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A tree-ring densitometric transect from Alaska to Labrador

Comparison of ring-width and maximum-latewood-density chronologies in the conifer belt of northern North America

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Abstract. We describe a recently completed network of densitometric tree-ring time series representing various aspects of tree-growth for up to 200 years at 69 sites spread across the northern North American conifer zone from Yukon to Labrador. Duplicate cores, from 12 to 15 trees per site, provide time series for a suite of growth parameters including earlywood (spring), latewood (summer) and total (annual) ring widths and mean early-wood, mean latewood, minimum and maximum ring density. These data form the basis for extensive analyses of intra- and inter-site parameter comparisons and regional climate/tree-growth comparisons. Five large-scale regional chronologies do not suggest that any anomalous growth increases have occurred in recent decades, at least on these regional scales, despite the observed changes in atmospheric composition and climate.

Key words: Dendroclimatology – Northern North America – Boreal zone – Maximum latewood density – Ring width – Summer temperature

Introduction

Considerable dendrochronological research has been undertaken in the Canadian boreal zone. A relatively recent review (Luckman and Innes 1990) cites 561 studies, of which 200 are concerned with tree growth and climate. Considerably less work has been concerned with tree-ring densitometry and the relationships between densitometric parameters and climate. Parker and Henoch (1971) and Parker and Jozca (1971), demonstrated a good relationship between maximum latewood density of Engelmann spruce near timberline and summer temperature in British Columbia. These results were confirmed by later work in Alberta by Luckman et al. (1985). Schweingruber et al. (1991) and Briffa et al. (1992) describe detailed reconstructions of summer temperatures in Alaska and Canada, west of the Mackenzie river, based on networks of densitometric chronologies.

A good review of dendroclimatological research in northern North America is provided in a recent paper by D'Arrigo et al. (1992). These authors compared and contrasted changes in the ring widths and densities of white spruce growing at five sites spread along the northern North American treeline. They show that while ring widths (and, to a lesser extent, densities) have apparently increased during the twentieth century at some sites, ring width has decreased at others.

The purpose of the present paper is to describe a recently constructed densitometric network of 69 tree-ring sample collections, from seven conifer species at 57 sites extending across the North American boreal forest zone from Alaska to Labrador. We describe the spatio-temporal coherence and the climate relationships of the ring-width and densitometric chronologies in the 20th century and illustrate the regional changes in ring width and ring density during the last 190 years.

The tree-ring material

Data collection. All of the samples were collected by the first author during two separate fieldwork seasons (but see acknowledgements). During the first, in August 1984, 25 sites were visited in British Columbia, Yukon and Alaska. The second sampling trip, in July and August 1989, involved visits to 44 sites, all in Canada, forming a longitudinal transect through the northern conifer zone from Yukon to Labrador. The full 69-site network (Fig. 1) is spread over more than 90° of longitude, from 58°40′ W to 149°35′ W and, at its maximum extent, reaches from 50°01′ N (in the east) to 64°50′ N (in the west), some 14°41′ of latitude. Details are listed in Table 1. The 69 collections, comprising two increment cores from 12 to 15 trees per site, are made up mostly of spruce species (34 Picea glauca, 24 P. mariana, 4 P. engelmanii and 3 P. sitchensis) with one larch (Larix

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Table 1. Details of 69 site chronologies which form the basis of the analyses described. The locality, species, length of chronologies with a minimum replication of 6 cores, and some raw measurement averages are shown for each site. The chronologies (except for series 45, see text) were first grouped and averaged into 18 sub-regional series (see Figure 1) and these subsequently averaged to form the 5 major regional series indicated. The region codes are: 1. ALAYUK, Southeast Alaska, southern Yukon and northern British Columbia; 2. BRITCO, Southern British Columbia and southern Alberta; 3. GRSLLA, the Great Slave Lake region and the northern Prairies; 4. WINNIP, Southern Manitoba and western Ontario; 5. QUEBLA, Quebec and Labrador. The species codes are as follows: PCGL, Picea glauca; PCMA, P. mariana; PCEN, P. engelmanii; PCSI, P. sitchensis; LALA, Larix laricina; PIBA, Pinus banksiana; PSME, Pseudotsuga menziesii. No mean latewood densities (MLD) or mean earlywood densities (MED) were recorded for the first 25 chronologies

Nr.	Ident	Locations	Lat.	Long.	Elev.	Species	Period n>=6	Mean raw data values						
								TRW	ERW	LRW	MAXD	MLD	MED	MIND
Region 1 ALAYUK														
1	WILLOW	Willow Island	6450N	14810W	99	PCGL	1802–1983	97.896	83.681	14.225	81.951			30.291
2	DENALI	Denali National-Park	6340N	14935W	750	PCGL	1634–1983	51.363	40.494	10.883	64.351			32.449
3	GLENN	Glenn Highway	6120N	14935W	100	PCGL	1810–1983	80.534	66.230	14.305	77.540			33.443
4	MOOSE	Moose Pass, Seward	6030N	14930W	100	PCSI	1749–1983	94.515	73.583	20.928	76.000			33.626
5	SLANA	Slana bei Tok	6250N	14355W	600	PCGL	1730–1983	61.346	50.724	10.685	73.756			31.185
6	EUREKA	Eureka Summit	6150N	14720W	960	PCGL	1725–1983	69.915	58.973	10.988	68.907			30.780
7	BILLY	Mt. Billy Mitchell	6120N	14515W	300	PCGL	1813–1983	105.708	91.351	14.450	79.936			30.041
8	NORTH	Northway Junction	6250N	14120W	600	PCGL	1800–1983	80.473	68.217	12.255	75.902			30.239
9	DONJEK	Don Jek River Bridge	6140N	13940W	750	PCGL	1737–1983	45.198	35.259	9.947	76.069			35.992
10	KATH	Kathleen Lake	6025N	13710W	780	PCMA	1772–1983	78.590	64.608	14.000	75.542			29.830
11	CHILK	Chilkat Pass	5955N	13650W	780	PCSI	1786–1983	166.747	139.828	26.975	71.268			29.717
12	CASSI	Cassiar	5905N	12955W	900	PCGL	1822–1983	90.185	76.562	13.630	72.667			30.710
13	DEASE	Gnat Pass	5820N	12955W	1200	PCGL	1792–1983	85.615	72.323	13.385	64.021			28.125
14	WATSON	Watson-Lake	6095N	12850W	750	PCGL	1827–1983	121.325	102.357	18.994	77.892			28.261
15	SUMMIT	Summit Lake Pass	5840N	12440W	1260	PCGL	1785–1983	69.568	55.759	13.834	71.312			32.312
16	NELSON	Fort Nelson	5820N	12250W	690	PCGL	1822–1983	115.364	93.932	21.420	78.710			31.056
17	NING	Ningunsaw Pass	5655N	13005W	459	PCSI	1733–1983	131.912	108.490	23.450	72.303			30.112
Region 2 BRITCO														
18	SMITH	Smithers Ski Aerea	5454N	12715W	1200	PCGL	1706–1983	96.633	78.906	17.741	67.899			29.072
19	PINE	Pine Pass	5530N	12240W	780	PCGL	1748–1983	114.665	93.415	21.301	74.835			28.487
20	BEAR	Bear Lake	5430N	12230W	690	PSME	1789–1983	112.159	82.354	29.831	91.462			32.610
21	BELL	Bell Mountain	5320N	12040W	1530	PCEN	1676–1983	78.253	60.701	17.568	65.205			30.344
22	SPRING	Spring Lake	5153N	12115W	810	PSME	1711–1983	125.901	95.440	30.487	95.187			33.656
23	SUNW	Sunwapta Pass	5215N	11700W	2000	PCEN	1629–1983	100.521	84.673	15.896	59.859			26.299
24	PEYTO	Peyto Lake	5145N	11613W	2050	PCEN	1703–1983	110.310	91.327	18.993	58.374			26.178
25	VERMIL	Vermilion Pass	5110N	11610W	1500	PCEN	1705–1983	78.344	62.430	15.932	69.570			29.591
Region 3 GRSLLA														
26	WILLOUFE	Willow Lake (lakeside)	6210N	11908W	620	PCMA	1869–1988	69.550	55.458	14.133	72.983	654.183	390.500	32.067
27	WILLOPLA	Willow Lake (plateau)	6210N	11908W	620	PCMA	1850–1988	50.935	40.022	10.971	71.719	652.770	406.417	34.842
28	BRASJUNG	Bras d'Or-Lake	6227N	11608W	700	PCGL	1893–1988	101.417	86.521	14.802	79.958	692.521	367.323	29.604
29	PROVIPGL	Fort Providence	6110N	11722W	500	PCGL	1832–1988	78.127	65.274	12.841	80.242	692.631	363.611	29.790
30	SIMPSPLA	Fort Simpson (plateau)	6141N	12043W	375	PCGL	1843–1988	112.986	94.349	18.685	73.904	640.795	349.199	29.007
31	BRASALT	Bras d'Or-Lake	6227N	11608W	700	PCGL	1772–1988	40.276	31.917	8.359	72.369	643.760	392.111	33.940
32	SIMPSUFE	Fort Simpson (lakeside)	6141N	12043W	375	PCGL	1831–1988	68.051	57.582	10.430	79.329	700.101	403.152	34.462
33	BUFFAPGL	Buffalo Lake	6017N	11516W	803	PCGL	1852–1988	106.153	87.518	18.672	81.197	708.292	372.416	30.234
34	PETHAPGL	Pethai-Peninsula	6241N	11058W	1400	PCGL	1646–1988	27.006	19.682	7.329	66.714	605.872	417.539	37.294
35	AUSTIPGL	Austin Lake	6210N	11005W	850	PCGL	1833–1988	92.724	77.949	14.846	69.340	601.833	348.455	29.487
36	MACKIPMA	Mac Kinley	6244N	11138W	1350	PCMA	1859–1988	57.685	45.800	11.938	68.308	611.592	403.415	35.415
37	ESKERPMA	Esker	5742N	10516W	2000	PCMA	1874–1988	55.409	43.852	11.557	77.191	693.009	398.122	34.661

38	CHURCPGL	Churchill	5840N	09350W	50	PCGL	1708–1988	39.174	30.028	9.153	64.573	578.779	375.014	32.979
39	CHURCLAR	Churchill	5840N	09329W	50	LALA	1807–1988	44.544	31.484	13.154	77.709	697.286	348.368	29.121
40	CHARLPLA	Charlie Lake	6002N	10026W	1055	PCMA	1842–1988	40.293	30.844	9.531	71.136	642.823	415.878	37.048
Region 4 WINNIP														
41	FISHIPMA	Fishing Creek	5201N	08284W	200	PCMA	1878–1988	76.126	62.613	13.450	80.495	718.072	436.207	37.622
42	WEBEQPGL	Webequie	5304N	08720W	645	PCGL	1818–1988	74.485	60.439	14.076	81.170	723.509	401.468	34.099
43	BRUNOPGL	Bruno Lake, Manitoba	5137N	09550W	1000	PCGL	1845–1988	120.069	99.542	20.535	83.396	730.993	369.458	30.257
44	GUNISPMA	Gunisao-Lake (moist)	5330N	09623W	860	PCMA	1897–1988	70.446	56.315	14.120	85.446	767.663	430.543	36.598
45	GUNISPBA	Gunisao-Lake (dry)	5330N	09623W	860	PIBA	1897–1988	108.609	81.598	26.935	86.707	783.543	396.065	33.935
46	HIGHSPGL	High Stone Lake	5024N	09127W	1300	PCGL	1826–1988	101.724	81.123	20.589	80.006	706.491	366.472	30.442
47	ARMSTPLA	Armstrong (plateau)	5018N	08903W	1120	PCGL	1844–1988	90.469	74.869	15.572	84.600	756.234	396.524	33.048
48	ARMSTUFE	Armstrong (lakeside)	5018N	08903W	1120	PCGL	1862–1988	76.228	59.638	16.669	84.315	747.740	424.244	35.898
Region 5 QUEBLA														
49	EASTMUFE	Eastmain River (moist)	5202N	07751W	450	PCMA	1848–1988	57.291	42.957	14.319	81.872	728.660	424.837	35.972
50	NONAMUFE	No Name Lake (moist)	5435N	07734W	450	PCMA	1765–1988	47.955	37.179	10.759	75.719	690.674	442.563	38.554
51	NONAMPLA	No Name Lake (dry)	5435N	07734W	450	PCMA	1757–1988	39.668	30.595	9.168	76.082	696.724	449.220	39.112
52	COATSPLA	Coats River (dry)	5544N	07609W	1000	PCMA	1798–1988	30.382	21.979	8.403	73.984	677.513	457.335	41.319
53	EASTMPLA	Eastmain River (dry)	5202N	07751W	450	PCMA	1791–1988	38.212	28.379	9.889	81.763	740.157	458.025	40.288
54	COATSUFE	Coats River (moist)	5544N	07609W	1000	PCMA	1795–1988	40.686	30.742	9.923	72.588	657.649	422.706	37.459
55	YASINPLA	Yasinski-Lake (dry)	5314N	07740W	450	PCMA	1869–1988	84.242	70.158	14.100	74.500	674.550	424.092	38.542
56	YASINUFE	Yasinski-Lake (moist)	5314N	07740W	450	PCMA	1858–1988	64.733	52.542	12.191	80.198	717.947	425.832	36.664
57	ROMANPLA	Lac Romanel (dry)	5614N	06743W	1000	PCMA	1846–1988	68.042	52.937	15.098	69.993	635.650	420.427	37.035
58	ROMANUFE	Lac Romanel (moist)	5614N	06743W	1000	PCMA	1742–1988	62.478	50.360	12.170	65.134	582.619	352.870	29.838
59	SCHEFPGL	Wakuach Lake (moist)	5517N	06707W	1200	PCGL	1718–1988	71.590	58.214	13.399	65.122	579.325	350.819	29.506
60	SCHEFPMA	Wakuach Lake (dry)	5517N	06707W	1200	PCMA	1870–1988	79.437	63.109	16.336	69.580	613.899	371.840	31.664
61	LANAPMAF	Lac Natuak (moist)	5713N	07130W	500	PCMA	1812–1988	40.723	31.401	9.362	72.712	668.277	442.243	38.621
62	LANAPMAT	Lac Natuak (dry)	5713N	07130W	500	PCMA	1861–1988	58.445	46.531	11.930	67.992	619.266	399.375	34.859
63	DOROTPMA	Dorothea Lake	5412N	06134W	1500	PCGL	1820–1988	80.296	66.740	13.609	71.645	653.290	379.213	31.580
64	MOUNTPLA	Mountain Lake (plateau)	5329N	05840W	1500	PCGL	1791–1988	65.162	52.793	12.439	65.086	592.889	362.247	30.485
65	MOUNTUFE	Mountain Lake (lakeside)	5329N	05840W	1500	PCGL	1818–1988	70.129	56.550	13.620	71.292	643.170	379.632	31.573
66	LACPEPMA	Lac Péribonca	5002N	07129W	1400	PCMA	1843–1988	84.110	66.562	17.562	79.904	698.534	387.788	32.534
67	CAPOTPMA	Capotigaman (moist)	5010N	06810W	1000	PCMA	1773–1988	51.606	40.588	11.083	83.556	745.806	437.440	37.653
68	CAPOTPGL	Capotigaman (wet)	5010N	06810W	1000	PCGL	1844–1988	99.572	81.910	17.621	78.276	684.269	374.766	31.724
69	LCHEVPMA	Lac Chevrillon	5001N	07427W	1200	PCMA	1808–1988	65.646	51.475	14.249	82.624	738.768	411.055	34.370

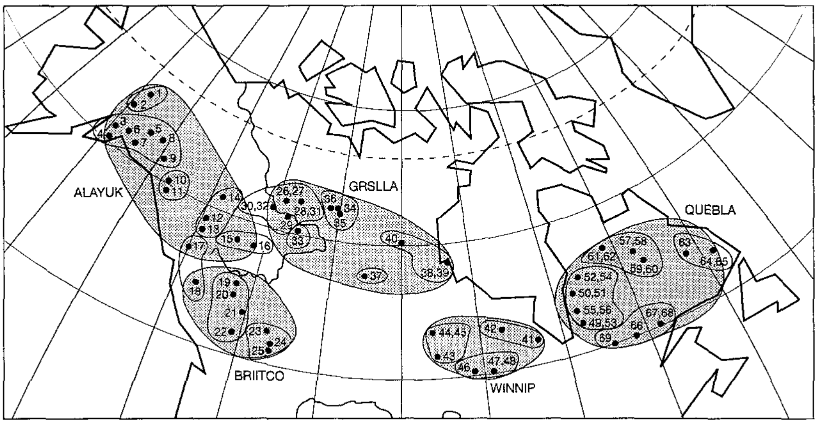


Fig. 1. The locations of the 69 individual chronologies. The stippled areas indicate the five large regional groupings. The smaller circled regions indicate the mean chronology groups used to demonstrate the teleconnections discussed in Section 5.4 and shown in Fig. 6. Details of the chronologies are given in Table 1

laricina), one pine (Pinus banksiana) and two Douglas firs (Pseudotsuga menziesii).

Only trees considered to be 'normal' (i.e. not krummholz) were sampled and trees growing on locally extreme sites were rejected. Each sample collection contains material representative of a particular ecological unit (e.g. a moist, level site or, alternatively, a well-drained slope). The prevalence of fires, logging activity, and the frequency of internal stem rot places a general restriction on the age of most of the samples and the majority of chronologies are subsequently less than 200 years in length.

Sample processing. The tree cores were analysed according to standard densitometric techniques employed at the Institute of Forest, Snow and Landscape Research, Birmensdorf. These are fully described in previous publications (e.g. Lenz et al. 1976; Schweingruber 1988; Schweingruber et al. 1991). The primary output of such analyses is comprised of various series of interannual ring width parameters representing different aspects of radial ring growth (including earlywood width, ERW; latewood width, LRW; and total ring width, TRW) and ring density (mean earlywood density, MED; mean latewood density, MLD; minimum ring density, MIND; and maximum latewood density, MAXD). Replicate series of annual values of each of these parameters are produced from the multiple cores sampled from each tree at each site. For each site, the sample series are combined to form absolutely-dated, mean time series or 'chronologies' for each of the specified variables. Before averaging the data, however, the raw (measured) series are 'standardized'. This means that a simple growth function is first fitted to the time series of measured values, which are then transformed to dimensionless indices by subtracting the approximated density value for each year (as given by the fitted curve) from the value actually measured. Ring-width indices are produced using division rather than subtraction, with the intention of stabilizing age-dependent changes of variance in these data. This produces, for each core series, new growth indices in which age-related growth trends have been removed. The indices from different trees are then averaged to produce a chronology representing the combined variation in that parameter in each year over the whole site.

The curve-fitting technique used in the work described here was the Hughershoff-function, described in Bräker (1981). This involves fitting a generalized exponential curve capable of tracking the increasing growth of juvenile series and the subsequent decline frequently seen in older ring-width or densitometric measurements. There is an underlying assumption in using this technique, that the general biological growth trends are simple in form. As such this approach is inherently less 'flexible' than many other (e.g. stochastic) forms of standardization (e.g. see Cook et al. 1990). The Hughershoff technique is, therefore, comparatively more 'conservative' in that it is likely to preserve longer-timescale variability in the standardized chronologies as compared to more data-adaptive techniques.

Nevertheless, it is important to appreciate that even this form of standardization will remove long-timescale variability from the final chronology. The degree is determined principally by the length (i.e. the number of years in) the sampled trees. Here, variability on timescales above about 200 years is certainly removed (see Table 1). The prevalence of forest fires in northern North America alluded to earlier, produces occasional obvious discontinuities or inhomogeneities in the tree-ring time series. These occur where tree-growth has been either temporally restricted in some trees as a result of direct fire damage, or sharply promoted, either by short-term fertilization of the generally nutrient-poor soils or increased availability of light, as a result of the destruction of surrounding vegetation immediately following the fire. In cases where such sharp discontinuities were apparent, the tree-ring data were split, the parts standard-

Fig. 2. Schematic representation of the inter-chronology relationships between all 69 chronologies. Symbols in the top right hand side of the Figure refer to maximum latewood density (MAXD) values. The bottom left section refers to total ring-width (TRW) data. The symbols represent similarity at various levels of significance (● 95%; ◆ 99%; ■ 99.9%) as measured using the Gleichläufigkeiten (see text) calculated over the period 1880–1983. The division of the data into five regional groups (see Section 3) is also indicated

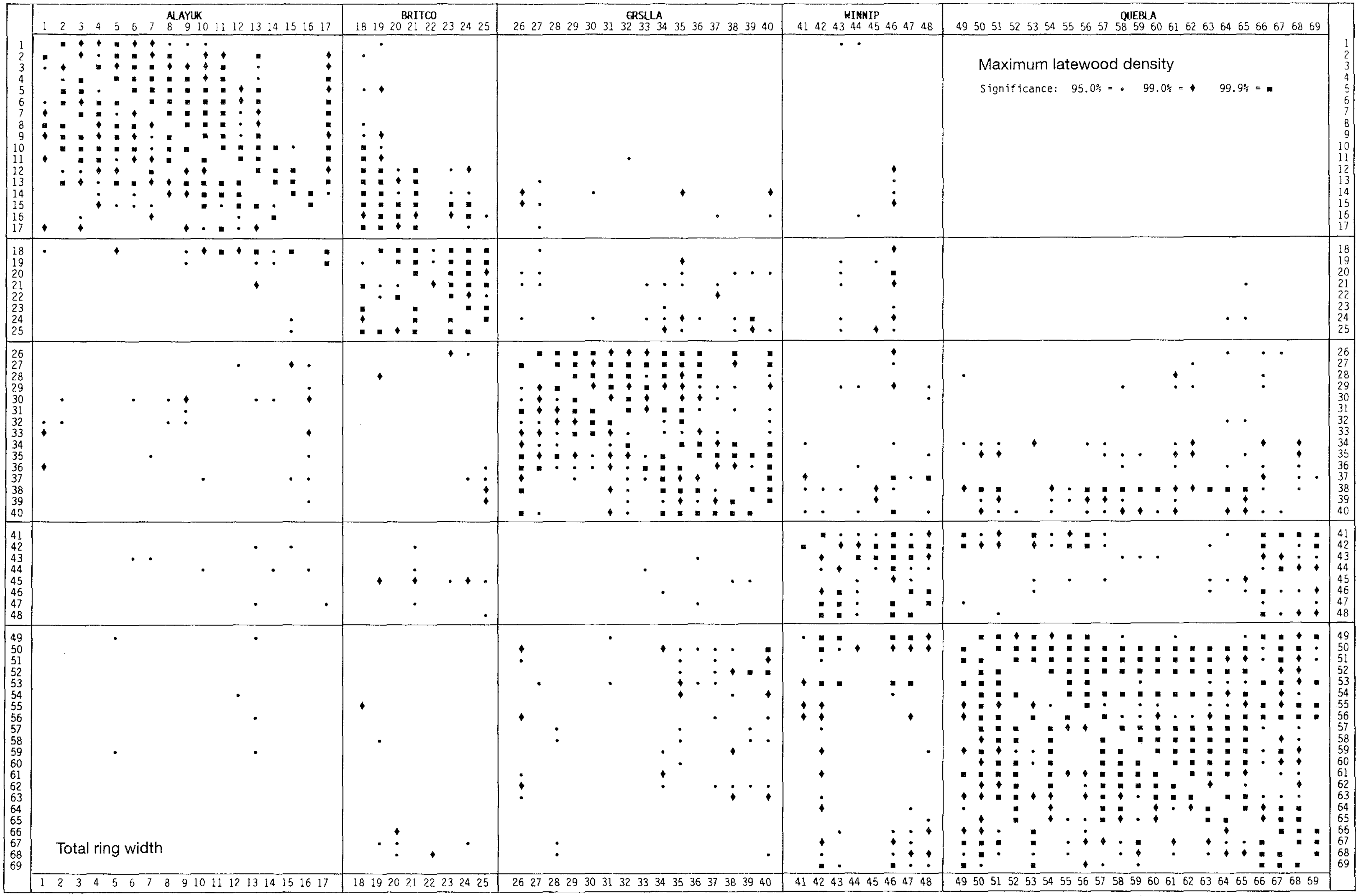

ALAYUK
BRITCO
GRSLLA
WINNIP
QUEBLA
Maximum latewood density
Significance: 95.0% = • 99.0% = ♦ 99.9% = ■
Total ring width

Table 2. Details of the 46 meteorological station temperature series used to compile large regional temperature averages equivalent to the chronology regions defined in Table 1 and Figure 1

Nr.	WMO-Nr.	Locations	Lat.	Long.	Elev.	Period
Region 1 ALAYUK						
1	702617	Fairbanks/Exp Stat.	6480N	14790W	133	1915–1981
2	702649	McKinley Park	6370N	14900W	631	1923–1981
3	702670	Big Delta	6400N	14570W	387	1942–1981
4	702710	Gulkana	6220N	14550W	479	1943–1981
5	702747	Matanuska/Exp Stat.	6160N	14930W	46	1918–1969
6	702750	Valdez	6110N	14630W	5	1917–1968
7	702820	Eagle	6480N	14120W	259	1899–1981
8	702910	Northway Aprt	6300N	14200W	522	1942–1981
9	702960	Cordova	6050N	14550W	13	1917–1981
10	703600	Cape St. Elias	5980N	14460W	18	1936–1969
11	703710	Sitka Magnetic Obs.	5710N	13530W	20	1832–1981
12	703870	Wrangell	5650N	13240W	11	1917–1981
13	710450	Teslin A	6020N	13280W	705	1944–1980
14	719450	Fort Nelson	5880N	12260W	382	1939–1990
15	719530	Watson Lake	6010N	12880W	689	1944–1990
16	719580	Dease Lake	5840N	13000W	816	1947–1990
17	719640	Whitehorse	6070N	13510W	703	1943–1990
18	719650	Mayo	6360N	13590W	504	1929–1990
19	719660	Dawson	6410N	13910W	369	1901–1990
Region 2 BRITCO						
20	710503	Fort St James	5450N	12430W	686	1895–1980
21	718811	Entrance	5340N	11770W	1006	1918–1980
22	718960	Prince George	5390N	12270W	676	1913–1990
23	718967	Barkerville	5300N	12160W	1274	1888–1969
24	719400	Grande Praire	5520N	11890W	669	1945–1990
25	719442	Beaverlodge	5520N	11940W	732	1913–1980
26	719500	Smithers	5480N	12720W	523	1943–1990
Region 3 GRSLLA						
27	710730	Fort Reliance	6270N	10920W	164	1949–1990
28	719130	Fort Churchill	5880N	9410W	29	1932–1990
29	719210	Brochet A	5790N	10170W	343	1949–1980
30	719230	Ennadai Lake	6110N	10090W	325	1950–1979
31	719333	Fort Vermilion	5840N	11600W	279	1905–1980
32	719340	Fort Smith	6000N	11200W	203	1915–1990
33	719350	Hay River	6080N	11580W	166	1900–1990
34	719360	Yellowknife	6250N	11450W	205	1948–1990
Region 4 WINNIP						
35	718410	Armstrong	5030N	8890W	320	1939–1990
36	718420	Sioux Lookout A	5010N	9190W	390	1915–1990
37	718460	Lansdowne house	5220N	8790W	256	1942–1990
38	718501	Ear Falls	5060N	9320W	361	1928–1980
Region 5 QUEBLA						
39	718110	Sept-Iles	5020N	6630W	58	1945–1990
40	718130	Natashquan	5020N	6180W	5	1915–1980
41	718160	Goose	5330N	6040W	49	1942–1990
42	718227	Mistassini Post	5030N	7390W	383	1921–1969
43	718260	Nitchequon	5320N	7090W	537	1943–1990
44	718280	Schefferville	5480N	6670W	512	1949–1969
45	719000	Hopedale	5550N	6020W	12	1942–1980
46	719050	Poste de la Baleine	5530N	7780W	26	1926–1980

ized separately and the indices recombined. This process will not affect very short-term variation in the chronologies (i.e. less than decadal timescales), but it imposes an additional potential restriction on the longer-timescale variability resolvable in the final tree-ring series depending on the frequency and temporal distribution of fires.

For these reasons we stress that the subsequent analyses described here (i.e. the inter-chronology comparisons and chronology/climate associations), refer principally to variability on timescales between one and 200 years at best, and more likely on timescales up to about 100 years. However, we also stress that the standardization process will have little, if any, appreciable influence on the ability of the chronologies to register anomalous positive growth trends that might or might not be expected to occur as a result of environmental change over the last century.

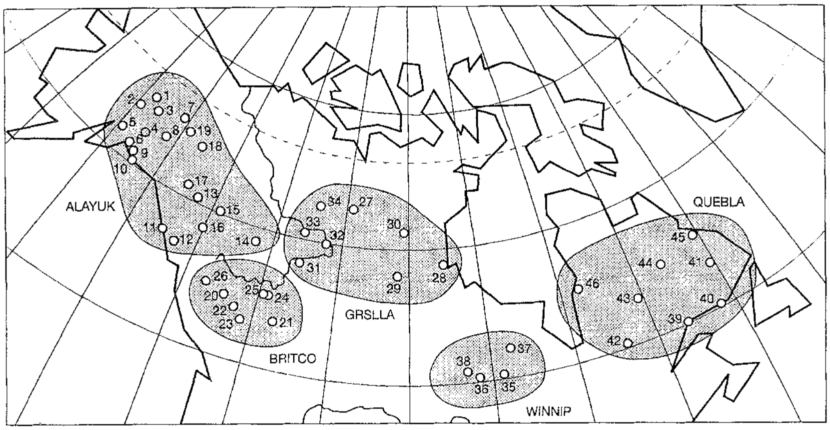


Fig. 3. The locations of the individual temperature records used to produce the large regional temperature averages indicated by the shaded areas. Station details are given in Table 2

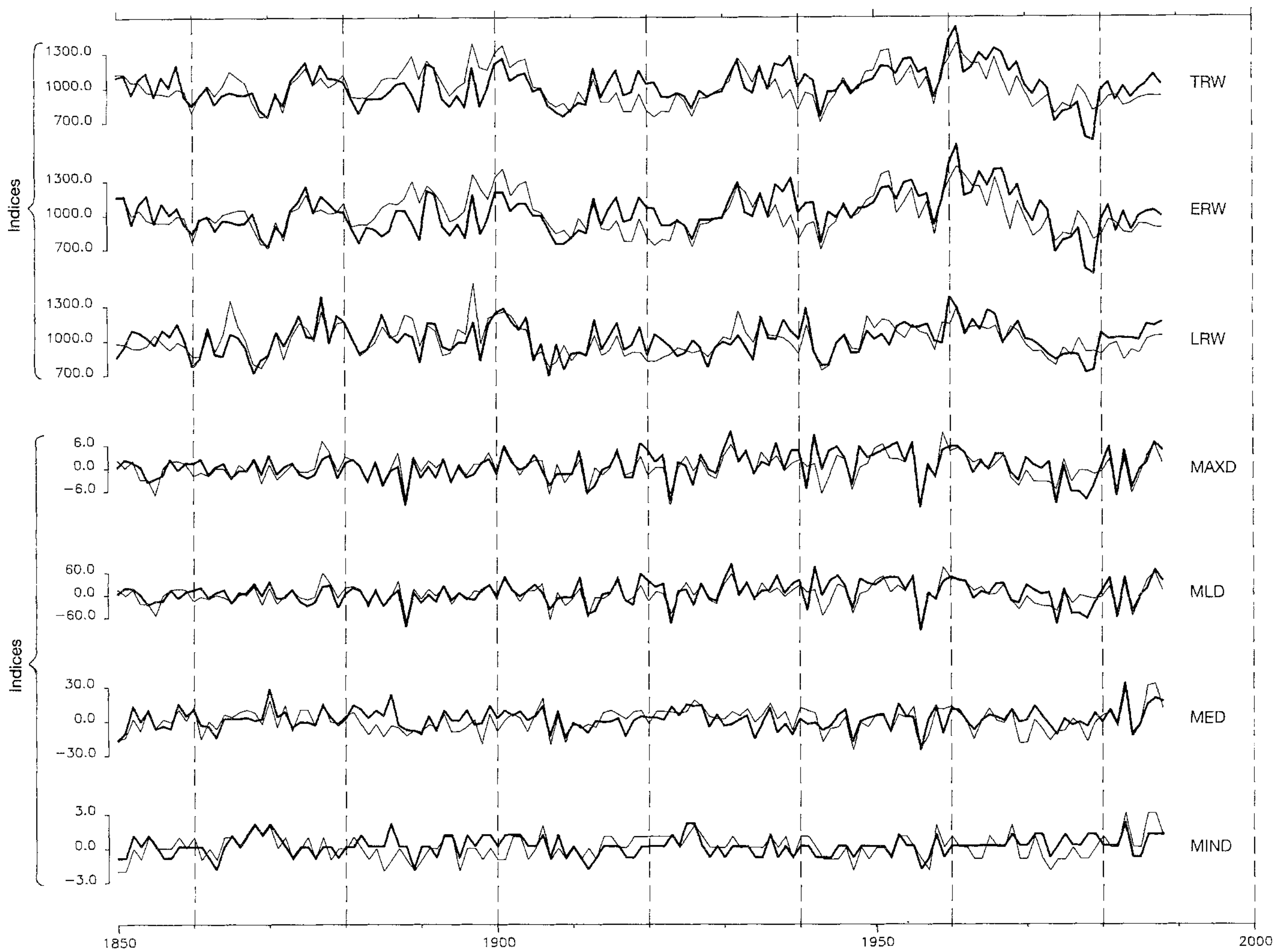


Fig. 4. Examples of standardized ring-width and densitometric chronologies for two different species: *Picea mariana* (thin line) and *Picea glauca* (thick line) growing at Capotigamen, Quebec. The various annual parameters are as follows: TRW total ring width; ERW earlywood width; LRW latewood ring width; MAXD maximum latewood density; MLD mean latewood density; MED mean earlywood density; MIND minimum density

Regional chronologies

The 69 individual chronologies were combined into five large regional mean chronologies (also indicated in Fig. 1 and Table 1). The selection of site chronologies included within each regional series was based on a consideration of their geographical location and the pattern of interchronology associations, defined principally on the basis of Gleichläufigkeit values for the TRW and MAXD (Fig. 2) series (calculated over the period 1880–1983). The Gleichläufigkeit is a measure of the percentage agreement in the signs of the first differences (from

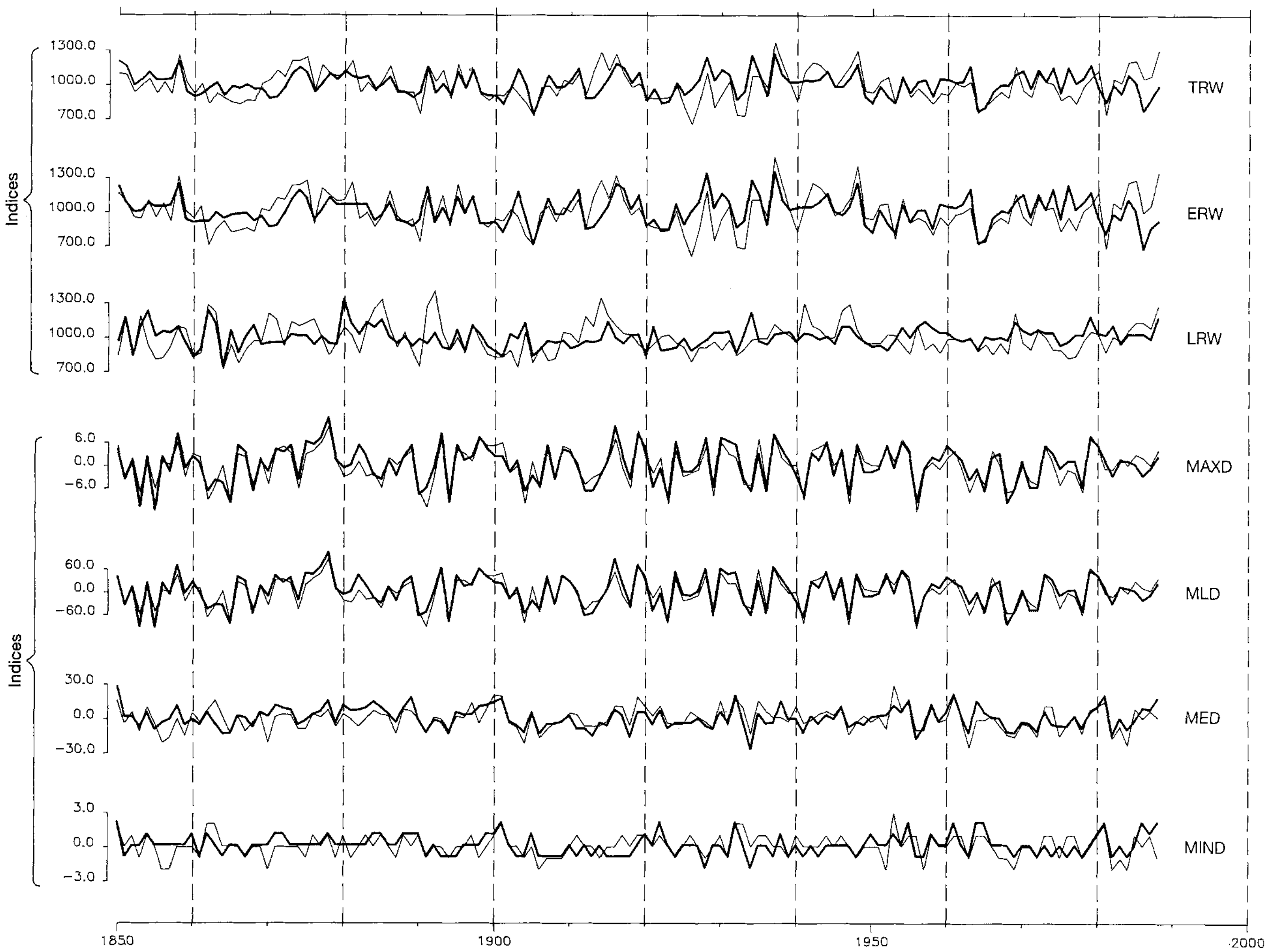


Fig. 5. Examples of standardized ring-width and densitometric chronologies for the same species (*Picea mariana*) growing on dry (thin lines) and relatively wet (thick lines) sites near Lake Romanel, Quebec. See Fig. 4 for an explanation of the parameter abbreviations

one year to the next) between two series. It is, therefore, a measure of the similarity of the series at very high-frequency. For each of the seven ring-width and densitometric parameters listed earlier we constructed the following regional mean series: Alaska and Yukon (ALAYUK) made up of the 17 most westerly chronologies in southeast Alaska, southern Yukon and northern British Columbia; British Columbia (BRITCO) made up 8 chronologies in southern British Columbia and southern Alberta; Great Slave Lake (GRSLLA) made up of 15 chronologies on the plain to the east of the Mackenzie in the northern Prairies; Winnipeg (WINNIP) made up of 8 chronologies in the southern Boreal zone, south of Hudsons Bay in southern Manitoba and western Ontario; and a Quebec and Labrador series (QUEBLA), the average of 21 chronologies located between Hudsons Bay and the Atlantic coast.

Regional temperature data

In order to construct temperature series of equivalent spatial domain to the regional mean tree-ring data, 61 individual site temperature records were assigned to one of 5 groups, approximately coincident with the distribution of the regional tree-ring sites (Table 2; Fig. 3). The temperature data were taken from the set of homogenized station records available at the Climatic Research Unit (Jones et al. 1986, updated). The temperature records within each group were then averaged to give mean monthly temperatures for each region for (at least) 1901–1990. Before averaging, the monthly mean data were transformed into anomalies with respect to the base period 1951–70. This mitigates the bias that can arise in an average series as a result of temporal changes in the constituent stations, especially when the station data have different climatologies. The monthly mean data were also averaged to form various 'seasonal' mean series.

Temporal and spatial relationships of the tree-ring parameters

Ring-width and maximum-latewood-density measurements. Comparison of the raw measurements from var-

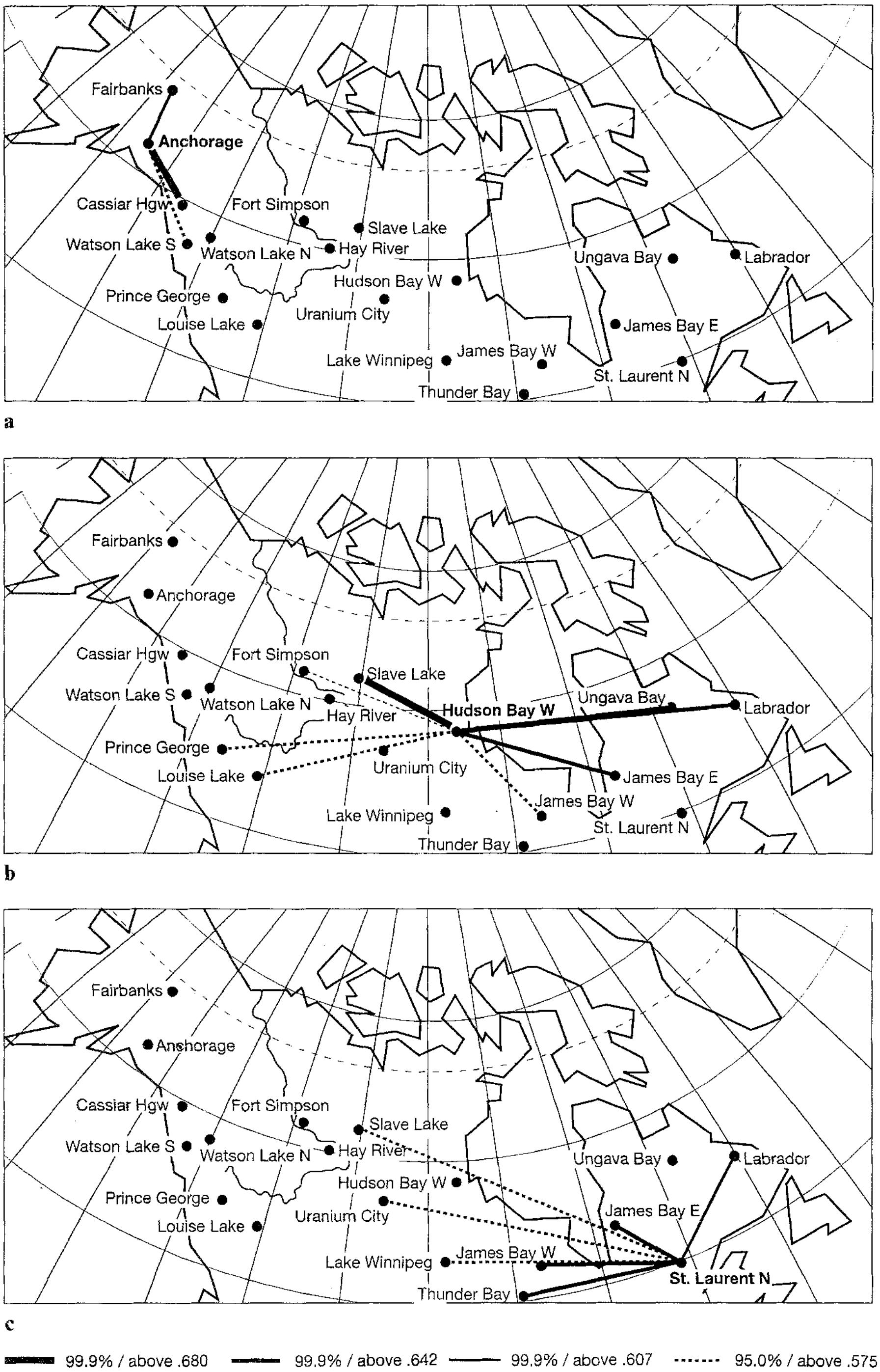
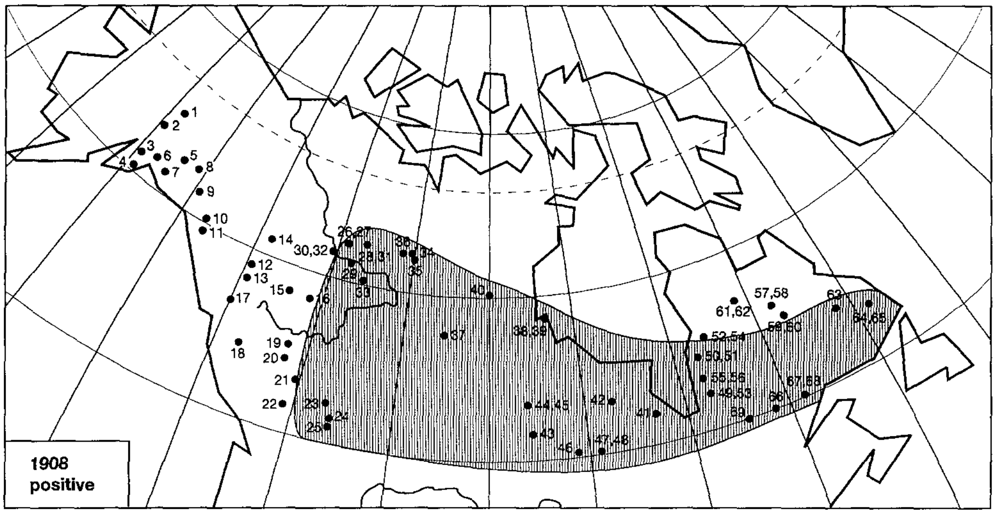


Fig. 6a–c. Three examples of the strength of remote crossdating in the maximum latewood density chronologies as measured using Gleichläufigkeiten. The significance of distant matches with subregional chronologies at (**a**) Anchorage, (**b**) Hudson Bay W. and (**c**) St. Laurent N. are shown. (See Fig. 1 and the text for further details)

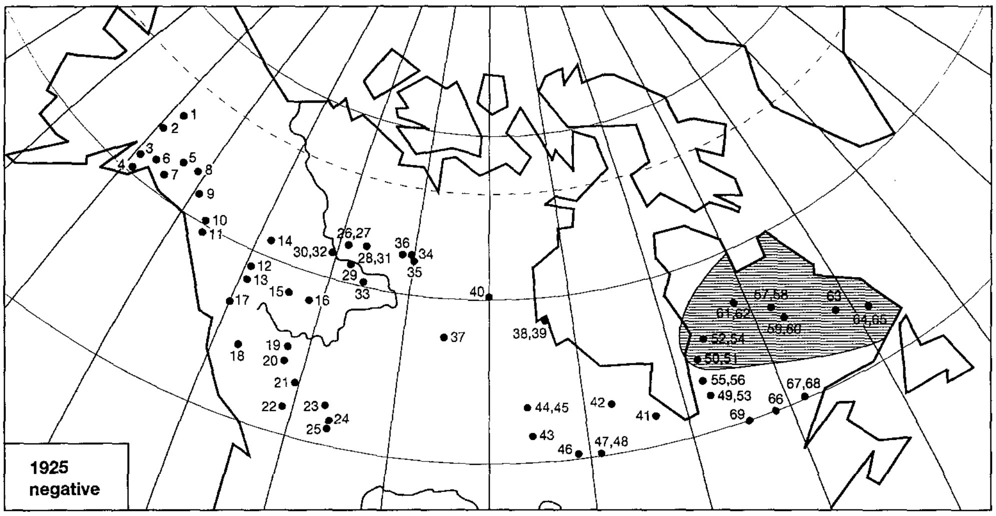
ious locations generally support the conclusions drawn in earlier studies of densitometric data (e.g. Polge 1966; Schweingruber et al. 1979) that both ring widths and maximum densities tend to decrease with increasing latitude and altitude. This is not true, however, for minimum density. It is not necessarily the absolute altitude or latitude which is relevant here, rather it is the ecological situation, in this case site position relative to the timber line. In the west of the continent (Alaska) the tree line reaches 68° N whereas in the east (Quebec) it is at 57° N. This explains why measured TRW or MAXD values in northern Quebec are lower than those at equivalent latitudes in, for example, British Columbia.

Regional versus localized growth forcing. The interchronology comparisons confirm previous results of densitometric analyses in the subalpine conifer zone (Schweingruber et al. 1979) that large-regional-scale forcing of interannual growth (generally summer temperature; see later) dominates over species or site factors (e.g. individual site characteristics or genetic differences in trees in different locations). There are differences in mean growth levels (e.g. Picea glauca) on ecologically similar sites. The standardized chronologies are, however, generally very similar, as are those for different species (Fig. 4).

Pinus banksiana was to be an exception to this rule.



a



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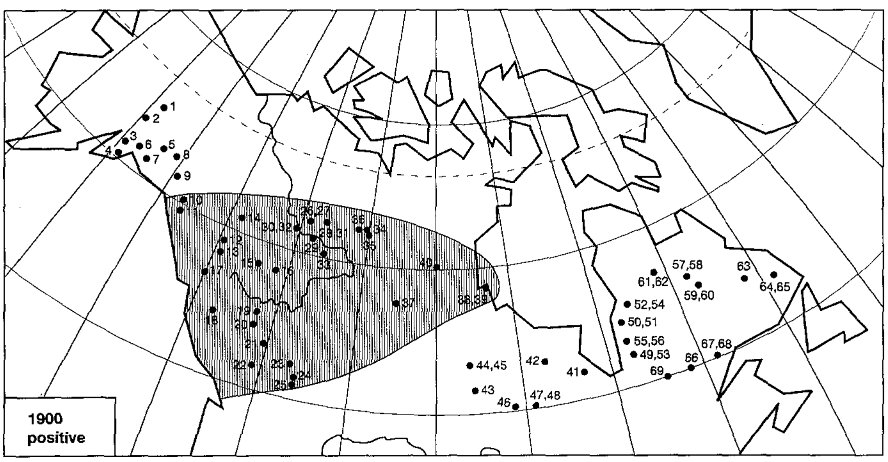

c

Fig. 7 a–f. Examples of the spatial distribution of selected pointer intervals illustrating the variation in the east (**a** and **b**), the west (**c** and **d**), and the east and west together (**e** and **f**)

The one chronology for this species (Table 1, No. 45) correlated poorly with other chronologies. This is a pioneer species, generally short lived growing well on very poor, well-drained and shallow soils. Its chronology was omitted from the regional averaging.

Within the regional chronologies, between-site differences in interannual variability are generally very small, even for trees growing on contrasting site types, either on drier sites (e.g. with a dense lichen vegetation) or from apparently moist conditions (e.g. as indicated by a dense Ledum palustre and Sphagnum vegetation, Fig. 5).

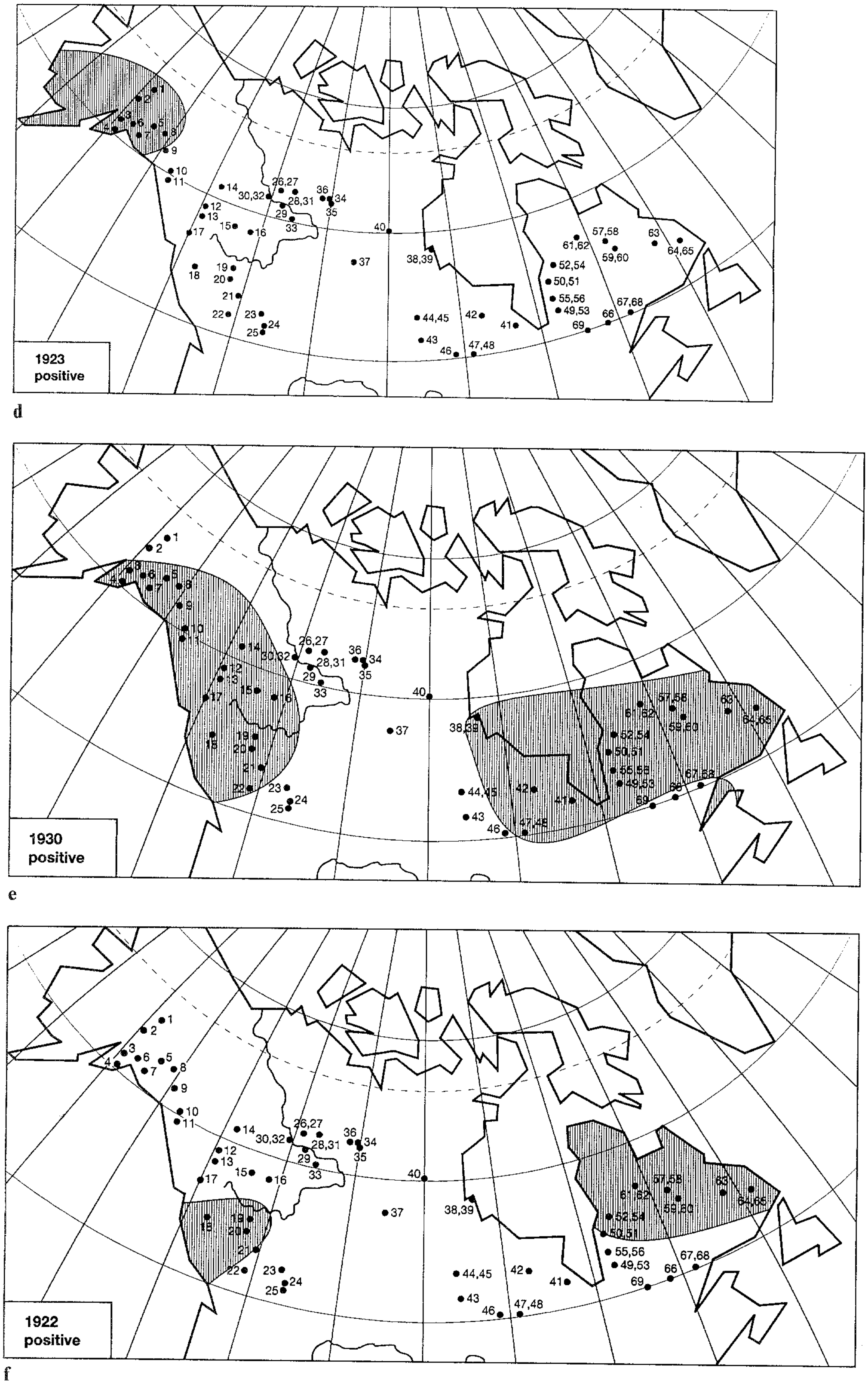

Fig. 7d–f

Intra-regional relationships between different tree-ring parameters. Table 3 shows the similarity between different ring-width and densitometric parameters expressed as squared correlation coefficients for each of the selected regional chronologies described earlier. The values are calculated over different periods, determined by the length of each regional series, varying from 171 values for the WINNIP series, to 355 for BRITCO. It is clear that the MAXD and MLD are essentially the same within each region ($r^2 > 0.97$) as are TRW and ERW (all regions $r^2 > 0.98$). The MIND and MED are also generally very similar (r^2 range 0.76–0.88). As expected, given

Table 3. Squared correlation coefficients representing inter-regional associations between various ring-width and densitometric parameter series shown for each region in turn, i.e. ALAYUK; BRITCO; GSLLA; WINNIP; QUEBLA; (see Section 3). The parameter abbreviations are explained in Section 2.2 and the legend to Figure 4

	1 TRW	2 ERW	3 LRW	4 MAXD	5 MLD	6 MED	7 MIND
1 Total Ring Width		0.987	0.700	0.127	0.034	−0.502	−0.624
TRW		0.987	0.558	0.097	0.049	−0.423	−0.561
		0.981	0.722	0.313	0.219	−0.492	−0.617
		0.985	0.700	0.144	0.023	−0.039	−0.168
		0.983	0.629	0.292	0.253	−0.025	−0.240
2 Earlywood Width			0.591	0.140	0.049	−0.514	−0.625
ERW			0.381	0.142	0.095	−0.450	−0.568
			0.600	0.360	0.072	−0.492	−0.621
			0.570	0.147	0.025	−0.107	−0.211
			0.486	0.310	0.273	−0.053	−0.260
3 Latewood Width				0.029	−0.049	−0.282	−0.417
LRW				−0.110	−0.140	−0.107	−0.245
				0.063	−0.021	−0.309	−0.394
				0.075	−0.004	0.241	−0.042
				0.087	−0.057	0.107	−0.044
4 Maximum Density					0.989	0.507	0.189
MAXD					0.991	0.381	0.003
					0.979	0.264	−0.049
					0.970	0.464	0.245
					0.992	0.646	0.243
5 Mean Latewood Density						0.574	0.267
MLD						0.421	0.049
						0.362	0.055
						0.472	0.296
						0.662	0.268
6 Mean Earlywood Density							0.840
MED							0.785
							0.884
							0.825
							0.760
7 Minimum Density							
MIND							

Table 4. Percentages of positive and negative pointer intervals during the period 1899–1989, identified within each regional chronology grouping as defined in Table 1

Ident	No. of yrs analyzed	Total ring width			Maximum density		
		negative	positive	total	negative	positive	total
ALAYUK	90	14.6	14.6	29.2	14.6	10.1	24.7
BRITCO	90	10.1	14.6	24.7	14.6	22.5	37.1
GRSLLA	90	6.7	1.2	7.9	3.4	5.6	9.0
WINNIP	90	7.9	3.4	11.2	6.7	2.2	9.0
QUEBLA	90	7.9	4.5	12.3	13.5	14.6	28.1

the above, ERW and LRW are generally well correlated ($r^2 \geq \sim 0.5$) though the correlations are lower for BRITCO (0.38). Generally positive correlations are apparent between MAXD and MED (and necessarily between MLD and MED), though values are noticeably higher for ALAYUK and QUEBLA ($r^2 > 0.5$) then the other regions (r^2 0.26–0.46). Comparisons between MAXD and MIND, MAXD and ERW, MED and MIND, MED and ERW, MED and TRW are almost all positive but generally low. Regional squared correlations between TRW and MAXD range from only 0.097 to 0.313. Negative correlations are ubiquitous in all of the comparisons of MED with ERW (and necessarily MED with TRW); MIND with ERW (and MIND with TRW) and MIND with LRW. However, the relationships in all cases are strong only in the ALAYUK, BRITCO and GRSLLA regions.

Explanations of the relationships summarized above can be grouped under a variety of interrelated headings such as technical/statistical, biological/anatomical and climatological factors. The correspondence between MAXD and MLD, for example, could be considered largely a technical artifact. The width of latewood in these chronologies is invariably very small. Even with a narrow density beam (0.02 mm), MLD and MAXD are registered in very few (overlapping) measurements. Combined with the statistical dependence of the mean on the maximum density level, this induces a high correlation in these variables. Similar statistical considera-

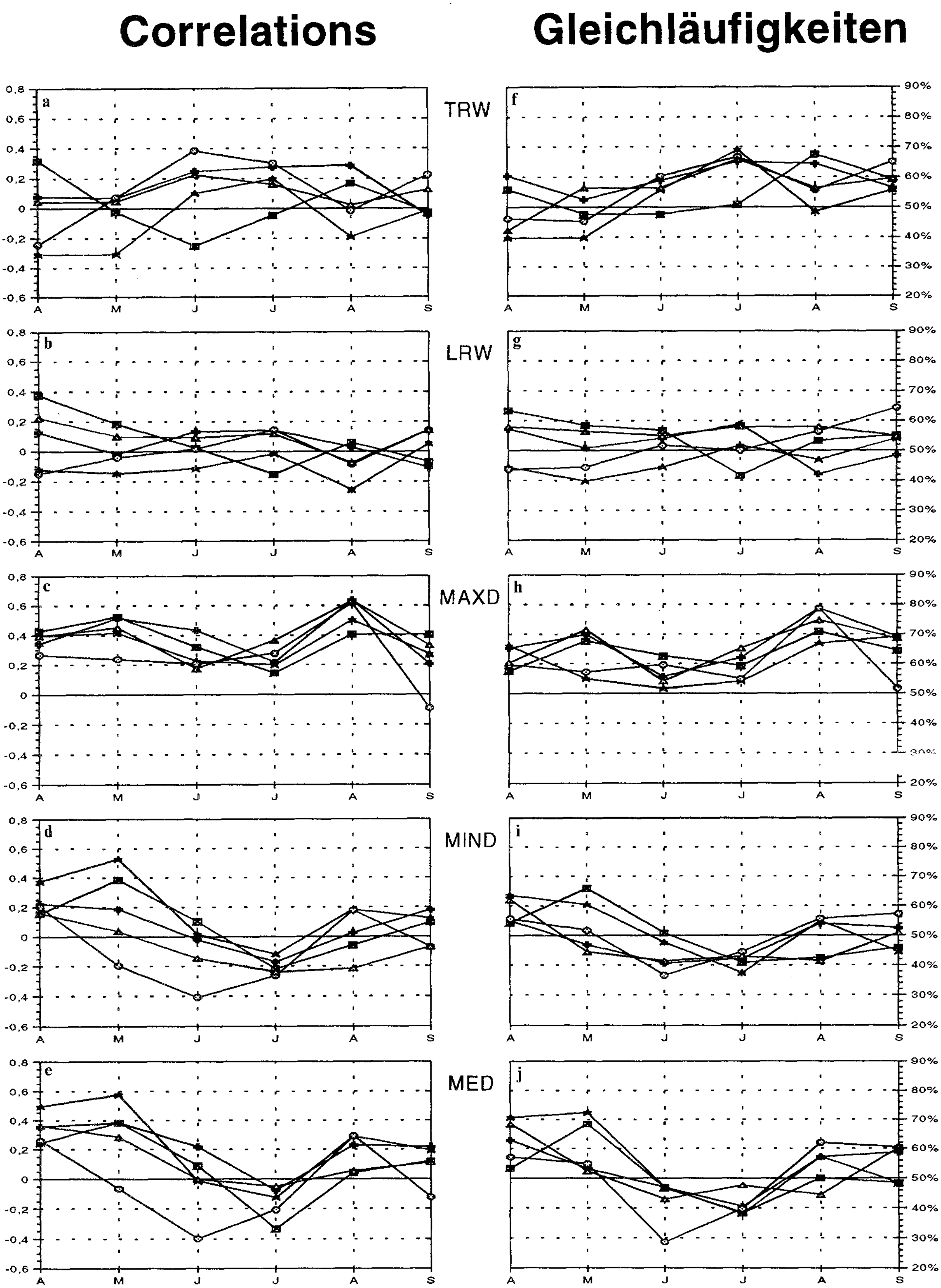

Fig. 8a–j. Relationships between tree-growth and monthly mean temperatures in the five regions defined in Table 1 and Fig. 1. (▲ ALAYUK; ● BRITCO; + GRSLLA; ■ WINNIP; ◆ QUEBLA). Correlations are shown based on alternative techniques: simple Pearson Correlation Coefficients (**a–e**) and Gleichläufigkeiten (**f–j**), calculated separately for each of the months from April to September, over the common period 1920 to 1983. The parameters are identified in Section 2.2 and the legend to Fig. 4. Note that, as the ERW and TRW, and MLD and MAXD series are so highly correlated in all regions (c.f. Section 5.3), the results for ERW and MLD are not shown

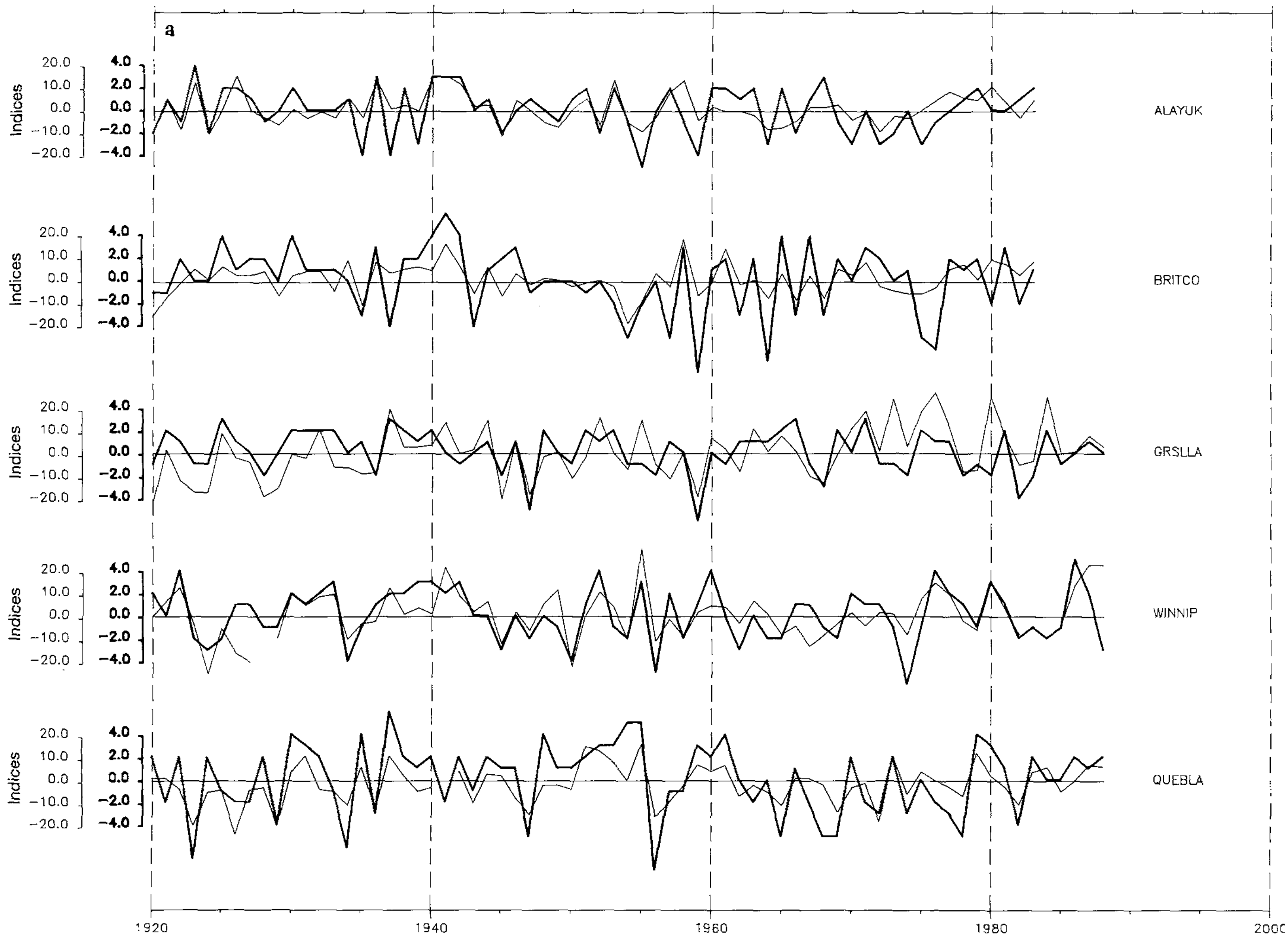

Fig. 9a, b. Comparisons between regional mean standardized MAXD chronologies and various seasonal mean temperature data for equivalent regions from 1920 to 1983: (**a**) April–August (**b**) August. Tree-ring data are shown as bold lines and temperature data as thin lines

tions explain the relationships between MIND and MED and TRW and ERW (i.e. ERW generally makes up more than 75% of TRW).

The inverse relationship between MED and ERW (and hence between MED and TRW also) could be considered biological/anatomical, but also climatological. In a warm spring, rapid earlywood growth (utilizing stored resources) would lead to a relatively large expansion of spring tracheids producing wide rings comprised of comparatively thin walled cells. The positive relationship between ERW and LRW can also be related to warm climate. Early springs will promote good early growth but the enhancement may carry through to the summer because of greater needle extension and increased net photosynthetic potential.

Remote crossdating in various tree-growth parameters. Many authors have previously drawn attention to the crossdating between either ring-width or density series within geographical regions of varying scale. Müller-Stoll (1951) used the term "teleconnection" in this regard. Schweingruber et al. (1985), referred to "dendroclimatological zones", whereas earlier authors (e.g. Fritts 1976; Hollstein 1980; Richter 1980) had quantified the similarity between various chronologies, at distance, according to statistical significance values. The results presented here, again confirm the concept of remote crossdating between tree-ring and densitometric parameter series but highlight several points relating to specific parameters.

The TRW, ERW and MED site chronologies generally display good coherence in relation to the five regional groupings but the WINNIP and QUEBLA groupings are less clearly delimited for these variables. LRW displays only weak crossdating and the regional grouping is indistinct. The same is true for MIND, though crossdating appears stronger in the QUEBLA region. MAXD and MLD display strong crossdating at relatively long distances but the regional grouping is nonetheless distinct (c.f. Fig. 2).

The crossdating range is also influenced by general location. This is illustrated, for the case of MAXD, in Fig. 6. This shows crossdating (measured by the significance of Gleichläufigkeit values) between selected subregional chronologies (Anchorage, the average of chronologies 3, 4, 6 and 7 in Table 1; Hudson Bay W., the

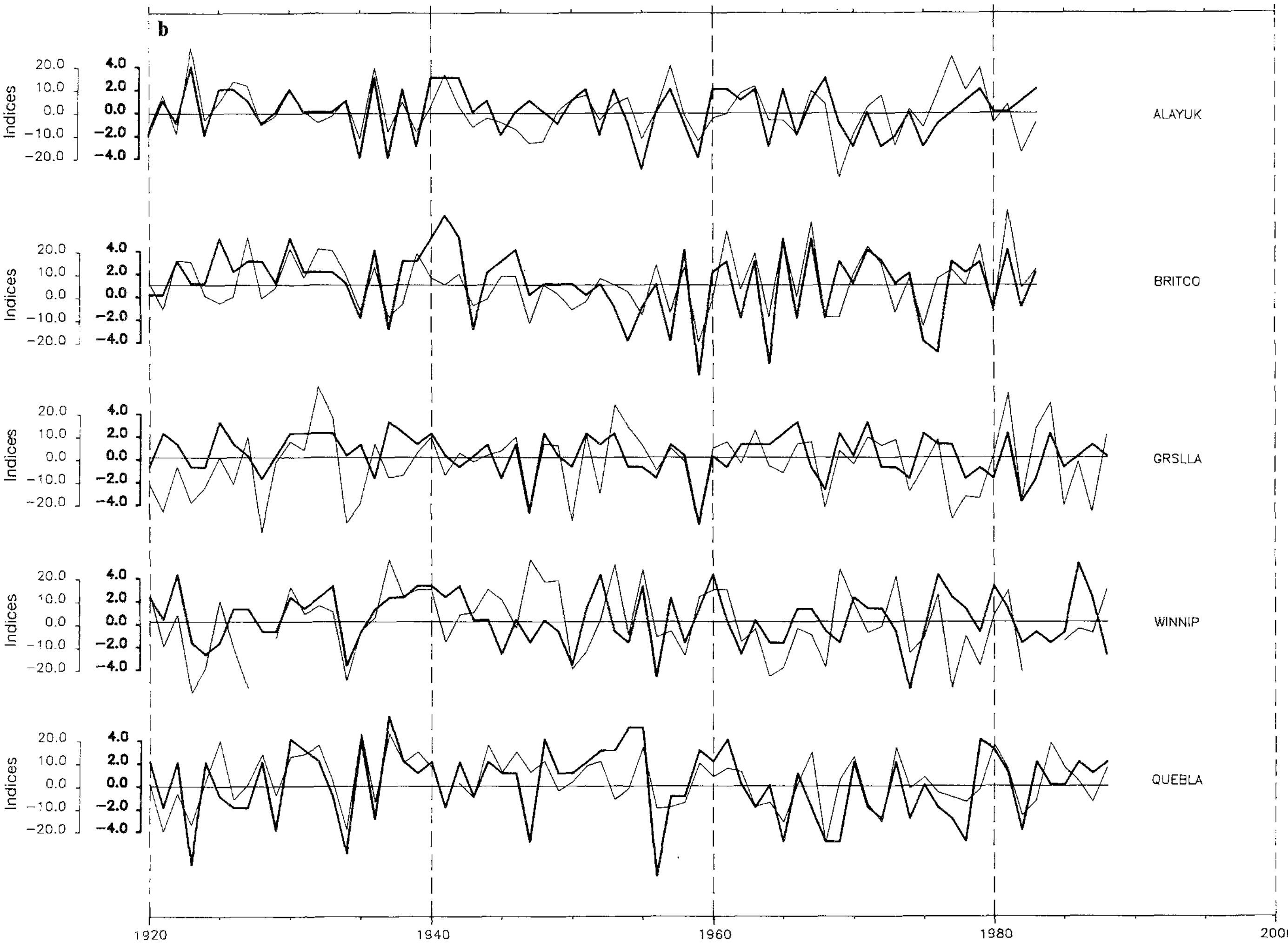

Fig. 9b

average of 37, 38, 39 and 40; and St. Laurent N., the average of 66, 67, 68 and 69). The Anchorage chronology (Fig. 6a) crossdates only with the subregional chronologies (also defined in Table 1) in the north west. There is virtually no crossdating with the series east of the Rocky Mountains. The Hudson Bay W. chronology (Fig. 6b) displays strong crossdating with chronologies across the whole continent, in an East/West direction but does not crossdate significantly with the two most southerly series of this network. The St. Laurent N. series (Figure 6c) crossdates with chronologies as far west as 120° W but not with the Ungava Bay series immediately to the north.

Regional pointer intervals (Years). A number of previous studies have focussed on the dendrochronological concept of 'pointer intervals' (Huber 1941; Eckstein and Bauch 1969; Baillie 1982; Kelly et al. 1989). These are defined as those years in which a statistically significant number of some dendrochronological sample (either core series making up a chronology or tree-ring chronologies in some pre-defined group) show the same sign of change when compared with their value in the previous year. The groups of MAXD and TRW site chronologies which made up the five regional series were each examined in order to identify the pointer intervals occurring over the period from 1899–1989. The results are summarized in Table 4. In the ALAYUK and BRITCO groups of chronologies, between about one quarter and one third of all years are pointer intervals, where these are defined here as 95% of site chronologies within a group displaying the same direction of change (counting changes of both positive and negative sign). In the middle part of the continent (GRSLLA and WINNIP) only about one tenth of the years are pointer intervals. In the QUEBLA region the MAXD and TRW data give different results: with 28% of the years in the density data and only 12% of the ring-width values being pointer intervals. These results are highly dependent on the analysis period, however, as is illustrated by the fact that the TRW data for ALAYUK has 11 pointer intervals between 1901 and 1920 but only two from 1921 to 1940. The GRSLLA data do not have any pointer intervals during the first of these two periods but have four in the second. Figure 7a–f illustrates the spatial diversity of some characteristic pointer years. No years

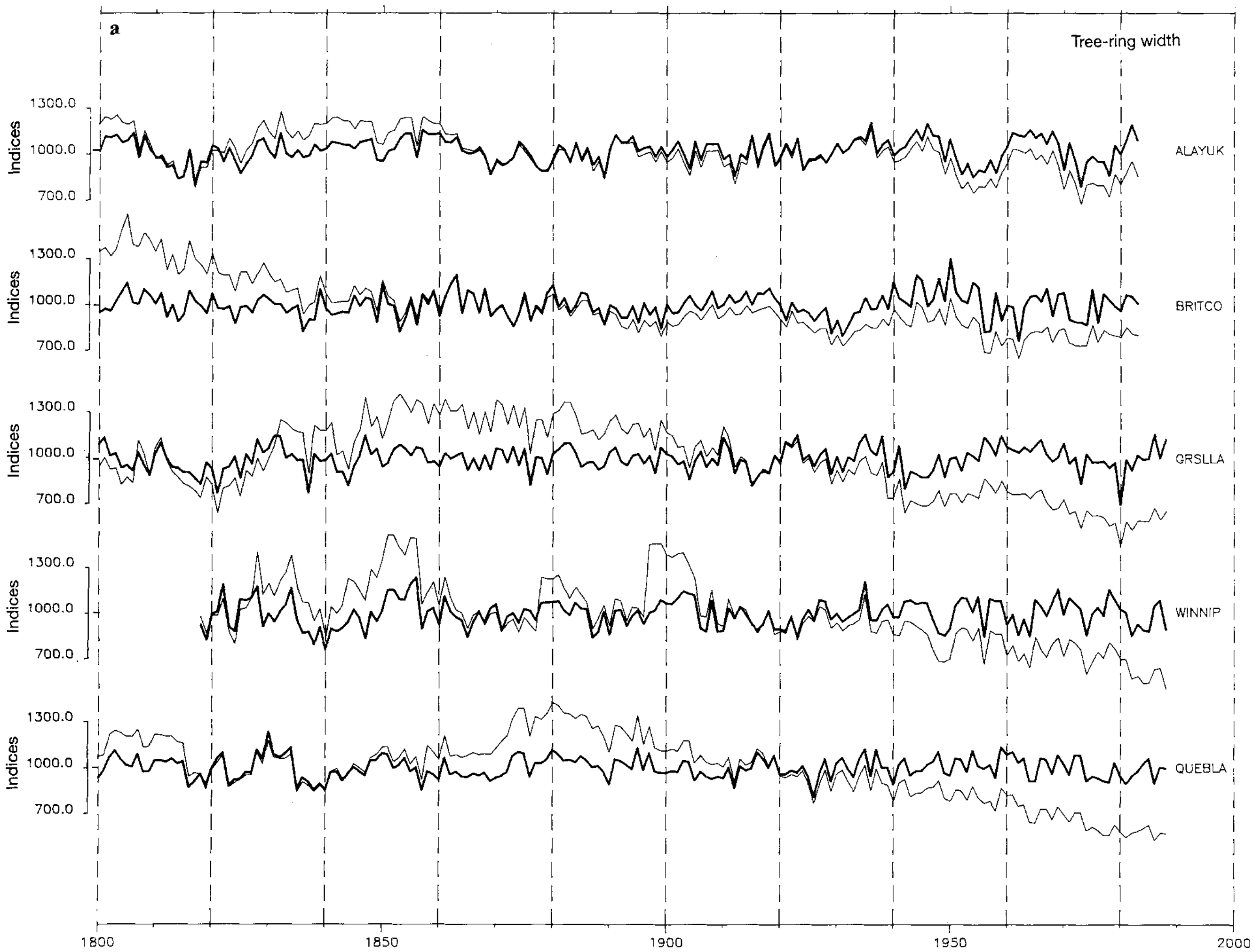

Fig. 10a, b. The various regional mean chronologies for Total Ring Width (**a**), and Maximum Latewood Density (**b**), plotted since A.D. 1800. Both standardized (thick line) and mean normalized raw data (thin line) are shown

can be identified as pointer intervals relating to the central part of the continent, or of course, the whole northern continent.

The significance of these observations as regards dating of tree-ring series is self-evident, but their particular interpretation with regard to climate forcing is not clear. It is often the case that such years correspond to extreme values in the mean chronology, but this is by no means always the case, as illustrated by the MAXD series for BRITCO during the intervals 1921/2, 1925/6, 1928/9 (see Fig. 9a, b). It is also of interest to note that whereas some periods, characterized by a frequent occurrence of pointer intervals, display a relatively strong correlation with climate, other periods with notably fewer pointer intervals may nonetheless display similar correlations. This can be illustrated by reference to the MAXD data for the period 1920 to 1983. The BRITCO and QUEBLA chronology groupings have 30 and 23 pointer intervals respectively, and the simple correlation coefficients between their mean chronologies and respective regional temperatures, averaged over the April–August season, are 0.74 und 0.78. The WINNIP and GRSLLA data have only 8 and 4 pointer intervals but their correlations with the equivalent temperature data are 0.77 und 0.79. Further work ist required to investigate details of the spatial pattern of temperature anomalies associated with the spatial patterns of pointer intervals in these data.

Temperature relationships of tree-ring parameters

The relationships between regional mean monthly temperatures and the ring-width and density parameters were explored separately in each of the five regions. For each region, the seven chronologies representing the different tree-growth parameters (listed in Section 3) were compared with the equivalent regional temperature data (see Section 4) in each of the months April through to September, over the period 1920–1983. Both Pearson correlation coefficients (Fig. 8a–e) and Gleichläufigkeit (Fig. 8f–j) values were computed (note that because MAXD and MLD are virtually the same series in each region, as are TRW and ERW, the correlations for ERW and MLD are not shown). The Gleichläufigkeit results reflect high-frequency coherence between the data

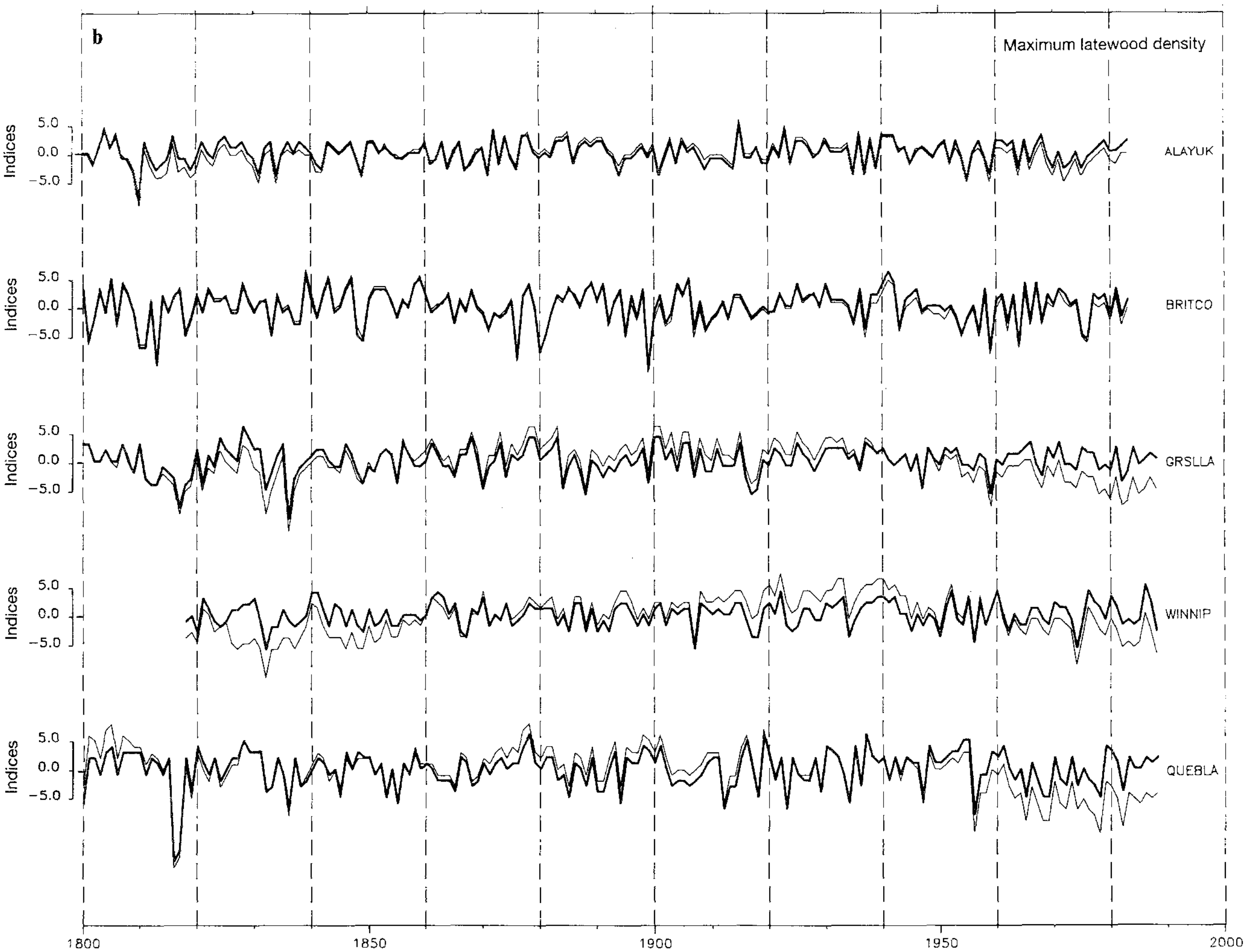

Fig. 10b

whereas the correlation values incorporate the influence of any coincident trends. These two sets of results, however, are essentially similar.

A number of conclusions can be drawn from Fig. 8. The most consistent and the strongest temperature relationships are apparent with MAXD (and MLD): correlations are generally highly positive in all months and all regions, with May and especially August registering the strongest similarities (the BRITCO MAXD series shows somewhat weaker values in April and May and no correlation in September). By comparison, the ring-width-related variables appear to be poorly correlated with temperature. Certainly LRW displays apparently random, insignificant associations. TRW (and ERW) display more consistently positive associations, at least for the months of June through September and more particularly in the Gleichläufigkeit values, with the June values (barring the WINNIP series) displaying consistently high values. It should be stressed here that it is probable that the ring-width-related variables integrate the effects of temperature over longer periods than can be represented by these results and we have not explored the temperature relationships of prewhitened tree-ring data in this context (see also Jacoby and D'Arrigo 1989; D'Arrigo et al. 1992). The MIND and MED data display opposite relationships with temperature in Spring as opposed to Summer. During April and May, higher MIND is apparently associated with warmer temperatures (most clearly evident in the GRSLLA and WINNIP series) and a negative relationship exists between MIND and temperatures during June. Though the magnitude is not statistically significant, this relationship is evident in all regions.

Figure 9a, b illustrates the similarity between the five regional MAXD curves and selected temperature anomaly series. These curves illustrate how the correspondence between trees and temperature is generally very good, but slight inconsistencies indicate that the relationships are subject to some apparently unpredictable variation associated with season, time and space. For each pair of curves (MAXD and Temperature) sequences of years can be found in which the correspondence is very high. However, other periods, when the matches are much poorer, can easily be identified. As an example, the BRITCO MAXD series between 1955 and 1967 is extremely similar to the curve of August temperature anomalies, but during the period 1937–42 the curves are very different. Between 1941 and 1958, the WINNIP MAXD series agrees closely with the mean April–August temperature series, but the correspondence with the August series is poor. Overall, the most consistent relationships between the various regional MAXD series and seasonal temperature data are for the April to August 'season'.

Maximum latewood density and total ring widths since A.D. 1800

Figure 10a, b shows the MAXD and TRW chronologies for each major region plotted from A.D. 1800 onwards. Two curves are plotted for each chronology: the standardized version, in which individual tree series have been detrended as described earlier (Section 2.2) and a 'non-standardized' version in which the measured data for each tree are transformed into z scores (by subtracting the mean and dividing by the standard deviation of the series) and averaged across years. The standardized curves reflect the strong influence of summer temperature, whereas the non-standardized curves include the additional effect of changing tree age and competition. These curves indicate that no recent anomalous growth increases have occurred. Previous work (Jacoby and D'Arrigo 1989) has highlighted significantly increasing ring-width growth of some trees. This previous work was concerned with severely-stressed trees growing in the forest-tundra ecotone. Selected sites and trees at these locations, with particular ecology and aspect, may exhibit a sensitivity to temperature variability representative of larger climatic regions (G. Jacoby, pers. comm.). Our results, along with other recent work (D'Arrigo et al. 1992), indicate that increasing tree growth through the 20th century is not characteristic of the wider North American boreal forest.

Conclusions

The tree-ring network we have discussed here, represents an important development in the Northern Hemisphere Dendroclimatological Program being undertaken by the Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf. In a northern North American context, this work demonstrates the large regional scale of climate-related variability that is expressed in various tree-ring parameters derived from trees of different species, growing under a variety of ecological conditions (Figs. 4 and 5). In a hemispheric context, these chronologies are less climatically sensitive than those in northern Eurasia though, as has been demonstrated previously for Europe and western North America, extensive regional crossdating is apparent. Both ring-width and maximum-latewood-density chronologies exhibit common variability that suggest regionally coherent association over an average distance of some 2000 km (Figs. 1 and 2), though local regional values range from 1100 to 3000 km (Fig. 6). Defined in terms of the geographic scale of similar individual yearly trends (pointer intervals), the geographic extent of teleconnections can range from very small to almost transcontinental (Fig. 7). We have grouped the site chronologies into five major regions: Alaska and Yukon; British Columbia; Great Slave Lake; Winnipeg; and Quebec and Labrador. These are reasonably geographically distinct (Figs. 1 and 2), with a separation between northern and southern units in both the Rocky Mountains and the Great Plain area further east, and all of these four regions clearly separate from the region east of Hudson Bay.

Within the large regional chronologies, some local chronology variability is removed. The production of long large-regional chronologies is, therefore, dependent on the availability of numbers of old local chronologies (e.g. Luckman 1992; D'Arrigo et al. 1992). As has been demonstrated for European conifers in subalpine and high-latitude sites, the variability of regional maximum-latewood-density chronologies in northern North America primarily reflects mean summer temperatures, between April and August, though thermal conditions in August are a major influence (Fig. 9). This re-emphasises the transcontinental dendroclimatological potential of such material. There is, however, still considerable scope for exploring the influence of other seasonal climate components and the detailed influence on other tree-ring parameters.

A combination of age and natural ecological conditions affecting this network, together with the standardization procedures used in processing the measured data, impart a limitation in the potential long-timescale variability manifest in the final chronologies. These factors would not, however, be expected to limit the potential of these chronologies to exhibit recent positive growth anomalies if such information were contained in the raw measurement data.

Over recent decades, the regional chronologies described here do not exhibit any clear increasing growth tendencies that might be expected to result as a consequence of the anthropic environmental modifications or 'natural' climate change.

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References

Baillie, MGL (1982) Tree-ring dating in archaeology. Croom Helm, London and Canberra. p 274

Bräker O (1981) Der Alterstrend bei Jahrringdichten und Jahrringbreiten von Nadelhölzern und sein Ausgleich. Mitt. forstl. Bundesvers Anst Wien 142:75–102

Briffa KR, Jones PD, Schweingruber FH (1992) Tree-Ring reconstructions of summer temperature patterns across western North America since 1600. J Clim 5:735–754

Cook E, Briffa K (1990) Data analysis. In: Cook ER, Kairiukstis LA (eds) Methods of dendrochronology. Kluwer, Dordrecht, Boston, London, pp 97–161

D'Arrigo RD, Jacoby GC, Free RM (1992) Tree-ring width and maximum latewood density at the North American treeline: parameters of climatic change. Can J For Res 22:1290–1296

Eckstein D, Bauch J (1969) Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. Forstwiss Zentralbl 88:230–250

Fritts HC (1976) Tree rings and climate. Academic Press. London, New York, San Francisco, p 567

Hollstein E (1980) Mitteleuropäische Eichenchronologie. Trierer Grabungen und Forschungen 11. Zabern, Mainz/Rhein

Huber B (1941) Aufbau einer mitteleuropäischen Jahrring-Chronologie. In: Mitt. d.H.G. Akademie 110–125

Jacoby GC, D'Arrigo RD (1989) Reconstructed Northern Hemisphere annual temperature since 1671 based on high latitude tree-ring data from North America. Clim Change 14:39–59

Jones PD, Raper, SCB, Bradley RS, Diaz HF, Kelly PM, Wigley TML (1986) Northern Hemisphere surface air temperature variations: 1851–1984. J Clim Appl Meteorol 25:161–179

Kelly PM, Munro MAR, Hughes MK, Goodess CM (1989) Climate and signature years in west European oaks. Nature 340:57–60

Lenz O, Schär E, Schweingruber FH (1976) Methodische Probleme bei der radiographisch-densitometrischen Bestimmung der Dichte und der Jahrringbreiten von Holz. Holzforschung 30:114–123

Luckman BH (1986) Reconstruction of Little Ice Age events in the Canadian Rocky Mountains. Geographie physique Quaternaire 40:17–28

Luckman BH (1992) Glacier and dendrochronological records for the Little Ice Age in the Canadian Rocky Mountains. Proc Int Symp on Little Ice Age Climate. Tokyo Metropolitan University 75–80

Luckman BH, Innes TR (1990) Tree-ring studies in Canada: a bibliography and data base. Department of Geography. University of Western Ontario, London, Ontario, p 247

Müller-Stoll H (1951) Vergleichende Untersuchungen über die Abhängigkeit der Jahrringfolge von Holzart, Standort und Klima. Bibliotheca Botanica 122:1–93

Parker ML, Henoch WES (1971) The use of Engelmann spruce latewood density for dendrochronological purposes. Can J For Res 1:90–98

Parker ML, Jozsa LA (1971) Dendrochronological investigation along the Mackenzie, Liard and South Nahanni Rivers. NWT Tech Rep 10 to Glaciol Div Water Res Branch Department of the Environment

Polge H (1966) Établissement des courbes de variation de la densité du bois par l'exploration densitometrique de radiographies d'échantillons prélevés à la tarière sur des arbres vivants. Ann Sci Forest 23:1–206

Richter K (1988) Dendrochronologische und dendroklimatologische Untersuchungen an Kiefern (Pinus sp.) in Spanien. Diss University Hamburg

Schweingruber FH (1985) Dendroecological zones in the coniferous forests of Europe. Dendrochronologia 3:67–75

Schweingruber FH (1988) Tree rings. Basics and applications of dendrochronology. Kluwer, Dordrecht, Boston, London, p 276

Schweingruber FH, Bräker OU, Schär E (1979) Dendroclimatic studies on conifers from central Europe and Britain. Boreas 8:427–453

Schweingruber FH, Briffa KR, Jones PD (1991) Yearly maps of summer temperatures in Western Europe from A.D. 1750 to 1975 and Western North America from 1600 to 1982. Vegetatio 92:5–71