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# An 80-year summer temperature history from the Xiao Dongkemadi ice core in the central Tibetan Plateau and its association with atmospheric circulation

Xiangying Li [a,b], Yongjian Ding [b,*], Zhongbo Yu [a], Sillanpää Mika [c], Shiyin Liu [b], Donghui Shangguan [b], Chengyang Lu [d]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering/College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[b] State Key Laboratory of Cryospheric Science, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China
[c] Laboratory of Green Chemistry, Lappeenranta University of Technology, Sammonkatu 12, 50130 Mikkeli, Finland
[d] Upstream of Hydrology and Water Resources Bureau in the Yellow River Conservancy Commission, Lanzhou 730030, China

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A B S T R A C T

The climate significance of oxygen isotopes from the central Tibetan Plateau (cTP) ice cores is a debated issue because of large scale atmospheric circulation. A high-resolution $\delta^{18}O$ record was recovered from the Xiao Dongkemadi (XD) ice core, which expanded the spatial coverage of $\delta^{18}O$ data in this region. Annual average $\delta^{18}O$ correlated significantly with nearby MJJAS air temperatures, suggesting the $\delta^{18}O$ can be used as a proxy to reconstruct regional climate change. The reconstructed temperature anomaly is related to the regional and global warming trends, and the greater warming amplitude since 1970s is related to the elevation dependency of the warming signal. The close relationship of the warming to variations in glacier mass balances and discharge reveal that recent warming has led to obvious glacier shrinkage and runoff increase. Correlation analysis suggests that monsoon and westerly moisture substantially influence the cTP ice core records, along with an increase in their level of contribution to the XD core accumulation in recent decades, and confirms a teleconnection of regional climate of the cTP ice cores with climate parameters in the Indian and North Atlantic Oceans.



## 1. Introduction

The Tibetan Plateau (TP) is one of the most sensitive areas to global warming and is recognized as the ‘water tower’ of central Asia (Kang et al., 2007; Immerzeel et al., 2010). Climate and environment over the TP are complex due to its high elevation, which exerts thermal and dynamical influences on atmospheric circulation (Yao et al., 2012). Atmospheric moisture in the northern TP is dominated by strong continental recycling with high evaporation and convective precipitation (westerly circulation). In the southern TP, moisture is mainly provided by the Indian monsoon with its humid oceanic origins (monsoon circulation) (Tian et al., 2001). The westerly circulation dominates the TP during the cold seasons, with the westerly surface winds splitting into the northern and southern branches. Meanwhile, during the warm seasons, the westerly jet is pushed northward with the maximum extent of the south Asian monsoon (Vuille et al., 2005). These interacting circulation systems provide converging moisture to the central TP (cTP) from vastly different source regions with distinct transport histories.

Temperature changes over the TP have been a controversial issue and relevant studies have been limited due to the uneven distribution of weather stations and the relatively shorter time series of recorded data (Yang et al., 2014). Using ice cores as an isotopic proxy provides a tool to extend the TP temperature record (Thompson et al., 2000; Tian et al., 2006; Kang et al., 2007). Isotopic dependence on temperature is established for the northern TP where the most depleted isotope ratios are related to the accumulation during the lowest temperatures and the least depleted ratios arrive with the warm-season moisture (Rozanski et al., 1992; Yao et al., 1996; Tian et al., 2006). Meanwhile, in the southern TP, the monsoon moisture dominates annual precipitation and more depleted monsoon moisture arrives during the warm seasons (Kang et al., 2002; Tian et al., 2003; Vuille et al., 2005). Thus the monsoon influence has greatly complicated the climate significance of ice core $\delta^{18}O$ in the cTP, further challenging the $\delta^{18}O$ interpretation in paleoclimate proxies. Kang et al. (2007) showed that

* Corresponding author.
*E-mail address:* dyj@lzb.ac.cn (Y. Ding).

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the $\delta^{18}O$ record in the Geladaindong (GLDD) ice core from the northwestern Tanggula Mts. of the cTP can be used to reconstruct regional JAS temperatures, based on significant correlations between the $\delta^{18}O$ and nearby JAS air temperatures. They speculated that the reconstructed temperature may be influenced by the North Atlantic Oscillation (NAO), based on the 2 and 7 year periods of temperature series. Joswiak et al. (2010, 2013) showed the influence of monsoon moisture on isotopic records in the Tanggula (TGL) ice core from the southeastern Tanggula Mts. on a shorter and longer time scale, based on correlations between isotopic records and northern India precipitation (NIP) and climate indices (SO, Niño3.4 and DMI), suggesting that it was impossible to reconstruct single climate parameters or indices from the cTP ice cores. Yang et al. (2014) showed that the $\delta^{18}O$ records in the cTP ice cores indicate an increased temperature in the past century, and suggested that the El Niño/Southern Oscillation (ENSO) history could be reconstructed from the TP ice cores. These studies indicate that the climate significance of stable isotopes in the cTP ice cores is still a debated issue because of large scale atmospheric circulation.

In this study, a 19.6 m-long ice core covering the past 80 years (1927–2006 AD) was drilled on the Xiao Dongkemadi (XD) Glacier in the northeastern Tanggula Mts. of the cTP (Fig. 1) to further explore the climate significance of stable isotopes in the cTP ice cores and their association with atmospheric circulation (monsoon and westerly moisture). The GLDD (Kang et al., 2007) and TGL (Joswiak et al., 2010, 2013) ice cores drilled previously from the same range (Fig. 1), about 100 km northwest and 5 km north of the XD drilling site, respectively, provided a comparison for the period 1935–2004. The main focus here is on: (1) the correlations of the XD ice core $\delta^{18}O$ records with summer air temperatures at nearby weather stations; (2) the reconstruction of an 80-year temperature record and its variability; (3) the influence of monsoon and westerly moisture on the XD ice core $\delta^{18}O$ records and corresponding temperature trends.

## 2. Data and methodology

The XD ice core (33.07°N, 92.08°E, 5700 m ASL) was obtained from the accumulation area of the XD Glacier in 2007. Low air temperature at the drilling site limits the possible melting of surface snow and is beneficial for the preservation of ice core records. Although strong winds do remove parts of the fresh snow, in situ observation shows that hard layers of snow formed by the wind on the snow surface prevent further snow surface erosion. The core was transported under frozen conditions to the State Key Laboratory of Cryospheric Sciences (SKLCS) for processing and analysis. The core was sampled continuously at intervals of about 3 cm in a cold room, and a total of 653 sections were obtained for isotopic and chemical analysis. These core sections were melted at room temperature immediately before analysis. All measurements were performed in the SKLCS. $\delta^{18}O$ was measured using a Finnigan MAT-252 mass spectrometer (accuracy of 0.05‰), and the results were expressed vs. the standard mean ocean water (SMOW). Major cations ($Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$ and $NH_4^+$) were analyzed by a Dionex 600 ion chromatograph using an IonPac CS12A column, 20 mM MSA eluent and CSRS-ULTRA-II suppressor. Major anions ($Cl^-$, $NO_3^-$ and $SO_4^{2-}$) were analyzed by a Dionex 2500 ion chromatograph using an IonPac AS11 column, 25 mM KOH eluent and ASRS-ULTRA-II suppressor. The detection limits for all measured ions were below 0.1 $\mu g\,L^{-1}$. $\beta$ activity was determined by a MINI20 low background $\alpha/\beta$ counting system (CANBERRA EURISYS). Analysis of field blanks showed that contamination during transport, processing and analysis is negligible. This study focusses exclusively on $\delta^{18}O$ data for the XD ice core from the Tanggula Mts. in the cTP.

Meteorological data from the nearest weather stations (Wudaoliang (WDL), Tuotuohe (TTH), Anduo (AD) and Naqu (NQ)) (Table 1; Fig. 2) were used for comparison with ice core $\delta^{18}O$ data. Station locations are shown in Fig. 1; coordinates, altitudes, periods

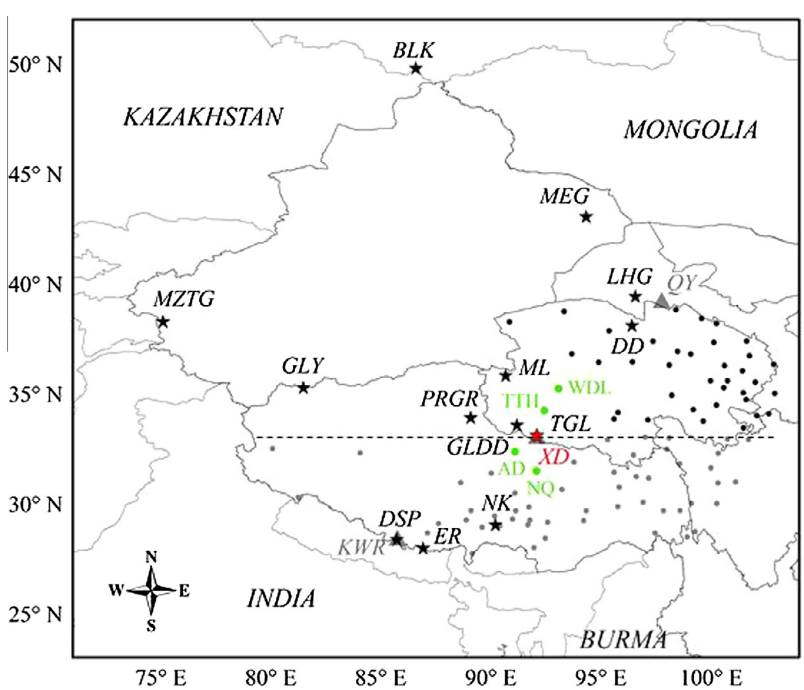


**Fig. 1.** Locations of the Xiao Dongkemadi (XD, red star) and other ice core drilling sites (Belukha (BLK), Miaoergou (MEG), Muztagata (MZTG), Laohugou (LHG), Dunde (DD), Guliya (GLY), Malan (ML), Puruogangri (PRGR), Geladaindong (GLDD), Tanggula (TGL), Dasuopu (DSP), East Rongbuk (ER) and Noijin Kangsang (NK)) (black stars), glaciers (Kangwure (KWR), Qiyi (QY), XD) (grey stars) and weather stations in northern (black dots) and southern (grey dots) regions of the XD drilling site divided by the horizontal dashed line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Ground-based meteorological data. *Pa* and *Ps* denote annual and summer (MJJAS) precipitation, respectively, and *Ta* and *Ts* indicate annual and summer air temperature, respectively. WDL, TTH, AD and NQ indicate the Wudaoliang, Tuotuohe, Anduo and Naqu weather stations, respectively.

| Stations | Periods | *LAT*/°N | *LON*/°E | ALT/m | *Pa*/mm | *Ps*/mm | *Ta*/°C | *Ts*/°C |
|---|---|---|---|---|---|---|---|---|
| WDL | 1957–2006 | 35.22 | 93.08 | 4612 | 278.1 | 256.0 | −5.37 | 2.94 |
| TTH | 1957–2006 | 34.22 | 92.43 | 4533 | 280.9 | 259.1 | −4.05 | 4.96 |
| AD | 1966–2006 | 32.35 | 91.10 | 4800 | 442.2 | 404.5 | −2.80 | 5.62 |
| NQ | 1955–2006 | 31.48 | 92.07 | 4507 | 398.7 | 353.8 | −1.28 | 6.85 |

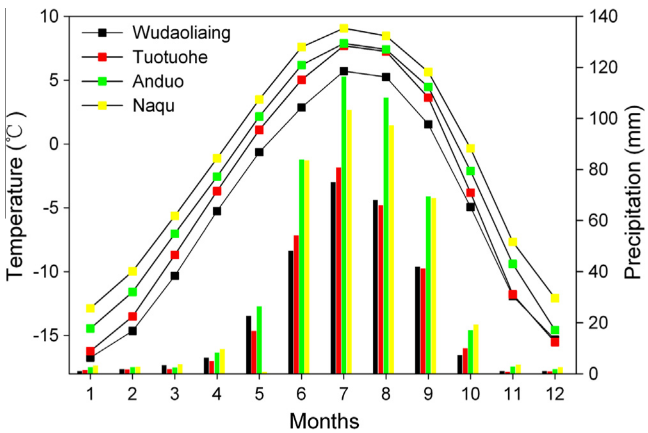


**Fig. 2.** Monthly distribution of air temperature (squares) and precipitation (bars) at the four weather stations (WDL, TTH, AD and NQ) nearest to the XD drilling site.

of record, annual and summer precipitation and temperature are summarized in Table 1. Although these are the nearest stations, distances from the XD drilling site are substantial. The closest stations are TTH and AD, located 150 km to the northeast and southwest respectively. NQ is located 180 km to the south, and WDL is 250 km to the northeast (Fig. 1). Mean temperatures over the northern ($n = 38$) and southern ($n = 54$) TP stations respectively to the north and south of the XD drilling site (see dashed line in Fig. 1), and over all TP stations ($n = 92$) (Fig. 1), were used for comparison with the ice core $\delta^{18}O$ and corresponding temperature trends. All meteorological data obtained from weather stations belong to the China Meteorological Administration. To assess the effect of climate warming on glacier ablation and discharge, the reconstructed temperature was compared to glacier mass balance (MB) and discharge. MB data were obtained from the XD, KWR and Qiyi glaciers with the longest time-series data over the TP, and discharge data were obtained from the TTH hydrological station where mostly glacier meltwater from the Tanggula Mts. converged. To examine the influence of atmospheric circulation on ice core $\delta^{18}O$ and corresponding temperature trends, annual $\delta^{18}O$ data were compared with global gridded sea surface temperature (SST) and air temperature, the NIP and climate indices from 1927 to 2006. The SST and air temperature series were obtained from the NOAA extended reconstructed SST produced by the National Climatic Data Center and the International Comprehensive Ocean-Atmosphere Data Set (ICOADS V2.5), respectively, with a resolution of $2° \times 2°$ grids (http://climexp.knmi.nl/registerform.cgi). NIP data was obtained from Sontakke et al. (2008), and its coverage includes the North Mountainous India, Northwest India, North Central India and Northeast India regions (north of 21°N) (http://www.tropmet.res.in/). The NAO index indicates the relative strength of the prevailing westerly wind (Joswiak et al., 2013), and data is obtained from the Climatic Research Unit of the University of East Anglia of the UK (http://www.cru.uea.ac.uk/cru/data/pci.htm). Considering the documented relationship between the monsoon rainfall and Indian Ocean surface temperatures (Ashok and Guan, 2004), the $\delta^{18}O$ is also compared with Dipole Mode Index (DMI). DMI data is provided by the Climate Variation Predictability and Applicability Research Program from the Research Institute for Global Change of the Japan Agency for Marine-Earth Science and Technology (http://www.jamstec.go.jp/). Owing to the previously documented relationship between the Pacific SSTs and ice core $\delta^{18}O$ in low-latitude regions (Bradley et al., 2003), the relationship between the $\delta^{18}O$ and the Niño3.4 index is investigated. Niño3.4 index is one of the ENSO indicators based on average SST anomaly in the region bounded from 5°N to 5°S and 170°W to 120°W. This region has high variability on El Niño time scales, and is close to the region where changes in local SST are important for shifting the large region of rainfall that is typically located in the far western Pacific. The Niño3.4 index is obtained from Kaplan et al. (1998) and the NOAA Climate Prediction Center (http://climexp.knmi.nl/upload.cgi).

## 3. Results and discussion

### 3.1. Ice core dating

Snow chemistry from the Tanggula Mts. indicates greater aerosol concentrations and greater $\delta^{18}O$ depletion during the dry winter seasons due to the high input of westerly moisture and mineral dust, compared to lower aerosol concentrations and less $\delta^{18}O$ enrichment during the wet summer seasons in response to monsoon precipitation (Zhang et al., 2007, 2010; Kang et al., 2010). Additionally, the Malan ice core adjacent to the Tanggula Mts. (Fig. 1) preserved visible dirty layers, which are generally deposited during the winter and spring (Wang, 2005). Therefore the XD core was dated using high-resolution records of ion concentrations, $\delta^{18}O$ ratios and visual dust stratigraphy. The local maximum of the three parameters was used to identify annual layer boundaries. On average, the offset of annual layer boundaries derived from different parameters was minor (Henderson et al., 2006). The multi-parameter layer counting at a depth of 11.4 m was verified by the $\beta$-activity horizons produced by the atmospheric thermonuclear tests in the Arctic, and possibly at the Lop Nur in western China during the periods 1967–1970 and 1973–1975 (Fig. 3), which have been found in the Northern Hemisphere (NH) ice cores (Clausen and Hammer, 1988; Zheng et al., 2010; Liu et al., 2011). By multi-parameter layer counting the XD core was dated to 1927 AD at a depth of 19.6 m spanning the period 1927–2006, with a mean resolution of 8–9 samples per year. Estimated dating uncertainties were ±1 year. To reduce the uncertainty related to the identification of specific years, we mainly report the long-term trends and decade averages.

### 3.2. $\delta^{18}O$ variability

Annual average accumulation retrieved from the XD core is around 210 mm w.eq. as determined from the dating result and density profile (Liu et al., 2011), which is less than the 256–405 mm (278–442 mm) summer (annual) precipitation at nearby weather stations (Table 1). This suggests that a mass loss has occurred, which can mostly be attributed to sublimation, weak

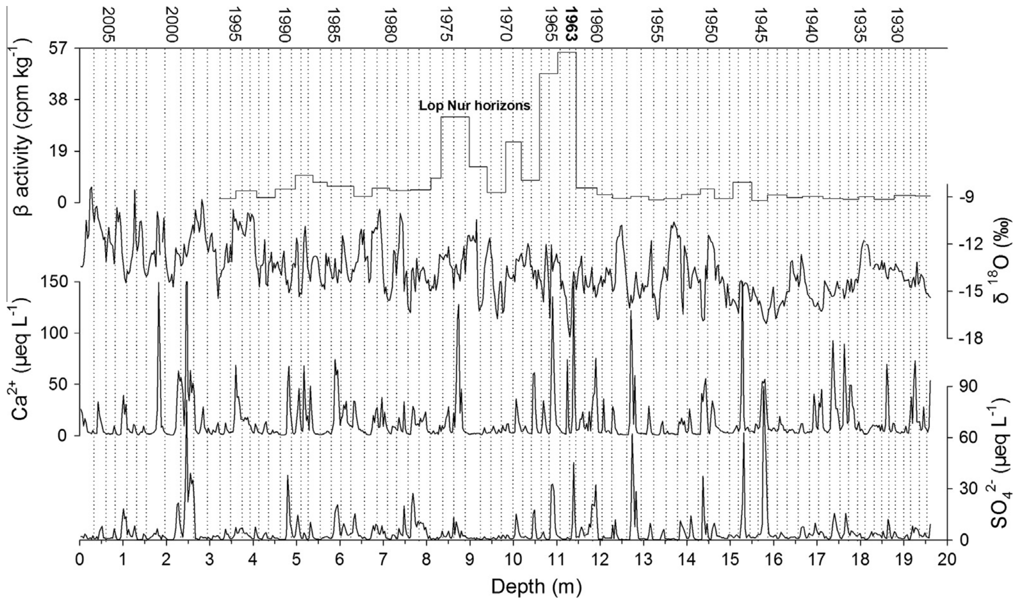


**Fig. 3.** Dating of the XD ice core based on seasonal variations in $\delta^{18}O$, $Ca^{2+}$ and $SO_4^{2-}$. The results were verified by the $\beta$ activity horizons produced by global atmospheric thermonuclear tests (1963 AD) in the Arctic, and possibly at Lop Nur in western China during the periods 1967–1970 and 1973–1975 AD.

ablation and wind erosion on the glacier surface at the XD drilling site. Seasonal variations in the XD core $\delta^{18}O$ are apparent throughout the stratigraphy profile (Fig. 3), further excluding the possibility of intensive melting and wind erosion of surface snow at the XD drilling site. In situ observation shows that a hard layer on the snow surface prevents further erosion of fresh snow in the drilling area. Annual average $\delta^{18}O$ values representing the period 1927–2007 are presented in Fig. 4 for comparison to those from the GLDD (Kang et al., 2007) and TGL (Joswiak et al., 2010) cores. The XD core $\delta^{18}O$ shows a relatively large span of 10‰ from −17.93‰ at 11.30 m depth to −8.38‰ at 0.27 m depth, and its median and mean values are −13.73‰ and −13.57‰, respectively. Moreover, annual $\delta^{18}O$ values (Fig. 4c) reveal an increasingly linear trend for the period 1927–2006 ($r^2 = 0.36$, $p < 0.01$). Periods of notable increase in annual $\delta^{18}O$ values were observed for the periods 1945–1954 and 1992–2006. There are also periods of annual $\delta^{18}O$ decrease, most notably the periods 1935–1945 and 1954–1964. Additionally, annual $\delta^{18}O$ values increased from −14.3‰ for 1927–1963 to −13.1‰ for 1964–2006. This could be in relation to significant warming in the TP since the mid-1950s (Yao et al., 1995).

The XD core $\delta^{18}O$ values exhibit slightly more depleted and moderate inter-annual variability compared with nearby GLDD and TGL cores (Fig. 4a–c). Differences between the XD, GLDD and TGL core records are most apparent prior to 1970. Despite similar elevations of around 5720 m ASL, the XD core $\delta^{18}O$ is generally 1–3‰ lower and presents a more significant decreasing trend prior to 1950, after which the time ratios generally increase, peaking in the mid-1950s and then decreasing to the mid-1960s. Subsequent to 1970, an obvious trend of an increasing $\delta^{18}O$ is present in the XD, GLDD and TGL cores, in which relatively more depleted $\delta^{18}O$ is most apparent prior to the mid-1950s, although three cores reveal an increasing trend since the 1970s. The greatest increase in the XD core $\delta^{18}O$ is observed for the period 1992–2006 (Fig. 4c), while the maximum increases in the GLDD and TGL cores begin slightly earlier and later, respectively (Fig. 4a and b). No significant correlation is found among annual average $\delta^{18}O$ values in the XD, GLDD and TGL cores. This indicates a relatively high local variation in $\delta^{18}O$ signals and the influence of local topography, atmospheric circulation and associated moisture sources on actual net accumulation on the glacier surface.

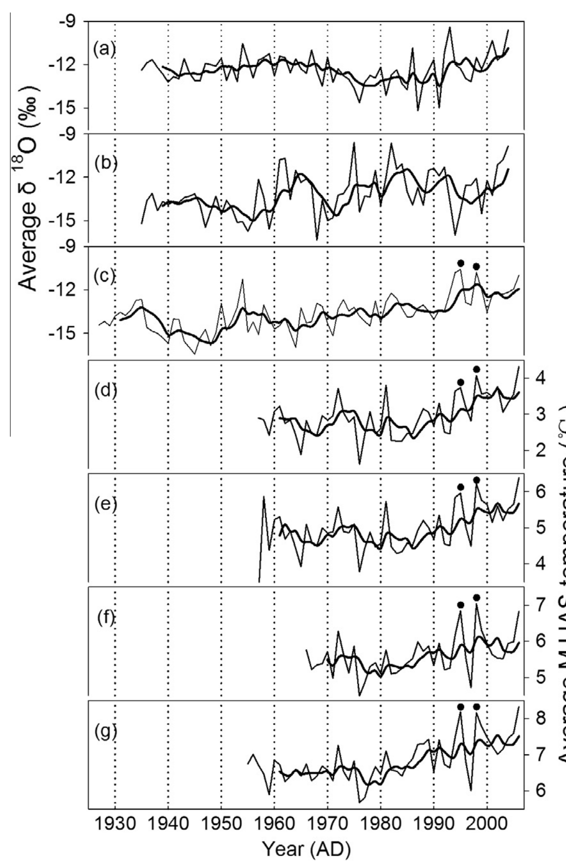


**Fig. 4.** Annual $\delta^{18}O$ values from the GLDD (a) (Kang et al., 2007), TGL (b) (Joswiak et al., 2010) and XD (c) ice cores. Annual summer (MJJAS) temperatures recorded at the WDL (d), TTH (e), AD (f) and NQ (g) weather stations. Annual and 5-yr running averages are depicted with fine and bold lines, respectively. Note that the black dots indicate the peak MJJAS temperatures at 1995 and 1998 AD.

### 3.3. Correlations of $\delta^{18}O$ with air temperatures

Previous results showed that annual $\delta^{18}O$ values in the GLDD core are significantly correlated with JAS temperature at nearby weather stations during the period 1935–2004 (Kang et al., 2007). Yet this correlation was not revealed by annual $\delta^{18}O$ values in the TGL core with JJAS temperature over the periods 1935–2004 and 1850–2004, which was attributed to the distance between the drilling site and weather stations and to the elevation differences (Joswiak et al., 2010, 2013). To investigate the extent to which the increasing $\delta^{18}O$ reflects the increasing temperature, annual $\delta^{18}O$ values in the XD core were compared to the ground-based MJJAS temperatures at the nearest weather stations (Fig. 4), and correlation coefficients between them were also analyzed for the XD core and previous GLDD and TGL cores (Table 2). Average MJJAS temperatures were used here for comparison because these months accounted for ~90% of annual precipitation during their recording times (Fig. 2). The WDL, TTH, AD and NQ stations showed consistent temperature variations for their respective recording times, with the greatest increase in MJJAS temperatures observed since the mid-1980s (Fig. 4d–g). An important finding from the XD core is an increasing trend of $\delta^{18}O$ since the mid-1960s, particularly since the early 1990s, which evidently results from changes in MJJAS temperatures at nearby stations (Fig. 4c–g). A significant correlation between annual and 5-yr running $\delta^{18}O$ values in the XD core and MJJAS temperature was observed for each station (Fig. 4c–g; Table 2). Moreover, the XD core $\delta^{18}O$ captured the warmest years, 1995 and 1998, which resulted from high May–June temperatures for the four stations. This indicates that the $\delta^{18}O$ record in the XD core does indeed preserve valuable climate information in this region. Slight discrepancies between the XD core $\delta^{18}O$ and MJJAS temperature exist (Fig. 4c–g), however, which can be attributed to the differences in elevation, discontinuous precipitation events vs. continuous air temperature records, seasonal shifts in precipitation, and loss of snow layers on the glacier surface (Tian et al., 2006). Correlations between the XD core $\delta^{18}O$ and MJJAS temperatures at the AD and NQ stations are more significant than those at the WDL and TTH stations for annual and 5-yr running averages. Correlations between the XD (and GLDD) core $\delta^{18}O$ and MJJAS temperature are also more significant to the south than to the north of the XD drilling site (Table 2). This suggests that the XD core $\delta^{18}O$ can be used as a proxy to reconstruct summer temperature for the southern Tanggula Mts. Also, Tian et al. (2001) showed that the Indian monsoon to the south of the TP can only just reach the Tanggula Mts., while its northern region (e.g. WDL, TTH) is rarely influenced. Yao et al. (1991) indicated that not only the Indian monsoon but also local convective moisture may have contributed to precipitation in this region. This shows that the Tanggula region has a very similar vapor source as areas to its south.

In comparison, the timing of MJJAS temperature increase at the WDL, TTH, AD and NQ stations is earlier than the $\delta^{18}O$ increases observed in the XD, GLDD and TGL cores (Fig. 4). Correlations between the XD core $\delta^{18}O$ values and MJJAS temperatures at four stations were compared to the isotope-temperature correlations for the GLDD and TGL cores for the same period (Table 2). Significant correlations between the XD core $\delta^{18}O$ value and MJJAS temperature were observed for the annual and 5-yr running means at each station. Additionally, significant correlation is also noted in the GLDD core for the 5-yr running means (Table 2). Yet no significant correlation was observed in the TGL core (Table 2). Even more revealing is the lack of correlation between the 5-yr running average $\delta^{18}O$ value and MJJAS temperature, given the consistent variation of the 5-yr running mean temperatures at the four stations (Fig. 4d–g). Differences between the XD, TGL and GLDD cores suggest that variable moisture sources, transport, and climatic conditions are impacting on the three locations, although the relative importance of each of these factors is unidentifiable from a single isotope parameter. Thus potential associations between annual average $\delta^{18}O$ and MJJAS temperatures for both the XD and GLDD cores from the cTP (Table 2) indicate that the oxygen isotope ratio in ice cores at a specific location can be used as a proxy to reconstruct regional climate change.

### 3.4. Reconstructed temperature variability

To better understand the amplitude of increasing $\delta^{18}O$-derived temperature variability, it is necessary to derive a $\delta^{18}O$-temperature relationship, which will help us reconstruct summer temperature variability from the ice core records. Based on a close association between annual $\delta^{18}O$ values and MJJAS temperature at the closest station, AD (Fig. 1), a regression equation was established: $\delta^{18}O = 1.24T\text{-}19.96$ ($r^2 = 0.41$, $p < 0.0001$), by which it is possible to transform the $\delta^{18}O$ notation into degrees Celsius (Fig. 5a). Clearly, the warming trend from the XD core is consistent with those from the GLDD and BLK cores since the 1970s (Fig. 5b, d), and correlates highly with that from the MZTG core since the 1960s (Fig. 5c). Additionally, the warming trend from the XD core is highly consistent with the summer warming trends from the instrumental records in both the TP and NH (Fig. 5e and f). Both instrumental records show that the warming had begun in the mid-1960s and 1970s for the NH and TP respectively with an abrupt warming since the early 1990s, which is consistent with the latest result of IPCC-AR5, as the latest decade is the warmest 10 years over the past 1400 years (Shen and Wang, 2013). Regression analysis between the XD core $\delta^{18}O$ and the TP and NH temperatures shows close relationships ($r > 0.65$, $p < 0.001$) since 1964. This indicates that, on a shorter time scale, regional warming from the XD core most probably resulted from local and global warming trends. Additionally, on a longer time scale, the millennial $\delta^{18}O$ records from ice cores (e.g. DD, GLY, ML) in the TP (Thompson et al., 2003) (Fig. 1) suggested a large area warming since 1800. Apparently, the record from the XD core reveals that warming has persisted and intensified in recent decades. There are exceptions, however, such as in the MEG and LHG cores (Fig. 1), where the $\delta^{18}O$ records showed inconspicuous warming in recent decades (e.g. Liu et al., 2011; Dong et al., 2013). This indicates that spatial differences among these ice cores probably reveal regional differences in the patterns of climate change.

To eliminate the influence of the start points of $\delta^{18}O$ data, the 1970s was chosen as the start period to study warming magnitudes in these core and instrumental records. The magnitude from the XD core is much greater than that from either the GLDD and BLK cores or the TP and NH instrumental records since the 1970s. The regression results show warming of 0.50 °C per decade for the GLDD (Kang et al., 2007), 0.18 °C per decade ($p = 0.002$) for the BLK, 0.29 °C per

**Table 2**
Correlation coefficients between the $\delta^{18}O$ and summer (MJJAS) air temperature at nearby stations and in the northern (NXD) ($n = 38$) and southern (SXD) ($n = 54$) stations of the XD drilling site. Data periods are the same as in Table 1 for the four nearby stations, and the period 1966–2006 for the NXD and SXD stations. Numbers to the left and right of the slash indicate annual and 5-yr running means, respectively. Bold numbers indicate a significance level of $p \leqslant 0.05$.

| | WDL | TTH | AD | NQ | NXD | SXD |
|---|---|---|---|---|---|---|
| XD | **0.50/0.70** | **0.58/0.72** | **0.64/0.75** | **0.63/0.80** | **0.62/0.77** | **0.75/0.82** |
| TGL | −0.00/−0.19 | −0.03/−0.20 | −0.02/−0.21 | 0.08/0.05 | −0.00/−0.19 | 0.14/−0.03 |
| GLDD | 0.11/**0.49** | 0.07/**0.52** | 0.14/**0.60** | 0.12/**0.38** | 0.15/**0.71** | 0.29/**0.73** |

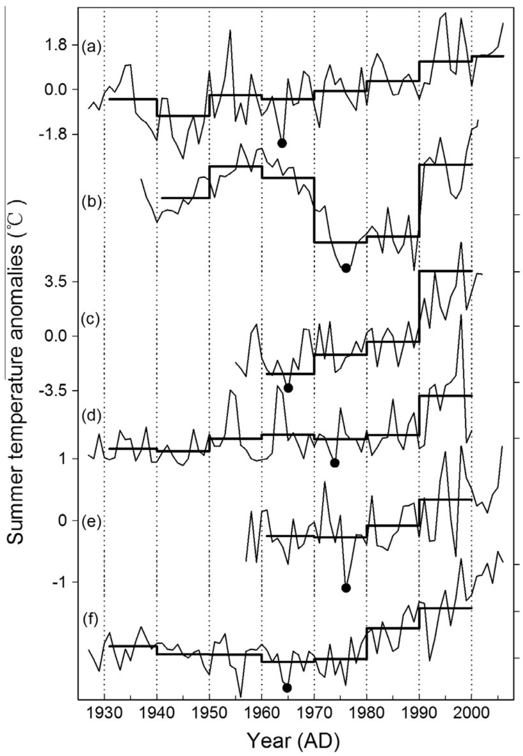


**Fig. 5.** Comparisons of summer temperature anomalies from the XD core (a) with summer temperature anomalies from the GLDD (b) (Kang et al., 2007) and BLK (d) (Okamoto et al., 2011) cores, with annual temperature anomalies from the MZTG core (c) (Tian et al., 2006), and with instrumentally-recorded summer temperature anomalies over the TP (e) (derived from average summer temperature at the 92 weather stations covering the TP, see Fig. 1) and NH (f) (http://data.giss.nasa.gov/gistemp/tabledata_v3/NH.Ts.txt). Decade variations of temperature anomalies are also given as straight bold lines. Note that the black dots indicate the approximate start years of recorded summer warming.

decade ($p < 0.001$) for the TP, and 0.26 °C per decade ($p < 0.001$) for the NH. Yet the warming magnitude from the XD core is around 0.62 °C per decade ($p < 0.001$). The relatively large magnitude at the XD drilling site could be associated with the elevation dependency of the warming signal. This could be supported by a larger magnitude (1.7 °C per decade; $p < 0.001$) in the MZTG core (7010 m ASL) (Tian et al., 2006). Liu et al. (2009) showed that warming was more prominent at higher than that at lower elevations over the TP during 1961–2006, and the elevation dependency was most likely caused by the combined effects of cloud-radiation and snow-albedo feedback. Pepin and Lundquist (2008) showed that the exposed mountain summits, away from the effects of topographic sheltering, could provide a relatively unbiased record of the planet's climate. Rapid warming is also found in other ice cores such as from the Wind River Range (Naftz et al., 2002), where the temperature increase is about 0.12 °C per decade from the mid-1960s to the early 1990s. The warming magnitude in some areas of northeastern parts of the North America is substantially above the global average with annual values of 2–3 °C per decade during the 1990s (http://data.giss.nasa.gov/gistemp/maps/). It is noteworthy that some processes could affect the warming magnitude, based on the isotope-derived temperature records in ice cores. For example, the standard lapse rate of air temperatures and the elevation gradients of both precipitation and its isotopes at high elevations are quite different from those measured at low elevation stations (Hou et al., 2003; Tian et al., 2006). Though warming magnitude is not well understood so far, the pattern of warming from the XD core is consistent with local, regional and hemispherical instrumental records, which is the pattern of a larger degree of warming with altitude.

Although instrumentally-recorded temperature at extremely high elevations is scarce, field observations on the glacier MB and river runoff provide a comparison with the temperature record reconstructed from the XD core (Fig. 6). Contrary to the increases in temperature anomalies (Fig. 6a), the MB of the XD, KWR and QY glaciers present a decreasing trend at rates of −313.1 mm per decade ($p = 0.02$), −170.2 mm per decade ($p = 0.09$) and −257.3 mm per decade ($p < 0.01$), respectively, during 1975–2010, over which cumulative mass balances (CB) decreased, particularly since the early 1990s (Fig. 6b–d). Specifically, the MB of the XD and QY glaciers were almost positive until the early 1990s, and then turned increasingly negative over time (Fig. 6b and d), while the MB of the KWR Glacier have been increasingly negative since 1992 (Fig. 6c). Additionally, decade variations of the MB for the three glaciers present a continuously decreasing trend and a significant negative relationship with that of temperature anomaly (Fig. 6a–d). This suggests that the ablation for most glaciers may have occurred in the TP since the mid-1960s with the retreat speed accelerating since the early 1990s due to global warming. In comparison, the runoff at the TTH gauging station, about 120 km north of the XD Glacier, presents an increasing trend at rate of $2.7 \times 10^8$ $m^3$ per decade ($p < 0.01$) during 1975–2010, over which cumulative discharge had continuously increased, particularly since the early 1990s (Fig. 6d), and the rate of annual discharge increased by 41.3% ($p < 0.01$). Moreover, the decade variation in discharge exhibits an increasing trend and a significant positive correlation with that of temperature anomaly (Fig. 6a and e). Despite the dominance of precipitation on river runoff at the TTH region, meltwater derived from snow cover and glaciers also play a crucial role (Zhang et al., 2013). This is supported by the partial correlation between MJJAS temperature and discharge ($r = 0.60$,

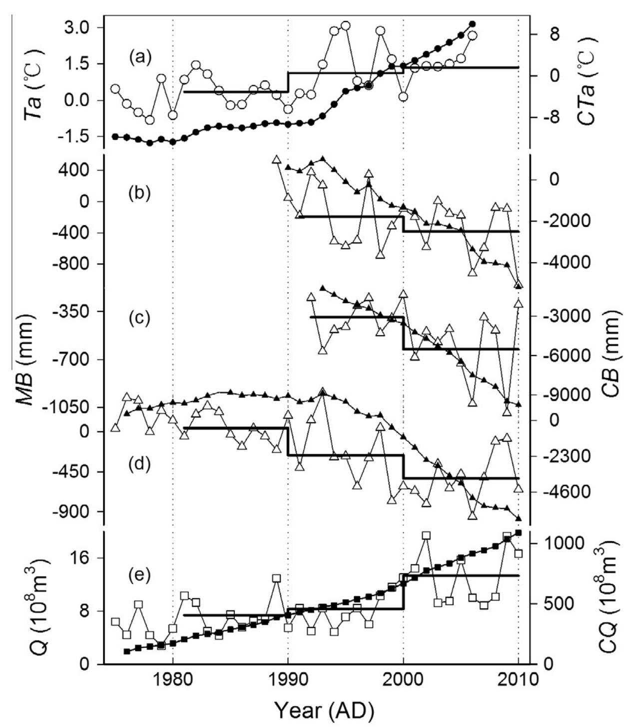


**Fig. 6.** Comparisons of summer temperature anomalies (*Ta*, white dots) and cumulative summer temperature anomalies (*CTa*, black dots) recorded in the XD core with glacier mass balances (*MB*, white triangles) and cumulative mass balances (*CB*, black triangles) for the XD (a), KWR (b) and QY (c) glaciers (Yao et al., 2012) with the longest time series on the TP, and with discharge (*Q*, white squares) and cumulative discharge (*CQ*, black squares) at the TTH gauging station (d) covering the period 1975–2010. Decade variations are also given as horizontal bold lines.

$p < 0.01$) with control of precipitation at the TTH stations for the period 1975–2007. Regression analysis between annual $\delta^{18}O$ values and the MB and discharge indicate that the XD core $\delta^{18}O$ record is significantly correlated with the MB for the XD ($r = -0.72$, $p < 0.01$), KWR ($r = -0.56$, $p = 0.03$) and QY ($r = -0.41$, $p = 0.02$) glaciers, and correlated with discharge at the TTH gauging station ($r = 0.31$, $p = 0.08$). Thus variations in both MB and discharge are highly consistent with the warming trend derived from the XD core $\delta^{18}O$ record. This suggests that the meltwater runoff observation is essential, and more effort should be made to separate meltwater discharge and to predict its variation and associated water resources in order to better serve water resource management in western China.

### *3.5. Associations with atmospheric circulations*

To investigate the influence of continental and marine evaporated moisture on the XD core $\delta^{18}O$ and corresponding temperature variations, spatial correlations were performed between annual average $\delta^{18}O$ and SST during the monsoon seasons (http://climexp.knmi.nl/registerform.cgi). Obvious positive correlations are revealed during the periods 1927–2006 (Fig. 7a) and 1964–2006 (Fig. 7b) in the equatorial Indian Ocean, Bay of Bengal and South China Sea, which have been proved to be the main sources of summer monsoon moisture over the TP (Liu et al., 2010; Zhao et al., 2012). This is because intensified (reduced) monsoon moisture leads to isotopic depletion (enrichment) during the La Niña (El Niño) events and corresponding cold (warm) SST years regardless of local temperature (Zhao et al., 2012). Noticeable positive correlations have also been observed over the east-central Pacific region (Fig. 7), indicating that Pacific SST variation might be responsible for the XD core accumulation and $\delta^{18}O$ variations, a finding that is consistent with previous ice core studies over the TP (Grigholm et al., 2009; Yang et al., 2014). Hence, the cTP ice core $\delta^{18}O$ records could potentially be teleconnected to the ENSO and corresponding SST variability. Low-latitude ice core $\delta^{18}O$ records from the Himalayas, Bolivia and Peru also revealed a similar correlation pattern with the Pacific SST (Bradley et al., 2003), which further confirms the importance of the Pacific SST in influencing ice core $\delta^{18}O$ on both sides of the Pacific Basin. These relationships suggest the possibility of combining multi-proxy records to reconstruct ENSO history. Noticeably, positive correlations over the Indian and Pacific oceans are much more significant during 1964–2006 (Fig. 7b) than 1927–2006 (Fig. 7a), indicating that the contribution of summer monsoon moisture to the XD core accumulation could have increased in recent decades, which is consistent with previous studies over the central and southern TP (Joswiak et al., 2013; Pang et al., 2014). This confirms the control of monsoon circulation on the XD core $\delta^{18}O$ and corresponding temperature variations during the monsoon seasons.

In addition, spatial correlation reveals a relatively weak association between the XD core $\delta^{18}O$ and SST over the North Atlantic during the periods 1927–2006 (Fig. 7a) and 1964–2006 (Fig. 7b), possibly indicating that there is no direct connection between the XD core isotopic record and North Atlantic climatic conditions. The NAO is the dominant mode of climate variability, with significant impact on climate patterns over the NH. A significant association between the ice core chemistry and NAO index has suggested a teleconnection between atmospheric processes in the North Atlantic and meteorological conditions in the TP (Wang et al., 2003). This weak association could be because the original isotopic signal in North Atlantic moisture has been largely modified by the mixing of water vapor from the Mediterranean Sea and other continental surface water bodies during its long-distance travel towards the TP. Yet a significant positive correlation is apparent over the North Atlantic during 1964–2006 (Fig. 7b) relative to 1927–2006 (Fig. 7a), implying that the influence of westerly moisture on the XD core accumulation could have been substantial,

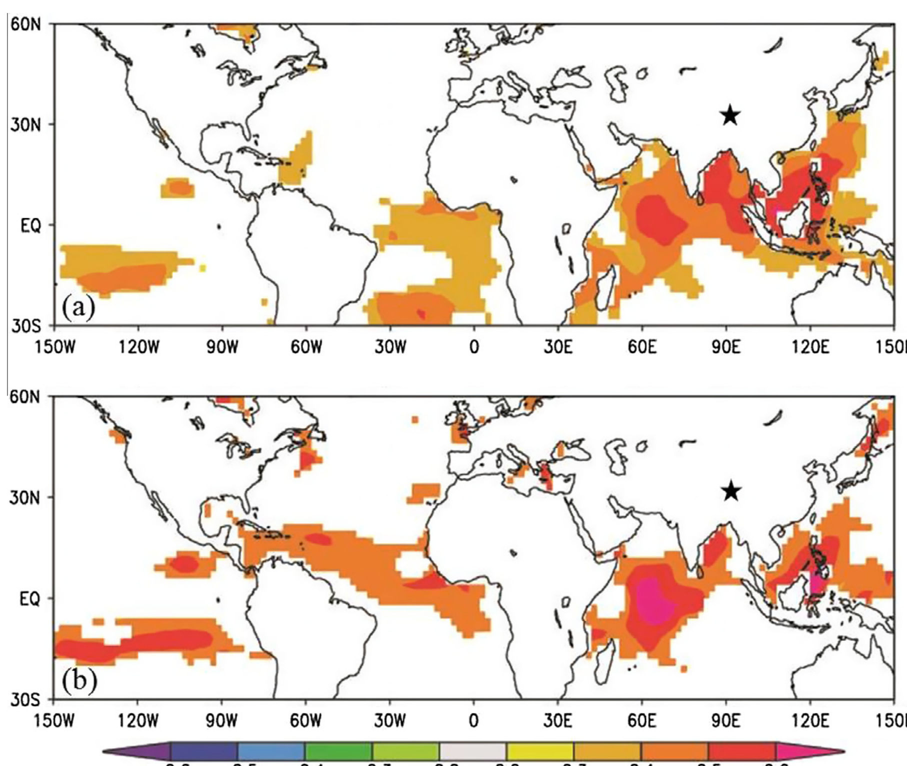


**Fig. 7.** Spatial correlations between the XD core $\delta^{18}O$ values and the NOAA extended reconstructed SST during the monsoon seasons (May to September) for the periods 1927–2006 (a) and 1964–2006 (b). Note that the black star indicates the location of the XD drilling site. Significant levels are at $p < 0.01$.

particularly in recent decades. It is well known that the mid-latitude westerly moisture is closely related to the NAO. When the NAO index is low (high), the stronger westerly over the mid-low (mid-high) latitudes leads to storm tracks shifting southward (northward), resulting in colder (milder) winters but more rainfall (Pang et al., 2014). Thus stronger (weaker) westerly over the mid-low latitudes not only brings higher (lower) precipitation but also leads to a colder (warmer) temperature environment over the TP because of more (less) and colder (warmer) air mass invasion. These colder (warmer) temperature environments could lead to ice core $\delta^{18}O$ depletion (enrichment) if the temperature effect was significant, as suggested by previous studies (Thompson et al., 2000; Davis et al., 2005; Kang et al., 2007). Hence the connection between the $\delta^{18}O$ and temperature environment can be used to further identify the influence of westerly moisture on the XD core accumulation by delimiting a specific region where air temperature is positively correlated with the $\delta^{18}O$. To determine where air temperature is related to XD core $\delta^{18}O$, spatial correlations were performed for the non-monsoon seasons (http://climexp.knmi.nl/registerform.cgi). A positive correlation region was revealed over the Azores High area and its adjacent regions during the periods 1927–2006 (Fig. 8a) and 1964–2006 (Fig. 8b). Lower (higher) air temperature over the Azores High region may imply the position of Azores High shifting southward (northward) in response to the westerly moisture shifting southward (northward). This indicates a visibly close relationship between the XD core $\delta^{18}O$ and NAO. The changes in winter westerly moisture travel trajectory associated with the NAO could be more important than local air temperature in influencing the XD core $\delta^{18}O$ record. Specifically, when the mid-low-latitude winter westerly is stronger (corresponding to lower NAO index and temperature), more marine vapor results in the higher XD core accumulation and lower XD core $\delta^{18}O$. Conversely, when the westerly is weaker (higher NAO index and temperature), more continental vapor leads to lower XD core accumulation and higher XD core $\delta^{18}O$. This further suggests that the XD core $\delta^{18}O$ record is closely associated with the contribution of westerly moisture. Strikingly, the correlation is much more significant over the North Atlantic during the non-monsoon season in 1964–2006 (Fig. 8b) relative to 1927–2006 (Fig. 8a), and this phenomenon is also found over the North Atlantic and Mediterranean regions during the monsoon seasons (Fig. 9). This implies that the contribution of westerly moisture to the XD core accumulation has been increasing in recent decades, which correspond to the increasing contribution of summer monsoon moisture. Additionally, the westerly moisture from the Atlantic is enhanced by the Mediterranean evaporation during its travel eastward, and d-excess in the mixing vapor is generally high due to isotopic disequilibrium (Rindsberger et al., 1983; Gat et al., 2003). For instance, d-excess in the Mediterranean vapor during winter in 1995 is as high as 21‰ (Gat et al., 2003), which is close to the TGL core d-excess (19.5‰) during 1942–2004 (Joswiak et al., 2013). Moreover, the d-excess of 54 snow pit samples from the XD Glacier was as high as 19.2‰ during September to October in 2013, whereas during May to July it was just 13.9‰. Higher d-excess at or near the XD core drilling site further suggests that the influence of westerly moisture is significant at this site.

Correlation coefficients between the $\delta^{18}O$ and climate indices and NIP for the XD and previous TGL and GLDD cores are presented in Table 3. The XD (and TGL) core $\delta^{18}O$ is negatively related to the NIP for annual and 5-yr running averages during the periods 1927–2006 and 1935/1964–2004, which indicates that enhanced (reduced) NIP causes a depleted (enriched) ice core $\delta^{18}O$ in the cTP. The XD core $\delta^{18}O$ is also positively correlated with the DMI index for annual and 5-yr running averages, which coincides with positive correlations of the TGL and GLDD core $\delta^{18}O$ with the DMI index for 5-yr running averages during 1935/1964–2004. This is related to enhanced travel of moisture associated with the westward shift of the Indian Ocean warm pool. Moreover, the prolonged differences in the tropical western Pacific air surface pressure associated with the ENSO are coupled with monsoon circulation and Indian monsoon rainfall (Krishnamurthy and Goswami, 2000). Although statistically no correlations were found between the XD (and TGL, GLDD) core $\delta^{18}O$ and Niño3.4 index, positive correlations were found between the XD core $\delta^{18}O$ and central-eastern equator Pacific SST (Fig. 7) and the Niño3.4 index is negatively correlated with the NIP ($r = -0.50$, $p < 0.0001$), confirming the relationship

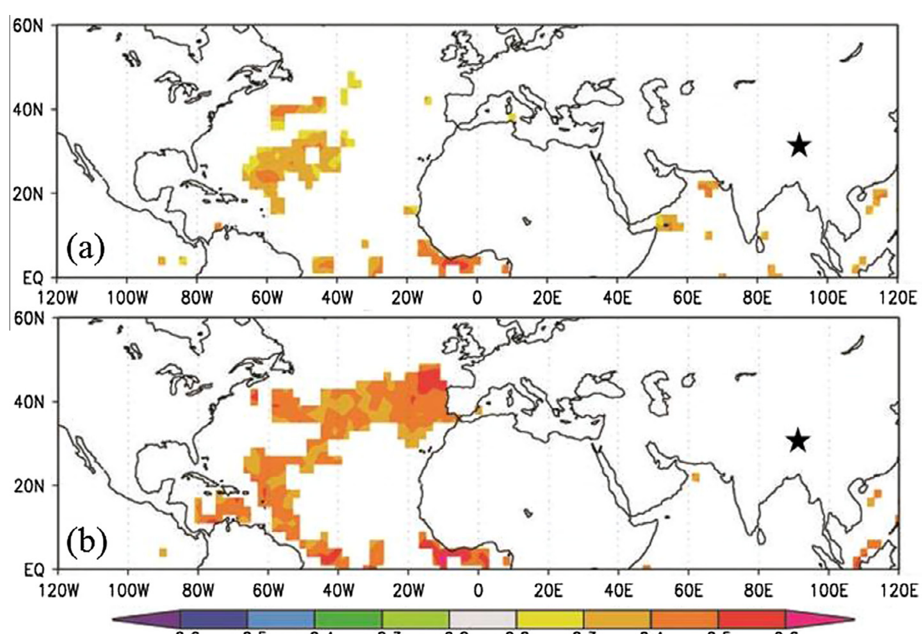


**Fig. 8.** Spatial correlations between the XD core $\delta^{18}O$ values and mean air temperature during the non-monsoon seasons (October to April) for the periods 1927–2006 (a) and 1964–2006 (b). Monthly air temperature with 2.0° × 2.0° resolution is from the ICOADS v2.5 reanalysis. Note that the black star indicates the location of the XD drilling site. Significant levels are at $p < 0.05$.

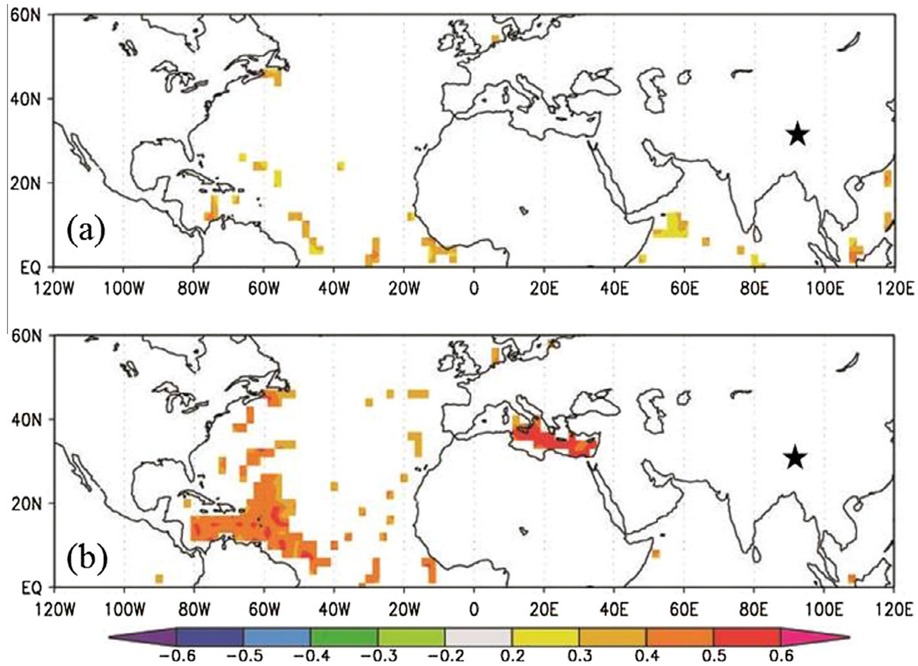


**Fig. 9.** Spatial correlations between the XD core $\delta^{18}O$ values and mean air temperature during the monsoon seasons (May to September) for the periods 1927–2006 (a) and 1964–2006 (b). Monthly air temperature with $2.0^\circ \times 2.0^\circ$ resolution is from the ICOADS v2.5 reanalysis. Note that the black star indicates the location of the XD drilling site. Significant levels are at $p < 0.05$.

**Table 3**
Correlation coefficients between annual $\delta^{18}O$ values, climate indices, and NIP for the cTP ice cores over the periods 1927–2006, 1935–2004, 1964–2006 and 1964–2004. Numbers to the left and right of the slash indicate annual and 5-yr running averages, respectively. Bold numbers indicate a significance level of $p \leqslant 0.05$.

| | Periods | NAO (Oct–Apr) | NIP (May–Sep) | DMI | NINO3.4 |
|---|---|---|---|---|---|
| XD | 1927–2006 | 0.02/0.04 | **−0.24**/**−0.51** | **0.26**/**0.51** | 0.08/0.10 |
| | 1964–2006 | 0.13/0.29 | −0.25/−0.18 | **0.37**/**0.60** | 0.15/0.23 |
| TGL | 1935–2004 | 0.08/0.05 | **−0.35**/**−0.71** | 0.11/**0.27** | 0.14/0.14 |
| | 1964–2004 | 0.19/**0.45** | **−0.32**/**−0.67** | −0.16/**−0.36** | 0.14/−0.02 |
| GLDD | 1935–2004 | **0.33**/0.20 | 0.11/0.21 | −0.15/−0.06 | −0.07/0.14 |
| | 1964–2004 | **0.35**/0.24 | 0.05/0.01 | −0.12/**0.40** | −0.01/0.21 |

between the Niño3.4 index and monsoon strength. Joswiak et al. (2013) showed that the TGL core $\delta^{18}O$ is positively correlated with the Niño3.4 index over a longer period (1866–2004 AD), suggesting that this relationship is not temporally consistent or stable. Even though the XD core $\delta^{18}O$ is not related to the NAO index, the nearby GLDD and TGL cores $\delta^{18}O$ are positively correlated with the NAO index during 1935/1964–2004 for annual and 5-yr running averages respectively (Table 3), and the XD core $\delta^{18}O$ is also positively related to mean air temperature over the North Atlantic and Mediterranean during the monsoon season (Fig. 9) and the MZTG core $\delta^{18}O$ (1955–2002 AD) ($r = 0.60$, $p < 0.0001$) belonging to the westerly-dominated region (Fig. 1), which provides direct evidence of westerly moisture contribution to the cTP ice core accumulation. The precipitation pattern over the TP is also teleconnected to the NAO index (Liu and Yin, 2001; Wang et al., 2007), which may also accordingly affect annual mean $\delta^{18}O$ in the cTP ice cores by modulating the relative contributions of different moisture sources. Joswiak et al. (2013) have suggested that westerly moisture influences the TGL core accumulation based on high d-excess associated with non-monsoon moisture contribution. A three-fold decrease in the GLDD core dust concentrations in the middle to late 1970s coincides with a major 1976–1977 shift in PDO (Grigholm et al., 2009), indicating a potential connection between the westerly and monsoon moisture. Together, these substantially influence the XD core $\delta^{18}O$ and corresponding temperature variations, which are closely associated with a relative share of moisture from diverse sources. It is difficult, however, to quantify the respective contributions of diverse moisture to the XD core $\delta^{18}O$ variation. In addition to annual moisture source variability, seasonal accumulation variability may also impact on ice core isotope records. Research into the long-term variation of precipitation isotopes has been performed at the Tanggula Glaciological Station about 10 km east of the XD Glacier since 2013, which will increase understanding of the atmospheric process in this area of converging monsoon and westerly moisture.

## 4. Conclusions

A 19.6 m-long ice core was recovered from the Xiao Dongkemadi (XD) Glacier on the central Tibetan Plateau (cTP) region, where the XD core $\delta^{18}O$ record preserved valuable information about climate and moisture sources. Annual average $\delta^{18}O$ values correlated significantly with nearby MJJAS air temperatures, suggesting that the XD core $\delta^{18}O$ can be used as a proxy to reconstruct regional climate change. The reconstructed temperature records indicate that the warming results from the regional and global warming trends and has intensified in recent decades. The greater warming magnitude (0.62 °C per decade) since the 1970s is related to the elevation dependency of the warming signal. The close association of the warming with a decrease in glacier mass balances and an increase in river discharge, particularly since the 1990s, reveals that the warming has led to obvious glacier shrinkage and runoff increase. This suggests that more effort should be made to observe and separate meltwater runoff in order to better serve water resource management in western China. Spatial correlations between the XD core $\delta^{18}O$ and sea surface temperature (SST) and air temperature suggest that monsoon and westerly moisture substantially influence the XD core accumulation, along with an increase in their level of contribution to XD core accumulation in recent decades. It may be possible to combine multi-proxy records to reconstruct ENSO history. Correlation coefficients between the ice core $\delta^{18}O$, climate indices, and northern India precipitation (NIP) provide further evidence of the contribution of westerly and monsoon moisture to the cTP core accumulation. These confirm a teleconnection between the regional climate of the cTP ice cores and climate parameters in the Indian Ocean and North Atlantic.

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