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Late Holocene moisture balance variability in the southwest Yukon Territory, Canada

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Abstract

Analyses of sediment cores from Marcella Lake, a small, hydrologically closed lake in the semi-arid southwest Yukon, provides effective moisture information for the last ~4500 years at century-scale resolution. Water chemistry and oxygen isotope analyses from lakes and precipitation in the region indicate that Marcella Lake is currently enriched in ^{18}O by summer evaporation. Past lake water values are inferred from oxygen isotope analyses of sedimentary endogenic carbonate in the form of algal Charophyte stem encrustations. A record of the $\delta^{18}O$ composition of mean annual precipitation at Jellybean Lake, a nearby evaporation-insensitive system, provides data of simultaneous $\delta^{18}O$ variations related to decade-to-century scale shifts in Aleutian Low intensity/position. The difference between the two isotope records, $\Delta\delta$, represents ^{18}O-enrichment in Marcella Lake water caused by summer effective moisture conditions. Results indicate increased effective moisture between ~3000 and 1200 cal BP and two marked shifts toward increased aridity at ~1200 and between 300 and 200 cal BP. These prominent late Holocene changes in effective moisture occurred simultaneously with changes in Aleutian Low circulation patterns over the Gulf of Alaska indicated by Jellybean Lake. The reconstructed climate patterns are consistent with the topographically controlled climatic heterogeneity observed in the coastal mountains and interior valleys of the region today.

1. Introduction

Air masses that influence the southwest Yukon Territory originate in the Bering Sea, the Gulf of Alaska and the Arctic Ocean. Trajectories of these air mass systems are strongly controlled by variations in the intensity and position of the semi-permanent Aleutian Low (AL) located over the Gulf of Alaska (Fig. 1; Trenberth and Hurrell, 1994; Mock et al., 1998). A major regional topographic feature is the ~3000-m high St. Elias massif and Coast Mountains of southeastern Alaska. Varying atmospheric circulation patterns superimposed on the regional topography produce notably different climates on the coast and the interior (Wahl et al., 1987). Relatively warm/wet Gulf of Alaska airmasses delivered by AL circulation result in high precipitation on the coastal side of the mountains (>6000 mm/yr) and a strong rain shadow in the southwest Yukon (<260 mm precipitation/year), approximately 200 km inland from the coast (Wahl et al., 1987).

Previous paleoclimatic studies suggest that variations in AL intensity and/or position were an important control on Northwest Pacific Holocene climate (e.g., Heusser et al., 1985; Mann and Hamilton, 1995; Edwards et al., 2001; Spooner et al., 2003). Oxygen isotope variations in endogenic carbonate at Jellybean Lake, an evaporation-insensitive system, located in the southwest Yukon, provides a detailed record of AL variability for the last ~7500 years at decade-to-century time scales (Anderson et al., 2005a). Abrupt oxygen isotope shifts at Jellybean Lake at ~1200 and 300 cal BP are verified by corresponding oxygen isotope shifts at the summit of Mt. Logan and interpreted to represent rapid AL intensification and/or eastward shifts (Fisher et al., in press). In contrast,

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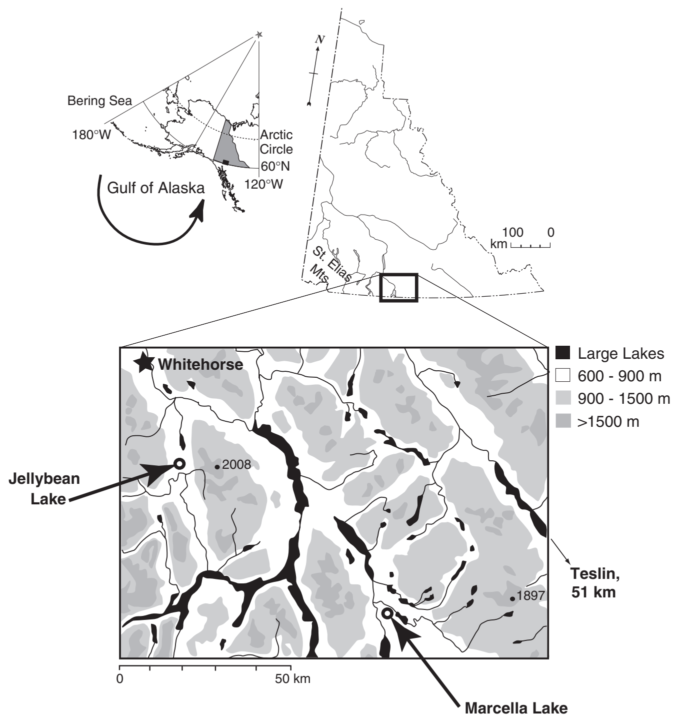

Fig. 1. Location map of the study area in the southwest Yukon Territory. The circular arrow indicates the general atmospheric circulation around the Aleutian Low in the Gulf of Alaska oriented towards the northeast to southwest trending St. Elias Mountains. The shaded relief map of the area surrounding Jellybean and Marcella Lakes shows the large lakes in the region (black areas), the locations of Whitehorse and Teslin, local topography and high elevations in each lake's watershed. Bathymetric maps of Marcella and Jellybean Lake including coring locations are in Anderson et al. (2005a, b).

hydrologically closed lakes located in the rain shadow of the southwest Yukon are sensitive to changes in moisture balance (precipitation minus evaporation). Evaporation-sensitive lakes that accumulate endogenic carbonate at relatively high rates (0.3–1.0 mm/yr) present the opportunity to investigate the relationship between interior moisture balance and AL circulation variations at decade-to-century time scales.

Previous studies in the southwest Yukon provide information regarding moisture balance variability on millennial- to century-scales (Cwynar, 1988; Pienitz et al., 2000; Anderson et al., 2005b). Conditions prior to 10,000 cal BP were dry. Effective moisture increased during the early Holocene. Conditions were wetter-than-modern by ~3000 cal BP but subsequently increasingly arid to present. Tree-ring studies in semi-arid central Alaska highlight the ecological impacts of inter-decadal changes in effective moisture during the last century (Barber et al., 2000). However, relatively little is known about sub-millennial scale moisture balance variability during the Holocene or about the relative importance of temperature and precipitation in controlling effective moisture.

We analyzed oxygen and carbon isotopes of endogenic carbonate in the form of Characean algae (*Chara* sp.) calcite encrustations at Marcella Lake to provide more detailed information on the moisture balance history of the southwest Yukon. Marcella Lake is small and hydrologically closed. Water loss is primarily by evaporation and oxygen isotope ratios of preserved *Chara* encrustations document changes in the oxygen isotope ratios of lake water caused by evaporation. The sampling resolution and analytical precision of the geochemical data are of sufficient quality to document changes at 50- to 200- year resolution back to ~4500 cal BP

2. Paleoclimatic application of Marcella Lake Oxygen Isotopes

Marcella Lake is a terminal hydrologically closed lake with a well-defined watershed that is small relative to the lake's surface area. In terminal lakes, the preferential evaporation of light ^{16}O-water leaves remaining lake water ^{18}O-enriched (Craig and Gordon, 1965; Gonfiantini, 1986). However, lake-water oxygen isotope ratios may also be affected by changes in isotopic composition of input water, including catchment runoff, groundwater and precipitation falling directly into the lake (Kendall and Caldwell, 1998). These effects are relatively small for evaporation-sensitive lakes, but they may be the dominant influence on lake-water $\delta^{18}O$ in hydrologically open lakes with large catchment-to-surface-area ratios. In such systems, evaporation processes are typically less significant because lake-water residence times are shorter (e.g., von Grafenstein et al., 2001; Anderson et al., 2005a). Although Marcella Lake water is dominantly controlled by evaporation, longer-term oxygen isotope variations of input waters could be important. We can account for these effects by utilizing our reconstruction of regional mean annual precipitation, $\delta^{18}O_p$, from endogenic carbonate (bulk marl) in Jellybean Lake, located ~75 km northwest of Marcella Lake (Fig. 1; Anderson et al., 2005a). The two records have comparable age control and temporal resolution and it is likely that $\delta^{18}O_p$ has been similar at both lakes.

The moisture balance history of evaporation sensitive lakes can be determined from oxygen isotope ratios of endogenic carbonate (e.g., Talbot, 1990; Hammerlund et al., 2003; Anderson and Leng, 2004). This study is based on analyses of calcite encrustations on *Chara* stems. *Chara* provide a locus and kinetic advantage for calcite precipitation as a 1:1 byproduct of photosynthesis (e.g., bio-induced calcification; McConnaughey et al., 1994). McConnaughey (1991) showed that calcite encrustation is beneficial (by providing structural support and facilitating proton and CO_2 generation), but not essential for *Chara* photosynthesis. *Chara* calcite records the oxygen isotope composition of lake water provided there is isotopic equilibrium. Previous studies of modern endogenic carbonate show that *Chara* oxygen isotope values can be ~1.5‰ more negative than estimated equilibrium values in eutrophic lakes undergoing rapid photosynthesis (Huon and Mojon, 1994; Fronval et al., 1995; Andrews et al., 2004). This is not the case in oligotrophic sub-Arctic lakes with limited growing seasons and low biological productivity. Others report that modern *Chara* oxygen isotope ratios contain reliable environmental information (Colleta et al., 2001). Numerous paleoclimatic studies utilizing *Chara* from temperate and high latitude lakes indicate that they accurately record the Younger Dryas, Pre-Boreal oscillation, post-glacial warming, Neoglacial cooling and the Little Ice Age (Drummond et al., 1995; Yu and Eicher, 1998; von Grafenstein et al., 2001; Anderson et al., 2001; Hammerlund et al., 2003). Here we show that living *Chara* in Marcella Lake, and other lakes in the Yukon, are typically within 0.5‰ of equilibrium values. During the past, Marcella Lake *Chara* calcite was probably in equilibrium because eutrophication is extremely unlikely.

3. Field Area

Marcella Lake (60.07 °N, 133.81 °W, 697 a.s.l.) and Jellybean Lake (60.35 °N, 134.80 °W, 730 m a.s.l.) are located within the interior Yukon Plateau physiographic region (Fig. 1). A detailed site description of Marcella Lake including limnologic conditions, modern sedimentation patterns, sediment core lithology and lake level are in Anderson et al. (2005b). Cwynar (1988) produced a late-Quaternary pollen record for Marcella Lake (referred to as Kettlehole Pond). The lake has a small, well-defined watershed (0.8 km^2), is up to 9.7-m deep and has a surface area of 0.4 km^2. Surface inflow is limited to surface run-off during rain events in the surrounding watershed. Surface outflow is restricted to evaporation. Sub-surface outflow is unknown but probably relatively low compared to evaporation as will be discussed. An active sub-aquatic spring feeds the lake in a shallow bay on the southeast edge near a large area of Charophyte vegetation. *Chara* are nearly absent from the rest of the shoreline. Descriptions of Jellybean Lake and its sediment core lithology, oxygen isotope results and interpretation are in Anderson et al. (2005a).

Meteorological data from Whitehorse and Teslin document mean annual precipitation of ~260 mm/yr (Wahl et al., 1987). Monthly precipitation maximums occur between June and September (Fig. 2). July mean temperatures are between 10 and 15 °C and mean annual temperatures are between −2 and 0 °C (Environment Canada, 2003). Regional lake-ice break-up occurs between April and May and freeze-up typically occurs during October or November. Summer (May-September) mean annual afternoon relative humidity ranges between 45% and 50%; mean annual relative humidity ranges between 60 and 65% (Environment Canada 2003; Fig. 2). Three years of continuous monthly oxygen and hydrogen isotope measurements of precipitation at Whitehorse (1962–1964) show $\delta^{18}O_p$ varies seasonally from −24.6‰ to −16.8‰ (Fig. 2; IAEA/WMO, 2002). More ^{18}O-enriched precipitation occurs during the summer months. Mean summer $\delta^{18}O$ and δ^2H values (May-September) between 1961 and

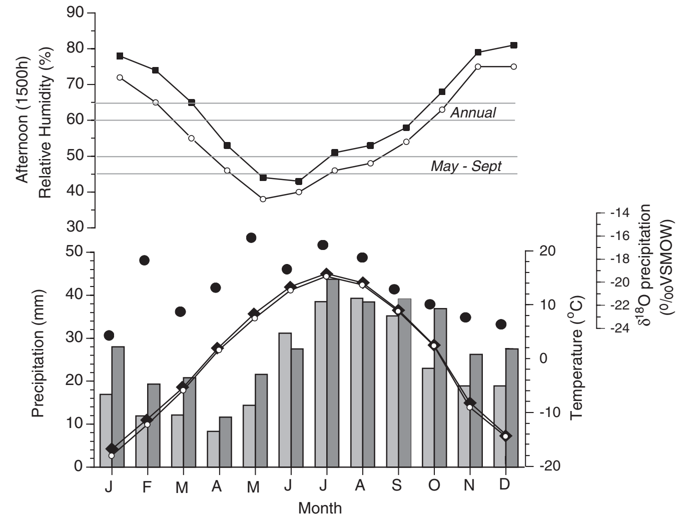

Fig. 2. Afternoon (15:00 hr) relative humidity observed at Whitehorse (open circles) and Teslin (squares). Summer humidity (May through September, morning and afternoon) at both locations ranges between 45 and 50% and the annual range is between 60 and 63% (horizontal lines). The lower panel shows mean monthly precipitation and temperature at Whitehorse (light vertical bars, open circles) and Teslin (dark vertical bars, diamonds), over the period 1944–1990 (Environment Canada, 2003). Monthly mean oxygen isotope ratios of precipitation (filled circles) were measured at Whitehorse between 1962 and 1964 (IAEA/WMO, 2002).

1965 were −18.3‰ and −142.8‰, respectively. Mean annual values between 1962 and 1964 were −20.4‰ and −160.1‰, respectively. Marcella Lake surface water $\delta^{18}O$ and δ^2H values in 2000 were −8.0‰ and −106‰, respectively. In 2002 they were −7.8‰ and −105.5‰, respectively (Anderson et al., 2005a).

4. Methods

The oxygen isotope record from Marcella Lake presented here is derived from a suite of sediment cores 156, 143 and 200-cm long, retrieved from 457, 451 and 430-cm water depth, respectively. The coring location is situated 3-m offshore from the edge of the Charophyte-dominated carbonate platform that gently dips toward the deepest area of the lake (Anderson et al., 2005b). The three cores were correlated using lithostratigraphy and magnetic susceptibility to produce a composite-core sediment stratigraphy labeled core C/E (Anderson, 2005). A detailed core description of C/E (and other cores), including bulk sedimentary properties and radiocarbon ages, was presented in Anderson et al. (2005b). Core C/E was retrieved from a floating platform in July 2000 and 2002 using a modified piston corer with a polycarbonate barrel designed for collection of undisturbed sediment–water interface cores and a Livingstone square rod piston corer for recovery of deeper sections of the record (e.g., Glew et al., 2001).

Water samples for major anion and cation analyses were collected from Marcella Lake, Jellybean Lake and six other nearby lakes in July 2000. Surface water for cation and anion chemistry were collected in 30-ml HDLP Nalgene bottles and stored in dark cool conditions. Alkalinity was determined by titration in the laboratory. Cation and anion concentrations were determined by ion chromatography in $mg\,L^{-1}$. Physical water-column measurements included temperature, pH, conductivity and dissolved oxygen using a Hydrolab Surveyor-4 and Datasonde-4 multi-probe. Dissolved carbon dioxide (pCO_2) in surface lake water was determined by applying Henry's Law to samples of ambient air and samples of CO_2 gas collected in a head space of known volume from a container of equilibrated lake water (Plummer and Busenberg, 1982). Near surface water samples for isotope analyses were taken from near-shore areas or the middle of each lake and filtered (0.45 μm) into 30-ml HDLP Nalgene bottles. Bottles were rinsed with lake water before sample collection and sealed to avoid air bubbles. Water samples were prepared for oxygen and hydrogen isotope ratios by automated constant temperature equilibration with CO_2 and automated H/D preparation systems, respectively.

Bulk sediment samples were taken from core C/E for isotope analyses at 0.5-cm increments for the uppermost 16.5 cm (32 field-extruded samples; Glew, 1988; Glew et al., 2001), at 1-cm increments from 16.5-cm depth to the White River Ash at 64-cm depth, and at 2-cm increments from 64- to 144-cm depth for a total of 121 samples. The bulk sediment carbonate fraction (60–80% by weight) is composed of *Chara* stem encrustations, ostracodes, gastropod and mollusk shells fragments within a fine-grained carbonate matrix. Smear-slide analysis indicates that carbonate particles in the bulk marl were difficult to distinguish from small fragments of the aforementioned components. To evaluate the paleoclimatic utility of the carbonate components, isotope analyses were conducted on *Chara* encrustations, ostracodes, gastropod and mollusk shell fragments and the <125-μm fraction of marl sediment from selected intervals of the core. The bulk marl isotope ratios strongly suggested the material was a mixture of the other materials. *Chara* were present in abundance throughout the sediment core, while the ostracode, gastropod and mollusks were sporadic. Thus, we determined that for this study *Chara* encrustations contained the most reliable and continuous source of oxygen isotope information.

The bulk sediment samples were wet sieved through nested screens (63, 125, 250-μm), collected separately and freeze dried. At least five individual *Chara* stem encrustations (~1–3 mm each in length) were picked from the dried fractions, examined for purity, homogenized and sub-sampled for CO_2 extraction by a Kiel automated device for isotope ratio mass spectrometry on a Finnigan Delta XL mass ratio spectrometer. Modern Charophyte plants were also sampled, dried in the field and subsequently freeze-dried. Calcite encrustations were sampled from dried plants, examined for purity, homogenized and sub-sampled for CO_2 extraction and isotope ratio mass spectrometry. All isotope results are reported as δ-values, representing deviations in per mil (‰) from Vienna Peedee Belemnite (VPDB) or standard mean ocean water (VSMOW) such that $\delta_{\text{sample}} = ([R_{\text{sample}}/R_{\text{standard}}]-1)\times 1000$ where $R = {}^2H/{}^1H$, $^{18}O/^{16}O$ or $^{13}C/^{12}C$ in sample and standard, respectively. Analytical uncertainties are within ± 0.5‰ and ± 0.05‰ for water hydrogen and oxygen, respectively. Duplicate analyses were carried out on select samples and individual *Chara* encrustations to assess variations. *Chara* sample reproducibility is approximately ± 0.5‰ for oxygen and carbon.

The chronology for composite core C/E is based on ^{210}Pb, ^{137}Cs, and AMS ^{14}C measurements on terrestrial macrofossils (Anderson et al., 2005b). Both measured radiocarbon and calibrated ages are reported here (median intercept and 1-sigma range), however only calibrated radiocarbon ages are reported in the discussion. Radiocarbon ages were calibrated using CALIB 4.1 following the methods of Stuiver et al. (1998). Marcella Lake ^{210}Pb and ^{137}Cs activity were measured at 0.5-cm intervals on the uppermost 32 field-extruded samples (0–16.5 cm; Appleby, 2001). Due to very low ^{210}Pb activities and a slightly irregular ^{137}C peak, only the surface age (2002) and the horizon where ^{210}Pb-excess is initially observed at 16.5-cm depth (110 cal BP) were used in the age model. Chronostratigraphic data from intervals of the cores that contained *Chara* analyzed for this study are shown in Table 1. Linear interpolation between dated levels was used to determine ages for isotope samples. The chronology indicates a fairly uniform sedimentation rate, ~0.03 to 0.05 mm/y. Based on sedimentation rates and sample thickness, the oxygen and carbon isotope samples integrate 5–10 years in the uppermost 16.5-cm, and 10–30 years for the remainder of the core. Sampling resolution decreases down core from 5–100 years depending on the sampling interval outlined above.

5. Results

5.1. Evaporative enrichment of Marcella Lake

Marcella Lake water is enriched in ^{18}O and ^{2}H (~14‰ and ~59‰) compared to estimates of unmodified mean annual precipitation and Jellybean Lake water (Anderson et al., 2005a). In addition to lake water oxygen and hydrogen isotope enrichment, the effects of evaporation on lake water can be independently documented by analyses of major ion concentration and limnophysical properties. We use Principal Component Analyses (PCA; MSVP software) and compare seven lakes, including Marcella and Jellybean Lakes, with three springs from the central and southern Yukon (e.g., Pienitz et al., 1997; Fig. 3).

The first axis on a plot of major ions accounts for 64.2% of the variance (Fig. 3a). High alkalinity and ion concentrations correspond with hydrologically closed lakes on the right side of the axis. Summer evaporation and prolonged lake-water residence times (~multiple years) result in elevated dissolved ion concentrations, especially

Table 1
Marcella Lake core C/E chronostratigraphic data

Core Depth (cm)	Material	Lab #	Measured age (^{14}C yr BP)	Median calibrated age (cal BP)[a]	1-Sigma range (cal BP)
0	^{210}Pb			AD 2002[b]	
16.5	^{210}Pb			AD 110[b]	
41	Wood	OS-38713	930±25	830	791–915
44	Wood	CAMS-96826	980±60	925	793–951
64	White River Ash			1150	1014–1256[c]
133	Wood	OS-38714	4080±35	4545	4451–4781

[a]Median intercept of calibrated radiocarbon ages.
[b]Sediment–water interface and ^{210}Pb-dating horizon in years AD.
[c]2-sigma range from Clague et al. (1995).

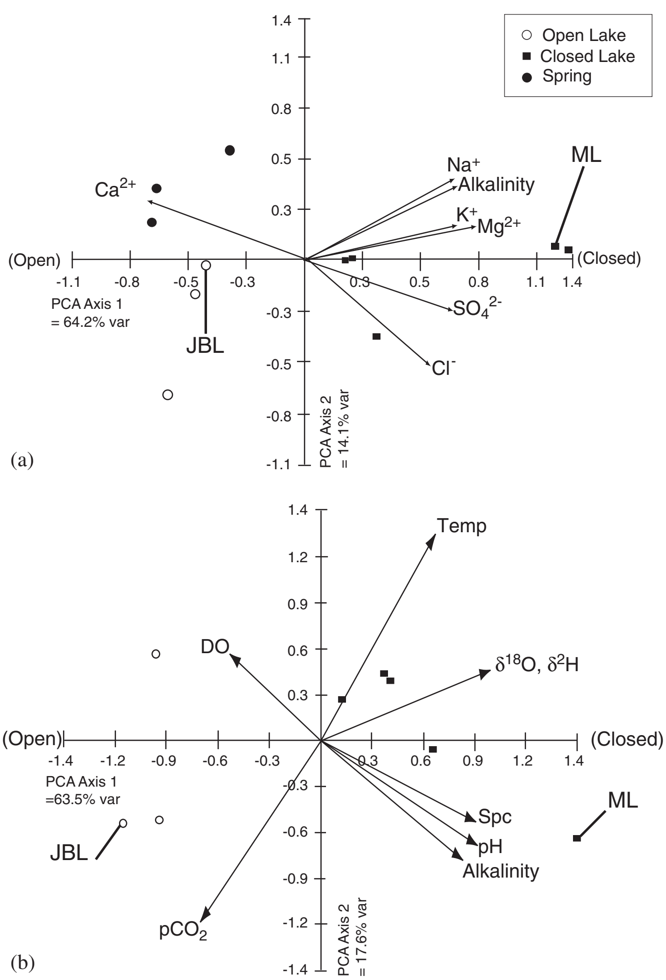

Fig. 3. PCA bi-plots of (a) major ions and (b) physiolimnological variables of water sampled from eight Yukon lakes and three springs, including Jellybean Lake (indicated by a line and JBL) and Marcella Lake (indicated by a line and ML). On the first axis of both plots, vectors on the left side group with hydrologically open lakes and springs. Vectors on the right group with hydrologically closed lakes.

for conservative species that are not consumed by endogenic calcification. On the left side of axis one, high calcium ion concentrations plot with spring-water. Groundwater transport through extensive carbonate-rich tills and outwash deposits result in elevated calcium. Similar distinctions between open and closed systems are observed in a plot of dissolved gas, oxygen and hydrogen isotopes, conductivity, pH and alkalinity (Fig. 3b). The first axis accounts for 63.5% of the variance. Higher temperature, $\delta^{18}O$, $\delta^{2}H$, conductivity, alkalinity and pH plot with hydrologically closed lakes on the right side of the axis (longer residence times). On the left side, higher dissolved gases plot with springs and hydrologically open lakes (shorter residence times).

5.2. Living Chara encrustations

Table 2 shows oxygen isotope values of calcite encrustations from living *Chara* in Marcella Lake and three other southwest Yukon lakes along with contemporaneous lake water oxygen isotope ratios and lake water temperature. Using the calcite equilibrium equation from Friedman and O'Neil (1977), predicted calcite equilibrium oxygen isotope values can be compared to measured values. In three of the four lakes including Marcella Lake, where lake-water $\delta^{18}O$ values range from −19.9‰ to −8.21‰, differences between measured and predicted calcite equilibrium values are <0.5‰. One site, Jackfish Lake, indicated the largest difference of 1.1‰.

5.3. Sediment oxygen and carbon isotopes

Oxygen isotope values of *Chara* calcite encrustations ($\delta^{18}O_{Chara}$) range between −13.5 and −7.5‰ (Fig. 4). Inferred lake-water $\delta^{18}O$, using a lake-water temperature of 16.0 °C for calcite precipitation, is 5–11‰ more ^{18}O-enriched than $\delta^{18}O_p$ (Fig. 2). $\delta^{18}O_{Chara}$ values below 70-cm depth are more variable and shifts as large as 3‰ occur over 2-cm intervals. In general, however, $\delta^{18}O_{Chara}$ are more negative than modern values. Between 144 and 70-cm depth, values vary near −11‰ while above 24 cm, they range between −9.5 and −8‰ and tend to increase towards the core top.

Carbon isotope values of Chara calcite encrustations ($\delta^{13}C_{Chara}$) range between 0‰ and 7‰. Shifts as large as ~4.5‰ occur over 2–6-cm intervals. $\delta^{13}C_{Chara}$ values in the

Table 2
Comparison of measured and predicted equilibrium $\delta^{18}O$ values for bio-induced carbonate in Yukon Lakes

Site Name	Lat/Long	Carbonate Sample Description	Measured $\delta^{18}O_{Calcite}$ (‰VPDB)	Measured $\delta^{13}C_{Calcite}$ (‰VPDB)	Measured $\delta^{18}O_{Water}$ (‰VSMOW)	Lake water temperature[a] (°C)	Predicted[b] Equilibrium $\delta^{18}O_{Calcite}$ (‰VPDB)	$\Delta\ \delta^{18}O_{Calcite}$: (measuredpredicted) (‰VPDB)
Jackfish Lake	63.02 °N, 136.47 °W	Living *Chara* from reef in lake center, <1.0-m water depth, 08/06/2000	−11.70	0.75	−10.6	17.9	−10.59	1.11
Seven-Mile Lake	62.18 °N, 136.39 °W	Living *Chara* from littoral zone, 1.5-m water depth. 08/09/2000	−10.69	2.10	−10.4	17.9	−10.75	−0.06
Waddington Pond	60.36 °N, 134.81 °W	Living *Chara* from surface sediment dredge, 1.5-m water depth. 08/01/2000	−18.41	−0.27	−18.5	16.0	−18.36	0.14
Marcella Lake	60.07 °N, 133.81 °W	Living *Chara* from littoral zone, <1-m water depth. 08/03/2000	−8.21	4.68	−8.0	16.33	−8.01	0.20
Jellybean Lake	60.35 °, 134.81 °W	Surface sediment bulk marl[c] 07/30/2002	−19.9	5.15	−21.0	14.8	−20.31	0.41

[a]Measured on the date and at the location that living *Chara* (or bulk marl) and lake water was sampled.
[b]Friedman and O'Neil (1977).
[c]Living or preserved *Chara* were not found in Jellybean Lake.

lower part of the core are relatively ^{13}C-depleted (0–4.5‰). Between 130 and 98-cm depth, values are persistently more positive-than-modern, whereas between 98 and 64-cm depth they are occasionally more negative-than-modern. Above 64-cm depth values shift again to more positive-than-modern values and above 21-cm depth they are generally lower than the preceding interval.

6. Discussion

6.1. Carbon isotopes

Chara calcite carbon isotope ratios record the isotopic composition of lake-water DIC provided they are in isotopic equilibrium. DIC is, in turn, a reflection of the carbon isotope ratios of atmospheric CO_2, biological respiration within the lake and incoming groundwater (McKenzie, 1985; Dean and Stuiver, 1993). DIC within the epilimnion and hypolimnion in thermally stratified lakes evolve in isolation. Microbial respiration of ^{12}C-enriched organic matter in the hypolimnion produces relatively ^{13}C-depleted DIC underneath the thermocline while aquatic photosynthesis in the epilimnion preferentially sequesters ^{12}C-enriched DIC into organic matter, thereby progressively enriching residual DIC-$\delta^{13}C$ (McConnaughy et al., 1994). Over-turn mixes the two DIC pools and generally causes epilimnion DIC-$\delta^{13}C$ to decrease (Hodell et al., 1998).

Marcella Lake is dimictic and thermally stratified during summer, being well protected from wind mixing. However, between ~4000 and 2000 cal BP meromixis and higher lake level was interpreted from lithologic (laminations) and organic carbon isotope (^{13}C-enriched) evidence from sediment cores taken beneath the thermocline (9-m water depth; Anderson et al., 2005b). It is possible that enriched $\delta^{13}C_{Chara}$ values over longer-term periods indicate more persistent stratification and warmer summer temperatures. Therefore, higher-than-modern values of $\delta^{13}C_{Chara}$ between ~4000 and 2000 cal BP (90 and 130 cm depth; Fig. 4) above the thermocline in core C/E are consistent with meromixis. However, equally high $\delta^{13}C_{Chara}$ values periodically occur when lake levels were lower after 2000 cal BP, suggesting changes in productivity may complicate this *Chara* carbon isotope interpretation. Thus, we focus on paleoclimatic interpretations of oxygen isotopes.

6.2. Oxygen isotopes

Our results from oxygen isotope analyses of living *Chara*, lake water and major ion chemistry from a range of hydrologic settings, suggest that variation in evaporation is responsible for driving the observed changes in Marcella Lake $\delta^{18}O$ and the *Chara* calcite formed in that lake water. Over time, it is also important to consider the long-term changes in $\delta^{18}O_p$ that will also affect lake-water-$\delta^{18}O$. We account for these changes using the nearby Jellybean Lake $\delta^{18}O_{Ca}$ record interpreted to reflect changes

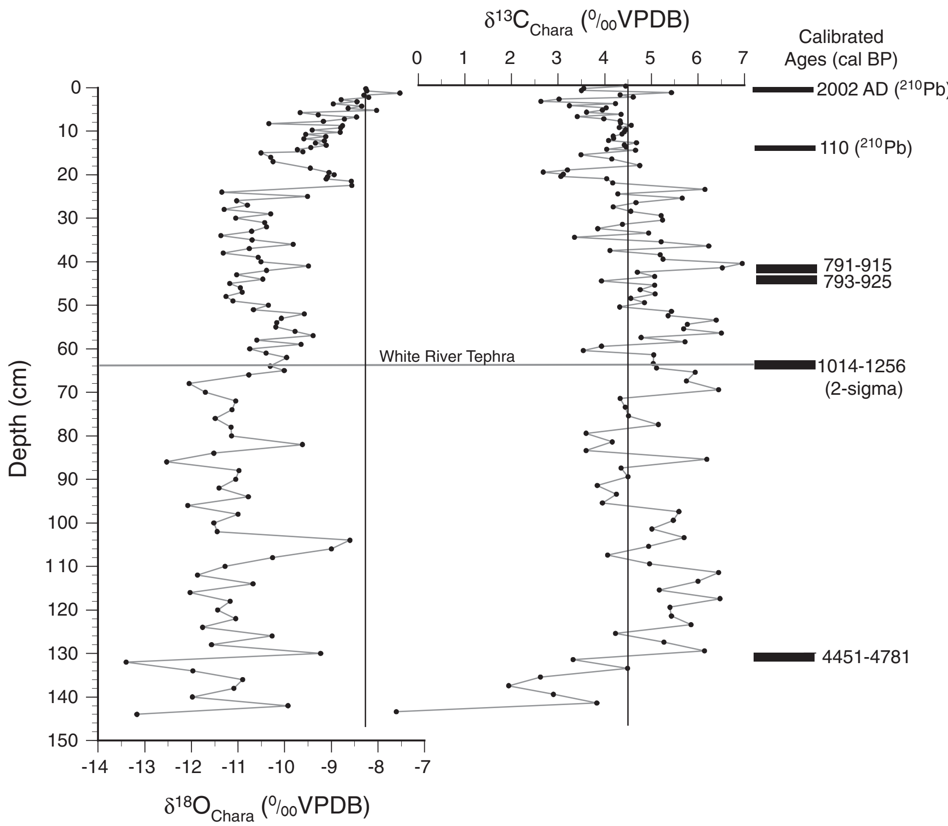

Fig. 4. Marcella Lake core C/E $\delta^{18}O_{Chara}$ and $\delta^{13}C_{Chara}$ data plotted on a depth scale. The vertical lines indicate the value of the uppermost, present day, sample. The black bars on the right indicate depths of ^{210}Pb and radiocarbon ages (Table 1). The horizontal line at 64-cm depth is the stratigraphic position of the White River tephra (Clague et al., 1995).

in $\delta^{18}O_p$ driven by AL intensity and/or position (Anderson et al., 2005a). Temperature fractionations between calcite and lake water were considered and are thought to be minor (~0.25‰/°C).

For times in the past, the difference between Marcella-$\delta^{18}O_{Chara}$ and Jellybean-$\delta^{18}O_{Ca}$ represents ^{18}O-enrichment (‰) of Marcella Lake caused by changes in evaporation. This calculation required two steps. First, the oxygen isotope stratigraphy from each lake was converted into three smoothed time-series at 50, 100 and 200-year intervals to examine multi-decadal and longer-term variations (Figs. 5a and b). Second, the Jellybean-$\delta^{18}O_{Ca}$ time-series were subtracted from the Marcella-$\delta^{18}O_{Chara}$ time-series to produce a third, $\Delta\delta$ (Fig. 5c). Variability of evaporation-insensitive Jellybean-$\delta^{18}O_{Ca}$ is relatively small (1.5–2‰) compared to Marcella Lake (4.0–5.0‰), but there are intervals where the $\delta^{18}O_p$ correction results in distinguishable effects on long-term trends of Marcella-$\delta^{18}O_{Chara}$ (note arrows in Fig. 5a and c). The smoothing procedure was done to eliminate problems due to temporal mismatches between individual samples from the two cores but given the nature of the trends does not significantly effect the uncertainty regarding timing of prominent shifts or long-term trends. We estimate that Marcella core C/E isotope sample age uncertainties increase down core from ± 20 yr in the upper section (between -50 and 1200 cal BP), to ± 50 to 300 yr for ages older than the White River tephra (~1200 cal BP). Jellybean Lake has more constant sedimentation rates and an additional radiocarbon age between the White River tephra and 4500 cal BP so that isotope sample age uncertainties are smaller and increase less down core (Anderson et al., 2005a).

6.3. Model estimates of humidity

Marcella Lake's permanently closed hydrologic status during the past and the relatively large $\Delta\delta$ shifts (~3‰) support a more quantitative description of changing moisture balance (e.g. Wolfe et al., 2001). Gat (1995) described a terminal lake basin at isotopic steady state by the equation: $\Delta\delta = (1-h)(\varepsilon^* + C_k)$ where h is humidity and ε^* is an equilibrium fractionation factor derived from the isotopic composition of input water and lake water temperature. C_k is a constant kinetic fractionation factor and has a value of 15 (Gonfiantini, 1986). Model input values include (1) -22‰ for precipitation input (IAEA/WMO, 2002; Anderson et al., 2005b), (2) 16 °C for lake water temperature and the assumption that there is isotopic equilibrium between atmospheric vapor and precipitation. Thus, humidity is related to $\Delta\delta$ by the following equation:

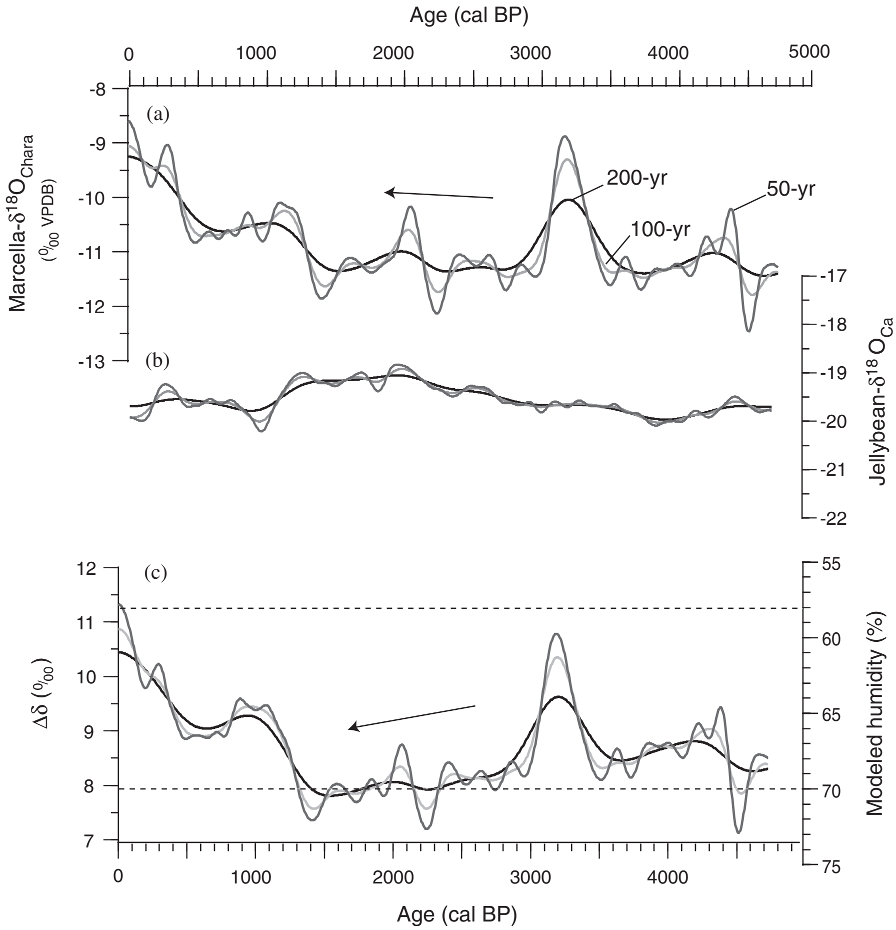

Fig. 5. The Marcella-$\delta^{18}O_{Chara}$ data (Fig. 4) (a) and Jellybean-$\delta^{18}O_{Ca}$ (Anderson et al., 2005a) (b) were smoothed using 50, 100 and 200-yr time intervals and plotted versus calibrated age. The difference between (a) and (b) is (c) $\Delta\delta$, isotopic enrichment due to evaporation and modeled relative humidity (%). Two arrows indicate the difference in trends between (a) and (c) and are discussed in the text. Horizontal dashed lines mark low and high $\Delta\delta$ values (8‰ and 11.4‰) and corresponding modeled humidity estimates (58 and 70%) for the record.

$h = (\Delta\delta - 26.58)/-26.57$, and h (%) is shown on the right of the plot of $\Delta\delta$ in Fig. 5c. The modeled mean humidity estimate for the last 100 years (~58%) is close to the measured mean annual relative humidity (60–63%), and to some extent validates the model. If the model is accurate, then humidity between 3000 and 1200 cal BP was possibly >10% greater than today (70%). However, uncertainties such as the effects of wind on evaporation and lake mixing lead us to favor using qualitative trends in $\Delta\delta$ for paleoclimatic interpretations.

7. Late Holocene Paleoclimate

Oxygen isotope ratios from Marcella Lake provide effective moisture information at higher temporal resolution than previous work in this region. It is important to recognize that changes in Marcella-$\Delta\delta$ reflect changes in the lake's moisture balance. For example, an increase in $\Delta\delta$ could be caused by either increased evaporation or less precipitation relative to evaporation (i.e., decreasing effective moisture). Keeping this consideration in mind, we suggest the following temporal patterns. Greater-than-modern effective moisture generally occurred between ~3000 and 1200 cal BP followed by decreasing effective moisture to the present day (Fig. 6). This reconstruction is consistent with the late Holocene trends of a diatom-inferred salinity profile in the central Yukon indicating persistently dry conditions after ~1200–1000 cal BP (Pienitz et al., 2000).

This isotope-based reconstruction is also broadly consistent with our previous sedimentologically- based lake-level reconstruction (Anderson et al., 2005b), but it is important to note that the two records are not strictly comparable. While both records show some similar trends, they do not precisely match because there are differences in resolution and the environmental factors being recorded. For instance, isotopic enrichment briefly shifts towards wetter conditions ~4500 cal BP before returning to near modern values and a ~400 year dry period between ~3500 and 3100 cal BP. The lake level reconstruction indicates a rising trend during the period of isotopic depletion, but subsequently indicates higher than modern lake

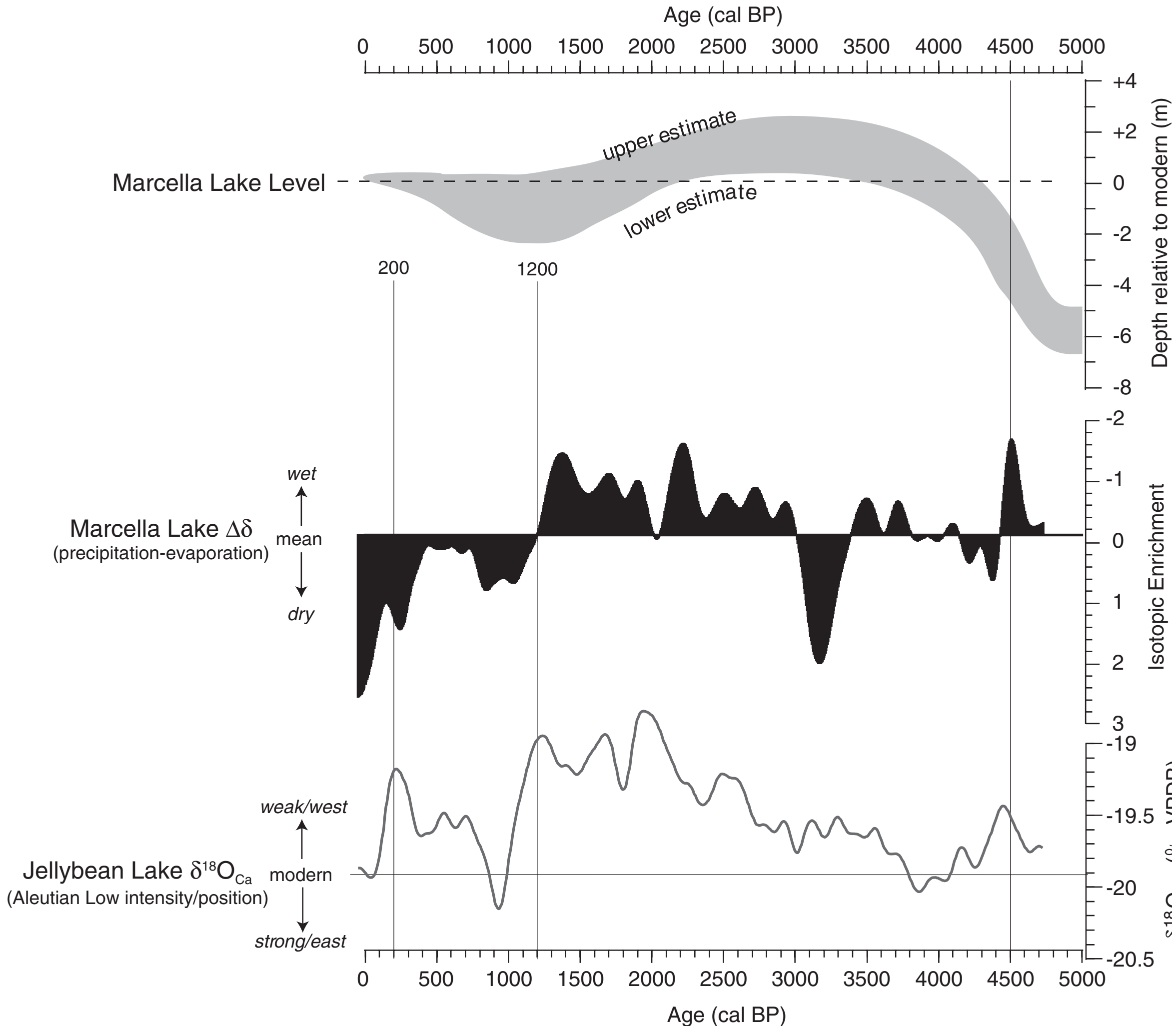

Fig. 6. Marcella lake level estimates from Anderson et al. (2005b) shown with isotopic enrichment caused by evaporation expressed as a 50-yr smoothed Δδ anomaly time series (difference from the mean for the record) (top), and Jellybean-$\delta^{18}O_{Ca}$ expressed as 50-yr smoothed time-series (bottom) since 5000 cal BP. The Marcella Lake isotope record is interpreted in terms of southwest Yukon low elevation interior moisture balance while the Jellybean Lake record is interpreted in terms of the strength and position (weak/west or strong/east) of the Aleutian Low over the Gulf of Alaska (Anderson et al., 2005a).

levels throughout this time period (Fig. 6). The isotopic trends indicate wetter than present conditions prior to ~1200 cal BP followed by increasing aridity to modern. However, the lake level reconstruction indicated lower levels after ~2000 cal B.P. and was unable to distinguish between a continued lowering, or alternatively, lowering to below modern followed by a rise (indicated by "upper" and "lower" estimates on Fig. 6). Closed basin lake level and isotope modeling studies indicate that water depth fluctuations may not define the magnitude or sign of lake water oxygen isotope composition (Ricketts and Johnson, 1996) depending on the factors causing the changes, and the exact history of rates of change in these factors. Instead, rates of change of input (I) and evaporation (E) were found to be the primary cause of isotopic variations. Following this line of reasoning, we view the Marcella lake-level reconstruction as a millennial-scale record of moisture balance and/or water table depth whereas the isotope-based reconstruction is a continuous record of $\Delta I/\Delta E$ information driven by factors including humidity, temperature and wind speed in addition to lake volume and surface area (Ricketts and Johnson, 1996; Ricketts and Anderson, 1998).

The marked changes in inferred effective moisture at Marcella Lake are related to periods of Neoglacial activity on the north and east flanks of the St. Elias Mountains (Denton and Karlen, 1977; Rampton, 1978; Calkin et al., 2001). The earliest dates of late Holocene advances in those locations are ~2800 cal BP. During this period, snow accumulation on the St. Elias ice fields appears to have sufficiently increased to cause north and east valley glacier advances at the same time that Marcella Lake levels were higher and oxygen isotope ratios were less ^{18}O-enriched (Fig. 6). Such a pattern suggests colder and/or wetter conditions on the coast and at lower elevations in the rain shadow region. However, glacier advances on the north and east side of the St. Elias Range and White Pass episodically occurred ~1200 cal BP and since 400 cal BP (Denton and Karlen, 1977; Lamoreaux and Cockburn, 2005) at the same time that Marcella Lake indicates low elevation areas were becoming increasingly dry. This pattern suggests that wet and/or cool conditions in the mountains occurred when the lee side of the rain shadow was drier. In summary, we hypothesize that two late Holocene climatic patterns emerge from this comparison: (1) simultaneously wet conditions at high, coastal-mountain elevations and low leeward elevations in the interior or (2) wet conditions at high, coastal-mountain elevations coinciding with dry conditions at low leeward elevations in the interior.

In general an intensified/eastward Aleutian Low is thought to cause stronger meridional storm trajectories into the ~3000-m high northwest-to-southeast trending St. Elias and Coast Mountain barrier. Meteorological observations between 1976 and 1988 A.D. showed that an eastward/intensified AL lead to warm moist air advection from the south into the northwest Pacific coast and caused increased coastal precipitation (Cayan and Peterson, 1989; Mantua et al., 1997; Trenberth and Hurrell, 1994). If stronger storms lead to intensified down-slope leeward winds, then the effect may be even drier conditions in the rain shadow (Streten, 1974; Wahl et al., 1987). Such a scenario suggests that meridional circulation predominated from 1200 cal BP to the present, when Jellybean Lake-$\delta^{18}O_{Ca}$ indicates a generally stronger/eastward Aleutian Low and conditions were drier at Marcella Lake (Fig. 6). Further, two relatively abrupt increases in the strength of this circulation pattern are suggested at 1200 and 300 cal BP.

In contrast, a weaker/westward Aleutian Low is associated with less intense and more zonal airflow that tends to allow cool and moist low-level airmasses that originated over the Bering Sea to infiltrate the northwest-to-southeast trending valleys in the southwest Yukon (Streten, 1974). Although airmasses could dry by the continental effect, a relative increase in moisture could reach the Yukon interior than from those airmasses that are strongly forced up and over the mountains. We suggest that such a zonal scenario was more dominant between 3000 and 1200 cal BP, when Jellybean-$\delta^{18}O_{Ca}$ indicates a weaker/westward Aleutian Low and it was wetter at Marcella Lake (Fig. 6). The Aleutian Low today is strongest during the winter and diminishes during the summer. Observations of the Mount Logan accumulation record indicate that only winters with high snow accumulation have a strong connection with AL circulation (Rupper et al., 2004). However, a persistent low in the western Gulf of Alaska is the most frequent weather pattern affecting the southwest Yukon during all seasons (Wahl et al., 1987; Mock et al., 1998), and it may be that the multi-decade-to-century circulation rearrangements discussed here would have affected climate throughout the year.

Similar spatial climatic heterogeneity was observed in the Kenai Mountains on the southern coast of Alaska (Wiles et al., 1994). Like the southwest Yukon, the AL dominates the climate of the Kenai Mountains. Land-terminating glaciers on the drier western side of the northeast to southwest trending mountain range retreated from their Little Ice Age maxima two centuries earlier than the tidewater glaciers on the wetter coastal side. Wiles et al. (1994) suggested that coastal advances coupled with leeward retreats might have been a response to greater winter precipitation coupled with warming. This suggestion is consistent with AL intensification and/or eastward shifts indicated by the response by Jellybean Lake and the increasingly dry conditions at Marcella Lake since ~1700 A.D (Fig. 6).

The prominent AL intensification at ~1200 cal BP was previously observed to be coincident with increasing North Pacific salmon abundance and diminished intensity of the Beaufort Gyre in the western Arctic basin (Anderson et al., 2005a; Finney et al., 2002; Dyke and Savelle, 2000). The oxygen isotope record presented here suggests that this shift in the mean AL state also led to increasing aridity in the interior valleys within the rain shadow of the St. Elias massif. These results connect prominent atmospheric circulation variations over the Gulf of Alaska to moisture balance variability in low elevation interior valleys of the southwest Yukon and document the region's spatially heterogeneous response to atmospheric circulation change.

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