Abrupt climate change and variability in the past four millennia of the southern Vancouver Island, Canada

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[1] The identification of past climatic extremes and norms is important for a better understanding of the climate systems and the way they change. Here we present an almost continuous tree-ring and climate record from Vancouver Island, Canada for the last four millennia from Douglas-fir trees (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) that are sensitive to precipitation variation. Spring droughts more severe than that of the mid-1920s occurred in the late 1840s, mid-1460s AD, and ~ mid-1860s BC. A remarkable climatic anomaly occurred in ~ the 19th century BC during which strong pentadecadal oscillation prevailed and radial growth decreased by 71% in four years. This event could have been the final stage in the process of climatic and environmental transition beginning 2–3 centuries earlier that led to major cultural transformation in regions sensitive to climate change. **Citation:** Zhang, Q.-B., and R. J. Hebda (2005), Abrupt climate change and variability in the past four millennia of the southern Vancouver Island, Canada, *Geophys. Res. Lett.*, *32*, L16708, doi:10.1029/2005GL022913.

1. Introduction

[2] Tree-ring records spanning millennia are of exceptional value in elucidating natural variability and answering questions about basic atmospheric process such as whether climate changes gradually or undergoes decadal regime shifts or longer scale state shifts [*Hughes and Diaz*, 1994]. Such proxy records, however, are usually inhibited by the scarcity of large sample sizes of well-preserved subfossil wood. We report a nearly complete 4000-year tree-ring record from subfossil Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) from southern Vancouver Island, Canada. Located in the path of the westerlies directly adjacent to the North Pacific Ocean, this region is in a critical position to record the behaviour of a major global climatic driver and its impacts on ecosystem development [*Mantua and Hare*, 2002]. Our study adds a new region to the complement of long tree-ring records. Notably the record contains a marked growth anomaly that would shed light on climate variability in the final stage of climate re-organization beginning at ~4.2 kaBP, a globally recognized point of climatic and cultural change [*Weiss*, 2000].

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2. Materials and Methods

[3] A large number of well-preserved subfossil logs were discovered at the bottom of Heal Lake (48°32′N Lat., 123°28′W Long., 120 m asl.) near the city of Victoria in 1992. Radiocarbon dates of selected log samples indicated that the age of these logs varied from 150 ± 50 radiocarbon years before present (BP) to 9230 ± 60 years BP. Most of these logs were from Douglas-fir as identified by wood anatomy. Disc samples were collected from 706 large and well-preserved logs for dendroclimatological studies. Increment core samples from living Douglas-fir trees in the vicinity of Heal Lake were collected in the late fall of 1992 to develop a master tree-ring chronology to the present and to analyze the current climate-tree-ring growth relationship.

[4] Tree-ring samples were prepared, and the ring widths measured and cross-dated following standard procedures [*Stokes and Smiley*, 1996]. To date, 150 samples (29 from recent trees and 121 from subfossil logs) have been cross-dated into a continuous two-millennium long series, and 37 and 42 samples have been cross-dated into two floating series for the past 3rd and 4th millennia, respectively. Radiocarbon dates from seven samples in the past 3rd millennium and three samples in the past 4th millennium help delimit the temporal position for the two floating chronologies. The length of the cross-dated tree-ring samples ranges from 62 to 505 years with a mean of 170 years and of these, 35 samples are more than 250 years long.

[5] The measured ring-width sequences were standardized using a conservative curve-fitting method to remove the age-related growth trend [*Cook et al.*, 1990]. The subsequent standardized series were then averaged together by year among different samples to minimize the random micro-site growth signals. The resulting tree-ring indices represent growth variations caused by large-scale environmental forcing, mainly climate. Our previous study of the climate-growth relationships using a nonlinear artificial neural network modelling and the same samples from Heal Lake site demonstrated that 66.8% of the tree-ring variance can be represented by climatic variables of which low precipitation in spring and early summer (April to July) is a major factor limiting radial growth of Douglas-fir [*Zhang et al.*, 2000]. Coherent variations in tree-ring growth among different sites in the coastal British Columbia [*Zhang and Hebda*, 2004] indicate that the Heal Lake chronology

Table 1. Dendrochronological Characteristics of the Douglas-Fir Tree-Ring Chronologies at Heal Lake, Southern Vancouver Island, BC, Canada

	Master Chronology	Floating Chronology I	Floating Chronology II
Chronology length	130 BC – A.D. 1992 (2122 years)	946 BC – 183 BC (764 years)	1949 BC – 1233 BC (717 years)
Number of trees	150	37	42
Mean sensitivity	0.20	0.19	0.19
Mean serial correlation	0.56	0.59	0.62
First-order autocorrelation	0.86	0.91	0.89

reflects variation in spring precipitation on macroregional scale.

[6] We used the technique of wavelet analysis [*Torrence and Compo*, 1998] to transform the tree-ring chronologies into a two-dimensional function of frequency and time. This approach allows us to assess climate oscillations on various time scales and how they vary in time. The wavelet function used in the study is a Morlet wavelet with a wave number of six, and the wavelet power significant at the 5% level is tested against a red noise process.

3. Results and Discussion

3.1. Climatic Anomalies and Oscillations

[7] The mean serial correlation coefficients for the three chronologies ranged from 0.56 to 0.62, suggesting that the radial growth of different trees was responding somewhat synchronously to a common growth-controlling factor, most probably the large-scale climate (Table 1). The strength of climatic signals expressed by the tree-ring indices increases with the increase in the number of sample replications. Among the three chronologies, the lowest signal strength was 0.68 when there were only five sample replications, and 0.81 when there were 10 sample replications. The chronology intervals used in this study contains usually at least 5 sample replications for each year except for a few short intervals that lack enough tree-ring samples (Figure 1). The tree-ring chronologies show that the magnitude and duration of climatic variability during the past 4000 years are not well represented by the variation in the brief modern period. Spring droughts more severe than that of the mid-1920s AD (as represented by growth departure exceeding 2 units of standard deviation below the mean in at least five consecutive years) occurred in the late 1840s, mid-1460s AD, and ~ mid-1860s BC. Some droughts prior to the 17th century had longer duration than those recorded in the last century, a phenomenon consistent with the observations in the central United States [*Woodhouse and Overpeck*, 1998]. The most persistent drought occurred during the 1440s–1560s AD. Other severe and multidecadal droughts included those in the mid-760s–800s, the 540s–560s, the 150s - late 190s AD, and around 800 BC. The climate during the Little Ice Age was characterized by a long-term wet condition during the late1560s - mid-1760s and by episodic wetness following this interval. There was no sign of apparent changes in the tree-ring chronology during the 10th–14th centuries, suggesting that, corresponding to the North Atlantic Medieval Warm Period, the spring precipitation regime in our study area was relatively stable around its mean condition. Our tree-ring data reveal variations at time-scales from annual, decadal to century. Trends in longer time scales cannot be detected because they might

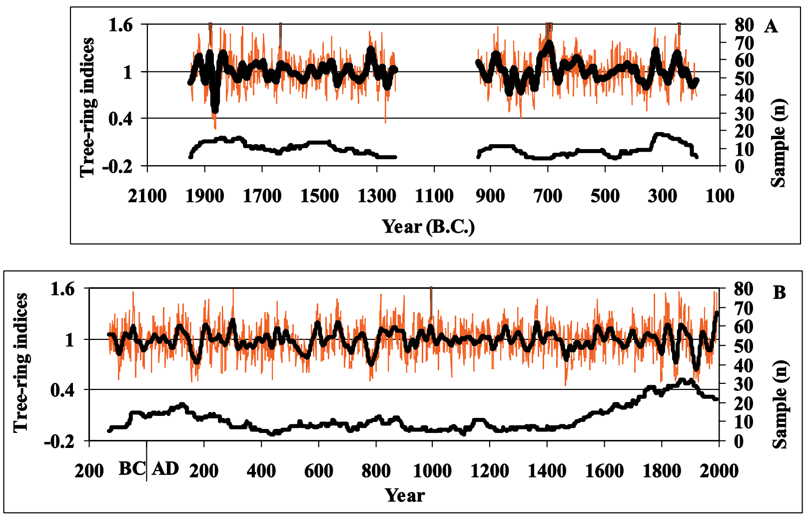

Figure 1. The ring-width chronologies of Douglas-fir for Heal Lake site, southern Vancouver Island, BC, Canada. (a) shows the two floating chronologies for the period ~1949 B.C.–1233 B.C. and ~946 B.C.–183 B.C., respectively, and (b) shows the continuous chronology for 130 B.C.–1992 A.D.. The smoothed curves superimposed on the chronologies are derived after filtering to emphasize long-term fluctuations (the filter is a cubic spline passing 50% of the variance in a sine function with a wavelength of 32 years). The number of samples shown below each chronology is indicative of the strength of climatic signals expressed by the chronology.

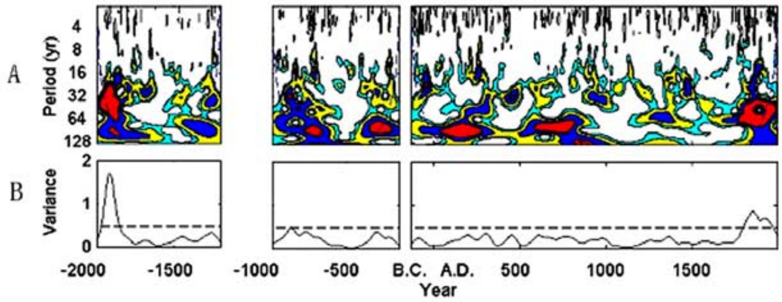

Figure 2. The wavelet power spectrum (a) and the scale-averaged wavelet power over the pentadecadal (30–80 years) band (b) for tree-ring chronology of Douglas-fir on southern Vancouver Island, British Columbia, Canada. Contours enclosing the red, blue, yellow and green regions are at wavelet powers of 16, 8, 4 and 2. Black contour is the 5% significance level, using a red-noise (autoregressive lag1) background spectrum. Region below the dashed curve is the cone of influence, where zero padding to the end of the finite time series has reduced the variance. The dashed horizontal line is the 5% significance level for a red noise process.

have been removed in the process of standardization [*Cook et al.*, 1995].

[8] The results of wavelet analysis of the tree-ring chronologies show that the pattern of climate variability has not remained the same during the last 4000 years (Figure 2a). Climate oscillation at pentadecadal time scale (30–80 years) prevailed in the 19th–20th century AD and ~ the 19th century BC, and drifted toward century time scale in the late 6th–early 9th century, the 2nd–mid-3rd century AD, ~ the mid-3rd–4th century, and ~ the mid-8th - mid-9th century BC. Bidecadal (10–30 years) and interannual (2–8 years) oscillations existed intermittently with varying amplitude and persistence in the past four millennia.

[9] Scale-averaged wavelet power over the 30–80-yr band for the tree-ring chronologies was calculated to examine the fluctuations in pentadecadal variance versus time [*Torrence and Compo*, 1998]. A most striking feature of the wavelet power spectrum and the averaged pentadecadal band power (Figure 2b) is that strong pentadecadal oscillation dominated in ~ the 19th century BC after which it almost disappeared for the rest period of record in the second millennium BC. Bidecadal and interannual oscillations also existed in this period of time. The tree-ring chronology shows that the growth state reversed five times during ~1910–1810 BC and these reversals were rapid.

3.2. Abrupt Climate Change at ~4000 yr B.P.

[10] A markedly unique growth anomaly occurred about the mid-1870s–mid-1850s BC. The tree-ring indices decrease precipitously from a growth surge to almost no growth within only seven years (~1879–1872 BC), with most of the decline (71%) in only four years. This sudden growth decline is clearly evident in the rings of 14 wood sections. The magnitude of the presumed climatic anomaly is exceptional because normally the degree of growth reduction caused by annual conditions is muted by the preconditioning of the trees for strong growth by previous years of excellent growth [*Zhang et al.*, 2000]. Whereas a decrease in spring precipitation must have been a major factor in reducing tree growth, the ecological mechanisms underpinning growth extremes are complex and temperature changes may have been involved in abrupt growth suppression. The sudden growth decline followed by persistent drought and a cyclic pattern of good and poor growth cannot to our knowledge be explained by non-climatic factors such as pest infestations.

[11] Within the geographic region, the 4000 yr BP horizon is notable as a time of climate change and fluctuation. Annually varved sediments at nearby (5 km distant) Saanich Inlet reveal an interval of severe drought in ~23rd century BC [*Nederbragt and Thurow*, 2001]. Pollen and spore analyses compiled for the Holocene of British Columbia place the transition from the relatively warm and moist mesothermic mid-Holocene to the cool and wet late Holocene at about ~4000 BP [*Hebda*, 1995].

[12] The Heal Lake event is not restricted to the surrounding region. Major climatic anomalies showing drought in ~4.2–3.9 kaBP have been noted in proxy records from numerous sites in North America [*Schwalb et al.*, 2003], Europe [*Dalfes et al.*, 1997; *Leuschner et al.*, 2002] and equatorial Africa [*Gasse*, 2000]. The importance of the ~4.2–3.9 kaBP horizon as time of Aegean, Egyptian, West-, South-, and Central Asian cultural change has been analysed intensively [*Weiss*, 2000]. In the Pacific Northwest this time also marks major cultural shifts on the Coast in the Interior [*Hebda and Mathewes*, 1984]. The apparent scale and rapidity of change indicated by our tree-ring record strongly suggests a climatic component to major cultural changes through its impacts on the landscape and its resources.

[13] Considering the widespread climatic phenomena in the northern hemisphere, we propose that the tree-ring sequence at Heal Lake identifies a period of major climatic fluctuation and state shift of macro regional and possibly global extent at ~4000 yr BP. Overall this period of climate instability falls within an interval of climatic transition from warm and moist mid-Holocene to cool and wet late Holocene in the region. The abrupt shift from a moist regime to a dry regime within four years, and the subsequent two decades of drought could have been the final stages in the process of climate re-organization begun about 2–3 centuries earlier [*Weiss et al.*, 1993; *Weiss*, 2000]. Considering the major cultural transformations, the relative climatic stability that followed may have allowed for the re-establishment of a subsistence-landscape equilibrium leading to the eventual development of the diverse and complex cultures we experience today.

3.3. Climatic Regime Shifts

[14] It is interesting to note that the tree-ring width pattern of the past two centuries is also characterized by rapid reversals of growth state (Figure 1) and by the dominance of strong pentadecadal oscillation (Figures 2a and 2b). The signal of bidecadal oscillation was weak in the 17th and 18th century, and that of the pentadecadal oscillation was relatively weak in the 15th to the mid-16th century. Climatic regime shifts, occurring in different strength and at varying time scales, were reported to be traceable back to the 17th century in the western North America [*Biondi et al.*, 2001; *Gedalof and Smith*, 2001]. Our tree-ring data suggest that such fluctuations were at smaller amplitude during the 17th and 18th centuries than during the 19th and 20th centuries. In fact, the pentadecadal signal has been either absent or weak during most the past 4000 years in our record. The dominance of pentadecadal oscillation and its co-existence with bidecadal and interannual oscillations at ~4000 yr BP and the recent past suggests that we may have just passed through nearly 4000 years of relative climatic stability, but are now entering an interval of climatic instability.

[15] The tree rings at ~4000 yr BP document a situation of major climate change and provide a baseline for examining the rapidity and amplitude of climate change we are experiencing today. Particularly, the tree rings at ~4000 yr BP provide evidence for the abrupt onset of climatic extremes in the Pacific Northwest where no such phenomenon had been observed before. The profound and prolonged reduction and fluctuation in growth and presumably primary productivity would have had profound impacts on ecosystem processes and structure. The mechanisms behind such climatic anomalies are, however, not currently known. Some studies have suggested that the climate variation in the Pacific Northwest is linked to large-scale atmospheric circulation and sea surface temperature anomaly patterns associated with the Pacific Decadal Oscillation (PDO) and its modulation of ENSO teleconnections [*Gershunov and Barnett*, 1998; *Mantua and Hare*, 2002; *Newman et al.*, 2003]. Resonance in the multi-time scale oscillations in the North Pacific Index has been suggested as a factor contributing to the occurrence of climatic regime shifts of North Pacific in the last century [*Minobe*, 1999]. ENSO proxy records from lake sediments in the southern Ecuadorian Andes reveal a relatively low ENSO activity during the recent past century and the period around 4000 yr BP [*Moy et al.*, 2002]. The occurrence of climatic anomalies at ~4.2–3.9 kaBP over different parts of the globe hints at a strong PDO-like climate involving large-scale air-sea interactions such as a connection between subtropical gyre circulation and variations in the Aleutian low-pressure system [*Latif and Barnett*, 1994]. Our data do not shed light on a specific mechanism but do point to phenomena operating on multi-time scales in the period of climate transition. The work also contributes to the database for calibrating and refining numerical models representing strong climatic oscillations. Knowledge of the magnitude, duration and co-existence of multiscale climatic oscillations during a horizon emerging as a widespread climate transition helps us understand better the climate system, and appreciate its ability to vary widely and rapidly.

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