons. First, a significant loss in uranium would decrease the U^{234}/U^{238} activity ratio, because U^{234} is preferentially released from the carbonate into solution. However, both samples display uranium isotope ratios of modern seawater. Second, the high U^{238}/Th^{232} ratios indicate that the carbonate was not altered by seawater. The latter would increase the Th concentration due to the high particle/surface reactivity of thorium.

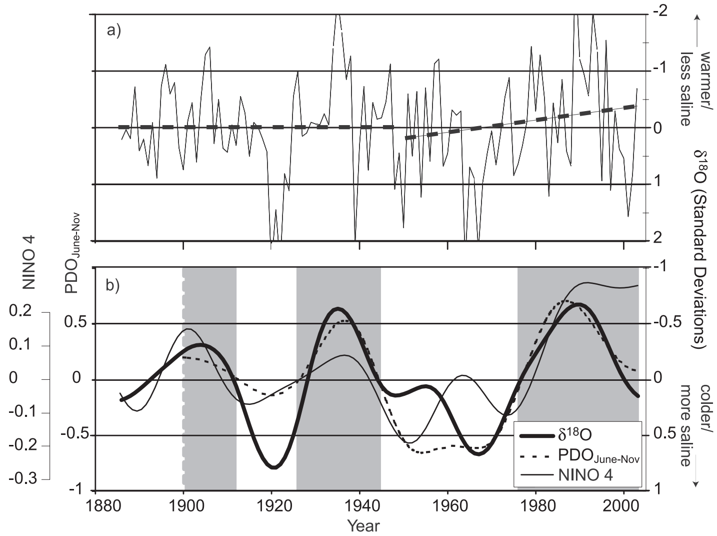

Figure 2. Δ^{18}O-values of Attu Island red algal time series compared to climate indices. (a) Annually-resolved time series; no significant trend exists before the middle of the 20th century, post-1940–1960 trend to negative δ^{18}O-values is significant at the 95% level (Figure 3). (b) Comparison of decadally-smoothed red-algal derived δ^{18}O-time series with $\mathrm{PDO}_{\mathrm{June-Nov}}$ and ENSO indices (low-pass filter, 10 yr). For sources of $\mathrm{PDO}_{\mathrm{June-Nov}}$ and NINO 4 indices see Table 2. We standardized all time series by subtracting mean and dividing by standard deviation. Gray boxes delimit time intervals where smoothed $\mathrm{PDO}_{\mathrm{June-Nov}}$ index is positive.

and 5). This may result from the fast and narrow Alaskan Stream transferring a northeastern Pacific PDO signature to the Attu Island site (Figure 5). Hence, Attu Island is in phase with the distant northeastern Pacific PDO rather than with the central North Pacific PDO.

[6] Along with spatial correlations to regions of cold and warm PDO anomalies, linear regression of the Attu Island δ^{18}O time series against ERSST data exhibits a tripole SST pattern with a weak positive pole in the mid-latitude central Pacific (Figure 5). Negative poles are located in the northeastern Pacific – northeastern Bering Sea area and in the central equatorial Pacific ENSO region. Spectral analyses of the proxy time series exhibit spectral power at typical ENSO periods (4 years; Figure 4). The Attu time series (lag–6 months) is linearly correlated with the NINO 4 index and significant throughout the entire record (Table 2). NINO 4 (5S–5N, 160E–150W) is the ENSO index most closely reflecting climate patterns in the central equatorial Pacific where correlation with the Attu δ^{18}O time series is highest (Figure 5). A similar lag of 6 months had also been observed in a study of summertime North Pacific temporal variability, which is highly correlated with ENSO during the preceding spring [*Lau et al.*, 2004]. Furthermore, a signif-

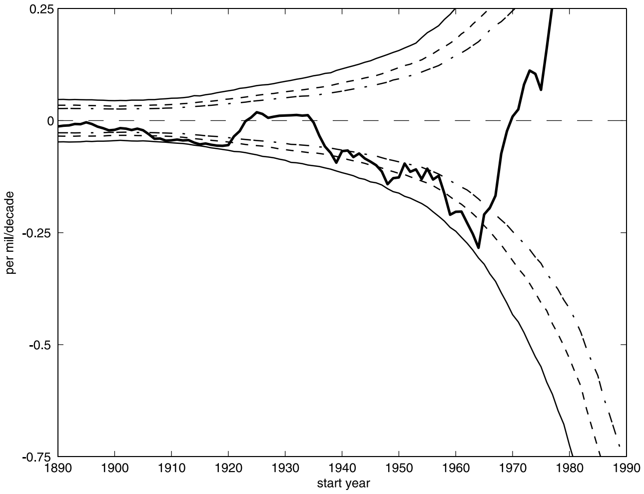

Figure 3. Variable startpoint analysis of the trend in the Attu Island time series (thick black curve) and confidence limits (1% and 99% solid curves; 5% and 95% dashed curves; 10% and 90% dash-dotted curves) indicating a negative trend (=warming and/or freshening of surface waters) becoming significant between 1940–1960.

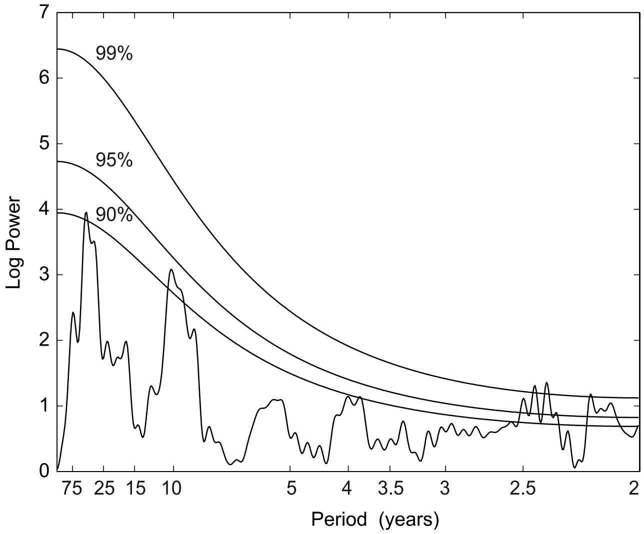

Figure 4. Multi-taper power spectrum of the Attu island annual δ^{18}O-time series (1886–2003) showing significant power at ~60, 10, 4, 2.5 and 2.25 years.

Table 2. Correlation Coefficients and Significance Levels of Annually Resolved *C. Nereostratum* Isotope Time Series From Attu Island, Alaska

	r	Significance Level, %	Years
Instrumental temperature$_{\text{June–Nov}}$[a]	−0.46	1	1960–2003
PDO$_{\text{June–Nov}}$[b]	−0.34	0.5	1900–2000
NINO 4[c]	−0.23	1.8	1900–2000
NAO$_{\text{Jan–Mar}}$[d]	−0.17	3.8	1900–2000

[a] Annually averaged June to November ERSST [*Smith and Reynolds*, 2004] are plotted.

[b] PDO index [*Mantua et al.*, 1997] shows annually averaged June–November data.

[c] Isotope values are correlated to NINO 4 index [*Kaplan et al.*, 1998] with 6 months lag.

[d] Isotope values are correlated to January–March NAO index [*Hurrell*, 1995] with 1 year lag.

icant lagged correlation is also found with the North Atlantic Oscillation (NAO) during the preceding winter months (Table 2). This result is in agreement with recent work that has identified a lagged response to the NAO in a number of long-term climate data sets from the western North Pacific that is related to strong atmospheric coupling between the Atlantic - Pacific and Eurasian snow anomalies [*Zhao and Moore*, 2006].

[7] Instrumental and proxy based studies have described atmospheric ENSO teleconnections in the northeastern Pacific region [*Alexander et al.*, 2002; *MacDonald and Case*, 2005; *Moore et al.*, 2001; *Trenberth and Stepaniak*, 2001]. However, regression of ENSO indices against global ERSST data indicates that the central North Pacific is outside the area of significant extratropical response to ENSO signals [*Trenberth and Stepaniak*, 2001]. ENSO patterns observed in our Attu proxy record can be explained by a combination of ENSO and PDO signals being transmitted from the northeastern Pacific to the Attu Island site via oceanic teleconnections through the Alaskan Stream and associated mesoscale eddies. Hence, we propose a scenario of atmospheric ENSO teleconnections to the northeastern Pacific and subsequent dynamic oceanic teleconnections of a combined northeastern Pacific PDO and ENSO signature to the outer Aleutians. This interpretation explains the weak correlation of the red algal time series, which reflects the oceanography of the narrow Alaskan Stream, with spatially averaged central North Pacific ERSST data. It also clarifies the lagged response of the proxy record to ENSO due to slow propagation of the ENSO signal via oceanic pathways to the outermost Aleutians.

[8] Diminished correlations of ENSO and PDO$_{\text{June–Nov}}$ with the Attu Island proxy time series were observed during intervals dominated by a negative PDO$_{\text{June–Nov}}$ such as during the 1947–1977 and the early 20th century cool phases (Figure 2). In contrast, during positive PDO$_{\text{June–Nov}}$ phases, ENSO and PDO$_{\text{June–Nov}}$ are highly correlated to the red algal proxy record. Reasons are that a) teleconnected ENSO signals tend to be stronger and more stable during preferred phases of the PDO [*Gershunov and Barnett*, 1998], and (b) the Alaskan Stream transport is enhanced during preferred phases of the PDO, i.e. when SSTs are high in the northeastern Pacific. This results in a stronger propagation of northeastern Pacific signatures to the Attu Island proxy site. In fact, an intensification of the Alaskan Stream (south of 54°N) after the mid-1970's regime shift

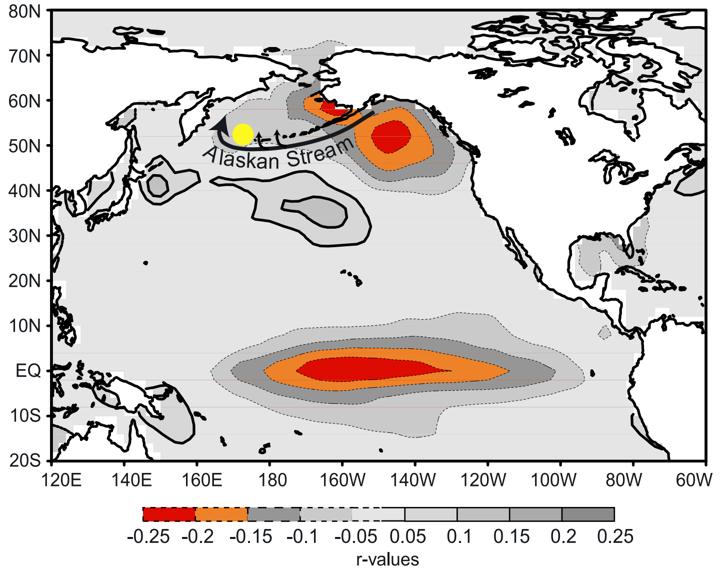

Figure 5. Regression of monthly ERSST [*Smith and Reynolds*, 2004] against annual Attu δ^{18}O time series (6 months lag) for the period of 1886–2003. Negative correlations shown by stippled line, positive ones by solid line. Orange color indicates 90%, red color 95% significance level. Yellow circle marks location of Attu proxy time series (computed at climexp.knmi.nl [*van Oldenborgh and Burgers*, 2005]).

(=shift toward positive northeastern Pacific PDO) has been observed [*Capotondi et al.*, 2005]. Furthermore, the Alaskan Stream decelerated along the Aleutian Islands since 1998 when the PDO shifted into a negative state [*Volkov and van Aken*, 2005]. Hence, the red algal proxy record enables a reconstruction of the Alaskan Stream transport variability. Even small fluctuations in the magnitude and position of the Alaskan Stream can have major consequences on the exchange of water masses between the North Pacific Ocean and the Bering Sea through Aleutian Island passages. Significant warming and or freshening of the Alaskan Stream is apparent from the proxy record beginning in the middle of the 20th century. This will not only affect climate and ecosystems in the Aleutian Islands and Bering Sea, but will ultimately influence water masses passing through the Bering Strait and contribute to Arctic climate change [*Woodgate et al.*, 2006].

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