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Abundant climatic information in water stable isotope record from a maritime glacier on southeastern Tibetan Plateau

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Abstract Climatic significance of ice core stable isotope record in the Himalayas and southern Tibetan Plateau (TP), where the climate is alternately influenced by Indian summer monsoon and mid-latitude westerlies, is still debated. A newly drilled Zuoqiupu ice core from a temperate maritime glacier on the southeastern TP covering 1942–2011 is investigated in terms of the relationships between $\delta^{18}O$ and climate parameters. Distinct seasonal variation of $\delta^{18}O$ is observed due to high precipitation amount in this area. Thus the monsoon (June to September) and non-monsoon (October to May) $\delta^{18}O$ records are reconstructed, respectively. The temperature effect is identified in the annual $\delta^{18}O$ record, which is predominantly contributed by temperature control on the non-monsoon precipitation $\delta^{18}O$ record. Conversely, the negative correlation between annual $\delta^{18}O$ record and precipitation amount over part of Northeast India is mostly contributed by the monsoon precipitation $\delta^{18}O$ record. The variation of monsoon $\delta^{18}O$ record is greatly impacted by the Indian summer monsoon strength, while that of non-monsoon $\delta^{18}O$ record is potentially associated with the mid-latitude westerly activity. The relationship between Zuoqiupu $\delta^{18}O$ record and Sea Surface Temperature (SST) is found to be inconsistent before and after the climate shift of 1976/1977. In summer monsoon season, the role of SST in the monsoon $\delta^{18}O$ record is more important in eastern equatorial Pacific Ocean and tropical Indian Ocean before and after the shift, respectively. In non-monsoon season, however, the Atlantic Multidecadal Oscillation has a negative impact before but positive impact after the climate shift on the non-monsoon $\delta^{18}O$ record.

Keywords Ice core · Maritime glacier · Stable isotope record · Indian summer monsoon · Westerly

1 Introduction

Tibetan Plateau (TP) and its surroundings, also known as the Third Pole, holds the largest number of glaciers outside the Polar Regions. Ice cores retrieved from the carefully selected glaciers over the Third Pole have provided a wealth of climate information that extends back far beyond the instrumental period (Thompson et al. 2000; Kaspari et al. 2007; Yao et al. 2008; Joswiak et al. 2010).

Among a variety of chemical and physical measurements, water stable isotope ratios have been measured for all ice cores. Unlike the water stable isotopes in Polar ice cores generally used as a good indicator of temperature (Jouzel 2013, and references therein), there is no consensus on the climatic implications of the stable isotope ratios in tropical and subtropical ice cores (Bradley et al. 2003; Hoffmann et al. 2003; Schneider and Noone 2007; Thompson et al. 2013). In the Himalayas and southern TP where the climate is influenced by the Indian monsoon from June to September, the interpretations of ice core stable isotope

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records remain ambiguous and controversial. Kang et al. (2000) and Tian et al. (2003) showed that the annual variation of $\delta^{18}O$ in Dasuopu firn cores could be explained by the amount effect. However, on multi-year to decadal timescales, temperature effect was found to be the dominant process controlling the isotope composition of Dasuopu ice cores (Thompson et al. 2000; Davis et al. 2005; Yang et al. 2007; Yao et al. 2007). Based on the ECHAM-4 stable isotope model, Vuille et al. (2005) suggested that the modern $\delta^{18}O$ record from the Dasuopu ice core was a proxy of large-scale monsoon circulation rather than local climate condition. A Tanggula ice core record from the northern margin of Indian monsoon region over the TP shows that the annual $\delta^{18}O$ record for the past 70 years was negatively correlated with precipitation amount over North India, indicating the impact of monsoon intensity on the $\delta^{18}O$ variations (Joswiak et al. 2010). However, Wu et al. (2013) stated that on multi-year to decadal timescales, the Tanggula $\delta^{18}O$ record showed similar variations with the Northern Hemisphere temperature anomalies over the past 150 years and thus could serve as an index of temperature.

There are many climatic factors more than temperature and precipitation amount that can affect the precipitation stable isotope ratios in the southern TP because of the complicated hydrological cycle during the monsoon season (Gao et al. 2010, 2013). On the seasonal timescale, precipitation over the southern TP is more depleted in the heavy isotopes during the Indian monsoon season (June to September) compared with the non-monsoon season (October–May), displaying an apparent amount effect. However, when the $\delta^{18}O$ values in monsoon and non-monsoon precipitation are separately considered, the temperature effect of precipitation $\delta^{18}O$ does exist (Yao et al. 2013). Thus, whether the ice core stable isotope records from the Indian monsoon region can be interpreted as the proxy of temperature is still debated.

In this study, we will analyze an ice core stable isotope record from a maritime glacier and attempt to investigate its relationships with temperature and precipitation amount, as well as other climate related variables. This ice core of Zuoqiupu glacier was recovered from the Kangri Garpo Range on the southeastern TP in the fall of 2012. The Kangri Garpo Range is located on the transport pathways of Indian monsoon moisture into the TP and is one of the most influenced areas by Indian monsoon over the TP.

2 Methods

2.1 Ice core drilling

The drilling site is located on a maritime glacier in the Kangri Garpo Range, southeastern TP (Fig. 1a). In November 2012, two ice cores with a diameter of 10 cm were extracted from the nearly flat saddle of Zuoqiupu glacier (29°11′56.65″N, 96°54′11.68″E, 5580 m a.s.l., Fig. 1b, c). Core 1 was drilled only to a depth of 35.2 m before a sudden snowstorm. Drilling was reestablished 3 days later and Core 2 was retrieved within 2 m of Core 1 site to a depth of 109.7 m. Ice core sections were sealed in polyethylene tubes in the field and transported frozen to State Key Laboratory of Cryospheric Sciences (SKLCS), Chinese Academy of Sciences (CAS), China.

2.2 Sample preparation and laboratory analysis

This study focuses on the investigation of the long Core 2. The transition from firn to ice of this ice core was observed to begin at a depth of about 31 m. Samples from the ice core sections were prepared in a cold room of SKLCS at −20 °C. Core sections were split in half along their vertical axis with a band saw. One half was preserved for archive sample. The second half was cut lengthwise into three portions for different kinds of measurement, with one portion for $\delta^{18}O$ and δD, one portion for black carbon (BC) and dust particle, and the other portion for air content. The portion of ice core for $\delta^{18}O$ and δD measurements was continuously subsectioned at a ~10 cm interval into 1126 samples. These ice samples were melted in PE zip-lock bags at room temperature, decanted into 15 ml HDPE bottles, and then refrigerated until analysis. Measurements of $\delta^{18}O$ and δD were made simultaneously for all samples using a Picarro L2130-i Cavity Ring-Down Spectrometer at the Key Laboratory of Tibetan Environment Changes and Land Surface Processes, CAS, China. $\delta^{18}O$ and δD values were expressed as per mil deviations relative to the Vienna Standard Mean Ocean Water (VSMOW2). The precision was 0.05 ‰ for $\delta^{18}O$ and 0.4 ‰ for δD. Deuterium excess (d) values were calculated as: $d = \delta D - 8 * \delta^{18}O$ (Dansgaard 1964). BC concentrations were measured by a single particle soot photometer and reported as refractory BC (rBC), the series of which was included in this study only for ice core dating.

2.3 Ice core dating

Precipitation $\delta^{18}O$ over the southern TP exhibits a distinct seasonal cycle with low values in Indian monsoon season and high in pre-monsoon season (Yao et al. 2013, and references therein). Similar feature has been found in precipitation $\delta^{18}O$ at Bomi (Gao et al. 2010) and Lulang (Yang et al. 2012), both of which are located nearby the Zuoqiupu glacier (Fig. 1a). In addition, the atmospheric pollutants generally begin to accumulate over the southern slopes of the Himalayas during post-monsoon season and reach the maximum buildup during pre-monsoon season (Bonasoni et al. 2010; Gautam et al. 2011). BC aerosol, as one of the

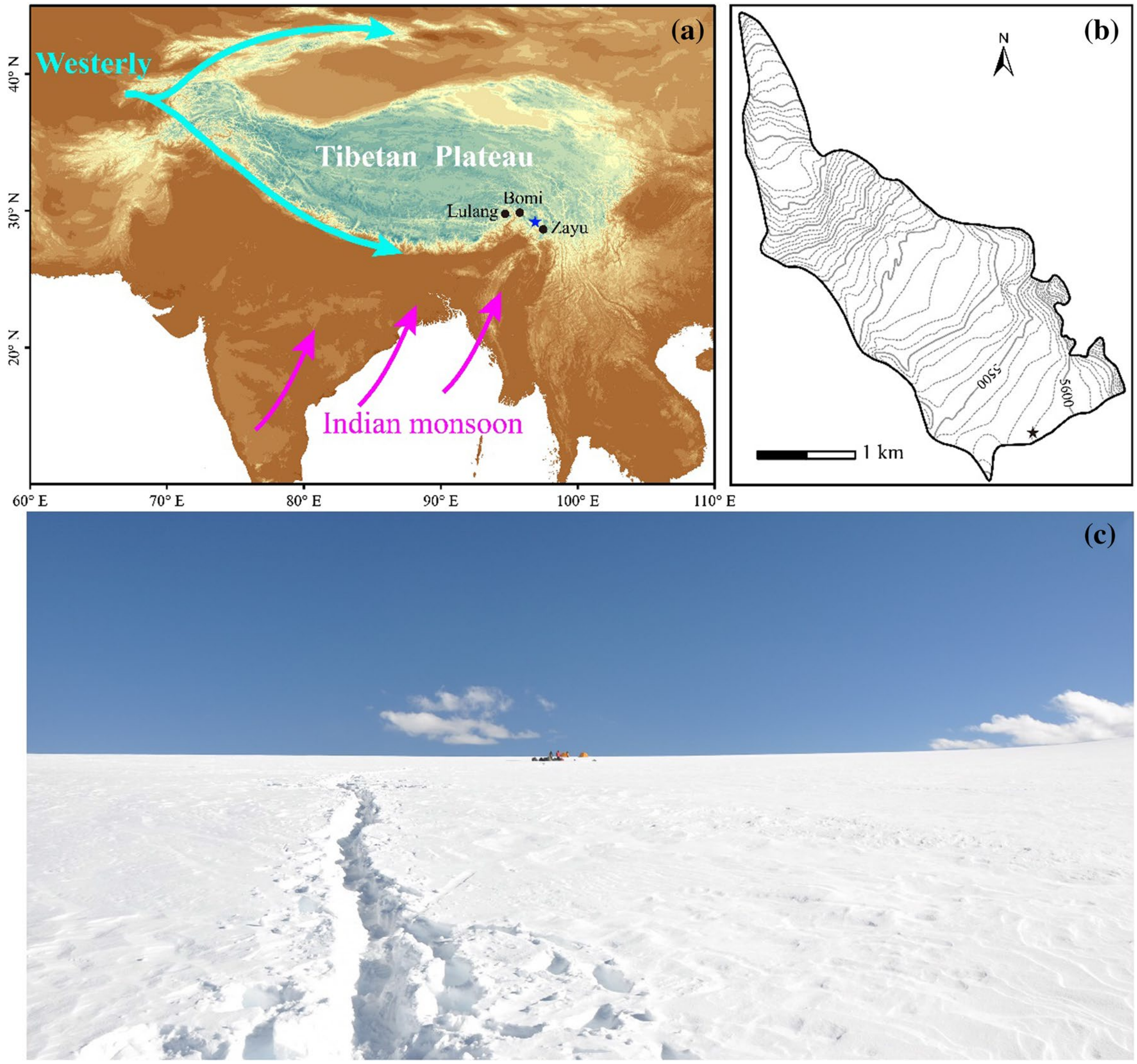

Fig. 1 Geographical location of the study area. **a** Map showing the locations of Zuoqiupu glacier (*blue star*) and stations mentioned in the text (*black dots*). The *arrows* indicate the major atmospheric circulation systems around the TP. **b** Ice core site (*black star*) on the Zuoqiupu glacier. **c** Photo of the drilling site during the camp installation. View to the Southeast from close to the drilling site

major components of the pollutants, can be transported to the southeastern TP by westerly winds (Xu et al. 2009; Zhao et al. 2013) and deposits from the atmosphere, leaving a strong seasonal signal of BC concentration recorded in the glaciers. Thanks to the very high net snow accumulation rates on the maritime glaciers over the southeastern TP (Xu et al. 2009), the strong seasonal cycles of $\delta^{18}O$ and rBC concentration are clearly visible in the Zuoqiupu ice core (see Supplementary Fig. A1). The chronology of Zuoqiupu ice core was thus determined to cover the period 1942–2011 AD by multi-parameter annual layer counting with an average sample resolution of 16 per year. Dating uncertainty was estimated to be less than ±1 year. Note that the ice core year refers to the months approximately from previous May to current April, unless otherwise specified. In a year, the interval of $\delta^{18}O$ consecutively lower than the annual average was defined as the monsoon period. We also divided the Zuoqiupu ice core into layers at the $\delta^{18}O$ minima, and defined the interval of $\delta^{18}O$ consecutively higher than the average in a layer as the non-monsoon period, which roughly lasts from previous October to current May. The annual, monsoon and non-monsoon $\delta^{18}O$ time series were derived from the arithmetic averages of individual $\delta^{18}O$ values in each year.

3 Results and discussions

3.1 Stable oxygen isotope and local meteoric water line along the ice core

The series of δ^{18}O and δD in the Zuoqiupu ice core are very strongly correlated with $r = 0.99$ ($p < 0.001$). So, only δ^{18}O is discussed below for the analysis of variation in stable isotope record (The raw data of δ^{18}O is provided in the Supplementary Online Material).

δ^{18}O values of the Zuoqiupu ice core vary between −29.8 and −6.7 ‰ with an average of −14.4 ± 2.1 ‰, and 97 % of the values are concentrated at −18.9 to −10.1 ‰. The most depleted δ^{18}O values occur mainly in approximately the top 1.5 m of the ice core (see Supplementary Fig. A1). This characteristic is also found in another Zuoqiupu ice core recovered in 2007 [see Fig. S2 in Xu et al. (2009)]. It indicates that snow deposited at the core site undergoes some melting during the subsequent melt season. The surface meltwater can percolate down to the snowpack and thus dampens the seasonal amplitude of δ^{18}O in the underlying layer. However, the modification of δ^{18}O by meltwater percolation is supposed to be mostly constrained in the annual stratigraphy because of the very high snow accumulation rate at the site. The discrete ice layers or ice lenses, typically 0.5–5 cm thick, are frequently found in the ice core, which can effectively preclude the newly formed meltwater further penetration into the lower layers. The well preservation of distinct seasonal variation in δ^{18}O along this ice core (see Supplementary Fig. A1) also corroborates that meltwater percolation does not significantly alter the stable isotope records.

Simultaneous measurements of δ^{18}O and δD enable us to establish the local meteoric water line (LMWL) by fitting a linear regression of δD against δ^{18}O along the ice core.

The relationship between δD and δ^{18}O in precipitation worldwide was defined as the global meteoric water line (GMWL) and expressed by the equation $\delta D = 8 * \delta^{18}O + 10$ (Craig 1961). The GMWL was later modified to $\delta D = 8.17 * \delta^{18}O + 10.35$ derived from the GNIP database (Rozanski et al. 1993). However, the LMWLs vary greatly across the globe depending on the climatic and geographic parameters. On the basis of 1123 samples, the LMWL for Zuoqiupu is established as $\delta D = 8.34 * \delta^{18}O + 20.28$, yielding an $R^2 = 0.99$ (Fig. 2). The LMWL has a slope of 8.34, very close to the slope of GMWL, indicating that isotope fractionation in condensation process occurs under equilibrium conditions and no major sublimation/evaporation occurs in snow falling and/or post deposition processes. Furthermore, the slope of LMWL from Zuoqiupu ice core is quite identical to that from Lulang precipitation with a slope of 8.32 (Yu et al. 2014), but a little greater than the value of 7.85 from Bomi precipitation (Gao et al. 2010). The slightly lower slope of LMWL at Bomi may suggest the precipitation has undergone evaporation during falling and/or sampling processes. The intercept of 20.28 of Zuoqiupu LMWL is much higher than that of GMWL, which reflects more intensive kinetic fractionation at the moisture source regions and/or enhanced moisture recycling *en route* to the Zuoqiupu glacier than global average conditions.

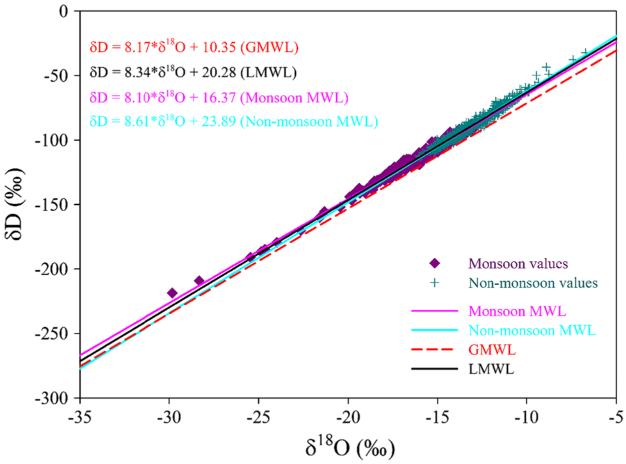

Fig. 2 MWLs for the monsoon, non-monsoon and entire samples of Zuoqiupu ice core. Also shown is the GMWL for reference

3.2 Relationships of δ^{18}O with temperature and precipitation amount

Increasing trends are definitely observed for the annual, monsoon and non-monsoon δ^{18}O records of the Zuoqiupu ice core (see Supplementary Fig. A2). Variations of ice core stable isotope ratios from the Himalayas and southern TP were often interpreted to be associated with the changes of precipitation amount (Qin et al. 2002; Tian et al. 2003; Kang et al. 2006). However, some researches show that air temperature and Pacific SST were critical important factors in controlling the δ^{18}O variability in Dasuopu ice core (Thompson et al. 2000; Bradley et al. 2003). In this section, the relationships of Zuoqiupu δ^{18}O record with temperature and precipitation amount at the nearby national meteorological stations of Bomi and Zayu are explored.

Pearson correlation analysis (Table 1) by using SPSS 11.0 for Windows shows that annual δ^{18}O is well correlated with annual (previous May–current April) and monsoon (June–September) temperature time series. Although there is no significant correlation between monsoon δ^{18}O record and temperature (Table 1), the non-monsoon δ^{18}O record is significantly correlated with temperature from previous October to current May (Table A1). Noteworthy is that significant negative correlations are not identified between

Table 1 Pearson correlation analyses of ice core δ^{18}O record with temperature (T) and precipitation amount (P) at the meteorological stations of Bomi (1961–2011 AD) and Zayu (1969–2011 AD)

	Bomi				Zayu			
	$T_{5–4}$	$T_{6–9}$	$P_{5–4}$	$P_{6–9}$	$T_{5–4}$	$T_{6–9}$	$P_{5–4}$	$P_{6–9}$
δ$^{18}O_{annual}$	**0.51**	**0.44**	0.08	−0.17	**0.41**	*0.37*	−0.18	−0.16
δ$^{18}O_{monsoon}$	0.22	0.02	0.07	−0.06	0.11	0.12	−0.08	0.08

The subscripts of ‘5–4’ and ‘6–9’ indicate the months from previous May to current April and June to September, respectively

Values in bold and italics denote significant at the 0.01 and 0.05 levels, respectively

Table 2 Pearson correlation coefficients of Zuoqiupu δ^{18}O record with all-Indian and macro-regional monsoon rainfall for the period 1942–2011

	AI	HI	PI	NWI	WCI	CNEI	NEI
δ$^{18}O_{annual}$	−0.21	−0.17	−0.05	−0.09	−0.20	−0.11	−0.27*
δ$^{18}O_{monsoon}$	−0.14	−0.16	−0.04	−0.09	−0.20	−0.07	0.01

AI all-Indian, *HI* homogeneous Indian monsoon region, *PI* peninsular India, *NWI* Northwest India, *WCI* West Central India, *CNEI* Central Northeast India, *NEI* Northeast India

* 0.05 level

annual and monsoon δ^{18}O records and station precipitation amount (Table 1). In this sense, the correlation analyses demonstrate that the annual variation of δ^{18}O in the Zuoqiupu ice core is apparently dominated locally by temperature effect rather than by precipitation amount effect. It is of interest to note that the annual (here denotes the months approximately from previous August to current July) and non-monsoon δ^{18}O records are positively and significantly correlated with the precipitation amount in the corresponding months at Bomi, but not at Zayu. This means that Bomi and Zuoqiupu glacier have received the non-monsoon precipitation from some identical moisture sources transported by the westerlies. Furthermore, temperature at Bomi exerts a greater influence on the Zuoqiupu ice core δ^{18}O record than that at Zayu (Tables 1 and A1), which is also derived from the contribution of non-monsoon precipitation. These correlations may imply that the site of Zuoqiupu glacier and Bomi are under the control of same climate regime.

Based on analysis of regional precipitation patterns, Pang et al. (2014) revealed that the contrasting interpretation of ice core δ^{18}O records from neighboring glaciers of Dasuopu and East Rongbuk was mostly related to the difference in precipitation seasonality between the two sites. The large non-monsoon precipitation was responsible for the temperature effect of Dasuopu δ^{18}O record (Pang et al. 2014). Similar to the precipitation regime at Nyalam station adjacent to Dasuopu glacier, both Bomi and Zayu receive about half the annual precipitation during non-monsoon season (see Supplementary Fig. A3). The seasonal characteristic of precipitation in this region determine the existence of temperature effect of Zuoqiupu δ^{18}O record.

Relationships between Zuoqiupu δ^{18}O record and all-Indian and macro-regional monsoon rainfall (precipitation data available at http://www.tropmet.res.in/) are explored. Results of the correlation analyses are given in Table 2. The inverse relationships are widely observed, although not statistically significant. It suggests a possible effect of Indian summer monsoon precipitation on the δ^{18}O record of Zuoqiupu ice core. The imprints of regional monsoon precipitation in India on ice core δ^{18}O records were previously found in the Himalayas and southern TP (Qin et al. 2002; Joswiak et al. 2010). Recently, researchers have revealed that during the Indian monsoon season, precipitation δ^{18}O on southern TP was substantially affected by the convective activity at its upstream region (Gao et al. 2013; He et al. 2015). Strong convections over northern regions of India left the moisture with relatively low stable isotope ratios (He et al. 2015), which was then transported and uplifted to the Himalayas and southern TP by Indian monsoon circulation and produced precipitation over there. In this way, signal of monsoon precipitation changes in the upstream regions was accordingly recorded in East Rongbuk (Qin et al. 2002), Tanggula (Joswiak et al. 2010), and this Zuoqiupu ice core.

To assess the spatial correlations of Zuoqiupu ice core δ^{18}O with temperature and precipitation, the monthly gridded climate dataset of CRU TS 3.22 (land) at a 0.5° × 0.5° resolution (data available from http://badc.nerc.ac.uk/browse/badc/cru/) is used here. Correlation analysis shows that the annual ice core δ^{18}O record can be served as a proxy indicator for regional temperature variation, especially in the middle and west of the TP (Fig. 3a). The correlation pattern between Zuoqiupu δ^{18}O and temperature for the non-monsoon time series (Fig. 3b) closely resembles that for the annual time series (Fig. 3a), but it is not the case for the monsoon series (Fig. 3c). This suggests that the correlations of annual mean values between ice core δ^{18}O and gridded temperature are primarily contributed

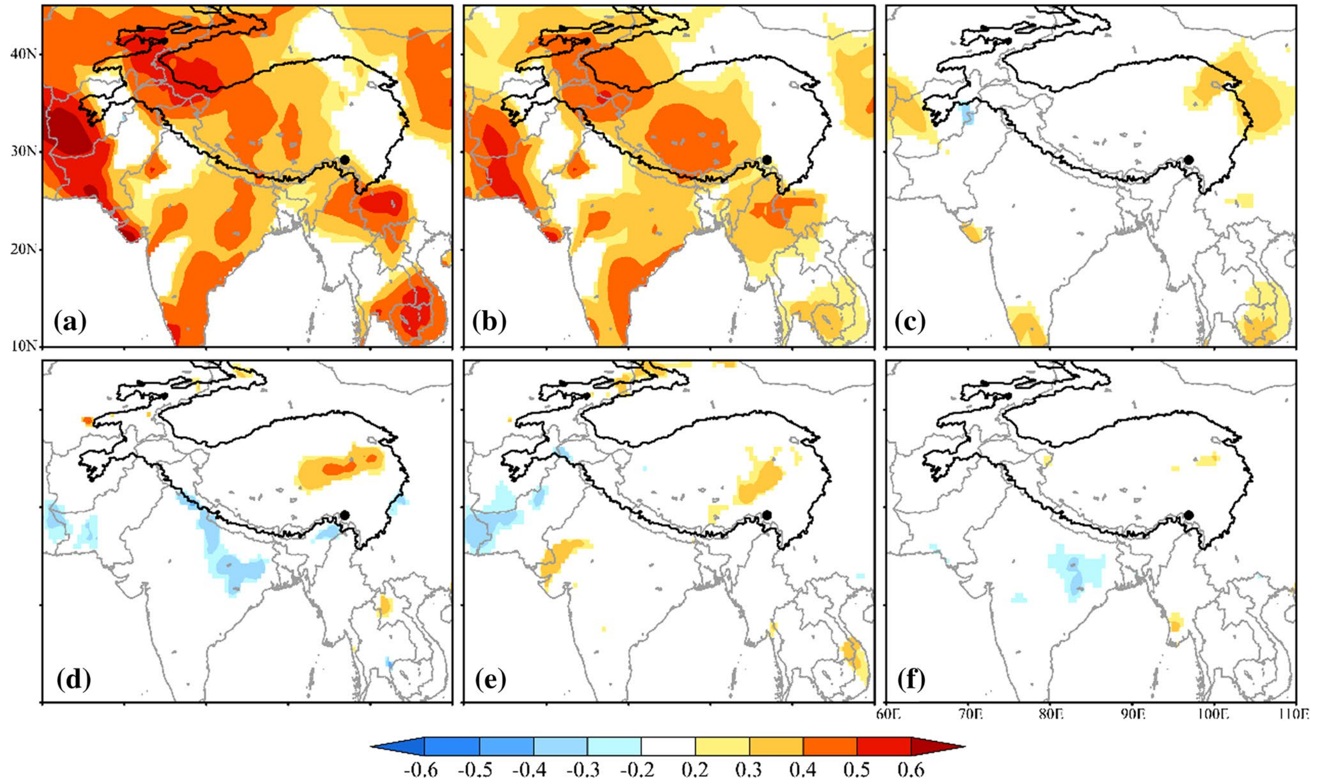

Fig. 3 Correlation patterns of Zuoqiupu $\delta^{18}O$ record with temperature and precipitation from CRU TS 3.22 dataset for the period 1942–2011 drawn using Grid Analysis and Display System (GrADS). Spatial correlations of ice core $\delta^{18}O$ record with temperature for the **a** annual, **b** non-monsoon, and **c** monsoon time series. **d–f** Same as (**a–c**), respectively, but with precipitation. *Shaded areas* denote significant correlations at the 0.05 level. *Black line* indicates the 3000 m contour outlining the TP, and *black dot* the site of Zuoqiupu ice core

by the temperature effect of non-monsoon precipitation in this core. With regard to the spatial relationship between ice core $\delta^{18}O$ and precipitation, the negative correlations for the annual time series occur mostly in the northeastern region of India (Fig. 3d), being similar to correlations for the monsoon time series (Fig. 3f). Again, the negative correlations stress the fact that Zuoqiupu $\delta^{18}O$ record is influenced by the variation of monsoon precipitation in the upstream region, as discussed above. Interestingly, positive correlations of ice core $\delta^{18}O$ with gridded precipitation are observed to the north of Zuoqiupu glacier in Fig. 3d, which also exists in Fig. 3e for the non-monsoon time series. The positive correlations indicate that recycled moisture from the interior of TP partly contributes to the non-monsoon precipitation at Zuoqiupu glacier. The recycled moisture on the TP is highly enriched in $\delta^{18}O$, thus producing a positive contribution to the annual mean level of Zuoqiupu $\delta^{18}O$. However, in the non-monsoon season, the contribution of the northern recycled moisture is much less than that of the westerly transported air mass according to the moisture flux field shown in Fig. 5b.

The evidence of seasonal shift of moisture contributing to the Zuoqiupu glacier is also provided by *d* variations shown in Supplementary Fig. A4. The isotope parameter of *d* in precipitation has been considered to be specifically sensitive to the moisture source conditions (Merlivat and Jouzel 1979; Uemura et al. 2008; Pfahl and Sodemann 2014). On the southern TP, *d* values are generally lower in the precipitation produced by Indian monsoon moisture while higher in the precipitation produced by westerly-derived air mass and recycled moisture (Tian et al. 2007; Hren et al. 2009). Nevertheless, the ice layers with high *d* values in the Zuoqiupu ice core cannot be clearly assigned to specific moisture source regions only by an ice core record (Kurita and Yamada 2008), since the westerly transported air mass and local recycled moisture are both characterized by high *d* value. It is demonstrated that local moisture recycling is a very significant process on the TP (van der Ent et al. 2010), and that the relative contribution of local recycled moisture to precipitation increases progressively from southern to northern TP (Bershaw et al. 2012). The mean *d* value of the Zuoqiupu ice core (15.4 ‰) is less than that of Tanggula (16.5 ‰) (Joswiak et al. 2010) but much larger than that of East Rongbuk (11.6 ‰) (Pang et al. 2012) during almost the same period, reflecting the competing

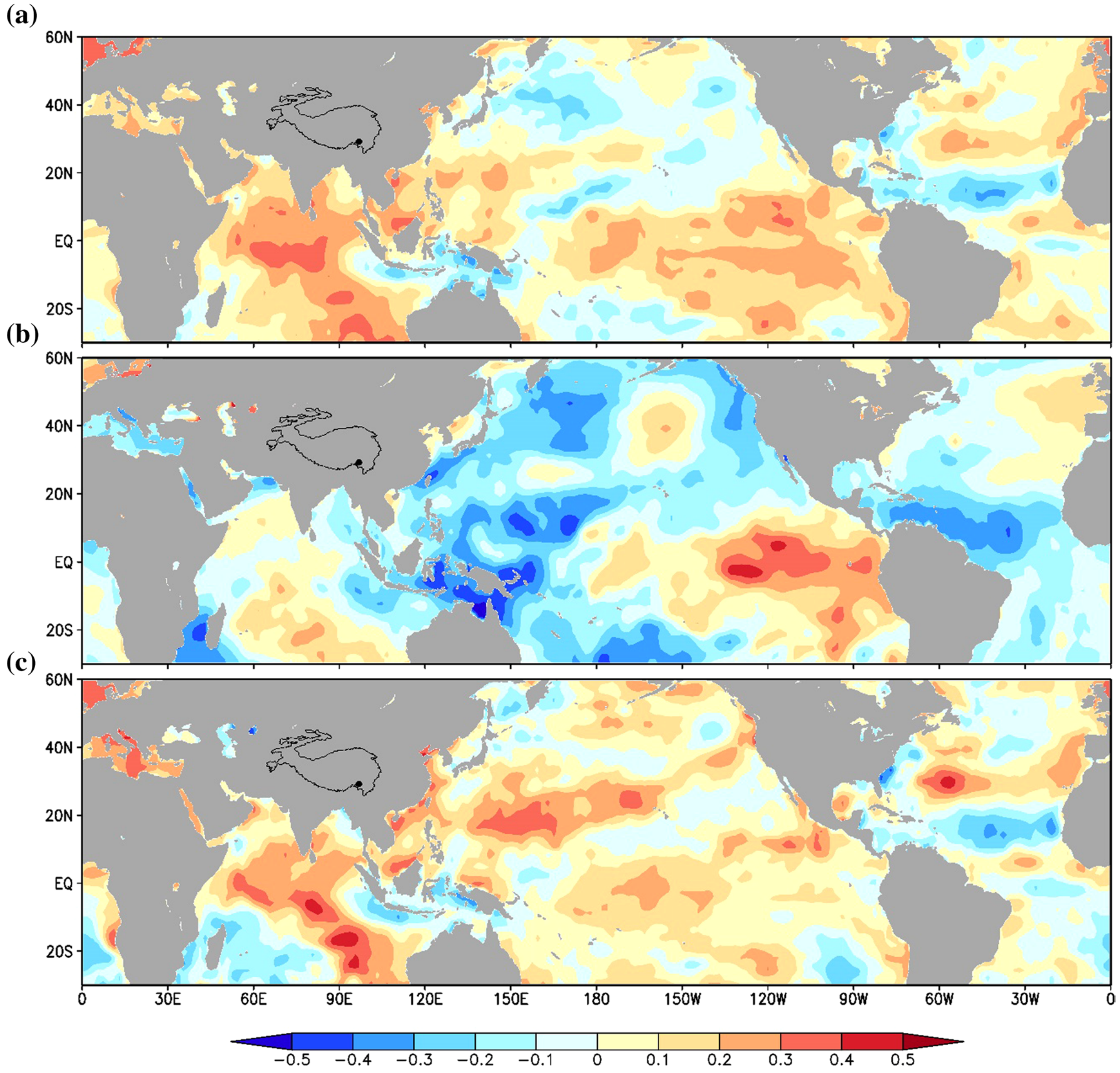

Fig. 4 Spatial correlations of monsoon δ^{18}O record of Zuoqiupu ice core with SST averaged from June to September during the period **a** 1948–2011, **b** 1948–1976, and **c** 1977–2011. The correlation patterns were calculated online at http://www.esrl.noaa.gov/psd/data/correlation/ and modified using GrADS. The meanings for the *black line* and *black dot* are the same as those in Fig. 3

influences of oceanic and continental moisture on the isotope composition of precipitation. Distinct seasonal variation with large amplitude in *d* values of the Zuoqiupu ice core clearly indicates significant differences in the moisture source in monsoon and non-monsoon seasons, as illustrated in Figs. 5b and A5. The less seasonal amplitude of *d* values in the East Rongbuk ice core (Pang et al. 2012) than in the Zuoqiupu should be derived from the lower fraction of non-monsoon precipitation in East Rongbuk ice core compared to Zuoqiupu ice core. This is one of the primary reasons why the temperature effect was identified in Zuoqiupu and Dasuopu δ^{18}O records but not in East Rongbuk δ^{18}O record (Pang et al. 2014).

3.3 Connections to the atmospheric circulation patterns

Stable isotope compositions of precipitation are also closely related to atmospheric circulation patterns by their effect on sources and transport pathways of the moisture (e.g., Tian et al. 2007; Hren et al. 2009). The climate of southeastern TP is alternately influenced by two major circulation systems, i.e. the Indian summer monsoon and the mid-latitude westerlies (Fig. 1a), during June to September and previous October to current May, respectively. Stable isotope ratios of precipitation in the study area have been reported to be impacted by the two circulation systems (Gao et al. 2010; Yu et al. 2014).

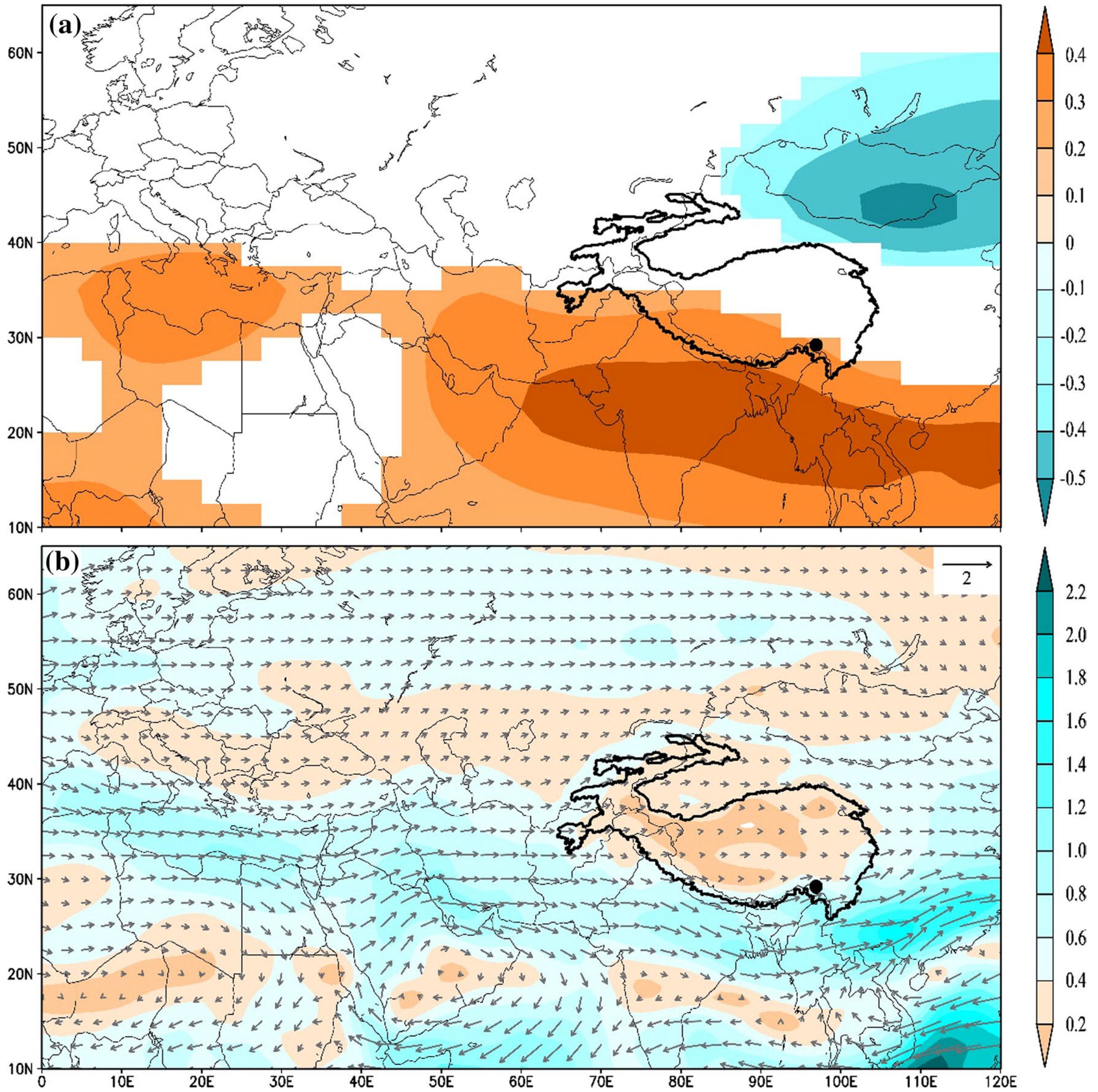

Fig. 5 **a** Spatial correlations between Zuoqiupu δ^{18}O record and 200 hPa geopotential height for the non-monsoon time series during 1948–2011. Significant correlations at the 0.05 level appear *colored here*. **b** Monthly mean moisture flux (unit: $\times 10^5$ g m^{-1} s^{-1}) in the non-monsoon season during 1948–2011. *Colored areas* and *vectors* both represent vertically integrated moisture flux. Graphics were generated using GrADS. The meanings for the *black line* and *black dot* are the same as those in Fig. 3

Figure 4a shows the correlation pattern (calculated online at http://www.esrl.noaa.gov/psd/data/correlation/) between monsoon δ^{18}O record of the Zuoqiupu ice core and SST averaged from June to September during 1948–2011. Positive correlations are mainly identified in the tropical Indian Ocean and eastern equatorial Pacific Ocean, which is the same for Dasuopu ice core (Bradley et al. 2003). The imprint of SST on δ^{18}O record, often by altering the isotope composition of water vapor over the ocean and/or the intensity of summer monsoon precipitation, has been previously found in other proxies such as tree ring (Sano et al. 2013), coral (Charles et al. 1997), and stalagmite (Burns et al. 2002) from tropical regions.

When inspecting the correlations over the Indian Ocean in Fig. 4a, we can find that areas of positive correlations almost overlap with areas of positive SST anomalies and vice versa, during the positive Indian Ocean Dipole (IOD) phase. In addition, the high positive correlations in the tropical central and eastern equatorial Pacific Ocean approximately locate in the El Niño Southern Oscillation (ENSO) region. However, previous researches have demonstrated that the inverse relationship between ENSO and Indian monsoon rainfall weakened (Kumar et al. 1999), and that IOD and ENSO oppositely affected the Indian monsoon rainfall (Ashok et al. 2001), during the recent decades. The Indian monsoon rainfall was also found to have an inverse relationship with the Pacific Decadal Oscillation (PDO) (Krishnan and Sugi 2003) which is often described as a long-lived El Niño-like pattern of Pacific climate variability. When in phase (out of) with PDO, ENSO exerted an enhanced (a weakened) impact on the Indian monsoon rainfall (Krishnan and Sugi 2003; Krishnamurthy and Krishnamurthy 2014). The PDO has changed from cold phase to warm phase around 1976/1977. Therefore, the relationship in Fig. 4a is further explored separately before and after 1976/1977 when a significant shift of Indian summer monsoon activity occurred (e.g., Sabeerali et al. 2012; Sahana et al. 2015). As illustrated in Fig. 4b, the strong positive correlations predominantly locate in the eastern equatorial Pacific, approximately in the Niño 3 region during 1948–1976. Also, correlations over the tropical Indian Ocean in Fig. 4c are improved during 1977–2011 compared to that in Fig. 4a. These analyses suggest that δ^{18}O record of the Zuoqiupu ice core is potentially influenced by the strengths of IOD and ENSO in different periods probably through modulation of Indian summer monsoon variability. It is further corroborated by the inverse relationships between annual and monsoon δ^{18}O records of the ice core and Indian monsoon index of Webster and Yang (1992) during 1948–2011 with significant correlation coefficients of -0.39 and -0.27, respectively, both at the 0.05 level. As suggested by Vuille et al. (2005), the inverse relationship indicates that ice core δ^{18}O variations in the monsoon region are sensitive to changes in Indian summer monsoon strength. A significant weakening of Indian summer monsoon circulation during 1901–2012 has been observed due to decreased land-sea thermal gradient over South Asia (Roxy et al. 2015), which is consistent with the increasing monsoon δ^{18}O record of the Zuoqiupu ice core (see Supplementary Fig. A2).

Spatial correlations of Zuoqiupu δ^{18}O record with 200 hPa geopotential height from NCEP/NCAR dataset for the non-monsoon time series during 1948–2011 are illustrated in Fig. 5a. It shows that significant positive correlations are observed mainly over North India to Indo-China Peninsula, while the negative correlations are on the area of Mongolia. This seesaw pattern of correlations may suggest the influence of mid-latitude westerly jet stream on stable isotope composition of non-monsoon precipitation over the southeastern TP (Cannon et al. 2015). Study (Hasson et al. 2013) shows that moisture from Atlantic Ocean and Mediterranean Sea by the westerly disturbances has limited direct contribution to precipitation on the southeastern TP, but the westerly winds will transport recycled moisture along the northern Indian subcontinent and water vapors over northern Arabian Sea and Bay of Bengal with high δ^{18}O values to our study area during non-monsoon season (Fig. 5b). A large fraction of precipitation amount in non-monsoon season especially in spring over the study area has been interpreted to be derived from the active southern branch trough generated by the mid-latitude westerlies (Suo and Ding 2009; Yang et al. 2013). In this way, the non-monsoon δ^{18}O record of Zuoqiupu ice core is connected to mid-latitude westerly jet activity. Interestingly, contrasting relationships between non-monsoon δ^{18}O record and Atlantic Multidecadal Oscillation (AMO) (Enfield et al. 2001) are found with significant negative correlations during 1942–1976, while positive correlations during 1977–2011 (Table A2). Although the mechanism that relates Zuoqiupu δ^{18}O record to AMO, probably through the strengths of the westerlies (e.g., Grossmann and Klotzbach 2009) and/or Indian monsoon rainfall (e.g., Wang et al. 2009), is not exactly understood, strong contrasts of that relationship before and after 1976/1977 reveal considerable changes in the contribution of AMO to precipitation δ^{18}O on the southeastern TP.

4 Summary and conclusions

In the fall of 2012, a 109.7 m long ice core was extracted from Zuoqiupu glacier, a temperate maritime glacier on the southeastern Tibetan Plateau. Seasonal cycles of δ^{18}O in the ice core are clearly observed due to the high accumulation rate. The ice core δ^{18}O record was thus retrieved covering the period 1942–2011.

Statistically significant and positive correlations exist between annual δ^{18}O record of the Zuoqiupu ice core and local temperature from meteorological stations of Bomi and Zayu, but significant negative correlations of annual δ^{18}O record with local precipitation amount are not found, indicating temperature effect on the ice core δ^{18}O record in the traditional sense. The temperature effect on the annual δ^{18}O record is predominantly resulted from the non-monsoon precipitation, while the inverse relationship between annual δ^{18}O record and precipitation amount in part of Northeast India is mainly contributed by the monsoon precipitation.

Variations of monsoon δ^{18}O record of the Zuoqiupu ice core are associated with SST changes in the tropical Indian and eastern equatorial Pacific Oceans. The role of SST in monsoon δ^{18}O record of Zuoqiupu ice core is more significant in eastern equatorial Pacific Ocean before the 1976/1977 climate shift, while it is in the tropical Indian Ocean after 1976/1977. The Indian monsoon strength, linked to SST changes in tropical Indian and eastern equatorial Pacific Oceans, is found to have an inverse impact on the Zuoqiupu ice core δ^{18}O record. The non-monsoon δ^{18}O record in the Zuoqiupu ice core is influenced directly and/or indirectly by the strength of mid-latitude westerlies. Most importantly, the AMO contributes to the variations of non-monsoon ice core δ^{18}O record in opposite directions before and after the North Pacific climate regime shift in 1976/1977.

All in all, this study has roughly identified some climate signals related to the Indian summer monsoon and westerly circulation from the Zuoqiupu ice core of a temperate maritime glacier. However, the climate information contained in maritime glaciers in the southeastern TP is far more abundant than those reported in this paper since precipitation over there is quite large and almost equally distributed between monsoon and non-monsoon seasons. Incorporation of ice core stable isotope composition into global circulation model is needed in the future in order to unravel the climate change processes on the TP associated with the relation and interaction between Indian summer monsoon and westerly circulation.

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