REPLY TO LIU ET AL.:

East Asian summer monsoon rainfall dominates Lake Dali lake area changes

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We thank Liu et al. (1) for their comments on our paper (2).

The first point of Liu et al. (1) is that the Lake Dali Early Holocene highstand could reflect increased winter precipitation and/or glacier melt rather than monsoon rainfall. First, modern winter precipitation contributes <10% annual precipitation (2, 3). To sustain the Early Holocene highstand solely based on winter precipitation requires a 10-fold winter precipitation increase. Such a large change in precipitation seasonality would require a massive reorganization of atmospheric circulation, yet there is no evidence that this occurred.

Second, the pollen precipitation reconstruction (4) requires a 3-km-thick remnant glacier to sustain the Early Holocene highstand of the lake. The lake hydrological balance is:

$$Q_{ice} + P * F_{runoff} * A_{catchment} + P * A_{Lake} = E_{Lake} * A_{Lake},$$

where Q_{ice} is melt water input into the lake ($m^3 \cdot y^{-1}$); P is annual rainfall, which, based on the pollen record, indicates the Early Holocene was similar to today (4)—for Dali Lake it is 0.39 m/y (2); A_{Lake} is surface area of the lake—for a lake filled to 1,280 masl (Early Holocene lake level) it is $1.4*10^9$ m^2; $A_{catchment}$ is area of catchment—$4.1*10^9$ m^2 (after subtracting area of lake); F_{runoff} is fraction of runoff—similar to modern is 7% (2); and E_{Lake} is evaporation, similar to modern—0.92 m/y (2).

Q_{ice} of 0.6 $km^3 \cdot y^{-1}$ is required to sustain the annual mass balance. The Early Holocene was 2,500 y long (11.5–9 ka), which requires ~1,650 km^3 of snowmelt water converted to ice (using a 9% volume increase). The size of the Dali catchment area at elevations between 1,800 and 1,400 m is ~550 km^2. Thus, the pollen reconstruction requires the presence of a 3-km-thick glacier at the onset of the Holocene to sustain the hydrological balance. This number is most likely impossible.

The second point of Liu et al. (1) is that the Lake Dali record shows a different pattern than pollen and dust proxies. Although this difference is true, it does not mean that the Dali lake area record is not a faithful recorder of monsoonal rainfall. Lake Dali lake area is a direct recorder of rainfall amount. It is based on physical evidence of lake area, where a larger surface area results in more evaporation, which requires more rainfall to sustain a steady-state lake level (5). Pollen and dust proxies are not direct recorders of past rainfall amount. Dust proxies (e.g., soils) respond primarily to spring wind intensity (e.g., ref. 6) and do not have a clear relationship with summer rainfall. Pollen records reflect the vegetation response to multiple climate factors. For example, the large discrepancies between the two pollen-based precipitation records presented by Liu et al. (1) indicate that other factors influence the pollen-based reconstructions.

The last point by Liu et al. (1) is that Lake Dali reached its highest highstand during the mid-Holocene. Because the lake overflowed at this time, this claim is certainly possible; therefore, our reconstruction of twice modern rainfall is a minimum estimate (2). Although higher rainfall during the mid-Holocene would decrease the mismatch between the lake level and pollen reconstructions, it still fails to reconcile the large Early Holocene discrepancy. Furthermore, it requires that mid-Holocene rainfall was much higher than twice-modern rainfall, yet no evidence for such a large change exists, even in the pollen-based records.

The physical evidence of lake level is a direct recorder of hydrological change. We show that Holocene Lake Dali hydrology primarily reflects changes in summer monsoonal rainfall. Thus, the scaling between the Lake Dali record and Chinese speleothem $\delta^{18}O$ is robust.

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The authors declare no conflict of interest.

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1 Liu J, Chen S, Chen J, Zhang Z, Chen F (2017) Chinese cave $\delta^{18}O$ records do not represent northern East Asian summer monsoon rainfall. *Proc Natl Acad Sci USA* 114:E2987–E2988.
2 Goldsmith Y, et al. (2017) Northward extent of East Asian monsoon covaries with intensity on orbital and millennial timescales. *Proc Natl Acad Sci USA* 114:1817–1821.
3 Compilatory Commission of Annals of Hexigten Banner (1993) *Annals of Hexigten Banner* (People's Press of Inner Mongolia, Hohhot, China).
4 Xiao J, Fan J, Zhai D, Wen R, Qin X (2015) Testing the model for linking grain-size component to lake level status of modern clastic lakes. *Quat Int* 355:34–43.
5 Broecker WS (2010) Long-term water prospects in the western United States. *J Clim* 23:6669–6683.
6 Roe G (2009) On the interpretation of Chinese Loess as a paleoclimate indicator. *Quat Res* 71:150–161.