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Dramatic weakening of the East Asian Summer Monsoon during the transition from the Medieval Warm Period to the Little Ice Age

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Supplementary Materials and Methods

Location.

Lake Zhongquanzi (Lake ZQZ; lat. 39°20′N, long. 102°40′E, alt. 1232 m a.s.l.) is located in the northernmost part of the Minqin Basin, between the Badain Jaran Desert and the Tengger Desert, in arid northern China. It is a terminal lake of the Shiyang River, which originates from the Qilian Mountains, northeastern Tibet Plateau, and is dry at present (Figs. 1 and S1).

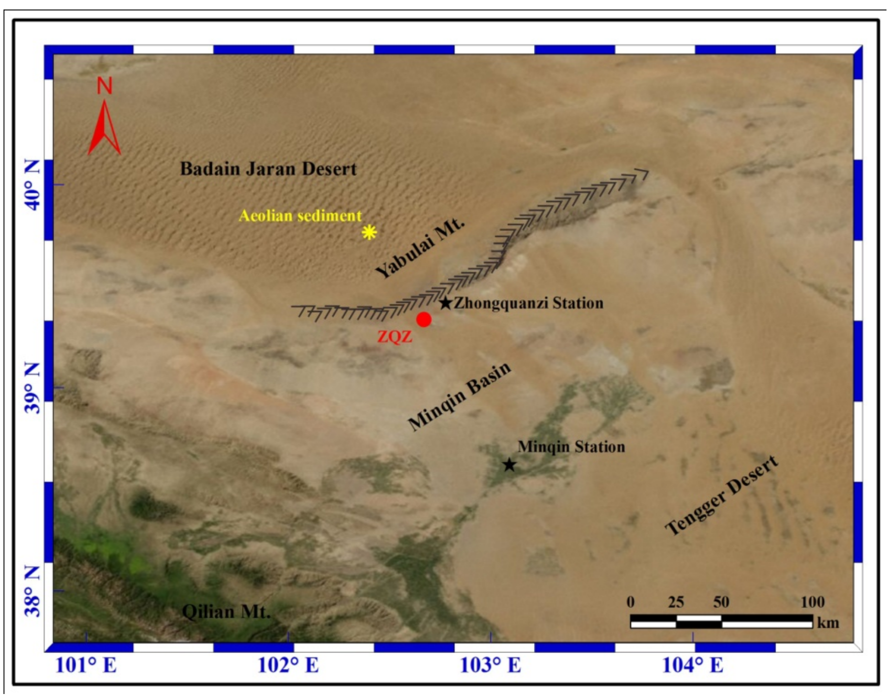

Fig. S1. Location of the study site

Modern Climatic Characteristics.

Modern climatology of Lake ZQZ was evaluated using a 52-yr record (1956-2007 AD) of precipitation and temperature from two meteorological stations located 5 km to the northeast (Zhongquanzi) and 90 km to the south (Minqin) of the lake (Fig. S1). Mean annual precipitation in the Minqin area is ~109 mm (data from Minqin meteorological station for 1956-2007 AD), with ~80% falling between June and September (Figs. S2a and S3). The results of a water vapor trajectory analysis (HYSPLIT Trajectory Model) suggest that the water vapor is supplied by the Asian monsoon from the south between June and September, and by the westerlies and/or winter monsoon from west and/or northwest during the other seasons (Figs. S2a and S3). Changes in precipitation at the Lake ZQZ area are significantly positively correlated with changes in the Minqin Basin during 1956-2007 AD (see the spatial correlation analysis in Fig. S4), and both show a similar trend to that of the mean precipitation over northern China (Fig. S2b; Ding et al., 2008). All of these features suggest that modern climatic changes in the Lake ZQZ area are consistent with and could represent changes in the modern northern Summer Monsoon Limit (SML).

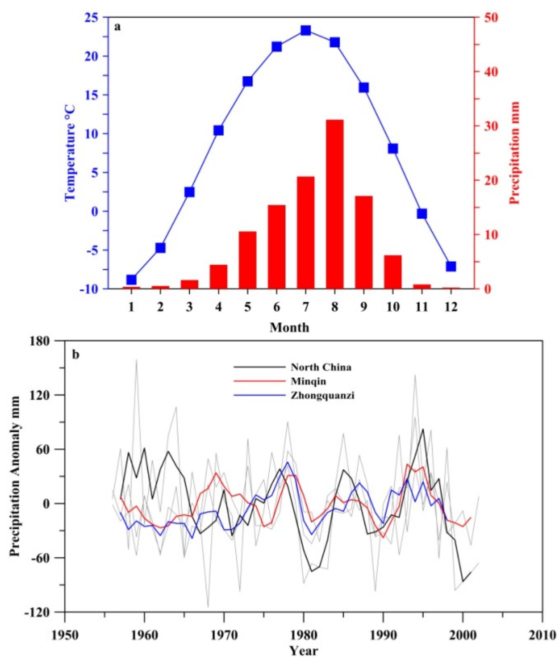

Fig. S2. ZQZ climatology. (a) The 52-yr (1956-2007 AD) monthly averages of precipitation (red bars) and temperature (blue solid line) for the Minqin meterological station. (b) 3-yr smoothed JJA (June-August) precipitation anomaly for North China (black solid line; Ding et al., 2008) and Minqin (red solid line), calculated from 1956 to 2000 average, and 3-yr smoothed annual precipitation anomaly for Zhongquanzi (blue solid line; Zhao et al., 2008).

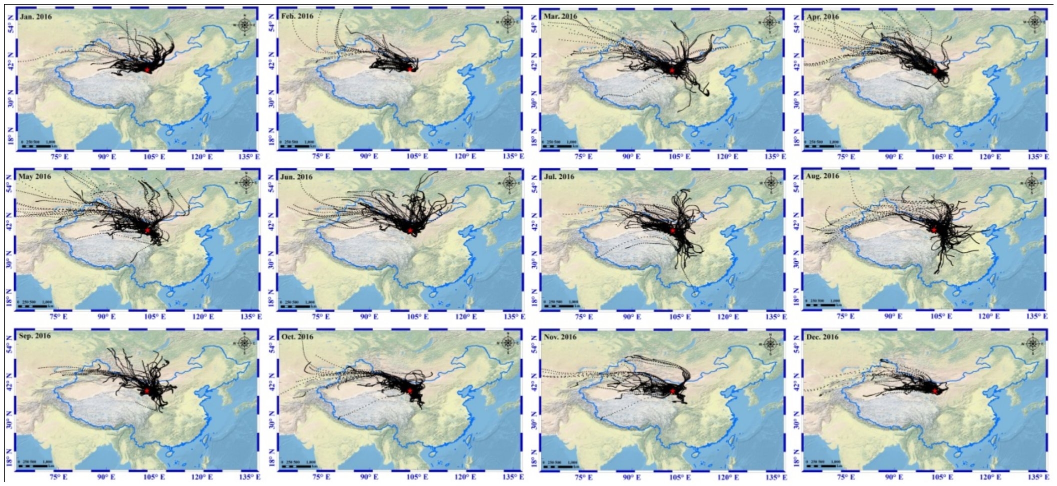

Fig. S3. HYSPLIT Trajectory Model analysis (GDAS 1degree; http://ready.arl.noaa.gov/hypub-bin/trajasrc.pl) from Lake ZQZ for 2016.

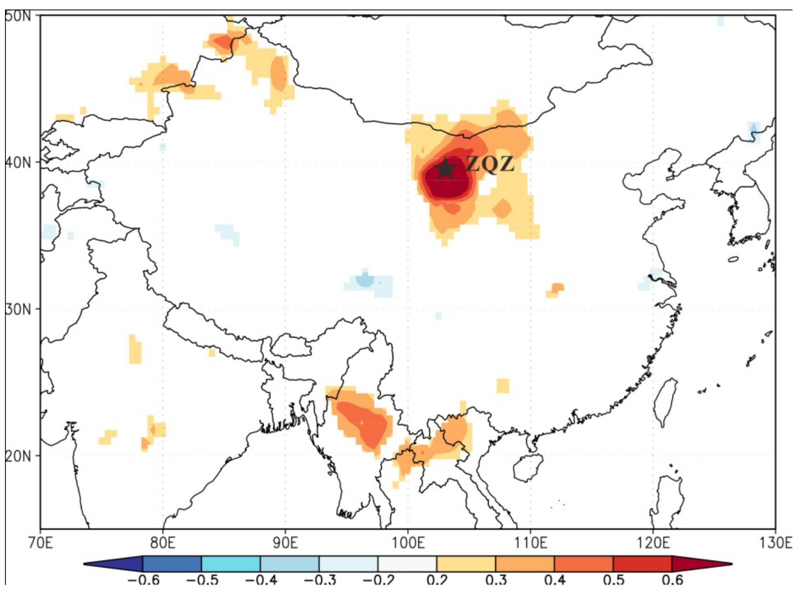

Fig. S4. Spatial correlation between annual precipitation in the Lake ZQZ area and the CRU TS3.24.01 precipitation grid datasets for 1956-2007. The star indicates the location of the Lake ZQZ profile. The scale shows correlation coefficients represented by different colors. The analysis was preformed using the KNMI Climate Explorer (http://climexp.knmi.nl).

Sample Collection and Lithology.

The ZQZ profile is 533 cm long (Fig. S5a) and was sampled *in situ* at an interval of 5 cm during field investigation in 2011, and this revealed changes in lithology (color, grain size, and composition; Fig. S5) as follows:

0~20 cm depth: aeolian sand.

20~100 cm: sodium sulfate with sand.

100~233 cm: light-brown fine-sand layers.

233~303 cm: light clay layers with a different lithology to overlying and underlying sediments.

Below 303 cm: interbeded light-brown fine-sand to silt layers.

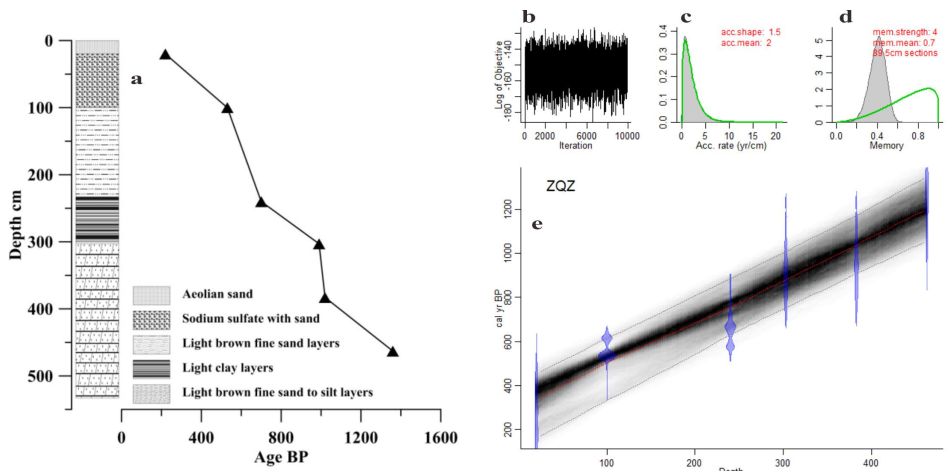

Fig. S5 Lithology (a) and OSL age model (e) for the Lake ZQZ profile. The six quartz OSL ages were used in a Bayesian age-depth model in Bacon (Blaauw and Christen, 2011). Results from Markov Chain Monte Carlo (MCMC) iterations, the distributions of accumulation rate prior and its memory (Fig. S5b-d) indicate the reliability of using the Bayesian age-depth model for the late Holocene chronology construction.

Dating Method.

Six luminescence samples were collected and dated using the Optically Stimulated Luminescence (OSL) dating technique, with sample IEE3614 measured using the coarse (90-125 μm) quartz single-aliquot regenerative-dose (SAR) approach (Murray and Wintle, 2000; Wintle and Murray, 2006), and the rest measured using the fine-grained (4~11 μm) quartz sensitivity-corrected multiple-aliquot regenerative-dose (MAR) protocol (Lu et al., 2007; Kang et al., 2012), at the Institute of Earth Environment, Chinese Academy of Sciences. The six quartz OSL ages were used in a Bayesian age-depth model in Bacon to establish the age model of the Lake ZQZ profile (Fig. S5e; Blaauw and Christen, 2011), and then were transferred to Common Era (Madsen and Murray, 2009). The results show that the profile spans 360 AD to present, and contains the DACP, MWP, and LIA periods (Figs. 2 and S5e).

Multi-Proxy Analysis.

All 83 samples were analyzed for $LOI_{550°C}$, $LOI_{950°C}$, carbonate content, grain size, and magnetic susceptibility at the Institute of Earth Environment, Chinese Academy of Sciences. The LOI was calculated as follows:

$$LOI_{550°C}\,(\%) = (M_2\text{-}M_3) \times 100/(M_2 - M_1)$$

$$LOI_{950°C}\,(\%) = (M_3\text{-}M_4) \times 100/(M_2 - M_1)$$

where M_1, M_2, M_3, and M_4 are the net weight of the porcelain crucibles after ignition at 550°C, the weight of M_1 plus the weight of sample after drying at 105°C, the weight of M_2 after ignition for 4 hours at 550°C, and the weight of M_3 after ignition for 2 hours at 950°C, respectively.

The carbonate content was titrated with diluted HCl (0.1 mol/L; Xu et al., 2015a, 2015b). Sediment samples were pretreated with diluted H_2O_2 (10%) to remove organic matter, and then grain size was measured using a Malvern Mastersizer 2000 laser particle size analyzer, with an experimental error of <3% (Sun et al., 2012). The magnetic susceptibility of ZQZ sediments was determined using a Bartington Meter (Model MS2; Xu et al., 2015b).

Climatic Significance of Proxy Indices.

Here, we present results for $LOI_{550°C}$ and $LOI_{950°C}$, carbonate content, grain size, and magnetic susceptibility. $LOI_{550°C}$ and $LOI_{950°C}$ values are widely recognized as indicators of organic matter content and carbonate content, respectively, in lacustrine sediments (Dean, 1974; Heiri et al., 2001; Santisteban et al., 2004). Organic matter in lacustrine sediments principally comes from two sources (Talbot and Johannessen, 1992; Meyers, 1994): autochthonous (aquatic plants living in the lake) and allochthonous (terrestrial plants from within the catchment). Data from well-studied lakes in the marginal monsoon region suggest that organic matter in lacustrine sediments can be used to infer changes of precipitation in the lake catchment and/or the amount of water input to lake, and thus generating fluctuations in lake level (Xu et al., 2006; Xiao et al., 2006, 2008). Therefore, organic matter content and thus $LOI_{550°C}$ can serve as a measure of precipitation/moisture and/or lake level change, triggered by changes in the EASM in the marginal monsoon region.

Generally, the carbonate precipitation rate in a lake is controlled mainly by the ratio of evaporation to precipitation (E/P), where higher E/P ratios may lead to the super-saturation of carbonate in the lake water and correspond to higher carbonate precipitation rates, and vice versa. Hence, a series of studies has supported the idea that variations in carbonate content in lake sediments are an indicator of E/P or regional effective moisture (Chen et al., 2006; Xu et al., 2006). However, rates of carbonate precipitation in the ZQZ region, which are high, perhaps due to high dissolved Ca^{2+} concentrations in runoff regulated by intense chemical weathering under warm-wet climatic condition (Jin et al., 2002), are inversely correlated with climatic parameters; e.g., higher (lower) carbonate contents and/or $LOI_{950°C}$ indicate higher (lower) precipitation.

Variations in grain size in lacustrine sediments from arid/semiarid regions may reflect changes in transport energy related to variations in regional precipitation (Peng et al., 2005; Qiang et al., 2007; Xiao et al., 2009; Chen et al., 2013); i.e., a larger silt size (sandy or coarse) fraction reflects increased monsoonal precipitation (aeolian deposition).

Magnetic susceptibility in lake sediment records is typically used as an indicator of amount of the clastic material washed into the lake from its catchments (Snowball et al., 1999; Liu et al., 2014). Increased runoff under humid conditions will transport more clastic material into the lake, and thus promote higher magnetic susceptibility values in lake sediments. Conversely, lower magnetic susceptibility values may correspond with intervals of decreased runoff.

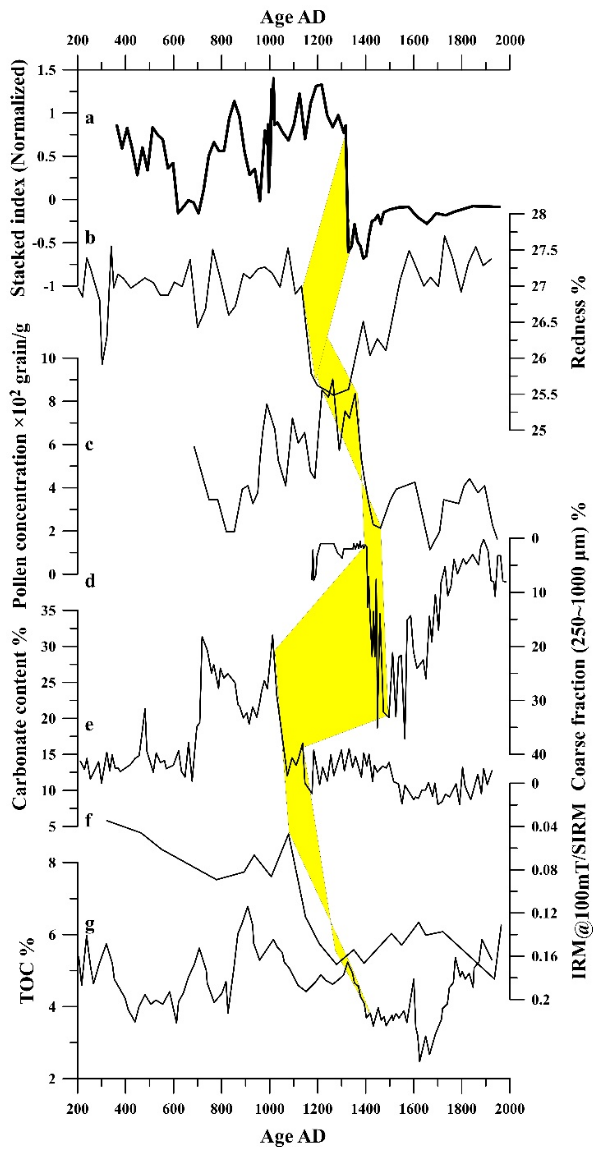

Fig. S6 Raw data showing a weakening in EASM intensity, as recorded from the marginal summer monsoon region: (a) normalized stacked index (*this study*); (b) sediment redness of Lake Qinghai (Ji et al., 2005); (c) pollen concentrations of Lake Gouchi (Meng et al., 2009); (d) coarse fraction of Lake Bojianghaizi (Yang and Zhang, 1997); (e) carbonate content of Lake Daihai (Jin et al., 2002); (f) $IRM_{@100mT}/SIRM$ of Lake Xiarinur (Tang et al., 2015); and (g) TOC of Lake Dali (Xiao et al., 2008).

Table S1 Proxies of Hydroclimate Records Mentioned in this Study

Site no.	Site name	Lat.(°N)	Long.(°E)	Proxies used	References
1	Aral Sea	45.01	59.49	Dinoflagellate cysts	Sorrel et al., 2006
2	Lake Sasikul	37.69	73.18	δ^{18}O, TIC	Lei et al., 2014
3	Lake Issky-Kul	42.43	77.36	Historical map	Narama et al., 2010
4	Lake Ebinur	44.88	83.18	$\delta^{18}O_{carb}$, $\delta^{13}C_{org}$	Ma et al., 2011
5	Lake Bosten	41.99	87.08	Carbonate content	Chen et al., 2006
6	Guliya ice core	35.20	81.15	Annual net accumulation	Thompson et al., 1995
7	Eastern Tarim Basin	39.77	88.38	Plant δ^{13}C	Liu et al., 2010
8	Lake Sugan	38.85	93.87	Chironomid	Chen et al., 2009; He et al., 2013
9	Dunde ice core	37.27	96.53	Pollen	Liu et al., 1998
10	Delingha tree ring	37.27	97.53	δ^{18}O	Wang et al., 2013
11	Lake Gahai	37.12	97.55	$\%C_{37:4}$	He et al., 2013
12	Aeolian sediment	39.77	102.40	Chloride concentration in unsaturated zone	Ma and Edmunds, 2006; Gates et al., 2008
13	Lake Tengernuur	42.43	110.68	Artemisia/Chenopodiaceae ratio	Zhao et al., 2011
14	ZQZ	39.34	102.67	LOI, carbonate content, grain size and magnetic susceptibility	*This study*
15	Lake Qinghai	36.88	100.18	Redness	Ji et al., 2005
16	Lake Gouchi	37.73	107.50	Pollen	Meng et al., 2009
17	Lake Bojianghaizi	39.78	109.30	Grain size	Yang and Zhang, 1997
18	Lake Dahai	40.57	112.68	Carbonate content	Jin et al., 2002
19	Lake Xiarinur	42.62	115.47	Mineral magnetic parameter	Tang et al., 2015
20	Lake Dali	43.27	116.63	TOC	Xiao et al., 2008
21	Wanxiang Cave	33.32	105.00	δ^{18}O	Zhang et al., 2008
22	Huangye Cave	33.58	105.12	δ^{18}O	Tan et al., 2011
23	Longxi	35.45	104.78	Historical document	Tan et al., 2008
24	Lake Gonghai	38.9	112.23	Magnetical parameter and pollen	Liu et al., 2011
25	Northern China	36.40	115.12	Historical document	Man, 2009
26	Shihua Cave	39.83	115.67	Thickness of stagamite lamina	Qin et al., 1999
27	Maili Bog	42.87	122.88	Pollen	Ren, 1998
28	Lake Xiaolongwan	42.30	126.35	$\delta^{13}C_{org}$	Chu et al., 2009
29	South Korea	37.82	127.00	Historical document	Kim and Choi, 1987

Table S2 Optically stimulated luminescence ages and related parameters for the Lake ZQZ profile

Laboratory no.	Depth (cm)	U (ppm)	Th (ppm)	K (%)	Water content (%)	Equivalent dose (Gy)	Dose rate (Gy/ka)	Age (AD)
IEE3614	20	1.90	5.29	1.51	10±5	0.54±0.35	2.49±0.09	1791±140
IEE3615	100	1.98	4.63	1.12	15±5	1.19±0.05	2.27±0.13	1481±40
IEE3616	240	8.35	8.67	1.79	15±5	3.64±0.14	5.21±0.41	1311±60
IEE3617	303	15.64	3.26	1.91	15±5	7.11±0.10	7.15±0.74	1021±100
IEE3618	383	15.02	3.91	2.10	25±5	6.65±0.10	6.50±0.63	991±100
IEE3619	463	17.39	3.52	1.98	25±5	9.58±0.13	7.05±0.73	651±140

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