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A 60,000-year record of hydrologic variability in the Central Andes from the hydrogen isotopic composition of leaf waxes in Lake Titicaca sediments

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ABSTRACT

A record of the hydrogen isotopic composition of terrestrial leaf waxes (δD_{wax}) in sediment cores from Lake Titicaca provides new insight into the precipitation history of the Central Andes and controls of South American Summer Monsoon (SASM) variability since the last glacial period. Comparison of the δD_{wax} record with a 19-kyr δD record from the nearby Illimani ice core supports the interpretation that precipitation δD is the primary control on δD_{wax} with a lesser but significant role for local evapotranspiration and other secondary influences on δD_{wax}. The Titicaca δD_{wax} record confirms overall wetter conditions in the Central Andes during the last glacial period relative to a drier Holocene. During the last deglaciation, abrupt δD_{wax} shifts correspond to millennial-scale events observed in the high-latitude North Atlantic, with dry conditions corresponding to the Bølling–Allerød and early Holocene periods and wetter conditions during late glacial and Younger Dryas intervals. We observe a trend of increasing monsoonal precipitation from the early to the late Holocene, consistent with summer insolation forcing of the SASM, but similar hydrologic variability on precessional timescales is not apparent during the last glacial period. Overall, this study demonstrates the relative importance of high-latitude versus tropical forcing as a dominant control on glacial SASM precipitation variability.

1. Introduction

Aided by the availability of different paleoclimate archives, the Central Andes have been the target of many studies of late Quaternary tropical South American climate. For example, sediment cores from the Lake Titicaca basin record changes in water balance (precipitation minus evaporation) and lake level on timescales from glacial–interglacial to millennial (Baker et al., 2001b; Fritz et al., 2007, 2010). Since the majority of regional precipitation falls during austral summer, the Central Andes are particularly sensitive to variability in the South American Summer Monsoon (SASM), a continental-scale circulation that produces much of summer precipitation throughout southern tropical and subtropical South America (Zhou and Lau, 1998). While studies of modern SASM precipitation have identified many controls on interannual to interdecadal SASM variability, including Pacific sea surface temperature (SST)/El Niño Southern Oscillation (ENSO) (Garreaud et al., 2009), Atlantic SST variability (Chiessi et al., 2009), and land surface processes (Collini et al., 2008), SASM behavior on longer timescales is not as well constrained. Characterizing the controls on SASM dynamics on millennial to interglacial–glacial timescales is thus critical to improving our understanding of past and future hydrologic variability throughout much of South America.

Proxies that record the isotopic composition of past precipitation in the Andes, from archives such as ice cores, speleothems and lacustrine calcite deposits, have proven to be particularly powerful tools for reconstructing past monsoon variability on geological timescales (e.g., Ramirez et al., 2003; Bird et al., 2011; Kanner et al., 2012). Although the interpretation of Andean stable isotopic records has been the subject of much debate (e.g., Broecker, 1997; Hoffmann, 2003; Pierrehumbert, 1999; Thompson et al., 1995), a number of recent modeling and observational studies clearly indicate a strong relationship between precipitation

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isotopes and the amount of precipitation along the SASM trajectory (Vuille et al., 2003; Vuille and Werner, 2005; Vimeux et al., 2005; Insel et al., 2013). Andean ice cores have yielded insight into the influence of global glacial cycles on regional hydrologic variability, with wetter conditions associated with Last Glacial Maximum (LGM) boundary conditions (Ramirez et al., 2003). In addition, changes in SASM precipitation have been linked to high-latitude millennial-scale variability, including Dansgaard–Oeschger cycles and Heinrich events during the last glacial period (Kanner et al., 2012), as well as the Younger Dryas and Bølling–Allerød intervals during the last deglaciation (Thompson et al., 1995, 1998). A number of Andean lacustrine calcite δ^{18}O records have pointed to the magnitude of local summer insolation as an important control of SASM intensity during the Holocene (Baker et al., 2009; Bird et al., 2011; Seltzer et al., 2000), consistent with southern Brazilian speleothems (Cruz et al., 2006; Wang et al., 2007) that show a strong influence of insolation on SASM precipitation over the entire last glacial cycle. In contrast, speleothem records from the Andes and western Amazonia do not vary strongly on precessional timescales during the last glacial period (MIS 2–4) (Kanner et al., 2012; Mosblech et al., 2012; Cheng et al., 2013).

Reaching a better understanding of past SASM variability is limited by the small number of continuous isotopic records from the Andes that extend into the last glacial period. Andean ice core records only extend as far back as the LGM (Ramirez et al., 2003; Thompson et al., 1995, 1998), while other extant Andean isotopic records are confined to the Holocene (e.g., Bird et al., 2011) or within the last glacial period (Kanner et al., 2012). Longer records are particularly valuable in light of new speleothem records from the western Amazon that provide important information on SASM activity upstream of the Andes over the last glacial–interglacial cycle (Mosblech et al., 2012; Cheng et al., 2013). The sediment record of Lake Titicaca (LT), continuous over the past four glacial cycles, is a valuable archive of regional climate variability, but traditional stable isotope archives (e.g., authigenic carbonate) are not present in much of the sediment record (Fritz et al., 2007). Compound-specific isotope analysis of biomarkers in LT sediments thus represents a new and advantageous approach to the study of past Andean climate. In particular, the hydrogen isotopic composition (δD) of leaf wax compounds produced by vascular plants has been shown to be highly correlated to precipitation δD (e.g., Sachse et al., 2012), allowing reconstruction of SASM precipitation variability when carbonate proxies are absent. Here we present a continuous record of regional hydrologic variability over the past 60,000 years from leaf wax δD in LT sediments.

2. Study site

The South American Altiplano is a semi-arid, internally drained plateau situated between the western and eastern cordilleras of the Central Andes (Fig. 1). Located on the Peruvian/Bolivian border on the northern Altiplano, Lake Titicaca (3810 m asl) is a large, freshwater lake comprised of two basins: the larger and deeper Lago Grande (7131 km^2) and the smaller shallow Lago Huiñaimarca (1428 km^2) connected by the Straits of Tiquina. The watershed of the Lago Grande basin consists of six major rivers (total catchment area: 52,800 km^2). Modern natural vegetation surrounding the lake largely consists of grasses, shrubs and herbs and is classified as puna vegetation (Paduano et al., 2003).

Present annual precipitation ranges from >700 mm in regions near Lake Titicaca to <200 mm on the southern Altiplano (Garreaud et al., 2003). The majority of annual precipitation (50–80%) on the Altiplano occurs during the austral summer and is associated with the SASM (Zhou and Lau, 1998). During the mature phase of the SASM (DJF), strengthened easterly trade winds increase moisture transport from the tropical Atlantic into the Amazon Basin towards the tropical Andes. The development of a continental-scale low-pressure system (Chaco Low) centered on the subtropical plains steers low-level flow southeastward along the eastern Andean flank, carrying moisture from the Amazon Basin to the subtropics (Garreaud et al., 2009). An upper-level anticyclone, known as the Bolivian High, develops over the Altiplano in response to latent heat release by Amazonian and Andean precipitation (Lenters and Cook, 1997). Upper level easterly flow associated with the north branch of the anticyclone allows upslope moisture transport from lowland Amazonia to the high Andes (Garreaud, 1999). During the peak months of the SASM (December–February), convective activity is concentrated over the southern Amazon Basin and Central Andes (Vuille and Werner, 2005). During the austral autumn (March–May), the SASM weakens and the region of maximum precipitation over continental South America retreats to the northern tropics. On the Altiplano, prevailing westerly flow from the arid west Andean slope results in dry conditions throughout much of the remainder of the year (May to October) (Garreaud et al., 2003).

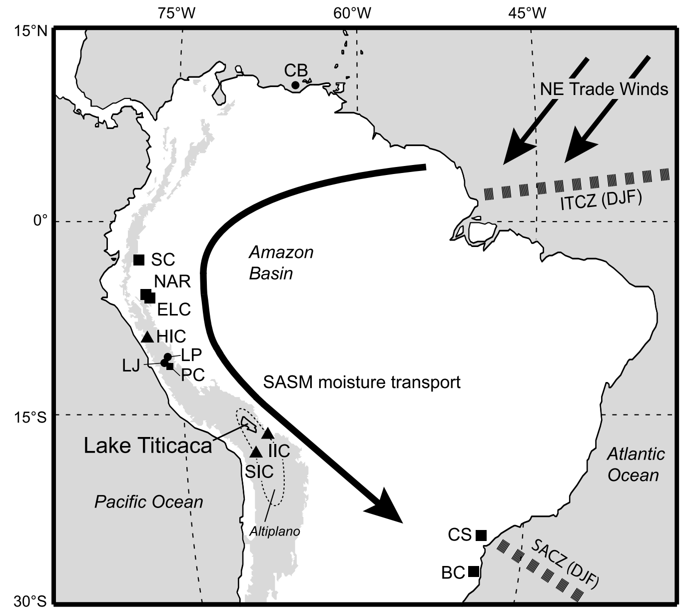

Fig. 1. Map of South American tropics showing location of Lake Titicaca and locations of ice core (triangles), speleothem (squares) and sediment (circles) records discussed in text. CB: Cariaco Basin (Hughen et al., 2004), SC: Santiago cave (Mosblech et al., 2012), NAR/ELC: Cueva del Diamante/El Condor (Cheng et al., 2013), HIC: Huascarán ice core (Thompson et al., 1995), LP: Laguna Pumacocha (Bird et al., 2011), LJ: Lake Junin (Seltzer et al., 2000), PC: Pacupahuain cave (Kanner et al., 2012), IIC: Illimani ice core (Ramirez et al., 2003), SIC: Sajama ice core (Thompson et al., 1998), CS: Santana cave (Cruz et al., 2006), BC: Botuverá cave (Cruz et al., 2006, 2007; Wang et al., 2007). Also shown are general features of the South American Summer Monsoon (SASM) including northeast trade winds, connections to the marine Intertropical Convergence Zone (ITCZ) and South Atlantic Convergence Zone (SACZ), and a representation of the general SASM moisture trajectory during austral summer. Shaded area indicates extent of Andes (area with elevation ≥2000 m), while dashed line indicates approximate extent of Altiplano.

3. Methods

3.1. Sediment core retrieval

Sediment cores from Lake Titicaca were raised in a 2001 International Continental Drilling Program expedition using the GLAD 800 drilling platform and coring system. Sediment samples analyzed here were taken from core LT01-2B, a 136 m core recovered from the Lago Grande basin at a water depth of 228 m (15.8533°S, 69.1404°W). The core was generally sampled at 2 cm resolution