Humidity changes and possible forcing mechanisms over the last millennium in arid Central Asia

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Abstract

Hydroclimate changes have exerted a significant influence on the historical trajectory of ancient civilizations in arid Central Asia where the central routes of the Silk Road have been hosted. However, the climate changes on different time scales and their possible forcing mechanisms over the last millennium remain unclear due to low-resolution records. Here, we provide a continuous high-resolution humidity history in arid Central Asia over the past millennium based on the ~1.8-year high-resolution multiproxy records with good chronological control from Lake Dalongchi in the central Tianshan Mountains. Generally, the climate was dry during the Medieval Warm Period (MWP) and Current Warm Period (CWP), and wet during the Little Ice Age (LIA), which could be attributed to the influence of the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). Furthermore, we find that the humidity oscillation was dramatic and unstable at multidecadal to century-scale. Especially within the LIA, four wet episodes and three dry periods occurred. The continuous wavelet analysis and wavelet coherence show that the humidity oscillation is modulated by the Gleissberg cycle at the century-scale and by the quasi-regular period of El Niño-Southern Oscillation (ENSO) at the multidecadal scale. Our findings suggest that the effect of the solar cycle and the quasi-regular period of ENSO should be seriously evaluated for hydroclimate predictions and climate simulations in arid Central Asia in the future.

1 Introduction

Arid Central Asia (ACA), far away from the ocean, is not only one of the driest and largest inland regions worldwide, but also the birthplace of the far-reaching ancient civilizations that spread along the Silk Road (Li et al., 2016; Narisma et al., 2007). Scarce precipitation, intense evaporation and fragile ecosystems render this region sensitive to abrupt changes in effective humidity. Arid Central Asia is primarily controlled by the prevailing westerlies (Chen et al., 2019a; Aizen et al., 2001; Sorrel et al., 2021; Huang et al., 2015b; Huang et al., 2014; Lauterbach et al., 2014). The moisture vapor was predominantly transported via the westerlies and originated from the North Atlantic Ocean, Mediterranean, Black Sea, and Aral-Caspian Sea (Lan et al., 2018; Chen et al., 2010; Huang et al., 2015b; Aizen et al., 2001; Mathis et al., 2014). Proxy records from ACA are valuable for understanding the driving factors and processes of underlying hydroclimate evolution in the inland region, which provides useful reference for human adaptation to hydroclimate changes at present and into future (Li et al., 2016). On the sub-orbital scale, solar radiation controlled the intensity of the westerlies through the variation of meridional radiation gradient between high and mid-latitudes, thus having the dominant influence on moisture changes of ACA during the Holocene (Chen et al., 2019a; Jin et al., 2011). In addition, the sub-orbital scale hydroclimate changes are also related to the shift of the Subtropical High, the strength and position of the Siberian High, North Atlantic Oscillation (NAO) mode, and the changes of the Laurentide and Scandinavian Ice Sheets (Sorrel et al., 2021; Chen et al., 2019a; Carlson and Clark, 2012; Aichner et al., 2015; Wolff et al., 2016; Huang et al., 2014; Schwarz et al., 2017; Lauterbach et al., 2014).

In the past decades, a couple of proxy archives from ACA have been recorded the hydroclimate changes during the key periods such as the Medieval Warm Period (MWP) and Little Ice Age (LIA) over the past millennium (Ling et al., 2018; He et al., 2013; Lan et al., 2019; Song et al., 2015; Ma et al., 2008; Zhang et al., 2009; Rousseau et al., 2020; Chen et al., 2006; Chen et al., 2019b). In earlier studies, a humid climate during the MWP and a dry climate condition during the LIA was documented by the tree ring of Sabina przewalskii Kom (Zhang et al., 2003). This climate pattern was further demonstrated by the records from Lake Lop Nur and Daxigou profile on the northern slope of central Tianshan Mountains (Zhang et al., 2009; Ma et al., 2008). However, a growing body of studies based on the lacustrine sediments, ice cores, tree ring, and peat profiles show a general similar climate pattern of a relatively dry MWP and a wet LIA in ACA over the last millennium (Chen et al., 2015; Chen et al., 2010; Chen et al., 2019a; Chen et al., 2019b; Lei et al., 2014; Rousseau et al., 2020; Lan et al., 2019; He et al., 2013; Song et al., 2015). Furthermore, some debates occur regarding the driving mechanism of the natural hydroclimate evolution over the last millennium. Many studies emphasize that internal climate variability (i.e., major sea and atmospheric modes) is supposed to be more marked than external factors (e.g., solar forcing) in influencing hydroclimate changes (Chen et al., 2019a; Chen et al., 2006; Lan et al., 2019). The notion believes that NAO and Atlantic Multidecadal Oscillation (AMO) play important roles by controlling the strength and shift of the westerly jet stream in determining hydroclimatic changes in ACA (Chen et al., 2015; Chen et al., 2010; Aichner et al., 2015; Lan et al., 2018; Lan et al., 2019). El Niño-Southern Oscillation (ENSO) also contributes the climate variability in ACA on a multi-centennial timescale (Chen et al., 2015; Chen et al., 2019a). In contrast, several paleoclimate records prefer to highlight the possible solar forcing to the humidity oscillation over the last millennium (Song et al., 2015; Zhao et al., 2009; He et al., 2013; Ling et al., 2018). For example, the solar imprint on the effective humidity fluctuations in ACA was proved by wavelet spectral analysis of the sediment record from Lake Manas (Song et al., 2015). Also, the ~200-year moisture oscillations related to the solar forcing recorded by the lake-level changes during the past 1000 years from the Lake Hurleg (Zhao et al., 2009). Therefore, the climate changes on different time scales and their possible forcing mechanisms remain controversial over the last millennium. These controversies are largely attributed to low-resolution records or chronological uncertainties due to the old carbon effect (Chen et al., 2010; Zhang et al., 2021c), which limit our understanding of the hydroclimate evolution on decadal to centennial scales and of the relative role of external and internal drivers over the past millennium. More well-dated, high-resolution records are needed to further investigate the humidity evolution.

Here, we present a continuous ~1.8-year high-resolution humidity reconstruction with good chronological control from Lake Dalongchi in the central Tianshan Mountains of ACA over the past millennium (1180-2018 CE). Low- and high-frequency signals recovered from our reconstruction offer the potential to detect climate fluctuations at decadal to centennial scales, as well as long-term changes. Then, we explore the contribution of internal climate variability (mainly refers to the NAO, AMO, and ENSO in this study) and solar activity to humidity oscillations on different timescales over the past millennium.

2 Study site

Lake Dalongchi (83°16'48"~83°18'15" E, 42°26'31"~42°26'58" N, 2400 m above sea level) located on the south slope of the central Tianshan Mountains, is an ideal location for investigating hydroclimate changes in ACA (Fig. 1a), as the lake sits in the core area of the 'westerlies dominated climatic regime (WDCR)' (Chen et al., 2019a). The bedrock in the catchment of Lake Dalongchi is composed of pillow lava, gabbro and limestone blocks included in a matrix of sheared calcareous turbidites. The ophiolitic mélanges are juxtaposed against Paleozoic sedimentary rocks, gneissic granitoids, and andalusite cordierite-bearing micaschist (Xiao et al., 2013; Ma et al., 2006; Gao et al., 1998). The main aquifer is hosted by ophiolitic rocks and categorized as a fissured rock aquifer (http://gis.geoscience.cn/website/hg/viewer.htm). This aquifer has multi-scale hydraulic discontinuities and low groundwater potentiality due to the structural heterogeneities of the ophiolitic rocks (Lods et al., 2020; Jeanpert et al., 2019; Boroninaa et al., 2003).

Lake Dalongchi is a small alpine freshwater lake formed by glacial moraine damming and has a mean pH of 8.03 and a salinity of 0.31 g L^{-1}. Both the north and south sides of the lake are surrounded by steep mountains (Fig. 1b). The lake is mainly fed by the river originating from mountains on the east, precipitation within the catchment, and glacial meltwater from the surrounding mountains at high elevations. The lake water flows out into Lake Xiaolongchi through a tunnel under the moraine and the outflow discharge is low. Then the lake water from Xiaolongchi flows westwards into the Kuche River basin (Fig. 1b).

Measured in July 2018, the lake covers a surface area of ~1.4 km^2 and has a catchment area of ~131 km^2. The maximum water depth of Lake Dalongchi reaches 7.4 m in the western lake and its depth largely decreases from west to east (Fig. 1c). Alpine coniferous forests dominated by Picea primarily thrive on the southern and western slopes of the surrounding mountains, while the northern slope is covered by herbs such as Chenopodiaceae, *Artemisia*, Poaceae, and Cyperaceae. According to the records from 1958 to 2019 at Bayanbuluk Station which is located ~100 km to the northeast of Lake Dalongchi, the mean annual temperature is -4.6 °C with a July average of 10.9 °C and a January average of -26.4 °C, and the mean annual precipitation and evaporation are 270 mm and 3200 mm, respectively. The mean annual precipitation is far less than the evaporation capacity. Moreover, most of the precipitation occurs as convective rainfall from June-August (Lan et al., 2018). The prevailing wind is from the northwest and the annual average wind speed is only 2.73 m/s. The average number of sandstorm days is less than 5 days/year based on the meteorological records from 1959 to 1998 (Zhang et al., 2021a; Zhou et al., 2002).

3 Materials and methods

3.1 Sampling

In July 2018 and August 2019, we retrieved several parallel long sediment cores from Lake Dalongchi at a maximum water depth of 7.4 m using the UWITEC platform manufactured in Austria, and several short cores using a piston gravity corer (Fig. 1c). To determine overlaps and ensure the continuity of the cores, magnetic susceptibility (MS) nondestructive scanning of all long and short sediment cores was used to obtain a 6.95m-long composite core (DLC1819) (Fig. 2).

3.2 Laboratory analysis

DLC1819 core was subsampled at 1-cm intervals. All subsamples were stored in a freezer in our laboratory at a constant temperature of 4 °C and used for MS, grain size, total organic carbon (TOC), and total nitrogen (TN) analyses. Samples for MS were dried at below 40 °C in a constant temperature air-blast drying oven and ground and packed into standard plastic boxes with a capacity of 2*2*2 cm^3. A Bartingon MS2 susceptibility meter was used to measure magnetic susceptibility. Samples used for grain size measurement were pretreated with 10-20 mL of 10% H_2O_2 to remove organic matter and then with 10 mL of 10% HCl to remove carbonates; next, samples were rinsed with deionized water and finally treated with 10 mL 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min to promote dispersion. Grain size distributions were determined using Malvern/MS 3000 laser grain size analyzer. The samples used for TOC and TN determination were decalcified with 10% HCl and rinsed repeatedly with deionized water. Then, ~3-5 mg dried and ground samples were analyzed using the EURO EA 3000 elemental analyzer.

Terrestrial plant remains at different depths in DLC1819 core were used for accelerator mass spectrometry (AMS) ^{14}C measurements at Beta Analytic Inc., U.S.A. (Table 1). The uppermost sediments were used for the radiometric dating by measuring the activity of ^{137}Cs as a function of depth. The samples of the uppermost sediments at 0.5 cm intervals were dried and ground to less than 100 mesh and then loaded into the 5 mL cylindrical PVC tube. Radio-activities measurement of ^{137}Cs was measured by Spectrum Analysis System consisting of a high-purity germanium well detector produced by American EG& G Ortec Company, Ortec 919 spectrum controller, and IBM microcomputer with a 16 K channel multichannel analyzer.

4 Results

4.1 Lithology and Chronology

DLC1819 core is mainly composed of clayey silt and can be divided into two lithology units from bottom to top (Fig.2). Unit A (695-430 cm) is mainly composed of dark or light brown clayey silt with clear lamination. Unit B (430-0 cm) has a dramatic lithological variation characterized by brown or greyish-green clayey silt without obvious lamination. There are lots of the plant residues in the core, but are more abundant in Unit B than in Unit A (Fig.2).

A significant increase in ^{137}Cs activities occurred at approximately 71 cm, which could be attributed to the onset of rising concentrations of ^{137}Cs in the Northern Hemisphere (NH) at 1952 CE (Fig. 3a). The distinct peak at the depth of 64 cm was taken as the 1963 CE global fallout maximum (Pennington et al., 1973) (Fig. 3a). We established the age-depth model of DLC1819 based on the 2 ^{137}Cs ages and 9 radiocarbon ages by the Bacon 2.5.7 procedure in R software using the Bayesian method (Blaauw and Christen, 2011) (Fig. 3b). Chronology results show that DLC1819 core covers the past 840 years with an approximate average sedimentation rate of 9.0 mm/yr. Unit A has unusually stable sediment accumulation rates with an average of 10.3 mm/yr., while the sediment accumulation rates vary greatly from 4.9 to 10.6 mm/yr. in Unit B (Fig. 2).

4.2 TOC, TN, C/N, MS, Grainsize

TOC and TN results show broadly similar changes and vary between 1.14% and 8.33%, and between 0.09% and 0.59%, respectively (Fig. 2). C/N ratios fluctuate between 7.95 and 18.42 with an average of 10.88 and the values of C/N ratios exceed 10 at the depth of 440-650 cm, 330-400 cm, 230-300 cm, and 130-180 cm (Fig. 2). MS values of DLC1819 core vary between 5.90 and 41.89×10^{-8} m^3/Kg with an average of 20.66×10^{-8} m^3/Kg (Fig. 2). The silt percentage fluctuates from 43.64% to 88.50% with an average of 71.91% while the variation of clay percentage has an opposite trend to that of silt, and its values vary from 11.84% to 54.26% with an average of 25.97% (Fig. 2). Sand content only accounts for 2.43% of the total grain size on average. Generally, the higher values of the MS and silt content and the lower clay content correspond to the higher C/N ratios and vice versa (Fig. 2).

5 Discussion

5.1 Proxy interpretation and Humidity Index reconstruction

The characteristics of 125-500 μm size particles with well-developed surface structure can fully reflect the transport distance and dynamic conditions of sediment in a specific environment, short distance, and weak transport dynamics usually result in a poor grain roundness of sediments (Moral Cardona et al., 2005; Mahaney et al., 2004). The surface microscopic properties of four randomly selected samples in DLC1819 core show that the grains in the range of 125-500 μm are characterized by poor roundness with an angular outline which is quite different from the aeolian materials (Zhang et al., 2021b) (Fig. S1 in the Supplement), excluding the possibility that the clastic particles are derived from aeolian deposition in Lake Dalongchi.

Terrestrial plants usually have C/N ratios of more than 20 (Meyers, 1994, 2003), so the increased C/N ratios in Lake Dalongchi sediments reflect the input amount of allochthonous organic matter (Fig. 2). Synchronously, the increase of the MS values and silt content also indicates the increased input of detrital materials and the intensified erosion of the basin (Fig. 2). Given that the weak inflows of the runoff into Lake Dalongchi which is a shallow and a small lake with an area only of 1.4 km^2, the distance from the lakeshore to the sampling site is the key to determining the amount of exogenous detrital materials in the core. Therefore, during the humid/dry period represented by high/low lake level and enlarged/reduced lake area, exogenous materials containing magnetic minerals, coarse grain components, and terrestrial plants were poorly/easily transported to the sampling site due to the long/short distance from the lakeshore and reduction/intensified erosion in the basin (Fig. 4). Thus, the high MS values, silt content, and C/N ratios indicate a dry climate and vice versa (Fig. 4).

Accordingly, multiple proxies, such as C/N ratios, MS, silt, and clay fractions, were synthetically employed to reconstruct the Humidity Index (HI) in Lake Dalongchi region over the past millennium (Fig. 5). As the high values of C/N ratios, MS, and silt contents, and low values of clay content reflect the arid climatic environment, the first three records multiplied by (-1) and clay content were normalized to a Z-score (Figs. 5b, c, d, e). Then the HI was derived from the average of the normalized standard Z-scores. Positive and negative Z-scores indicate wet and dry climatic conditions (Fig. 5a).

5.2 Humidity changes over the last millennium

There is a generally positive correlation (r = 0.298*) between the reconstructed HI and the instrumental relative humidity records over the past 60 years from the nearby Bayanbuluk meteorological station at the 0.05 significant level, verifying the reliability of the humidity reconstruction (Fig. 6a). The HI changes show that the climate was dry during the MWP (1180-1420 CE) and CWP (1920-2018 CE), and wet during the LIA (1420-1920 CE) (Fig. 6b). Moreover, our preliminary palynological data also show that a dry climate characterized by herb pollen (~71 %) dominated by *Artemisia*, Chenopodiaceae, and Poaceae during in the MWP, and a wet climate characterized by the rapid increased tree pollen dominated by the *Picea* (up to 45%) during in the LIA (unpublished data). This multi-centennial climate pattern is generally in agreement with the hydroclimatic patterns revealed by recent numerous studies in ACA (Chen et al., 2006; Song et al., 2015; Lan et al., 2018; Lan et al., 2019; Zhao et al., 2009; He et al., 2013; Ma and Edmunds, 2006; Gates et al., 2008; Rousseau et al., 2020) (Figs. 6c, d, e, f, g, h), although several studies tend to suggest humid climate conditions during the MWP in ACA (Zhang et al., 2009; Ma et al., 2008; Zhang et al., 2003). 5 of the 17 records selected on the basis of reliable chronologies and robust proxies from ACA show a relatively dry MWP, and a wet LIA characterized not only by relatively humid but also by high precipitation (Chen et al., 2010) (Figs. 6c). Recently, records from Lake Ala Kol, Kyrgyzstan reveal the cold and wet climate conditions during in the LIA indicated by the prominent glacier advances (Rousseau et al., 2020) (Fig. 6h), which corresponds to the maximal ice accumulation in the Guliya ice core (Rousseau et al., 2020; Yang et al., 2009). Thus, the humidity changes of Dalongchi lake do not indicate a local signal but a regional signal, i.e., the typical 'westerlies-dominated climatic regime' (WDCR) (Chen et al., 2019a).

The previous study shows that the higher anomalous climatic instability during the LIA compared to the MWP, suggesting the moisture instability prefers to occur within the conditions of an overall cold climate (Chen et al., 2019b). However, it is not clear how the specific unstable wet and dry climate fluctuated during the LIA, due to the relative low-resolution records in ACA (Chen et al., 2006; Zhao et al., 2009; Lan et al., 2019). The HI reconstruction of Lake Dalongchi provides new evidence for the unstable hydroclimatic variability during the LIA (Fig. 6b). Four wet episodes with the sharp high HI values were recorded in the 1420-1470, 1550-1600, 1650-1720, 1800-1920 CE, and three dramatic dry periods with the low HI values were recorded in the 1470-1550, 1600-1650, 1720-1800 CE during the LIA (Fig. 6b). Our high-resolution reconstruction clearly documented several obvious and dramatic secondary humidity fluctuations within the LIA, which are not clearly captured in other current records from ACA (Chen et al., 2006; Ma and Edmunds, 2006; Gates et al., 2008; He et al., 2013) (Fig. 6). The climatic instability during the LIA can also be reflected by the dramatic lithological variations and the unstable sediment accumulation rates in Unit B (Fig. 2). Moreover, Continuous Wavelet Transform (CWT) of HI exhibits a significant century-scale dominant oscillation ranging from ~88 to 146 years, which is nearly throughout the entire time series and prominent in 1450-1800 CE, as well as a strong ~50 to 65-year multidecadal oscillation at a 95% confidence level relative to the red noise spectrum (Fig. 7a).

5.3 Possible forcing mechanisms

5.3.1 The influence of NAO and AMO

Several studies have linked hydroclimate changes in arid Central Asia to the NAO and the AMO over the last millennium (Aichner et al., 2015; Yan et al., 2019; Chen et al., 2006; Lan et al., 2018; Chen et al., 2019b; Chen et al., 2019a). On multidecadal timescales, most records show that the NAO and AMO are dominated by alternating sea surface temperatures (SSTs) and sea-level pressure (SLP) anomalies, respectively (Ortega et al., 2015; Knudsen et al., 2014). The climatic instability during the LIA may be link to the NAO and AMO via the westerlies (Chen et al., 2019b). However, the relationship between HI and NAO, and AMO is ambiguous on multidecadal timescales (Figs 6b, i, g). Although the Wavelet Coherence (WTC) results show that the NAO and HI have approximately ~25-, 50-, and 128-year periodicities, and the AMO and HI have the periodicities of ~32-, 70-, and 128-year, these periodicities are nonpersistent (Fig. S2 in the Supplement). Therefore, our results suggest that the periodic variations in NAO and AMO themselves have little influence on the humidity fluctuation in Lake Dalongchi at the multidecadal timescale.

However, on multi-centennial timescales, the dominant dry climate conditions during the MWP and humid climate conditions during the LIA seems related to the relatively positive and negative phases exhibited in the NAO and AMO, respectively (Figs 6b, i, g). Previous studies indicate the negative phase of the NAO and AMO during the LIA favors increasing precipitation in ACA (Chen et al., 2019b; Chen et al., 2015; Lan et al., 2018; Aichner et al., 2015; Chen et al., 2006; Chen et al., 2016). During the MWP, the positive phase of the NAO with enhanced pressure between the Azores High and the Icelandic Low would lead to strengthened zonal flow, and the axis of maximum moisture transport and preferred storm track extend to the north and east (Trouet et al., 2009). In contrast, the axis of maximum moisture transport and preferred storm track migrated southwards when the NAO was in a negative phase during the LIA (Hurrell, 1995). A general cold (warm) phase of the AMO corresponds to the negative (positive) NAO phase during the LIA (MWP) (Wang et al., 2017; Ortega et al., 2015), leading to a weaker (strong) upper-level jet stream intensity and further resulting in development (recession) of the through-ridge system, consequently contributing to the increased (decreased) precipitation in ACA (Chen et al., 2019b).

Thus, the multi-centennial behavior in our reconstruction might be related to the influence of the NAO and AMO on hydroclimate changes between the MWP and the LIA.

5.3.2 The role of the Gleissberg cycle

Solar forcing has been treated as a critical factor for influencing key components (e.g., temperature, precipitation, evaporation, winds, ocean circulation, and iceberg transport) of the climate system (Sha et al., 2016; Bond et al., 2001; Bard and Frank, 2006; Knudsen et al., 2014). As the largest dry inland regions in the globe, the climate records from ACA are valuable for investigating the fingerprint of solar forcing. We compared HI with the reconstructed total solar irradiance (TSI) (Bard et al., 2000) and found a strong link and inverse relationship between the HI and TSI, especially during the LIA (Fig. 7b). The HI increased significantly and reached its peak during the several grand solar minimums (Wolf, Spörer, Maunder, Dalton), whereas the humidity decreased rapidly in the maximum solar activity period (Fig. 7b). The WTC spectrum between HI and TSI shows a strong correlation and anti-phase pattern (Fig. 7c). Periodicities of significant coherence for HI and TSI occurred at ~88 to 146 years, particularly from 1400 CE to the present. Arrows in the significant coherence spectral area point almost entirely to the left, implying the persistent negative correlation of HI and TSI (Fig. 7c). Therefore, the WTC result confirms that the persistent ~88-146-year cycle of HI in CWT is associated with solar activity (Figs. 7a, c). The cycle of 88-146 years should be attributed to the century-scale solar cycle of Gleissberg (Gleissberg, 1958; Gleissberg, 1965; Ogurtsov et al., 2015) (Fig. 7a). Accordingly, we extracted this century-signal from the original HI series based on the Ensemble empirical mode decomposition (EEMD), a new noise-assisted data analysis (NADA) method (Wu and Huang, 2009; Huang et al., 1998). The relationship between the century component and TSI has an apparent correlation ($r = -0.217^{**}$) and a clear coherence spectral area (Fig. 7f and Fig. S3a in the supplement). The HI shows an extreme instability accompanied by obvious secondary oscillations of cold-wet and warm-dry at century timescales during the LIA under the regulation of solar activity (Fig. 7f). This verifies the critical role of the Gleissberg solar cycle in controlling the effective humidity at the century-scale during the last millennium in ACA. Shindell et al. examined the climate response to the solar forcing at the Maunder Minimum and indicated that even relatively small solar activity might play a primary role in century-scale climate change in NH (Shindell et al., 2001). The possible solar contribution of the Gleissberg century cycle to climate changes over at least the last millennium has been reported from the North Atlantic region (Moffa-Sánchez et al., 2014;

Ogurtsov et al., 2002b; Ogurtsov et al., 2002a; Ogurtsov et al., 2015). In arid Central Asia, several records documented the solar fingerprint by the evidence of ~200-year periodicity between the proxy data and solar activity time series (Zhao et al., 2009; Yin et al., 2016), and sediment records from Lake Toson and lake Manas exhibited periodicities of 93 years and 70 to 100 years respectively through the Spectral and wavelet analysis, which may be linked with the Gleissberg solar cycle (Ling et al., 2018; Song et al., 2015). However, still, rare records in ACA documented the good relationship between the effective humidity changes and the fluctuations of the Gleissberg cycle. Our reconstruction provides strong evidence for negative link between the Gleissberg solar cycle and humidity changes at century timescales during the last millennium in ACA.

The confusion we focus on now is how solar activity significantly affected hydroclimate fluctuations in ACA over the last millennium. Several studies proposed that the solar forcing may influence the variability of the sea-atmospheric modes, the NAO in particular (Swingedouw et al., 2011; Kirov and Georgieva, 2002; Kodera, 2002; Gimeno et al., 2003). Kodera (2002) suggests that the NAO extends to the stratosphere during the high solar activity and to the troposphere during the low solar activity. Such relationship between the solar activity and troposphere/stratosphere subsequently determines the positive or negative phase of NAO (Shindell et al., 2001; Kodera and Kuroda, 2002; Gray, 2003). Solar irradiance also has been served as a trigger for the shifts of the precipitation-bearing westerlies during winter (Brahim et al., 2018; Kodera, 2002; Yukimoto et al., 2017). Ultimately, the solar variability indirectly affects the hydroclimate changes through modulating the NAO state, suggesting solar regulation for hydroclimate might be amplified on a regional scale through atmospheric circulation (Ineson et al., 2011; Shindell et al., 2001; Gray, 2003; Brahim et al., 2018; Kodera, 2002; Yukimoto et al., 2017).

However, for ACA far from the ocean with scare precipitation and intense evaporation, the mechanism of solar forcing on humidity may be direct. Our reconstruction reveals the robust negative relationship between the TSI and HI, but the ambiguous relationship between the NAO and HI (Figs. 6, 7). The paleoclimate records from ACA also highlight that the intense evaporation and direct heating caused by the enhanced solar irradiance control the effective humidity (Liu et al., 2019; Song et al., 2015; He et al., 2013; Wu et al., 2020; Ling et al., 2018; Zhao et al., 2009). To further investigate the potential feedback processes between the solar variability and effective humidity at century timescales in ACA, we performed transient experiment forced only by the TSI for the last millennium using the Max Planck

Institute Earth System Model (MPI-ESM) (Jungclaus et al., 2014) (Fig. S4 in the supplement). Most of the precipitation occurs in June-August in the study area and the evaporation process is intensified in summer (Lan et al., 2018), so we mainly considered the results of June-July-August (JJA). There is a positive relationship between the TSI, temperature, and evaporation (Fig. S4 in the supplement), indicating that high solar output favor to high temperature and intensified evaporation at century timescales in arid Central Asia. Moreover, the effective humidity shows a negative association with evaporation, temperature, and TSI variability (Fig. S4 in the supplement). However, the relationship between precipitation and effective humidity appears to be obscure at the century timescale (Fig. S4 in the supplement). Therefore, the solar forcing has a direct contribution in regulating the humidity in ACA by the century Gleissberg cycle forcing on the temperature and evaporation over the last millennium, albeit water vapor was transported by westerlies and precipitation might be affected by ocean-atmosphere modes.

5.3.3 Linkage to ENSO

ENSO is a mode of variability representing changes in sea-surface temperatures and atmospheric circulation across the equatorial Pacific Ocean (Jiménez-Moreno et al., 2021; Cane, 2005). Paleoclimatic proxies and historical records suggest ENSO has long-term variability in amplitude and frequency on multidecadal to centennial timescales (Yeh and Kirtman, 2007; D'arrigo et al., 2005; Li et al., 2011; Mann et al., 2000). The amplitude of ENSO variability is the important factor to affect the occurrence of climate extremes over the globe (Mcphaden et al., 2006; Cheng et al., 2008). On the multi-centennial timescale (i.e., MWP to LIA), the HI and ENSO variance (Li et al., 2011) show a similar trend in amplitude changes (Fig. 7d). The amplitudes of HI and ENSO variance both show a distinctly increasing trend during the LIA and maintain a relatively high level from ~1650 to 1950 CE (Fig. 7d). This trend suggests that the relatively humid environment and unstable hydroclimate in ACA may be associated with the increase in ENSO variance amplitude (Li et al., 2011) and more frequent ENSO events (Rustic et al., 2015) during the LIA, which possible owing to a major reorganization within the tropical ocean-atmosphere system or significant ENSO teleconnection changes from the MWP to LIA (Rustic et al., 2015; Li et al., 2011). The results here support previous studies showing that ENSO might affect hydroclimate variability in ACA at multi-centennial timescales with La Niña-like (EI Niño-like) conditions during the MWP (LIA) (Chen et al., 2019a; Chen et al., 2015). During the LIA with a relative warm EI Niño-like conditions, the Western

Pacific Subtropical High enhanced and extended westwards, and a low-pressure trough related to the weakening of the Siberian High over the Central-Southwest Asia region formed, together resulting wetter climatic conditions in arid Central Asia (Chen et al., 2015; Feng et al., 2016; Syed et al., 2006; Chen et al., 2019a).

On the multidecadal timescales, however, the WTC between the HI and ENSO variance shows a robust negative phase relationship (Fig. 7e). In particular, the WTC result shows that the HI has a similar quasi-regular cycle of ENSO variance from 82-90-yr during the MWP to 50-60-yr thereafter (Li et al., 2011), which reveals the potential modulation of these quasi-regular cycles of ENSO variance to extreme humidity oscillations at the multidecadal timescales in ACA (Fig. 7e). Furthermore, the multidecadal component of the HI extracted by the EEMD (Wu and Huang, 2009; Huang et al., 1998) also exhibits an obvious inverse relationship with ENSO variance (Fig. 7g). The influence of ENSO on the extratropical climate has been shown to be modulated by ENSO variance at multidecadal timescales, and the calculated 31-year running correlations between the reconstructed ENSO variance and other records of ENSO teleconnections shows that the ENSO teleconnection is robust over Central Asia during the past seven centuries only except for the Maunder minimum (Li et al., 2013). The quasi-regular periodic variation of ENSO variance effect on the hydroclimate changes of ACA at multidecadal timescales might be through modulating the extreme precipitation. The water vapor from the Arabian Sea may be transported to the Xinjiang region and cause heavy precipitation, although the water vapor fluxes mostly come from the west transported by the prevailing westerlies (Huang et al., 2015a; Huang et al., 2013). Daily observational precipitation and National Center for Environmental Prediction (NCEP) reanalysis data also suggest that the low-level water vapor fluxes from the Indian Ocean, transported along the eastern periphery of the Tibetan Plateau, are the most important factor leading to rainstorms in ACA (Huang et al., 2017). However, our knowledge of the cause of ENSO variance influence on hydroclimate oscillations in ACA at multidecadal timescales is still in its infancy and remains uncertain, owing to the complicated interactions of the tropical and subtropical ocean basins at decadal to multidecadal timescales (Cai et al., 2019). The mechanisms for the different timescales between the ENSO amplitude and hydroclimate changes in ACA require further exploration through high-resolution records and simulation experiments.

6 Conclusions

We present the Humidity Index (HI) in ACA over the past millennium based on the ~1.8-year high-resolution multiproxy records from Lake Dalongchi in the central Tianshan Mountains. Our results reveal dramatic and unstable multidecadal to century-scale humidity oscillations over the last millennium, especially within the LIA, which is distinct from other records of ACA. Our findings emphasize that the Gleissberg solar cycle and quasi-regular period of ENSO amplitude play critical roles in controlling the effective humidity in ACA at century and multidecadal timescales, respectively. However, high-resolution records on different time scales and climate model simulations are still needed to improve our understanding of the physical mechanisms of the links between solar irradiance and ocean-atmosphere modes and how their coupling affects moisture variation in ACA.

Data availability

The reconstructed Humidity Index in this study are submitted to the datasets of the 4TU Center for Research Data, which can be temporarily available at https://doi.org/10.4121/16570398.v1.

Supplement

The supplement related to the article contains the supplementary methods and four supplementary diagrams.

Author contributions

SF and XL conceived this study, carried out the laboratory analysis and data interpretation, and wrote the manuscript; FS and YL performed the data analysis; XM and JW participated in the retrieval of the sediment core and sampling. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1. Accelerator mass spectrometry (AMS) ^{14}C dating results of DLC1819 core.

No.	Lab. No	Sample ID	Composite depth (cm)	Analyzed material	$\delta^{13}C$ (‰)	^{14}C age /a BP	Calendar age/CE
1	Beta - 514897	DLC-1-1-61	69	Wood	-24.9	90+/-30	1870-1928
2	Beta - 507553	DLC-1-1-135	143	Wood	-27.4	170+/-30	1721-1818
3	Beta - 507554	DLC-1-2-82	210	Wood	-31.4	230+/-30	1635-1684
4	Beta - 507555	DLC-1-2-155	283	Wood	-26.1	340+/-30	1470-1640
5	Beta - 507556	DLC-1-3-61	324	Wood	-28.1	430+/-30	1420-1498
6	Beta - 507557	DLC-1-3-119	382	Wood	-22.3	440+/-30	1416-1490
7	Beta - 514898	DLC-1-3-131	394	Wood	-23.7	370+/-30	1446-1528
8	Beta - 514901	DLC-3-5’-37	585	Wood	-23.6	670+/-30	1274-1320
9	Beta - 542591	DLC2019-1-5-76	625	Wood	-23.1	800+/-30	1184-1275

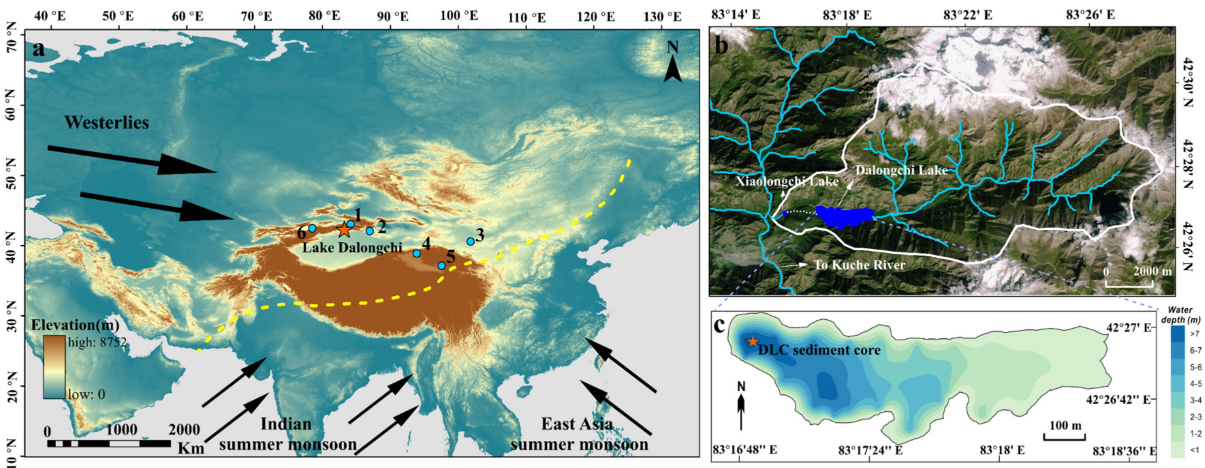

Figure 1. Maps of the study site. (a) Locations of Lake Dalongchi and other humidity records mentioned on the text in arid Central Asia. Sites 1-6 denote the Bayanbuluk meteorological station, Lake Bosten (Chen et al., 2006), Badian Jaran Desert (Ma and Edmunds, 2006; Gates et al., 2008), Lake Sugan (He et al., 2013), Lake Gahai (He et al., 2013), and Lake Ala Kol (Rousseau et al., 2020), respectively. The dashed yellow line indicates the boundary of the modern Asia summer monsoon, the mid-latitude inland region on the western side of the modern Asia summer monsoon boundary line is arid central Asia (ACA) (Chen et al., 2010; Chen et al., 2019a). The map was generated by ArcMap 10.2 software (ESRI, USA, http://www.esri.com). (b) Watershed map of the study site. (c) Bathymetric contour map of Lake Dalongchi with the coring site.

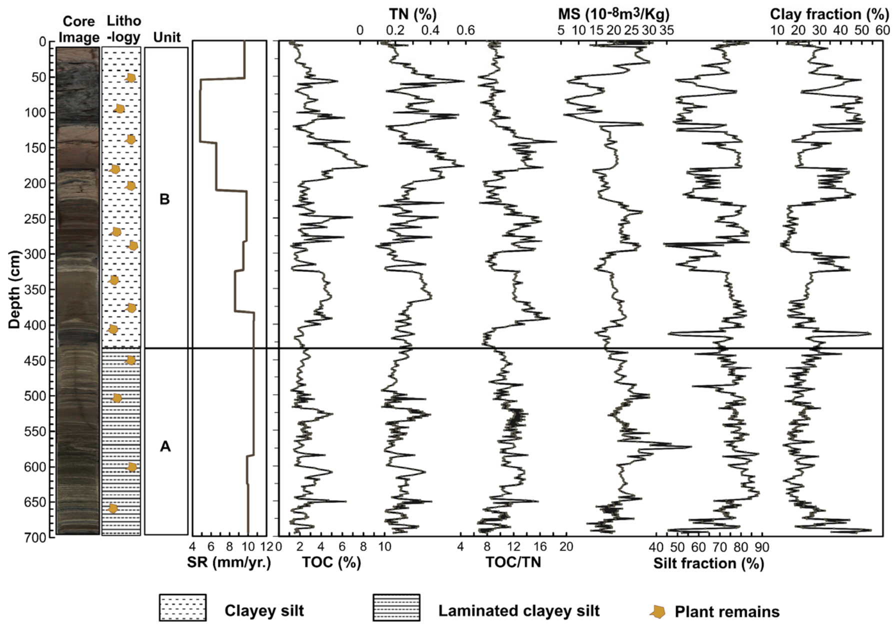

Figure 2. Sedimentary lithology and multi-proxy variation versus depth for the composite DLC1819 core.

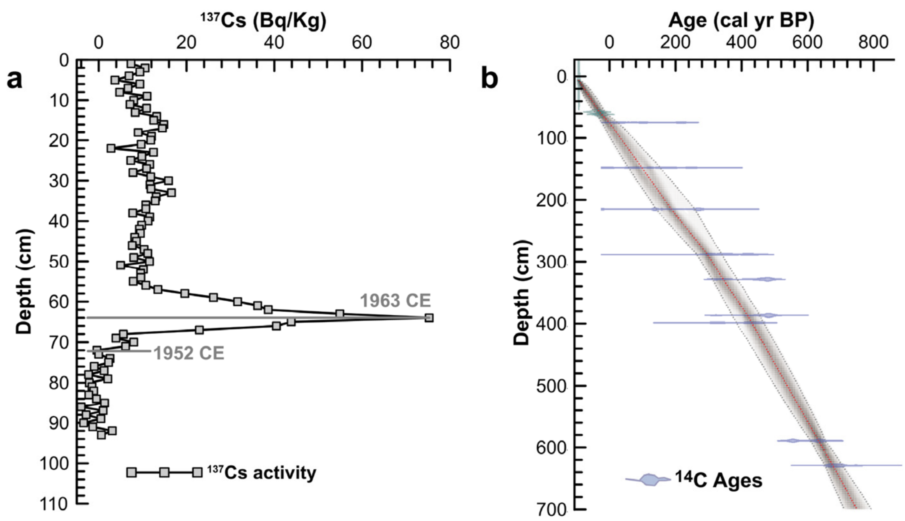

Figure 3. Age-depth model for the DLC1819 core of Lake Dalongchi. (a) The ^{137}Cs activity versus depth in the uppermost sediments. (b) Bayesian age-model for the calibrated ages. The black dotted lines indicate the 95% probability intervals of the model.

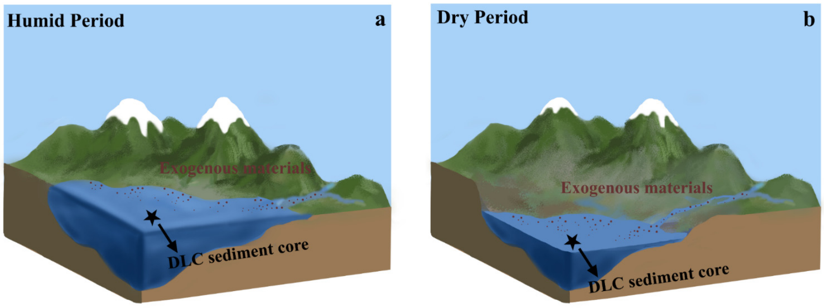

Figure 4. Cartoon schematic diagram illustrating a simple explanation of the lacustrine depositional process in Lake Dalongchi region. Lake level condition and the transport process of exogenous materials in the humid period (a) and the dry period (b).

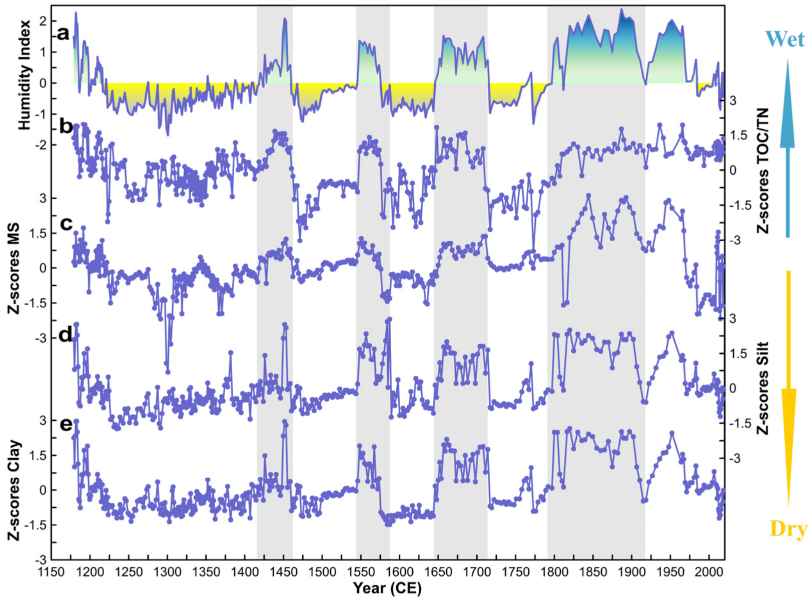

Figure 5. Humidity Index reconstruction (a) based on the Z-scores of total organic carbon/total nitrogen (TOC/TN) ratios (b), the Z-scores of magnetic susceptibility (MS) (c), the Z-scores of silt fraction (d), and the Z-scores of clay fraction variation (e) in the DLC1819 core in Lake Dalongchi. Light grey bars highlight intervals of increased humidity in Lake Dalongchi during the LIA.

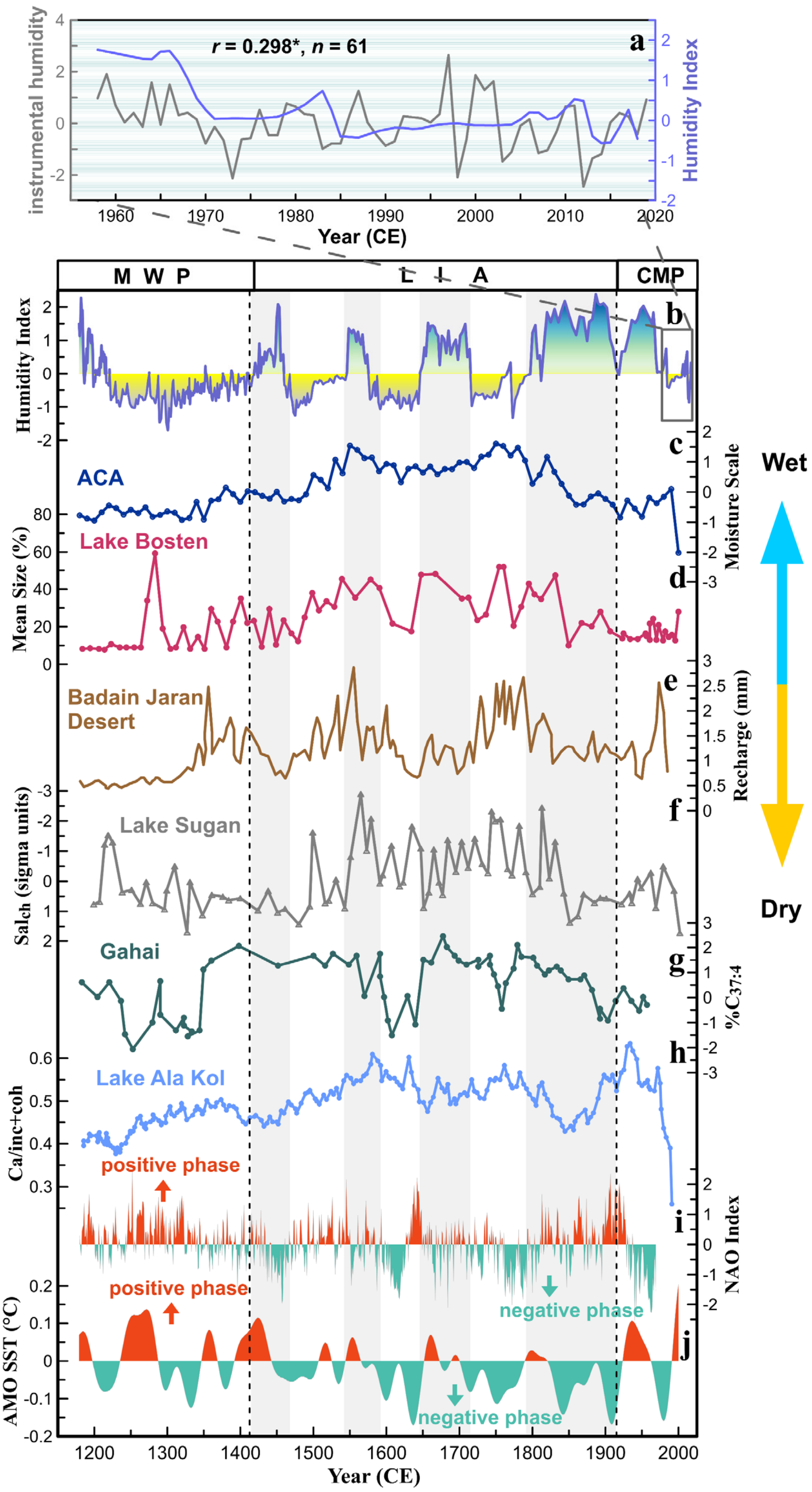

Figure 6. Humidity Index (HI) of Lake Dalongchi and comparison to other records in ACA over the last millennium. (a) Comparison between the HI (blue line) and the standardized instrumental effective humidity recorded by Bayanbuluk meteorological station (grey line). * represents the 0.05 significance level. (b) The reconstructed HI for the past millennium (1180-2018 CE). (c) The synthesized moisture curve over the last millennium in ACA (Chen et al., 2010). (d) Variations in the mean grain size along

the BST04H core in Bosten Lake (Chen et al., 2006). (e) The unsaturated recharge history in Badian Jaran (Gates et al., 2008; Ma and Edmunds, 2006). (f) Chironomid inferred salinity (Salch) in SG03I of Sugan Lake (Chen et al., 2009). (g) %$C_{37:4}$ from Lake Gahai (He et al., 2013). (h) Ca/inc+coh from Lake Ala Kol (Rousseau et al., 2020). (i) the reconstructed NAO (Ortega et al., 2015). (j) the reconstructed AMO (Wang et al., 2017). Light grey bars highlight intervals of increased humidity in Lake Dalongchi during the LIA.

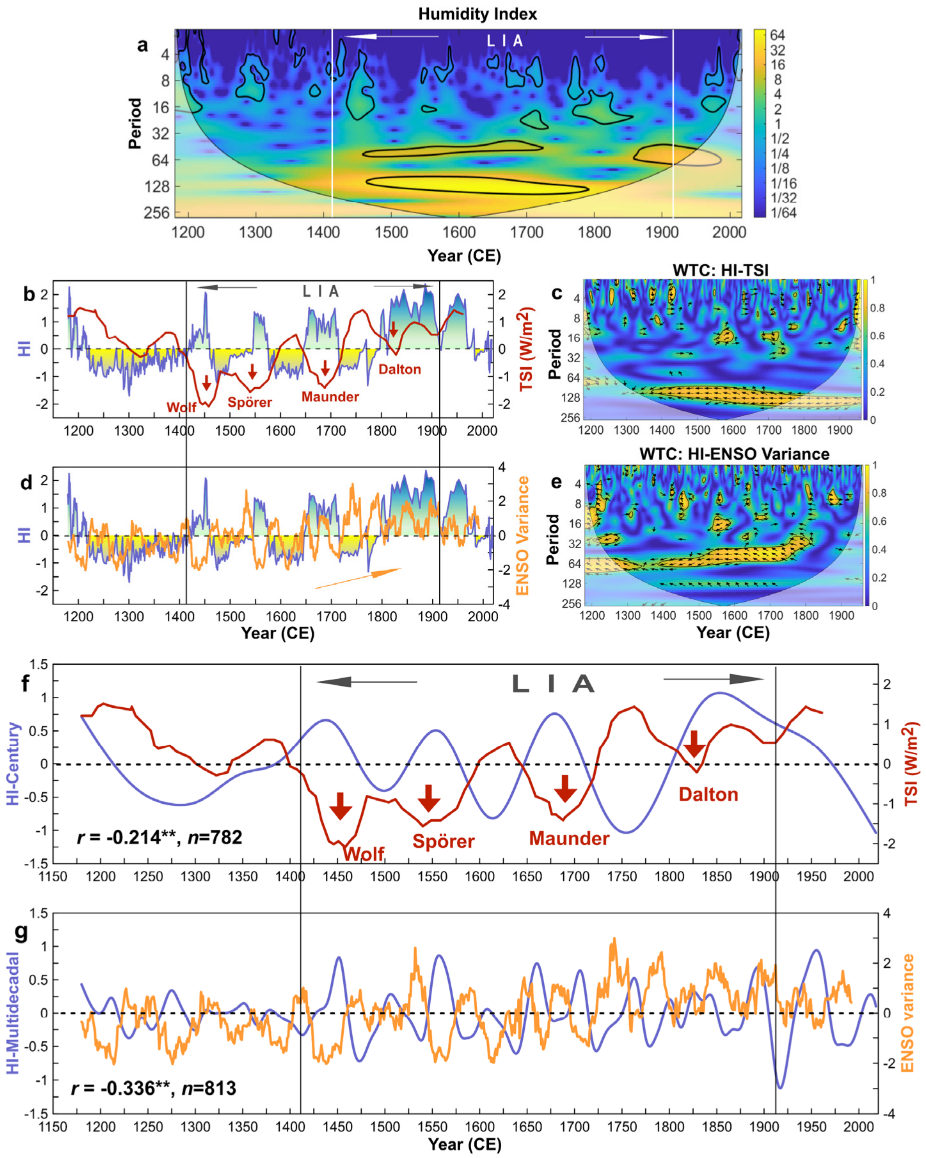

Figure 7. The wavelet analysis of the HI and the relationship between the HI and the TSI or ENSO. (a) Continuous wavelet (CWT) power spectrum of the HI. The irregular thick black contour represents the 95% confidence level against red noise and the thin curved black solid line is the cone of influence (COI)

(Grinsted et al., 2004). (b) A comparison between the HI and the reconstructed total solar irradiance (TSI) (Bard et al., 2000). Wolf, Spörer, Maunder, and Dalton represent several grand solar minimums that occurred during the LIA. (c) The wavelet coherence (WTC) result between the HI and the TSI (Bard et al., 2000). (d) As (b), but for ENSO variance reconstruction (Li et al., 2011). Orange arrows represent the enhanced ENSO amplitude trend. (e) As (c), but for ENSO variance (Li et al., 2011). (f) A comparison between the century component of HI and TSI (Bard et al., 2000) (g) A comparison between the multidecadal component of the HI and ENSO variance reconstruction (Li et al., 2011). The 95% confidence level against red noise is shown as an irregular thick black contour. The black arrows illustrate the relative phase relationship: arrows pointing right are in-phase and those pointing left are anti-phase (Grinsted et al., 2004). ** represents the 0.01 significance level.