Changes in dominant moisture sources and the consequences for hydroclimate on the northeastern Tibetan Plateau during the past 32 kyr

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Abstract:

Lake Qinghai, located on the northeastern Tibetan Plateau north of the modern maximum summer monsoon extent, is well situated to record northward advances of the summer monsoon. Existing paleoclimate records contain conflicting evidence for the timing of summer monsoon advance into this region: an early arrival pre-Younger Dryas or a late arrival at the beginning of the Holocene. A 30-kyr-long leaf wax hydrogen isotope (*n*-alkanoic acid, $\delta^2\text{H}_{\text{wax}}$) record from Lake Qinghai helps to address this discrepancy by elucidating changes in the three main moisture sources in this region: southerly (summer monsoon), northwesterly, and local precipitation. Lake Qinghai $\delta^2\text{H}_{\text{wax}}$ indicates that the arid glacial period was dominated by northwesterly moisture. Extremely arid conditions prevailed from 15 to 14 ka, likely because westerly winds were weakening and the summer monsoon had not yet reached this region. This arid period ended by 13.6 ka when small amounts of summer monsoon precipitation reached Lake Qinghai. Summer monsoon moisture subsequently retreated off of the northeastern Tibetan Plateau during the Younger Dryas and re-advanced in the early Holocene. Summer monsoon precipitation decreased progressively throughout the Holocene in response to decreasing summer insolation, and the modern northwesterly- and local-dominated moisture regime was attained ca. 2.6 ka. Lake Qinghai $\delta^2\text{H}_{\text{wax}}$ demonstrates that the summer monsoon extent was dynamic during the past 30 kyr, responding dramatically to insolation and North Atlantic circulation changes. Moreover, Lake Qinghai $\delta^2\text{H}_{\text{wax}}$ demonstrates that local and northwesterly air masses are important moisture sources to the northeastern Tibetan Plateau, and should be considered when reconstructing past hydroclimate in this region.

Keywords: leaf wax hydrogen isotopes, Tibetan Plateau, monsoon, westerlies, Younger Dryas, Holocene

1.1 Introduction

More than half the global population lives in Asia and depends on rivers that originate in Tibet for water, making a clear understanding of hydroclimate in this region of primary interest to scientists and policy makers (Christensen et al., 2007; Cruz et al., 2007). Predicting future hydroclimate is hampered by low-resolution climate models that perform poorly in heterogeneous mountain regions, and by the short observational record, which encompasses a relatively narrow climatic range (China Meteorological Administration, 2012; Christensen et al., 2007). Reconstructions of past hydroclimate on the Tibetan Plateau are useful for understanding the sources of precipitation to this region and the mechanisms that cause hydroclimatic change, and may provide insights into future variability in this region.

The Last Glacial Maximum (~21 ka) on the northeastern Tibetan Plateau was arid and strongly influenced by westerly winds (An et al., 2012; Herzschuh, 2006; Morrill et al., 2003; Y. Wang et al., 2014; Wang et al., 2010; Yang et al., 2011). In contrast, the early Holocene was wet, likely with greater summer monsoon influence. In some areas east of Lake Qinghai, which are more strongly influenced by the summer monsoon today, the middle Holocene was wetter than the early Holocene (H. Wang et al., 2014; Wang et al., 2010; X. Yang et al., 2010; Yang et al., 2014).

The existing paleoclimate records on the northeastern Tibetan Plateau disagree on the timing and nature of climate change during the last glacial termination. Reconstructions based on Lake Qinghai organic carbon and carbonate show an abrupt precipitation increase at 11.5 ka (An et al., 2012; X. J. Liu et al., 2013), whereas pollen records from throughout the region show a more gradual precipitation increase beginning ca. 17 to 14 ka. It is unclear whether these differences are due to hydroclimatic spatial heterogeneity on the Tibetan Plateau, or due to differences between proxies. Furthermore, it is difficult to distinguish between the influence of different moisture sources using existing individual proxy reconstructions. In addition, summer monsoon and extratropical circulation are controlled by different forcing mechanisms on millennial and orbital time scales. Summer monsoon precipitation amount and the position of maximum precipitation in east Asia are controlled by changes in sea level and by changes in interhemispheric temperature and pressure gradients, which are driven by insolation and latent heat transport (Cai et al., 2015; Caley et al., 2014; Clemens and Prell, 2003; Hao et al., 2012; Molnar et al., 2010). In contrast, westerly wind strength and moisture transport are controlled by

changes in Atlantic Meridional Overturning Circulation and Northern Hemisphere snow cover and ice volume (Hao et al., 2012; Sun et al., 2012). Precipitation isotope records can clarify moisture source variability, and can help address outstanding questions regarding the timing and nature of summer monsoon arrival on the northeastern Tibetan Plateau.

1.1.1 Moisture sources for the northeastern Tibetan Plateau

Hydroclimate on the Tibetan Plateau is spatially heterogeneous, caused by topographic heterogeneity and the influence of multiple moisture sources (Araguás-Araguás et al., 1998; Kalnay et al., 1996; Tian et al., 2001). Different moisture sources to the northeastern Tibetan Plateau have distinct seasonality and carry different amounts of precipitation (Fig. 1) (Chen et al., 2012; Drumond et al., 2011). Changes in moisture source contributions to this region can result in changes in total amount and seasonality of precipitation, so determining past moisture source change can elucidate the causes of past hydroclimatic variability.

Today the Lake Qinghai catchment receives moisture from three main sources: 1. Southerly (summer monsoon), 2. Northwesterly, and 3. Local (Fig. 1), as identified by precipitation isotope studies and by air mass trajectory analyses (Chen et al., 2012; Drumond et al., 2011; Lee et al., 2012; Sun and Wang, 2014; Tian et al., 2007, 2001). We illustrate these sources using HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) analysis of NCEP-NCAR Reanalysis data from 2007 to 2011 for air masses that resulted in precipitation at Lake Qinghai (Supp. Info.) (Draxler and Hess, 1998; Kalnay et al., 1996). Although HYSPLIT analysis overestimates precipitation amount at Lake Qinghai (Fig. 1) (Peña-Arancibia et al., 2013), likely due to the low spatial resolution of the NCEP-NCAR Reanalysis data, this analysis yields similar source regions as a backtracking analysis using FLEXPART modeling with higher-resolution ECMWF Reanalysis data (Drumond et al., 2011). In addition, we use modern precipitation isotope data to estimate the relative isotopic values of the precipitation sources and guide our interpretation of the paleo-isotope record (IAEA/WMO, 2011).

1.1.1.1 The southerly, or summer monsoon, moisture source

In the Lake Qinghai catchment, 90% of annual precipitation occurs during the growing season (mid-April to September) (Fig. 1) (Chen et al., 2005; China Meteorological Administration, 2012). Of the three modern moisture sources to the northeastern Tibetan Plateau,

the southerly, or summer monsoon, source has the most pronounced seasonality, with more than 90% of summer monsoon moisture falling at Lake Qinghai in July, August, and September. Yet today, the average maximum summer monsoon extent on the Tibetan Plateau is south of Lake Qinghai, and monsoon moisture contributes only 6% of growing season precipitation to Lake Qinghai (Fig. 1) (Araguás-Araguás et al., 1998; Drumond et al., 2011; IAEA/WMO, 2011; Tian et al., 2001).

For this study, we define the summer monsoon as moisture derived directly from southerly sources, the Bay of Bengal and the South China Sea. The millennial and orbital-scale isotopic variation associated with this moisture source is likely most closely linked with hydrologic processes of the Indian Monsoon (Lee et al., 2012; Molnar et al., 2010; Pausata et al., 2011). We estimate the summer monsoon isotopic end member using data from Yushu, 500 km SW of Lake Qinghai near the modern northernmost summer monsoon extent on the Tibetan Plateau. Summer monsoon precipitation at this station is characterized by low $\delta^{18}\text{O}$ and high d-excess (Tian et al., 2007), so we calculate an average summer monsoon precipitation $\delta^2\text{H}$ value of $-129 \pm 18\text{‰}$ using samples with those characteristics. Thus, even a small northward incursion of summer monsoon moisture to Lake Qinghai would increase late growing season (July to September) precipitation amount while decreasing growing season precipitation $\delta^2\text{H}$.

1.1.1.2 The local and northwesterly moisture sources

Local moisture derived from continental recycling results in 60% of growing season precipitation at Lake Qinghai, with the remaining 30% derived from northwesterly air masses (Fig. 1) (Draxler and Hess, 1998; Kalnay et al., 1996; Lee et al., 2012). Local moisture is mostly derived from eastern and southern China, which are wettest in summer because of ^2H -depleted summer monsoon rainfall. Yet modern precipitation at Lake Qinghai is more ^2H -enriched in summer than in winter. This is because rain falling on the arid northeastern Tibetan Plateau may be ^2H -enriched by up to 24‰ via non-equilibrium re-evaporation as raindrops fall through the arid atmosphere (Lee et al., 2012). Locally derived vapor may also be ^2H -enriched via evaporative enrichment of soil moisture (Araguás-Araguás et al., 1998). Both of these ^2H -enrichment processes are more pronounced at lower humidity: a dry atmosphere would result in greater non-equilibrium ^2H -enrichment via raindrop re-evaporation and higher precipitation $\delta^2\text{H}$

values, whereas a humid atmosphere would result in less non-equilibrium ^2H -enrichment and lower precipitation $\delta^2\text{H}$ values.

Growing season precipitation that falls during relatively arid periods has $\delta^2\text{H}$ values around $-32\pm 9\text{‰}$, estimated using growing season precipitation $\delta^2\text{H}$ at Zhangye, north of Lake Qinghai and $-40\pm 11\text{‰}$, estimated using growing season precipitation $\delta^2\text{H}$ at Delingha, west of and at a similar elevation to Lake Qinghai (Fig. 1) (IAEA/WMO, 2011; Tian et al., 2001). This precipitation is predominantly from the local and northwesterly sources. Growing season moisture that is more ^2H -depleted indicates moist conditions on the northeastern Tibetan Plateau, in part because raindrop re-evaporation is reduced when humidity increases. There is likely always some raindrop re-evaporation at Lake Qinghai, but if humidity were to increase enough such that raindrop re-evaporation did not occur, growing season precipitation would decrease to values of $-56\pm 9\text{‰}$ (modern summer moisture $\delta^2\text{H}$ with the 24‰ raindrop re-evaporation enrichment removed).

Westerly and local air masses each contribute half of winter precipitation on the northeastern Tibetan Plateau (Fig. 1). Winter precipitation is a small percentage of annual precipitation, but snowmelt may provide an important water source for plants early in the growing season. The winter isotopic end member has low values of $-119\pm 43\text{‰}$ (Aggarwal et al., 2004; Araguás-Araguás et al., 1998; IAEA/WMO, 2011; Tian et al., 2001), estimated using winter precipitation $\delta^2\text{H}$ data from GNIP sites on the northern Tibetan Plateau.

We take advantage of the different isotopic signatures of seasonal and source area precipitation at Lake Qinghai to generate a record of source area and precipitation seasonality changes during the last glacial cycle. We reconstruct past precipitation $\delta^2\text{H}$ using hydrogen isotopes of *n*-alkanoic acids ($\delta^2\text{H}_{\text{wax}}$). Millennial- and orbital-scale changes in source area evaporation and vapor transport history can affect precipitation source $\delta^2\text{H}$ values, and therefore we use the above end member $\delta^2\text{H}$ values only as a guide for our paleohydrological interpretations.

1.1.2 Factors influencing glacial-interglacial-scale precipitation isotope variability

The main factors that influence $\delta^2\text{H}_p$ variability on the northeastern Tibetan Plateau are precipitation source area, evaporative enrichment of rain, soil, and groundwater, and condensation temperature (Araguás-Araguás et al., 1998; Lee et al., 2012).

As discussed above, on event-to-interannual time scales, precipitation isotopes on the northeastern Tibetan Plateau are controlled by precipitation source area and transport history, and the influence of source areas on precipitation isotopes likely extends to millennial and orbital time scales (Aggarwal et al., 2004; Ishizaki et al., 2012). Modern growing season precipitation on the northeastern Tibetan Plateau is ^2H -enriched by re-evaporation of raindrop and soil moisture (Araguás-Araguás et al., 1998; Lee et al., 2012), an effect that would be enhanced during arid periods and diminished during moist periods on orbital- and millennial-time scales.

Annual average temperature changed by several degrees during the last glacial cycle, likely also affecting $\delta^2\text{H}_p$ (Araguás-Araguás et al., 1998; Peterse et al., 2014; Thomas et al., 2014a; Thompson et al., 2000; Tian et al., 2001). The effect of temperature during the last glacial cycle can be removed from $\delta^2\text{H}_p$ proxy records using an independent temperature proxy record (Supp. Info.) (Thomas et al., 2014a).

The amount effect is not the dominant process operating at glacial-interglacial timescales on the northeastern Tibetan Plateau: we know this by comparing $\delta^2\text{H}_{\text{wax}}$ with existing pollen- and geochemistry-based paleoprecipitation records, which reconstruct a dry last glacial maximum and wet early Holocene, when $\delta^2\text{H}_{\text{wax}}$ has similar values (Fig. 2).

1.1.3 Factors influencing glacial-interglacial-scale leaf wax isotope variability

The precipitation $\delta^2\text{H}$ signal can be further altered as plants biosynthesize leaf waxes and as the leaf waxes are integrated from throughout the catchment and deposited in lake sediments.

Plants in the Lake Qinghai catchment likely use growing season rainfall as their main source water, although ^2H -depleted snowmelt also may be source water for plants in the early growth season. The amount of snowmelt used by plants likely varies through time as snowfall amount and melt season length and strength change. Because snowmelt $\delta^2\text{H}$ is much lower than growing season rainfall ($-119\pm 43\text{‰}$ for snow vs. $-32\pm 9\text{‰}$ to $-56\pm 9\text{‰}$ for growing season rainfall), $\delta^2\text{H}_{\text{wax}}$ would decrease if plants use snowmelt for source water.

Leaf waxes record the isotopic composition of source water with an apparent fractionation between $\delta^2\text{H}_p$ and $\delta^2\text{H}_{\text{wax}}$ (ϵ_{app}). Evapotranspiration in extremely arid regions can enrich ^2H in

leaf water up to 100‰, modern evapotranspiration at Lake Qinghai enriches ^2H in leaf water by approximately 60‰ (Douglas et al., 2012; Kahmen et al., 2013; Ponton et al., 2014; Sachse et al., 2012). This effect may be offset by plant type (Gao et al., 2014; Hou et al., 2008), and the ϵ_{app} of modern *n*-alkanes along a humid-to-arid transect on the Tibetan Plateau changes at most by 10‰, indicating a minor aridity influence on modern $\delta^2\text{H}_{\text{wax}}$ (Günther et al., 2013; Xia et al., 2008). When modified to consider only growing season precipitation, the modern ϵ_{app} for *n*-alkanes on the northeastern Tibetan Plateau is -110‰ (Xia et al., 2008). Here we study C_{28} *n*-alkanoic acids, and the ϵ_{app} for *n*-alkanoic acids on the Tibetan Plateau is similar to that for *n*-alkanes (Aichner et al., 2015). We use the -110‰ ϵ_{app} to estimate the $\delta^2\text{H}_{\text{wax}}$ values that would result from each distinct precipitation source area and season discussed above (Fig. 2).

Aquatic plants are an important source of primary productivity in Lake Qinghai (An et al., 2012; Liu et al., in press; Wang and Liu, 2012). Some aquatic plants in Lake Qinghai produce large amounts of C_{29} and C_{31} *n*-alkanes, but only small amounts of C_{26} , C_{28} , and C_{30} *n*-alkanoic acids (Wang and Liu, 2012). We therefore target C_{28} *n*-alkanoic acids for our analyses, as these compounds are representative of terrestrial plant productivity and are unlikely to be influenced by aquatic sources. Even if some portion of C_{28} *n*-alkanoic acids are derived from aquatic plants, the aquatic plant source water experiences isotopic changes in the same direction as terrestrial plant source water: high values would indicate lake water evaporation and/or moisture derived locally, and low values indicate less evaporation and/or moisture derived from snow or the summer monsoon. Moreover, C_{28} *n*-alkanoic acids likely have shorter residence times than *n*-alkanes (Kusch et al., 2010).

When interpreted in conjunction with other proxy records for moisture and aridity, and by controlling for plant type via detailed pollen stratigraphy and ϵ_{app} data for modern plants, $\delta^2\text{H}_{\text{wax}}$ can be used to infer changes in moisture source area and transport history.

2.1 Setting

We present a 30-kyr-long leaf wax hydrogen isotope ($\delta^2\text{H}_{\text{wax}}$) reconstruction from Lake Qinghai on the northeastern Tibetan Plateau. Lake Qinghai (36.7°N, 100.0°E, 3194 m above sea level; Fig. 1) is well suited for evaluating regional hydroclimate because the closed-basin lake integrates leaf waxes from a large catchment at high elevations (30,000 km^2 , up to >4000 m above sea level) (An et al., 2012). Wind and water efficiently and rapidly transport and

homogenize leaf waxes from throughout the catchment, so are suitable for centennial-scale paleoclimate reconstructions (Douglas et al., 2012; Ponton et al., 2014). Moreover, Lake Qinghai is situated north of the modern boundary of summer monsoon precipitation (Tian et al., 2001), and therefore may be sensitive to millennial- and orbital-scale changes in the extent of the summer monsoon. Today, annual precipitation in the Lake Qinghai catchment is 370 mm, with 90% falling in April through September (Fig. 1); annual evaporation is > 1000 mm (China Meteorological Administration, 2012). The average temperature for July, the warmest month, is 16°C. The modern growing season at Lake Qinghai is April through September (Chen et al., 2005), so Lake Qinghai $\delta^2\text{H}_{\text{wax}}$ reflects spring and summer precipitation sources and moisture balance.

3.1 Methods

359 samples were obtained from core LQDP05 1Fs (An et al., 2012) for organics analysis. Samples were prepared and analyzed using methods described in (Thomas et al., 2012). Fatty acid methyl ester (FAME) concentrations were measured on a gas chromatograph (GC, Agilent model 6890) with split/splitless injection and a flame ionization detector. 240 samples contained enough C_{28} FAME for hydrogen isotope analysis. The hydrogen isotope ratio of the C_{28} FAME was determined using gas chromatography-pyrolysis-isotope ratio mass spectrometry (Agilent model 6890 GC interfaced to a Thermo Finnigan Delta + XL isotope ratio mass spectrometer) at Brown University. The H_3^+ factor was determined every 2 days prior to sample analysis. Isotope values are expressed in per mille (‰) relative to Vienna Standard Mean Ocean Water (VSMOW). Each extract was measured two or three times, and the pooled standard deviation of all analyses was 2.5‰ (1σ). FAME $\delta^2\text{H}$ values were corrected for the isotopic contribution of the hydrogens in the methyl group added during methylation using the formula: $\delta^2\text{H}_{\text{wax}} = [(2n + 2) \times \delta^2\text{H}_{\text{measured}} + 123.7\text{‰} \times 3] / (2n - 1)$ where n is the number of carbons in the molecule and -123.7‰ is the $\delta^2\text{H}$ value for the added methyl group. Analysis of an external FAME standard consisting of C_{16} , C_{18} , C_{22} , C_{24} , C_{26} and C_{28} FAMES with known $\delta^2\text{H}$ values, injected twice after every sixth sample injection, had an analytical error of <2‰ (1σ).

To isolate regional hydrological variability, we remove the effects of temperature and global ice volume from our $\delta^2\text{H}_{\text{wax}}$ record (hereafter, $\delta^2\text{H}_{\text{wax-TIV}}$, Supp. Info.), propagating error where appropriate, as in (Thomas et al., 2014a) (Figs. 2, S1). We use the Lake Qinghai pollen record (Ji

et al., 2005) and ε_{app} measured in modern plant species (Sachse et al., 2012) to determine the effect that changing plant types have on the Lake Qinghai $\delta^2\text{H}_{\text{wax}}$ record (Supp. Info., Fig. S1, Table S1). Accounting for ε_{app} does not change the structure or amplitude of the $\delta^2\text{H}_{\text{wax}}$ record, so we consider the effect of changing plant types in the Lake Qinghai catchment to have a minor effect on $\delta^2\text{H}_{\text{wax}}$, and herein discuss only $\delta^2\text{H}_{\text{wax-TIV}}$.

4.1 Results

N-acids in Lake Qinghai sediments have a strong even-over-odd carbon preference index (> 5.5), and C_{26} and C_{28} *n*-acids are the most abundant. Terrestrial plants are therefore the dominant source of long-chain *n*-acids (Wang and Liu, 2012), with the possible exception of 1-kyr-long intervals between 20.5 and 15.5 ka when aquatic plant pollen increased to a mean value of $6 \pm 1\%$ of total pollen, with peak abundances of 65% of total pollen (Fig. S2) (Ji et al., 2005); S. Xue, pers. comm.). C_{28} *n*-acid concentrations were lowest from 32 to 21 ka and 15.7 to 14.4 ka, and highest from 20.5 to 16.3 ka and 11.5 to 7.7 ka (Fig. 2).

Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ ranged from -110 to -210‰ (Fig. 2). $\delta^2\text{H}_{\text{wax-TIV}}$ was relatively constant at $-170 \pm 4\text{‰}$ from 32.0 to 18.2 ka and reached low values 18.0 to 15.0 ka ($-190 \pm 19\text{‰}$) before a dramatic ^2H -enrichment to -110‰ at 14.6 ka. This enrichment was followed by a shift to relatively low values at 13.6 ka (-180‰), high values from 13.0 to 11.4 ka ($-170 \pm 2\text{‰}$), and low values from 11.2 to 7.0 ka ($-195 \pm 5\text{‰}$). $\delta^2\text{H}_{\text{wax-TIV}}$ became ^2H -enriched in a stepwise fashion at 7.0, 5.0, and 2.6 ka, reaching stable late Holocene values ($-165 \pm 4\text{‰}$) at 2.6 ka.

5.1 Interpretation and Discussion

We interpret $\delta^2\text{H}_{\text{wax-TIV}}$ to reflect growing season moisture source changes, with potential additional effects of evaporative enrichment of plant source water and ^2H -depleted snowmelt. We bolster our findings with multiple proxy records: regional pollen- and geochemistry-based paleoprecipitation records, geochemistry-based paleotemperature records, and grain-size-based wind strength records. We also compare paleoclimate reconstructions to a 21 kyr transient simulation of the Community Climate System Model 3 (TraCE-21 ka) (He, 2011; Z. Liu et al., 2012; Liu et al., 2009). We derive the timing of events in all proxy records from the original publications; we interpret age models that are constructed using ^{14}C only on relatively broad

millennial time scales, as the reservoir effect in lakes on Tibet is large and changeable (Hou et al., 2012).

5.1.1 The cold, arid glacial period (32 to 15 ka)

Moderate $\delta^2\text{H}_{\text{wax-TIV}}$ values (-170‰) at Lake Qinghai during the arid glacial period (ca. 32 to 15 ka) suggest that local rainfall, modified via raindrop re-evaporation, and snowmelt were the dominant moisture sources to the northeastern Tibetan Plateau. Multi-proxy evidence shows that the northeastern Tibetan Plateau was cold, arid and dominated by westerly winds during the glacial period, so moisture was likely from northwesterly air masses. Pollen, lake level, and primary productivity reconstructions indicate that climate on the northeastern Tibetan Plateau was extremely arid at this time, with only 100-250 mm precipitation per year falling prior to 15 ka at nearby lakes Luanhaizi, Kuhai and Donggi Cona (Fig. 3) (An et al., 2012; Colman et al., 2007; Herzschuh et al., 2010; Y. Wang et al., 2014). In the Lake Qinghai catchment, soil formation was limited and the plant ecosystem was dominated by cold and drought-tolerant C_3 plants until ca. 12 ka (Fig. S2) (X. J. Liu et al., 2012; Thomas et al., 2014b). Large and increasing grain size on the northwestern Chinese Loess Plateau suggests that westerly wind strength was strong and increasing between 32 ka and 15 ka (Sun et al., 2003, 2012), and could have been a major source of moisture to the northeastern Tibetan Plateau at that time. Based on these multiple proxies, the glacial period has been interpreted as cold and dry. The Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ record supports this conclusion, and allows for further insight into hydroclimate. From 32 to 18 ka, $\delta^2\text{H}_{\text{wax-TIV}}$ has similar values as the late Holocene, although there was less annual precipitation. The arid conditions would have caused greater raindrop re-evaporation (Lee et al., 2012), so growing season precipitation on the northeastern Tibetan Plateau was ^2H -enriched compared to the late Holocene. Evapotranspiration would have further enriched soil and plant water during the arid glacial period (Kahmen et al., 2013). Snow may have contributed a larger portion of source water for plants, balancing the ^2H -enriched summer rainfall and plant source water with ^2H -depleted snowmelt. We infer that hydroclimate during the arid glacial period was dominated by northwesterly and local precipitation.

The interval from 18.0 to 15.0 ka was characterized by lower $\delta^2\text{H}_{\text{wax-TIV}}$ values (ca. $-190\pm 19\text{‰}$) and continued arid conditions. We infer that a large portion of plant source water during this period was derived from snowmelt. Pollen and ^{10}Be -inferred rainfall records suggest

that mean annual precipitation in the region began to increase after a minimum around 20 ka (Figs. 2 and 3) (Herzschuh et al., 2010; Ji et al., 2005; Y. Wang et al., 2014; Zhou et al., in press). Large grain size on the Chinese Loess Plateau suggest that westerly winds were strongest at ca. 16 ka, and so the moisture that did reach Lake Qinghai would most likely be via the westerlies in the form of snow (Fig. 2) (Sun et al., 2012). Together, the Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ and regional paleoclimate records suggest that most of the precipitation that reached the Lake Qinghai catchment from 18.0 to 15.0 ka was derived from ever-stronger westerly winds.

5.1.2 Extreme aridity 15 to 14 ka was caused by weak westerlies and a weak summer monsoon

The interval from 15 to 14 ka in the Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ record contains extremely high values (-110‰; Fig. 2). This ^2H -enrichment was probably not caused by source area changes alone, since $\delta^2\text{H}_{\text{wax-TIV}}$ is at least 20‰ more enriched than it would be if growing season precipitation, modified by raindrop re-evaporation, were the sole moisture source (Fig. 2). Plant source water must have been ^2H -enriched prior to leaf wax biosynthesis. We infer that the high $\delta^2\text{H}_{\text{wax-TIV}}$ values at 15 ka were caused by two factors related to aridity: 1. ^2H -enrichment of all moisture sources as they traveled over a more arid landmass and incorporated ^2H -enriched soil moisture and groundwater, a process that occurs today in extremely arid regions west of Lake Qinghai (Araguás-Araguás et al., 1998), and 2. Increased evaporative ^2H -enrichment of soil and leaf water prior to leaf wax biosynthesis (Kahmen et al., 2013). Both of these mechanisms can ^2H -enrich plant source water by 30 to 40‰, and so could explain the observed high $\delta^2\text{H}_{\text{wax-TIV}}$ values. This arid period may be due to an unusual combination of weak westerly winds and minimal monsoon precipitation east of Lake Qinghai, which in turn decreased local vapor transport to Lake Qinghai.

Although the evidence for aridity at 15 ka is particularly dramatic in Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$, multiple proxies indicate that central China and the northeastern Tibetan Plateau were arid around 15-14 ka (Figs. 2 and 3). The western Chinese Loess Plateau contains small grain size and low magnetic susceptibility at 15 ka, evidence for simultaneous weak westerly winds and low summer monsoon precipitation (Sun et al., 2012). Annual precipitation amount inferred from meteoric ^{10}Be on the central Chinese Loess Plateau decreased by 50 mm/yr at this time (Fig. 2) (Zhou et al., in press). Additionally, soil formation in the Lake Qinghai catchment ceased from 17 to 12.2 ka, indicating cold, dry conditions (X. J. Liu et al., 2012). Pollen-based precipitation

reconstructions at lakes Luanhaizi and Kuhai show that precipitation was low but increasing at 15 ka (Herzschuh et al., 2010; Wischniewski et al., 2011). The pollen-based precipitation reconstruction at Donggi Cona, 200 km southwest of Lake Qinghai, contains evidence for a brief, severe arid period ca. 14 ka (Fig. 3) (Y. Wang et al., 2014). Lake Koucha near Lake Qinghai also contains a ^{18}O - and ^2H -enriched interval ca. 15 ka (Figs. 2 and 3) (Aichner et al., 2010; Yu et al., 2009).

Synchronous weak westerlies and summer monsoon winds would be unusual, because during the Pleistocene, the summer monsoon is usually weak when westerly winds are strong (An et al., 2012; Sun et al., 2010). There is evidence from the Chinese Loess Plateau for simultaneous weak winter winds and summer monsoon during several Pleistocene glacial periods (e.g., Marine Isotope Stage 10 and 11) (Hao et al., 2012). Weaker westerlies were caused by reduced Arctic snow and ice and a weaker summer monsoon on the Chinese Loess Plateau was due to a longer transport path resulting from lower sea level (Hao et al., 2012). These conditions may have also existed from 15-14 ka: Northern Hemisphere snow and ice cover was reduced during the warm Bølling oscillation, and sea level began to rise as a result of Meltwater Pulse 1A at 14.5 ka (Deschamps et al., 2012; Rasmussen et al., 2006). Lake Qinghai is north of the modern extent of summer monsoon rains and wind, so $\delta^2\text{H}_{\text{wax-TIV}}$ may capture a brief interval when westerlies were weakening as glacial conditions waned (Sun et al., 2012), and the summer monsoon had not yet reached this far northwest (Wang et al., 2010). Extreme aridity would have resulted in increased evaporative enrichment of plant source water and leaf water, resulting in the observed high $\delta^2\text{H}_{\text{wax-TIV}}$ values.

5.1.3 Penetration of summer monsoon precipitation to the northeastern Tibetan Plateau by 13.6 ka

Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ returned to relatively low values by 13.6 ka (-180‰). In conjunction with independent evidence for warmer conditions, increased precipitation, and weaker westerly winds, we interpret these low $\delta^2\text{H}_{\text{wax-TIV}}$ values to indicate summer monsoon moisture reaching the northeastern Tibetan Plateau.

The $\delta^2\text{H}_{\text{wax-TIV}}$ record helps to clarify when summer monsoon precipitation first reached this region. Most records contain evidence for a large precipitation increase at the end of the Younger Dryas, although some records show precipitation increases prior to the Younger Dryas. The

oldest deglacial soil in the Lake Qinghai catchment is dated to 12.2 ka; climate was likely cool and arid before then (X. J. Liu et al., 2012). Percent carbonate (%CaCO₃) and %TOC from several sites in Lake Qinghai increased slightly at 14 ka, but increased dramatically at 11.5 ka (Fig. 2) (An et al., 2012; Liu et al., 2014; X. J. Liu et al., 2013). These records are interpreted as an increase in river inflow (%CaCO₃) and as lake water freshening (%TOC) due to an influx of summer monsoon moisture (An et al., 2012; Liu et al., 2014; X. J. Liu et al., 2013). These studies infer that summer monsoon moisture was likely present in small amounts prior to the early Holocene, but the greatest increase in monsoon moisture occurred at the Younger Dryas-Holocene transition.

Multiple proxies from sites throughout the northeastern Tibetan Plateau suggest that precipitation began to increase prior to the Younger Dryas. Annual precipitation amount inferred from ¹⁰Be on the Chinese Loess Plateau increased rapidly by >100 mm/yr at 14 ka (Zhou et al., in press). Pollen from lakes on the northeastern Tibetan Plateau also indicates moist conditions starting before the Younger Dryas (Figs. 2 and 3) (Herzschuh et al., 2010; Y. Wang et al., 2014; Wischnewski et al., 2011). C₄ plants, pollen, C₂₈ *n*-acid, and C₃₇ alkenone concentrations in the Lake Qinghai catchment began increasing ca. 13.8 ka, indicating a period of greater primary productivity caused by warmer, wetter conditions (Figs. 2 and S2). Lake Qinghai ostracode δ¹⁸O is ¹⁸O-depleted relative to surrounding intervals ca. 13.5 ka, indicating increased moisture availability at that time (Fig. 2) (Liu et al., 2007). In eastern China, cave δ¹⁸O is ¹⁸O-depleted 14–13 ka, interpreted as stronger monsoon circulation (Caley et al., 2014; Dykoski et al., 2005; Wang et al., 2001). In addition, climate on the Chinese Loess Plateau was reaching interglacial conditions by 14 ka, characterized by warm conditions and weak westerly winds (Peterse et al., 2011; Sun et al., 2012). The TraCE-21ka transient climate model simulation indicates that warm, wet growing season conditions were established by ca. 14 ka in response to increasing Northern Hemisphere summer insolation (Fig. S2). At 14 ka, δ²H_{wax-TIV} is 10‰ lower than during the glacial period, which could be caused by even a small (10%) increase in monsoon precipitation to Lake Qinghai. The summer monsoon is the most likely source of ²H-depleted moisture, since there is strong evidence for increased precipitation amount, warm climate, and weak westerly winds at this time. We hypothesize that the combination of weakening westerly winds at 14 ka (Chiang et al., 2015; Sampe and Xie, 2010; Sun et al., 2012) and increasing summer insolation

allowed small amounts of summer monsoon moisture to reach the Lake Qinghai catchment prior to the Younger Dryas.

5.1.4 Summer monsoon precipitation decreased on the northeastern Tibetan Plateau during the Younger Dryas (13.2 to 11.4 ka)

The period from 13.2 to 11.4 ka was characterized by a 10‰ ^2H -enrichment of $\delta^2\text{H}_{\text{wax-TIV}}$ to $170 \pm 2\text{‰}$ at Lake Qinghai, likely due to a return to glacial-like conditions. We infer that the summer monsoon retreated off the northeastern Tibetan Plateau, leaving arid conditions characterized by local- and northwesterly-derived moisture and greater evaporative enrichment. Lake Qinghai ostracode $\delta^{18}\text{O}$ became 1‰ ^{18}O -enriched during this interval (Fig. 2), indicating arid conditions and corroborating the $\delta^2\text{H}_{\text{wax-TIV}}$ record. Leaf wax and alkenone concentration, %TOC, and % CaCO_3 from Lake Qinghai show a decline in terrestrial and aquatic productivity and a decline in river inflow from 13.2 to 11.4 ka (Figs. 2 and S2), also indicating arid conditions. Low-resolution pollen records from lakes Luanhaizi, Kuhai, and Donngi Cona may not have captured this brief interval, but show moderate, stable precipitation amount during this period (Fig. 3) (Herzschuh et al., 2010; Y. Wang et al., 2014; Wischniewski et al., 2011). Climate on the Chinese Loess Plateau also returned to near glacial values, with low precipitation amount and stronger westerly winds (Fig. 2) (Sun et al., 2012; Y. Wang et al., 2014; Zhou et al., in press). We interpret this relatively dry interval with ^2H -enriched $\delta^2\text{H}_{\text{wax-TIV}}$ as a response to the Younger Dryas event (Johnsen et al., 2001). An isotopically enriched Younger Dryas is also expressed in cave $\delta^{18}\text{O}$ records throughout Asia (Dong et al., 2010; Dykoski et al., 2005; Shakun et al., 2007; Sinha et al., 2005; Wang et al., 2008, 2001; Y. Yang et al., 2010). The dry climate and low precipitation isotope values in East Asia during the Younger Dryas have been interpreted as a response to increasing westerly wind strength resulting from weaker Atlantic Meridional Overturning Circulation (Liu et al., 2014; Sun et al., 2012).

5.1.5. The early Holocene (11.2 to 7.0 ka) was dominated by summer monsoon precipitation, which decreased during the late Holocene (7.0 ka to present)

The early Holocene on the northeastern Tibetan Plateau is characterized as wet and warm, followed by cooler, more arid conditions during the late Holocene, a finding which is supported by $\delta^2\text{H}_{\text{wax-TIV}}$ at Lake Qinghai and $\delta^2\text{H}$ of alkanes from Hongyuan peat bog in eastern Tibet (Fig.

2) (An et al., 2012; Dietze et al., 2013; Herzsuh, 2006; X. J. Liu et al., 2013, 2012; Seki et al., 2011; Y. Wang et al., 2014; Zhou et al., in press). Penetration of summer monsoon moisture onto the Tibetan Plateau has been suggested as the cause of the wet early Holocene (An et al., 2012; Liu et al., 2014; X. J. Liu et al., 2013; Y. Wang et al., 2014). Low $\delta^2\text{H}_{\text{wax-TIV}}$ values ($-195 \pm 5\text{‰}$) 11.2 to 7.0 ka were likely caused by an increase in ^2H -depleted monsoon moisture at Lake Qinghai. The increase in monsoon moisture would increase total growing season rainfall in this region. The resulting moist atmosphere would drive less raindrop re-evaporation, thus preserving the ^2H -depleted monsoon source signature. Further evidence for an early Holocene increase in summer monsoon precipitation is the proliferation of C_4 plants in the Lake Qinghai catchment. Whereas C_3 plants thrive in cool, wet conditions, C_4 plants thrive during warm, wet growing seasons. C_4 plants are therefore more abundant than C_3 plants in regions with warm, wet summers and low spring rainfall (Ehleringer et al., 1997). C_4 plants composed ca. 50% of terrestrial vegetation around Lake Qinghai from 11.4 to 5 ka (Fig. S2) (Thomas et al., 2014b), indicating that summer monsoon precipitation was particularly strong during the early Holocene, because the monsoon is the only moisture source that could result in an increase in summer precipitation amount without increasing spring rainfall (Fig. 1). Thus, low $\delta^2\text{H}_{\text{wax-TIV}}$ supports the hypothesis that summer monsoon precipitation was enhanced on the northeastern Tibetan Plateau during the early Holocene.

This evidence for wet conditions on the northeastern Tibetan Plateau in the Early and mid Holocene apparently conflicts with $\delta^{13}\text{C}$ records from Lake Qinghai that have been interpreted to represent lake level changes (Liu et al., in press, 2015; W. Liu et al., 2013). Bulk organic carbon and *n*-alkane carbon isotope records from Lake Qinghai are both ^{13}C -enriched in the early Holocene and have been interpreted to indicate an increase in aquatic plant productivity and therefore lower lake levels during the early Holocene (Liu et al., in press; W. Liu et al., 2013). Although aquatic plant contribution to lacustrine organic matter likely occurred during the early Holocene, aquatic primary productivity has been interpreted to increase in response to lake water freshening, rather than lower lake levels (An et al., 2012; Liu et al., 2014; X. J. Liu et al., 2013). In addition, *n*-alkanoic acid $\delta^{13}\text{C}$ from Lake Qinghai showing similar changes as the *n*-alkane $\delta^{13}\text{C}$, but without some of the complications that aquatic plants introduce in the *n*-alkane record, has been interpreted to indicate changes in C_4 plant abundance (Thomas et al., 2014b). One piece of evidence that has been cited to indicate dry conditions may instead indicate wet early

Holocene conditions: an increase in early Holocene optically stimulated luminescence-based aeolian sand ages around Lake Qinghai is likely due to vegetation growth and soil development that stabilized sand deposits that, prior to the Holocene, had been unstable and therefore continuously reset (X. J. Liu et al., 2012; Lu et al., 2011). Lake Qinghai ostracode $\delta^{18}\text{O}$ and $\delta^2\text{H}_{\text{wax-TIV}}$ are low during the early Holocene (Fig. 2) (Liu et al., 2007), indicating that Lake Qinghai was not evaporatively enriched and that the early Holocene was wetter due to incursion of summer monsoon moisture onto the northeastern Tibetan Plateau. Furthermore, *n*-alkane $\delta^2\text{H}$ at Hongyuan peat bog suggests that maximum Holocene precipitation occurred during the early Holocene (Seki et al., 2011), supporting our inference that summer monsoon precipitation was greatest at Lake Qinghai during the early Holocene, so lake levels were likely high during the Early Holocene.

If, however, the lake level interpretations of bulk and *n*-alkane $\delta^{13}\text{C}$ are correct and Lake Qinghai was low during the early Holocene, the discrepancy between low lake level and increased precipitation will have to be explained. Model experiments testing the sensitivity of lake levels in the northeastern United States to precipitation seasonality and transpiration rates suggest that increased summer precipitation and transpiration can cause lower lake levels (Shuman and Donnelly, 2006). Because plants uptake water without ^2H fractionation (Ehleringer and Dawson, 1992), the early Holocene increase in summer plant productivity (Figs. 2 and S2) could have removed water from the Lake Qinghai catchment, resulting in lower lake levels, without causing a ^2H - or ^{18}O -enrichment of lake water. Further research is needed to reconcile the apparent disagreement between the interpretations of bulk and *n*-alkane $\delta^{13}\text{C}$ records and other paleoclimate proxy evidence.

Following the monsoon-dominated early Holocene, Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ recorded stepwise enrichments ca. 7.0, 5.0, and 2.6 ka, indicating declines in summer monsoon precipitation and increasing aridity at Lake Qinghai. Asian cave $\delta^{18}\text{O}$ records also show an ^{18}O -enrichment of late Holocene precipitation relative to the early Holocene, interpreted as increasing aridity (Fig. 2) (Cai et al., 2010; Cheng et al., 2012; Dong et al., 2010; Dykoski et al., 2005; Fleitmann et al., 2007; Yuan et al., 2004), but perhaps also linked to changing moisture sources (Maher, 2008). Decreasing $\delta^{13}\text{C}_{\text{wax}}$ at Lake Qinghai indicates that C_4 plants declined to near zero abundance by the mid-Holocene, likely due to drier summers (Fig. S2) (Thomas et al., 2014b). Multiple proxies suggest that the late Holocene on the northeastern Tibetan Plateau was

drier than the early Holocene due to the retreat of monsoon precipitation out of this region (An et al., 2000; Chiang et al., 2015; Morrill et al., 2003; X. Yang et al., 2010; Zhou et al., 2015). The modern circulation regime, with local and northwesterly air masses as the dominant moisture sources to the Lake Qinghai catchment, was established around 2.6 ka, as indicated by $\delta^2\text{H}_{\text{wax-TIV}}$ values similar to modern.

The pattern of a strong summer monsoon in the early Holocene and weakening monsoon strength into the late Holocene suggests forcing by summer insolation. The TraCE-21ka transient climate model simulation indicates that growing season precipitation decreased gradually throughout the Holocene in the region around Lake Qinghai in response to decreasing summer insolation (Fig. S2). Threshold changes in proxies at the onset of the Holocene and from early to late Holocene may be indicative of either a threshold response of the climate system to the linear decrease in insolation forcing, or a threshold response by the proxies. Since multiple proxies contain a dramatic precipitation increase at the onset of the Holocene, there was likely a rapid response by the climate system (Morrill et al., 2003). Some proxies (e.g., %TOC and %CaCO₃) contain a much more dramatic response than others (e.g., $\delta^2\text{H}_{\text{wax-TIV}}$ and pollen-inferred precipitation). This may suggest that %TOC and %CaCO₃ experienced threshold responses to the precipitation increase at the onset of the Holocene, so inferences based on these proxies alone may overestimate the magnitude of precipitation change. This finding highlights the utility of multiproxy studies as robust indicators of climate system change. Isotope proxies are useful indicators of precipitation source area changes, an aspect of the climate system that most other proxies cannot reconstruct.

6.1 Conclusions

Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ supports previous reconstructions of dramatic hydroclimatic change on the northeastern Tibetan Plateau during the past 30 kyr, and provides insights into the sources of precipitation and forcing mechanisms that cause hydroclimatic changes. The arid glacial period was dominated by local and northwesterly precipitation. An extreme ^2H -enrichment at 15-14 ka indicates extreme aridity, likely linked to weak precipitation from all source areas. This is unusual, as westerly and summer monsoon winds are generally anti-phased. There are a few times during the Pleistocene when westerly and summer monsoon winds were both weak in central China, likely due to longer monsoon transport paths linked to lower sea levels and a weak

westerly jet linked to small Northern Hemisphere snow and ice cover (Hao et al., 2012). As northern hemisphere summer insolation increased, summer monsoon precipitation reached the northeastern Tibetan Plateau, but did not become a significant moisture source until the early Holocene when northern hemisphere summer insolation was high and westerly winds were weak. Local and northwesterly air masses gradually became the dominant moisture sources as summer monsoon precipitation retreated off of the northeastern Tibetan Plateau throughout the Holocene. The Lake Qinghai $\delta^2\text{H}_{\text{wax-TIV}}$ record illustrates the utility of precipitation isotope proxies in inferring changes in source area and complex hydroclimatic dynamics in East Asia.

Acknowledgements:

We thank R. Taroza for lab assistance, the ICDP, the US and China National Science Foundations, the Ministry of Science and Technology of China for their support for the Lake Qinghai Drilling Project, Z. Liu and B. Otto-Bliesner for sharing CCSM3 output, and Phil Meyers and an anonymous reviewer for comments. TraCE-21ka was made possible by the DOE INCITE computing program, and supported by NCAR, the NSF P2C2 program, and the DOE Abrupt Change and EaSM programs. This research was funded by NSF grant #ATM-0902805 to YH, NSF grant #EAR-0602412 to SMC, and an NSF Graduate Research Fellowship to EKT.

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Figure captions

1. Location map and modern climate on the northeastern Tibetan Plateau. A. Digital elevation model of Lake Qinghai and surroundings (white is high elevation, black is low elevation) (USGS, 2004). Catchment outlined in black, Lake Qinghai at 2010 AD elevation (Google Earth, 2010). Location of LQDP05 drill cores shown with white bulls-eye, Zhangye Global Network of Isotopes in Precipitation (GNIP) station shown with black dot outlined in white, sites mentioned in text shown with white dots outlined in black. Inset: Location of lakes Qinghai (Q) and Koucha (LK), Dongge (D) and Hulu (H) caves, and Mangshan (M) on the Chinese Loess Plateau. Tibetan Plateau shown in light gray. B. Precipitation sources for the Lake Qinghai catchment, grouped by cluster analysis into three distinct trajectory directions: Local, Northwesterly, and Southerly (summer monsoon). The trajectories from the southwestern edge of the Himalaya are grouped with the westerlies because they occur during the dry season. C. Monthly temperature (red), precipitation (gray bars) and $\delta^2\text{H}_p$ (black triangles) at Zhangye GNIP station. D. Amount (mm) of monthly precipitation that falls at Lake Qinghai as a result of the three trajectories in B. Dashed box highlights growing season months April to Sept. Southerly air masses contribute 16% of total growing season precipitation (IAEA/WMO, 2011; Kalnay et al., 1996).
2. Lake Qinghai and regional paleoclimate reconstructions. Horizontal bars at the top indicate inferred strength of summer monsoon precipitation; black indicates stronger precipitation. A. Lake Qinghai $\delta^2\text{H}_{\text{wax}}$. White dots are raw data, bold black curve with gray error shading has ice volume and temperature removed. White lines and vertical black or gray bars are hypothetical $\delta^2\text{H}_{\text{wax}}$ values and ranges if plants were to use precipitation from a single source area, values calculated using an ε_{app} of -110‰, from Xia et al. (2008), modified to account for growing season; snow, winter snowfall; SM, summer monsoon; LH, local rainfall without raindrop re-evaporation; LA, local rainfall with raindrop re-evaporation. Horizontal black and gray bars are ^{14}C age constraints, shown with 1σ calibrated range; gray arrows and numbers indicate reservoir correction applied to ages of the same shade, Holocene ages had a 135-year reservoir correction; black stars indicate ^{14}C ages that are > 20 kyr older than their depositional age based on this age model (An et al., 2012). Fine black curve is maximum annual insolation at 35° N (Laskar et al., 2004). B. Ostracode $\delta^{18}\text{O}$ (Liu et al., 2007). C. Percent carbonate (An et al.,

933 2012). D. Percent organic carbon (An et al., 2012). E. C_{28} *n*-acid concentration. F. $\delta^{18}O$
 934 carbonate from Hulu and Dongge caves (Dykoski et al., 2005; Wang et al., 2001). G. Annual
 935 precipitation on the Chinese Loess Plateau inferred from meteoric ^{10}Be (Zhou et al., in press). H.
 936 Mean grain size (black) and magnetic susceptibility (gray) at Gulang on the Chinese Loess
 937 Plateau (Sun et al., 2012). I. Mean annual air temperature anomaly relative to late Holocene from
 938 Mangshan on the Chinese Loess Plateau (Peterse et al., 2011). Vertical gray bars indicate
 939 Heinrich events and the Younger Dryas, as defined in the Hulu Cave record (Wang et al., 2001).
 940 3. Lake Qinghai and regional paleoclimate reconstructions for the deglacial period. A.
 941 Inferred strength of summer monsoon precipitation. Black indicates stronger precipitation. B.
 942 Lake Qinghai $\delta^2H_{wax-TIV}$ (solid line, gray error shading). Lake Koucha δ^2H_{wax} (dashed line)
 943 (Aichner et al., 2010). C. Lake Qinghai percent organic carbon (An et al., 2012). D. Pollen-
 944 inferred precipitation from lakes on the northeastern Tibetan Plateau (Herzschuh et al., 2010; Y.
 945 Wang et al., 2014; Wischniewski et al., 2011). E. $\delta^{18}O$ carbonate from Hulu and Dongge caves
 946 (Dykoski et al., 2005; Wang et al., 2001). Vertical gray bars indicate Heinrich Event 1 and the
 947 Younger Dryas, as defined in the Hulu Cave record (Wang et al., 2001).

Figure 1

Figure 2

Figure 3