The primacy of multidecadal to centennial variability over late-Holocene forced change of the Asian Monsoon on the southern Tibetan Plateau

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Abstract

The nature of multidecadal to centennial variability of the Asian monsoon is largely unknown, hindering our understanding of how the modern precipitation regime compares to preindustrial variability, as well as how the Asian monsoon may change in coming decades. Here we use the sediment record from a closed-basin lake in southern Tibet, Ngamring Tso, along with other published paleoclimatic records, to assess summer monsoon precipitation variability over the 20th century and during the late Holocene (4100 cal yr BP to present). The first principal component of the Ngamring Tso grain size record, which is highly correlated with median grain size, correlates significantly with observed summer (June-September) precipitation. From CE 1940 to 2007, grain size decreased with increasing summer precipitation and increased with decreasing summer precipitation. Satellite images of Ngamring Tso reveal larger lake area in the 1970s and 2000s and smaller lake area in the 1980s and 1990s, suggesting monsoon precipitation-induced changes in lake depth or area likely govern grain size variability. In the context of the last 4100 years, prolonged periods of relatively weak summer monsoon precipitation occurred from 2800-2600 cal yr BP, 2500-2300 cal yr BP, and 1600-400 cal yr BP. A trend toward increased summer precipitation began around 1000 cal yr BP, with above-average summer precipitation from 400 cal yr BP to present, peaking between 200-100 cal yr BP (CE 1750-1850). Dry and wet periods are coincident with dry and wet periods in other south-central Tibetan lake sediment records that reflect precipitation or moisture balance, and with regional proxies of the ISM and EASM, indicating south-central Tibet is influenced by both monsoon subsystems. However, western Tibet lake sediment records do not covary with the Ngamring Tso record, suggesting the spatial variability in Tibet precipitation that occurs on interannual timescales today may also characterize precipitation on multidecadal and centennial

timescales during the late Holocene. 20th century precipitation variability in southern Tibet falls within the range of natural variability in the last 4100 years, and does not show a clear trend of increasing precipitation as projected by models. Instead, it appears that poorly understood multidecadal to centennial internal modes of monsoon variability remained influential throughout the last 4100 years. Thus, substantial multidecadal to centennial-scale hydroclimatic variability will complicate our ability to project and prepare for anthropogenic changes in the region's monsoon precipitation.

1 Introduction

A warming trend from the mid 20th century to present is strongly apparent across the Tibetan Plateau (Xu et al., 2008) and is projected to continue into the future (Christensen et al., 2013). This recent warming has already had profound effects on the landscape, manifested as changes in glacial and lake surface area (Li et al., 2008; Liu et al., 2009) across this high-elevation region. Although there is strong evidence for increasing temperature across the Tibetan Plateau, observed trends in precipitation are less clear and spatially variable, given the few long-term instrumental precipitation records available and the general heterogeneity that defines spatial precipitation variability. One analysis suggests a decline in annual precipitation in the western Tibetan Plateau and an increase in the eastern Tibetan Plateau from CE 1961-2001 (Xu et al., 2008), supporting the hypothesis that precipitation variability on seasonal and interannual timescales is different in eastern and the western regions of the plateau (Conroy and Overpeck, 2011). Another synthesis of station-based precipitation trends from CE 1979-2001 shows increasing precipitation during spring, summer, and fall across the entire Tibetan Plateau, with the most dramatic increase occurring in the southeast relative to the northwest (You et al., 2014). However, (You et al., 2014) highlight differences in the magnitude and direction of precipitation trends in different merged satellite-gauge products and reanalysis datasets.

Climate projections for the 21st century show increasing warm season precipitation across the Tibetan Plateau (Christensen et al., 2013). This projected increase is partly due to projections of increasing ISM and EASM precipitation, but it remains difficult to evaluate the nature of ongoing trends in precipitation on the Tibetan Plateau in the face of limited observational data, which often do not even span the entire 20th century. Across monsoon Asia, instrumental records fail to clearly support projections of increasing warm season precipitation, perhaps because of

black carbon and/or sulfate aerosols, land-use, and poorly understood sea surface temperature (SST) change (Christensen et al., 2013). Well-dated, high temporal resolution paleoclimate records of past precipitation variability are needed to place late 20th-century instrumental perspectives in a broader context of natural monsoon variability, and to improve our understanding of how the Asian monsoon may change in the future. A wealth of paleoclimate indicators of past precipitation, moisture balance (precipitation – evaporation), and atmospheric circulation have been developed from across the Tibetan Plateau and adjacent monsoon regions (e.g., (Anderson et al., 2002; Bird et al., 2014; Cai et al., 2012; Chen et al., 2008; Dykoski et al., 2005; Fleitmann et al., 2003; Gupta et al., 2005; Kasper et al., 2012; Mischke et al., 2010; Morrill et al., 2003; Morrill et al., 2006; Mugler et al., 2010; Overpeck et al., 1996; Shen et al., 2008; Wang et al., 2005; Wei and Gasse, 1999; Zhao et al., 2010). Although many of these records focus on millennial, orbitally-forced changes in monsoon strength over the Holocene, they collectively suggest that natural multidecadal to centennial variation in the monsoon in some cases overwhelmed variability simply forced by changes in the Earth’s orbit. Here we test this conclusion and the implication that changes in monsoon precipitation driven by multidecadal to centennial modes internal to the climate system could be an important component of monsoon variability into the future.

The emerging view of Tibetan precipitation variability through the Holocene, deduced primarily from lake sediment indicators of past moisture balance, indicates a precipitation maximum in the early Holocene, as boreal summer insolation peaked, and a subsequent decline in precipitation through the mid-Holocene, with evidence for a gradual retreat of maximum moisture from northwest to southeast (Bird et al., 2014; Mugler et al., 2010). The spatial heterogeneity of precipitation observed on recent time scales has also been detected in a

compendium of past lake area maxima across the Tibetan Plateau: in western Tibet, lake area increased substantially more relative to lake area in eastern Tibet during the early Holocene, suggesting greater precipitation in the west relative to the east (Hudson and Quade, 2013). However, while some clear patterns of Holocene millennial-scale changes in Tibetan Plateau moisture have emerged, the spatial patterns of multidecadal to centennial summer precipitation over the Holocene are still unclear. In addition, few records of past precipitation or moisture balance on the Tibetan Plateau have been calibrated with instrumental data (e.g., (Zhao et al., 2008), limiting interpretive efforts. Hence, previous interpretations of past monsoon variability, especially in the southern Tibetan Plateau, remains largely qualitative.

Here we present a new monsoon precipitation proxy record from Ngamring Tso. This record is unique in that it spans millennia, but captures the 20th century in high temporal resolution, allowing us to relate recent changes in lake sediment properties to instrumental precipitation data and obtain a richer perspective on the nature of 20th century precipitation in the context of long-term, natural variability. Most importantly, we demonstrate a quantitative relationship between the dominant component of the lake sediment grain size record and instrumental precipitation, producing a calibrated reconstruction of past summer precipitation. Such a record permits consideration of monsoon precipitation variability at timescales meaningful for anticipating future precipitation variability on the southern Tibetan Plateau. In the following sections we present the new record from Ngamring Tso, show its relationship with observed precipitation, examine the interpretation of this new record in the context of other regional paleoclimate records, and discuss the implications for future hydroclimate of the southern Tibetan Plateau.

2 Study Site

Ngamring Tso (29.30°N, 87.2°E, 4303 meters above sea level) is a closed basin lake located on the southern Tibetan Plateau, ~20 km north of the Yarlung Tsangpo River. Its maximum diameter, trending northwest-southeast, is 7.7 km. The Ngamring Tso watershed comprises 196 km² and is unglaciated, with several streams draining into the lake from higher elevation mountains to the north and south (Figure 1). As Ngamring Co is located in a watershed without glaciers, changes in lake hydrology are independent of the influence of glacial ice volume. The lake lies close to the Indus-Yarlung Suture Zone, in late Cretaceous clastic sedimentary rocks of the Xigaze forearc basin (Wu et al., 2010). The town of Ngamring sits along the eastern shore, with smaller villages located along the southern shore. In July 2007, near the center of the lake, surface temperature was 15.8°C, and declined to a minimum of 13.2°C between 9 and 11 m (Figure S1). Dissolved oxygen decreased with depth, and indicated an anoxic hypolimnion below 10 m (Figure S1). Conductivity was fairly consistent through the water column, ranging from 8.5 mS/cm at 1 m to 6.6 mS/cm between 8 and 11 m (Figure S1). Surface water pH was 9.0.

Mean temperature, precipitation and wind climatology for Ngamring Tso are presented in Figure 2, based on station data from Shigatse, 160 km east of Ngamring Tso (Peterson and Vose, 1997), 20th century V2 reanalysis (Compo et al., 2011) and the gridded Climate Prediction Center Merged Analysis of Precipitation (Xie and Arkin, 1997). In the 20th century reanalysis for 30.5-32.5°N, 87-89°E, mean monthly temperatures range from -17.5°C to 12.5°C, with above freezing temperatures from May to October (Figure 2A). Temperatures are warmer at Shigatse, as it is 450 m lower in elevation than Ngamring Tso. Satellite imagery indicates Ngamring Tso is typically ice covered from December through February. 500 mb winds are weakest and

189 southwesterly during the summer months, becoming stronger and more westerly in the winter
190 months (Figure 2C). The regional precipitation climatology is monsoonal, with the majority of
191 the annual precipitation (94% for station data, 87% for CMAP and 77% for 20th century
192 reanalysis) arriving from June to September (Figure 2B). Ngamring Tso is located on a boundary
193 where, to the west, seasonal precipitation and interannual variability are strongly correlated with
194 the Indian Summer Monsoon (ISM), and to the east, precipitation is correlated with the Western
195 North Pacific Monsoon (Conroy and Overpeck, 2011).

197 **3 Methodology**

198 In July 2007, we retrieved 3 cores, KH-1 (86 cm long), KH-2 (116 cm long), and KH-3
199 (42 cm long) from near the center of the lake (Figure 1) at 10.2 m water depth using a universal
200 gravity corer. 8.25 cm of surface sediments were extruded at 0.25 cm intervals from KH-1 and
201 5.50 cm were extruded from KH-3, which captured the undisturbed mud-water interface. Here
202 we report results from the longest cores, KH-1 and KH-2. The cores were split, imaged, and
203 measured for density and magnetic susceptibility using a GeoTek multi-sensor core logger at the
204 University of Rhode Island. We correlated cores KH-1 and KH-2 using magnetic susceptibility,
205 which indicates that KH-2 begins 22.0 cm below the mud-water interface (Figure S2).

206 An age model was constructed from ²¹⁰Pb and ¹³⁷Cs measurements on the top 30 cm of
207 core KH-1, as well as ¹⁴C measurements on bulk sediment organic matter and aquatic
208 macrophyte fragments from KH-1 and KH-2 (Figure 3). ²¹⁰Pb ages were calculated using the
209 constant rate of supply model (Appleby, 2001), which was validated with the ¹³⁷Cs bomb-spike,
210 representing the height of aboveground nuclear testing in AD 1963 (Figure 3A-B). ¹⁴C samples
211 were pretreated with the standard acid-base-base protocol, combusted, graphitized, and measured

at the University of Arizona AMS Lab. Reported ^{14}C ages were calibrated using INTCAL13 (Reimer et al., 2013). We created an age model using all of the above ages with Bacon 2.2 (Blaauw and Christen, 2011). Modern aquatic macrophyte ^{14}C ages indicate no reservoir effect, although a reservoir effect is found in bulk sediment organic matter (Table 1). The aquatic macrophytes are likely less prone to incorporation of old carbon due to incorporation of atmospheric carbon, if they are emergent or semi-emergent. A 1000 ± 100 year reservoir age for bulk sediment ^{14}C ages was calculated based on the difference between an aquatic macrophyte fragment at 7.4 cm and bulk sediment at 8.5 cm (1000 ^{14}C years), as well as the y-intercept value of 1080 ^{14}C years, determined from a linear regression of bulk sediment ^{14}C ages and depth (Figure 3C).

We measured particle size distribution, sediment mineralogy, elemental abundance, and weight percent loss on ignition down core to characterize terrigenous and authigenic sediment variability in Ngamring Tso. Particle size distributions were measured at 0.5 cm intervals. Samples were first pretreated with 10% HCl to remove calcium carbonate, 30% H_2O_2 to remove organic matter, and 1M NaOH to remove biogenic silica. The samples were then dispersed in a solution of DI water and sodium hexametaphosphate and measured on a Malvern Mastersizer 2000 at the University of Arizona. Each measurement is reported as the average of 5 consecutive measurements on five individual aliquots. Minerals present in samples from 1-2 cm, 30-31 cm, and 75-76 cm depth in KH-1 were identified using a Bruker D8 Advance Powder XRD at the University of Arizona. Elemental abundance was measured using an Eagle Edax scanning-micro XRF at the University of Arizona. XRF measurements on resin-embedded, slabbed sediment sections of KH-1 and KH-2 were taken at 100 μm intervals with a Mo X-ray source set to Kev = 40 and $\mu\text{A} = 285\text{-}485$. Dried, ground, and pelletized sediment from the extruded intervals of KH-

1 were measured five times at $\text{Kev} = 40$ and $\mu\text{A} = 325$. A section of resin-embedded, slabbed, laminated sediment from the top of KH-1 (11.5-9.75 cm) was also mapped to reveal the spatial variability of elemental abundance and the relationship between laminae type and elemental abundance. Mean pellet XRF anomalies were normalized to the mean resin-embedded sediment values for the topmost, laminated section of KH-1 (Figure S3). We also measured weight percent loss on ignition on 0.25 cc samples of bulk sediment at 1 cm intervals in cores KH-1 and KH-2 to estimate organic matter content. Samples dried at 60°C for 36 hours were weighed, combusted at 550°C for four hours, and then reweighed to estimate organic matter content.

20th century lake areas for Ngamring Tso were derived using 25 sequential georegistered Landsat images from 1972 to 2010 in ArcGIS, following the methods of Hudson and Quade (2013). Landsat images were obtained from the US Geological Survey online data repository (<http://earthexplorer.usgs.gov/>). Lake areas were extracted using a maximum-likelihood image classification routine to demarcate all pixels corresponding to dark-colored water bodies, then areas were calculated using an equal area map projection. The standard error in calculated area estimated from six independent classifications of the same image is 0.20 km^2 , and is similar for both older (1970s) Landsat Multispectral Scanner (MSS) images with 60 m pixel size, and Landsat Thematic Mapper (TM) images with 30 m pixel size (1980s to present). Fall season images (September to early December) were used to compile the annual lake area time series, where available, to eliminate cloud cover, snow and ice cover, and seasonal variations in lake area. For four years with no suitable fall images, spring images (March and April) were selected. Estimates of the magnitude of seasonal variation, based on lake areas for all 12 months for years 2005 and 2009, had standard deviations of 0.37 and 0.20 km^2 , respectively. This is not substantially greater than the standard error for the classification routine, suggesting the month of

observation should not introduce significant bias into the record.

4 Results

The majority of the Ngamring Tso sediment record, from 139.0 to 30.0 cm, is dark gray-brown, massive, fine silt. Occasional dark grey laminations of coarse material, with particularly prominent dark laminations, occur at 39.0 cm, 43.0 cm, 69.5 cm, and 77.5 cm. At 39.0 cm, the dark, coarse lamination contains abundant Cladocera ephippia. A major shift from massive to laminated sediment occurs at 30.0 cm depth, with mm- to sub-mm thick light brown and medium brown laminae from 30.0 cm to 0 cm. Within this section, occasional coarse, dark gray laminae, bounded by medium brown laminae, contain visible sand-sized grains, dark gray organic matter fragments, and red-brown chitinous insect fragments. The age model for the Ngamring Tso sediment cores extends to 4150 ± 300 (1σ) cal yr BP. The sedimentation rate within the laminated, uppermost sediment is 0.30 cm/yr. An abrupt change in sedimentation rate occurs at the transition from massive to laminated sediment at 30.0 cm, with an order of magnitude slower sedimentation rate (0.03 cm/yr) in the massive section. According to the age model, the transition to laminated sediment at 30.0 cm occurs at 39 cal yr BP (~CE 1910).

XRD results indicate the presence of quartz, muscovite, biotite, chlorite-serpentine, magnetite, and Mg-calcite throughout core KH-1, with no major differences in mineralogy between the three samples, with the exception of the absence of magnetite in the uppermost sediment sample. XRF elemental analysis indicates the presence of both clastic and carbonate-related elements in the Ngamring Tso sediment record. The first principal component of the Ngamring Tso XRF dataset explains 39.4% of the variance in the dataset and loads highly on Al, Si, K, Ti, and Fe abundances. The second principal component explains 21.5% of the variance in

the dataset and loads highly on Ca, Mn, and Sr. The elements strongly represented in the three types of laminations observed in the uppermost 30 cm of sediment indicate that the coarse, dark gray laminae contain sand-sized fragments high in Ca, Si, Fe, Ti, and K. The medium brown laminae contain relatively more Ca and Ti, whereas Ca and Si are absent in the light brown laminae, and Ti counts are reduced (Figure S4).

The average median grain size diameter of the Ngamring Tso sediment is $3.7 \pm 0.5 \mu\text{m}$ (Figure S5A). The first principal component of the grain size dataset explains 38.3% of its variance and loads highly on median grain size ($r = 0.90$, Figure S5B). Higher values of grain size PC1 indicate a greater abundance of larger diameter grains. The second principal component explains 25.9% of the grain size variance and loads most highly on clay-sized particles ($< 2 \mu\text{m}$ diameter, Figure S5C). The highest median grain size values in the Ngamring Tso sediment record occurred in two periods, from 2800-2600 cal yr BP and 2500-2300 cal yr BP. A prolonged period of higher median grain size values also occurred from 1600-400 cal yr BP, followed by a period of lower median grain size values from 200-100 cal yr BP. In the 20th century AD, we observe periods of lower median grain size from CE 1900-1915, 1960-1970, and 2000-2007.

Recent lake areas were reconstructed using intermittently available Landsat images for CE 1972-2010 and ranged from 17.65 km^2 to 23.27 km^2 over this period (Figure 5; Table 2). No images were available for years CE 1973-74, 1979-1986, 1991, and 1997-1998. Lake areas were highest during the mid-1970s, followed by a significant interval with no data. Lake area was less than 19.0 km^2 during late 1980s, declining to its smallest extent in 1996. By 1999, lake area had expanded to $>19.0 \text{ km}^2$ again, and increased steadily until 2005, after which lake area remained steady at $\sim 21.5 \text{ km}^2$. Lake area changes were associated with horizontal advance and retreat of

the shoreline from the core site by 150-1000 m, depending upon the steepness of the basin slopes.

5 Discussion

Millennia-length climate records are critical for understanding the full range of natural climate variability and the mechanisms behind this change. Records of past climate variability are made even more useful when there is a significant relationship of the proxy with instrumental climate records, although such demonstrated relationships remain rare in lake sediment records. Such a calibration framework also adds confidence to our understanding of covariation between a given proxy record, other uncalibrated records, and, in the case of monsoon Asia, allows us to provide more convincing evidence for coherent variability in the monsoon across broad regions. In the subsequent sections, we present such a calibration framework for the grain size record from Ngamring Tso, instrumental summer monsoon precipitation, and remotely sensed lake area estimates. We then interpret past variability in summer monsoon precipitation using the new record, and synthesize the new record with other records of inferred monsoon precipitation from across the Tibetan Plateau. Finally, we discuss potential forcing factors of the observed spatial and temporal variability in monsoon precipitation of the southern Tibetan Plateau.

5.1 Interpretation and calibration of sediment variables

We find that PC1 of the grain size record is significantly correlated with regional summer (JJAS) precipitation, which provides over three-quarters of the annual precipitation to this region (Figure 6). Prior to correlation with instrumental precipitation, we interpolated the 20th century portion of the PC1 time series to annual resolution and applied a 5-year low pass filter to

accommodate the interannual resolution of the age model during the 20th century. We then applied a 5-year low pass filter to the instrumental JJAS precipitation time series. PC1 of the grain size dataset and precipitation covary in the CE 1956-2007 Global Historical Climatology Network precipitation data from the nearby Shigatse station, the CE 1979-2007 CMAP dataset for 30-32.5°N, 87.5-90°E, and the CE 1940-2007 20th century reanalysis precipitation for 30.5-32.5°N, 87-89°E (Figure 6). The most significant relationship is found using the 20th century reanalysis precipitation from CE 1940-2007 ($r=-0.75$, $N=67$, $N_{\text{effective}}=7$, $p_{\text{effective}}=0.086$, with $p_{\text{effective}}$ accounting for autocorrelation). Prior to CE 1940, variance in the reanalysis precipitation time series diminishes substantially, suggesting a transition to unreliable data at this time. This decline in variance is also seen in average, Tibetan Plateau-wide (30°-40°N, 70-110°E) reanalysis precipitation (Figure S3), suggesting some data bias, likely due to extremely limited, if not completely absent, instrumental climate data from this remote region prior to the mid 20th century. Therefore, we only utilize precipitation data from CE 1940 to present.

The relationship between grain size and summer precipitation is such that greater JJAS precipitation coincides with lower PC1 values, and hence increased fine-grained sediment relative to coarse-grained sediment. Such a relationship in a large lake like Ngamring Tso suggests that during wet intervals, the lake area expands, effectively moving the higher-energy shoreline environment away from the center of the lake, where the sediment cores were taken. In addition, the weak relationship between terrigenous elemental abundance and particle size suggests the overall flux of terrigenous sediment into the lake cannot be invoked to interpret median grain size variability as it can in other, smaller lakes that receive greater streamflow relative to the surface area and water volume of the lake (Bird et al., 2014). XRF and organic carbon abundance data support the interpretation of periods of finer grain size as periods of

greater summer precipitation: periods of coarser grain size generally coincide with periods of increased calcium relative to terrigenous elements (Ca/Ti) and organic matter, which together suggest a shallower, more productive shoreline environment closer to the center of the lake during periods of deposition of larger diameter particles (Figure 4): the shallower water of a shoreline environment would likely mediate increased authigenic precipitation of calcium carbonate due to evaporation concentration. Reduced summer precipitation would also dilute solutes. Finally, greater productivity near the shoreline relative to the anoxic bottom waters of the deeper part of the lake could induce carbonate precipitation,

We test this hypothesis, namely, that increased summer precipitation drove an increase in lake area, using satellite data spanning CE 1972 to 2010. We find that satellite imagery shows changes of up to 1 km in shoreline location within the past forty years. Ngamring Tso was at its largest spatial extent in CE 1972, and at its smallest spatial extent in CE 1996 (Figure 5). Periods of greater lake area from CE 1986-2006 closely coincide with periods of increased summer precipitation, supporting the idea that increased precipitation drives increases in lake area. Although a complete lake budget, taking into account evaporation as well as surface and subsurface inflow and outflow, is beyond the scope of this study, it is clear these other factors also influence lake area, as observed from the relatively larger lake area in the 1970s, when summer precipitation amount was similar to the late 1990s-early 2000s. In observations, lake extent lags summer precipitation by 1-2 years. Our core data suggest a coincident relationship between grain size and summer precipitation, but this is consistent with the observed lag given the interannual age model error in the 20th century portion of the sediment record. At Ngamring Tso, there may also be more fine-grained sediment transported into the lake during periods of increased precipitation due to erosion of previous, fine-grained, lake highstand sediment, as

paleoshorelines extend along existing drainages up to 2 km from the current shoreline of Ngamring Tso.

5.2 Past summer precipitation variability

The relationship between Ngamring Tso grain size and JJAS precipitation allows us to extend our knowledge of precipitation variability beyond the period of instrumental observation, which, in the case of this part of the Tibetan Plateau, is only the mid 20th century. To do this, we used the relationship between PC1 and 20th century reanalysis JJAS precipitation anomalies from AD 1940-2007 to calibrate the PC1 grain size record in terms of precipitation from 4100 cal yr BP to present. A partial least squares model best fits the grain size-reanalysis precipitation dataset (Figures 6, S7). Reconstructed JJAS precipitation anomalies are plotted in Figure 7D. Shading indicates 2 σ error based on 10,000 bootstrapped iterations of the model.

Periods of relatively dry conditions characterized 2800-2600 cal yr BP, 2500-2300 cal yr BP, and 1700-400 cal yr BP. However, the grain size values in these periods are outside of the calibration range and thus have greater error (Figure 7D); that said, these periods must have been dry relative to the rest of the record. We observe an overall increasing trend in summer precipitation from 1000 cal yr BP to present, and the highest reconstructed summer precipitation occurred from 200-100 cal yr BP. Since that time, there has been a downward trend in summer precipitation. Despite the decline in JJAS precipitation since its apex at 200 cal yr BP (CE 1750), the 19th and 20th centuries still appear to be relatively wet in the context of the last 4100 years. However, we do not observe an upward trend in recent summer monsoon precipitation coincident with increased greenhouse gas forcing in the 19th-20th centuries. Such an increase in future monsoon precipitation with increasing greenhouse gas forcing is projected in model

simulations (Christensen et al., 2013). The lack of an upward trend in precipitation in the 20th century—a feature not reproduced by many models simulating observed Indian Summer Monsoon precipitation (Saha et al., 2014) thus suggests other forcing factors—internal or external—may play a strong role in driving multidecadal to centennial monsoon precipitation variability in southern Tibet.

5.3 Comparison of Ngamring Tso precipitation proxy and Tibetan lake sediment records

Syntheses of paleo-moisture and paleo-precipitation records from across the Tibetan Plateau show the late Holocene (4200 cal yr BP to present) was considerably more arid relative to the early-mid Holocene, due to a large-scale weakening of monsoon precipitation (Bird et al., 2014; Morrill et al., 2003; Mugler et al., 2010). This millennial scale weakening of the monsoon through the Holocene has been generally considered to be spatially coherent, with some evidence for a directional retreat over the course of 1-2 millennia (Mugler et al., 2010). Monsoon changes during the late Holocene are more difficult to synthesize, as significant spatial and temporal heterogeneity exists among records. In addition, sediment ages are subject to decadal and longer uncertainty, challenging comparison of independent records. Despite this inherent limitation, our dataset has the resolution, continuity, and calibration to add meaningful information to existing interpretations of past monsoon variability from Tibetan lake sediment records. Several high-temporal resolution hydroclimate records from the south-central Tibetan Plateau agree with our reconstructed JJAS precipitation record (Figure 7). The period of two large summer monsoon dry periods at Ngamring Tso, from 2800-2300 cal yr BP, coincide with evidence of two droughts in a pollen-based mean annual precipitation reconstruction from Co Ngion, a lake similar in size 500 km to the northeast of Ngamring Tso (Shen et al., 2008), as well as a decrease in inferred

precipitation from Paru Co, 500 km to the east of Ngamring Tso (Bird et al., 2014). A lake level reconstruction from Ngangla Ring Tso, a 500 km² lake 450 km to the northwest of Ngamring Tso, also shows a decline in lake level at 2300 cal yr BP, suggesting these droughts may have reduced lake level to its current levels or lower in this basin (Hudson et al., 2015). The $\delta^{18}\text{O}$ record from Tianmen Cave (Cai et al., 2012), the cave record closest to Ngamring Tso, does not overlap temporally with the 2800-2300 cal yr BP dry periods, but generally covaries with the Ngamring Tso precipitation reconstruction on multidecadal timescales over the short period of overlap between the two records. Lower $\delta^{18}\text{O}$ values in the Tianmen Cave record, interpreted as higher regional moisture availability, coincide with higher JJAS precipitation at Ngamring Tso (Figure S8). However, these dry periods are not observed in records from Nam Co, such as the median grain size plotted in Figure 7, or other moisture balance indicators (Kasper et al., 2012; Mugler et al., 2010). As Nam Co is far larger in size than Ngamring Tso, Paru Co, or Co Ngion, it may not archive high frequency variability in moisture balance or precipitation as well as small lakes. However, the prolonged period of lower summer monsoon moisture from 1600-400 cal yr BP observed at Ngamring Tso is seen in both the Paru Co and Nam Co records. An increasing trend in monsoon moisture from 1000-1500 cal yr BP toward present is also observed at Ngamring Tso, Co Ngion and Paru Co (Figure 7). Finally, a period of relatively high precipitation in the last 100-300 years is apparent in all four south-central Tibetan Plateau lakes, highlighting substantial centennial variation in the regional monsoon. This recent increase in monsoon precipitation is also revealed in the reestablishment of sediment deposition in Ahung Co following a late Holocene hiatus, due to prolonged dry conditions (Morrill et al., 2006).

Not all Tibetan lakes show the same variability as Ngamring Tso. In particular, lake records from the western Tibetan Plateau, such as Bangong Co and Sumxi-Longmu Co (Wei and

Gasse, 1999) do not show similar wet and dry periods in the late Holocene. This result is not surprising as asynchronous, east-west shifts in moisture have been observed in the context of recent (Conroy and Overpeck 2011), and millennial-scale variability over the Holocene. For example, there is evidence for a gradual orbitally-driven retreat of monsoon moisture from the NW to the SE over the early to mid Holocene, leading to dry conditions in western lakes such as Bangong Co and Sumxi-Longmu Co coincident with wetter conditions at eastern lakes, such as Lake Qinghai, Cuo Co, and Nam Co (Mugler et al., 2010). Larger changes in maximum lake area have also been observed in the western Tibetan Plateau relative to the east (Hudson and Quade, 2013). Thus, regional differences in the expression of monsoon moisture variability may also be manifested in lake sediment records on shorter timescales in the late Holocene. In addition, many lake sediment indicators are interpreted in the context of monsoon strength, but are not calibrated to instrumental precipitation or other monsoon indices, lending uncertainty to subsequent interpretations. For example, in glaciated basins, glacial melting may confound a precipitation or moisture balance signal in some proxies. In Ngamring Tso, the demonstrated relationship between particle size and observed summer monsoon precipitation quantitatively supports our interpretation of past monsoon variability, as does agreement with inferred monsoon moisture from many nearby records.

5.4 Role of monsoon subsystems, external, and internal forcing

Comparing our reconstruction with key speleothem and marine sediment-based monsoon records beyond the Tibetan Plateau offers additional insights into the nature of late Holocene monsoon variability archived in Ngamring Tso. In the domain of EASM, the $\delta^{18}\text{O}$ record from Dongge Cave in southwest China (Figure 7F) shows two weak monsoon periods coincident,

within age model error, with the two largest droughts at Ngamring Tso from 2800-2300 yr BP (Dykoski et al., 2005; Wang et al., 2005). Similar weak monsoon periods are also evident in the late Holocene Sanbao Cave speleothem (Dong et al., 2010), although another weak monsoon period occurred at 2000 yr BP, when we infer a stronger monsoon at Ngamring Tso (Figure S8). A hiatus in a speleothem record of the Holocene ISM (Fleitmann et al., 2003) also begins at 2800 yr BP, suggesting potential weakening of both the ISM and EASM at this time. However, the Arabian Sea *G. bulloides* record does not show a weakening of ISM circulation during the large droughts from 2800-2300 cal yr BP (Gupta et al., 2005).

The prolonged dry period from 1600-400 cal yr BP observed at Ngamring Tso, Paru Co, and Nam Co coincides with higher $\delta^{18}\text{O}$ values from Qunf Cave (Fleitmann et al., 2003), suggesting a weakened ISM, although the Arabian Sea *G. bulloides* record shows an increase in inferred ISM circulation (Anderson et al., 2002; Gupta et al., 2003). A weaker than average EASM is also inferred from the Dongge Cave $\delta^{18}\text{O}$ and detrended Sanbao Cave record during this time period (Dong et al., 2010; Dykoski et al., 2005; Wang et al., 2005). From 400 cal yr BP to present, both ISM and EASM proxies indicate increasing monsoon strength, particularly from 300-100 yr BP, a period that predates anthropogenic greenhouse impacts. The coincidence of dry and wet periods in both the ISM and EASM subsystems and in south-central Tibet suggests this region is influenced by both monsoon subsystems. However, this comparison highlights the complexity of interpreting drivers of monsoon variability on the Tibetan Plateau during the Holocene: precipitation variability in the ISM and EASM may not always be synchronous, and may influence the Tibetan Plateau at differing magnitudes during the Late Holocene. Furthermore, the magnitude and direction of monsoon circulation changes, such as that inferred

from marine foraminifera, may be oppose those of monsoon precipitation, a scenario also projected with future anthropogenic warming (Christiansen et al., 2013).

The nature of the multidecadal to centennial variability in the Ngamring Tso record highlights a limited forcing role for orbital changes over the late Holocene (Figure 8). Multidecadal changes in solar irradiance could have also influenced the magnitude of monsoon precipitation (Gupta et al., 2005). A comparison of total solar irradiance anomalies (Steinhilber et al., 2012) and Ngamring Tso precipitation proxy record shows mixed results. The two time series are not strongly correlated ($r=0.17$, $N=166$, $p=0.028$ for 25-year interpolated data), and there is not a periodic, significantly coherent component across both records (Figure S9). However, the two largest dry periods at 2800-2600 cal yr BP and 2500-2300 cal yr BP do coincide, within age model error, with two large solar anomalies (Figure 8). Thus, larger magnitude negative solar irradiance anomalies could contribute to dry periods in southern Tibet, either by a direct mechanism, such as reduced sensible heating of the Tibetan Plateau (Li and Yanai, 1996), or an indirect mechanism, such as the effect of climate in teleconnected regions, like the North Atlantic (Fleitmann et al., 2003; Wang et al., 2005). The sequence of lower solar anomalies from 1500-300 cal yr BP also coincides with the most prolonged period of reduced monsoon precipitation. If solar anomalies did contribute to this prolonged dry period at Ngamring Tso, other factors must have played a role in sustaining it. Thus in sum, while there is some evidence for solar irradiance as a driver of late Holocene monsoon precipitation anomalies in southern Tibet, the observed multidecadal to centennial variability also points to a role for internal variability in shaping the spectrum of monsoon precipitation through the late Holocene.

What type of internal variability can contribute to monsoon precipitation variability on multidecadal to centennial timescales? Ocean-atmosphere variability is typically implicated as

the most important internal source of multidecadal to centennial monsoon variability: Tropical Indo-Pacific ocean-atmosphere circulation influences Asian monsoon precipitation on interannual timescales (Webster and Yang, 1992), and long-term SST patterns evocative of an interannual El Niño state (i.e., with a cooler western tropical Pacific) have been hypothesized to reduce Asian monsoon precipitation on multidecadal to centennial timescales (Chen et al., 2015; Cook et al., 2010). However, comparing average, late Holocene Indo-Pacific SST (Linsley et al., 2010) to the Ngamring Tso record shows reduced monsoon precipitation coincident with periods of warmer Indo-Pacific SST. The two periods of highest monsoon precipitation at 2000 cal yr BP and 200 cal yr BP are coincident with cooler Indo-Pacific SST (Figure 9C-D).

The Indian Ocean is a key source of latent heat for the ISM and recognized source of monsoon precipitation variability (Clark et al., 2000; Clemens and Prell, 2003). Cooler SST in the Indian Ocean, especially in the western Indian Ocean is hypothesized to reduce ISM precipitation on millennial timescales (Tierney et al., 2016). Such may be the case on centennial timescales in the late Holocene: recent, century-resolution records of late Holocene SST from the southeastern Arabian Sea (Saraswat et al., 2013; Tiwari et al., 2015) show cooler SST coincident with weaker monsoon periods at Ngamring Tso (Figure 9E).

The North Atlantic has been implicated as a driver of monsoon variability in many paleomonsoon studies (Berkelhammer et al., 2010; Fleitmann et al., 2003; Wang et al., 2005). Often North Atlantic climate variability is tied to solar anomalies, but internal modes of variability, namely the Atlantic Multidecadal Oscillation (AMO), have existed throughout the Holocene (Knudsen et al., 2011) and could influence monsoon precipitation via its influence on Indo-Pacific ocean-atmosphere dynamics and continental temperature (Berkelhammer et al., 2010; Feng and Hu, 2008; Goswami et al., 2006; Zhang and Delworth, 2006). We do find

significant power in the Ngamring Tso record at the 60-70 year period, overlapping the 60-90 year AMO band (Figure S9). A detrended, composite reconstruction of North Atlantic SST that emphasizes centennial-scale variability (Feng et al., 2009) shows cooler SST during the two largest dry periods between 2800 and 2300 cal yr BP and the beginning of the prolonged dry period from 1600-400 cal yr BP at Ngamring Tso (Figure 9A). However, even with warmer North Atlantic SST around 1000 cal yr BP, southern Tibet remained in a dry spell. Aside from ocean-based internal variability, variability internal to the monsoon system itself (Sinha et al., 2011) and its interaction with remote ocean or solar forcing could additionally enhance or suppress monsoon strength.

6 Conclusions

During the 20th century, Ngamring Tso median particle size, reflected in the first principal component of the grain size dataset, is strongly correlated with observed regional precipitation. Median grain size decreases with increasing summer (JJAS) precipitation, and this relationship allows us to confidently interpret the 4100-year record of median grain size variability as a proxy for monsoon precipitation. Over the last 4100 years, the precipitation reconstruction from Ngamring Tso documents large multidecadal to centennial components of monsoon variability superimposed on millennial-scale changes likely due to orbital forcing. In particular, the Ngamring Tso record indicates that two large amplitude dry periods occurred between 2800 and 2300 cal yr BP. Comparison with other regional records indicates that these dry periods had a large geographical footprint, extending to other lakes on the south-central Tibetan Plateau and to a Chinese speleothem record of EASM variability. Hence, these dry periods were likely partly due to a weaker EASM, and may have been a result of large negative

solar irradiance anomalies that also occurred at this time. A prolonged dry interval between 1600-400 cal yr BP at Ngamring Tso is also observed in other lakes of the south-central Tibetan Plateau. EASM proxies also reflect this dry period, but the evidence from the ISM region is equivocal: ISM proxies show strengthened circulation, but reduced moisture. Summer precipitation began to increase at Ngamring Tso at 1000 cal yr BP, and peaked at its highest level of the last 4100 years at 200 cal yr BP. Relative pluvial periods are also observed in nearby sediment records on the south-central Tibetan Plateau between 300 and 100 cal yr BP, and proxy records of both the EASM and ISM indicate a stronger monsoon at this time. Our new record and synthesis shows coherent precipitation variability on the south-central Tibetan Plateau during the late Holocene and highlights that the south-central Tibetan Plateau may receive variable moisture from both monsoon subsystems.

Our reconstruction adds important elements to the broader understanding of monsoon variability, with implications for future changes. The Asian monsoon has responded to past changes in external orbital and solar forcing over the Holocene and is likely to do so in the future (Christensen et al., 2013), but the role of substantial unforced variability remains underappreciated. Such variation could drive unanticipated and prolonged periods of below- and above-normal monsoon precipitation in the future, affecting the livelihoods of billions and the sustainability of natural and agricultural systems. Although external forcing may play a role, some of this variability likely has a source internal to the climate system, and is not well-represented in current climate models (Ault et al., 2014; Laepple and Huybers, 2014). Until we have a predictive understanding of multidecade to multi-century variability in the Asian monsoon system, it would be wise to consider the risk of prolonged periods of anomalously dry and wet monsoon conditions to be substantial (Ault et al., 2014). Such variability may also

explain why the predicted anthropogenic increase in Asian monsoon precipitation is not widely observed.

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Tables

Table 1: ^{210}Pb , ^{137}Cs , and ^{14}C ages used to construct the Ngamring Tso age model. Asterisk indicates calibration in Calib Bomb (Hua et al., 2013). Double asterisk indicates sample not used in Bacon age modeling.

Sample type	Depth (cm)	Lab Number	FMC	^{14}C yr	cal yr BP
^{210}Pb bulk sediment	1.25				-55.0 $\pm$ 2.5
^{210}Pb bulk sediment	2.25				-53.3 $\pm$ 2.6
^{210}Pb bulk sediment	3.25				-52.6 $\pm$ 2.6
^{210}Pb bulk sediment	4.25				-51.4 $\pm$ 2.6
^{210}Pb bulk sediment	5.25				-50.8 $\pm$ 2.7
^{210}Pb bulk sediment	6.25				-49.5 $\pm$ 2.7
^{210}Pb bulk sediment	7.25				-48.5 $\pm$ 2.7
^{210}Pb bulk sediment	8.75				-42.9 $\pm$ 3.0
^{210}Pb bulk sediment	10.75				-35.4 $\pm$ 3.3
^{210}Pb bulk sediment	12.75				-29.3 $\pm$ 3.7
^{210}Pb bulk sediment	14.75				-19.5 $\pm$ 4.4
^{210}Pb bulk sediment	17.75				-10.4 $\pm$ 5.2
^{210}Pb bulk sediment	20.75				-8.0 $\pm$ 5.9
^{210}Pb bulk sediment	26.75				12.6 $\pm$ 6.2
^{137}Cs bomb spike	20.75				-13.0 $\pm$ 2.0
^{14}C aquatic macrophyte	7.375	AA89074	1.1100 $\pm$ 0.0076	Post-bomb	-47.3 $\pm$ 3.1 *
^{14}C modern aquatic macrophyte		AA82310	1.0350 $\pm$ 0.0050	Post-bomb	**
^{14}C modern aquatic macrophyte		AA89073	1.0844 $\pm$ 0.0047	Post-bomb	**
^{14}C bulk OM	8.5	AA91766	0.8884 $\pm$ 0.0042	951 $\pm$ 38	**
^{14}C bulk OM	30.5	AA91767	0.7700 $\pm$ 0.0038	2099 $\pm$ 40	
^{14}C bulk OM	60.5	AA91768	0.6973 $\pm$ 0.0036	2896 $\pm$ 41	
^{14}C bulk OM	120.5	AA91769	0.6570 $\pm$ 0.0035	3374 $\pm$ 43	
^{14}C bulk OM	138.5	AA91770	0.5477 $\pm$ 0.0031	4836 $\pm$ 45	

Figures

Figure 1: Map of study site. A. Tibetan Plateau and greater surrounding monsoon Asia.

Numbered symbols indicate location of Ngamring Tso (star) and other key paleoclimate records discussed in text: Qunf Cave (1), Arabian Sea core ODP 723 (2), Ngangla Ring Tso (3), Tianmen Cave (4), Co Ngion (5), Paru Co (6), Nam Co (7), Cuo Co (8), Bangong Co (9), Sumxi Co (10), Dongge Cave (12), and Sanbao Cave (13). Lakes are squares, diamonds caves, and circles marine sediment records. B. Map of Ngamring Tso. Red outline denotes watershed. White circle indicates coring location.

Figure 2: Regional temperature, precipitation and 500mb wind climatology for grid cell or station nearest to Ngamring Tso. Data from GHCN (Peterson and Vose, 1997), CMAP (Xie and Arkin, 1997), and 20th century reanalysis (Compo et al., 2011). A. Temperature: thin line denotes Shigatse station (1956-2012), thick line is 20th century reanalysis (1940-2012). B. Precipitation: solid line is Shigatse station (1956-2012), dashed line is CMAP (1979-2012), thick line is 20th century reanalysis. C. 500 mb zonal (u, solid line) and meridional (v, dashed line) wind speeds from 20th century reanalysis. Note elevation of Shigatse, 160 km east of lake, is 450m lower than the elevation of Ngamring Tso.

Figure 3: Ngamring Tso age model. A. ¹³⁷Cs measurements. B. uppermost age model including ²¹⁰Pb ages (small black circles), calibrated ¹⁴C ages (large gray circles) and ¹³⁷Cs bomb-spike date of AD 1963 (gray circle). C. Bacon age model (Blaauw and Christen, 2011) incorporating ²¹⁰Pb and ¹³⁷Cs age estimates (teal) and calibrated, reservoir corrected ¹⁴C age (purple). Gray shaded region denotes Markov Chain Monte Carlo iterations, with darker gray indicating more

likely ages. Red line indicates best-fit age model based on median age. D. ^{14}C reservoir estimate derived from linear regression of ^{14}C ages versus depth (circles). Squares indicate ^{14}C age estimate from Calib-bomb (Hua et al., 2013) (calibrated) age on plant macrofossil (white) and bulk sediment (black).

Figure 4: Ngamring Tso sediment variables. A. Percent loss on ignition at 550°C. B. PC1 of grain size C. Ca/Ti ratio D. PC2 of XRF dataset E. PC1 of XRF dataset. Bold lines are 21-point moving average; dashed lines indicate raw data. Gray bars denote periods of inferred prolonged or extreme droughts.

Figure 5: Satellite images of lake area in CE A. 1972, B. 1995, and C. 2009. D. Lake area versus 5-year low pass filtered 20th century reanalysis JJAS precipitation. Lake area was identified from Landsat images (obtained from <http://earthexplorer.usgs.gov/>) using a maximum-likelihood classification method and lake areas were calculated using an equal area projection. All points in D are from the fall season, with the exception of the pink points, which were measured using spring images.

Figure 6: 20th century Ngamring Tso grain size and 20th-century instrumental precipitation (Peterson and Vose, 1997) and precipitation inferred from CMAP (Xie and Arkin, 1997) and reanalysis (Compo et al., 2011). Instrumental and sediment data are plotted with 5-year smooth. A. PC1 of grain size versus CMAP precipitation for 1979-2007. B. PC1 of grain size versus Shigatse station precipitation, 1956-2007. C. PC1 of grain size versus 20th century reanalysis

precipitation, 1900-2007. Dashed section of 20th century reanalysis indicates period of data that is likely unreliable (Figure S6).

Figure 7: Time series of regional hydroclimatic and monsoon circulation records compared to Ngamring Tso reconstructed JJAS precipitation. In all time series, ‘up’ direction denotes stronger monsoon or greater precipitation. Brown shaded areas denote periods of reduced monsoon precipitation at Ngamring Tso, blue shaded areas denote periods of enhanced monsoon precipitation at Ngamring Tso. A. Percent abundance *G. bulloides*, Arabian Sea box core RC2730 (gray) (Anderson et al., 2002) and hole 732A (black) (Gupta et al., 2005). B. Qunf Cave $\delta^{18}\text{O}$ record (Fleitmann et al., 2003). C. Paru Co PC1 grain size (Bird et al., 2014). D. Ngamring Tso JJAS precipitation: Horizontal line is long-term mean, shading indicates 2σ error of the reconstruction methodology. E. Co Ngion mean annual precipitation (Shen et al., 2008). F. Nam Co median grain size record (Kasper et al., 2012) G. 50-year interpolated average of two highest resolution Holocene Dongge Cave $\delta^{18}\text{O}$ records (Dykoski et al., 2005; Wang et al., 2005).

Figure 8: Time series of solar irradiance and insolation compared to Ngamring Tso reconstructed JJAS precipitation. A. June insolation at 30°N (Berger and Loutre, 1991). B. Ngamring Tso JJAS precipitation: Horizontal line is long-term mean, shading indicates 2σ error of the reconstruction methodology. C. Total solar irradiance anomalies (Steinhilber et al., 2012).

Figure 9: Time series of late Holocene SST reconstructions compared to Ngamring Tso reconstructed JJAS precipitation. A. Detrended PC1 of 24 North Atlantic SST records (Feng et al., 2009). B. Ngamring Tso JJAS precipitation: Horizontal line is long-term mean, shading

indicates 2σ error of the reconstruction methodology. C. Average Indo-Pacific Warm Pool SST (Linsely et al., 2010). D. Average of two centennial resolution, late Holocene SST records from the southeastern Arabian Sea (Saraswat et al., 2013; Tiwari et al., 2015). Anomalies were calculated for each record and the records were interpolated at a 100-year timescale prior to averaging.

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