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PROXY CLIMATIC DATA FROM TREE RINGS AT LAKE LOUISE, ALBERTA: A PRELIMINARY REPORT

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ABSTRACT Preliminary results are presented of studies using oxygen isotopes and tree-ring densitometry to derive proxy climatic data from *Picea engelmannii* and *Abies lasiocarpa* in the Canadian Rockies. Significant correlations occur between mean annual temperatures and $\delta^{18}O$ determinations from five year groups of tree rings from three trees. However, unexplained anomalies in these relationships indicate that ring-width effects may reduce this correlation in some cases and that further exploratory work is necessary. Indexed chronologies for the period 1705-1980 were developed for 15 tree-ring variables derived by X-ray densitometry from 16 *Picea* cores. Principal components analysis was used to identify three groups of highly intercorrelated variables related to ring width, earlywood density and latewood characteristics. Each group responds differently to climatic controls increasing the potential for development of proxy climatic data over ring-width measures alone. Transfer function development is incomplete but preliminary results for summer temperature (June and July, R^2 = 0.46) and December-March precipitation (R^2 = 0.40) are presented as examples. Using these equations preliminary reconstructions for the period 1710-1980 are presented.

RÉSUMÉ *Données climatiques indirectes obtenues à partir des anneaux de croissance des arbres, Lake Louise, Alberta: rapport préliminaire*. On présente ici les résultats préliminaires d'études dont le but est d'obtenir des données climatiques par l'intermédiaire, chez *Picea engelmannii* et *Abies lasiocarpa*, dans les Rocheuses du Canada, des isotopes d'oxygène et de la densité des anneaux de croissance. On obtient des corrélations significatives entre les températures moyennes annuelles et les déterminations au $\delta^{18}O$ sur les anneaux de croissance de trois arbres, par périodes de 5 ans. Toutefois, des anomalies encore inexpliquées révèlent que certaines caractéristiques de la largeur des anneaux pourraient, dans certains cas, réduire la corrélation. Il est donc nécessaire de poursuivre les recherches dans ce domaine. On a dressé des répertoires chronologiques, allant de 1705 à 1980. Ils tiennent compte de 15 variables provenant des anneaux de croissance et obtenues par densitométrie radiologique sur 16 noyaux de *Picea*. On a ensuite réparti les variables en trois groupes principaux en se fondant sur la largeur des anneaux, la densité du bois de printemps et les particularités du bois d'automne. Chaque groupe réagit différemment au climat, si bien que les données climatiques indirectes risquent d'être plus importantes que celles que fournissent les seules mesures de largeur des anneaux de croissance. L'élaboration de la fonction de transfert est incomplète, mais on donne, à titre d'exemple, les résultats préliminaires touchant les températures d'été de juin à juillet (R^2 = 0,46) et les précipitations de décembre à mars (R^2 = 0,40). À l'aide de ces équations on a pu effectuer des reconstitutions climatiques préliminaires pour la période allant de 1710 à 1980.

ZUSAMMENFASSUNG *Indirekte klimatische Daten, die anhand der Jahresringe der Bäume gewonnen wurden, Lake Louise, Alberta: Ein vorläufiger Bericht*. Es werden vorläufige Ergebnisse vorgestellt von Studien, die mittels Sauerstoff-Isotopen und der Dichte der Baumjahresringe indirekte klimatische Daten von *Picea engelmannii* und *Abies lasiocarpa* in den kanadischen Rockies gewinnen. Es erscheinen signifikante Korrelationen zwischen durchschnittlichen Jahrestemperaturen und den $\delta^{18}O$ Bestimmungen auf den Jahresringen von drei Bäumen in fünf Jahresgruppen. Jedoch weisen unerklärte Anomalien in diesen Beziehungen darauf hin, daß Wirkungen der Ring-Breite diese Korrelation in manchen Fällen reduzieren kann, und daß weitere Forschungsarbeit notwendig ist. Für die Zeit von 1705-1980 wurden chronologische Register entwickelt für 15 Baum-Ring-Variablen. Diese wurden durch Messung der Dichte von 16 *Picea* Kernen mittels Röntgenaufnahmen gewonnen. Die Analyse der hauptsächlichen Komponenten diente der Identifizierung von drei Gruppen von Variablen, die in intensiver Wechselbeziehung stehen, wobei man sich auf die Breite der Ringe, die Dichte des Frühjahrsbaumwuchses und die Charakteristika des Herbstbaumwuchses bezog. Jede Gruppe reagiert anders auf klimatische Einflüsse, so daß die indirekt gewonnenen klimatischen Daten wichtiger sind, als die allein durch Messung der Ring-Weite gewonnenen. Die Ausarbeitung der Transferfunktion ist unvollständig, aber vorläufige Ergebnisse für Sommertemperatur (Juni und Juli, R^2=0.46) und Dezember bis März Niederschlag (R^2=0.40) werden als Beispiel dargestellt. Mittels dieser Gleichungen werden vorläufige Rekonstruktionen für die Periode von 1710 bis 1980 vorgestellt.

INTRODUCTION

The annual nature and year to year variability of the growth increments of many species of tree has made tree-ring series a potentially excellent source of proxy climatic data. In North America the development of tree-ring studies has been strongly linked with the Laboratory of Tree Ring Research of the University of Arizona and an excellent summary of this work is found in FRITTS (1976). In recent years dendroclimatological studies have diversified considerably with the expansion of research to new geographical areas and species, the application of new and more sophisticated techniques in the analysis of ring-width data and experimentation with the use of other tree-ring characteristics as potential paleoclimatic tools (see HUGHES *et al.*, 1982). Two of these new developments involve the application of stable isotope techniques and X-ray densitometry to tree rings. This paper reports the preliminary results of studies attempting to derive proxy climatic data by these techniques from *Picea engelmannii* and *Abies lasiocarpa* specimens near Lake Louise in the Canadian Rockies.

STUDY SITE AND SAMPLING PROCEDURES

One of the major difficulties in calibration studies of tree-ring data from mountain areas is that instrumental records are few, often of short duration and usually located in valley floor sites which are a considerable distance, both horizontally and vertically, from the tree-ring sites of interest. The availability of an adequate climatic record is therefore a principal limiting factor in the selection of a calibration site. Lake Louise is the highest (1534 m) of the four meteorological stations in the four contiguous Canadian Rocky Mountain National Parks (*ca.* 20,150 km^2) with over 25 years of record. Observations began in 1915 and minor gaps in the record may be estimated by correlation with adjacent stations at Banff, Anthracite or Field, B.C. Although the actual site of the station has been changed twice, the distances involved are less than 0.5 km and all were valley floor sites near the settlement.

The principal focus of our tree-ring studies within the Canadian Rocky Mountains has been on timberline or upper subalpine sites where the dominant species are *Picea engelmannii* and *Abies lasiocarpa* (*e.g.* LUCKMAN 1982; LUCKMAN *et al.*, 1984a, 1984b; KEARNEY and LUCKMAN, 1983). Lake Louise is the only meteorological station with adequate records within the subalpine forest zone. Although it would have been ideal to sample trees adjacent to the meteorological site, this is not possible as the valley floor is dominated by secondary forest growth of *Pinus contorta* resulting from human disturbance (fire) in the early part of this century (NELSON and BYRNE, 1966). The tree-ring site selected is a mature stand of subalpine forest about 3 km west of Lake Louise post office (Fig. 1). It is situated on a north-facing, gently inclined valley-side bench, probably of glacial origin, at an elevation of about 1680 m, approximately 150 m higher than and 2,5 km from the meteorological station. The site is a moderately well drained example of the CV1 ecosite of the Biophysical Inventory of Banff and Jasper National Parks (HOLLAND and COEN, 1982) with a C13 vegetation type (*Picea englemannii-Abies lasiocarpa/Hylocomium splendens*, HOLLAND and COEN, 1982, p. 85). Although there has been some cutting of timber near the road, the site is otherwise undisturbed by human activity.

Sampling for both oxygen-isotope and densitometric studies was carried out at the same site. In June 1981 ¾″ (19 mm) cores were obtained at breast height from 3 mature trees (2 *Picea*, 1 *Abies*) by Luckman, Jozsa and G. Frazer using a power-corer developed at Forintek. These three trees all grew within a 10 m diameter circle and were, respectively, 298 (L81-2P), >276 (L81-3P), and 148 (L81-1A) years old. Two standard tree cores (4 or 5 mm diameter, at least 90° apart) were also extracted from these trees and 12 other spruce trees at the site using Djos or Haglof increment corers. In June 1983 increment cores were obtained from another 25-30 trees by Luckman, Hamilton and Frazer. Densitometric and ring-width chronologies were derived from increment cores selected from these two sampling programmes.

OXYGEN-ISOTOPE STUDIES

Isotopic studies from sequences of tree rings began in the 1970's and the initial results and developments are reviewed by GRAY (1981), LONG (1982) and WIGLEY (1982). The earliest work was carried out using analyses of whole wood (*e.g.* LIBBY *et al.*, 1976) but more recent work has shown that different components of the wood have varying isotopic contents and that α-cellulose contains the strongest climatic signal (EPSTEIN and YAPP, 1976; GRAY and THOMPSON, 1977).

Several authors, *e.g.* GRAY and THOMPSON (1976), GRAY (1981) and BURK and STUIVER (1981), have demonstrated strong statistical relationships between $\delta^{18}O$ content of the α-cellulose in tree rings and climatic parameters. GRAY and THOMPSON (1976), using five year increments of rings from a *Picea glauca* which grew at Edmonton between 1882 and 1969, found that the best correlations were with mean annual temperature (September-August of the ring year). They also present results for other sites in Western Canada where determinations from groups of rings from the same species of tree have been correlated with climatic variables but the relationships are not as strong. BURK and STUIVER (1981) demonstrated that both temperature and relative humidity were correlated with the $\delta^{18}O$ content of rings from trees growing at different latitudes or varying altitudes on Mount Rainier.

The exact nature of the $\delta^{18}O$: temperature relationship is still the subject of some controversy (*e.g.* EPSTEIN *et al.*, 1977; BURK and STUIVER, 1981; GRAY, 1981). Nevertheless, the results reported above suggested that tree-ring isotope data have considerable potential for yielding proxy climatic data. The Lake Louise study was an attempt to apply these techniques to different tree species from a subalpine location.

ANALYTICAL PROCEDURES

Samples of five year groups of rings covering the period 1921-1980 were cut from the three 19 mm cores at the University of Alberta. α-cellulose was extracted from each sample using standard techniques (GREEN 1963) and oxygen was

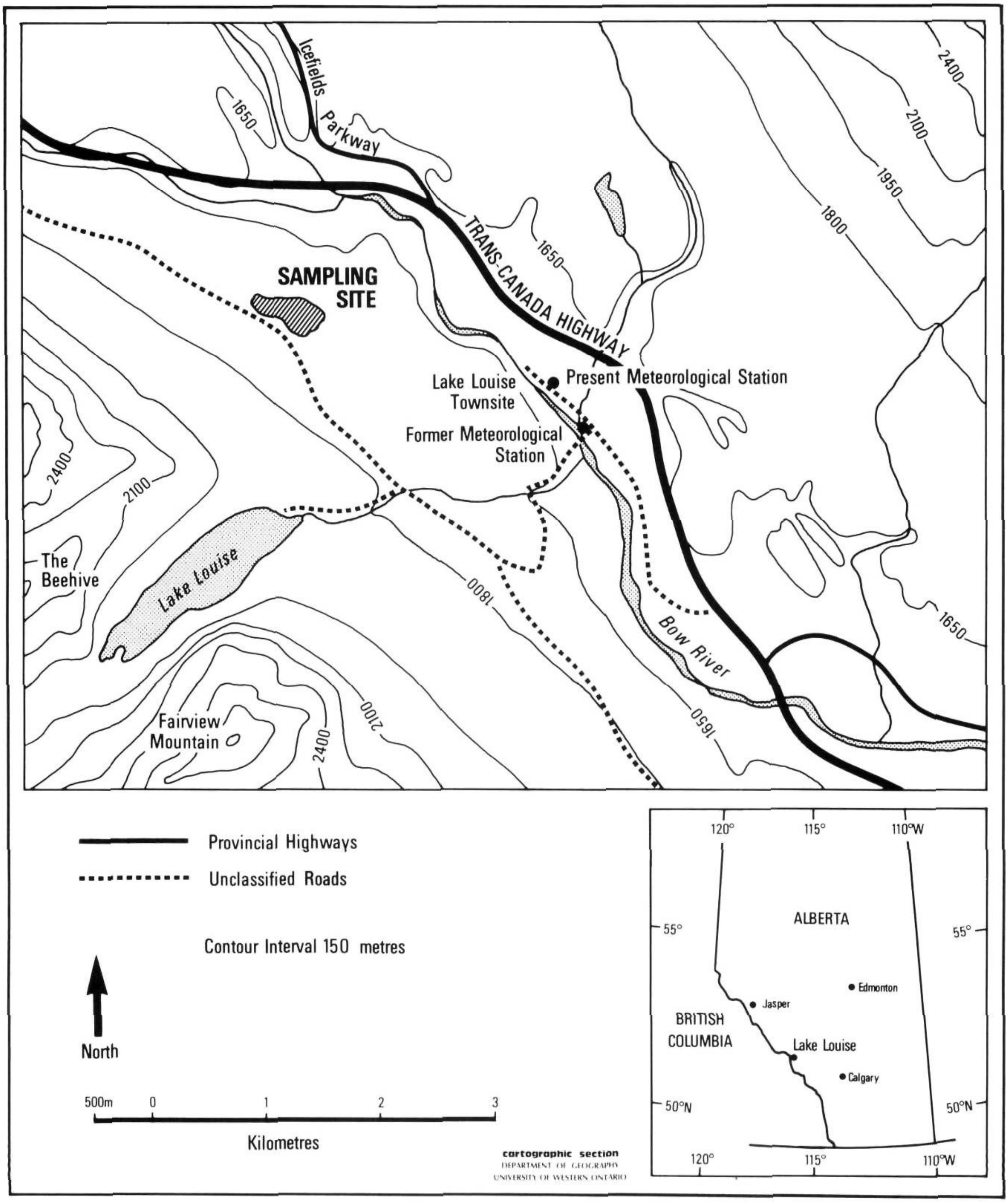

FIGURE 1. Location of the Lake Louise sampling site and meteorological stations.

Localisation du site d'échantillonnage et des stations météorologiques de Lake Louise.

extracted from the α-cellulose for isotopic analysis in the form of CO_2 by pyrolysing the samples in a nickel reaction vessel at 1150°C (THOMPSON and GRAY, 1977). $\delta^{18}O$ determinations were made using a VG Micromass 602C isotope ratio mass spectrometer at the University of Alberta. Results are *expressed relative to* V-SMOW (*Vienna-Standard Mean Ocean* Water) (GONFIANTINI, 1978), in terms of the delta notation (‰) (CRAIG, 1957). Replicate analyses were carried out on all samples and the precision is normally better than 0.2‰.

RESULTS

The results of $\delta^{18}O$ determinations on the three trees from Lake Louise (denoted by 2P and 3P for the *Picea* and 1A for the *Abies*) are shown in Table I. The two *Picea* show excellent replication (Fig. 2). Only three sample pairs, namely the highest (1941) and two lowest (1951, 1966) values from tree 2P, have differences greater than the single determination precision of 0.2‰ (Table I). The 3P values have the greater range but 70% of the determinations are between 21.0 and 21.5‰. However, despite the high correlation, the slope of the best fit regression line is not unity (Fig. 2), indicating that there may be some systematic differences between the isotopic signal in these two trees.

The isotopic determinations from the *Abies* tree sampled show both a wider range (2.5‰) and slightly higher values than the two *Picea* samples (Table I). Nevertheless, correlation between the results from both species is high. Further sampling would be needed to determine whether the differences can be attributed to differences between individual trees or between species. The *Abies* was only about half the age of two *Picea* and has a much higher latewood component in the annual rings (34% compared with 14% for the *Picea* over the 1921 to 1980 period).

Evaluation of oxygen isotope/climate relationships was carried out using the climatic data recorded at Lake Louise

TABLE I

$\delta^{18}O$ determinations from three trees at Lake Louise

Sample period	L81-1A	L81-2P	L81-3P
1921	22.0	21.2	21.1
1926	21.2	21.0	21.1
1931	21.9	21.5	21.4
1936	22.0	21.4	21.5
1941	22.4	21.4	21.7
1946	21.8	21.5	21.5
1951	19.9	20.3	19.9
1956	21.6	21.4	21.2
1961	22.2	21.8	21.7
1966	21.5	20.8	20.5
1971	21.1	21.4	21.2
1976	21.2	20.9	21.0
Mean	21.65‰	21.22‰	21.15‰
Range	2.5‰	1.5‰	1.8‰

The values are for five year groups of rings beginning in the year shown. Tree L81-1A is an *Abies*, 2P and 3P are *Picea*.

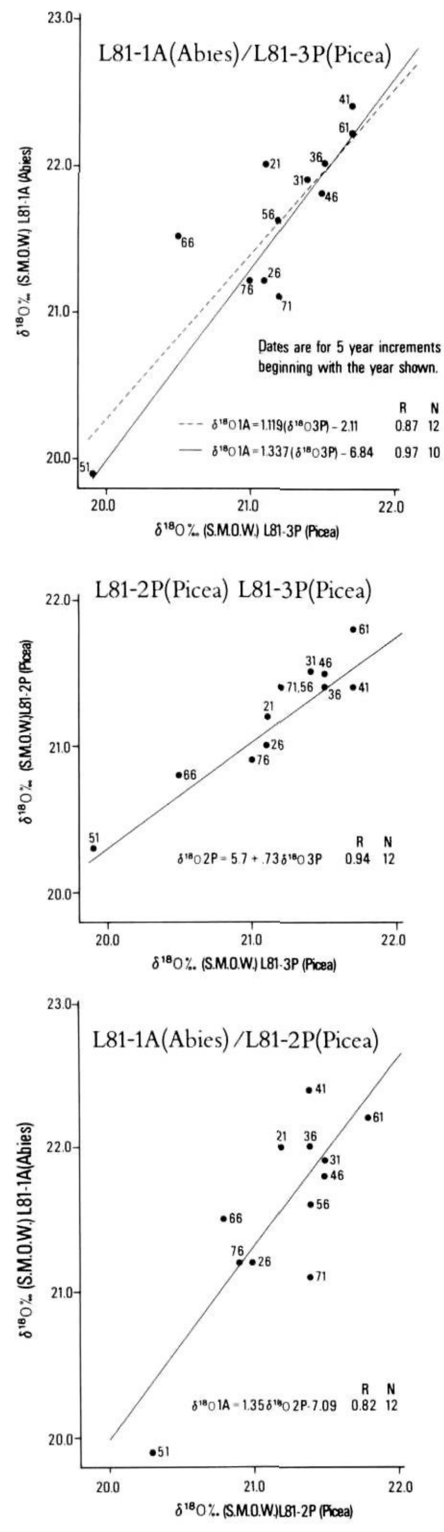

FIGURE 2. Relationships between $\delta^{18}O$ determinations for tree-ring samples from three living trees at Lake Louise. The 1921 and 1966 samples are omitted from relationship shown by the solid line in the upper figure.

Relations entre les déterminations au $\delta^{18}O$ sur les échantillons d'anneaux de croissance de trois arbres vivants, Lake Louise. Les échantillons de 1921 et de 1966 ne font pas partie de la relation représentée par la courbe continue sur l'illustration du haut.

TABLE II

Correlation coefficients between $\delta^{18}O$ values and various climatic parameters at Lake Louise

Sample	N	MATJD	MATSA	JFM	Winter	Summer	Snow	Summer rain	Total precip.	Precip. JJA
A. All Samples										
^{18}O 2P	12	.58*	.47	.47	.35	.42	.05	.07	.07	.07
^{18}O 3P	12	.55*	.45	.39	.30	.47	−.10	.21	−.01	.18
^{18}O P	12	.56*	.44	.41	.30	.30	−.04	.14	.02	.11
^{18}O 1A	12	.65**	.59*	.54*	.47	.55*	−.13	.16	−.06	.18
B. Selected samples										
^{18}O 2P	10	.73**	.69*	.70*	.71*	.52	.62*	.22	.58*	.43
^{18}O 3P	10	.88**	.91**	.75**	.82**	.79**	.45	.59*	.59*	.80**
^{18}O P	10	.85**	.84**	.73**	.79**	.70*	.59*	.42	.64*	.65*
^{18}O 1A	10	.93**	.94**	.70*	.89**	.80**	.44	.63*	.59*	.83**

The three samples are 1A *(Abies)*, 2 P and 3P *(Picea)*. Sample P is the mean of 2P and 3P.
* Significant at 5% level; ** Significant at 1% level.
Data are for 12 5 year periods. The samples used in Part B exclude 1951-55 and 1966-70 *(Picea)* or 1921-25 and 1951-55 *(Abies)*.

MATJD = Mean Annual Temperature Jan.-Dec.
MATSA = M.A.T. Sept.-August
JFM = Mean Temperature Jan.-March
Winter = Mean Temperature Oct.-April
Summer = Mean Temperature May-Sept.
Snow = Total snowfall Sept.-May
Summer rain = Total precipitation May-Sept.
Total precip. = Snow + Summer Rain
Precip. JJA = June, July, August Precipitation

aggregated into five year periods between 1921 and 1980. Aggregate data were necessary because it was difficult to obtain adequate sample volumes for isotopic analyses of individual ring years. The climatic variables tested were similar to those used by GRAY and THOMPSON (1976). Missing values (13 scattered months of temperature data, 18 months of precipitation records) were estimated using equations developed by regression analysis of monthly values from Lake Louise and Banff, Alta. or Field, B.C. The initial results (Table IIA) show that the only statistically significant relationships involve temperature data (mean annual temperature; January to December — MATJD) and that no relationships with precipitation amounts are apparent.

A more detailed evaluation of some of these data is presented in Figure 3 and Table IIB. These results show strong relationships between $\delta^{18}O$ values and mean annual temperatures, September to August (MATSA, correlation with MATJD are very similar) for the majority of samples (10/12) in all three trees. However the 1951 determinations are considerably lower in all three trees and a similar effect occurs with the 1966 sample in both *Picea* specimens. The result for the 1921 sample from the *Abies* also deviates considerably from the best-fit line. Examination of the relationships between $\delta^{18}O$ and other tree-ring variables revealed no significant results except with latewood variables in one tree. This result largely reflects the exceptional 1951 values and disappears if that value is excluded (Table III).

Examination of these data in conjunction with a variety of tree-ring parameters (ring width, density, percentage latewood, maximum density, etc.) has failed to yield a satisfactory explanation for these anomalies. There is some evidence that they may be related to variation in ring characteristics between the samples. WIGLEY *et al.* (1978) have pointed out a number of problems in the analysis of oxygen isotope-climate relationships using aggregated data. If the rings in the sampled sequence vary in width they will contribute unequally to the isotopic average (determined volumetrically) whereas the climatic data are arithmetic averages. Furthermore, as the isotopic composition of latewood and earlywood α-cellulose is different (GRAY and THOMPSON, 1978) variation in the earlywood/latewood ratio between rings could compound these effects.

The 1951 samples (1951-55 rings) plot well below the best fit regression line for all three trees (Fig. 3). Analysis of the Lake Louise tree-ring chronologies (see below) suggests that 1951-55 is a very exceptional period. These chronologies contain a number of low density "marker" rings which are listed in Table IV. The years 1951, 1952, 1953 and 1968 rank in the lowest 15 (out of 290 years) in maximum density and in the lowest five in terms of latewood width, latewood density and percentage latewood width. Examination of the cores used for isotope analysis reveals that the 1951-55 rings had no latewood[1] in the 2P core and only two of the years had latewood in the 3P core. The *Abies* core does not show similar effects because of the higher percentage latewood in that tree. Nevertheless the 1951 sample rings have the lowest latewood width and second lowest percentage latewood and latewood density of the 12 ring periods sampled. There are five other sample periods from the two *Picea* cores where latewood is absent for one or two rings but the 1966 sample is the only one where it occurs in both trees (1968 year). These data indicate that samples which contain years with

1. The earlywood-latewood boundary used in scanning was a density of 0.54 gm / cm^3 (PARKER *et al.*, 1980, Fig. 5).

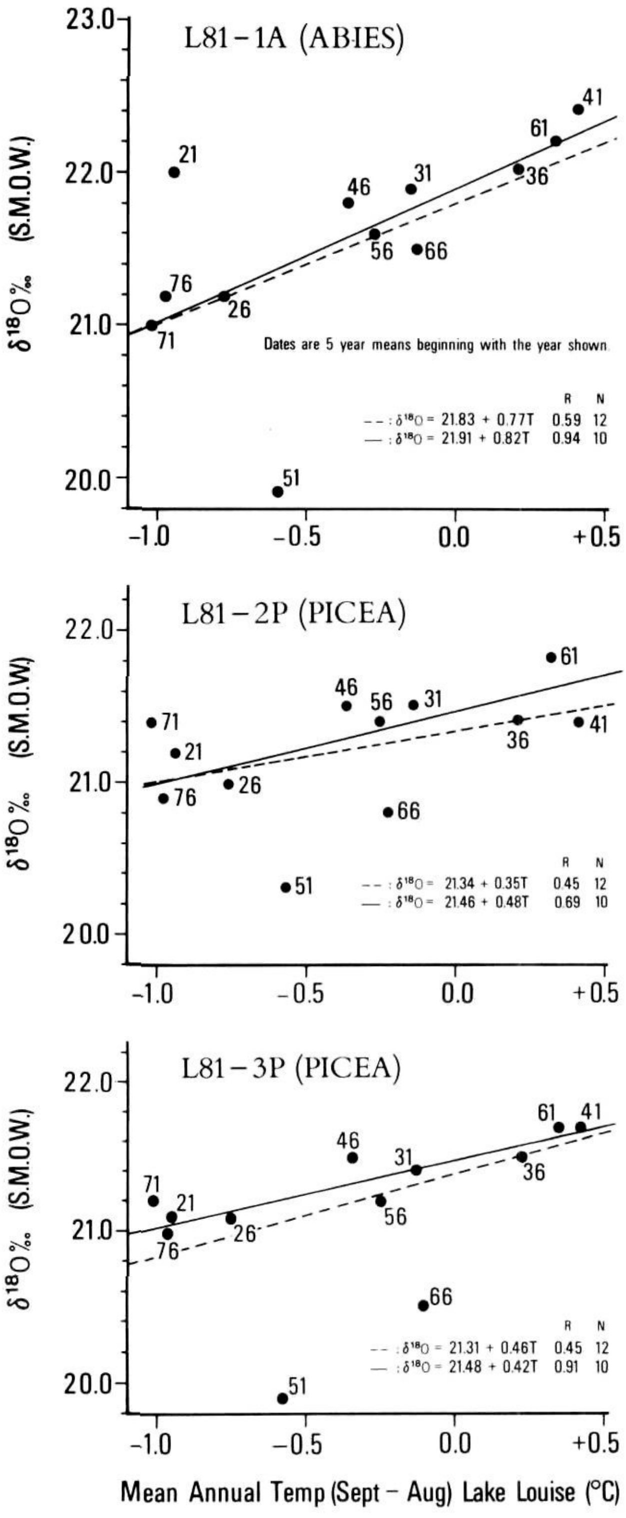

FIGURE 3. Relationships between $\delta^{18}O$ values and mean annual temperature for three trees at Lake Louise. The sample points 1921 and 1951 (*Abies*) and 1951 and 1966 (*Picea*) are omitted from the regression equations shown as solid lines

*Relations entre les valeurs $\delta^{18}O$ et la température moyenne annuelle provenant de trois arbres, Lake Louise. Les points représentant 1921 et 1951 (*Abies*) et 1951 et 1966 (*Picea*) ne font pas partie des équations de régression indiquées par la ligne continue.*

supressed latewood development may have much lower $\delta^{18}O$ ∝-cellulose content than expected from the general relationship derived from the majority of samples at this site.

It is evident, however, that the ring-width effect described by WIGLEY *et al.* (1978) cannot in itself account for the much lower $\delta^{18}O$ values obtained. GRAY and THOMPSON (1978) measured $\delta^{18}O$ values on early and latewood ∝-cellulose samples on 3 consecutive annual rings from a *Picea* which grew in Edmonton. The earlywood ∝-cellulose was found to be heavier than latewood ∝-cellulose in general by 0.5 to 0.8‰. Thus the absence of latewood in a given group of rings would tend to yield a higher $\delta^{18}O$ value than expected. BRENNINKMEIJER (1983) in a more extensive study involving ten annual rings of an elm tree (*Ulmus glabra*) found a decrease of the $\delta^{18}O$ of latewood ∝-cellulose of as much as 1.4‰ relative to the earlywood ∝-cellulose. In addition the variation

TABLE III

Correlation coefficients between oxygen isotope determinations and selected tree-ring parameters for three trees at Lake Louise

Core number	N	*Ring width*	*Maximum density*	*% Latewood width*	*Mean ring density*
L81-1A	12	0.37	0.22	−0.26	−0.17
L82-2P	12	0.35	0.68**	0.54*	0.30
L81-2P[1]	11	0.26	0.28	−0.15	−0.26
L81-3P	12	0.00	0.39	0.40	0.20

** significant at 1% level
* significant at 5% level
[1] The 1951 data were excluded in this run.

TABLE IV

Rings with exceptional latewood characteristics in the Lake Louise chronology

Year	Latewood width	% Latewood width	Latewood density	Maximum density
1731	.87	.95	.84	.85(6)
1738	.66	.66(10)	.68(6)	.80(1)
1811	.62(8)	.57(4)	.72(9)	.80(1)
1813	.50(5)	.50(2)	.72(9)	.80(1)
1880	.72	.68	.71(8)	.85(6)
1884	.68	.64(7)	.89	.92
1899	.58(6)	.63(8)	.63(5)	.82(4)
1924	.61(7)	.93	.75	.98
1950	.65(10)	.64(9)	.76	.94
1951	.45(3)	.61(5)	.57(4)	.85(6)
1952	.42(2)	.57(3)	.52(2)	.87(9)
1953	.30(1)	.48(1)	.43(1)	.82(4)
1958	.64(9)	.94	1.00	1.00
1962	.58(6)	.73	.68(6)	.92
1968	.47(4)	.61(5)	.56(3)	.89(14)

The numbers quoted are indices for the 290 year chronology. The mean index value is 1.00 but the variance differs between index chronologies. Figures in parentheses indicate the rank (lowest = 1, only ranks 1-10 listed).

within single rings was compared with the climatic events during the growth periods of the rings. No link was found between any of the environmental variables and variations in the $\delta^{18}O$ in the α-cellulose. Thus while it is likely that the anomalously low $\delta^{18}O$ values for the 1951 sample are linked to the absence or suppression of latewood in these samples, the reasons for this are not clear. Furthermore the aggregated data available in this study have inadequate resolution to resolve the problem fully.

The 1921 sample from the *Abies* produced the only large positive anomaly. The main difference between this tree and the two *Picea* is that the 1925 ring in the *Abies* is much narrower (50%) than the 1921-24 rings. This suggests that the anomaly might be related to the unequal contribution of the ring years to the α-cellulose used for isotopic determination and is restricted to this particular tree.

DISCUSSION

The data shown in Figure 3 and Table II support the conclusion that there is a strong temperature signal in the $\delta^{18}O$ content of α-cellulose in tree rings which may potentially yield proxy climatic data. They also indicate that the patterns of isotopic variation in rings of *Picea* and *Abies* from the same site are similar and that either species will be useful for isotopic work. However, the Lake Louise results are not as clear cut as those published by GRAY and THOMPSON (1976) and indicate that the temperature: isotope relationship is not a simple one. The unexplained deviation of some sample values from the well defined relationship suggests that other controls are present which have not been identified in this study. Examination of the data presented above suggests that groups of rings containing years without latewood may not conform to the relationship defined by the majority of samples. Ring-width effects alone cannot be responsible for the anomalies and it is possible that these deviations may reflect the control of other variables not examined in this analysis (*e.g.* evaporation/humidity or physiological effects).

The oxygen isotope determinations for the trees at Lake Louise have a much lower range of values than those reported in previous studies and consequently the slopes of the $\delta^{18}O$: MAT curves are also lower (Table V). The low range of values compared to the analytical error term also increases the relative scatter about the best fit regression line. This suggests that interior forest sites may be less suitable for oxygen isotope studies than more exposed sites (*e.g.* at tree line) where evaporation/humidity effects may be more marked.

EPSTEIN and YAPP (1982) and GRAY and SONG (1984) have recently demonstrated excellent relationships between δD values and mean annual temperatures. Complementary studies of the hydrogen isotopes in these rings may resolve some of the questions raised by the present study, not the least because of the greater range in the δD values in tree-rings. Such studies will, unfortunately, have to await resampling of these trees.

TABLE V

$\delta^{18}O$: Temperature relationships from various studies

Site or sample #	Species	MAT (Jan.-Dec.) Intercept	MAT (Jan.-Dec.) Slope	MAT (Jan.-Dec.) r	N.	MAT (Sept.-August) Intercept	MAT (Sept.-August) Slope	MAT (Sept.-August) r	Best fit
Lake Louise samples									
L81-1A	*A. lasiocarpa*	21.88	0.92	0.67	12	21.83	0.77	0.59	JD
	"	21.99	0.85	0.85	10	21.91	0.82	0.94	SA
L81-2P	*P. engelmannii*	21.38	0.33	0.58	12	21.34	0.35	0.45	JD
L81-2P	"	21.47	0.36	0.73	10	21.46	0.32	0.69	JD
L81-3P	"	21.35	0.58	0.56	12	21.31	0.46	0.45	JD
L81-3P	"	21.47	0.43	0.88	10	21.48	0.42	0.91	SA
Watchtower	*P. engelmannii*	(Compression)	Luckman, unpublished		7	16.11	1.97	0.94	–
Watchtower		(Opposite)			4	15.67	1.74	0.97	
Maligne Pass	*P. engelmannii*		"		4	13.95	1.67	0.92	–
Edmonton	*P. glauca*	(Gray & Thompson, 1976)		0.94	18	20.5	1.30	0.97	SA
Edmonton	*P. glauca*	20.9	1.22	0.62	17	21.5	1.00	0.66	SA**
	(Song, 1982)	23.1	0.70	0.51	15	23.1	0.69	0.62	SA**
		22.3	0.79	0.40	15	22.2	0.86	0.56	SA**
Various*	Various	22.97	0.41	0.95	5	(Burk & Stuiver, 1981)			–
Various*	Various	(Gray, 1981)			7	22.9	0.54	0.98	–
Various*	Peat	(Gray, 1981)			7	20.2	0.51	0.98	–
Various*	Aquatic Plants	(Gray, 1981)			5	16.6	0.52	0.98	–

* These estimates compare trees or other organics between sites: the other results are for single specimens.

** Song obtained slightly better results with MATSA of the previous year (r = 0.71, 0.76 and 0.77 respectively).

MAT = Mean Annual Temperature.

TREE-RING DENSITOMETRY

The technique of X-ray densitometry involves exposing carefully prepared tree cores or sections to X-ray radiation and measuring various ring width and density characteristics from the X-ray negative using a scanning densitometer (PARKER *et al.*, 1980; SCHWEINGRUBER *et al.*, 1978; SCHWEINGRUBER, 1982). The potential of densitometry for dendroclimatic studies has been demonstrated by several authors (PARKER and HENOCH 1971; SCHWEINGRUBER *et al.* 1978; JOZSA *et al.* 1983) but the small number of densitometric facilities has limited its application. The principal advantage of densitometry is that it provides information about a greater range of tree-ring characteristics thereby enabling a wider examination of climate-growth relationships. This is extremely useful in environments with complacent ring width characteristics such as temperate interior forest sites (*e.g.* CONKEY, 1979).

CHRONOLOGY DEVELOPMENT

The number of ring variables determined in tree-ring densitometric studies enables the construction of multiple tree-ring chronologies for a single site. Fifteen tree-ring variables were used in this study: eight of these are determined by direct measurement (whole ring, earlywood and latewood widths; whole ring, earlywood, latewood, maximum and minimum densities) and seven others are derived from these data (percentage latewood width plus weight and volume measures). The tree-ring chronologies cover the period from 1690 to 1982 and were constructed using 16 cores from 12 mature *Picea engelmannii* sampled at Lake Louise in 1981 and 1983. Indexed chronologies were developed for each variable through digital filtration techniques (PARKER *et al.*, 1981). The raw data from each tree were standardized by a weighted 99 year running mean to remove the growth trend (A chronology) to produce tree-ring indices (B and C chronology). Indices from the individual trees were averaged to produce master summary chronologies for each tree-ring variable and subsequent analyses were restricted to these 15 indexed chronologies. Core selection, densitometric scanning and chronology development was carried out at Forintek Canada Corporation by Jozsa.

THE CLIMATE-GROWTH RESPONSE

The relationships between tree-ring variables for the fifteen chronologies and five monthly climatic parameters (mean and maximum temperatures, rainfall, snowfall and total precipitation) were examined using simple correlation analysis. The climatic variables used included monthly values for both the ring year and preceding year. Only the measured values from 1915-1980 were used in these analyses and therefore calibrations are based on between 56 and 66 years of data (depending on the month and parameter). These results indicate that ring characteristics are more closely linked to temperature than precipitation (HAMILTON, 1984). Several ring variables are significantly correlated with spring and fall temperatures of the prior year and summer temperatures of the growth year. The best correlations with precipitation variables are inverse relationships with January and July precipitation.

There is clearly some cross-correlation between the ring variables used (*e.g.* ring width, weight and volume). Principal component analysis may be used to identify those tree-ring variables which respond to climate in a similar way and to transform them into a smaller number of uncorrelated variables (eigenvectors, FRITTS, 1976). Three major groups of variables were identified by this technique (Table VI): earlywood/total ring measures, latewood variables and earlywood density variables. As earlywood constitutes about 80% of total ring width the Component 1 groupings are not unexpected and correlation coefficients between variables all exceed 0.93. A similar pattern occurs in the latewood group of variables except that percentage latewood is less highly correlated with other group variables (correlation coefficients range from 0.72 to 0.84). Intercorrelation of Component 3 variables ranges from 0.70 to 0.92.

The results in Table VI indicate that the density and latewood variables contribute a considerable amount of information to the data set which is not found in the ring-width variables. This is more clearly emphasised in Figure 4 which shows the relationship between one variable from each component group and mean monthly temperature and precipitation values. Component 1 and Component 3 variables correlate with early summer temperatures of the previous (*e.g.* for April ring width = 0.37, earlywood density = −0.37) and current year (*e.g.* for June ring-width = 0.44, earlywood density = −0.32). Latewood variables are inversely related to fall temperatures of the previous year (*e.g.* percentage latewood = −0.37 for November) and positively correlated with summer temperatures

TABLE VI

Principal components analysis of tree-ring variables

Variable	Principal component loadings 1	2	3	
Ring width	.8883	.3468	−.2894	
Earlywood width	.9087	.1664	−.3785	
Ring volume	.8841	.3551	−.2760	
Earlywood volume	.9076	.1636	−.3822	
Ring weight	.8655	.4644	−.1801	
Earlywood weight	.9305	.1740	−.3113	
Latewood width	.3950	.9136	−.0339	
Latewood density	.2334	.9396	−.1163	
Maximum density	.4783	.8289	.1149	
Percentage latewood	−.1625	.9529	.2216	
Latewood volume	.3952	.9135	−.0329	
Latewood weight	.4014	.9094	−.0010	
Ring density	−.2504	.5914	.7428	
Earlywood density	−.4770	−.0662	.8535	
Minimum density	−.5183	.0328	.8175	
Eigenvalue	6.18	5.88	2.61	
% of variance	41.2	39.1	17.4	97.7 TOTAL

The components were derived from the principal components solution, grouping and eigenvalues based on loadings matrix following varimax rotation. Analysis was done on the basis of ring measures from 1915 to 1980.

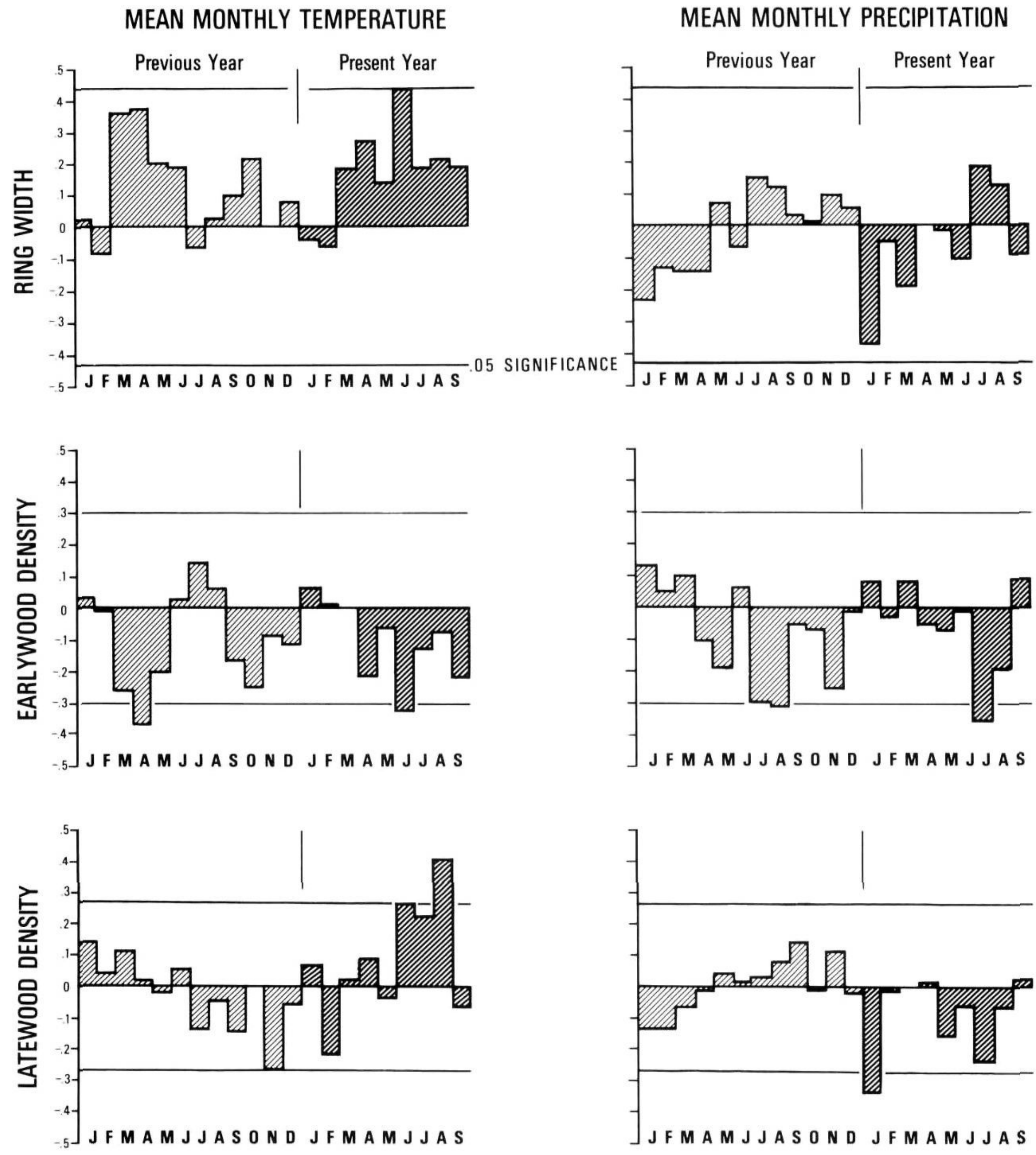

FIGURE 4. Relationships between selected tree ring characteristics and monthly temperature and precipitation at Lake Louise. Significance levels are for the "effective sample size" of these samples as defined by FRITTS (1976, Eqn. 7.1). The values plotted are correlation coefficients.

Relations entre certaines particularités caractérisant les anneaux de croissance et la température et les précipitations mensuelles à Lake Louise. Les degrés de signification s'appliquent à la «taille véritable des échantillons», selon la définition de FRITTS (1976, Équ. 7.1). Les valeurs traitées sont des coefficients de corrélation.

in the ring year (*e.g.* latewood density = 0.41, maximum density = 0.42 for August). The best correlations with precipitation variables are all inverse relationships between Component 3 variables and summer rainfall (ring density = −0.50 for July) and between Component 1 and 2 variables and January snowfall (maximum density = −0.43, ring width = −0.37).

Examination of Figure 4 indicates that the relationships between the climatic variables and the ring parameters shown differ considerably in sign, magnitude and pattern. Similar contrasts occur between other variables from the three major factors identified in Table VI. It is clear that the Component 2 and 3 variables are responding to climate in a different fashion than the ring-width variables.

One of the major difficulties to be overcome in extracting proxy climatic data from tree rings is the high amount of autocorrelation within tree-ring series. However the 15 tree-ring variables listed in Table VII show considerable differences in the amount of autocorrelation. Autocorrelation within each chronology appears to be stronger and more persistant for Component 1 variables. The density variables however are much more closely related to conditions in the growth year. Employment of these data enhance the capability to extract data on the shorter term climatic fluctuations more precisely than is possible with ring-width data alone. Therefore the diversity of response to climatic factors shown by the variables derived by densitometry increases the potential for the development of proxy climatic data from such chronologies.

TABLE VII

Autocorrelation characteristics of the Lake Louise chronologies

	Level of autocorrelation		
	1st order	2nd order	3rd order
Component 1 variables			
Ring width	.61**	.62**	.43*
Earlywood width	.61**	.58**	.46*
Ring volume	.59**	.60**	.41*
Earlywood volume	.61**	.58**	.46*
Ring weight	.58**	.62**	.36*
Earlywood weight	.60**	.59**	.44*
Component 2 variables			
Latewood width	.29*	.26	−.07
Latewood volume	.29*	.26	−.07
Latewood weight	.28*	.27	−.08
Latewood density	.25	.17	−.14
Maximum density	.35*	.36*	.00
Percentage latewood	.30*	.00	−.20
Component 3 variables			
Ring density	.46*	.07	.05
Earlywood density	.36*	.33*	.29*
Minimum density	.54**	.39*	.40*

All values are correlation coefficients.
** significant at 1% level.
* significant at 5% level.
Significance levels adjusted for loss of degrees of freedom
Correlations based on ring measures from 1915-80.

CLIMATIC RECONSTRUCTIONS

The ultimate goal of dendroclimatic studies is the reconstruction of former climate from various tree-ring indices. Transfer functions are normally multiple regression models that use the tree-ring indices as the independent variables to predict climate. Most tree-ring transfer functions have been based on ring-width chronologies from a single or multiple sites and use tree-ring variables that have been transformed into eigenvectors (uncorrelated variables) through principal components analysis (FRITTS 1976; HUGHES *et al.*, 1982). However, where chronologies are available for a number of different tree-ring variables at the same site, transfer functions may be developed without prior principal components analysis.

This type of analysis was attempted for the Lake Louise site and the results are given in HAMILTON (1984). The indexed chronologies available for the 15 tree-ring variables and a set of 15 chronologies lagged one year were utilized in a multiple regression analysis as the predictor variables. Equations were developed for a variety of predictands (climate variables) and often contained a large number of variables, many of which were highly correlated with one another. This multicolinearity lead to an inflation of the values for R^2, F and significance. In addition, verification attempts were only significant when random subsamples were used, the result of a positive bias introduced by the technique (GORDON, 1982). It was possible to limit colinearity and achieve significant verification from continous parts of the record by reducing the number of independant variables to one from each of the component groups in Table VI. However, this limited variable selection does not maximize the potential for extracting climatic information from the available ring series. Therefore the standard method of principal components analysis (FRITTS *et al.*, 1971; FRITTS, 1976) was employed to develop a set of orthogonal variables for use in multiple regression.

TRANSFER FUNCTION DEVELOPMENT FOLLOWING PRINCIPAL COMPONENTS ANALYSIS

As tree-ring characteristics in a given year are, in part, determined by conditions in other years, information about climate in year (N) may be contained within rings of subsequent years (N+1, N+2, ...) while growth in year N is influenced by prior years (N−1, N−2, N−3, ...) (FRITTS, 1976). The 15 indexed chronologies were displaced to account for lag and prior growth effects (N−3 to N+2), thus 90 tree-ring variables were available for each year of record. These variables were then entered into a principal components analysis and 18 eigenvectors accounting for 98.6% of the growth variance were extracted. Amplitudes from 1915 to 1980 (component scores) from the eigenvectors were entered into a stepwise multiple regression procedure to select the most significant eigenvectors for prediction for a variety of climatic parameters.

Transfer functions were developed by multiplying the significant regression coefficients (from the eigenvectors selected) by the eigenvector matrix (FRITTS, 1976). Reconstructions were derived by mutiplying the transfer function by the normalized tree-ring data. The transfer functions were verified using continuous subsamples (GORDON, 1982). A number of cases are held back from calibration while the original set of eigenvectors are used to generate estimates based on regression over a shorter calibration interval. Pearson's r and RE are calculated between the estimated and actual values for the verification intervals to test the strength of the transfer function and thus the reconstruction. Transfer functions are sensitive to the range and absolute values of the climatic data and tree-ring indices from the period used for calibration. For example, using the 1951-67 period chosen by PARKER and HENOCH (1971), many Component 2 variables are highly correlated with summer temperatures (*e.g.* $r = .67$, $\alpha = .02$ for July temperature and latewood width) but these relationships are not as strong over the complete record ($r = .27$, $\alpha = .10$, 1915-1980). Therefore to take advantage of the full range of climatic data and to reduce the effects of anomalous periods the final transfer functions used were based on calibration of all available cases between 1915 and 1980 with missing cases excluded.

Development and testing of transfer functions for the Lake Louise site is not yet complete but two preliminary reconstructions are presented here to illustrate the potential of these data. The temperature variable modelled is mean June/July temperature and the precipitation variable is total precipitation from December to March (62% of the average annual snowfall occurs in this period). The stability of the transfer functions was explored using various combinations of calibration and verification periods from the instrumental record at Lake Louise (Table VIIIA). Correlation coefficients between actual and reconstructed data in the verification periods ranged from $r = .60 - .80$ for June/July temperatures and $r = .30 - .72$ for December to March precipitation (the $r = .30$ value largely reflects a single value in a small data set: when this is removed $r = .48$, RE = 0.41 for $n = 14$). The reduction of error statistics are also highly significant in all cases (with one exception, discussed above) and these verification trials indicate the combinations of the eigenvectors chosen perform well when tested against independent data from various portions of the instrumental record.

The stepwise solutions for the regressions are presented in Table VIIIB. The R^2 values of these equations are comparable with those used in the verification trials ($R^2 = 0.46$, June-July temperatures, $R^2 = 0.40$, December-March precipitation, see Table VIIIB). The reconstructed data show excellent agreement with the instrumental record in overall trends and

TABLE VIII

Transfer function verification

A. Verification trials

Dependent variable	Predictands	Period of Calibration Years	N	Period of Verification Years	N	R^2	R_A^2	r_v	RE
June July Temp.	E2,E11,E6	1915-64	46	1965-80	16	.42	.37	.77**	.55**
"	E2,E11,E6	1934-80	45	1915-33	17	.44	.40	.80**	.44**
"	E11,E2,E6	1915-49	31	1950-80	31	.51	.46	.65**	.40**
"	E11,E2,E6	1951-80	31	1915-50	31	.44	.38	.69**	.45**
"	E11,E2,E6	1915-34, 1968-80	31	1935-67	31	.61	.57	.60**	.41**
"	E2,E11,E6	1931-70	38	1915-30, 1971-80	24	.46	.41	.73**	.42**
Dec-Mar Prec.	E14,E15,E6	1915-64	39	1965-80	15	.49	.45	.30	.02
"	E14,E6,E15	1937-80	39	1915-36	15	.35	.30	.72**	.50**
"	E14,E15,E6	1915-52	27	1953-80	27	.44	.36	.62**	.34**
"	E14,E6,E15	1953-80	27	1915-52	27	.40	.32	.61**	.36**
"	E14,E6,E15	1915-34, 1969-80	25	1935-68	29	.32	.22	.57*	.48**
"	E14,E15,E6	1931-69	33	1915-30, 1970-80	21	.41	.35	.52*	.42**

B. Transfer functions used in reconstructions

Dependent variable	Predictands	Years	N	R^2	R_A^2	F	Sig.
June July Temp.	E11,E2,E6	1915-80	62	0.46	0.43	16.32	.000
Dec-Mar Prec.	E14,E15,E6	1915-80	54	0.40	0.37	11.26	.000

R^2: Coefficient of Determination
R_A^2: Adjusted R^2
r_v: Correlation Coefficient between the actual and estimated values in the verification interval
RE: Reduction of Error between the actual and estimated values in the verification interval
** Significant at 1% level
* Significant at 5% level

TABLE IX

Comparison of actual and reconstructed climatic data for Lake Louise

Parameter	June-July temperature (°C)			December-March precipitation (mm)		
	Actual 1915-80	Reconstructed 1915-1980	Reconstructed 1710-1980	Actual 1915-80	Reconstructed 1915-80	Reconstructed 1710-1980
Mean	10.9	10.9	10.9	263.9	263.9	252.4
Standard Deviation	0.84	0.57	0.49	97.3	61.8	66.1
Coefficient of Variation	7.7%	5.2%	4.5%	36.9%	23.4%	26.2%
Maximum (date)	13.2 (1970)	12.1 (1970)	12.5 (1839)	490.3 (1956)[1]	405.2 (1953)[1]	453.1 (1886)
Minimum (date)	9.1 (1976)	9.7 (1976)	9.6 (1841)	79.8 (1926)	95.2 (1926)	30.7 (1810)
Range	4.1	2.4	2.9	410.5	310.0	422.4

Note: [1] The second highest values are: actual 459.6 (1953), reconstructed 394.3 (1956).

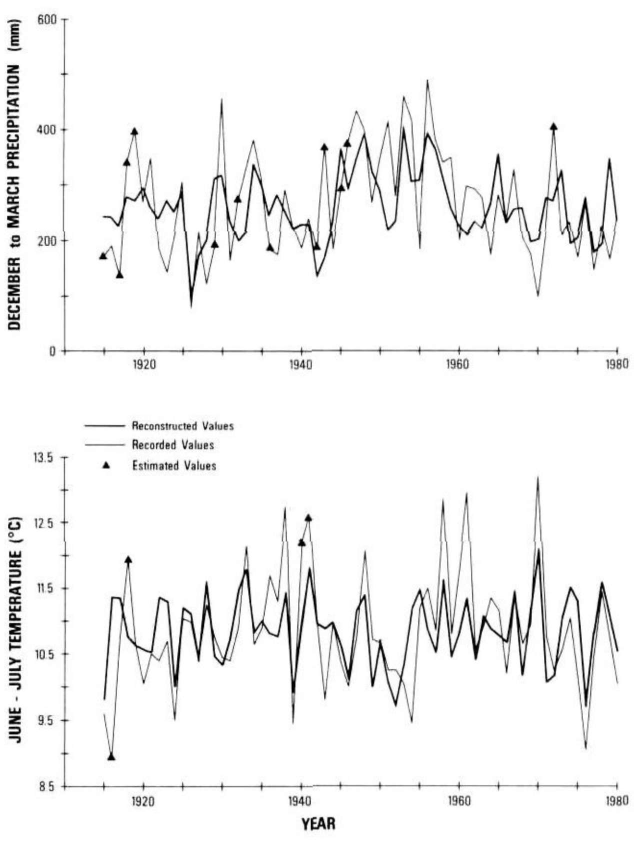

FIGURE 5. Comparison of Proxy Climatic Data generated by Transfer Functions with the Instrumental Record at Lake Louise, 1915-1980. The heavy line shows the reconstructed values. The small triangles represent values which include data estimated from adjacent stations because no data are available at Lake Louise.

Comparaison entre les données climatiques indirectes obtenues par les fonctions de transfert et les données enregistrées de 1915 à 1980 à Lake Louise. Les courbes en gras représentent des valeurs reconstituées. Les triangles noirs représentent des valeurs qui comprennent les données estimées à partir de celles de stations voisines, les données n'ayant pas été enregistrées à Lake Louise.

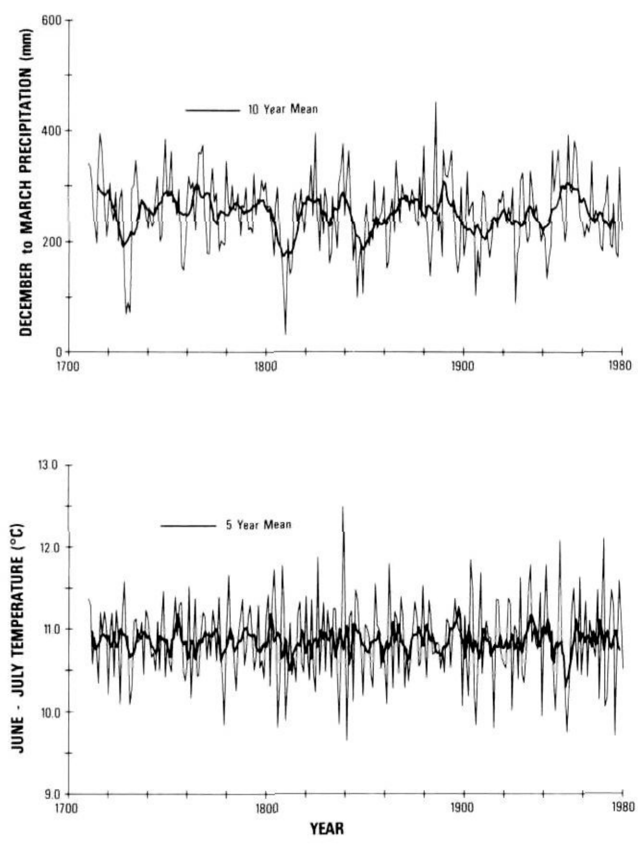

FIGURE 6. December-March Precipitation and June-July Temperatures at Lake Louise from 1710-1980 reconstructed using the Transfer Functions in Table VIIIB. The solid lines are 5 (temperature) or 10 year (precipitation) running means.

Reconstitution des précipitations de décembre à mars et les températures de juin et juillet pour la période allant de 1710 à 1980 à Lake Louise, effectuée à l'aide des fonctions de transfert présentées au tableau VIIIB. Les traits représentent des moyennes mobiles de 5 (températures) ou 10 ans (précipitations).

year to year fluctuations (Fig. 5). However the proxy data for both modelled parameters have a lower variance than the instrumental data (Table IX). This is to be anticipated as the reconstructions only account for approximately 40 or 50% of the original variance. However, several of the discrepancies in the earliest parts of both reconstructed records occur for years where the Lake Louise data are estimates based on correlation with adjacent stations (see Fig. 5). These estimates are presently for graphic comparison only: they were not used in the calculations.

Reconstructions for the period 1710-1980 are shown in Figure 6. Both reconstructions are preliminary and should be interpreted with caution. The gross differences between these reconstructed records is, in part, a reflection of differences in these data over the calibration periods. June-July temperatures have a much lower variance and range than the December-March precipitation values (Table IX) and the high frequency noise in the reconstructed temperature record reflects this. The precipitation record however appears to have a greater amplitude and persistance of trend in both the original and reconstructed records. Both reconstructed records show an absence of long-term trend. The application of a 99-year filter during the standardization procedure has clearly removed any long-term trend from these reconstructions. General considerations of climatic history for the last few centuries make it highly unlikely that the means of any climatic parameter for 1915-1980 and 1710-1980 would be identical. Therefore although the verification results suggest that the direction and duration of short and medium term (30-40 years) fluctuations may be successfully modelled in these reconstructions they can only be treated as relative, not absolute values over the 1710-1980 period.

Independant verification of these data beyond the period of the instrumental record is difficult. General climatic fluctuations during the Little Ice Age can be inferred from the glacial record (LUCKMAN and OSBORN, 1979) but these data do not usually have adequate temporal resolution for detailed comparison; also, the linkage between periods of moraine abandonment and climatic factors is not straightforward. Information on the Little Ice Age fluctuation of glaciers at Lake Louise has not been published except for the Wenkchemna Glacier which is anomalous because of its extensive debris cover (GARDNER, 1978). The nearest dated moraine sequences are in Yoho National Park where moraines have been dated at 1714 and 1832 (BRAY, 1964, President's Peak) plus 1844, 1877 and the 1890's (Yoho Glacier, BRAY and STRUIK, 1963). Elsewhere in the Rockies many glaciers show their maximum Little Ice Age extent in the early eighteenth century with major readvances in the late eighteenth — early nineteenth centuries and middle-late nineteenth centuries (KEARNEY and LUCKMAN, 1981, Fig. 2). These data lend some support to the reconstructions in Figure 6, particularly the two periods of higher precipitation in the nineteenth century and the depressed summer temperatures from *ca.* 1850-1900. However these general indicators are not specific enough for verification. Ongoing studies of climate-tree ring relationships in *Pseudotsuga menziesii* stands at Banff by Forintek should shortly provide other sets of proxy climatic data for the same period using trees in the lower montane forest. Detailed comparisons ot these reconstructions will be an interesting test of the Lake Louise results.

CONCLUSIONS

The principal goal of this paper was to present the initial results of studies at Lake Louise to derive proxy climatic data from oxygen isotope and densitometric studies of tree rings. The oxygen isotope work indicates good replication of results between trees and species. Although significant correlations were found between mean annual temperature and oxygen isotope data, unexplained anomalies in these data suggest other controls, either due to ring characteristics or unmeasured variables, affect these relationships. Additional work using hydrogen isotopes is recommended to examine possible humidity effects in these data.

The wide range of tree-ring variables derived from densitometric data (15 in this study) may be classified into three main groups related to ring width, earlywood density and latewood characteristics. The variables in each group have different degrees of autocorrelation and respond differently to climatic controls thereby increasing the potential for deriving proxy climatic data. Preliminary transfer functions developed for June-July temperatures and December-March precipitation using multiple regression techniques following principal component analysis have R^2 values of 0.46 and 0.40 respectively, correlating well with the instrumental record at Lake Louise. However, it should be stressed that these results are presented as examples: only the short to medium term fluctuations appear to have been modelled by these reconstructions and improvements in the standardization techniques are required to model longer term changes successfully.

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