

A 2122-Year Tree-Ring Chronology of Douglas-fir and Spring Precipitation  
Reconstruction at Heal Lake, Southern Vancouver Island, British Columbia.

by

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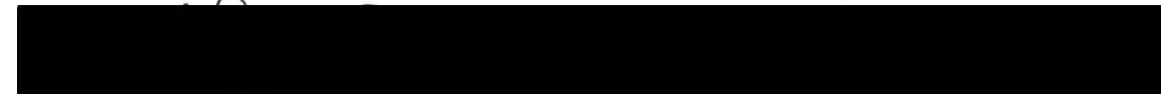
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ABSTRACT

A 2122-year tree-ring chronology was developed from living and submerged logs of Douglas-fir at Heal Lake, near Victoria, southern Vancouver Island, British Columbia. Correlations between the tree-ring indices and monthly mean temperature and monthly total precipitation indicated that the radial growth of Douglas-fir was strongly correlated with the spring and early summer (April-July) precipitation and the previous years' growth. A transfer function was established using tree-ring indices to predict the weighted 5 years' effective precipitation. The reconstructed precipitation history for the last two millennia exhibited eight distinct climatic intervals involving long periods of wetness and drought and extreme events. The result showed that the Little Ice Age was featured by wetness in the interval A.D. 1567-1765 and there were occurrences of wet episodes before and after this interval. There was no evidence of Medieval Warm Period in the area. Comparison with other studies in the nearby regions showed general agreement and demonstrated a regional climatic control. The result can be applied in a broad range from the fundamental understanding of the climate system to the practical management of our natural resources.

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DEDICATION

This thesis is dedicated to my hometown working unit: Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Lanzhou, Gansu, P.R. China.

## Chapter 1: INTRODUCTION

### 1.1 Climate History and Dendroclimatology

Climatic change has impacts on food, water and energy resources which are essential to our human life. Past climate history can offer a good reference to understand patterns of climate variability. Particular research interests in climatic variations during the last two millennia have increased because two major climate episodes, i.e. the Medieval Warm Period and the Little Ice Age, stand out and may help us understand the dynamics of our climate (Folland *et al.*, 1990; Hughes and Diaz, 1994; Stahle and Cleaveland, 1994). A well-documented history of past climate covering the whole of the last two millennia with dating good to the calendar year and capable of recording interannual, decadal and century-scale fluctuations is critical to deciphering the patterns of climatic change (Hughes and Diaz, 1994).

Dendroclimatology, which is concerned with reconstructing past climate by use of tree rings, is one of the best approaches to providing such a year-by-year proxy climate documentation of the past (LaMarche, 1978). Tree growth is frequently affected by variations in climate and the yearly sequence of favourable and unfavourable climatic conditions is faithfully recorded by sequences of wide and narrow rings in large number of trees (Fritts, 1976). These sequences of ring-width can be assigned to, or associated with specific calendar years by means of cross-dating and averaged to form a tree-ring chronology (Fritts, 1976). This process characterizes the discipline of dendrochronology. The past climate can then be reconstructed from the year-to-year changes in annual ring-

width (Fritts, 1976; Hughes et al., 1982; Cook and Kairiukstis, 1990). The precise dating and annual resolution of tree rings is superior to most other sources of palaeoclimatic information especially in temperate and subpolar regions where trees have a broad geographical distribution and high climatic sensitivity (Cook et al., 1994). At present, however, there are not enough tree-ring chronologies established for different parts of the world, and there are only a few chronologies that can extend back for several thousand years (Ferguson, 1969; Baillie, 1977a, 1977b; Pilcher and Hughes, 1982; Brown et al., 1992; Hughes and Diaz, 1994; Kelly et al., 1994). This lack of record inhibits our understanding of the long-term global-scale pattern of climatic change. Thus, the construction of tree-ring chronologies in new regions of the world and the extension of tree-ring records backward in time is significant not only for understanding the local climate history but also for exploring the global-scale climate system. Long sequences of dendroclimatic data can help us to examine current climatic fluctuations such as those attributed to "global warming" in a long term perspective and, in addition, the long data sets can be used to test numerical models of climate (Pittock, 1982) to improve the prediction of future climates.

### 1.2 Heal Lake Study on Tree-Rings and Climate

The excavation of Heal Lake near Victoria, BC, Canada revealed the presence of numerous subfossil logs buried within the lake sediments (Hebda, 1993a; 1993b). These logs provided an opportunity to build a long tree-ring chronology for the purpose of reconstructing past climate in this area (Hebda, 1993a; 1993b).

The objectives of this study were 1) to construct a tree-ring chronology for the Heal Lake site in southern Vancouver Island; 2) to establish the dendroclimatic relationship between this chronology and climatic factors; and 3) to reconstruct the late Holocene climate history of the Heal Lake area.

This thesis begins by introducing the reasons for conducting this dendroclimatic study, the purpose of the study, and major related previous studies. Chapter 2 describes the setting of the study area and the collection of samples. Chapter 3 covers the method of tree-ring chronology construction including measurement, crossdating, standardization and the chronology results and discussion. Chapter 4 treats the relationship between tree-rings and climate. Chapter 5 describes and discusses the reconstruction of spring and early summer precipitation history of the last two millennia. Finally, chapter 6 presents the summary, applications and conclusions of the study.

### 1.3 Previous Studies

To date, there are no detailed millennium-long dendroclimatic studies for southern Vancouver Island. However, a number of relevant studies were conducted in the Pacific Northwest and other parts of British Columbia (Keen, 1937; Schulman, 1947; Blasing and Fritts, 1976; Fritts et al., 1979; Fritts, 1991; Graumlich, 1987; Luckman, 1993, 1995; Desloges and Ryder, 1990; Laroque, 1995; Smith and Laroque, 1996; Wiles et al., 1996). These studies not only provide valuable tree-ring chronologies but also shed light on past climate history of the region. Several review papers (Smith, 1970; Brubaker, 1982; Luckman and Innes, 1991; Hughes and Diaz, 1994) and one book on large-scale climate

reconstruction (Fritts, 1991) have been published containing information on dendroclimatic studies in the Pacific Northwest and BC.

In the Pacific Northwest, Keen (1937) was one of the first to conduct an extensive study of the tree-rings and their relationship with precipitation. He developed a chronology extending back to A.D. 1268 using stump sections of ponderosa pine in eastern Oregon and showed that precipitation varied over the period. Graumlich (1987) reconstructed precipitation variation in the Pacific Northwest for the period of 1675-1975 based on ring-width data from seven drought-sensitive conifer species. The results indicated that droughts similar in magnitude and duration to those in the 1920s and 1930s had occurred frequently in the past, though the timing of drought episodes varied spatially. She also pointed out that severe, single-year drought events had affected the Pacific Northwest as a whole, and suggested that regional atmospheric circulation features caused the extreme events.

Tree-ring chronologies and climate reconstructions in western North America have been widely studied (Fritts, 1965; Blasing and Fritts, 1976; Fritts *et al.*, 1979; Brubaker, 1982). Many of these are summarized by Fritts (1991). He used 65 tree-ring chronologies from eight species to reconstruct large-scale climatic patterns from A.D. 1602 to 1963 for western North America. The results provide a firm basis for comparisons with reconstructions of climatic patterns over other parts of the Northern Hemisphere.

A pioneer study for British Columbia was that of Schulman (1947), who collected samples of Douglas-fir and ponderosa pine near Quesnel, Williams Lake, Alkali Lake, Tranquille, Vernon and Penticton. Schulman provided a tree-ring chronology from A.D.

1420 to 1944 and which showed a positive correlation between ring-width and the winter-season rainfall. Luckman (1993, 1995) and his colleagues (Luckman and Osborn, 1979; Luckman et al., 1993) studied climate variation for the last millennium in the Canadian Rocky Mountains by means of dendrochronologically dating glacier advances. His work at Robson Glacier (1995) suggested that there was an early "Little Ice Age" glacier advance between A.D. 1142 and 1150 that continued until at least A.D. 1350. Smith and Laroque (1996) used the same technique to study Moving Glacier on Vancouver Island and the results showed that the glacier expanded to its maximum Little Ice Age position after A.D. 1818, and that significant recession did not begin until this century. These results are in agreement with those of Desloges and Ryder (1990) who studied the Neoglacial history of the Coast Mountains near Bella Coola, British Columbia. Laroque (1995) investigated the dendrochronological and dendroclimatological potential of yellow-cedar on Vancouver Island and concluded that the tree's radial growth was sensitive to climatic fluctuations. Previous August temperature was the most likely variable to influence variation in ring width. Wiles et al. (1996) reconstructed April-September temperature variation for the period A.D. 1750-1983 on the Pacific Northwest coast based on a network of coastal ring-width and maximum latewood density tree-ring chronologies. Their results showed summer temperature cooling in the early 1800s, warming in the 1850s and around 1870, and also indicated large-scale oceanic-atmospheric influences.

Smith (1970) summarized the states of many subfields of tree-ring studies in BC and emphasized the aspects of forest management. Luckman and Innes (1991) examined the development of dendrochronology in Canada. Among their lists of chronologies

established in BC, the oldest one from Douglas-fir is about 550-year old in Naramata.

Brubaker (1982) reviewed tree-ring collections and dendroclimatic research in western North America and also discussed the future prospects and opportunities. Hughes and Diaz (1991) reviewed the dendroclimatic studies concerning the Medieval Warm Period and Little Ice Age, and concluded that the available evidence offer little support for a sustained Medieval Warm Period/Little Ice Age sequence in the last 1000 years.

The previous studies carried out in the Pacific Northwest have suggested that many trees, e.g. Douglas-fir, ponderosa pine, yellow-cedar, are sensitive to either precipitation or temperature in different areas. However, the available chronologies are short due to the lack of materials extending back to earlier time. Possibilities for developing longer tree-ring chronologies exist using long-lived species and subfossil materials (Pilcher and Hughes, 1982; Luckman and Innes, 1991).

## Chapter 2: THE SETTING AND SAMPLE COLLECTION

The growth of trees is influenced by a complex of environmental factors of a regional and local nature (Glock, 1955; Fritts, 1976). It is important in dendroclimatology that one or more critically limiting environmental factors should persist sufficiently long, and act over a wide enough geographic area, to cause ring widths to vary the same way in many trees (Fritts, 1976). This chapter describes the setting of southern Vancouver Island and the Heal Lake site and then introduces the source of samples for this study.

### 2.1 The Setting

#### 2.1.1 The Study Area -- Southern Vancouver Island

British Columbia's physiography strongly shapes its climate and vegetation (Hebda, 1995). Vancouver Island, the largest island of the north Pacific, has relatively low flatlands along the east and west coasts, and rugged mountains in the central interior. Southern Vancouver Island contains three physiographic regions: lowlands, highlands and mountains (Yorath and Nasmith, 1995) (Figure 2.1). The Nanaimo lowland is on the east and south side of the island, and consists of gently rolling hills that give way to flatter plains bordering much of the Strait of Georgia. The South Vancouver Island Ranges lie southeast of Alberni Inlet, and consist of many rugged mountains. Nanaimo Lakes Highland and Victoria Highland are regions of transition between the South Vancouver Island Ranges and the Nanaimo Lowland.

Generally the climate of the southern Vancouver Island is mild in temperature,

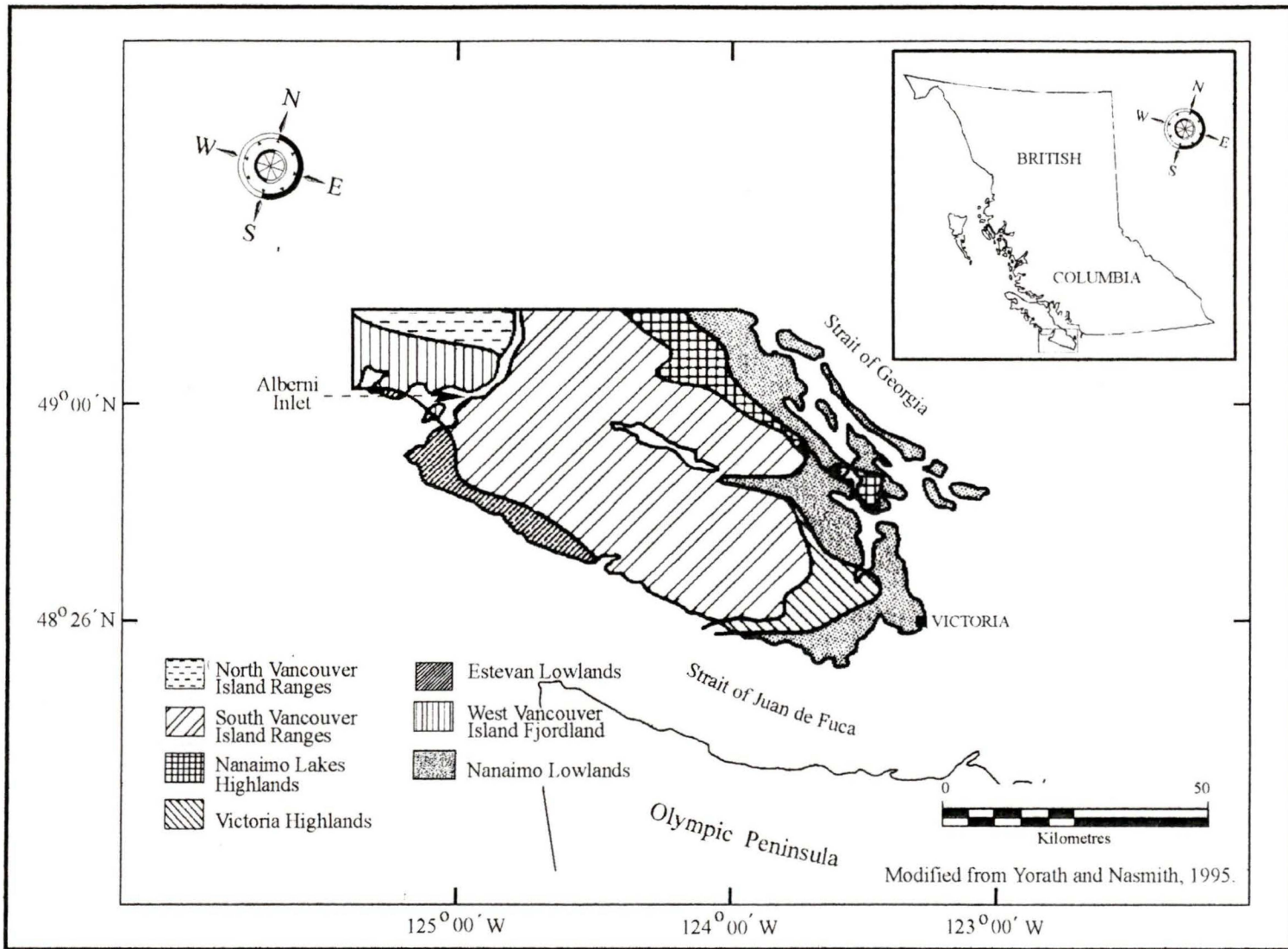


Figure 2.1 Physiographic regions of southern Vancouver Island

with wet winters and relatively dry summers. The Pacific Ocean provides a moderating influence and a source of moisture along the western boundary. The mountain ranges alter the moist air masses moving eastward and result in a steep precipitation gradient from west to east and south to north (Schaefer, 1978). Consequently different ecosystem types exist and reflect strongly the climatic and topographic characteristics of the regions.

The biogeoclimatic zone classification system, derived by Krajina on the basis of broad characteristics of climate, physiography and vegetation, is used to categorize the ecosystems for B.C. (Klinka *et al.*, 1979). Southern Vancouver Island has three biogeoclimatic zones: Coastal Douglas-Fir (CDF), Coastal Western Hemlock (CWH) and Mountain Hemlock (MH) zones (Meidinger and Pojar, 1991) (Figure 2.2). The CDF zone is located along the southeast coastal lowland in the rainshadow of the Olympic Peninsula and Vancouver Island Mountains. It has warm dry summers and mild wet winters. The mean annual temperature is from 9.2 to 10.5°C and the total precipitation ranges between 647 and 1263 mm respectively with December and January being the coldest and wettest months and July and August the warmest and driest months in the year (Meidinger and Pojar, 1991). The most common tree species in the CDF is the coastal variety of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirbel) Franco). Other species include western red-cedar (*Thuja plicata* Donn), grand fir (*Abies grandis* (Dougl.) Forbes), arbutus (*Arbutus menziesii* Pursh.) and Garry oak (*Quercus garryana* Dougl.), depending on site moisture and nutrient regime. Zonal soils are mostly Dystric Brunisols which has thin organic horizon and median base saturation, grading with increasing precipitation into Humo-Ferric Podzols which has little organic matter and accumulated iron and aluminum

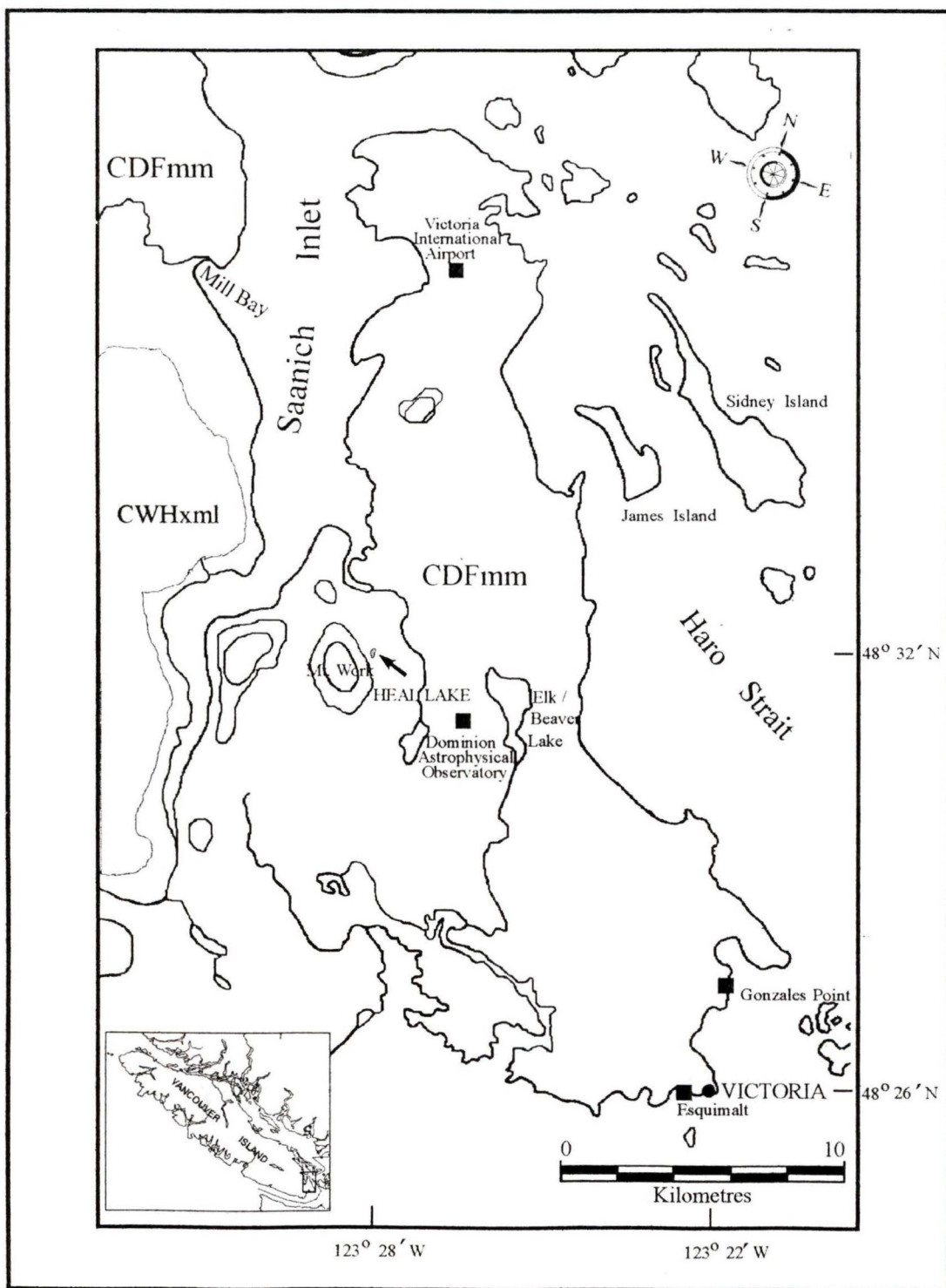


Figure 2.2. The biogeoclimatic zones of southern Vancouver Island and locations of sample site and climatic stations.

(Meidinger and Pojar, 1991).

The CWH zone covers much of the Vancouver Island. It has cool summers and mild winters and is the rainiest biogeoclimatic zone in B.C. (Meidinger and Pojar, 1991). The MH zone is usually the subalpine zone above the CWH and has short, cool summers, and long, cool, wet winters (Meidinger and Pojar, 1991).

### 2.1.2 The Study Site -- Heal Lake

Heal Lake (123°28'W Long., 48°32'N Lat.), before being drained, was situated in the CDF zone and located at the Hartland Road Landfill on the Saanich Peninsula (Figure 2.2). The lake was at 126 metres above sea level and was about 150 metres wide and over 300 metres in length covering approximately 4 ha. The long axis of the lake trended north-west by south-east. The lake was shallow, and was confined on the eastern side by a large rock bluff and on the western side by the slopes of Mt. Work.

Trees surrounding the lake site include Douglas-fir, western red-cedar, arbutus, red alder (*Alnus rubra* Bong.) and bigleaf maple (*Acer macrophyllum* Pursh). Douglas-fir is the dominant species and is largely distributed on the rocky slopes of nearby Mt. Work, whereas bigleaf maple occupies the moister, unstable stream margins (Allen, 1995). The most characteristic soils of the site are Dystric Brunisols and Humo-Ferric Podzols (Valentine et al., 1978). The annual climatic regime (Figure 2.3) for the site shows that abundant precipitation occurs during the winter and water deficit is considerable in the growing season. Thus soil moisture appears to be an important factor limiting the growth of trees.

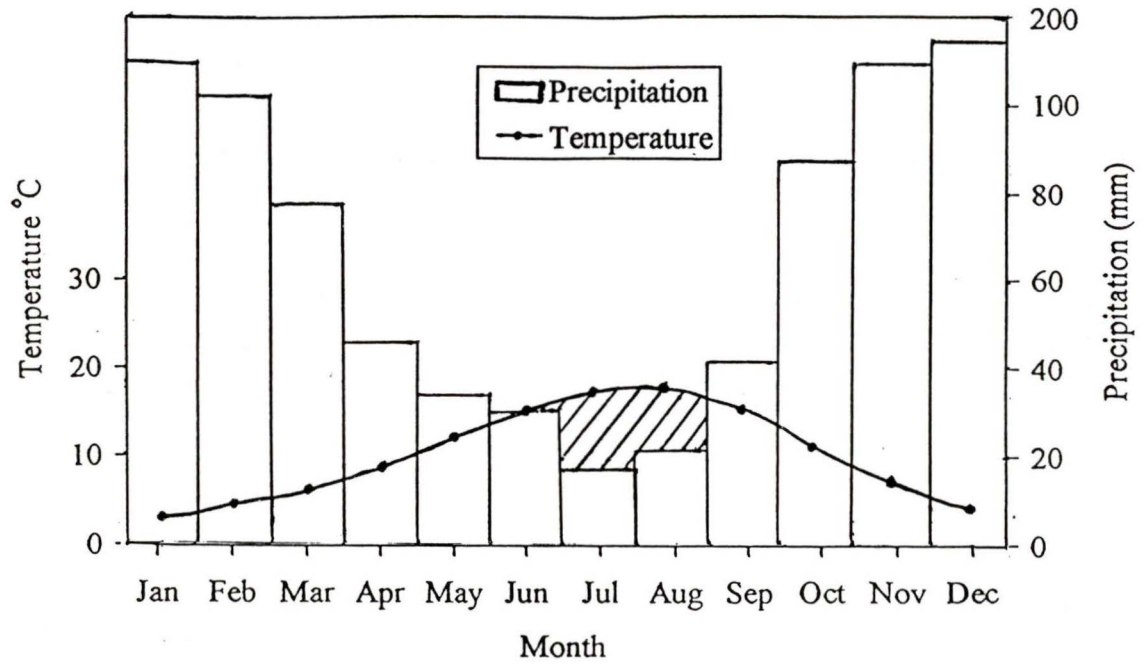


Figure 2.3. Annual climatic regime for the Heal Lake area (Averaged for A.D. 1891-1992 using records from meteorological stations at the Little Sannich Mountain, Victoria International Airport, Gonzales Hill and Esquimalt. Spittlehouse, personal communication, 1994. The shaded area represents seasons of drought).

## 2.2 Sample Collection

### 2.2.1 Submerged Logs

In the fall of 1991, Heal Lake was drained by the Capital Regional District to provide additional space for the disposal of municipal wastes (Figure 2.4). The sediments exposed in the bottom of the lake revealed large amounts of well-preserved ancient logs (Hebda, 1993a; 1993b) (Figure 2.5). Presumably these were trees that at one time lived on the surrounding slopes and subsequently were buried in the lake sediments by some causes, e.g. felling by storm, flooding, slope failure, root rot and fire. The sampling of these buried logs began in the summer of 1992 as the lake-bottom sediments were being excavated.

The logs were buried irregularly in the lake-bottom sediments in the near shore zone and were pulled out by machine during the excavation operations. Hence there is little indication of their stratigraphic position. In the field, a 15-20 cm thick disk was cut from selected logs and, in addition, a 3-metre long section of selected sufficiently long and large logs was retained. In total, 706 disks and 300 long logs were collected in the field. All of these samples were then shipped to Pacific Forestry Centre (PFC), Canadian Forestry Service, Victoria, for storage and measurement.



Figure 2.4. Heal Lake excavation in the summer of 1992.

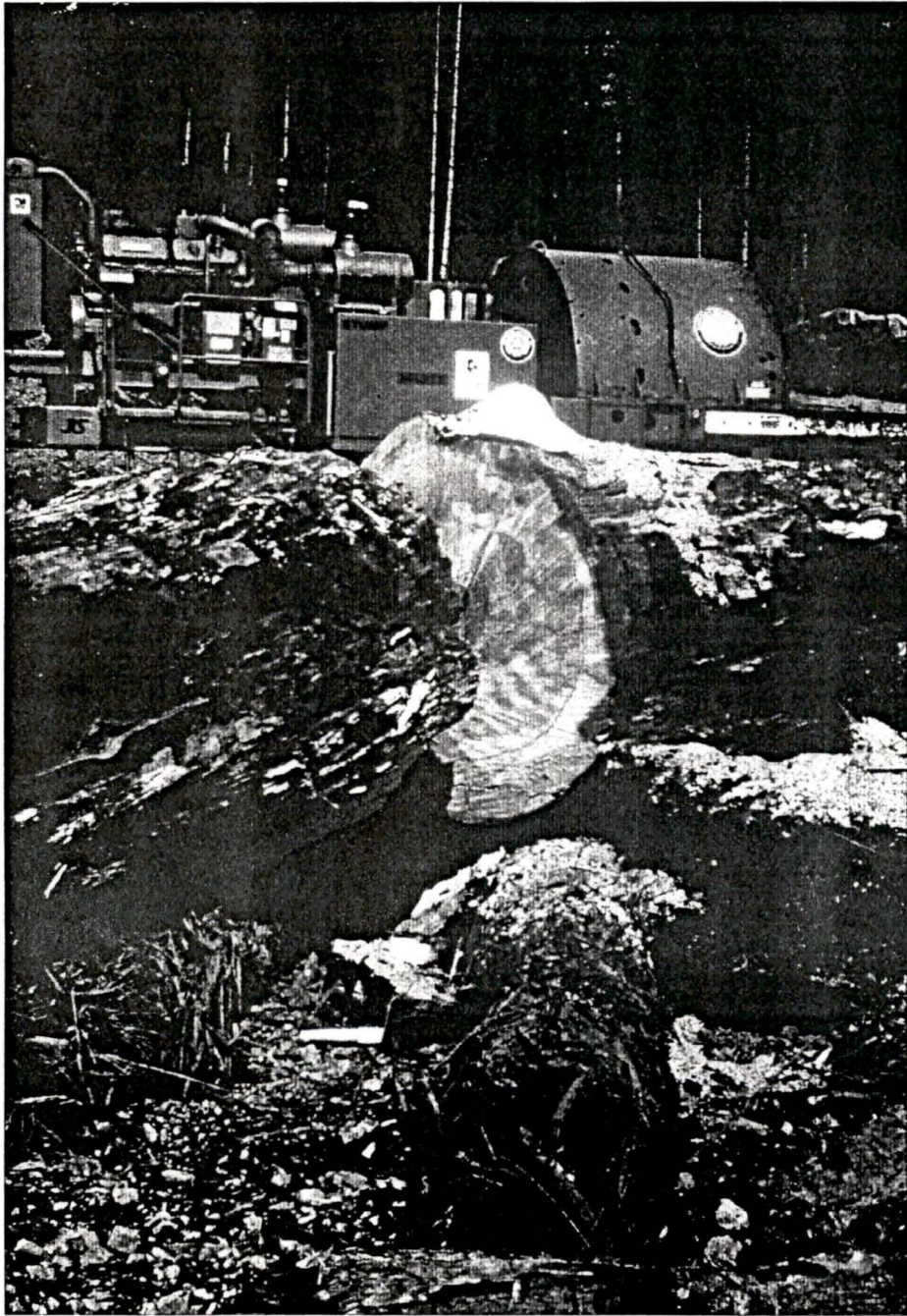


Figure 2.5. Subfossil logs discovered from the lake sediments.

### 2.2.2 Living Trees

In order to fix the chronology developed from those buried logs of unknown age to calendric scale and to make calibration analysis with the climate record, samples from living trees were needed to construct a living chronology. Samples were collected on dry and mesic sites in the vicinity of Heal Lake in the fall of 1992. Increment borers were used to extract cores at breast height on side slope position from trees of old living Douglas-fir. The cores, 4 or 5 mm in diameter, were kept in plastic straws and labelled with site and tree numbers. Some large stumps containing rings further back in time were also found in the field and disks were cut and collected from them. In total 25 increment cores from living trees and 5 disks from large stumps were obtained. The former were stored in a refrigerator, and the latter were stored in a shed, all at PFC.

## Chapter 3: CHRONOLOGY BUILDING

With the large numbers of wood samples collected at Heal Lake, a long ring-width chronology could be built. Samples were identified to species in order to restrict the chronology to a single species. Ring widths were measured and cross-dated to produce the master series. The ring series were then standardized to reduce the non-climatic effect. The result was a ring-width chronology that would be used later to interpret the climatic variation in the past.

### 3.1 Wood Identification.

It is well known that trees of different species may have different physiological processes in changing ecological conditions, and consequently the characteristics of annual growth rings may be different (Fritts, 1976). In order to keep the climatic information clear and simple the construction of chronology is usually restricted to a single species (Fritts, 1976, 1982). In this study, only the samples from Douglas-fir were selected to build the chronology and the other species were left to a later separate study to examine the climatic or nonclimatic events that can cause different responses in different tree species. To do so, all the wood samples were identified to species based on botanical features.

The identification of species for buried logs and stumps were based on microscopic examination of internal wood anatomy. Thin slices of cross, radial and tangential sections of the wood were cut and mounted on a microscope slide in glycerin

jelly (Friedman, 1978). After being heated to expel air bubbles and sealed to avoid drying out, the slide was ready for storage and examination. All the permanent slides were stored in the laboratory of the Royal B.C. Museum. The species was determined according to the arrangement of tracheid cell and ray cell, structure of pit, patterns of secondary wall thickening, presence of canal and other features (Table 3.1) under microscope using a wood anatomy key (Friedman, 1978). The result showed that among the 678 good quality wood samples from which slides were made, 614 (90.6%) were Douglas-fir, 56 (8.3%) were western red-cedar, 5 (0.7%) were western white pine, and 3 (0.4%) were lodgepole pine.

For the living chronology only Douglas-fir was selected because it was the dominant species and grew on drought sensitive sites near Heal Lake. The recognition of Douglas-fir in the field was based on its external morphology (e.g. distinct cone with three-toothed bracts).

### 3.2 Measurement of Ring-Width.

All the wood cores and disks were measured at the Tree-Ring Lab, Pacific Forestry Centre, Canadian Forestry Service, Victoria. Samples were first prepared to get a clear resolution of surface structure. Some disc characteristics (e.g. colour, ratio of early wood/latewood and fire scars) were recorded in a notebook during the measurement. These features are helpful for crossdating of samples.

The preparation method for increment cores involved using a razor blade to trim the sample surface at a cutting angle of 35 degrees to the grain of the wood (Douglass,

Table 3.1. Diagnostic wood anatomy features of *Pseudotsuga menziesii* (Mirbel) Franco, *Thuja plicata* Donn, *Pinus monticola* Dougl. and *P. contorta* Dougl. (From Friedman, 1978)

	<i>Pseudotsuga menziesii</i> (Mirbel) Franco	<i>Thuja plicata</i> Donn	<i>Pinus monticola</i> Dougl.	<i>Pinus contorta</i> Dougl.
Cross section	transition from earlywood to latewood generally abrupt; resin canals present.	transition from earlywood to latewood generally abrupt; resin canals absent.	transition from earlywood to latewood gradual; resin canals present.	transition from earlywood to latewood more or less abrupt; resin canals present.
Radial section	ray tracheids nondentated; ray end walls are indentured; large bordered pits present in one row on radial walls of tracheids.	ray tracheids absent; ray end-walls smooth and indentured; large bordered pits present in one or, characteristically, two rows on radial walls of tracheids.	ray tracheids nondentated; ray end walls nodular; large bordered pits present in one or, occasionally, paired rows on radial walls of tracheids.	large dentations present in ray tracheids; ray end walls smooth; large bordered pits present in one or, occasionally, paired rows on radial walls of tracheids.
Tangential section	rays of two types: uniseriate and fusiform; spiral thickening present.	rays uniseriate; spiral thickening absent.	rays of two types: uniseriate and fusiform; spiral thickening absent.	rays of two types: uniseriate, (or occasionally partly biseriate) and fusiform; spiral thickening absent.

1941). This gave a clear surface suitable for ring-width measurement without further treatment. The surface of the disks were prepared in three steps: 1) selecting a radius for measurement based on the length, sensitivity and quality; 2) wetting the radius with water; 3) cutting along the wetted radius using a 17 mm wide carving gouge.

The measurement of ring widths was carried out on a "MEASU-CHRON" tree-ring incremental measuring system (Micro-Measurement Technology, Bangor, Maine, USA). The system was composed of a measuring stage, microcomputer, software, digitizer, and binocular microscope. The samples were clamped to the measuring stage on which a travelling binocular microscope (40× magnification) could move along the radius. Ring-widths were measured using a digital micrometer electronically interfaced to the microcomputer that serves as the data recorder and editor. The precision of the measurement is 0.01 mm.

In order to make the measurement accurate and precise, all the measurement data were checked by a program TCHECK, produced and owned by R. Alfaro of PFC, to detect major mistakes caused by either machine or human error. Machine error may come from occasional screw slippage on the moving microscope, whereas human error may come from the operator's wrong judgement of the ring boundary. The result of the program TCHECK showed the possible position of mistakes where the measured ring width looked to be too wide or too narrow in relation to its neighbour rings. When this occurred, the sample was remeasured, paying particular attention to those positions indicated by TCHECK. This process could remove the apparent major errors in the measurement. Another quality control step was to measure a proportion of the samples by

two independent operators (Fritts, 1976). All the 30 samples from living trees and stumps were measured independently by James Clowater, and the author. Clowater also measured 202 old disks. I measured all the other 504 old disks and randomly remeasured 26 of those measured by Clowater. The replicated measurements were compared through program VERIFY (Grissino-Mayer *et al.*, 1993). The results showed that both measurements were satisfactory concerning the precision of measuring the ring widths, whereas there were some errors in the accuracy of recording the number of rings. When the two independent measurements had accurate number of rings, there was little difference between the two measurements at 0.01 confidence level. For those measurements that disagreed with each other, the errors were mainly caused by inaccurate counting of rings. One year of error in the record of rings number could destroy the verification result (Pilcher, 1990). Errors of this type were normally detected at the cross-dating stage and the samples were checked again and corrected.

### 3.3 Crossdating

Crossdating is the most important principle of dendrochronology (Fritts, 1976). Matching of patterns of wide and narrow rings among trees establishes the exact year in which each ring was formed (Fritts, 1976) (Figure 3.1). Such crossdating of living trees can produce a master dating series in which exact calendar dates are assigned to each ring based on the fact that the outermost ring represents the current or known year's growth. Crossdating can also be applied to sequences from dead stumps and buried logs in lake sediments, producing some floating series because their outer edges lack a calendric

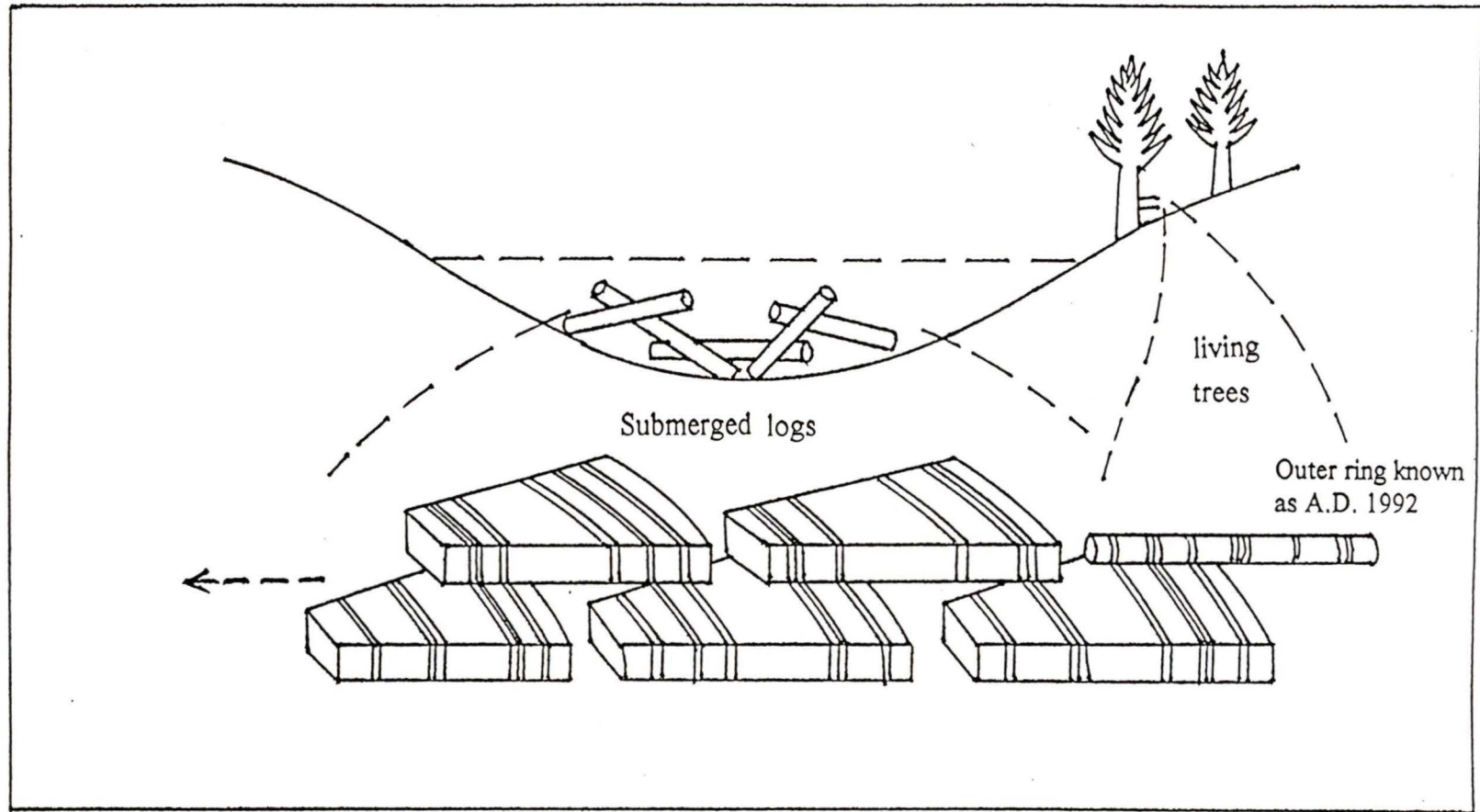


Figure 3.1. The extension of dated ring series backward in time by means of crossdating of samples from living trees and subfossil logs.

reference point in time. In addition, the sequence of ring width from old stumps and logs can be crossdated with the early record in the master living series, as long as their life spans overlap. Thus, each ring in the crossdated dead tree can be assigned an exact calendar date. In this way, a master dating series can be extended back in time by incorporating progressively older trees into the series. If the sequence bridging the master dating series and floating series is identified, the two can be combined into one extended master dating series. Eventually, a continuous long tree-ring series is produced.

Crossdating is possible because trees growing during the same interval should exhibit synchronous variations in ring width provided they are under the control of the same factors, namely climate. The master series for all specimens involved is unique in its year-by-year pattern; at no point throughout a long series, is precisely the same long-term sequence of wide and narrow rings repeated, because year-to-year variation in climate is never exactly the same (Ferguson, 1968).

Since the subfossil logs discovered from the Heal Lake sediments might have a wide time distribution, it was practically impossible to find crossdating without computer assistance. The building up of a chronology from these separate tree-ring sequences amounted to no less than a jigsaw puzzle of time series. The computer could scan all ring series very quickly and indicate those having high correlations.

The computer aided crossdating of the tree-ring series in this study was achieved using the dendrochronology program COFECHA (Holmes, 1983; Holmes *et al*, 1986) which served as a tool for finding the most probable dating of unknown series and for assessing tree-ring data quality. This program calculated the correlation of successive 50-

year segments of the unknown ring series with the master series at all possible positions, and these segments were lagged 25 years, giving a 50% overlap. For each segment the eleven highest correlating positions were shown on the output. This technique helped establish whether the unknown series could be tentatively dated within the master series by examining the values of correlation coefficient and the consistency of segment positions at sequential matches. If a tentative dating was suggested, the unknown series was then set to that date and joined the master series as a component. A second run of the program was operated to assess the data quality of the newly formed master series by thoroughly checking the crossdating of the components as a whole. Each component series was tested segment by segment against the adjusted master series (the mean of all the other series in this operation) at the corresponding matched time interval. The successive segments tested were 50 years long and lagged 25 years. Correlation coefficients were calculated for each segment of the series under examination with the adjusted master series matched at the point of crossdating, and also at each position from 10 years earlier to ten years later than dated. Correlation values less than 0.3281, representing the 99% confidence level of significance, were underlined and flagged on the output. The result provided information about possible errors in dating or measurement. The samples having such problems were rechecked and corrected. By repeating use of the program the master series incorporated more and more component series and covered the last two millennia.

Besides the computer assistance in crossdating, radiocarbon dates were also used to aid in approximating floating series in a proper position. Twenty-eight dendrochronologically high quality samples were selected for radiocarbon dating at Beta

Analytic Inc. Miami, Florida, USA. Conventional radiocarbon ages and calibrated dates were obtained. Thus, the ring sequences from these samples were anchored to the proper range of ages, and then they were used to find cross-dating with those from unknown age samples, extending the length of floating series forward and backward. Finally some floating series were joined together, then combined with the master dating series. In this way, five radiocarbon dated samples (Table 3.2) of Douglas-fir were added to the 2122 year-long master dating series (Figure 3.2).

Extremely narrow and wide rings, relative to their neighbouring rings, could serve as pointer years which also helped crossdating (Heikkinen, 1984; Schweingruber, 1990; Swetnam *et al.*, 1985). For this purpose, all the ring sequences from our samples were plotted and the pointer years were marked on the graphs. Crossdating of the sequences was checked and verified visually by examining the coincidence of pointer years from sequence to sequence.

In addition, wood characteristics (e.g. ratio of early wood and latewood and colour) were also compared to verify the crossdating of samples. This approach was based on the fact that trees growing in the same time interval would have similar wood characteristics (Schweingruber, 1990).

In summary, the crossdating of tree-ring sequences in this study was carried out by virtue of the computer programs, radiocarbon dates, graphs of ring sequences and pointer years, and wood characteristics. The result was a two-millennium long master dating series incorporating 155 crossdated tree-ring sequences from Douglas-fir (Table 3.3).

Table 3.2. Radiocarbon dates of the selected samples from Heal Lake buried logs  
(reported from Beta Analytic Inc., Miami, Florida, USA).

No.	Sample ID	Span of Years	Rings for Dating	<sup>14</sup> C Dates (BP)	Calibrated Dates (BP)
1	HLL001	369	38 -- 49	330 +/- 50	320; 390; 425
2	HLL003	210	8-- 12	1880 +/- 50	1822
3	HLL035	287	30 -- 39	410 +/- 50	497
4	HLL051	240	47 -- 52	1650 +/- 50	1545
5	HLL548	175	50 -- 59	1200 +/- 50	1103

Note: the dates BP are relative to the year AD 1950 and represent the midpoints of rings in the samples. Ring numbers are counted from pith to bark.

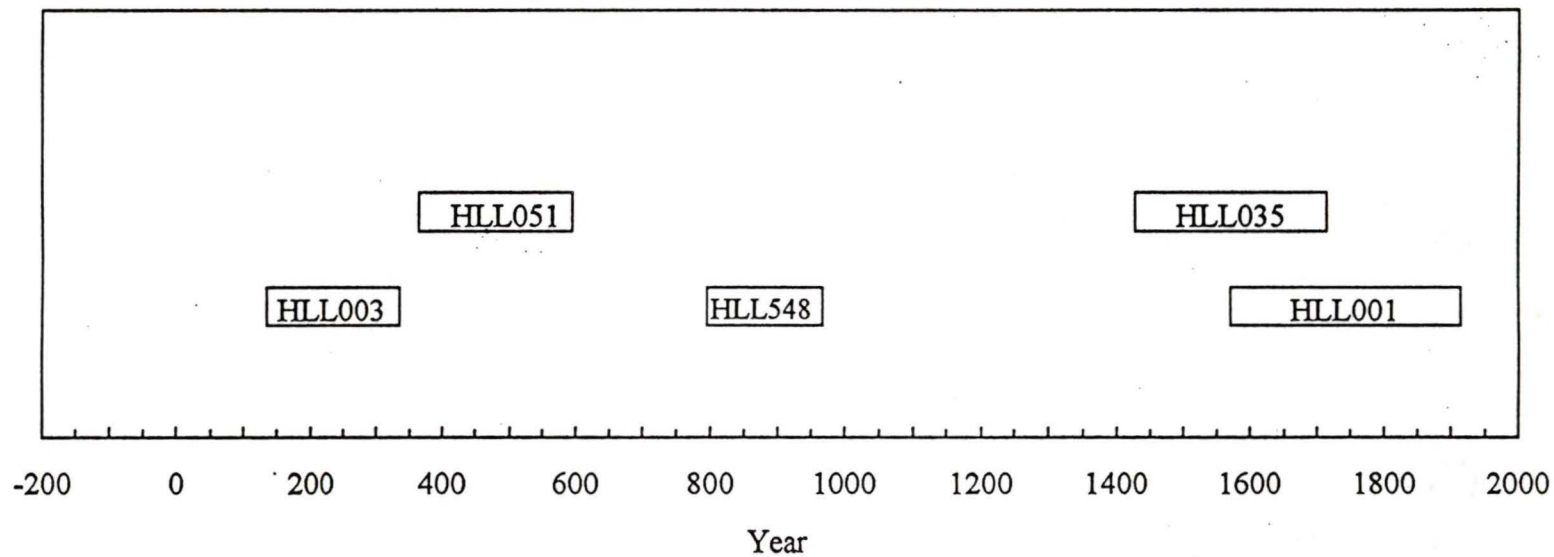


Figure 3.2. The position of  $^{14}\text{C}$  dated samples anchoring in the chronology.

Table 3.3. Result of crossdating for the 155 samples incorporated in the 2122-year master ring series.

No.	Sample ID	Interval	Span of years	No. of segments	No of flags	Correlation with master	Mean sensitivity
1	HLIC001	1857 -- 1992	136	5	0	0.557	0.252
2	HLIC002	1900 -- 1992	93	3	0	0.424	0.316
3	HLIC003	1860 -- 1992	133	5	0	0.617	0.209
4	HLIC004	1865 -- 1992	128	5	0	0.541	0.220
5	HLIC005	1739 -- 1992	254	10	0	0.635	0.246
6	HLIC006	1713 -- 1992	280	11	0	0.573	0.246
7	HLIC025	1671 -- 1992	322	13	1	0.455	0.138
8	HLIC026	1893 -- 1992	100	4	0	0.483	0.197
9	HLIC027	1808 -- 1992	185	7	0	0.740	0.210
10	HLIC028	1785 -- 1992	208	8	0	0.628	0.300
11	HLIC029	1741 -- 1992	252	10	0	0.516	0.200
12	HLIC030	1699 -- 1944	246	10	0	0.495	0.268
13	HLIC031	1710 -- 1992	283	11	2	0.579	0.247
14	HLIC032	1690 -- 1920	231	9	0	0.593	0.245
15	HLIC033	1740 -- 1992	253	10	0	0.741	0.277
16	HLIC034	1800 -- 1992	193	7	0	0.779	0.302
17	HLIC035	1675 -- 1992	318	12	0	0.598	0.189
18	HLIC036	1793 -- 1992	200	8	1	0.421	0.196
19	HLIC037	1834 -- 1992	159	6	0	0.681	0.243
20	HLIC038	1822 -- 1992	171	7	0	0.669	0.191
21	HLIC039	1746 -- 1992	247	10	0	0.690	0.197
22	HLIC040	1697 -- 1992	296	12	0	0.602	0.257
23	HLIC041	1807 -- 1992	186	7	0	0.705	0.175
24	HLIC043	1821 -- 1992	172	7	0	0.654	0.197
25	HLIC021	1475 -- 1980	506	20	3	0.467	0.248
26	HLIC019	1538 -- 1940	403	16	0	0.557	0.259
27	HLL004	1719 -- 1927	209	9	0	0.604	0.168
28	HLL002	1719 -- 1927	209	9	0	0.611	0.169
29	HLL001	1557 -- 1925	369	15	1	0.601	0.159
30	HLL476	1694 -- 1910	217	9	0	0.568	0.236
31	HLIC017	1525 -- 1909	385	15	0	0.558	0.208
32	HLL119	1624 -- 1901	278	12	0	0.500	0.176
33	HLL233	1615 -- 1881	267	11	1	0.567	0.177
34	HLL480	1754 -- 1878	125	5	0	0.518	0.190
35	HLL147	1635 -- 1824	190	7	0	0.487	0.158
36	HLIC020	1550 -- 1794	245	9	2	0.432	0.255
37	HLL912	1527 -- 1793	267	10	1	0.528	0.270
38	HLL079	1630 -- 1792	163	6	0	0.550	0.239
39	HLIC018	1500 -- 1778	279	11	0	0.557	0.201

40	HLL342	1586 -- 1774	189	7	0	0.514	0.193
41	HLL427	1594 -- 1773	180	7	0	0.586	0.207
42	HLL035	1424 -- 1707	284	12	0	0.539	0.188
43	HLL372	1340 -- 1687	348	14	1	0.605	0.197
44	HLL461	1340 -- 1702	363	15	0	0.596	0.184
45	HLL154	1493 -- 1692	200	8	2	0.483	0.213
46	HLL143	1444 -- 1656	213	9	2	0.481	0.149
47	HLL041	1400 -- 1647	248	9	1	0.397	0.316
48	HLL970	1415 -- 1591	177	7	1	0.557	0.181
49	HLL635	1512 -- 1588	77	3	0	0.560	0.273
50	HLL257	1400 -- 1524	125	4	1	0.436	0.164
51	HLL433	1345 -- 1458	114	5	0	0.535	0.183
52	HLL085	1327 -- 1416	90	3	0	0.402	0.157
53	HLL027	1201 -- 1408	208	8	0	0.590	0.175
54	HLL100	1224 -- 1400	177	8	2	0.510	0.152
55	HLL211	1245 -- 1363	119	5	0	0.612	0.181
56	HLL348	1270 -- 1355	86	4	2	0.349	0.206
57	HLL506	1292 -- 1342	51	2	1	0.320	0.261
58	HLL291	1244 -- 1334	91	4	2	0.329	0.177
59	HLL544	1260 -- 1329	70	3	0	0.368	0.166
60	HLL049	1136 -- 1282	147	6	0	0.563	0.185
61	HLL226	1162 -- 1258	97	4	0	0.554	0.203
62	HLL334	1139 -- 1246	108	4	1	0.390	0.147
63	HLL677	1143 -- 1226	84	4	0	0.455	0.204
64	HLL262	1132 -- 1219	88	3	0	0.494	0.176
65	HLL015	1121 -- 1214	94	4	0	0.423	0.267
66	HLL169	1102 -- 1207	106	4	1	0.346	0.168
67	HLL050	1051 -- 1201	151	6	0	0.698	0.133
68	HLL598	1113 -- 1197	85	3	1	0.499	0.228
69	HLL432	1143 -- 1189	47	1	0	0.664	0.190
70	HLL614	1110 -- 1183	74	3	0	0.450	0.193
71	HLL338	1114 -- 1179	66	3	0	0.400	0.134
72	HLL276	1111 -- 1161	51	2	0	0.551	0.191
73	HLL510	1064 -- 1127	64	3	0	0.404	0.157
74	HLL639	1070 -- 1118	49	1	0	0.415	0.149
75	HLL028	989 -- 1112	124	5	2	0.399	0.193
76	HLL133	1056 -- 1108	53	2	0	0.541	0.106
77	HLL453	920 -- 1094	175	7	0	0.528	0.262
78	HLL114	1028 -- 1077	50	1	0	0.418	0.112
79	HLL251	866 -- 1052	187	8	0	0.467	0.151
80	HLL585	964 -- 1050	87	4	0	0.572	0.271
81	HLL323	921 -- 1026	106	5	2	0.494	0.244
82	HLL606	849 -- 992	144	6	0	0.680	0.203
83	HLL548	802 -- 976	175	7	0	0.707	0.164
84	HLL418	857 -- 975	119	5	0	0.450	0.136

85	HLL067	850 -- 927	78	3	0	0.451	0.135
86	HLL365	788 -- 914	127	5	0	0.665	0.242
87	HLL055	766 -- 903	138	6	0	0.580	0.225
88	HLL552	744 -- 894	151	6	0	0.661	0.204
89	HLL157	648 -- 891	244	10	0	0.562	0.131
90	HLL691	773 -- 889	117	5	1	0.694	0.161
91	HLL707	810 -- 885	76	3	0	0.653	0.197
92	HLL229	650 -- 879	230	9	0	0.597	0.126
93	HLL499	739 -- 855	117	5	0	0.652	0.208
94	HLL820	739 -- 823	85	3	0	0.681	0.216
95	HLL384	716 -- 823	108	4	0	0.598	0.232
96	HLL434	720 -- 816	97	4	1	0.403	0.172
97	HLL345	680 -- 815	136	5	2	0.395	0.187
98	HLL595	588 -- 750	163	7	0	0.580	0.184
99	HLL006	598 -- 732	135	6	0	0.484	0.182
100	HLL969	637 -- 705	69	3	0	0.608	0.123
101	HLL005	533 -- 698	166	6	0	0.679	0.133
102	HLL202	610 -- 671	62	2	0	0.447	0.241
103	HLL042	571 -- 654	84	4	0	0.506	0.183
104	HLL645	567 -- 625	59	3	0	0.527	0.171
105	HLL051	347 -- 587	241	10	0	0.467	0.216
106	HLL474	533 -- 585	53	2	0	0.393	0.153
107	HLL292	502 -- 573	72	2	0	0.661	0.179
108	HLL052	458 -- 558	101	4	0	0.439	0.160
109	HLL626	475 -- 539	65	2	0	0.591	0.140
110	HLL709	466 -- 539	74	3	0	0.583	0.119
111	HLL596	376 -- 460	85	3	1	0.409	0.233
112	HLL017	331 -- 454	124	5	0	0.451	0.216
113	HLL435	339 -- 433	95	4	0	0.504	0.212
114	HLL530	351 -- 424	74	2	0	0.425	0.303
115	HLL285	346 -- 396	51	2	0	0.540	0.123
116	HLL129	280 -- 378	99	4	1	0.368	0.195
117	HLL551	220 -- 365	146	6	0	0.478	0.203
118	HLL577	204 -- 363	160	6	0	0.518	0.231
119	HLL128	282 -- 363	82	3	0	0.614	0.205
120	HLL123	259 -- 352	94	4	0	0.430	0.206
121	HLL003	121 -- 330	210	9	0	0.579	0.185
122	HLL417	195 -- 293	99	4	0	0.667	0.221
123	HLL101	43 -- 292	250	10	0	0.593	0.199
124	HLL621	210 -- 287	78	3	0	0.465	0.190
125	HLL153	105 -- 284	180	7	0	0.745	0.222
126	HLL607	182 -- 279	98	4	0	0.585	0.149
127	HLL971	141 -- 270	130	5	0	0.561	0.262
128	HLL289	97 -- 257	161	7	0	0.762	0.232
129	HLL354	113 -- 257	145	6	0	0.495	0.171

130	HLL275	79 -- 256	178	7	0	0.616	0.236
131	HLL156	80 -- 236	157	6	0	0.521	0.195
132	HLL497	87 -- 222	136	5	1	0.459	0.169
133	HLL135	59 -- 204	146	6	1	0.548	0.171
134	HLL034	10 -- 190	181	7	0	0.667	0.177
135	HLL023	10 -- 178	169	7	0	0.643	0.226
136	HLL008	-2 -- 168	170	7	0	0.747	0.173
137	HLL916	65 -- 166	102	4	0	0.661	0.160
138	HLL996	64 -- 164	101	4	0	0.621	0.139
139	HLL181	21 -- 142	122	5	0	0.683	0.265
140	HLL078	-53 -- 141	194	8	1	0.545	0.172
141	HLL346	15 -- 139	125	5	0	0.656	0.175
142	HLL203	7 -- 130	124	5	0	0.766	0.196
143	HLL209	-56 -- 111	167	7	0	0.565	0.218
144	HLL082	-67 -- 88	155	6	0	0.506	0.168
145	HLL241	-59 -- 77	136	6	0	0.610	0.163
146	HLL333	-52 -- 63	115	5	0	0.604	0.160
147	HLL268	-58 -- 64	122	5	0	0.586	0.199
148	HLL281	-56 -- 43	99	4	0	0.557	0.203
149	HLL266	-130 -- 30	160	7	0	0.575	0.212
150	HLL273	-122 -- 12	134	5	0	0.530	0.211
151	HLL290	-162 -- 9	171	7	0	0.611	0.170
152	HLL088	-144 -- 8	152	6	0	0.640	0.222
153	HLL468	-145 -- -4	142	5	0	0.458	0.236
154	HLL249	-125 -- -14	112	4	0	0.721	0.271
155	HLL158	-152 -- -23	130	6	0	0.641	0.204

(Note: Samples with HLIC in the ID refer to recent living cores or dead stumps; and those with HLL refer to buried logs in Heal Lake. The flag is a segment of which the correlation with the master series is below the 95% significance level. The mean sensitivity is a measure of the relative difference in width from one ring to the next)

### 3.4 Standardization and Chronology Formation

Every tree's radial growth is affected by numerous climatic and nonclimatic factors (Glock, 1955; Fritts, 1976; Cook, 1987). In this study the climatic information is of major concern and hence considered as the signal. Nonclimatic information such as the aging process, local disturbance from competition between trees, and standwide disturbance from insect attack, fire, and other impacts is considered as "noise". The process of reducing nonclimatic "noise" and preserving the climatic signal from tree-ring series is called standardization (Fritts, 1976).

The nonclimatic "noise" from the aging process reflects, in part, the geometrical constraint of adding a volume of wood to a stem of increasing radius (Fritts, 1976). A large number of the samples in this study exhibit an exponential decrease in ring-width as a function of time. A negative exponential function can thus be used to estimate the aging process for these samples (Figure 3.3a). This type of curve fitting has been found to be adequate for many North American conifers (Fritts, 1976).

The actual ring series,  $R_t$ , not only contains nonclimatic trends but also has nonhomogeneous variance through time (Fritts, 1976). The local variance of ring widths is proportional to the local mean. The fitted growth curve,  $G_t$ , represents the expected growth trend in the absence of higher-frequency of climate variability (Cook et al., 1995). Division of the actual ring widths by the expected growth values both removes the growth trend and scales the variance of ring widths (Fritts, 1976). The resulting series,  $I_t = R_t/G_t$ , is a stationary tree-ring index series with a mean of 1 and constant variance (Fritts, 1976; Cook and Peters, 1981).

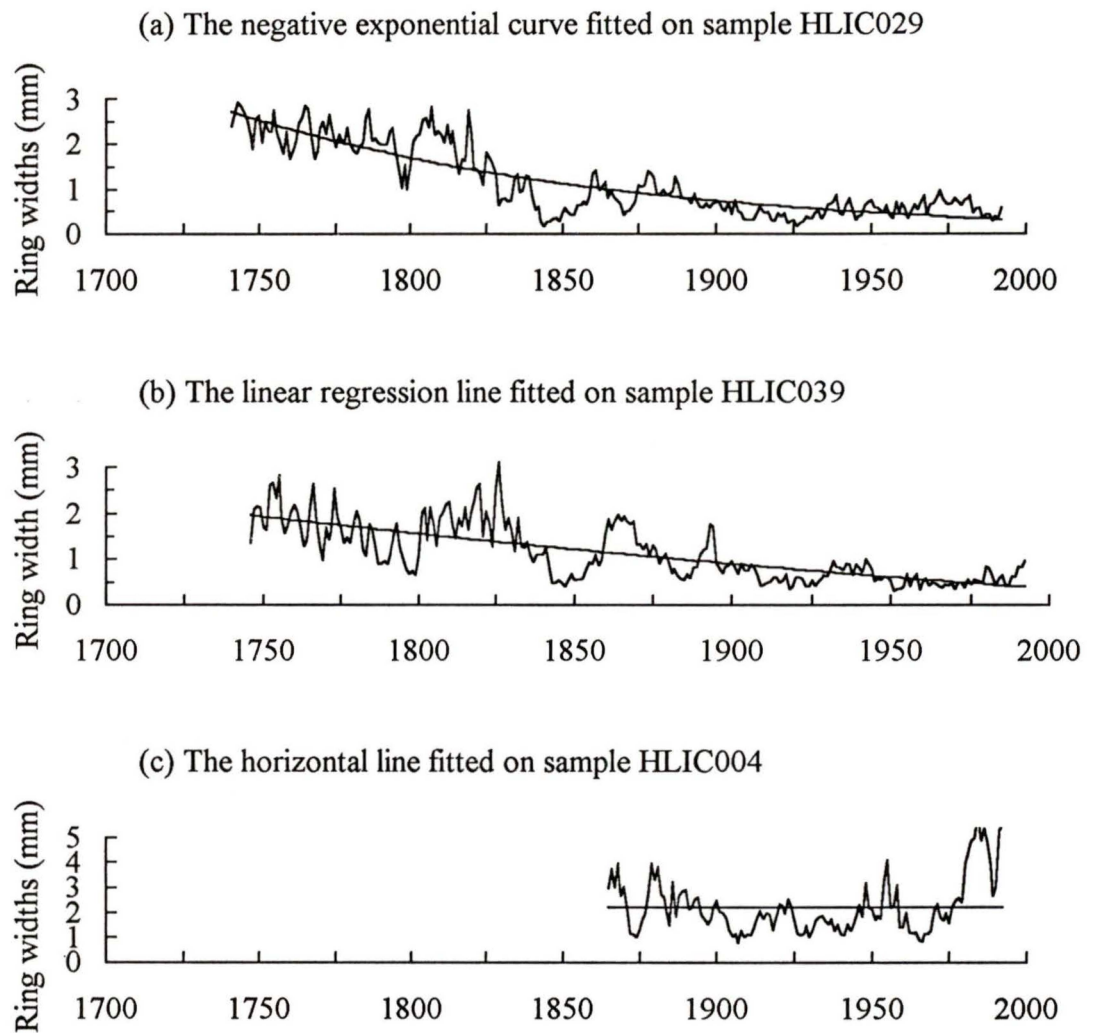


Figure 3.3. Examples of detrending using (a) negative exponential curve, (b) linear regression line of negative slope, and (c) horizontal line through the mean.

The standard ring-width indices in this study were produced by fitting a negative exponential curve, a straight line with negative slope, or horizontal line (Figure 3.3) to the raw ring-width series using the program CHRONOL (Grissino-Mayer *et al.*, 1993). This method of standardization mainly removed the biological growth trend and remained the climatic variation at wavelength shorter than the observed time series.

The standard ring-width chronology was then computed by averaging over individual standardized tree-ring series using a biweight robust mean. The average of replicated indices from a number of samples retained the common climatic signal among individual trees and minimized the non-climatic noise which differs from tree to tree. The biweight robust mean was superior to the arithmetic mean because it discounted the influence of outliers, which may be caused by local disturbances to tree's growth, and thus kept the mean unbiased (Grissino-Mayer *et al.*, 1993).

### 3.5 Result and Discussion

After sample collection, measurement, crossdating and standardization, a 2122-year ring-width chronology, spanning the period 130 B.C. - A.D. 1992, is developed by combining 155 of the most highly correlated series from Douglas-fir at Heal Lake (Figure 3.4). A list of relevant chronology statistics is presented in Table 3.4. The mean sensitivity is 0.203, indicating that the chronology is sensitive to climatic changes and hence contains much climatic information (Fritts and Shatz, 1975). The high mean correlation between each individual series with the master series shows the agreement of trees' responses to the macro-environmental changes (Fritts, 1976). The high autocorrelation statistics

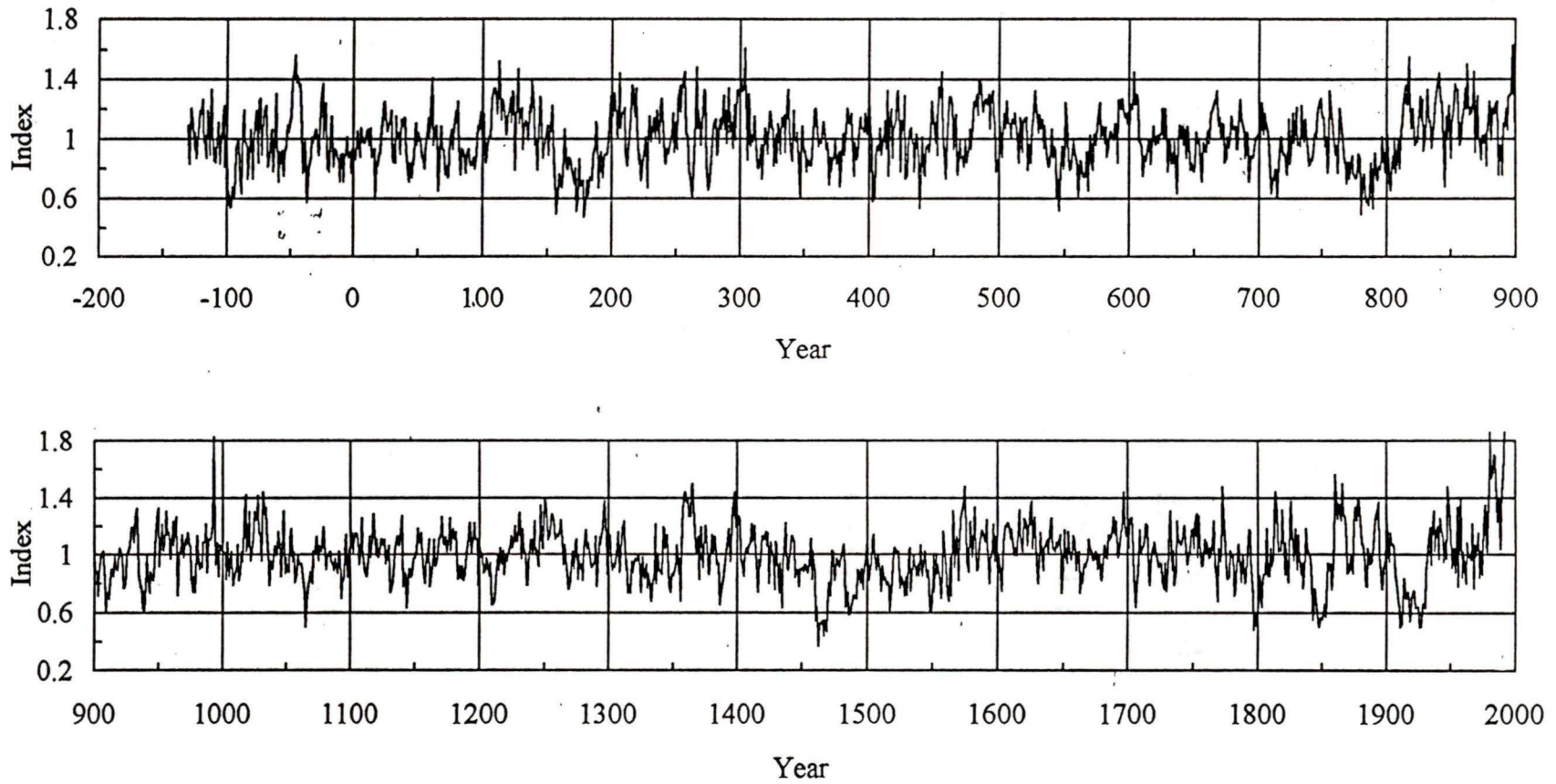


Figure 3.4. The 2122-year tree-ring width chronology of Douglas-fir for Heal Lake.

Table 3.4. Dendrochronological characteristics of the Heal Lake tree-ring chronology.

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Tree species	Douglas-fir
Number of trees	155
Chronology length	130 B.C. -- A.D. 1992 (2122 years)
Mean sensitivity	0.203
Mean correlation between trees	0.561
Chronology standard deviation	0.195
Chronology first order autocorrelation	0.627
Chronology second order autocorrelation	0.458
Chronology third order autocorrelation	0.393

---

suggest that lower frequency variation exists in the chronology (Fritts, 1976).

The sample depth of the chronology is presented in Figure 3.5. Most periods of the chronology have no less than 5 sample depths except a few short intervals between A.D. 425-501, A.D. 559-566, A.D. 586-597, A.D. 1027, and A.D. 1053-1055. In general a minimum of 5 sample depths is needed for a robust chronology (Adams, personal communication, 1994) and the more the sample depth, the less the noise in the chronology. The starting year for the chronology, 130 B.C., is chosen as the first year that has five sample replications.

No missing rings and false rings were identified in the samples for this study due to the following reasons. 1) All the samples used in this study were collected from a single site, thus the environmental stress influenced all the trees simultaneously making it rings or false rings, if they existed, by cross-dating. 2) The climate of the study area exhibits mild temperatures, and the beginning of tree growth in March is still in rainfall season, making the cambium activity always proceed. 3) Douglas-fir has a large ecological amplitude and rarely produces missing rings and false rings on the coast (Alfaro, personal communication, 1994).

This chronology was developed by linking the overlapping segments of crossdated ring series and hence the variations in climatic pattern that occurred at wavelengths longer than the length of tree-ring series were removed in the procedure of detrending as part of the expected, biologically based growth trend. This so called “segment length curse” (Cook *et al.*, 1995) still remains problematical. Nevertheless, the chronology was able to reflect interannual, decadal and century scale climatic variations in the following climatic

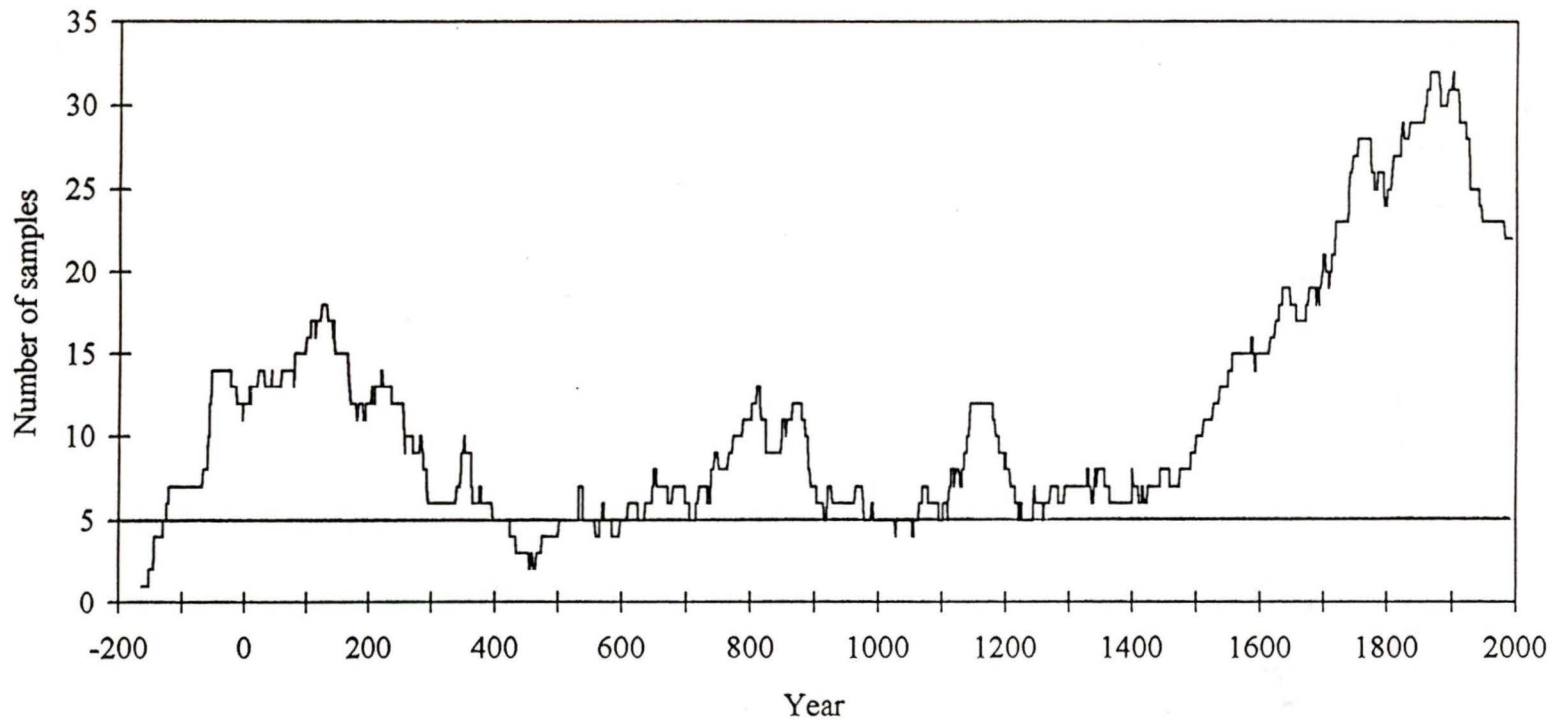


Figure 3.5. Sample depth of the Heal Lake tree-ring chronology of Douglas-fir. (The line for sample depth of 5 replications is presented on the graph)

calibration and reconstruction analysis.

## Chapter 4: RELATIONSHIP BETWEEN TREE-RINGS AND CLIMATE

A tree-ring index of a chronology established specifically for climatic study is considered to be a measure of the macroclimate that governed the growth of the trees in the chronology. Using the recent measured climatic record, a statistical ring index - climate relationship can be established. This procedure is called calibration (Fritts, 1976) and it includes both response function and transfer function analysis.

Response function (Fritts *et al.*, 1971) is designed to detect which climatic variable is responsible for the variation of a tree's radial growth. Transfer function (Fritts, 1976) refers to using tree-ring indices to deduce past climate conditions. The verification (Fritts, 1976) of the transfer function is given by comparing the reconstructed climatic information with those of actual record in an independent interval; thus the accuracy of the estimate can be assessed.

### 4.1 Response Function Analysis

The modelling of tree-ring climatic relationships can be explored through a variety of simple and multiple regression analysis (Fritts, 1976; Jozsa and Robertson, 1987; Guiot, 1990; Horacek, 1995). Multicollinearity (correlations among the independent variables) within climatic variables is a potential problem in using regression analysis because it can cause the rejection of important variables and loss of precision of the estimates, and consequently produces misleading results (Cropper, 1984). To overcome this problem, Fritts *et al.* (1971) developed the response function technique which used the principle

components of monthly climatic data to estimate ring-width indices. Using this technique the regression coefficients are multiplied by the PCs of climate to obtain a new set of regression coefficients related to the original monthly climatic data variables (Fritts *et al.*, 1971; Fritts, 1976).

The program RES (Holmes, 1994), developed on the basis of this concept from Fritts *et al.* (1971) was used in this study to produce the response function. The tree-ring indices were derived from the master living chronology, spanning the years of 1891-1992. The meteorological data, provided by Dave Spittlehouse from the Research Branch, Ministry of Forests, Province of BC, were generated specifically for the Heal Lake project using records from four Victoria meteorological stations at the Little Saanich Mountain, Victoria International Airport, Gonzales Hill and Esquimalt (Figure 2.2). The techniques producing the averaged regional climatic data involved filling the missing data of certain station by considering the ratio of the climatic variables between stations. The resultant data included monthly mean temperature and total precipitation values for the years of 1891 -- 1992, and they represented the climate situations for the CDF biogeoclimatic zone near Victoria (Spittlehouse, personal communication, 1994). The response function analysis was carried out on two calibration intervals: the full interval of 1891-1992 and the interval of 1921-1992. The latter interval eliminated the years of 1891-1920 because this interval contained a severe nonclimatic event at this region, insect defoliation around the year of 1910 (Harris *et al.*, 1985), that might destroy the relationship of tree growth and climatic factors. The period of the climatic variables used for analysis of each annual ring index was 16 months. It began in June of the prior growth year and ended in September of

the growth year. This interval of time was likely to include the most important climatic factors that affect the radial growth of Douglas-fir (Allen and Owens, 1972). Tree's prior growth was not included in the principle components because prior growth values did not have biological linkages with the current climatic conditions and in addition, it could mask climatic effects in regression (Blasing *et al.*, 1984). The PVP criterion (Guiot, 1985), which was the point where the cumulative product of the eigenvalues fell just below 1, was used in the program RES to select the principle components into regression analysis.

Figure 4.1 is the plotted result of the response function for the two calibration intervals. The result from the interval 1891-1992 shows that the tree growth responds positively to: 1) precipitation in current April, June and July; and 2) temperature in previous September, current March, August and September. The total variance explained is 48%. Whereas the result from the interval 1921-1992 shows that the tree growth responds: 1) positively to precipitation from current April to July; 2) positively to precipitation in previous July and November; and 3) negatively to precipitation in current September. The total variance explained is 61%.

Response function is very sensitive to the number of monthly climatic variables, the response period, and the criterion for screening eigenvectors (Blasing *et al.*, 1984; Fritts and Wu, 1986). Biological consideration is needed when interpreting the results. In addition, a simple correlation function can be used as an aid or reference to the response function for testing the growth-climate relationships because it is more easily understood, easier to replicate, and harder to alter subjectively than is response function (Blasing *et al.*, 1984).

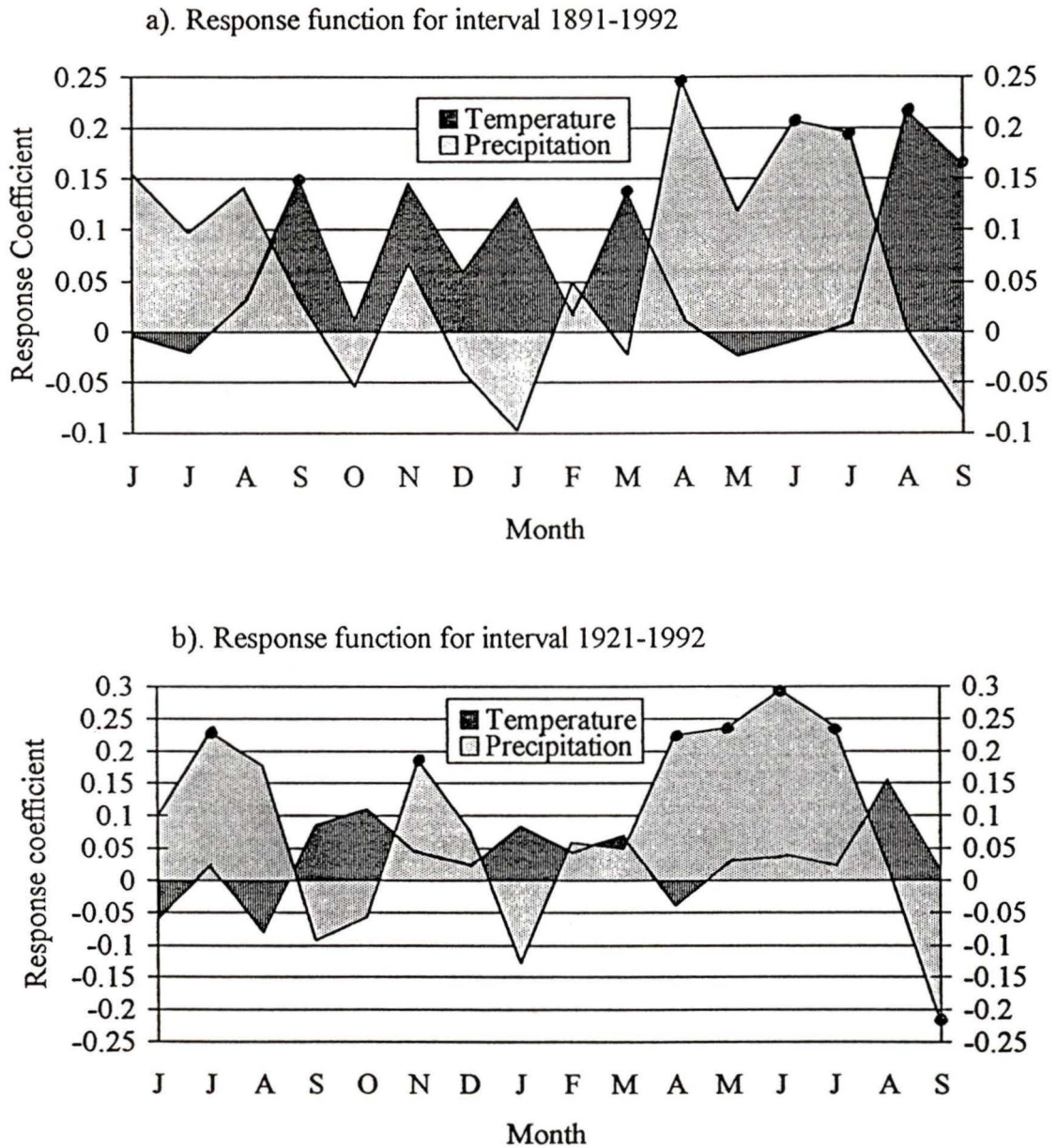


Figure 4.1. Response functions of Heal Lake tree-ring chronology with monthly mean temperature and monthly total precipitation for intervals a) A.D. 1891-1992 and b) A.D. 1921-1992. (The labeled dots indicate values significant at the 95% confidence level.)

Figure 4.2 is a plotted result of the simple correlation function using the same data set in response function. The result from the interval 1891-1992 shows that the tree growth is 1) positively related to precipitation in current April, June, July and previous June; 2) positively related to temperature in previous September, current January, March and August. Whereas the result from the interval 1921-1992 shows that the tree growth is 1) positively related to precipitation from April to July; 2) positively related to precipitation in previous June and November; 3) negatively related to precipitation in previous October.

The results from response function and simple correlation function showed that the tree growth was highly correlated with the precipitation in spring and early summer months. The differences in the results between interval 1891-1992 and 1921-1992 suggest that nonclimatic effects such as insect defoliation (Harris *et al.*, 1985) and possible inaccuracy of measurement of climatic variables in early years can influence the modelling of tree growth-climate relationship.

Both the response function and simple correlation function were obtained empirically through statistical processing of the data sets from tree-ring indices and climatic variables. These statistical models were used to describe a phenomenon, not to predict or reconstruct it (Fritts, 1976). They provided clues for developing biologically reasonable climate-growth models that could reflect the main physiological relationship of climate to tree growth. Such knowledge of growth system behaviour is helpful for the establishment of transfer function to estimate the past climate. The following analyses are based mainly on the results from the interval 1921-1992.

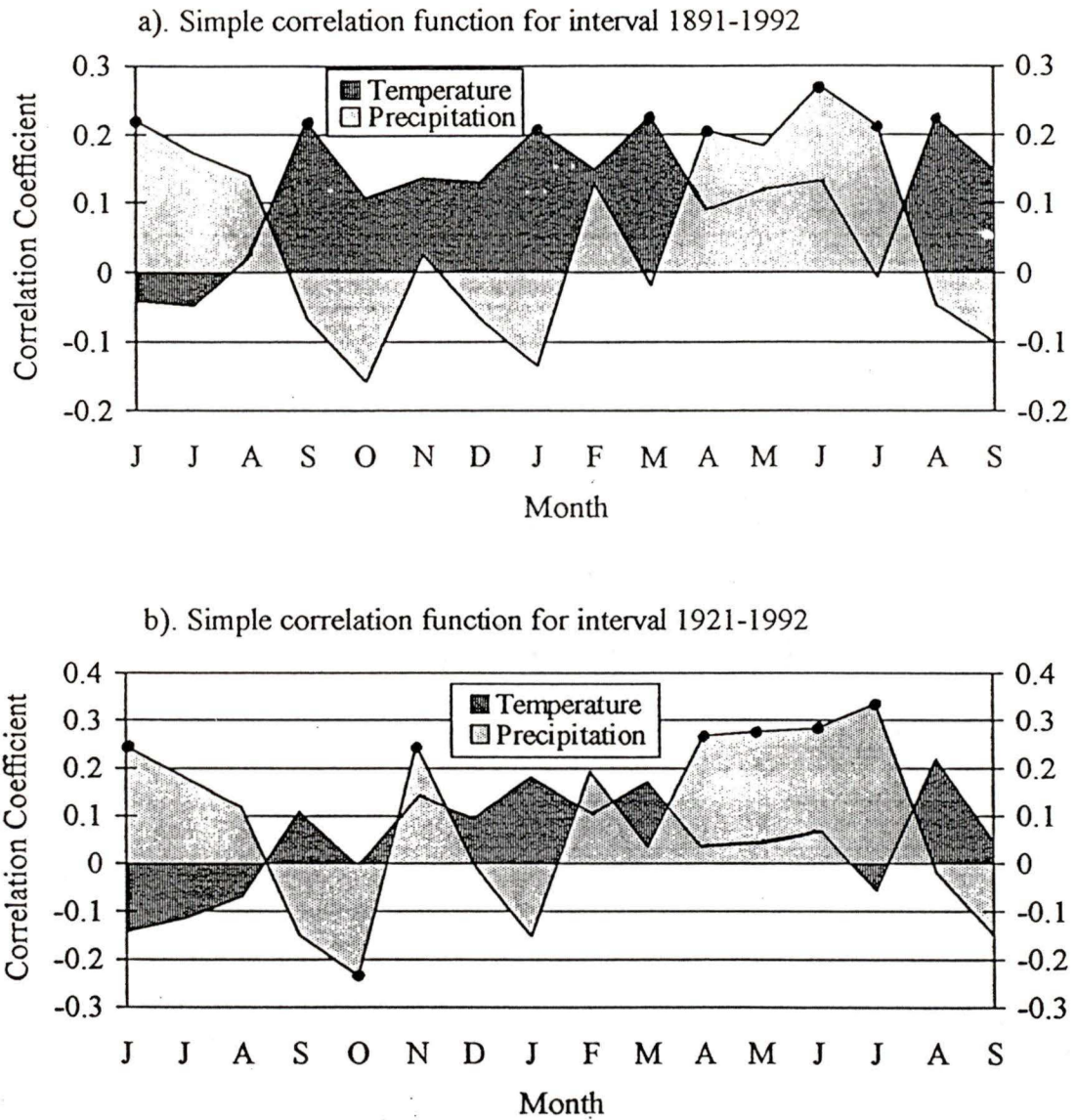


Figure 4.2. Simple correlation functions of Heal Lake tree-ring chronology with monthly mean temperature and monthly total precipitation for intervals a) A.D. 1891-1992 and b) A.D. 1921-1992. (The labeled dots indicate values significant at the 95% confidence level.)

#### 4.2 Biological Basis of Ring Growth

A tree's radial growth is a result of cambial cell division, enlargement and differentiation. The cambium is a kind of plant tissue that is capable of dividing and producing new cells between the wood and the bark. Its activity is related to many physical and biochemical processes (e.g. food transportation, plant photosynthesis and respiration). These processes are affected by many environmental factors such as moisture and temperature. During the growing season in spring, tracheid cells produced by the cambium form earlywood. The cells have large diameters and thin walls. As the growing season progresses and the environment becomes stressed, latewood forms and the tracheid cells, newly produced, become smaller and the cell walls thicken greatly. The diameter growth of the tree stops when the cambium becomes dormant in autumn and during the winter. The width of the ring is the average of growth processes throughout the entire growing season (Fritts, 1976). Thus, all environmental factors related to the growth processes may play some role in determining the ring-width.

Positive correlations between the tree-ring indices and precipitation in April-July (AJ) has been found in the response function (Figure 4.1b) and simple correlation function (Figure 4.2b) for the interval 1921-1992. This indicates that the spring and early summer (AJ) precipitation is the major limiting factor in the growth of Douglas-fir at Heal Lake. Water has long been recognized to be one of the most important substances in many physiological processes (Fritts, 1976). Environmental water stress affects the production of net photosynthesis through the control of stomatal closure and biochemical reactions. Water deficit in cambium during the growing season can lead to a slower rate of cell

division, reduction in cell size and change in cell-wall thickening. At lower elevations in much of the Pacific Northwest and coastal British Columbia, the beginning of rapid cell division within the buds of Douglas-fir occurs about the first of April and the growing season normally ends in late August (Allen and Owens, 1972). The precipitation in spring and early summer is often not sufficient for sustained rapid growth (Lassoie and Salo, 1981; Robertson *et al.*, 1990; Ronda *et al.*, 1995) and, therefore, seems to limit the radial growth of Douglas-fir.

The high autocorrelation within tree-ring indices (Table 3.4) shows that tree growth is highly correlated with the growth in the previous several years. This autocorrelation phenomenon is often observed in dendrochronological studies (Hughes *et al.*, 1982; Briffa *et al.*, 1983) and it is explained to be related to the tree's biological growth processes. The weather of a given year has a large effect on ring width for the same year, and in addition, it also affects ring width in the following several years through effects on the food reserves, bud formation, persistence of needles, and general vigor of the tree (Fritts, 1976). The food is produced by photosynthesis and transported to different plant tissues for storage and use. The reserve of food can be used for the following several years. The vegetative bud of Douglas-fir is formed and influenced by the climate in the previous year (Allen and Owens, 1972). The needles of Douglas-fir usually persist for five years or even longer when they remain photosynthetically active and can influence the food accumulation (Pollard, personal communication, 1995). The change in vigor of tree growth is usually a gradual process. All of these suggest that the climate of one year can have some effects on the following several years' ring-width growth.

Other correlations between the tree-ring indices and climatic variables exist in the response function (Figure 4.1) and simple correlation function (Figure 4.2) and they may account for some variations in the ring width growth. However, taking into consideration the tree's growth behaviour, the spring and early summer precipitation and the previous years' climate are the most important contributing factors to the tree's radial growth. Other factors such as temperature may have some effects on ring-width formation through its control of the length of growing period and the process of assimilation (Glock, 1955) but these effects may be better revealed from the ring density analysis (Conkey, 1986; D'Arrigo *et al.*, 1992; Hughes *et al.*, 1994) rather than the total ring-width analysis. Consequently, only the AJ precipitation and the previous years' growth are taken into account in the following transfer function analysis.

#### 4.3 Transfer Function Analysis

A transfer function is a regression equation that uses the tree-ring index as predictor and climatic data as predictand. It is determined statistically by matching the tree-ring data and the corresponding climatic data during a calibration time interval covered by both data sets. The derived equation can then be applied to tree-ring data to deduce estimates of the past climate.

The transfer function in this study was developed according to the result of response function (Figure 4.1) and simple correlation function (Figure 4.2) analysis, autocorrelation analysis and the biological considerations of Douglas-fir growth behaviour. The ring-width series was highly correlated with precipitation in April-July and

with the prior several years' growth. Thus, the AJ precipitation could be calibrated from tree-ring series. The problem of autocorrelation within the series could be overcome through several ways. One of the methods was to incorporate the previous several years' growth into the predictor set to calibrate the current year's climate (Fritts *et al.*, 1979; Briffa *et al.*, 1983). Another method was to use autoregressive models (e.g. ARMA) to process the tree-ring series and then use the residual series to develop the transfer function (Monserud, 1986; Biondi and Swetnam, 1987; Graumlich, 1987). In this study a new conceptual model was developed to deal with the autocorrelation phenomenon, and accordingly produce the transfer function. The new model did not modify the ring-width indices to remove the autocorrelation but rather it considered the prior several years AJ precipitation as the factor that contributed to this high autocorrelation. As stated in the previous section, the ring-width growth of one year was a result of climatic effects from both the same year and the prior several years. Using autocorrelation function, regression technique (Wilkinson, 1990) and the above biological consideration, the AJ precipitation of one year and the prior four years were found to have effects on the current year's tree growth though these effects were less in the early years of the series. A series of weights (0.50, 0.20, 0.15, 0.10 and 0.05) were given to each year and the weighted AJ precipitation were summed ( $0.50 \times P_t + 0.20 \times P_{t-1} + 0.15 \times P_{t-2} + 0.10 \times P_{t-3} + 0.05 \times P_{t-4} = P_{5\text{-year}}$ ) to represent an integral of AJ precipitation over the five years which could be thought as "one functional biological ring year". The transfer function was subsequently produced using the tree-ring index as a predictor and the integrated five-year AJ precipitation as predictand. In effect the tree-ring was used as a measure of AJ

precipitation of five years, rather than that of a single year.

Because of this five-year integration the length of actual meteorological data (1891-1994) shrunk four years and started from 1895 to 1992. This period of 98 years was divided into two halves. The late period of 1944-1992 was used as dependent interval to model the transfer function, whereas the early period of 1895-1943 was left as independent interval to verify the model. A linear relationship was found between the integrated AJ precipitation of five years and the tree-ring index with the following form:

$$P5\text{-year} = 42.06 + 65.31 \times \text{Index}$$

The calibration statistics are given in Table 4.1 (Wilkinson, 1990; Clarke and Cooke, 1983). The variance explained by this model was 47%, which could be considered adequate for the model (Loaiciga *et al.*, 1993).

#### 4.4 Verification

The relationship between climate and tree-ring indices as shown in the transfer function is developed empirically using dependent data sets in the calibration interval. To demonstrate that such transfer function will perform well when applied to different time intervals, the reconstructions need to be compared to actual data in the independent interval to assess the accuracy of the estimates. This procedure is called verification and it can be approached in several ways using independent instrumental data, historical accounts of events, or proxy data other than tree rings (Gordon, 1982).

The actual AJ precipitation for the period of 1895-1943 was used here as independent climatic data to compare those estimated from transfer function. The

Table 4.1. Calibration and verification statistics for predicting April-July precipitation from ring widths

Calibration				Verification			
Period	R	R <sup>2</sup>	R <sup>2</sup> adj	Period	Sign test	r	RE
1944-1992	0.685	0.470	0.459	I: 1895-1943	34/15**	0.314*	-0.700
				II: 1898-1910 and 1921-1943	28/8**	0.577***	0.088

Note: R: multiple correlation coefficient, R<sup>2</sup> : variance in AJ precipitation explained by model, R<sup>2</sup> adj: adjusted R<sup>2</sup> for loss of degrees of freedom, r: correlation coefficient, RE: reduction of error, \*:significant at 95% level, \*\*: significant at 99% level, \*\*\*: significant at 99.9% level. II Verification period: anomalous years 1895-1897 and 1911-1920 were not included in this period (see text page 52).

comparison was carried out on two intervals. One was the whole period of 1895-1943 (I verification period) and the other was the combination of 1898-1910 and 1921-1943 (II verification period). In the second verification period the years of 1895-1897 and 1911-1920 were removed because of the unusual events that destroyed the spring precipitation-tree growth relationship. The years of 1893 and 1894 were the wettest spring years during the period 1891-1992; the AJ precipitation received was 337 mm (4 standard deviation outlier) and 288 mm (3 standard deviation outlier) respectively. This extremely wet condition no longer limited the tree's growth and its effect lasted until at least 1898. The years of 1911-1920 were removed because of the effect of severe insect attack in 1909-1910 (Harris et al., 1985). The defoliation of Douglas-fir by western spruce budworm (*Choristoneura occidentalis* (Freeman)) severely reduces tree growth and its effect usually appears one year after the defoliation (Thomson and Van Sickle, 1980; Alfaro et al., 1982). The defoliated trees might take as many as over 10 years to develop a full and vigorous crown and resume their full growing potential depending on the severity of the defoliation and the site condition (Alfaro and Maclauchlan, 1992; Swetnam and Lynch, 1993).

The method of testing the association between the actual and estimated AJ precipitation involved the calculation of "sign test", correlation coefficient, and reduction of error statistics (Fritts, 1976). These parameters were calculated in different ways and could address different attributes of similarity. The results are presented in Table 4.1. A visual comparison of actual vs. reconstructed AJ precipitation in the period of 1895-1992 is given in Figure 4.3.

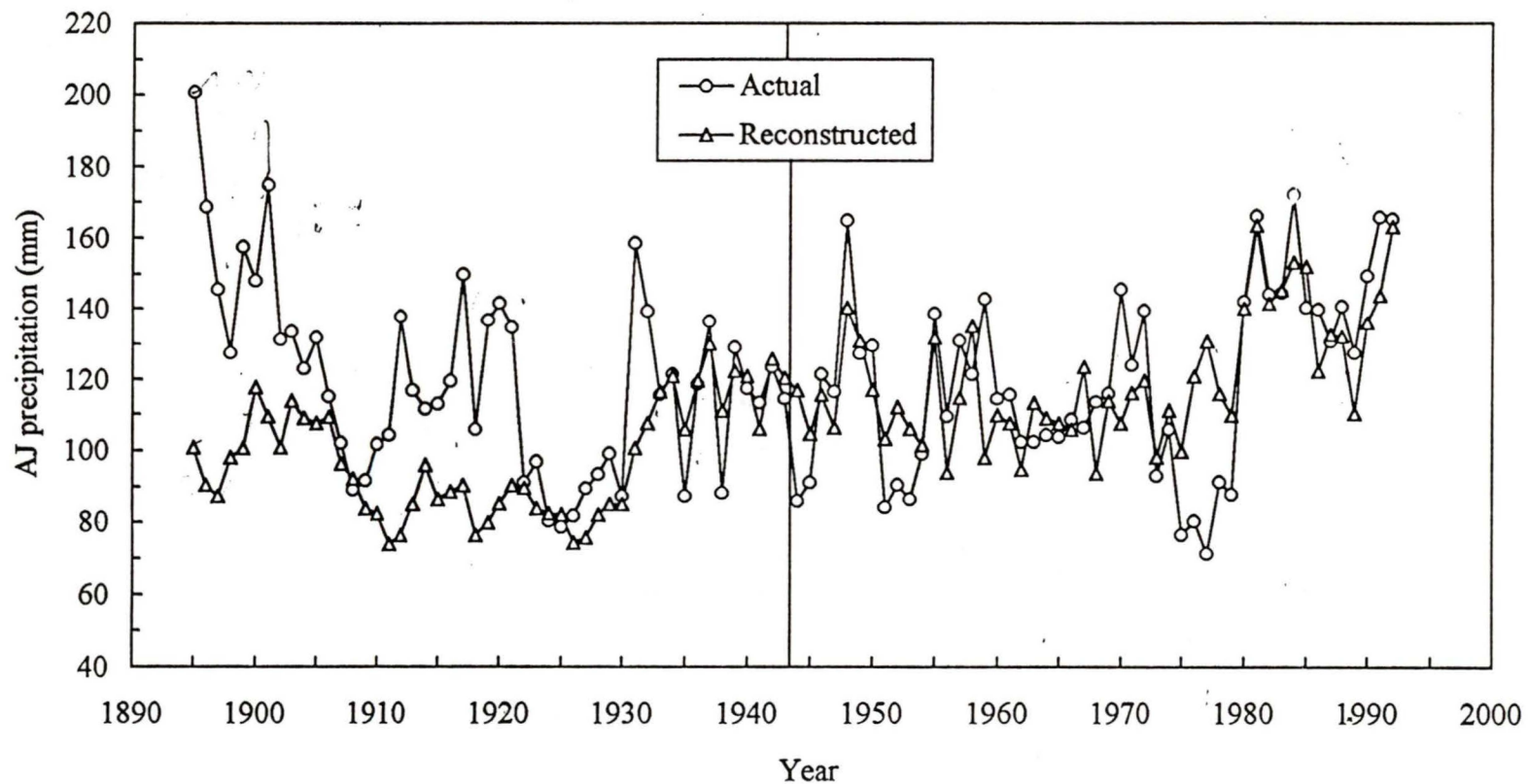


Figure 4.3. Actual vs. Reconstructed April-July precipitation at Heal Lake for the period A.D. 1895-1992.

The sign test is a count of the number of times that the signs of departures from the sample mean agree or disagree (Fritts, 1976). No consideration is given to the magnitude of the departure. There is significant association between the two data sets if the number of agreements is significantly larger than the number of disagreements. The sign test in the I verification period is 34/15 just meeting the 0.01 significant level, whereas that in the II verification period is 28/8 far exceeding the 0.01 significant level. The result suggests that the reconstruction is more reliable in the II verification period than in the I verification period.

The correlation coefficient is a commonly used parameter to test association between two data sets. It takes into account not only the number of cases of agreement and disagreement between variables, but also the relative degree of correspondence. The correlation coefficient is 0.314 in the I verification period and 0.577 in the II verification period, the former is significant at 0.01 level and the latter is significant at 0.001 level.

The reduction-of-error (RE) is a statistic that compares the reconstructed values with actual values by simply assuming the mean of the calibration period to be the reference for verification period. The value of RE ranges from minus infinity to a maximum value of 1.0. The better the reconstructions estimate the actual values, the more the error is reduced by the reconstruction, and the bigger the value of RE will get. This parameter provides a more sensitive measure of the reliability. The positive value of RE in the II verification period indicates that the climatic reconstruction from the transfer function is reliable (Fritts, 1976). The negative value of RE for the I verification period suggests that there are a few extremely bad estimates in the period that can greatly offset

the effects of many very good estimates (Fritts, 1976).

The result of the above analysis (Table 4.1) showed that the estimated values passed two of the verification tests in the I verification period and passed all the three tests in the II verification period. All the three parameters used for verification tests were more significant in the II verification period than in the I one. The transfer function obtained in the calibration period was thus a reliable model that could be used to reconstruct the past AJ precipitation from tree-ring series. Being aware of the difference in the results between the I and II verification period, one should keep in mind that extreme events such as insect attack or extreme wet years could decrease the quality of the climatic reconstruction and therefore one should be careful when interpreting the climate in these years.

## Chapter 5: RECONSTRUCTION OF THE PAST CLIMATE

This chapter gives the reconstruction of climate for the last two millennia using the tree-ring chronology and the transfer function established in the previous chapters. The curve of the reconstruction is smoothed and patterns of variations are examined. Eight distinct intervals are recognized and explained climatically. The notably wet and dry climatic events are also identified. The results are discussed with focus on the Little Ice Age and the Medieval Warm Period, and are compared with other studies in the nearby regions. Finally some limitations of the reconstruction are acknowledged and discussed.

### 5.1 Reconstructed Climatic Variations for the Interval 130 B.C.-A.D. 1992

#### 5.1.1 The Curve of the Reconstruction and Its Pattern

The weighted 5-year April-July (AJ) precipitation for the interval 130 B.C.-A.D.1992 was reconstructed (Figure 5.1) by applying tree-ring indices into the transfer function,  $P_{5\text{-year}} = 42.06 + 65.31 \times \text{Index}$ , which was developed in chapter 4. The reconstruction showed that the mean of AJ precipitation over the past 2122 years was 107 mm, the standard deviation was 13 mm, and the range of deviation was 97 mm.

Though the last two millennia did not experience apparent major change in mean annual precipitation in this area (Allen, 1995; Hebda, 1995), some minor very long term trends might possibly exist and were removed from the chronology due to the 'segment length curse' (Cook *et al*, 1995). Therefore, the value of reconstructed precipitation is not able to indicate accurately the absolute amount of true precipitation but rather it reflects

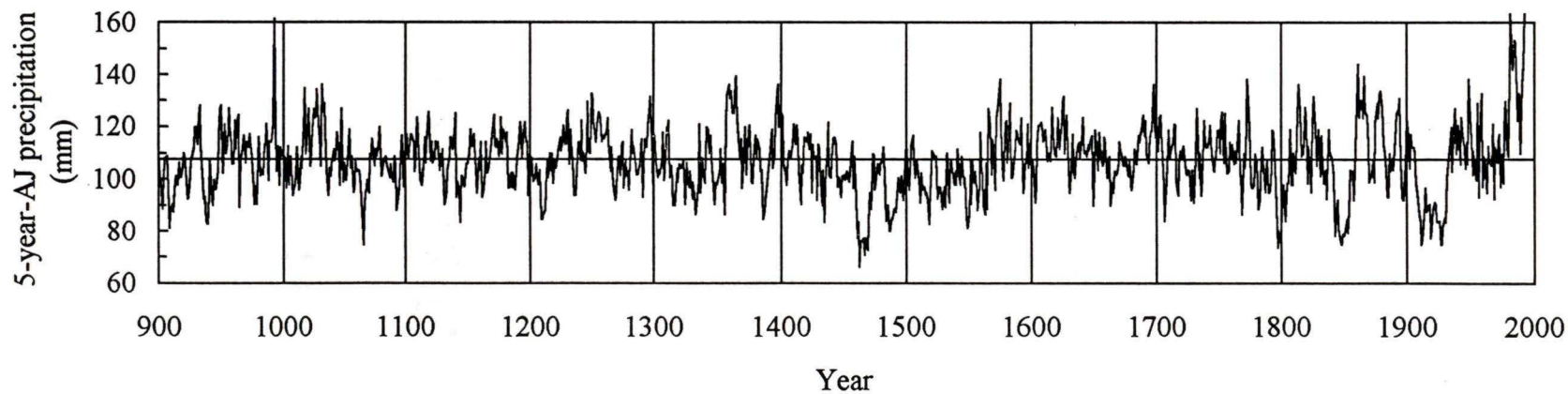
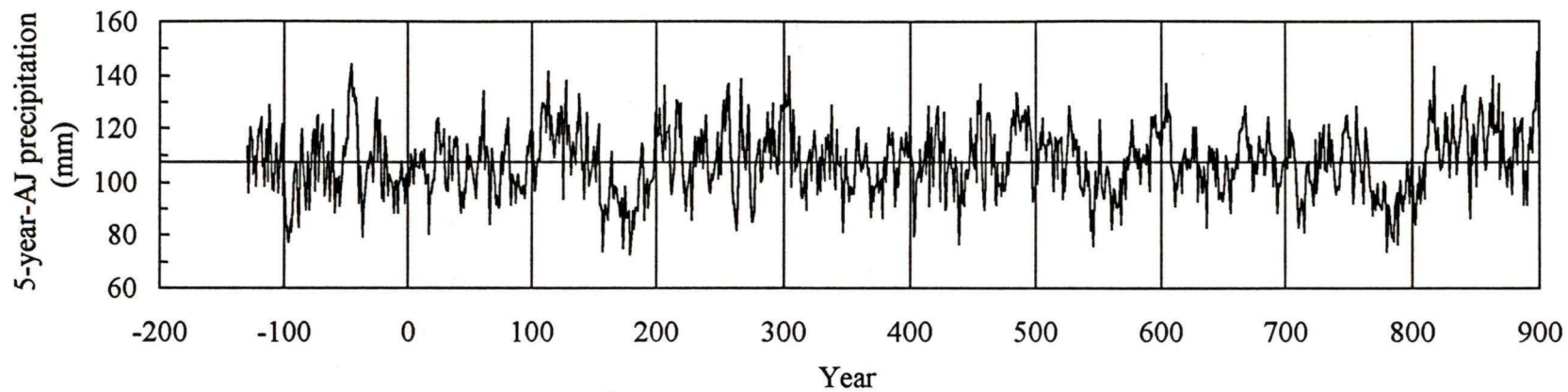


Figure 5.1. Reconstructed 5-year April-July (AJ) precipitation at Heal Lake, 130 B.C.-A.D. 1992 ( the 5-year AJ precipitation has the structure of  $0.50 \times P_t + 0.20 \times P_{t-1} + 0.15 \times P_{t-2} + 0.10 \times P_{t-3} + 0.05 \times P_{t-4}$ , where P represents the AJ precipitation and t represents the year).

the relative variations at time scales of interannual, decadal, and century long ranges. In the following analysis, the series of reconstructions was standardized to zero mean and unit standard deviation to see the relative variation of precipitation throughout the 2122 years. In order to reveal the decade to century long precipitation variations the reconstructions were smoothed using a robust LOWESS smoothing function (Wilkinson, 1990). This method of smoothing was based on fitting a series of locally weighted regression curves to the series, where the "local" was defined here as a 15-year time window.

Figure 5.2 shows the smoothed curve of standardized reconstruction of AJ precipitation for the interval 130 B.C.-A.D. 1992. It is apparent that the variability of precipitation changes throughout the time and both the magnitude of reconstructed precipitation departures and the duration of wet or dry periods vary throughout the 2122 years. Using the magnitude and duration of wet or dry periods to classify patterns, four different kinds of patterns can be recognized i.e. low magnitude and short duration, low magnitude and long duration, high magnitude and short duration, and high magnitude and long duration, where the high magnitude is defined as having precipitation departures greater than 1 unit of standard deviation; the long duration is defined as having periods of wetness or drought longer than 40 years and for high magnitude the long duration also needs to contain more than 60 percent of the years that have departure values greater than 0.5 unit of standard deviation. These definitions are based on the physical and statistical features of the reconstruction. By further defining that a distinct climatic interval should have a persistent pattern of more than 100 years, the 2122-year of precipitation

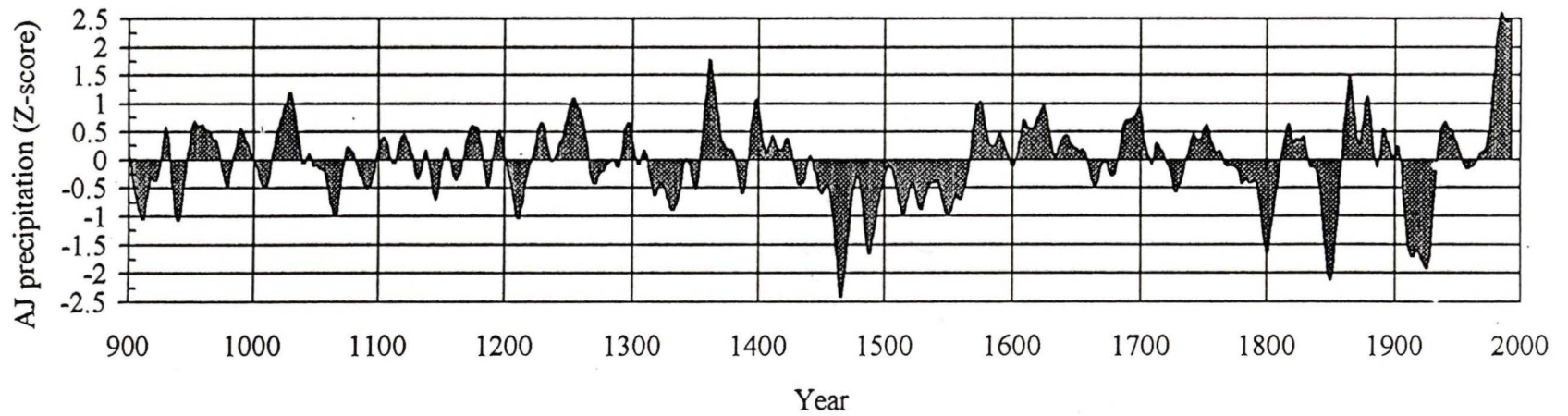
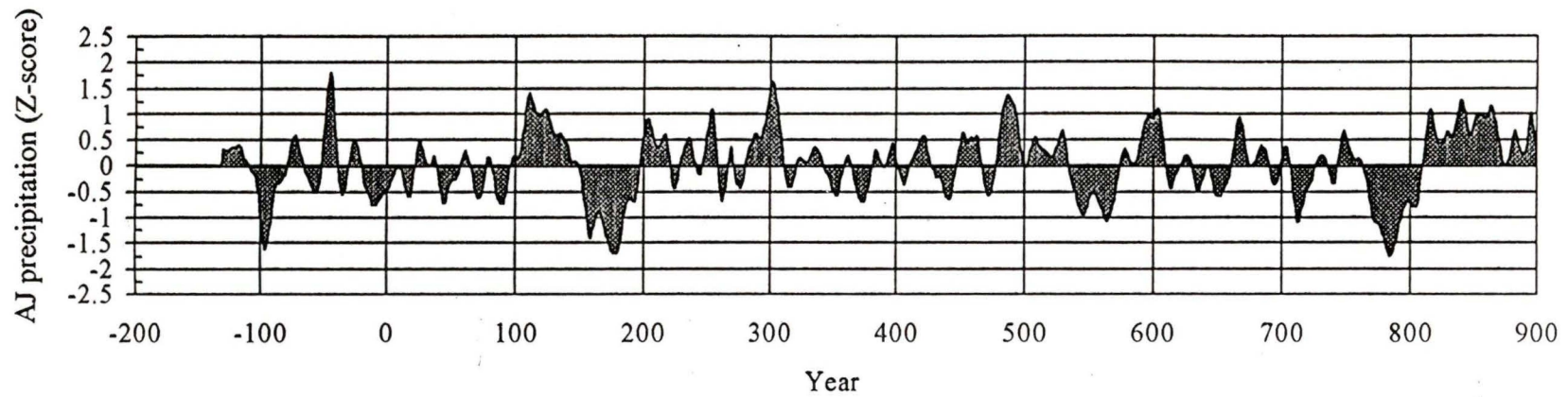


Figure 5.2. The smoothed reconstruction of April-July precipitation at Heal Lake, 130 B.C.-A.D. 1992. (Z-scores are dimensionless units, obtained by subtracting the mean and dividing by the standard deviation of the reconstructed precipitation)

reconstruction are divided into eight climatic intervals: 1) 130 B.C. - A.D. 96: low magnitude and short duration; 2) A.D. 97-197: high magnitude and long duration; 3) A.D. 198-762: low magnitude and short duration; 4) A.D. 763-901: high magnitude and long duration; 5) A.D. 902-1443: low magnitude and short duration; 6) A.D. 1444-1566: high magnitude and long duration; 7) A.D. 1567-1765: low magnitude and short duration; 8) A.D. 1766 - 1992: high magnitude and short duration.

### 5.1.2 Climatic Variations through Time

1) 130 BC-A.D. 96. This 226-year interval is characterized by low magnitude and short duration of precipitation variation with the exception of two anomalies having brief and large precipitation departures. The precipitation fluctuates slightly around the mean during most of the years in the interval suggesting that the climate system is relatively stable during the interval. The negative (defined as below the mean) anomaly has extremely dry AJ years between 100-92 B.C. during which the precipitation departures extend beyond -1 unit. The positive (defined as above the mean) anomaly has the extremely wet AJ years between 49-42 B.C. during which the precipitation departures exceed 1 unit.

2) A.D. 97-197. This interval is characterized by two episodes of high magnitude and long duration, one is positive and the other is negative. The first precipitation episode lasts from A.D. 97 to 150 during which the AJ months are slightly wet in the first 7 years and then become rapidly much wetter in the following 8 years. The moisture decreases gradually from that point while still remaining in the wet mode. There are 33 years during

which the departures of precipitation are over 0.5 unit above the mean. The AJ precipitation drops below the mean in A.D. 151, the start of a dry climatic episode which ends in A.D. 197. The April-July period in this episode is very dry with 41 years of precipitation departures extending beyond -0.5 unit and 24 years extending beyond -1 unit. The changes from state of wet to dry and dry to wet occur within about 10 years in this episode.

3) A.D. 198-762. This long interval is characterized by low precipitation departure from the mean of short duration and includes four positive and two negative anomalies with short periods of large precipitation departures from the mean. The general pattern in this interval is similar to that of the interval 1) and suggests that the AJ precipitation conditions are relatively stable around the mean. The four positive anomalies or extremely wet events, occurring in the years of A.D. 253-255, 298-306, 483-493 and 601-604, have precipitation departures greater than 1 unit above the mean. The other two extremely dry events occur in the years of A.D. 563-565 and 712-714 during which the precipitation departures extend -1 unit below the mean.

4) A.D. 763-901. This interval contains two precipitation episodes of major deviation from the mean, one is negative and the other positive, and both are persistent. The first episode is a 47 year-long state (A.D. 763-809) of relative drought. Forty years of AJ precipitation in this episode depart 0.5 unit below the mean and 23 out of these 40 years have departures greater than 1 unit below the mean. Extreme AJ drought occurs in the period of A.D. 781-788 during which the precipitation departs more than 1.5 unit below the mean. The precipitation increases very rapidly in the end of this episode and

crosses the mean in A.D. 810, the start of a long wet episode that lasts 92 years. Sixty-four years of precipitation in this wet episode depart more than 0.5 unit above the mean.

5) A.D. 902-1442. This long interval is characterized by low deviation from the mean, short duration of precipitation states and seven anomalies of brief and high deviation. Like the interval 1) and 3), the low variability in precipitation during this interval suggests a relatively stable precipitation regime and the anomalies suggest possible extreme and short dry or wet climatic events. The three negative anomalies represent dry events and they occur in the years of A.D. 911-912, 939-941 and 1209-1211. The four positive anomalies or wet events occur in the years of A.D. 1027-1032, 1252-1255, 1358-1366 and 1397-1399. Hence dry and wet anomalies do not occur in pairs.

6) A.D. 1443-1566. This interval is characterized by a 124 year-long state of sustained low AJ precipitation. Eighty-two years in this interval exhibit precipitation values lower than -0.5 unit indicating a prolonged dry climate. The driest years occur between A.D. 1461-1470 and 1487-1490 during which the departures of precipitation extend -1.5 unit below the mean.

7) A.D. 1567-1765. This interval exhibits low magnitude of precipitation departures and mostly short duration of wet or dry states. The wet states are dominant in this 199-year interval and the dry states only occur in the periods of A.D. 1598-1602, 1659-1682, 1708-1709 and 1720-1737. There is one long duration of wet state with low deviation from the mean in the years of A.D. 1603-1658. This pattern of precipitation variation suggests that the AJ precipitation in this interval is generally in a slightly wet mode with little variation.

8) A.D. 1766-1992. This most recent interval is characterized by major precipitation departures from the mean of short duration. Three extremely dry states occur in the years of A.D. 1795-1804, 1843-1855 and 1909-1930. The lowest precipitation of all the three periods extends to -1.5 units. There are two wet states having high magnitude and short duration. The first wet state contains two peaks in A.D. 1862-1867 and 1877-1879 during which the departures of precipitation exceed 1 unit. The second wet state occurs in A.D. 1978-1992 and has the highest peaks (greater than 2.5 unit) throughout the time covered by the analysis.

### 5.1.3 Climatic Extreme Years

The reconstructed precipitation series provides both the general pattern of low frequency variation in precipitation and the years of extremes. The extreme wetnesses and droughts, usually form the pointer years for crossdating, have great impacts on our human life especially if they occur frequently or in consecutive years (Fritts, 1976; Lamb, 1982; Michaelsen *et al.*, 1987). The 40 most extremely dry or wet years, defined as having the precipitation departures more than two units of standard deviation from the mean in this study, are listed in the Table 5.1. These extreme years occurred throughout the 8 climatic intervals and had high frequency in the eighth interval. The driest year is A.D. 1463 which has only 66 mm precipitation in April-July, whereas the wettest years are A.D. 1981 and 1992 which have 164 mm precipitation in April-July. The extreme years as deduced from tree-rings may contain information on climatic or nonclimatic events such as large scale circulation features, insect attacks, and large explosive volcanoes etc (Graumlich, 1987;

Table 5.1. The 40 driest and wettest years in the past two millennia at Heal Lake.

Driest				Wettest			
Rank	Year (A.D.)	Rank	Year (A.D.)	Rank	Year (A.D.)	Rank	Year (A.D.)
1	1463	10	97 B.C.	1	1981	15	127
2	1467		1461		1992		1575
3	179		1466	2	993 *		1773
	1469		1468	3	1984		1948
4	1797		1847	4	1985		1980
5	157		1918	5	898	16	1364
	780	11	786	6	304	17	257
6	1065		1843	7	1983		456 *
	1848		1850	8	46 B.C.		604 *
	1911	12	96 B.C.		1861		868
	1926		1849		1991	18	206
7	173	13	37 B.C.	9	817		841
	1799		784	10	1982		1032 *
	1927		785	11	113		1359
8	546 *		1851	12	863		1398
	1464		1853	13	1365		1697
	1465	14	403 *		1866		1814
9	439 *		1487	14	266		1990
	789		1798		994 *	19	44 B.C.
	1912	15	17	15	47 B.C.	20	1018 *

(\*: The years having sample depth equal or less than 5)

Alfaro and Shepherd, 1991; Jones *et al.*, 1995). Noticing that the tree-rings of Douglas-fir at Heal Lake represent sums of weighted five-year AJ precipitation (see chapter 4), the reconstructed climatic extremes also contain information of AJ precipitation in the previous four years.

## 5.2 Discussion

The reconstruction of AJ precipitation at Heal Lake on southern Vancouver Island shows that long period of notably wet or dry states and brief extreme climatic anomalies have occurred during the last two millennia, and they are not well represented in the brief modern instrumental record. This section focuses the discussion on precipitation variations in the Little Ice Age and Medieval Warm Period because they are the most significant climatic events recognized in many parts of the world during the last two millennia (Ingram *et al.*, 1981; Lamb, 1969, 1982; Hughes and Diaz, 1994; Villalba, 1994). Other climatic phenomena, although identified and described in the previous section, are not included in the discussion at this point and more work will be carried on in a later stage to evaluate possible cyclic characteristics and forcing factors. Finally, the results are compared with other studies in the nearby regions to examine the occurrence of synchronous phenomena over a large spatial scale.

### 5.2 1. The Little Ice Age

The little Ice Age is commonly referred to as a cool period between the Middle Ages and the first half of the twentieth century (Grove, 1988). The nature and timing of

this period vary from region to region (Lamb, 1982; Grove, 1988). An investigation of the characteristics of this most recent major cooling period is helpful for understanding the behaviour of the climate system (Grove, 1988).

It is not easy to discern patterns of cooling and warming from the tree-ring chronology developed in this study because the growth of Douglas-fir at Heal Lake is moisture sensitive rather than temperature sensitive. However, since the climate is a consequence of redistribution of heat and moisture through the circulation of the atmosphere and ocean (Lamb, 1982), a major long-term temperature deviation may also exhibit certain changes in precipitation patterns or at least influences, through the process of evaporation, the amount of effective water available to the growth of trees. Therefore, the reconstruction of precipitation from this study can be used to detect some particular features of climate in the Little Ice Age.

The period of A.D. 1567-1765, the climatic interval 7), falls within the scope of Little Ice Age and exhibits wetness over most of the years. This observation suggests that the precipitation is relatively high during this so called period of Little Ice Age. This observation is reasonable because the Little Ice Age is characterized by expansion and/or advance of glaciers which requires low temperature and/or high moisture (Grove, 1988). The reconstruction of climate in this study does show a moist state at Heal Lake on southern Vancouver Island during the Little Ice Age. Several wet climax periods occur in the 1570s, 1610-20s, 1690s, and 1740-50s. In the following climatic interval, interval eight, there are occurrences of wetness in 1810-20s, 1860-70s and early 1890s, and these periods coincide with glacier activity in the nearby regions (Heusser, 1957; Smith and

Laroque, 1996). The preceding climatic interval, A.D. 1443-1566, is an apparently sustained dry state. It has different precipitation features with the Little Ice Age in the interval seven. It is not clear so far what caused such century-long drought in the interval 6) and interestingly a tree-ring study in southwestern US (Grissino-Mayer, 1995) also reveals a similar century-long drought during this interval. There are several wet episodes in the earlier times such as A.D. 1252-1255, 1358-1366 and 1397-1399 that may be related with the 'early Little Ice Age' events (Desloges and Ryder, 1990; Luckman, 1995).

In summary, the reconstruction of AJ precipitation in this study shows that the Little Ice Age was in a moist state during the interval A.D. 1567-1765, and there were several occurrences of wet episodes before and after this interval and they might be related with the Little Ice Age event. This relationship needs to be verified through comparison with other studies that contain information of temperature variations.

### 5.2.2. The Medieval Warm Period

The Medieval Warm Period is generally considered as a prolonged interval of warmth from approximately the ninth to the fourteenth centuries (Lamb, 1982; Hughes and Diaz, 1994). Hughes and Diaz (1994) reviewed the available evidence concerning the warmer climate in this period and concluded that there was insufficient evidence to support the concept of a global Medieval Warm Period so far, and much work remained to be done to portray in greater detail the climatic essence of this period.

In this study, the climatic interval five, A.D. 902-1442, corresponds approximately to the duration of Medieval Warm Period. The reconstructed precipitation in this interval

shows small variability and does not have any long duration of persistent departures from the mean. The pattern seems to be similar with the interval three, another long interval with small variability of precipitation. These observations suggest that there is no strong evidence from the AJ precipitation reconstruction to support the argument that this interval was a uniquely featured Medieval Warm Period.

### 5.2.3. Comparison With Other Studies

The results of this study are compared to other independent proxy climatic records in the Pacific Northwest to examine the large-scale features of the climatic system. These proxy data come from published tree-ring reconstructions and glacial records.

Fritts (1991) reconstructed large-scale climatic patterns for the western North America using 65 tree-ring chronologies from eight species (*Pseudotsuga menziesii*, *P. macrocarpa*, *Pinus ponderosa*, *P. edulis*, *P. flexilis*, *P. longaeva*, *P. jeffreyi*, and *Abies concolor*), 96 grid points of annual precipitation and sea-level pressure data, and 77 grid points of annual temperature data. The reconstructed wet years of 1610s, 1830s, and the drought years of 1663-1672, 1800s, 1840s, 1920s, 1950s and 1960s for North Pacific are in general agreement with my study on southern Vancouver Island (Table 5.2).

Graumlich (1987) studied precipitation variation in the Pacific Northwest (1675-1975) using tree-ring chronologies from seven species (*Pseudotsuga menziesii*, *Pinus ponderosa*, *P. jeffreyi*, *P. lambertiana*, *P. albicaulis*, *Larix lyallii* and *L. occidentalis*). The reconstruction in the Columbia Basin showed that wet years occurred in late 1870s, 1810-1815, 1740-1760, 1695-1715; and drought years occurred in 1920s, 1865-1895,

Table 5.2. Comparison of Heal Lake result with other studies.

	Heal Lake on southern Vancouver Island (This study)	Large-scale western North America (Fritts, 1991)	Western Washington and northwestern Oregon (Graumlich, 1987)	Coastal central California (Michaelsen <i>et al.</i> , 1987)
Dry years	1663-65, 1679-80, 1705-08, 1727-31, 1768-69, 1776-78, 1782-83, 1790-91, 1796-1809, 1843-54, 1870-71, 1884-85, 1907-31,	1663-72, 1680s, 1700s, 1730s, 1750s, 1770s, early 1790s, 1800s, 1840s, 1860s, 1920s, 1950s, 1960s	around 1680, late 1710s, late 1730s around 1770 1790s, early 1800s, 1840s, around 1870, 1880s, early 1890s, around 1910, 1920s	1653-57, 1752-56, 1841-45, 1856-60, 1947-51
Wet years	1606-12, 1616-18, 1624-29, 1685-91, 1695-1704, 1713-15, 1742-44, 1749-53, 1813-15, 1825-27, 1860-68, 1875-80 1891-94, 1942-44, 1948-50, 1980-92	1610s, 1630s 1718-27 1830s, around 1940	1695-1715, 1740-60, 1810-28, late 1870s, 1950s	1640-44, 1658-62, 1679-83 1905-09, 1979-83

1840s, 1790s, 1780s, around 1680 and 1770 (Table 5.2). The timing of wet and dry episodes was similar with my reconstruction.

Michaelsen *et al.* (1987) developed tree-ring chronologies from cores of *Pseudotsuga macrocarpa* (Torr.) Mayr. growing in the transverse ranges of central California and was able to reconstruct annual precipitation fluctuations for the region. The reconstructions show that there have been major fluctuations in precipitation variability including changes in the frequency of extremes and rare events that have not occurred in the modern record.

Smith and Laroque (1996) conducted a dendroglaciological study at Moving Glacier and provided the first calendar dating of a Little Ice Age glacial advance on Vancouver Island. The results showed that Moving Glacier advanced in the early eighteenth century and reached a maximum position after 1818. No significant recession was observed before the current century. These results matched with the precipitation history in my study which showed an increased moisture in the turn of 1700, 1813-1822 and 1860-1906. This correlation was reasonable because higher precipitation rather than lower temperature might be responsible for glacier expansion in the Little Ice Age for Northwest America (Denton and Porter 1970; Desloges and Ryder, 1990; Grove, 1988).

The general similarity of these studies to my results (Table 5.2) demonstrates that the reconstructed precipitation variation at Heal Lake does exist and contains much climatic information on a local and regional scale. Nevertheless, dissimilarities (Table 5.2) in timing and intensity of wet or dry events do occur at some times. These differences may be due to the fact that my result is from a very local area at Heal Lake whereas other

studies are from different areas or large-scale regions. Local climate can be influenced by some local factors, e.g. elevation or aspect; and it can vary more sharply than averaged regional climate. Another reason for the differences may be due to the different sensitivity of trees species used in different study areas.

### 5.3 Limitations

The past climate is reconstructed from the transfer function and the tree-ring chronology by assuming that the relationship between AJ precipitation and tree-ring indices is time stable and the tree-ring chronology correctly reflects the past climate regime. However, the methods of developing tree-ring chronology and transfer function have some features that lead to important limitations to the climatic reconstruction.

1). Extreme climatic conditions in the past might not be reconstructed. It is possible that the prehistoric climate fell outside the range covered by the year-to-year variations during the time of recent instrumental recording (Pilcher and Hughes, 1982). Thus, the relationship between the extreme condition and tree-ring indices in the past may not be adequately represented by the transfer function modeled using the recent tree-rings and instrumental records. However, other proxy data suggest that this should not be a serious problem in the later prehistoric period (Pilcher and Hughes, 1982).

2). Some non-climatic events can affect the climatic reconstructions. The spring and early summer precipitation is no longer a limiting factor to tree's growth when the tree experiences some extreme non-climatic events, e.g. insect defoliation or fire. These events, which usually have lapse effects, can destroy the relationship between AJ precipitation and

a tree's radial growth making the reconstructed spring precipitation inaccurate. The relevant information of the occurrence of such non-climatic events in the past will help to assess their effects on climate reconstruction.

3). Multi-century or even longer-term climatic trends can not be revealed in the reconstruction. The procedure of standardization during the construction of chronology removes the long-term climatic trends beyond the length of individual segments (LaMarche, 1974; Cook *et al.*, 1995). The result from pollen studies at Heal Lake (Allen, 1995) suggests that there are no major very long-term climatic changes during the last two millennia and, thus, it provides a framework for this study. Another solution is to use long records of ring series in a single tree as a reference for standardization.

4). The reliability of climatic reconstruction changes in different parts of the period. The sample depths are uneven through time and thus the reliability of reconstruction decreases when the replications are poor. Some of the reconstructed climatic intervals may in part be related to variations in sample number. Finding more samples in the poor replicated period will increase the reliability of climatic reconstruction.

5). The relationship between tree growth and AJ precipitation is a simplified model. The growth of trees is affected by a complex of environmental factors (Glock, 1955). Even though the AJ precipitation has been identified as the major limiting factor controlling a tree's radial growth, some factors as the following enter to make the relationship complicated: the distribution of precipitation during the growing season; the depletion of soil moisture due to evaporation related with the temperature changes; and the competition for water from neighbouring trees (Glock, 1955). The knowledge of

variations of such factors will help to evaluate the reconstructed precipitation history.

## Chapter 6: SUMMARY, APPLICATIONS AND CONCLUSIONS

### 6.1 Summary

A 2122 year-long tree-ring width chronology of Douglas-fir was developed for the Heal Lake site, near Victoria, southern Vancouver Island, BC. The materials are from well-preserved buried logs in the sediments of Heal Lake and from living trees growing nearby the lake. The logs became available when the lake was drained in the summer of 1992 by the Capital Regional District for the expansion of the land fill facilities. Increment cores from living trees were collected using an increment borer in the autumn of 1992. Ring-widths were measured to the nearest 0.01 mm on a tree-ring measuring system, *MEASU-CHRON Digital Micrometer*. Cross-dating of the tree-ring series was achieved using the dendrochronology program COFECHA (Holmes, 1983; Holmes et al., 1986), radiocarbon dates, graphs of ring sequences and pointer years, and wood characteristics. The cross-dated individual tree-ring series were then standardized using the program CHRONOL (Grissino-Mayer et al., 1993) to form the standard ring-width chronology.

Using the chronology and the monthly temperature and precipitation record, the response function and simple correlation function were calculated by the program RES (Holmes, 1994) on the intervals A.D. 1891-1992 and A.D. 1921-1992 to detect the relationship between the radial growth of Douglas-fir and the climate. The results showed that tree growth was positively correlated with the spring and early summer (April-July) precipitation. A transfer function to reconstruct the past AJ precipitation was developed empirically based on a new conceptual model dealing with the feature of high

autocorrelation in the chronology. The model considered the current and the previous four years' spring precipitation as the factors that contributed to the high autocorrelation, and these five years' spring precipitation were weighted appropriately and summed into a functional complex responsible for the current year's ring growth. The reconstructed values were verified using independent data outside the calibration period. The statistics of Reduction of Error, correlation coefficient and sign test were calculated and the results showed that the estimated values agreed well with the actual values.

A proxy AJ precipitation history for the last two millennia was reconstructed using the transfer function and the tree-ring chronology. The reconstructions revealed the interannual, decadal and century-scale precipitation patterns although the multicentury and longer scale climatic trends might have been removed due to the 'segment length curse' problem in the course of the chronology construction. The smoothed curve of the standardized reconstructions were presented and eight distinct climatic intervals were classified according to the magnitude of precipitation departures and the duration of persistent wetness and drought. The pattern of climatic variation during the last two millennia was described and the climatic extreme single years were identified. The timing and nature of the Little Ice Age and Medieval Warm Period were discussed. The results from this study were in general agreement with other independent climatic data in the nearby regions. The study clearly demonstrates the climatic sensitivity of coastal Douglas-fir and its considerable value for constructing proxy climate records.

## 6.2 Applications

The results from this study have a broad range of applications ranging from the fundamental data collection to the practical management of our natural resources.

1) The tree-ring chronology developed in this study contributes to a growing international tree-ring data bank (ITRDB) operated by the Laboratory of Tree-Ring Research at the University of Arizona. The data are available to all researchers in the field, and thus will enable people to understand dendrochronologically related questions, e.g. climatic variations, at a global scale. In particular, it adds a relatively long record for a region not well represented by long tree-ring records. This chronology also establishes a tree-ring standard for dating wood samples from ecological and archaeological studies in the region.

2) The result of the response function and transfer function analysis helps us to understand forest growth dynamics in relation to climatic factors. Consecutive low precipitation in spring and early summer may cause depression in wood productivity whilst consecutive years of wetness in spring and early summer may bring potentially high wood harvests. In conjunction with other records of ecological factors, e.g. insect attack, fire or flood, the relationship between tree growth and climate can be applied in the practice of forest management (Fritts and Swetnam, 1989).

3) The reconstruction of precipitation history can be used in many aspects. First, it extends the local precipitation record far back in time. This long proxy data can improve our understanding of climate, its variations, and extremes (Pittock, 1982), and in particular, help us to examine the current climatic fluctuations such as those attributed to

"global warming" in a long perspective. Second, the long proxy data set can be used to test numerical models of climate (Pittock, 1982), analyze the probability of future recurrence of past climatic episodes and therefore predict the future climate (LaMarche, 1978). In particular, the high sensitivity of Douglas-fir ring-width to climate variation suggests the possibility of using the species as a monitor of local and regional climate change. Third, it can aid the practical management of our natural resources such as water supply and forest production. The reconstructed precipitation time series suggests that we are now situated in a moist and forest productive interval, but the quasi-periodic features exhibited in the past two and half centuries also anticipate a possible dry interval with reduced wood productivity in the next climatic episode. These features can thus be used as a reference frame for the planning of future wood yields and the planning of annual allowable cut.

### 6.3 Conclusions

1) Douglas-fir on southern Vancouver Island is a useful species for dendroclimatological studies. Spring and early summer precipitation (April-July) is the major factor that limits the tree's radial growth. The previous four years as well as the current year's climate can affect the current year's ring-width growth.

2) A 2122 year-long tree-ring chronology of Douglas-fir is developed by overlapping segments of cross-dated ring-width series from buried logs and living trees at Heal Lake site, southern Vancouver Island.

3) The reconstructed AJ precipitation history for the past two millennia reveals

eight distinct climatic intervals. Four of the intervals, B.C. 130-A.D. 96, A.D. 198-762, A.D. 902-1443, and A.D. 1567-1765, are characterized by low magnitude of precipitation departures and short duration of wet or dry periods. Three intervals, A.D. 97-197, A.D. 763-901 and A.D. 1444-1566, exhibit high precipitation departures and long duration of wetness or drought. The most recent climatic interval, A.D. 1766 - 1992, has high precipitation departures and short duration of wetness and drought. There are climatic anomalies and extreme wetness and drought single years throughout the past two millennia.

4) The Little Ice Age is identified to be in a moist state in the interval A.D. 1567-1765. There are several occurrences of wet episodes before and after this interval. The Medieval Warm Period, to the extent that it may be reflected by AJ precipitation, is not clearly identifiable.

5) Comparison with other studies in the nearby regions shows general agreement in the climatic variation, indicating that the reconstructions contain much information in common at a large scale. The dissimilarities in the reconstruction suggest that some local climatic features exist at Heal Lake on southern Vancouver Island.

The reconstruction of climatic variations for the past two millennia represents results derived from one single study site. More work is needed to be done at other sites on southern Vancouver Island so as to draw a broader regional climatic history. In addition, floating chronology segments from the uncovered logs in the sediments of Heal Lake have been already worked out for part of the early and middle Holocene and anchored by radiocarbon dates. The study of dendrochronology and dendroclimatology on

southern Vancouver Island from the Heal Lake logs will be continued to provide detailed proxy climatic information throughout the Holocene.

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