Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: atmospheric-circulation controls of regional temperature and moisture responses

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Abstract

The paleoclimatic history of a region can be viewed as a series of surface temperature and moisture anomalies through time. The effects of changes in large-scale climatic controls (e.g., insolation, major circulation controls) can be mediated by the influence of smaller-scale controls (e.g., topographic barriers, coastlines); this may result in heterogeneous surface climatic responses at the regional and sub-regional scale. Divergent paleoclimatic trajectories between regions may be explainable in terms of such meso-scale patterns. Using modern analogues for paleoclimate we examine how the sequence of climatic variations in eastern interior Alaska during the interval 12,000–14\(^{14}\)C yr BP could have been generated by specific atmospheric circulation patterns. Fossil-pollen and lake-level records document the long-term trends in temperature and effective moisture for the region. Water-balance modelling provides additional estimates of paleoprecipitation. Synoptic climatological patterns are described using the modern (instrumental) record of upper-level and sea-level pressure, surface temperature, and precipitation. At 12,000 \(^{14}\)C yr BP, eastern interior Alaska was cooler and drier than present, a situation generated today by a southward displacement of the jet stream. Conditions warmer and drier than present at 9000 \(^{14}\)C yr BP may have been generated by increased ridging north of Alaska and a weakened westerly circulation. Warmer, wetter conditions than present possibly prevailed in the late-middle Holocene; these might reflect ridging over Alaska and troughing further west. Cool, wet conditions feature enhanced westerly flow into Alaska through an eastward shift in the east Asian trough and positive pressure anomalies in the North Pacific; they may be analogous to cold periods of the Little Ice Age. The analogues demonstrate how surface conditions in other parts of Beringia may sometimes be similar to, while at other times different from those in the eastern interior. These broader spatial patterns provide hypotheses about past climates that can be tested with paleoclimatological data. For example, the widespread positive temperature anomalies associated with the warm/dry (9000 \(^{14}\)C yr BP) analogue fit with the expansion northward of the eastern Siberian treeline. The anomalously cool conditions in northeast Siberia associated with the warm/wet analogue may explain the continued (late-middle Holocene) treeline advance in Alaska while there was retreat in Siberia. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The high northern latitudes play an important role the earth’s climate system. Both simulations by general circulation models (GCMs) and empirical evidence from paleorecords indicate that the Arctic is sensitive to changes in global controls of the climate system such as insolation and CO\textsubscript{2} (Bartlein et al., 1992; Wright et al., 1993). In turn, responses of the Arctic have important consequences for lower latitudes through a variety of biological, physical and geochemical feedbacks, including changes in vegetation, snow and sea-ice albedo, the fresh-water flux to the oceans (as it governs the thermohaline circulation), and trace gas emissions (Imbrie et al., 1992; Foley et al., 1994; Gallimore and Kutzbach, 1996).

Essential to a comprehensive description of the role of the Arctic is the understanding of how large-scale...
controls, such as atmospheric circulation and the latitudinal and seasonal distribution of insolation, govern regional (and even local) ecological and hydrological conditions. This is because the potential feedbacks to the global system are realized or generated at the landscape scale. For example, the feedback from vegetation changes that likely amplifies global-scale cooling (e.g. Gallimore and Kutzbach, 1996; de Noblet et al., 1996) or warming (Foley et al., 1994; TEMPO, 1996), is ultimately generated by the landscape-scale ecological processes that accomplish the necessary changes in species ranges and abundances. Furthermore, physiographic barriers, coastlines, and major river valleys mediate the effects of the large-scale controls, even to the extent that adjacent regions may show responses of opposite sign (Whitlock and Bartlein, 1996; Mock and Bartlein, 1995).

Climate models can produce patterns of simulated surface climates that are consistent with a particular arrangement of the large-scale controls of the climate system, or “boundary conditions” (e.g. the area and height of the ice sheets, atmospheric composition, insolation, etc.). However, the spatial resolution of general circulation models (GCMs, a few degrees of latitude and longitude), and even regional climate models (RegCMs, 10s of kilometers), is too coarse to simulate many of the local and regional patterns of change in vegetation or hydrology that are evident in paleoenvironmental data sets (Mock and Bartlein, 1995). Moreover, inadequacies in the climate models or the experimental designs within which they are applied, may result in severe mismatches between paleoclimatic simulations and observations (Bartlein et al., in press), compromising the utility of the models for explaining the patterns evident in the paleorecord.

In this paper we use an alternative approach: the analysis of modern analogues (drawn from the instrumental record) for paleoclimatic situations. We examine how particular combinations of surface temperature and effective moisture anomalies observed during the interval from 12,000 $^{14}$C yr BP to present could have been generated by specific atmospheric circulation patterns (Barry, 1981; Diaz and Andrews, 1982; Mock and Bartlein, 1995). The paleoclimatic record (fossil pollen and lake-level status) for eastern interior Alaska provides the long-term trends in temperature, effective moisture, and precipitation. The kinds of summer atmospheric circulation patterns that could give rise to specific combinations of past temperature and moisture conditions are illustrated using the modern (instrumental) record of upper-level and sea-level pressure, and surface temperature and precipitation. It is then possible, in some cases, to compare the surface temperature and moisture patterns generated by an analogue based on conditions in eastern interior Alaska with paleoclimate data from Beringia (northwest Canada, Alaska, and northeast Siberia (Fig. 1), in order to test whether the analogue remains appropriate for the larger region.

Clearly, over the past 14,000 (calendar) years there have been changes in global climate boundary conditions (ice-sheet extent, insolation). These would have affected circulation patterns, evaporation rates, etc. such that different regional climate configurations from those experienced at present occurred. Although no modern analogues exist for these global conditions, similar regional and sub-regional anomaly patterns can result from different combinations of external forcing, and thus suitable analogues may be found at these smaller scales. The examination of modern synoptic patterns provides an additional approach to understanding the observed changes within and between regions, and this perspective may be combined with regional and landscape-scale simulations of past climate, when they are available, and with GCM simulations (Mock and Bartlein, 1995).

2. Study region, Paleoenvironmental data, and modern synoptic climatological data

2.1. Study region

We define eastern interior Alaska as the region contained, approximately, within the boundaries 67–63°N and 140–155°W (see Fig. 1). It is bounded to the north and south by the Brooks and Alaska Ranges, respectively, to the east by the Yukon Territory, and to the west by a climatic boundary where annual precipitation generally exceeds 400 mm. The climate is cold continental, with January means > –20°C and July means 15–20°C. Stations record precipitation of 350 to <200 mm annually, with precipitation tending to decline eastward, but strongly locally influenced by topography; about 60% falls as summer rain. The region includes large low-lying tectonic basins (Tanana valley and Yukon Flats) separated by uplands 500–1000 m in elevation; in general it behaves as a coherent climatic region. The dominant vegetation is northern boreal forest, characterized by white and black spruce (Picea glauca, P. mariana) and the boreal hardwoods poplar, alder, birch, and willow (Populus, Alnus, Betula, Salix). Alpine tundra occurs above ca 600–800 m, sparsely forested or treeless muskegs cover the coldest, wettest sites, and boreal grasslands occupy the warmest, driest landscape facies on south-facing slopes (Viereck et al., 1992).

2.2. Vegetation history

The vegetation history of the region is recorded in a number of pollen records (Ager, 1975; Ager and Brubaker, 1985; Edwards and Brubaker, 1986; Lamb and Edwards, 1988; Hu et al., 1993, 1995) and has been most recently summarized by Edwards and Barker (1994). The general biostratigraphy is well known, but the ages of key
events in the late Wisconsin and early Holocene may be 1000–2000 yr too old, based on comparisons of AMS and bulk radiocarbon dates from the same site (Ager, 1975; Abbott, 1996). For this reason our regional chronology rests largely on the sites that were AMS-dated as part of this study. Vegetation was herbaceous tundra prior to ca. 12,000 $^{14}$C yr BP, after which shrub birch expanded across the entire landscape. *Populus* was locally important at many sites between ca. 10,500 and 8,500 $^{14}$C yr BP. Spruce, mainly *Picea glauca*, expanded ca. 8500 $^{14}$C yr BP and alder about 7000 $^{14}$C yr BP. In the mid-to-late-Holocene, after ca. 6000 $^{14}$C yr BP, *P. mariana* assumed greater importance regionally.

2.3. Lake-status reconstruction

Lake-level changes can provide an important source of paleohydrologic information (Harrison and Digerfelt, 1993), but so far have been little studied in arctic and subarctic regions. We studied four lakes in the Tanana and Yukon lowlands: Birch, Dune, Jan, and Sands of Time (Abbott, 1996; Bigelow, 1997; B. Finney and M. Edwards, unpublished data; Fig. 1). All four lakes lie within the lowland boreal forest. Birch and Jan lakes lie on Pleistocene river terraces. Dune lies within a stabilized Pleistocene dune-field, and Sands of Time in an extensive region of thick loess deposits. Dune and Jan Lake are closed basins today, and appear to have been sensitive to moisture changes throughout the Holocene. Birch and Sands of Time are currently open basins, but were evidently closed earlier in their history.

Paleo-lake levels were reconstructed from spatial and temporal changes in sediment characteristics (e.g., the sediment limit, Digerfelt, 1986), which were determined from an offshore sediment-core transect (Abbott, 1996). Seismic profiling aided lake-level reconstruction at Birch Lake, and age control was based on AMS $^{14}$C-dating of macrofossils and pollen (Abbott, 1996). The results indicate significant changes in lake level over the past 13,000 yr. Based on the lake-level changes, we developed semi-quantitative estimates of precipitation for the last 12,000 years. Large changes in the moisture balance through time are indicated and are coincident with major vegetational and limnological transitions (Bigelow, 1997).

We assume all lakes experience a similar regional climate, but as their bathymetries and hydrologic systems differ, their responses to various climate changes are not identical. Hypsographic relationships were determined by calculation of the area and volume of the lakes at 1 m depth intervals. Modern water budgets were established for Birch and Jan Lakes based on our data and other published data. Discharge is zero at Jan; for Birch it was calculated by monitoring water depth in the outlet stream during the 1993 open-water season. We used precipitation and temperature data from the station closest to each site, but most climate stations in the Fairbanks region do not record all the parameters.
necessary to calculate energy budgets. Our estimates for evaporation are based on other interior Alaskan studies (Kane and Carlson, 1973; Kane et al., 1979, 1990; Dingman et al., 1980; Nakao et al., 1981; Hinzman, 1990), from Patric and Black’s (1968) calculations using Thornwaite’s equation, from Canadian studies in similar climatic regions (Landals and Gill, 1973; Marsh and Woo, 1977; Newberry et al., 1979; Roulet and Woo, 1986; Marsh and Bigras, 1988) and from empirical calculations using monthly climate parameter averages (Penman, 1948; Penman, 1956; Ward and Elliot, 1995. After incorporation of all other parameters, difference estimates were used to obtain a value for evapotranspiration (ET). For the purposes of modeling, soil moisture was considered part of the evapotranspiration parameter.

The modern budgets were used to constrain water-balance estimates for Birch and Jan in a model run for past conditions. We focussed on 3 time slices: 12,000, 9000, and 6000 $^{14}$C yr BP. For each time slice, we selected a field of E and ET values that seemed reasonable for the catchment vegetation (as reconstructed from pollen data) and summer evaporative conditions (as inferred from pollen and lake sediment data). For a series of precipitation values, the set of E and ET values necessary to maintain the lake at the reconstructed level were calculated. The most likely precipitation level was the one which required E and ET to intersect the pre-defined field. (further details of the reconstructions are presented in Barber and Finney, in press).

2.4. Modern climate data and synoptic analysis

The summer climate of interior Alaska is primarily affected by mid-tropospheric variations of ridges and troughs. July and August are normally the wettest months of the year (Barry and Hare, 1974). Influence of the westerlies becomes more prevalent as the general circulation shifts northward during spring, and the higher amplitude of the Jet Stream pattern creates 4–5 smaller long waves (troughs) as compared to 3 larger ones during the winter (Harman, 1991). Normally during summer, the subtropical highs are prevalent at mid-latitudes, and the East Asian trough is centered along the eastern Siberian coast, steering storms into southwest Alaska (Moritz, 1979; Strenthen, 1974). However, variations in atmospheric circulation create variations in surface patterns for the region. Fairbanks and adjacent stations show more variability than many other Alaskan stations because of their inland location (Mock et al., 1998).

In this study we are interested in anomalous conditions in interior Alaska. These were defined by abnormal July temperature and precipitation extremes at the Fairbanks station, which lies approximately in the center of the region represented by the four lakes in the paleohydrologic study (Fig. 1). We use July because it represents a range of circulation patterns that normally occur in the warm season when precipitation is at its peak during the annual cycle (Mock et al., 1998). Abnormal temperature and precipitation conditions were classified as those being below and above the 25th and 75th percentiles, respectively. This classification was used because precipitation data at Fairbanks are negatively skewed.

Having defined the anomalous years (Table 1) we average pressure temperature and precipitation data for stations across a wider region (for the years selected) to investigate the regional circulation patterns associated with anomalies in interior Alaska. The circulation data consist of mean July gridded 500 mb heights and sea-level pressure for the period 1946–1989 (Mass, 1993). Both the 500 mb surface and sea-level were analyzed because circulation patterns may differ between the two surfaces, with the former indicating large-scale ridges and troughs, and the latter representing patterns influenced by surface heating and cooling. The data cover a region from central Asia to central North America in order that synoptic controls such as the Pacific subtropical high are described adequately.

Table 1

<table>
<thead>
<tr>
<th>Climatic conditions</th>
<th>Abnormal years</th>
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</thead>
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<tr>
<td>Cold and Dry</td>
<td>1964</td>
</tr>
<tr>
<td>Warm and Wet</td>
<td>1962</td>
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</table>

Monthly surface climatic data include 59 temperature and 87 precipitation stations across Beringia (far eastern Siberia, Alaska, and northwest Canada; Fig. 1), also available for the period 1946–1989 (Groisman et al., 1991; Vose et al., 1992). The data were carefully screened, and corrected where necessary, with regard to station moves and instrument exposure. Further descriptions of the data are provided by Mock et al. (1998). Although this study emphasizes the surface climate of the Fairbanks region, all of Beringia was examined in order to determine whether or not climatic patterns at Fairbanks are regional-scale climatic signals that are synchronous throughout Beringia.

We used the data to create and analyze composite maps of 500 mb heights, 500 mb height anomalies, sea-level pressure, sea-level pressure anomalies, temperature anomalies, and precipitation anomalies (e.g., Yarnal, 1993; Mock and Bartlein, 1995). Both raw values of 500 mb heights as well as sea-level pressure were mapped in addition to the anomalies as an aid in interpretation. For example, a positive pressure anomaly does not necessarily indicate that a high-pressure system (e.g., Pacific subtropical high) was particularly strong at a certain location — it may rather represent a weaker low-pressure system compared with normal. The composite maps of
500 mb heights and sea-level pressure depict spatial patterns and the controls responsible for climatic extremes. The interpretation of circulation composite anomaly maps is similar to traditional climate anomaly maps, with increased clockwise flow around positive centers and increased counterclockwise flow around negative centers. The temperature and precipitation composite anomaly maps illustrate the spatial patterns of responses to the atmospheric circulation patterns.

3. Results

3.1. Vegetation and lake-status history

The pollen and lake-level data are independent, and they together provide a more detailed and secure history of moisture and temperature for the region than is possible with pollen data alone. Table 2 shows the major trends in vegetation and lake-levels from 14,000 cal yr BP to present and inferred changes in thermal and moisture regimes based on these data. At Birch Lake, basal non-lacustrine sediments suggest the lake was dry shortly before 13,000 \(^{14}\text{C}\) yr BP. All lakes we studied were extremely low, intermittent, or dry prior to ca 12,000 \(^{14}\text{C}\) yr BP, and water-balance modeling suggests that precipitation was 30–60% of modern values (Barber and Finney, in press). Tundra vegetation and the very low precipitation levels strongly suggest that temperatures were cooler than present.

The herb-birch transition at ca 12,000 \(^{14}\text{C}\) yr BP probably represents a temperature rise, and from lake data it clearly coincides with a major, rapid, moisture increase. The later appearance of Populus (ca. 9500 \(^{14}\text{C}\) yr BP) suggests another temperature increase. During the birch and birch-poplar periods, effective moisture fluctuated, but was always less than present.

Range extensions and increases in abundance of various thermophilic minor taxa in northern Alaska are the clearest pollen evidence of warmer-than-present conditions in the early Holocene (Nelson and Carter, 1987; Edwards et al., 1985; Anderson, 1988; Lamb and Edwards, 1988; Edwards and Barker, 1994). Hydrologically, the rapid filling of Dune Lake, which probably responds to groundwater flow fed by snow and glacial melt in the Alaska Range, but lower levels of Birch and Jan lakes, which are more sensitive to evaporation (Barber and Finney, in press), also suggest that conditions were warmer than present by 9000–8000 \(^{14}\text{C}\) yr BP. Water-balance modeling suggests precipitation was 60–90% that of present. Birch, Dune, and Sands of Time show a further increase in levels at about 8500 \(^{14}\text{C}\) yr BP (which is coincident with the arrival of Picea glauca). However, water-balance modeling shows that precipitation was still less than present (80–90%) as late as 6000 \(^{14}\text{C}\) yr BP. (Barber and Finney, in press). Between 7500 and 6000 \(^{14}\text{C}\) yr BP effective moisture, though still less than present, crossed the critical threshold for Alnus, which expanded regionally at that time (Anderson and Brubaker, 1993). Expansion of Picea mariana after 6000 \(^{14}\text{C}\) yr BP and renewal of lowland ice-wedge growth in the late Holocene (Hamilton et al., 1983) imply a probable cooling of temperatures toward the present. At the closed-basin lakes, Dune and Jan, we have noted prominent shorelines above present lake level which presumably are mid- or late-Holocene in age, but which we have been

<table>
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<tr>
<th>Age of interval (cal yr BP)</th>
<th>Paleoclimatic evidence</th>
<th>Inferred paleoclimates</th>
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<tbody>
<tr>
<td></td>
<td>Vegetation and Interpretation</td>
<td>Lake Status and Interpretation</td>
</tr>
<tr>
<td>&gt; 16,000</td>
<td>Herb zone/cold and dry</td>
<td>Lakes dry/driest part of record</td>
</tr>
<tr>
<td>&gt; 14,000</td>
<td>Herb zone/cold and dry</td>
<td>Low or intermittent/slightly moister than before but still very dry (precip 30–60% modern)</td>
</tr>
<tr>
<td>14,000–11,500</td>
<td>Birch zone/warmer than earlier, but still cool</td>
<td>Rapid rise in levels/moister than earlier</td>
</tr>
<tr>
<td>11,500–9500</td>
<td>Populus expansion and peak/further warming to near-modern temps.</td>
<td>Intermediate levels/moister than earlier, drier than present (precip 60–90% modern)</td>
</tr>
<tr>
<td>9500–8500</td>
<td>Picea glauca expansion/warmer than present</td>
<td>Near-present lake levels, moister than before, but drier than present</td>
</tr>
<tr>
<td>8500–6500</td>
<td>Alnus expansion/ further moisture increase</td>
<td>Near-present lake levels (precip 80–90% modern)</td>
</tr>
<tr>
<td>6500-present</td>
<td>Picea mariana expansion/slight cooling</td>
<td>Near-present lake levels (possibly higher at times)</td>
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3.2. Paleoclimatic analogues

Figs. 2a–d shows the climate data and climate anomalies associated with the four anomalous climate states in interior Alaska: warm and dry, cold and dry, warm and wet, and cold and wet. We identified 13 abnormal months for the Fairbanks station. Five are warm and dry and six are cold and wet (Table 1). This inverse relationship is the dominant mode in the modern record. Cold and dry and warm and wet are represented each by only one month. Although these conditions are rare in the modern record, they provide important information on climate controls that may have been more common in the past.

The 500 mb heights for warm and dry reveal a trough centered in the Bering Sea south of its normal position. The 500 mb composite and sea-level pressure anomaly maps indicate positive anomalies that reflect increased ridging north of Alaska — a region that is a major center of circulation variability (Mock and Anderson, 1997). Increased easterly flow around the ridge towards Fairbanks is warmer and drier as compared to normal, as trajectories are more directly over land. Sea-level pressure indicates that the eastern Pacific subtropical high is predominant as normal, but negative height anomalies at 500 mb indicate a weakening aloft that would reduce cooler westerly flow into Fairbanks. Positive temperature anomalies are evident throughout most of Beringia, perhaps reflecting the strong ridging north of Alaska and a general weakened westerly circulation, but some negative temperature anomalies are evident along the Kamchatka Peninsula, related to a stronger easterly onshore flow from the Bering Sea. The anomalous easterly flow causes negative precipitation anomalies over most of Alaska. Precipitation anomalies over Siberia are generally weak and mixed in sign and do not appear clearly related to circulation variations over Alaska.

July 1964 is the only month that has abnormally cold and dry conditions at Fairbanks (however, the same anomaly patterns are apparent for the unusually cool, wet summer of 1998). The 500 mb anomalies are large, probably because we only have one month’s data, but the general configuration provides a picture of the synoptic patterns that may have occurred in the past. 500 mb heights show increased westerly flow well south of the Bering Sea, and negative 500 mb and sea-level pressure anomalies are widespread — thus representing a southward displacement of the jetstream as compared to normal (Andrews, 1964). The sea-level pressure map also shows a diminished spatial extent of the Pacific subtropical high. Temperature anomalies are mostly negative throughout Beringia, corresponding to the southward movement of colder polar air masses, but large positive anomalies are evident in western Alaska. These may relate to increased easterly flow around low-pressure systems as they traverse south of Alaska. This easterly flow brings relatively cool air to Fairbanks from the south, but the air warms as the airstream progresses farther west over land, perhaps also influenced by down-slope movements over mountain ranges. Precipitation anomalies are mostly negative since storm tracks are farther south, but some positive anomalies in Siberia result because of the negative pressure anomalies over the Arctic Ocean; these are conducive to cyclogenesis, which may move storms along the East Siberian Sea (Serreze et al., 1993).

July 1962 is the only month classified as warm and wet at Fairbanks. 500 mb heights generally show a weak westerly flow, with troughing centered westward as compared to normal over Kamchatka. 500 mb anomalies show characteristics that lie somewhere between those for the warm and dry and the cold and wet anomaly maps; ridging is prevalent over Alaska but negative anomalies over the East Siberian Sea perhaps allow a few storms to enter the region from the west (Andrews, 1962). Temperature anomalies are positive throughout Alaska, and mostly negative north of 60° N in Siberia. These opposite conditions are related to the ridging over Alaska and the trough centered farther west. Precipitation anomalies exhibit heterogeneous patterns, with positive anomalies at Fairbanks and elsewhere in the interior.

The 500 mb height pattern for cold and wet also shows troughing centered in the Bering Sea, but the contours are more widely spaced apart, suggesting a northward shift of the westerlies into the Bering Sea as compared to the warm and dry pattern. Both the 500 mb and sea-level pressure anomaly maps indicate positive anomalies in the north Pacific, with clockwise flow around these positive centers bringing increased westerly flow into Fairbanks. Negative circulation anomalies are also evident north of Alaska, indicating a slight eastward shift of the East Asian trough, also enhancing westerly flow and storms into Fairbanks. The temperature composite map shows negative anomalies over all of Alaska and along the coast of northern Siberia, associated with positive precipitation anomalies. Both these temperature and precipitation anomalies are related to the northward displacement of the westerlies and colder air. Precipitation anomalies along the Sea of Okhotsk are negative perhaps because of dry westerly flow through a low-elevation corridor to the west (Lydolph, 1977; Mock et al., 1998).
**Warm and Dry (5 months)**

Fig. 2. Anomaly maps for: (a) warm/dry; (b) cold/dry; (c) warm/wet; and (d) cold/wet conditions in the eastern interior Alaska study region. 500 mb map units are geopotential meters. Sea-level pressure is in mb. Temperature composite anomalies are in °C (large plus = > 0.5 °C, small plus = 0-0.5 °C, small minus = < − 0.5 °C, large minus = < − 0.5 °C). Precipitation composite maps are expressed as percentage departures from normal (large plus = > 30%, small plus = 10-30%, dot = − 10-10%, small minus = − 30 to − 10%, large minus = < − 30%).
4. Discussion

The paleoclimatic data indicate that the late Wisconsin prior to 12,000 $^{14}$C yr BP was colder and drier than present. Subsequently, summer temperatures increased and exceeded those of the present, though exactly when is unclear. At 9000 $^{14}$C yr BP conditions were almost certainly warmer and drier than present. Thus we can consider the synoptic data for cold/dry and warm/dry anomalous conditions.
as potential analogues for the 12,000 and 9000 $^{14}$C yr BP situations in eastern interior Alaska. Furthermore, the analogues can act as hypotheses that generate predictions of surface temperature and moisture conditions over the whole of Beringia. These can be tested with paleoclimatic data from adjacent regions. Although not all parts of Beringia are yet adequately described, enough data exist for an initial assessment of some predictions, and to examine the potential of the approach.
4.1. 12,000 $^{14}$C yr BP — colder and drier than present

The Laurentide ice sheet probably had a dominant effect on the ice sheet of eastern Beringia during the late Wisconsin, indirectly through its control of hemispheric circulation, and directly through cooling adjacent regions (Bartlein et al., 1992). From GCM simulations (e.g., Kutzbach et al., 1993), the size of the 16,000 cal/14,000 $^{14}$C yr BP ice sheet was great enough to generate a strong anticyclone. Several simulations for summer at
21,000 cal/18,000 $^{14}$C yr BP indicate that the ice sheet produces a much weaker Pacific subtropical high than present (e.g., Lorenz et al., 1996; Hall et al., 1996), implying a southward-displaced jet stream off southern Alaska; this would be conducive to cold and dry conditions. As the ice sheet diminished, so its control on circulation decreased, so that by the time it was reduced to the size imposed in simulations for 14,000 cal/12,000 $^{14}$C yr BP, westerly flow, more typical of interglacial conditions, predominated.

The July 1964 (cold and dry) analogue shows circulation anomalies over Beringia similar to those generated by the 21,000 cal/18,000 $^{14}$C yr BP GCM simulation. It is unlikely, however, that the Laurentide ice sheet was exerting anything like its 21,000 cal/18,000 $^{14}$C yr BP dominance at 14,000 cal/12,000 $^{14}$C yr BP. Furthermore, the modern analogue is generated under very different sets of large-scale controls. However, a pattern similar to that described by the modern analogue may have dominated the summer climate in the late glacial, maintaining cool, dry conditions in eastern Beringia until ca 14,000 cal/12,000 $^{14}$C yr BP. If this pattern is hypothesized as representing Beringian conditions at this time, the data suggest that Western Alaska should have positive temperature anomalies (Fig. 2b; note that this does not necessarily mean that temperatures were warmer than present). There is some evidence for an early birch expansion in northwestern Alaska (ca 14,000 $^{14}$C yr BP; Anderson, 1985), and of therophilous insects present in the late Wisconsin in southwest Alaska (Elias, 1992). It is possible that the modern W-E summer temperature gradient in Alaska was reversed prior to 14,000 cal/12,000$^{14}$C yr BP.

4.2. 9000 $^{14}$C yr BP — warmer and drier than present

The early Holocene period was warm and dry compared present. Such conditions are generated particularly when there is a strong ridge north of Alaska, perhaps enhanced also by a weakened Pacific subtropical high, as indicated by the modern analogue. For the early Holocene, numerous GCM simulations generate a stronger Pacific subtropical high (e.g., Mitchell et al., 1988), but its effects are mainly experienced further south, primarily in the western United States (Barnosky et al., 1987). Thus a southward displacement of a stronger high could generate the negative anomaly associated with the Pacific high in the analogue situation. None of the GCM simulations published to date, with the possible exception of NCAR CCM0 (Kutzbach et al., 1993), simulate a strong ridge north of Alaska. However, this pattern is common in the instrumental record, and the analogues clearly indicate the importance of this ridge in causing a strong dry easterly flow that is required to create warm and dry conditions.

The warm temperature anomaly is consistent across Beringia, which fits with various elements of the paleoclimatic record, for example, the Populus subzone, which occurs between 11,000 and 8000 $^{14}$C yr BP at many sites in Alaska (Anderson and Brubaker, 1994; Bartlein et al., 1995) and the Juniperus sub-zone ca 8000 $^{14}$C yr BP. (Ritchie, 1984, p. 121; Edwards and Barker, 1994). At Killeak Lake, tundra vegetation changes suggest the warmest period of the Holocene at this time (P.M. Anderson, personal communication). In Siberia, the temperature anomalies are strongly positive in the north for this pattern, which coincides with a northern displacement of treeline at this time (Khotinsky, 1984).

4.3. Climate states of the mid-to-late Holocene

After ca 8500 $^{14}$C yr BP, moisture levels in the Alaskan interior increased, suggesting the warm-dry configuration lessened in importance. Raised shorelines (B. Finney and M. Edwards, unpublished data) and lake-sediment data (Bigelow, 1997) suggest that some time after ca 6000 $^{14}$C yr BP, effective moisture levels may have been the highest at any time during the Holocene. Two possible climate scenarios could generate higher effective moisture: warm/wet and cold/wet. The former may have occurred after 6000 $^{14}$C yr BP, and prior to the last millennium, but evidence from vegetation or lake-level data is circumstantial. The latter may have occurred in the last millennium during cold phases of the Little Ice Age (LIA), but again, definitive paleoclimatic evidence is lacking.

The warm/wet analogue implies ridging over Alaska and a trough further west than normal — an unusual situation today. However, some 6000 cal yr BP. GCM simulations show negative sea-level pressure anomalies over the Arctic Ocean north of Beringia (e.g., Lorenz et al., 1996; Hewitt and Mitchell, 1996). This configuration would allow occasional storms to traverse Alaska from the east Siberian Sea. The simulated trough is probably weak enough for higher summer insolation to cause widespread positive temperature anomalies. The Pacific subtropical high is also simulated stronger than present, and a slight northward migration could inject moisture into interior Alaska. In the modern climate analogue for warm/wet, temperature anomalies in northern Siberia are negative. Cooling in this region would be consistent with the reatreat of the northeast Siberian treeline (Khotinsky, 1984). The persistence of positive temperature anomalies over Alaska is probably consistent with the continued spread of Picea in the mid-Holocene.

Tree-ring data record LIA climate fluctuations in Alaska and adjacent Canada (Jacoby et al., 1985, 1996; Jacoby and D’Arrigo, 1989; Szeicz and MacDonald, 1995; Wiles et al., 1996) and Kamchatka (Gostev et al., 1996), but to date there are no other detailed time series of paleoclimatic data for the last millennium (although reconstructions of summer sea-level pressure patterns in
the North Pacific during the LIA were made by Blasing and Fritts, 1975). The cold/wet pattern may be an analogue for cold periods of the LIA. It features an enhancement of westerly flow into Alaska through an eastward shift in the east Asian trough and development of positive anomalies in the North Pacific. Negative temperature anomalies are fairly consistent across Alaska, northeast Siberia, and Kamchatka under this pattern. If the cold/wet pattern was important during the LIA, cold periods should have been widespread and synchronous across Beringia. A preliminary comparison of the timing of decadal-length cold periods over the last several centuries (see references above) shows that some (e.g., a cold period centered on 1860 A.D.), but not all, are synchronous. The implication is that the cold/wet pattern is at best only a partial analogue; cold but dry conditions may also have prevailed, and our analogues may not capture the full complexity of climate variation over the growing season that might affect tree-ring growth.

5. Conclusions

Modern climate analogues can provide a useful means of determining how synoptic-scale controls may have given rise to patterns of temperature and precipitation in the past. They can be used to test paleoclimatic hypotheses as suggested by output from GCM simulations, and they also provide explanations of paleoclimatic variation at smaller spatial scales, as observed in paleoclimatic data. For eastern interior Alaska, some analogues identify circulation features that appear to be important in controlling regional climate but which have not been simulated by GCMs. In other cases, the major circulation features simulated by GCMs are consistent with the regional synoptic patterns. Some analogues show significant spatial heterogeneity in surface moisture and temperature, which may in some cases explain paleoclimatic data that indicate variability between different parts of Beringia. The method may be particularly useful in understanding the climate fluctuations of the Little Ice Age and the Younger Dryas, although in these cases there is a need for additional high-resolution paleoclimatic data.

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