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PALEOCLIMATIC RECONSTRUCTION IN THE BOLIVIAN ANDES FROM OXYGEN ISOTOPE ANALYSIS OF LAKE SEDIMENT CELLULOSE

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Abstract. Cellulose-inferred lake water $\delta^{18}O$ ($\delta^{18}O_{lw}$) records from Lago Potosi, a seasonally-closed lake in a watershed that is not currently glaciated, and Lago Taypi Chaka Kkota, an overflowing lake in a glaciated watershed, provide the basis for late Pleistocene and Holocene paleoclimatic reconstruction in the Bolivian Andes. Deconvolution of the histories of changing evaporative isotopic enrichment from source water $\delta^{18}O$ in the lake sediment records is constrained by comparison to the Sajama ice core oxygen isotope profile. At Lago Potosi, the $\delta^{18}O_{lw}$ record appears to be dominantly controlled by evaporative ^{18}O-enrichment, reflecting shifts in local effective moisture. Using an isotope-mass balance model, a preliminary quantitative reconstruction of summer relative humidity spanning the past 11,500 cal yr is derived from the Lago Potosi $\delta^{18}O_{lw}$ record. Results indicate that the late Pleistocene was moist with summer relative humidity values estimated at 10-20% greater than present. Increasing aridity developed in the early Holocene with maximum prolonged dryness spanning 7500 to 6000 cal yr BP at Lago Potosi, an interval characterized by summer relative humidity values that may have been 20% lower than present. Highly variable but dominantly arid conditions persist in the mid- to late Holocene, with average summer relative humidity values estimated at 15% below present, which then increase to about 10-20% greater than present by 2000 cal yr BP. Slightly more arid conditions characterize the last millennium with summer relative humidity values ranging from 5-10% lower than present. Similar long-term variations are evident in the Lago Taypi Chaka Kkota $\delta^{18}O_{lw}$ profile, except during the early Holocene when lake water evaporative ^{18}O-enrichment in response to low relative humidity appears to have been offset by enhanced inflow from ^{18}O-depleted snowmelt or groundwater from the large catchment. Close correspondence occurs between the isotope-inferred paleohumidity reconstruction and other paleohydrological proxies from the region.

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1. INTRODUCTION

Large moisture fluctuations are dominant features of late Pleistocene and Holocene climate on the Bolivian Altiplano. Wetter conditions compared to the present characterized the late Pleistocene and early Holocene as indicated by pluvial lake high stands spanning from prior to 19,000 to about 14,000 and 10,700 to 9500 cal yr BP [1-2]. Marked aridity, however, is believed to have prevailed during most of the Holocene from about 9500 to 3900 cal yr BP, based mainly on studies of sediment cores from Lake Titicaca [3-7]. New paleo-water level estimates suggest that Lake Titicaca experienced lowest lake levels between 8000 and 5500 cal yr BP [7]. Desiccation may have been widespread at this time in the shallower southern basin of Lake Titicaca and likely in many other ephemeral lakes resulting in discontinuous sedimentary records, which has hampered Holocene paleoclimatic reconstruction in this region. In order to generate a continuous quantitative record of climate change for this region, we have combined a regional lake water sampling survey to assess modern isotope systematics in basins of varying hydrological settings, cellulose-inferred lake water oxygen isotope profiles from two small alpine basins (Lago Taypi Chaka Kkota and Lago Potosi), and an ice core record of precipitation $\delta^{18}O$ from Sajama [8].

2. CLIMATIC AND HYDROLOGICAL SETTING

Precipitation in the Altiplano region is strongly seasonal with about 75% of the annual total occurring during the austral summer months (December to March) due to convective activity associated with the Bolivian High. Latitudinal gradients in precipitation and relative humidity are evident between Lago Taypi Chaka Kkota (LTCK) and Lago Potosi (LP). At El Alto, La Paz (4105 m asl; 16°30'S; 68°12'W) in the northern Altiplano near LTCK, mean annual precipitation is 564 mm (Dec-Mar: 388 mm) and mean annual relative humidity is 60% (Dec-Mar: 70%). Further south at the town of Potosi (4640 m asl; 19°38'S; 65°41'W) near LP, mean annual precipitation is 301.5 mm (Dec-Mar: 226 mm) and mean annual relative humidity is 38% (Dec-Mar: 50%) [9].

LTCK and LP have significantly different hydrological settings. The LTCK watershed (84 km^2) is located at 16°13' S, 68°21' W in the Rio Palcoco Valley on the western slope of the Cordillera Real. Situated at 4300 m asl in elevation, LTCK is 1.3 km^2 in area and 12 m deep. Through-flow at LTCK is maintained throughout the year by drainage from lakes upstream, which are presently fed by several small alpine glaciers. The LP watershed (3.9 km^2) is located at 19°38' S, 65°41' W in the Cordillera Chichas at 4640 m asl and the lake is 0.2 km^2 in area and 11 m deep. LP is a headwater lake whose watershed does not presently contain glaciers. LP was observed to form a thin ice cover at night and the lake was below its overflow level during June 1997, although outflow channels suggest the water-level reaches the overflowing stage during the summer wet season.

A regional water sampling survey spanning latitudes 13°54' to 19°38' S, conducted during the dry season of 1997, revealed that the $\delta^{18}O$ and δD composition of lake waters diverge from the Global Meteoric Water Line (GMWL) due to evaporative enrichment (Figure 1). A Regional Evaporation Line can be drawn through these data points ($\delta D = 5.1\delta^{18}O-35.5$; $R^2 = 0.97$) indicating a common atmospheric moisture source for this region. Furthermore, the extent of evaporative enrichment for a given lake was found to vary systematically in relation to the local hydrological setting. Progressively increasing offset from the GMWL was found for lakes directly receiving glacial meltwater, overflowing lakes in glaciated watersheds, overflowing lakes in non-glaciated watersheds, and seasonally-closed lakes. End-members of the hydrological spectrum in this region are well represented by the depleted isotopic composition of LTCK ($\delta^{18}O$ = -14.8‰, δD = -112‰), typical for lakes in glaciated watersheds, and the comparatively enriched isotopic composition of LP ($\delta^{18}O$ = -5.6‰, δD = -59‰), representing the group of lakes that develop hydrological closure during the dry season (Figure 1).

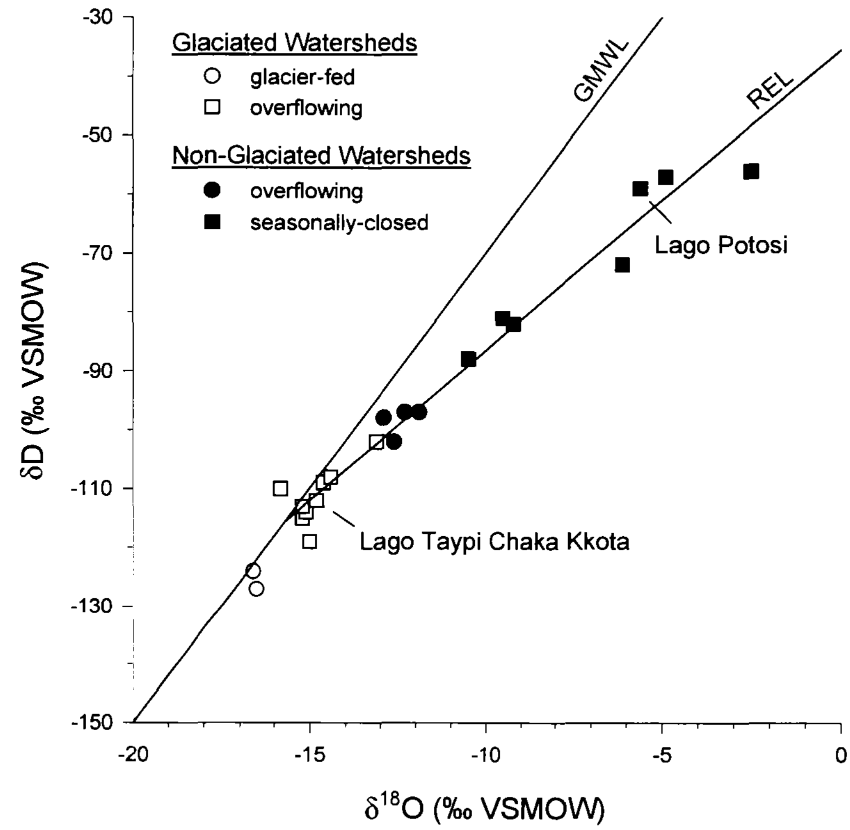

FIG.1. Isotopic composition of lake waters from the Bolivian Andes sampled in June 1997 [10]. Also shown are the Global Meteoric Water Line (GMWL: $\delta D = 8\ \delta^{18}O + 10$) and the Regional Evaporation Line (REL: $\delta D = 5.1\ \delta^{18}O - 35.5$).

3. METHODS

Lake sediment sample preparation and analysis for bulk organic elemental (C, N) and cellulose oxygen isotope composition followed methods in [11]. Cellulose oxygen isotope composition was determined using off-line nickel-tube pyrolysis to generate CO_2 for dual inlet isotope ratio mass spectrometry. All elemental and isotopic analyses were conducted at the University of Waterloo - Environmental Isotope Laboratory, Canada. Oxygen isotope results are expressed as "δ" values, representing deviations in per mil (‰) from the VSMOW standard for oxygen normalized to $\delta^{18}O_{SLAP}$ = -55.5 ‰ [12], such that $\delta_{sample} = [(R_{sample}/R_{standard})-1]*10^3$ where R is the $^{18}O/^{16}O$ ratio in the sample and standard. The $\delta^{18}O_{cell}$ values have uncertainties of ±0.5‰ based on repeated analyses of samples.

Terrestrial macrofossil material was not present in sufficient quantities for AMS ^{14}C measurements from most stratigraphic levels. Therefore, we used Isoetes macrofossils at LTCK as well as bulk sediment at LP for AMS ^{14}C measurements. The contemporary radiocarbon reservoir was assessed in two ways. In LTCK, the ^{14}C activity of live submerged macrophytes was measured and found to be 114% Modern for the year A.D. 1992, indicating that the lake reservoir effect is minimal in the LTCK system today, although it could have been a factor in the past. For LP, the contemporary radiocarbon reservoir was assessed by comparing the ^{14}C activity of paired bulk sediment and macrofossils samples from the same stratigraphic level. Results indicate there is no significant difference between the ages.

4. RESULTS AND DISCUSSION

4.1. Isotope-inferred lake paleohydrology

Cellulose-inferred $\delta^{18}O_{lw}$ records for LP and LTCK are shown in Figure 2. Interpretation of $\delta^{18}O_{lw}$ records requires identifying signals related to changes in the isotopic composition of source water, reflecting the integrated signature of surface and subsurface inflow and precipitation, from changing hydrological factors (often primarily evaporative enrichment) that may subsequently modify the isotopic content of the lake water. Deconvolution of these isotopic signals in lake sediments from this region benefit from an independent 25,000-year record of precipitation $\delta^{18}O$ ($\delta^{18}O_p$) from the Sajama ice core [8]. The ice-core oxygen isotope stratigraphy, which is also shown in Figure 2, illustrates that values at the base of this interval increased to a maximum at about 14,300 cal yr BP, interpreted to reflect climate warming [8]. Subsequent ^{18}O-depletion with low values persisting until 11,500 cal yr BP has been interpreted as a climatic reversal [8] or may be due to dilution of atmospheric precipitation with ^{18}O-depleted vapour derived from pluvial lakes on the Altiplano [10]. Values increase after 11,500 cal yr BP in response to climate warming [8] and/or draw-down of pluvial lakes and reduction in derived vapour [10], and remain at about -17±1‰ throughout the Holocene presumably reflecting constant temperature as well as moisture source and history. Notably, shifting LP and LTCK $\delta^{18}O_{lw}$ offsets from the Sajama ice core $\delta^{18}O_p$ record provides a measure of changing lake water evaporative enrichment [e.g. 16], which appears to be mainly a function of similarly changing moisture regimes at these two locations, as described below.

Although late Pleistocene $\delta^{18}O_{lw}$ data at both LP and LTCK are sparse, results are broadly consistent with regional evidence for moisture fluctuations derived from the recently revised chronology of pluvial lake level history on the southern Bolivian Altiplano [2]. Roughly 10‰ offset of LP $\delta^{18}O_{lw}$ from Sajama ice core $\delta^{18}O_p$ between 14,000 and 11,500 cal yr BP may reflect the importance of lake water evaporative enrichment, corresponding to the Ticaña arid phase [2], or may be partly in response to reduced glacial meltwater supply. Reduced LP-Sajama isotopic offset after 11,500 until 9000 cal yr BP correlates with the final, albeit less significant, pluvial lake high stand (the Coipasa high lake phase), which occurred between about 10,500 and 9500 cal yr BP [2]. Similarly, large LTCK-Sajama isotopic offset beginning prior to 12,700 to about 10,500 cal yr BP may be related to the Ticaña arid phase with subsequent reduced isotopic offset until about 9500 cal yr BP due to wetter conditions during the Coipasa event. The lake water shift to more ^{18}O-depleted values, which we presume to indicate the end of the Ticaña arid phase, appears to take place about 1000 years later at LTCK compared to LP perhaps reflecting poor chronological control in these strata, a greater hydrological threshold at LTCK, or reduced significance of this climate change in the northern Bolivian Altiplano. The latter appears to be consistent with the greater prominence of this event in stratigraphic records from the southern Bolivian Altiplano and Chilean Atacama, whereas evidence for this event in Lake Titicaca sediment records is inconclusive [see 2].

Increasing aridity during the early Holocene at LP is indicated by lake water ^{18}O-enrichment beginning after 9000 cal yr BP, broadly consistent with the paleohydrological record of Lake Titicaca, although a brief return to moist conditions is suggested by ^{18}O-depleted values at about 8000 cal yr BP. Based on the LP record, maximum mid-Holocene aridity developed between 7500 and 6000 cal yr BP. The corresponding 9000 to 6000 cal yr BP interval at LTCK, which is dominated by ^{18}O-depleted values, is most likely a result of a local catchment effect, such as input of ^{18}O-depleted water from snowmelt or groundwater and rapid hydrological flushing [10]. Furthermore, abrupt ^{18}O-enrichment at 6000 cal yr BP observed in the LTCK record would appear to be consistent with a rapid change in water balance resulting from cessation of significant snowmelt and/or groundwater supply from the large catchment [10] and very dry conditions.

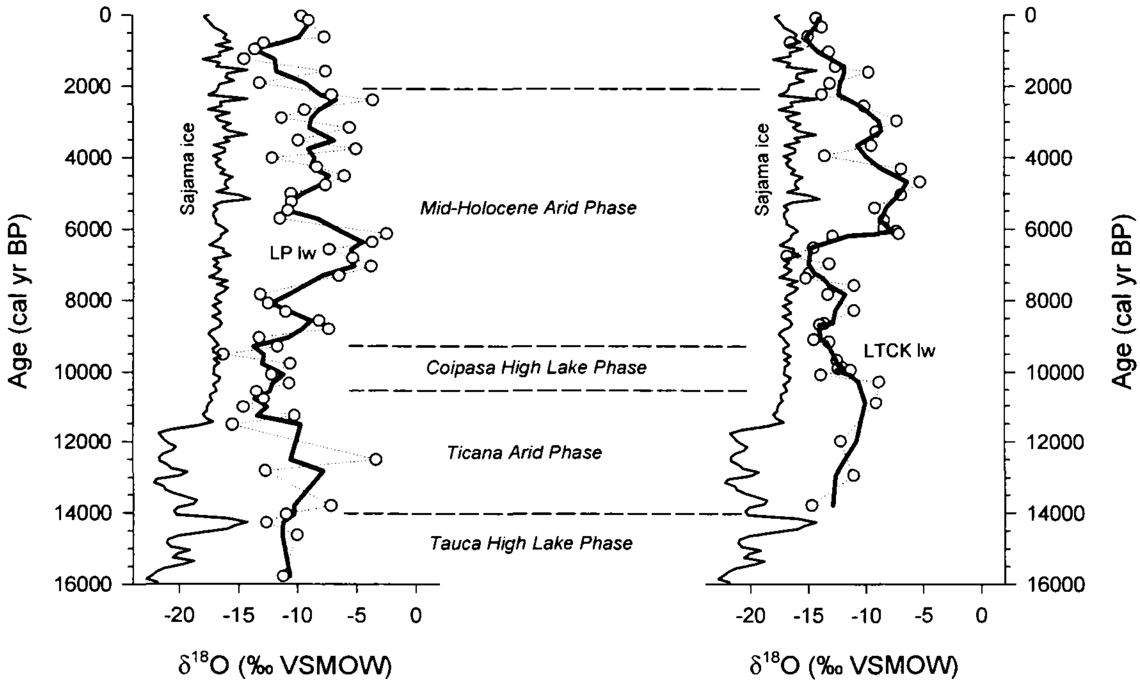

FIG. 2. Lake water $\delta^{18}O_{lw}$ records for Lago Potosi and Lago Taypi Chaka Kkota versus cal yr BP, calculated using a cellulose-water oxygen isotope fractionation factor of 1.028 [11,13-14]. Solid lines represent three-point running means. Bulk organic C/N weight ratios range from about 6 to12 (not shown), which support a dominantly autochthonous origin [15]. Also shown is 16,000 cal yr of the $\delta^{18}O$ record in the Sajama ice core [8], and stratigraphic zonation of major hydroclimatic intervals based partly on [2].

Analysis of closely-spaced samples has revealed substantial hydrological variability in the 6000 to 2000 cal yr BP $\delta^{18}O_{lw}$ record from LP. Highly variable oxygen isotope values have also been obtained on ostracode profiles in lake sediment cores from the Chilean Altiplano during this time interval suggesting predominantly arid conditions were punctuated by short-term climatic shifts [17]. The transition to a more moist climate during the mid- to late Holocene was evidently a step-wise shift characterized by fluctuating moisture conditions on both the Bolivian and Chilean Altiplano [17-19]. Less variability observed in the LTCK $\delta^{18}O_{lw}$ during this interval is consistent with this lake's larger size and catchment, and the weak trend to lower $\delta^{18}O_{lw}$ values also suggests a gradual shift to more moist conditions overall.

The end of the mid-Holocene arid phase at LP is marked by a decline in $\delta^{18}O_{lw}$ values around 2000 cal yr BP, similar to the $\delta^{18}O_{lw}$ record from LTCK where glacial meltwater influx returned as a source for the lake [10]. A recent increase in aridity is suggested by ^{18}O-enrichment at both LTCK and LP after 1000 cal yr BP.

4.2. Quantitative reconstruction of paleohumidity

Largely coherent $\delta^{18}O_{lw}$ trends between LTCK and LP that conform to the regional paleoclimatic framework can be used to support a more quantitative description of changing paleohumidity by using an isotope-mass balance approach (Figure 3a). At isotopic steady-state, the relationship between the fraction of lake water lost by evaporation and isotopic enrichment by evaporation for a lake with both inflow and outflow can be described by the following equations [20]:

(1) $E/I = (1\text{-}h)/h \times (*_{lw}\text{-}*_{p})/(*^{*}\text{-}*_{lw})$

where E = vapour flux,

I = inflow,

h = relative humidity at the air-water interface (which may be slightly higher than ambient),

$*^{*}$ = limiting isotopic enrichment attainable where the water body evaporates to near zero volume

$*_{lw}$ = lake water isotopic composition,

$*_{p}$ = precipitation isotopic composition,

and

(2) $\delta^{*} = (h\delta_{a} + \varepsilon)/(h\text{-}\varepsilon)$

where δ_a = vapour isotopic composition,

ε = isotopic separation between liquid and vapour including both equilibrium (ε^{*}) and kinetic (ε_K) effects.

Isotope-mass balance methods can be used to assess contemporary water balance of lakes [21-22], as well as to reconstruct past water balance from lacustrine records of $\delta^{18}O$ [23]. Here, we use this model to estimate summer relative paleohumidity (SRH) from the LP cellulose-inferred three-point running mean $\delta^{18}O_{lw}$ record. The LP $\delta^{18}O_{lw}$ record was chosen for SRH reconstruction because the record at this site does not appear to be complicated by additional hydrological effects, as is the case at LTCK during the early Holocene (possible snowmelt and/or groundwater supply) and late Holocene (glacial meltwater influx) [see 10]. The reconstruction is limited to the past 11,500 cal yr where the LP $\delta^{18}O_{lw}$ record is more highly resolved and temporally constrained. Model input values include: 1) δ_p = -17‰ estimated from the Sajama ice core $\delta^{18}O$ record (Figure 2), which also closely approximates the intersection of the REL and GMWL in Figure 1, 2) $\delta_a = \delta_p - \varepsilon^{*}$ (i.e. isotopic equilibrium between atmospheric vapour and precipitation), 3) ε^{*} = 10.66‰ from [24] and using an average air temperature of 10°C [9], and 4) $\varepsilon_K = 14.2\,(1\text{-}h)$ [25].

SRH is solved iteratively for three water balance scenarios that conservatively span the probable maximum range in natural variability over the past 11,500 cal yr (Figure 3b). 1) E/I = 1.00 defines conditions for a terminal basin where evaporation balances inflow so that no liquid outflow occurs. This represents the maximum fraction of lake water lost by evaporation as long-term hydrological status characterized by $E/I > 1$ is considered unlikely because this would lead to lake desiccation and absence of a stratigraphic record. 2) $E/I = 0.20$ was used to represent the minimum fraction of lake water lost by evaporation. This value is estimated from calculation of modern E/I ratios for overflowing lakes in non-glaciated watersheds and using the most isotopically-enriched lake water sample in our modern data set as a lower limit for δ^* (Figure 1). 3) $E/I = 0.36$ represents an estimate of the average summer water balance at present for LP based on a modern SRH value of 50% [9]. Comparison to modern conditions was used to derive a range in SRH values, bracketing concomitant water balance response to changing effective moisture using the three E/I scenarios. Results are plotted in Figure 3c in terms of minimum, maximum, and mean SRH values.

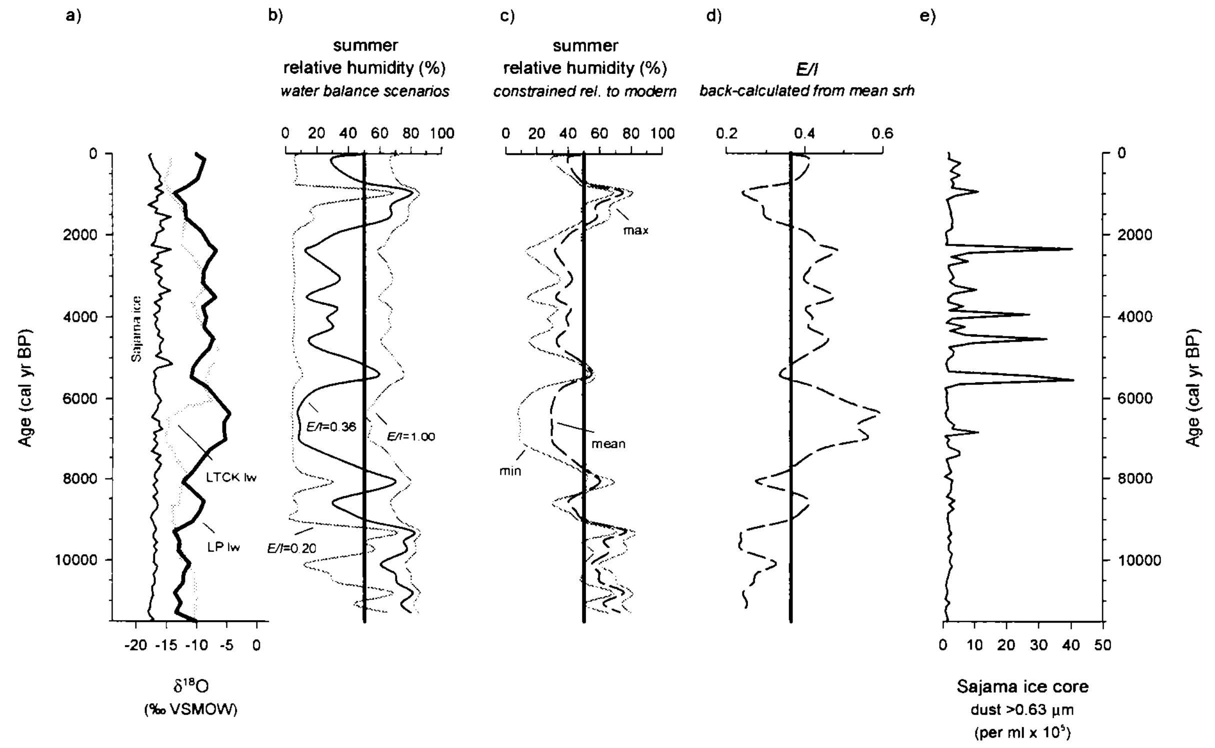

FIG. 3a) Sajama ice core $\delta^{18}O$ (Thompson et al., 1998) and cellulose-inferred three-point running mean $\delta^{18}O_{lw}$ records for Lago Taypi Chaka Kkota and Lago Potosi from Figure 2. b) Summer relative humidity profiles generated by E/I scenarios of 0.20, 0.36, and 1.00 based on the Lago Potosi three-point running mean $\delta^{18}O_{lw}$ profile. c) Summer relative humidity reconstruction representing minimum, maximum, and mean values constrained by values generated by the three E/I scenarios in b) and the modern summer relative humidity value of 50%. d) Estimated average summer water balance conditions (expressed as E/I) derived from back-calculation using mean summer relative humidity values in c). e) The Sajama ice core dust record from [8]. All records are plotted versus cal yr BP.

In general, results from Figure 3c show that SRH values averaged 10-20% higher relative to present at 11,500 cal yr BP with oscillating but generally declining values developing during the early Holocene. This trend culminates in maximum SRH decrease between 7500 and 6000 cal yr BP when reconstructed values average 20% lower than present. SRH values are near present between 6000 and 5000 cal yr BP and then decline to values averaging 15% lower than present until about 2500 cal yr BP. Mean SRH values increase to about 20% greater than present by about 1500 cal yr BP and then decline to around 5-10% less than present over the last 1000 years.

Notably large ranges between minimum and maximum SRH values are evident at low SRH compared to the present value of 50%, which is primarily a function of the large uncertainty in *E/I* ratios (0.36 to close to 1.00) that bracket these intervals. This extreme sensitivity is somewhat artificial, however, because the actual *E/I* ratios are relatively high during phases of low SRH, although not as high as 1.00 as values generated by this scenario are nearly always higher than 50%. This indicates that LP may have rarely attained wet-season terminal hydrological status for an extended period even during more arid intervals; a result that is not unexpected, however, as overcoming this threshold would likely have led to rapid volume draw-down, lake desiccation and hiatuses in sedimentation due to the low relative humidity. Indeed, the $\delta^{18}O_{lw}$ record is very sensitive to SRH below about 50% and because extreme ^{18}O-enrichment is not observed, SRH values substantially less than 40% are probably not reasonable. Conversely, less uncertainty is evident at high SRH mainly because of the narrower range in *E/I* ratios (0.20 to 0.36) that were used to delineate these phases (mainly 11,500 to 9000 and 2000 to 1000 cal yr BP). Based on back-calculation using the mean SRH reconstruction, we estimate that the average summer *E/I* ratio spanned mainly from about 0.25 to 0.60 over the past 11,500 cal yr (Figure 3d).

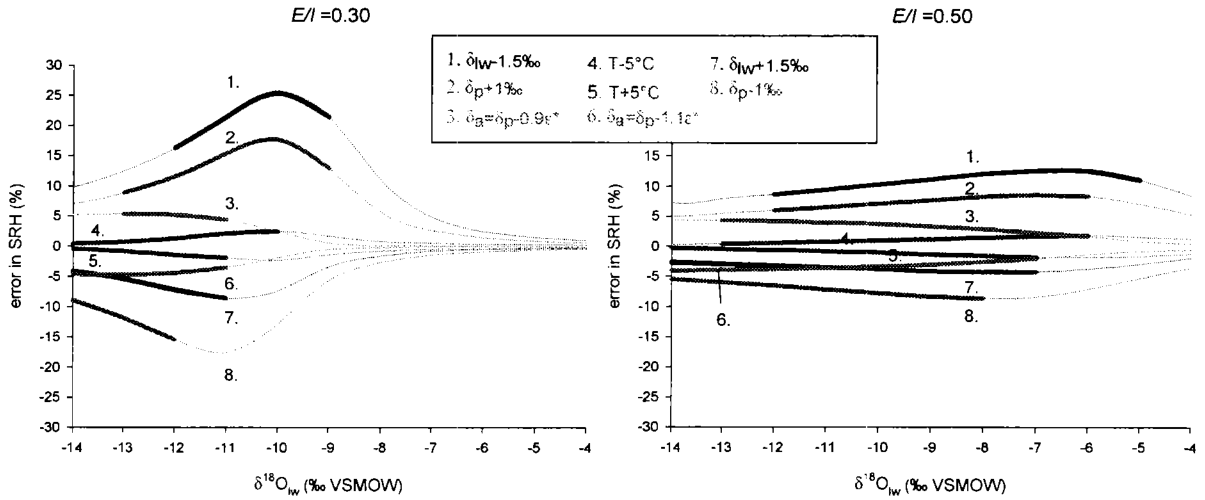

FIG. 4. Sensitivity analysis illustrating potential errors in summer relative humidity (SRH) values for variations of δ_{lw} = ±1.5‰ (incorporating analytical and cellulose-water oxygen isotope fractionation uncertainty), δ_p = ±1.0‰ (comprising most of the variation in the isotopic record from Sajama ice core over the past 11,500 cal yr BP) [8], T = ±5°C (estimated to reflect changes during the late Pleistocene - early Holocene transition and possibly during the interval of maximum aridity), and $\delta_a = \delta_p$ - ±10%(ε^*) (10 % deviation from isotopic equilibrium between δ_a and δ_p). Results are shown for the average summer E/I ratio during wet (0.30) and dry intervals (0.50), as estimated from Figure 3d. Note that solid lines define SRH errors that result in absolute values ranging from 30 to 85%, representing an estimate of the natural range potential in SRH.

Supporting evidence for widespread and similarly arid conditions during the mid- to late Holocene is provided by the LTCK $\delta^{18}O_{lw}$ profile and other records of past climate change. Between 6000 and 2000 cal yr BP, the $\delta^{18}O_{lw}$ values are broadly similar (Figure 3a) and in the range of lakes that presently drop below their overflow level under more moderate conditions (Figure 1). These overlapping trends may reflect similar *E/I* ratios and SRH during this time interval. Offset in cellulose-inferred $\delta^{18}O_{lw}$ over the last 1000 years suggests that the current effective moisture gradient between these two lakes may be a recent development. SRH minima during the mid- to late Holocene interval also shows close correspondence between dust concentration maxima in the Sajama ice core record, with both records reflecting dominantly arid but highly variable moisture conditions (Figure 3e), in agreement with other records on the Chilean Altiplano as mentioned above [17-19]. Lake Titicaca lowstands at about 6100 and 2400 cal yr BP [5, 26] and lake-level inferred maximum aridity between 8000 and 5500 cal yr BP [7] also compare well with the SRH reconstruction.

4.3 Model uncertainties

A sensitivity analysis was conducted to estimate potential sources of error associated with input parameters to equations (1) and (2) to derive past SRH values, in addition to uncertainties due to shifting *E/I*. Figure 4 illustrates the effect of $\delta_{lw} = \pm 1.5‰$, $\delta_p = \pm 1.0$ ‰, T = ±5°C, and $\delta_a = \delta_p - \pm 10\% \ (\varepsilon^*)$ on reconstructed SRH values for two water balance scenarios: 1) *E/I* = 0.30, which is estimated to reflect average conditions during wet intervals, and 2) *E/I* = 0.50 corresponding to estimated average conditions during dry phases (see Figure 3c). Overall, potential error in SRH values is less in the *E/I* = 0.50 scenario, with δ_{lw} and δ_p input variations resulting in mostly <10% error, and T and δ_a input variations producing <5% error.

Potential SRH errors are greater in the *E/I* = 0.30 scenario, although only δ_{lw}-1.5‰ and δ_p+1‰ variations over a narrow range of $\delta^{18}O_{lw}$ values result in errors in excess of (+)15%.

5. CONCLUSION

Comparison of cellulose-inferred lake water oxygen isotope profiles from two lakes in the Bolivian Andes provides a record of late Pleistocene and Holocene paleohydrological history that is largely in agreement with the regional framework based mainly on pluvial lake history, water level changes in Lake Titicaca, and the Sajama ice core record. Overall, the isotopic records indicate dominantly moist conditions during the late Pleistocene - early Holocene transition (roughly 10,500 to 9000 cal yr BP) and between 2000 and 1000 cal yr BP, whereas more arid conditions prevailed during the mid-late Holocene (mainly 8000 to 2000 cal yr BP) and over the past millennium. At LP, sustained maximum mid-Holocene aridity occurred between 7500 and 6000 cal yr BP and quantitative reconstruction of SRH, based on an isotope-mass balance model, indicates a decline of perhaps as much as 20% during this time. SRH values averaged 15% less than present but was highly variable during the later part of the mid-Holocene arid interval (*ca.* 5000-2000 cal yr BP), in agreement with other paleoclimatic records from the region [17-19, 26] including the Sajama ice core record where close correspondence occurs between several elevated dust particle concentrations [8] and SRH minima. Sensitivity analyses suggests potential errors in reconstructed SRH values are mainly related to uncertainty in the *E/I* ratio during arid intervals and cellulose-inferred $\delta^{18}O_{lw}$ and ice-inferred $\delta^{18}O_p$ values during wet intervals.

Notably, the SRH reconstruction sets the stage for comparison with new proxy records currently being obtained from similar lakes north of the equator in the Venezuelan Andes. In addition, these results reveal the potential for quantitative paleoclimatic reconstructions based on cellulose-inferred lake water oxygen isotope records. Key factors that have contributed to the viability of this approach include an independent detailed record of $\delta^{18}O_p$ and analysis of lake sediment records in contrasting settings, the latter having effectively allowed differentiation of local hydrological variations from regional climatic changes.

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PALAEOCLIMATE ARCHIVES III
ICE CORES AND RELATED ENVIRONMENTS

(Session 5)

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