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Assessing the strength of the monsoon during the late Pleistocene in southwestern United States

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Improved predictions of drought require an understanding of natural and human-induced climate variability. Long-term records across glacial–interglacial cycles provide the natural component of variability, however few such records exist for the southwestern United States (US) and quantitative or semi-quantitative records of precipitation are absent. Here we use the hydrogen isotope (δD) value of C_{28} *n*-alkanoic acid in lacustrine sediments of Pleistocene age to reconstruct δD values of precipitation in northern New Mexico over two glacial–interglacial cycles (~550,000–360,000 years before present) and obtain a record of monsoon strength. Overall, reconstructed δD values range from −53.8‰ to −94.4‰, with a mean value of −77.5 ± 8‰. Remarkably, this variation falls within the measured present-day summer monsoonal and winter weighted means (−50.3 ± 3‰ and −106.4 ± 20‰ respectively), suggesting that processes similar to those of present time also controlled precipitation during Marine Isotope Stage (MIS) 13 to 10. Using the δD summer monsoonal and winter mean values as end-members, we interpret our reconstructed δD record of precipitation as a direct, and semi-quantitative, indicator of monsoon strength during MIS 13 to 10. Interglacial periods were characterized by greater monsoon strength but also greater variability compared to glacial periods. Pronounced cycles in the strength of the monsoon occurred during interglacial periods and in general were positively correlated with maximum mean annual temperatures. Our estimates of monsoon strength are supported by independent proxies of ecosystem productivity, namely, TOC, $\delta^{13}C$ of TOC and Si/Ti ratio and warm pollen taxa *Juniperus* and *Quercus*. Interglacial variability in the strength of the monsoon resembles a response to the land-sea surface temperature contrast (LSTC) except for the early part of MIS 11. During this period, LSTC would have remained relatively strong while monsoonal strength decreased to a minimum. This minimum occurred following the warmest interval of MIS 11, suggesting a more complex driving of monsoon strength during warm periods. In addition, this period of monsoon minimum coincided with a core section of mud-cracked sediments that suggest low monsoonal precipitation was an important factor in the onset of drought. Our estimates of monsoon strength represent a record of natural variability

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in the region that is relevant to present time, in particular the variability during interglacial MIS 11, which is considered an analog for the current interglacial. Our results suggest that natural variability can cause significant reductions in monsoonal precipitation with the implication of a potentially adverse effect from sustained warming.

1. Introduction

As a result of human-induced forcing, the arid region of the southwestern US is projected to enter a climate that is drier than what has been observed in the instrumental record (Seager et al., 2007). Ultimately, the combined effect of human-induced forcing and natural forcing will dictate future climate change in the region. One aspect of natural variability is controlled by changes in sea surface temperature. For instance, models suggest that natural variability in tropical Pacific sea surface temperatures (Cook et al., 2007) was a significant source of precipitation variability in the southwest during the last ca 400 years (Seager et al., 2005). However the projected drier climate for the southwestern US is expected to have a more complex forcing involving changes in atmospheric circulation cells (Seager et al., 2007). Whereas all model projections take into account the known past variability available from the instrumental record, these records are limited to ~120 years and thus capture a relatively short period of natural variability. Longer records of precipitation across glacial–interglacial cycles can greatly improve our understanding of natural forcing. In the southwestern US, only a few long-term records exist and these are qualitative in nature (Sears and Clisby, 1952; Winograd et al., 1992; Coplen et al., 1994; Fawcett et al., 2011). Evidence of past dry/wet climate intervals in the southwestern US exists from a chronologically unconstrained lacustrine record retrieved over 60-years ago from the Valles Caldera in northern New Mexico (Sears and Clisby, 1952). A subsequent study on Pleistocene interglacials identified periods of aridity from a new lake core retrieved from Valles Caldera (VC-3 core) (Fawcett et al., 2011). The VC-3 core contained mud-cracked sections, and a multi-proxy analysis provided indirect evidence of significantly reduced precipitation during MIS 13 and 11.

Here we measure compound-specific δD values in the VC-3 core to obtain a semi-quantitative record of monsoonal precipitation during MIS 13 through the onset of MIS 10. We use the δD values of terrestrial plant waxes (C_{28} *n*-alkanoic acid) extracted from the VC-3 core and the modern correlation between the δD value of sedimentary terrestrial plant waxes and that of local precipitation (Hou et al., 2008) to obtain a δD record of precipitation ~550,000–360,000 years before present. In addition, we used the apparent fractionation factor between the δD value of plant leaf waxes and the δD of precipitation (Hou et al., 2008) to obtain a second reconstruction of the δD of precipitation. Using the reconstructed δD of precipitation and a two end-member approach (validated with modern precipitation data), we present a record for the strength of the monsoon during Pleistocene interglacials in northern New Mexico. Our estimates of monsoon strength constitute a record of natural variability in precipitation in the southwestern US that extends considerably longer than the instrumental record and provides direct evidence of semi-quantitative changes not yet available from paleoclimate records. This new record of monsoonal precipitation, particularly during MIS 11, an insolation analog for the current interglacial, will contribute to a better understanding of the mechanisms behind current and future droughts in the region.

2. Materials and methods

2.1. Core sampling

Lacustrine sediments were retrieved from Valles Caldera, New Mexico (35° 52′ N, 106° 28′ W, 2553 m a.s.l.; Fig. 1). Details on the geology of Valles Caldera, the chronology and lithology of the core, pollen, magnetic susceptibility, total organic carbon (TOC), mean annual temperature (MAT), $\delta^{13}C_{TOC}$ and SI/Ti analyses are described elsewhere (Fawcett et al., 2007, 2011). The 82-m VC-3 core is stored at the Limnological Research Center National Lacustrine Core Repository (LacCore) at the University of Minnesota. Sediment

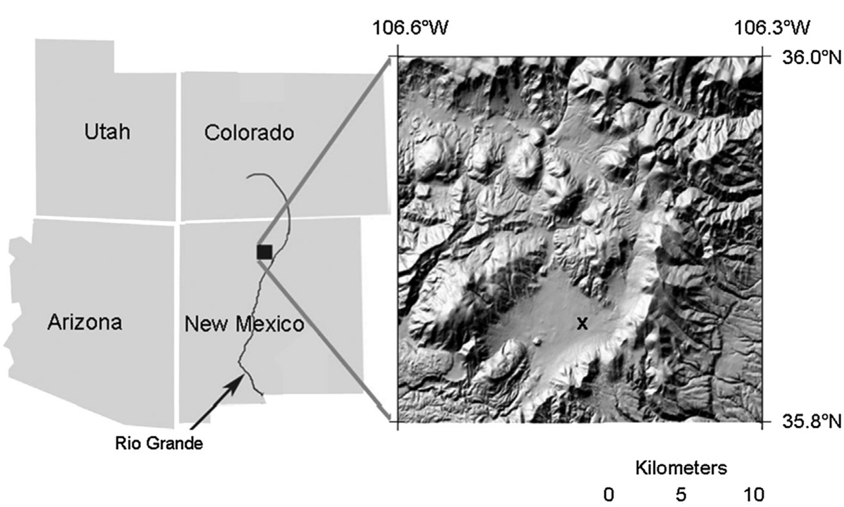

Fig. 1. Location map of Valles Caldera, New Mexico and elevation map showing the drilling location of the lake core (cross).