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
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 pres-
sures 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 compo-
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1. 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
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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 counter-
clockwise circulation around the AL. To the south,
wind blows 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 westerly 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 investiga-
tions 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 tem-
poral 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 Neoglacial 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 (km²) 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

Sites referred to in text


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.
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
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 neoglacialation in the region. They suggested
that glaciation in the White Pass Region of north
western 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 pre
liminary survey indicated a paucity of Little Ice Age
terminal moraines in the region compared to sites to the

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

*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.
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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