The Holocene 9,1 (1999) pp. 79–84

A 1119-year tree-ring-width chronology from western Prince William Sound, southern Alaska

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Received 5 January 1998; revised manuscript accepted 1 June 1998

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Abstract: Living and subfossil trees from glacier forefields are used to develop a 1119-year-long tree-ring-width chronology. Strong cross-dating among ring-width series from sites up to 60 km apart and an analysis of sample homogeneity support combination of all samples into a single, regional composite chronology. Comparison with instrumental climate data indicates May through July temperatures of the growth year are the primary control on ring-widths. Multidecadal-length warm periods in western Prince William Sound during the past 800 years were centred on AD 1300, 1440 and possibly 1820. Multidecadal-length cool periods were centred on AD 1400, 1660 and 1870. This is the first tree-ring chronology from the Gulf of Alaska region to extend into the first millennium AD.

Key words: Dendroclimatology, dendrochronology, tree-rings, palaeoclimate, late Holocene, Alaska.

Introduction

The Gulf of Alaska is a key centre of action in the north Pacific atmosphere-ocean climate system (Wilson and Overland, 1987). Instrumental climate records in this region seldom exceed 100 years in length and so cannot provide the 'palaeo-perspective' required for evaluation of possible future climate change (Bradley and Jones, 1993; Overpeck, 1995). A partial solution to this problem is given by tree-ring chronologies developed from forests fringing the Gulf of Alaska. These proxy records of past environmental change preserve information on subannual to century timescales and so enable a more complete picture of natural climate variability to be discerned.

Ring-width and densitometric chronologies from living trees around the Gulf of Alaska have previously been used in several dendroclimatic and dendrogeomorphic studies (Cropper and Fritts, 1981; Jacoby and Ulan, 1983; Schweingruber *et al*., 1993; Wiles and Calkin, 1994; Wiles *et al*., 1996; 1998). However, these chronologies are temporally limited by the biological longevity of the tree species used and most span less than 400 years. The few exceptions that are up to 900 years long suffer from low sample size in the early sections or contain climatic signals that are not readily interpretable (Jacoby *et al*., 1996).

Rapid decay of subaerially exposed dead wood in the maritime climate of the Gulf of Alaska means that snags are generally not available for extending living tree-ring chronologies back in time. However, large amounts of subfossil wood have been preserved under glaciers and in glacial and fluvial sediments in the western Prince William Sound area of the Gulf. These remnants of low elevation coastal forests were killed by 'Little Ice Age' glacial advances and provide an opportunity to develop a well replicated tree-ring chronology reaching back over 1000 years. In this paper we report on the construction and preliminary interpretation of the first such millennium-length tree-ring chronology from the Gulf of Alaska region. Implications of dates of the subfossil wood for the glacial history of western Prince William Sound are discussed in a companion paper (Wiles *et al*., 1999).

Setting

The study area is located among the coastal Kenai and Chugach mountains of western Prince William Sound, southern Alaska (Figure 1). Climate is maritime, with the Town of Seward having a mean temperature of −4.1°C in January, 13.2°C in July and mean annual precipitation of 1710 mm (unpublished data from Alaska Climate Research Center, 1997). Whittier to the north (Figure 1) records similar temperatures with a much greater mean annual precipitation of 4520 mm for the period 1957 to 1971 (Farr and Hard, 1987). Mountains of the region locally reach to 1800 m (6000 ft) and are heavily glacierized. Many outlet glaciers of the Sargent Icefield and the Spencer-Blackstone Ice Complex

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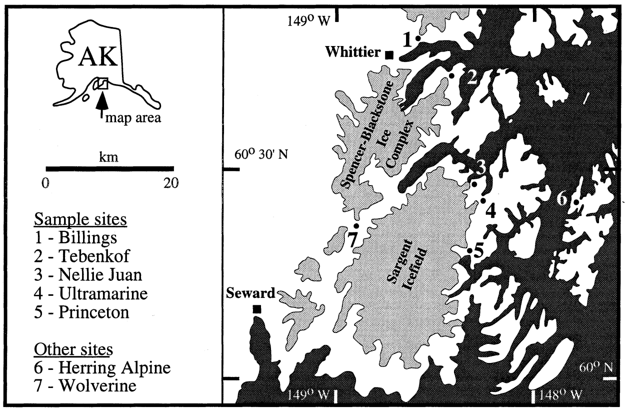

Figure 1 Location map of the western Prince William Sound study sites, southern Alaska.

reach close to sea level and the forefields of these ice tongues form the study sites (Figure 1).

Forests of western Prince William Sound are dominated by mountain hemlock (*Tsuga mertensiana* (Bong.) carr.) with minor amounts of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) carr.) also present (Cooper, 1942; Viereck and Little, 1972). Mountain hemlock forms almost pure stands close to sea level in some areas of the inner fjords in addition to being the only species found near the altitudinal tree-line at 610 to 915 m.

Sample collection and cross-dating

Subfossil wood was collected in western Prince William Sound during the summers of 1991 through 1993. Sites that yielded ring-width series discussed in this paper are located in Figure 1 and summarized in Table 1; further details and maps of the sample sites are given in Wiles *et al.* (1999). Samples were collected as cores or discs from the least rotted portion of each log found. Cores were also taken from living mountain hemlock growing within 90 m of sea level adjacent to the forefields of Tebenkof and Nellie Juan glaciers (Figure 1). Both growth sites were bedrock knobs at or close to the respective 'Little Ice Age' terminal moraines and we consider these sites to be similar to the growth settings of the majority of the subfossil wood used in this study.

Almost all subfossil samples were identified in the laboratory as being hemlock based on gross features of the sanded surfaces (Brown *et al.*, 1949). Identification to species level was not attempted, but as mountain hemlock dominates the composition of forests around the sample sites it probably forms the majority of the subfossil wood collected. Inclusion of some western hemlock and Sitka spruce in this study should not pose a problem as their dendroclimatic response in the northern Gulf of Alaska region is similar to that of mountain hemlock (Cropper and Fritts, 1981; Jacoby and Ulan, 1983; Wiles *et al.*, 1998).

Initial cross-dating focused on the development of 'floating' tree-ring-width chronologies for subfossil samples from the Billings-Tebenkof, Nellie Juan, Ultramarine and Princeton areas (Figure 1). Ring-widths along one or two radii from each tree were measured to the nearest 0.001 mm and cross-date positions were suggested using the XDATE routine (E. Cook, unpublished). Chronology verification was performed with the COFECHA routine (Holmes, 1983) and by visual analysis of marker rings. One floating chronology was developed from each of the Nellie Juan, Ultramarine and Princeton sites while the subfossil wood at Billings-Tebenkof formed three distinct floating chronologies.

The floating site chronologies were then compared with one another and with the two calendar-dated chronologies developed from the living trees at Tebenkof and Nellie Juan. The Nellie Juan, Ultramarine and one of the Billings-Tebenkof subfossil floating chronologies cross-dated with the two living tree chronologies while the Princeton and second Billings-Tebenkof chronologies matched with the early portion of the subfossil Nellie Juan chronology (Figure 2). All cross-dates between the chronologies (Table 2) are significant at the 0.01% level or better. The third floating subfossil chronology from Billings-Tebenkof did not cross-date with any other ring-width chronologies; a radiocarbon age of 1500 BP (cal. AD 590) from one of the undated samples at Tebenkof confirms that this chronology is too old to cross-date with any wood collected at the other sites.

During cross-dating we noticed that the last rings in some samples were anomalously narrow when compared with samples from other trees that did not die at the same time. Mathews (1951)

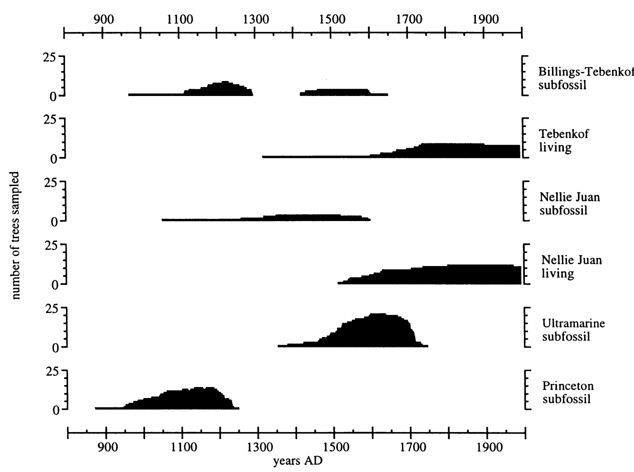

Figure 2 Histograms showing number of trees per calendar year in each of the site chronologies.

Table 1 Sample sites of ring-width series

Glacier* forefield	Sample type	Latitude	Longitude	Elevation (m)	Number of series	Number of trees	Timespan
Billings	subfossil	60° 49′ N	148° 37′ W	25	3	3	1419–1601
Tebenkof	living	60° 45′ N	148° 27′ W	25	11	9	1318–1991
Tebenkof	subfossil	60° 44′ N	148° 28′ W	60	13	10	968–1293
							1464–1647
Nellie Juan	living	60° 28′ N	148° 20′ W	90	16	12	1513–1991
Nellie Juan	subfossil	60° 27′ N	148° 21′ W	30	8	4	1052–1598
Ultramarine	subfossil	60° 25′ N	148° 18′ W	90	31	21	1354–1746
Princeton	subfossil	60° 18′ N	148° 22′ W	90	29	17	873–1249

*See Figure 1 for location.

Table 2 Correlation coefficients (upper right of matrix) and number of years of overlap between site chronologies. Series were detrended using a 32-year spline and prewhitened to remove biological persistence

	BI-TB	TBL	NJ	NJL	UL	PR
BI-TB	–	0.40	0.49	0.36	0.58	0.57
TBL	229	–	0.43	0.71	0.56	–
NJ	422	281	–	0.68	0.58	0.55
NJL	135	479	86	–	0.69	–
UL	229	393	245	234	–	–
PR	282	0	198	0	0	–

BI-TB = Billings-Tebenkof subfossil.
TBL = Tebenkof living.
NJ = Nellie Juan subfossil.
NJL = Nellie Juan living.
UL = Ultramarine subfossil.
PR = Princeton subfossil.

attributed such growth suppression in glacially killed trees to the influence of the advancing ice margin and Bray and Struik (1963) suggested that cold air drainage from the glacier may be the cause. However, glacially induced growth suppression is generally limited to within a few metres of the ice margin (Mathews, 1951; Bray and Struik, 1963; Luckman, 1996; Nicolussi and Patzelt, 1996) and so should not introduce significant error into dendroclimatic inferences from the trees used in this study. Ring-width series with strong suppression of the last years of growth had the anomalous sections deleted before final chronology construction.

Missing rings and exceptionally slow growth were found by Cropper and Fritts (1981) to present significant difficulties to cross-dating of their cores from hemlock. We encountered similar problems but with the large number of subfossil discs collected were able to trace most missing rings around the circumference to pinch-outs. Pinch-out rings along measured radii occurred in years of below average ring-width in other trees 72% of the time supporting a climatic cause for the locally missing growth increment. However, several samples were found to have up to five pinch-out or completely absent rings in a row; these did not occur at times of generally decreased ring-widths in other trees and so trauma local to the individual tree seems the most likely cause of these multiple absent ring events.

Development of the composite chronology

The strong cross-dating among the individual site chronologies suggested that it was appropriate to combine all the samples into a regional composite chronology. This would provide a continuous ring-width record from AD 873 to 1991 and also, through the averaging process used to develop the composite chronology, enhance the regional climatic signal common between all samples while reducing local, site-specific signals as noise.

The raw ring-width data were detrended (Fritts, 1976; Cook and Kairiukstis, 1990) using splines with a 50% frequency response cutoff equal to 67% of the length of each series. This data adaptive method involves no *a priori* assumptions regarding the form of the raw ring-width data (Cook, 1985) and so is appropriate for the subfossil samples in this study whose exact growth environment is unknown. Standardization using the 67%n criteria should also preserve most of the low frequency information that can theoretically be recovered from each tree-ring series (Cook, 1985). The composite chronology was calculated in the ARSTAN routine (Cook and Holmes, 1984) using a biweight robust mean and no autoregressive modelling. Basic chronology statistics are given in Table 3.

Homogeneity of the composite chronology was examined using the Principal Component Analysis (PCA) method of Peters *et al.* (1982). Although cross-dating among site chronologies was very strong, local soil and/or microclimate conditions at the sample sites could impart enough influence on tree growth to make the individual ring-width series used in the composite chronology heterogeneous in their signal. PCA was performed on three common intervals selected to contain the maximum possible overlap of series from different sites: AD 1120 to 1210, 1434 to 1552, and 1745 to 1991. In all three PCAs the first eigenvector accounted for 36 to 41% of the total variance which is typical for ring-width series within a site from the Gulf of Alaska region. Loadings of all detrended ring-width series onto the first eigenvector were virtually identical and no patterns attributable to specific sites were noted. The PCA results suggest that, at least for the periods examined, the series comprising the composite chronology are homogenous in their signal.

The Expressed Population Signal (EPS) was used to determine the minimum number of trees required to provide an acceptable estimate of the composite chronology mean value function (Wigley *et al.*, 1984). Correlations between all detrended series with 20 or more years overlap were used to calculate between tree ($\bar{r}_{bt}$) and within tree ($\bar{r}_{wt}$) mean correlations (Table 3). Because the number of series taken from individual trees varied through the chronology, minimum and maximum values of the effective number of cores (c_{eff}) and the effective chronology signal ($\bar{r}_{eff}$) were calculated (Briffa and Jones, 1990). Using an EPS of 0.85 (Wigley *et al.*, 1984) suggests that a minimum of nine or ten trees is required to maintain an acceptable level of statistical quality in the chronology signal.

Climatic response and chronology signals

Monthly climate records at Seward (unpublished data from Alaska Climate Research Center, 1997) were compared with the composite chronology and strong positive correlations were found with May, June and July temperatures (Figure 3). A strong negative relationship was also determined for May precipitation. All the correlations are significant at the 1% level and these results are consistent with other ring-width dendroclimatic studies from the Gulf of Alaska region (Cropper and Fritts, 1981; Jacoby and Ulan, 1983; Wiles *et al.*, 1998). The tree-line chronologies studied by Wiles *et al.* (1998) were also significantly correlated with temperatures in March and April in addition to May through July, suggesting that the lower elevation trees used in this study have a shorter annual period of climatic sensitivity.

The composite chronology (Figure 4) shows considerable variance on interannual to decadal timescales. Both El Niño-Southern

Table 3 Descriptive statistics of the composite chronology. Mean correlations are based on all detrended series with 20 or more years of overlap

Mean sensitivty	0.216
Lag-1 autocorrelation	0.554
Mean correlation between trees, $\bar{r}_{bt}$	0.350
Number of correlations between trees, N_{bt}	2421
Mean correlation within trees, $\bar{r}_{wt}$	0.762
Number of correlations within trees, N_{wt}	35
Min/max effective chronology signal, $\bar{r}_{eff}$	0.359/0.398
Min/max effective number of cores, c_{eff}	1.11/2.00

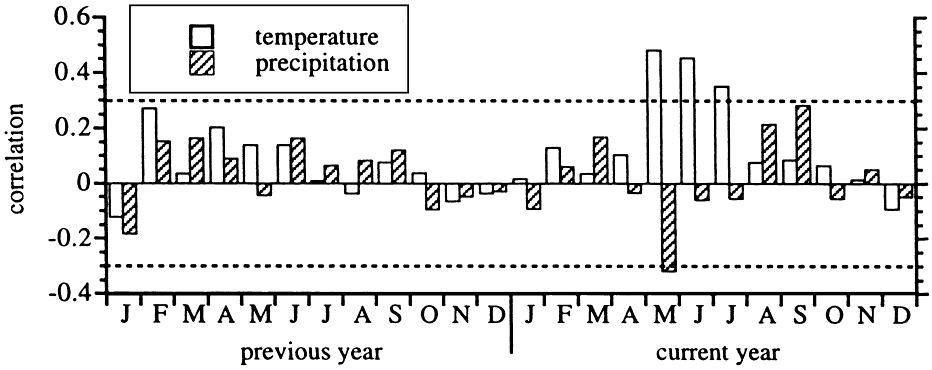

Figure 3 Correlation of the composite chronology with monthly records of mean temperature (open bars) and total precipitation (patterned bars) from Seward, 1908 to 1991. The dashed lines indicate the 1% significance level.

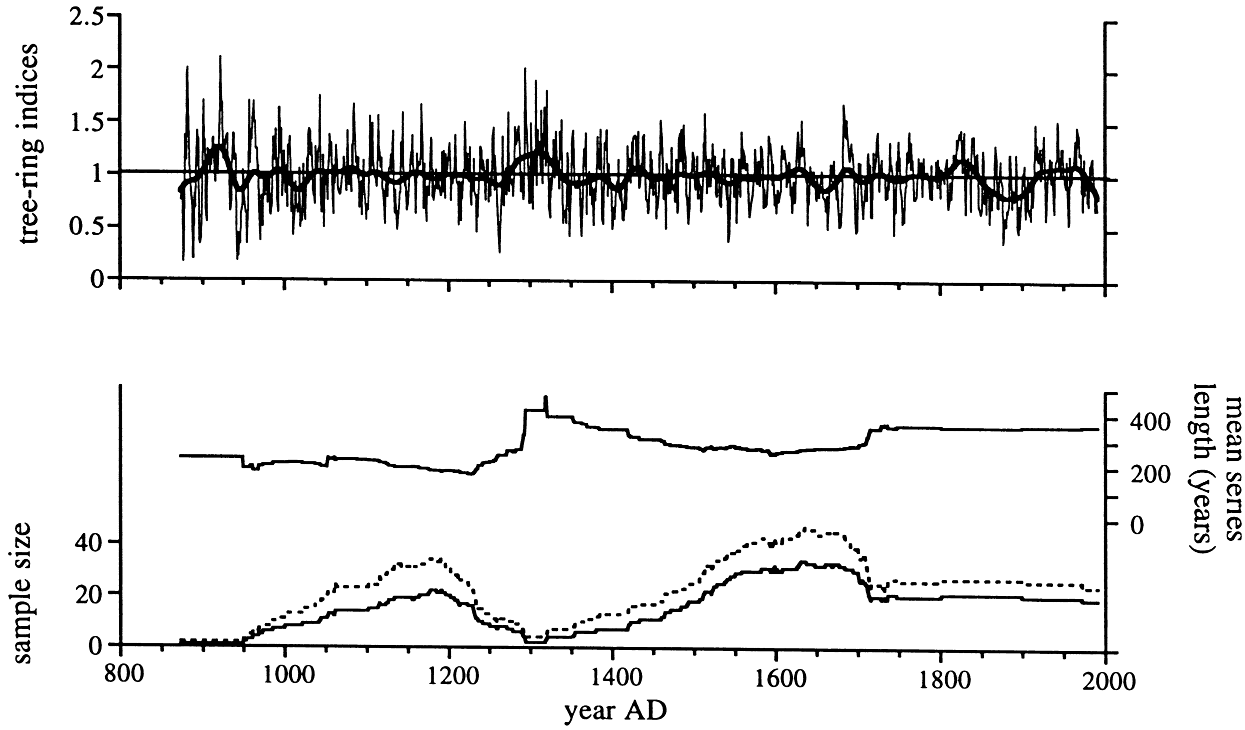

Figure 4 Upper panel shows the western Prince William Sound composite chronology. The bold line is a 50-year smoothing spline that emphasizes low frequency variations. Lower panel depicts the mean series length and sample size in the composite chronology. Mean series length was calculated by averaging the lengths of all series contributing to the chronology index in each year of record. Sample size through time shows number of ring-width series (dashed line) and number of trees (solid line) in each year.

Oscillation (Quinn *et al.*, 1987) and the proposed North Pacific bidecadal oscillation (Latif and Barnett, 1994) fall within this general bandwidth, and so the composite chronology presented herein may compliment other millennial-length proxy records of past activity of these important atmosphere-ocean phenomena (D'Arrigo and Jacoby, 1992; Diaz and Pulwarty, 1994).

Preservation of multidecadal or longer fluctuations in the composite chronology are complicated by the 'segment length curse', that is, the maximum wavelength of information remaining in a ring-width series after standardization is roughly equal to one third of the series length (Cook *et al.*, 1995). This means that although the composite chronology is over 1000 years long it will only contain information in proportion to the lengths of its component ring-width series. The composite chronology is composed of many short series from ~AD 1050 to 1250 (Figure 4) and the spline-smoothed chronology shows little deviation from the long-term mean during this interval. In contrast, multidecadal signals are more evident during the last 300 years of the chronology when the component ring-width series are typically 300 to 400 years long.

Sample size within the composite chronology is below nine trees from AD 873 to 1020 and from AD 1250 to 1419 (Figure 4). While the chronology signal is not necessarily in error at these times it should be interpreted with caution. Sample size reaches a minimum of four series from two trees between AD 1294 and 1317; visual examination of these two sample discs found no evidence to suggest missing rings through this period and so we consider the calendar dates given to the first 400 years of the chronology to be accurate.

Comparison with other regional proxy records of climate

In general, the relative magnitude of multidecadal departures from the long-term mean in the composite chronology are not directly comparable with each other or with other climate proxy records due to the segment length curse and temporal changes in sample size. However, these dendroclimatic problems should not affect the timing of low-frequency fluctuations in the composite chronology. In Figure 5 we compare the last 800 years of the spline-smoothed composite chronology with two tree-ring records from western Prince William Sound that are independent of the low-elevation trees used in this study. The Herring Alpine chronology (Figures 1 and 5b) is from western hemlock growing at tree-line on Knight Island over 25 km from the nearest glacier (Cropper and Fritts, 1981), whereas the 'Wolverine tree' ring-width series is from the oldest living mountain hemlock yet found at tree-line in western Prince William Sound (from near Wolverine Glacier; Figures 1 and 5c). The latter record, while derived from only a single tree, should preserve multidecadal- to century-length signals that may have been lost during development of the two tree-ring chronologies.

These tree-ring records show general consensus with cool intervals centred on AD 1400, 1660 and 1870, and warm intervals at AD 1300 and 1440. The two tree-ring chronologies also show a warm interval centred on 1820; however, the Wolverine tree indicates a gradual century-length warming that peaked around AD 1760 instead. Examination of raw ring-width data from trees of this study that extend through this period found some that mirrored the century-length fluctuation of the Wolverine tree while others showed the later, more abrupt warming reflected in the western Prince William Sound composite and Herring Alpine

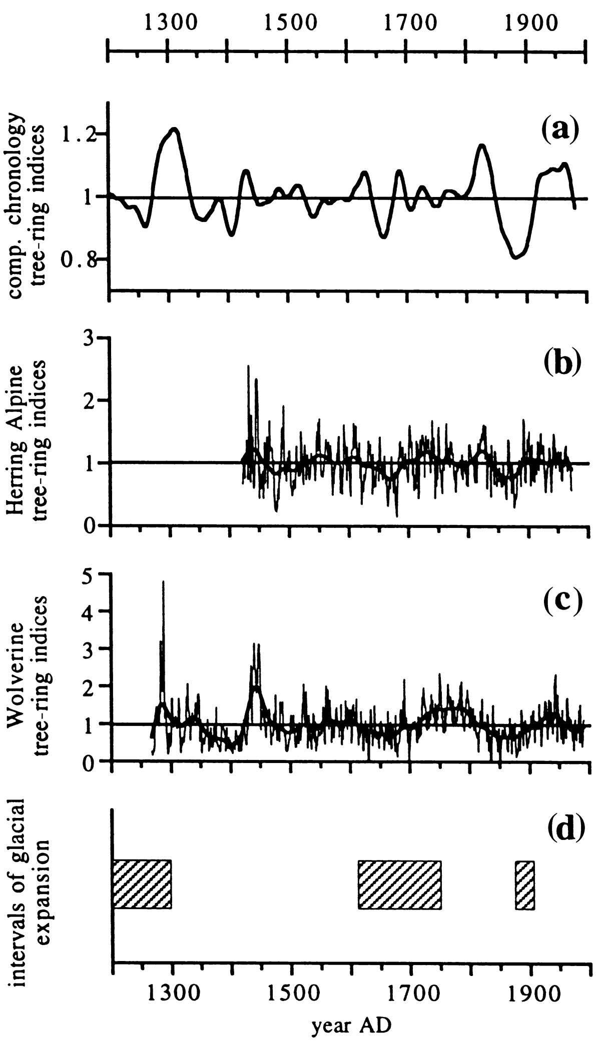

Figure 5 Comparison of western Prince William Sound proxy records of climate: (a) composite tree-ring chronology of this study smoothed with a 50-year spline; (b) Herring Alpine tree-ring chronology (Cropper and Fritts, 1981); (c) ring-width series from a tree-line mountain hemlock near Wolverine Glacier, standardized using a spline with stiffness equal to 67% of the series length; (d) intervals of glacial expansion in the western Prince William Sound region.

chronologies. This question of eighteenth- through early nineteenth-century temperatures will require further study to be resolved.

Many glaciers in the western Prince William Sound region advanced to reach maxima during the late nineteenth century (Wiles *et al.*, 1999), and this corresponds with the multidecadal cool interval centred on 1870 in the tree-ring records (Figure 5). Two earlier intervals of regional glacier expansion in the thirteenth and eighteenth centuries were also centred on multidecadal cool intervals recorded in the composite chronology. However, these times of glacier advance also partially overlap with multidecadal warm intervals, indicating that the response of glaciers in this region to climatic forcing is more complex than a direct relationship with spring and summer temperatures.

Conclusions

The objective of this study was to demonstrate the dendrochronologic and dendroclimatic potential of low-elevation trees from glacier forefields around western Prince William Sound. Due to the biological longevity of tree species in the region and the rapid decay of dead wood in this maritime climate, subfossil wood preserved in glacial deposits provides the best opportunity for construction of multimillennial-length tree-ring records in the region.

May through July temperatures of the year of growth were found to be the dominant climatic control on ring-width variation, and samples collected from sites up to 60 km apart were sufficiently similar in their growth signal to be combined into a single chronology. The resulting composite chronology of this study extends from AD 873 to 1991 and is the first tree-ring chronology from the Gulf of Alaska region to span over 1000 years. Multidecadal cool periods during the past 800 years were centred on AD 1400, 1660 and 1870, and warm intervals were centred on AD 1300, 1440 and possibly 1820.

Climatic interpretation of the western Prince William Sound composite chronology is currently limited by the segment length curse and temporal changes in sample size. Future sampling will attempt to increase the number of ring-width series bridging intervals with low sample size, and also add more long ring-width series to the chronology to improve preservation of low-frequency signals.

Acknowledgements

We thank Gordon Jacoby for advice during this project and for reviewing an earlier version of this manuscript. Comments by Brian Luckman and an anonymous reviewer also helped improve this paper. Luigi Cremis and Dino Maraldo assisted in the field. Climate data were provided by the Alaska Climate Research Center (http://climate.gi.alaska.edu). This work was supported by National Science Foundation grants DPP-8922696 and OPP-9321213.

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