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The impact of air mass circulation dynamics on Late Holocene paleoclimate in northwestern North America

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Abstract

Paleoclimate records from northern British Columbia, southwestern Yukon, and adjacent Alaska suggest that Late Holocene climate may have been influenced by specific air mass circulation dynamics. The Aleutian low pressure index (ALPI) is a measure of sea level pressure fluctuations in the Pacific Northwest associated with the Aleutian low (AL) pressure system. In this study, we show that the AL has a strong influence on historical climate change in the study area and explore the relationships between ALPI polarity and changes in late Holocene paleoclimate records.

Analyses of weather station data in the study area indicate positive correlations ($r > 0.63$) between mean wintertime (December–March) temperature and ALPI values; total wintertime snowfall accumulation and total precipitation show moderate and weak negative correlations, respectively. A Late Holocene increase in exotic western hemlock (*Tsuga heterophylla*) pollen has been observed in regional paleoclimate studies. A sustained positive ALPI phase during the late Holocene is considered as a causative mechanism. Under such conditions, warm maritime air masses would more frequently penetrate inland, potentially resulting in eastward pollen transfer, enhanced growing conditions at coastal sites, and an increase eastwards in the range limit of these species. This study indicates that apparent conflicts in the timing and magnitude of Late Holocene climate change may be the result of a strong regional climate-forcing mechanism that exhibits both temporal and geographical variation.

1. Introduction

In northwestern British Columbia (BC), southeastern Alaska (AK), and southwestern Yukon (YK), a number of paleoclimate records have exhibited Late Holocene (ca. 3.0–2.0 ^{14}C ka BP) increases in far-travelled (exotic) western hemlock (*Tsuga heterophylla*) pollen which have been attributed to long-term changes in air mass circulation (Miller and Anderson, 1974; Cwynar 1993; Spooner et al., 1997; Mazzucchi, 2000; Spooner et al., 2002). This change occurred significantly later than climate change indicated by other proxies such as changes in the local vegetation assemblages primarily recorded by treeline shift (Spooner et al., 1997; Mazzucchi, 2000) and lithostratigraphic changes associated with lake productivity (Spooner et al., 2002). The western hemlock pollen increase is not recorded in paleoclimate records outside the study region (Banner et al., 1983; Gottesfeld et al., 1991; White and Mathewes, 1982; MacDonald et al., 1984, 1987; MacDonald and Cwynar, 1985). A number of recent studies have identified the importance of air mass circulation change in governing regional climate in northwestern North America. In particular, the Aleutian low (AL) pressure system has been identified as having a strong synoptic effect on climate throughout the Pacific Northwest (Miller et al., 1994; Latif and Barnett, 1996; Mantua et al., 1997; Hare and Mantua, 2000). Basin-scale drops in sea level pressure (SLP) centred over the Aleutian Islands are often described as intensifications of the AL pressure cell (Graham, 1994, Trenberth and Hurrell, 1994). As the AL changes in location and strength, it influences the position of winter storm tracks, and precipitation and surface temperature trends over North America (Miller et al., 1994). When the AL intensifies and shifts eastward, it increases its area of influence and warm, moist air is transferred to the western North America coast (Miller et al., 1994; Latif and Barnett, 1996). Historical variation in the

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strength of the AL has been calculated; a resultant index (Aleutian low pressure index, ALPI) is a measure of variation in the nature of the AL and measures deviation from the 1950–1997 mean (Beamish et al., 1997). Although the ALPI exhibits much interannual variability there have been several periods when one phase (+ve or –ve) of the ALPI has dominated for many winters (Fig. 2). For example, basin-scale pressures were anomalously high from 1900 until 1922 (see Fig. 2); under these conditions (–ve AL phase), fewer and weaker intensifications of the AL occurred. From 1922 until 1943, the opposite occurred and the ALPI was in a generally +ve phase, resulting in stronger and more frequent storm tracks (Fig. 2).

Through monitoring of changes in patterns of Pacific wind, pressure, temperature, and precipitation patterns, Mantua et al. (1997) concluded that intensifications of the AL pattern are strongly correlated with the Pacific decadal oscillation (PDO, the leading principle component, PC, from an un-rotated empirical orthogonal function, EOF, analysis of monthly sea surface temperature (SST) anomalies in the Pacific ocean poleward of 20°N for the 1900–1993 period of record; *see* Mantua and Hare, 2002). In general, warm PDO phases result in more frequently intensified ALs and vice versa. There is some variability between the PDO and AL correlation within each phase though they both appear to follow a similar pattern of decadal scale climatic phase shifts. Although North Pacific variability manifested by ALPI and PDO has largely been described as a process which involves the winter deepening of the AL, Barnes (2002) has shown that a moderate (+ve) correlation between temperature and these indices exits year-round.

In this study, we investigate whether correlation exists between the ALPI and wintertime climate at eight sites in northwestern BC and adjacent AK. We regressed historical climate records of wintertime (November–March) precipitation, temperature and pressure against the ALPI (Beamish et al., 1997). We then use the results to interpret records of Late Holocene climate change from the region.

2. Regional climate

The climate of southeastern AK and coastal northern BC is dominantly maritime due to the proximity of the Pacific Ocean. Isohyets typically exhibit a steep increasing gradient near the coast and diminish eastward. From November to March, approximately 1400 mm total precipitation falls in Prince Rupert in contrast to only 350 mm total precipitation in Prince George (Figs. 1 and 2). Along with abundant rainfall, the coastal region has mild temperatures and long frost-free periods associated with a maritime climate. The climate in the interior lowland areas of BC is dry and continental.

The AL dominates the winter climate of the North Pacific and beginning about mid-October intensifies and migrates southeastward to a location centred over the Gulf of Alaska. Winter surface winds blow in a counterclockwise circulation around the AL. To the south, winds blow in a clockwise circulation around a semi-permanent centre of high pressure (Pacific High, PH) that intensifies in the summer months. Together, these systems bring moist, onshore southwesterly and westerly flow into the Pacific northwest from October through early spring. During the late spring and summer, the west to east upper airflow weakens and the AL retreats to the northwest and becomes less intense. At the same time the PH intensifies off the coast and results in fewer frontal systems moving through northern BC. As a result, summers tend to be moderately dry.

3. Paleoenvironmental records

Relatively few studies in northwestern BC and adjacent AK have focused on reconstructing Holocene climatic change (Hebda, 1995). Palynological investigations indicated that discrepancies exist in the timing of palynological change at maritime and continental sites (Miller and Anderson, 1974, Fig. 1). They attributed this behaviour to an inland shift in the location of maritime and arctic air masses and associated storm paths along the north Pacific coast. Other studies (Cwynar, 1988, 1993; Spear and Cwynar, 1997; Spooner et al., 1997; Mazzucchi, 2000; Barnes, 2002, Fig. 1) indicated temporal variations in moisture and temperature states and trends. Cwynar 1993, Spooner et al. (1997, 2002), and Mazzucchi (2000) suggested that Late Holocene air mass circulation changes reinforced the eastward dispersal of coastal pollen. In all cases a significant increase in western hemlock pollen occurs progressively later in eastern sites, and well after the transition to modern climate (see Fig. 3). Studies to the south (Banner et al., 1983; Gottesfeld et al. 1991, Fig. 1) and on the eastern margin of BC (White and Mathewes,1982; MacDonald et al., 1984, 1987; MacDonald and Cwynar, 1985) also documented Late Holocene climatic change but with no inference of changes in regional atmospheric circulation. A study in the White Pass region on the BC-AK-YK border (see Fig. 1) indicated that the onset of Neoglaciation in the region was comparatively late (ca. 1800 yr BP) and was driven by an increase in the frequency of the inland penetration of low pressure cells and coincident precipitation (Lamoureux and Cockburn, 2002). In a paleolimnological study at Meziadin Lake, BC, (Fig. 1) varves and tree ring thicknesses correlated well with historical climate conditions (Barnes, 2002). As well, climate sensitive tree ring-width chronologies have been used to demonstrate that decadal-scale climate shifts in the North Pacific have occurred frequently during the past 400 years (Gedalof and Smith, 2001). Lakes have been cored in AK, BC, and the US Pacific Northwest to study the interannual and interdecadal variability of Pacific sockeye salmon populations (Finney et al., 2000, 2002). These studies indicated that substantial decadal and centennial-scale changes in populations have occurred in the Late Holocene and appear to be related to climate change.

4. Method

The study area for this research was in northwestern BC, southwestern Yukon and southeastern AK, between limits of 53°–62°N and 122°–135°W (Fig. 1). Stations were included in the study if they contained long-term climate data records with no more than 4 years of missing data. Application of these criteria yielded eight sites for investigation, six of which are in BC (Atlin, Dease Lake, Prince Rupert, Prince George, Smithers, and Stewart; Fig. 1) and two of which are in southeastern AK (Sitka, Juneau; Fig. 1). Wintertime (November–March) mean temperature, total precipitation and total snowfall were obtained from the Canadian Monthly Precipitation Database and the National Climate Data Center. These data were plotted against ALPI which is calculated as the mean area (km^2) with sea level pressure >100.5 kPa and expressed as an anomaly from the 1950–1997 mean (*Beamish* et al., 1997). A positive index value occurs when the area of low pressure (AL) is large. Time series and regression analysis was performed. The degree of correlation was established quantitatively by determining the strength of the correlation coefficient (r value).

5. Results

Results for all sites are summarized in Table 1. Data availability for the study region was good with most sites having monthly records of temperature, snow and total precipitation that span at least 50 years. Atlin, BC, was the one exception as neither snowfall nor precipitation data were available from either of the databases used in the study. Both Prince Rupert, BC, and Prince George, BC, had records of greater than 80 years owing to their proximity to transportation routes. Temperature

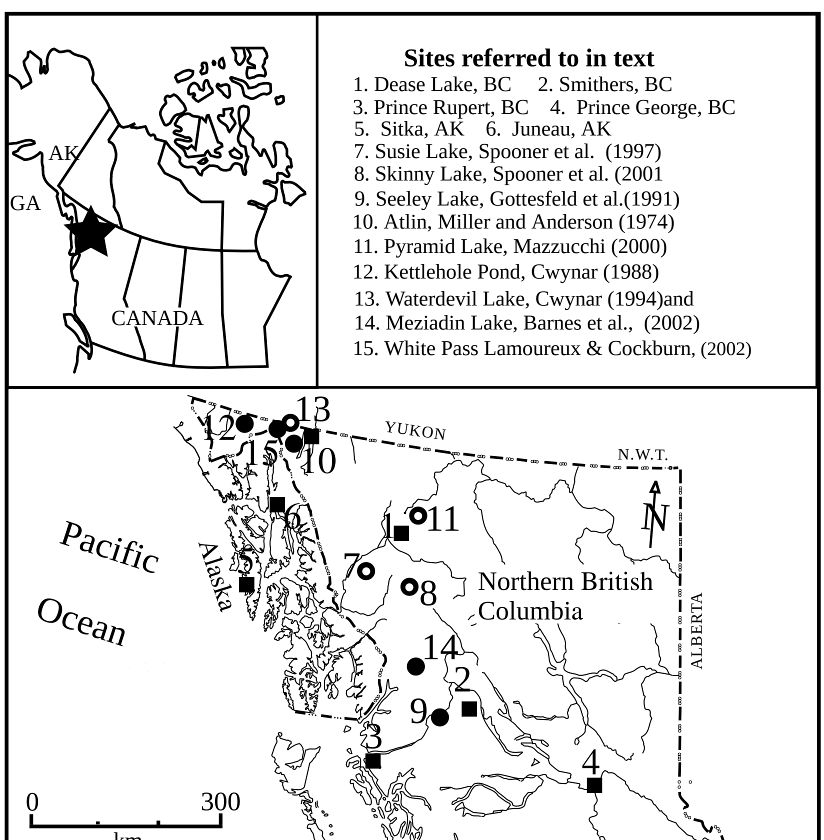

Fig. 1. Location of study region and sites referred to in text. Circles are select paleoclimate sites, those that have open centres record a Late Holocene increase in exotic western hemlock pollen and are discussed in detail in Fig. 3. Squares are sites for which historical climate data were available. GA refers to Gulf of Alaska.

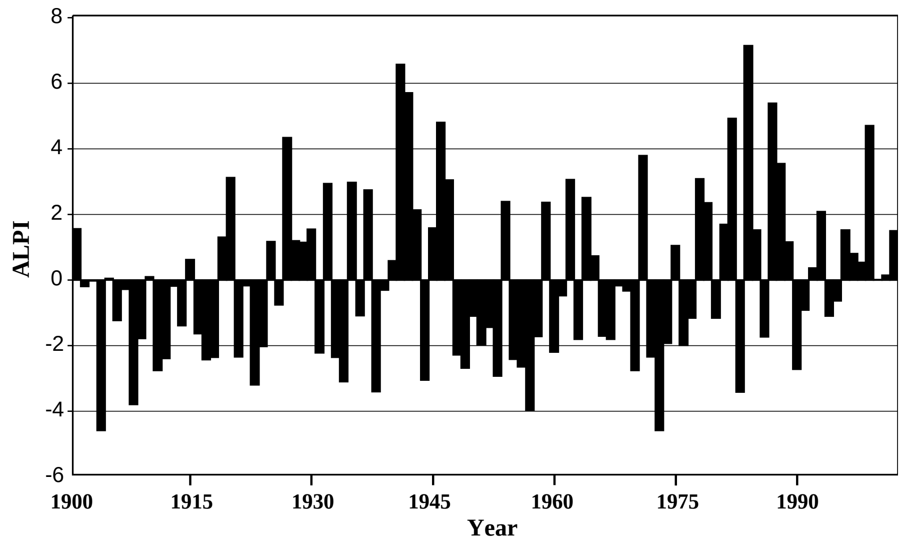

Fig. 2. ALPI for the period 1900–2000 AD. Note that for much of the early 1900s (1900–1922) and from 1947–1977 the ALPI was dominantly negative whereas from 1923–1946 and 1978–1989 the ALPI was in a strongly positive phase. Data from http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd/climate/clm_indx_alpi.htm

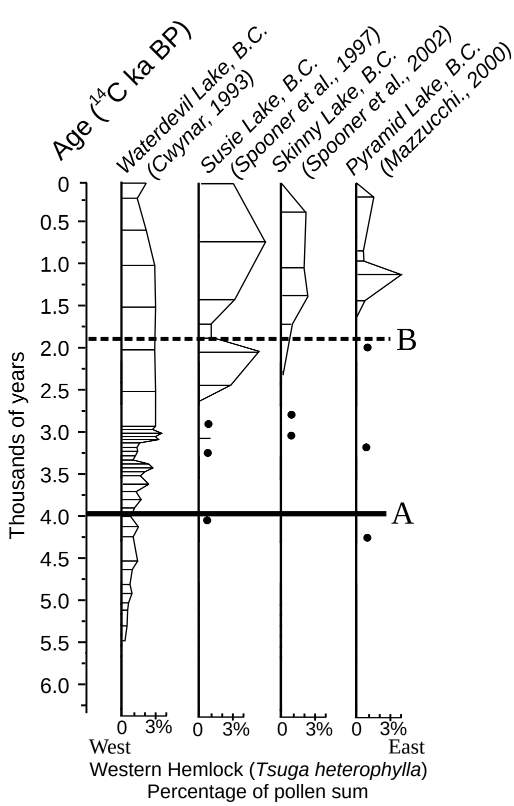

Fig. 3. Compilation figure showing the temporal relationships between western hemlock increases, interpreted transition to modern climate (A) as indicated in Spooner et al. (2002) and the onset of Late Holocene alpine glaciation (B) as suggested by Lamoureux and Cockburn (2002). Site locations are shown in Fig. 1. Note that significant increases in western hemlock pollen percentages occur progressively later in eastern sites and occur well after the transition to modern climate.

data show moderate to strong positive correlation at all sites with the highest values being attained at Sitka ($r = 0.80$) and the lowest values at Atlin ($r = 0.50$). Snow data show moderate to poor negative correlation and total precipitation data show poor negative correlation.

Of note is the moderate to strong correlation at all sites, especially during the latter part of this century (Table 1; note that sites with longer records have r results for the 1946–1990 period in brackets). This is no doubt due to greater consistency in the multi-decadal trend of the ALPI during this time. The weak response of temperature at Atlin to ALPI phase shifts may be attributed to the fact that it is located in a deep valley with steep mountains on both sides, and thus is susceptible to the strong diurnal rhythms of temperature and wind direction that are a feature of mountain climates. This short-term variability is superimposed upon the general climate characteristics of the area. The sites with moderate to high temperature correlation are located either in large valleys or on the coastline and hence topographic factors are diminished. In summary all sites exhibited warmer (cooler) temperatures and less (more) snow during +ve (−ve) ALPI phases. These findings are consistent with other studies and indicate that, in general, the AL has a strong synoptic effect on climate in the study region (Mantua and Hare, 2002).

6. Discussion

Cwynar (1993), Mazzucchi, (2000), and Spooner et al. (1997, 2002) reported that western hemlock pollen was a minor contributor to the pollen spectrum during the

Table 1
Results of correlation (r) analyses of the ALPI against historical climate records for selected sites in northwestern British Columbia and adjacent Alaska[a]

Site location (years of record)	Mean temperature (r)	Total snow (r)	Total precipitation (r)
Sitka, AK (1952–1996)	0.80*	−0.66*	−0.14
Juneau, AK (1951–1996)	0.74*	−0.57*	−0.07
Stewart, BC (1912–1999)	0.66 (0.74)*	−0.54*	−0.14
Atlin, BC (1906–1946)	0.50*	na	na
Dease Lake, BC (1946–1991)	0.63*	−0.20	−0.20
Prince Rupert, BC (1909–1984)	0.64 (0.79)*	−0.045	−0.03
Smithers, BC (1943–1998)	0.69 *	−0.42*	−0.33*
Prince George, BC (1913–1998)	0.64 (0.73)*	−0.50*	−0.26*

[a] Data in brackets are correlation coefficient values for the period 1946 to most recent record.
Note: * indicates those values that are significant at the 99% or greater confidence interval.

transition to modern climate, however significant increases occurred between 500 and 1000 years later (Fig. 3). Although air mass circulation change has been proposed as a causative mechanism for these increases in western hemlock pollen there has been little focus on mechanisms that might result in this change. Of interest then is whether circulation change associated with either a +ve or –ve ALPI phase might result in the changes observed. During a +ve ALPI phase the AL is more frequently intense. Under these conditions the AL is frequently combined with a deep longwave trough of low pressure that is dominant toward the central portion of the North Pacific. As a result, a ridge of high pressure remains over western North America. When this ridge is close to or slightly east of the coastline, North Pacific storms will be more likely to reach the coast before weakening under the ridge's high pressure gradient, resulting in the translation of warm maritime air inland (Miller et al., 1994; Latif and Barnett, 1996; Mantua et al., 1997). We suggest that this mechanism is largely responsible for the strong positive correlation at all sites between temperature and the ALPI. Although both the frequency and strength of the eastward translation of maritime air decreases somewhat during the spring (the time during which western hemlock pollinates), it does provide a potential vehicle for the transportation of west-sourced pollen to inland sites.

There are two other means by which an increase in western hemlock pollen at paleoclimate sites could also occur. An eastward migration of western hemlock and/or an increase in productivity at its range limit might occur due to enhanced growth resulting from warmer wintertime conditions (associated with a prolonged +ve ALPI phase). Conversely, a local reduction in pollen productivity could result in an apparent increase in the amount of exotic pollen transported to the site. Under the drier inland winter and spring conditions associated with a +ve (warm) ALPI phase lower local pollen productivity might also be expected. In those records that did include pollen concentration, percentages did decline after 3000 ^{14}C ka BP (Cwynar 1993; Spooner et al., 1997, 2002; Mazzucchi, 2000). As well, during a –ve (cool) ALPI phase, cooler temperatures and slightly more snow occurred both at inland and coastal sites, conditions that would not be conducive to enhanced productivity of western hemlock.

It is evident that the regional conditions that develop during a +ve ALPI phase are complementary to a local increase in western hemlock pollen. However, the low resolution of the pollen records from the region preclude a direct comparison of pollen concentrations and historical variations in ALPI phase to determine if correlation exists. Worthy of note though is the possibility that the Late Holocene rise in western hemlock pollen could be attributed to a sustained intensification of the Aleutian low pressure cell (+ve phase ALPI). Recent work by Sandweiss et al. (2001) indicated that there has been an increase in El Niño frequency after 3.2–2.8 ^{14}C ka BP and Mantua et al. (1997) have noted that there appears to be a link between warm phase ENSO-like conditions (El Niño) and +ve phase PDO (and, by proxy, +ve phase ALPI). The timing of this change coincides broadly with the increases in western hemlock pollen noted in the paleolimnological records.

Other paleoenvironmental records from the region show climate change coeval with the increase in western hemlock pollen. Finney et al. (2002) noted that salmon populations in the Aleutian Islands were significantly reduced from 100 BC to AD 800 (ca. 2.3–1.7 ^{14}C ka BP), but were consistently more abundant from AD 1200 to AD 1900 (ca. 1.2 ^{14}C ka BP—present) and suggested regional climate change as a forcing mechanism. Lamoureux and Cockburn (2002) noted a comparatively late onset of neoglaciation in the region. They suggested that glaciation in the White Pass Region of northwestern BC began about 1.8 ^{14}C ka BP (see Figs. 1, 3) and was coincident with increases in exotic western hemlock noted by Cwynar 1993. As well, Late Holocene glacier behaviour may have been anomalous. A preliminary survey indicated a paucity of Little Ice Age terminal moraines in the region compared to sites to the south and east suggesting short-lived ice extents at terminal positions. Although these studies have not directly linked the changes noted to AL dynamics they have all demonstrated that pronounced change has occurred coincident with increases in western hemlock pollen.

7. Summary

Paleoenvironmental records from northwestern British Columbia, southwestern Yukon, and adjacent Alaska suggest much variability in Late Holocene climate. We propose that the strong correlation between historical climate records and the ALPI implies that prehistoric climate was also likely influenced by variations in the intensity of the ALP cell. A long lasting +ve phase ALPI is a potential mechanism for the inland transfer of exotic western hemlock pollen noted in paleolimnological records. Other paleoenvironmental records record coincident climate change but a relationship to AL dynamics (either +ve or –ve phase ALPI) has not been established.

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References

Banner, A., Pojar, J., Rouse, G.E., 1983. Postglacial paleoecology and successional relationships of bog woodland near Prince Rupert, British Columbia. Canadian Journal of Forest Research 13, 938–947.

Barnes, S., 2002. The relationship between tree rings, varves and the PDO: Meziadin Lake, northern British Columbia. Proceedings of the 98th Annual American Association of Geographers Annual Meeting, Los Angeles, California.

Beamish, R.J., Neville, C.E., Cass, A.J., 1997. Production of Fraser River sockeye salmon (Oncorhynchus nerka) in relation to decadal-scale changes in the climate and the ocean. Canadian Journal of Fisheries and Aquatic Science 54, 543–554.

Cwynar, L.C., 1988. The late Quaternary vegetation history of Kettlehole pond, southwestern yukon. Canadian Journal of Forest Research 18, 1270–1279.

Cwynar, L.C., 1993. The abundance of exotic western hemlock pollen at Waterdevil Lake, White Pass, northern British Columbia: a preliminary analysis. Review of Palaeobotany and Palynology 79, 113–119.

Finney, B.P., Gregory-Eaves, I., Sweetman, J., Douglas, M.S.V., Smol, J.P., 2000. Impacts of climate change and fishing on Pacific salmon abundance over the past 300 years. Science 290, 795–799.

Finney, B.P., Gregory-Eaves, I., Douglas, M.S.V., Smol, J.P., 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2200 years. Nature 416, 729–733.

Gedalof, Z., Smith, D.J., 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophysical Research Letters 28, 1515–1518.

Gottesfeld, A.S.Mathewes, Gottesfeld, R.W., 1991. Holocene debris flows and environmental history, Hazelton area, British Columbia. Canadian Journal of Earth Science 28, 1583–1593.

Graham, N.E., 1994. Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results. Climate Dynamics 10, 135–162.

Hare, S.R., Mantua, N.J., 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47, 103–145.

Hebda, R.J., 1995. British Columbia vegetation and climate history with focus on 6 ka BP. Géographie Physique et Quaternaire 49, 55–79.

Lamoureux, S., Cockburn, J.M.H., 2002. Sedimentary evidence for the late onset of neoglaciation in Northwest British Columbia coast mountains. Geological Society of America Abstracts with Programs 34, 49.

Latif, M., Barnett, T.P., 1996. Decadal variability over the North Pacific and North America: dynamics and predictability. Journal of Climate 9, 2407–2422.

MacDonald, G.M.Postglacial plant migration vegetation development in the western Canadian boreal forest.Ph.D.Thesis, University of Toronto, 1984.

MacDonald, G.M., 1987. Postglacial development of the subalpine-boreal transition forest of western Canada. Journal of Ecology 75, 303–320.

MacDonald, G.M., Cwynar, L.C., 1985. A fossil pollen based reconstruction of the late Quaternary history of lodgepole pine (Pinus contorta ssp. latifolia) in the Western interior of Canada. Canadian Journal of Forest Research 15, 1039–1044.

Mantua, N.J., Hare, S.R., 2002. The Pacific decadal oscillation. Journal of Oceanography 58, 35–44.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78, 1069–1079.

Mazzucchi, D., 2000. Holocene environmental reconstruction of the Cassiar Region, northwestern British Columbia. M.Sc Thesis, Queen's University, Kingston, Canada.

Miller, M.M., Anderson, J.H., 1974. Out-of-phase Holocene climatic trends in the maritime and continental sectors of the Alaska-Canada boundary range. In: Mahaney, W.C. (Ed.), Quaternary Environments: Proceedings of a Symposium, Vol. 5. Geography Monographs, York University, pp. 33–58.

Miller, A.J., Cayan, D.C., Barnett, T.P., Graham, N.E., Oberhuber, J.M., 1994. Interdeacdal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies. Climate Dynamics 9, 287–302.

Sandweiss, D.H., Maasch, K.A., Burger, R.L., Richardson lll, J.B., Rollins, H.B., Clement, A., 2001. Variation in Holocene El Niño frequencies: climate records and cultural consequences in ancient peru. Geology 29, 603–606.

Spear, R.W., Cwynar, L.C., 1997. Late quaternary vegatation history of white pass, Northern British Columbia, Canada. Journal of Arctic and Alpine Research 29, 45–52.

Spooner, I.S., Hills, L.V., Osborn, G.D., 1997. Palynological reconstruction of late Quaternary paleoclimate, Susie Lake, Boundary Ranges, Coast Mountains. Journal of Arctic and Alpine Research 29, 156–163.

Spooner, I.S., Mazzucchi, D., Osborn, G.D., Gilbert, R., Larocque, I., 2002 . Reconstruction of Holocene vegetation and climate change, Iskut Region, northern British Columbia, Canada. Journal of Paleolimnology, in press.

Trenberth, K.E., Hurrell, J.W., 1994. Decadal atmospheric-ocean variations in the Pacific. Climate Dynamics 9, 303–319.

White, J.M., Mathewes, R.W., 1982. Holocene vegetation and climate changes in the Peace River district Canada. Canadian Journal of Earth Science 19, 555–570.