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A 70-yr record of oxygen-18 variability in accumulation from the Tanggula Mountains, central Tibetan Plateau

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Abstract

A 33 m ice core was retrieved from the Tanggula Mtns, central Tibetan Plateau at 5743 m a.s.l. in August 2005. Annual average δ^{18}O ratios were determined for the upper 17 m depth, representing the time series since the mid-1930's based on multi-parameter dating techniques. Data are compared to previous results (Kang et al., 2007) of an ice core from Mt. Geladaindong, 100 km to the northwest, for the period 1935–2003. During the time 1935–1960, δ^{18}O ratios differed by 2–3‰ between the two ice cores, with generally lower ratios preserved in the Tanggula 2005 core. Differences in interannual variability and overall average ratios between the two study locations highlight the spatially variable climatic signals of ice core isotope ratios within the boundary of monsoon- and westerly-impacted regions of the central Tibetan Plateau. Average annual net accumulation was 261 mm w.eq. yr^{-1} for the period 1935–2004. Overall average δ^{18}O ratio was –13.2‰ and exhibited a statistically significant increase from the 1935–1969 average (–413.7‰) to the 1970–2004 average (–12.6‰). Despite the observed increase in isotope ratios, temperature dependence was not found based on comparison with long-term data from meteorological stations to the north and southwest of the study location. Lack of temperature dependence is likely due monsoon influence, which results in relatively more depleted moisture arriving during the warm season. Evidence of monsoon impacts on precipitation in the central Tibetan Plateau has been previously documented, and statistically significant negative correlation ($r = -0.37$, $p < 0.01$) between the annual average ice core δ^{18}O ratio and N. India monsoon rainfall was observed for the period 1935–2004.

1 Introduction

High elevation ice cores from the mid- and low-latitude regions have been instrumental for reconstructing environmental records. With sufficiently high elevation to preserve annual accumulation, the mountain regions of the Tibetan Plateau (TP) provide an ideal location to examine interannual variability of geochemical signals preserved in snow and ice. Stable isotopes in ice cores have been widely used as a paleo-thermometer in this region. However, moisture sources and water vapor recycling differ between the northern and southern TP (Tian et al., 2001a), resulting in spatially and temporally variable isotope-temperature relationships. The main moisture in the northern TP is dominated by strong continental recycling with high evaporation and mainly convective precipitation, while moisture in the southern TP is controlled by the Indian monsoon, with mainly humid moisture origins such as the Bay of Bengal (Tian et al., 2001b). Temperature dependence on the isotopic depletion is established for continental locations in the northern TP, far-removed from monsoon moisture (Yao et al., 1996). In those areas, the most depleted isotope ratios are associated with accumulation during the coldest temperatures and the least depleted ratios arrive with warm-season moisture, recognized as the typical temperature dependence observed at continental locations (Rozanski et al., 1993). Areas in the southern TP exhibit the opposite relationship; more depleted monsoon moisture arrives during the warm season resulting in a negative isotope-temperature correlation (Kang et al., 2002; Tian et al., 2001c, 2003; Vuille et al., 2005). It is important to note the influence of temporal scales associated with ice core isotope-temperature relationships in regions under the influence of the Indian Southern Monsoon. As outlined by Yu et al. (2008), ice core δ^{18}O ratios in the southern TP are impacted by monsoon seasonality on short time scales, but may still match temperature trends on longer time scales. It is therefore necessary to evaluate central TP locations more thoroughly, in order to determine the possibility of using an ice cores for temperature reconstructions in this region.

Increasing positive correlation between temperature and δ^{18}O from the southern to the northern TP indicates a gradual northward weakening of monsoon activity (Yu et al., 2008), with the Tanggula Mtns acting as the main orographic barrier to the southeast monsoon (Tian et al., 2001c). Although long-term isotope precipitation data is sparse within the central TP, prior results (Ohata et al., 1994; Tian et al., 2003; Zhang et al., 2007b) have reported the influenced of monsoon precipitation manifesting as depleted δ^{18}O ratios in precipitation or accumulation during the main Indian Summer Monsoon period from June through September (JJAS). It has been suggested that the main latitudinal zone where tropical monsoon circulation interacts with westerly-dominated air masses coincides with the Tanggula Mtns, around 33° N (Tian et al., 2001b; Thompson et al., 2006). The ice core presented here was retrieved at 33°7′4.26″ N, 92°5′26.16″ E , elevation 5743 m a.s.l. (Fig. 1a and b), directly within this boundary region.

Previous results (Kang et al., 2007) from an ice core near Mt. Geladaindong (33°34′37.8″ N, 91°10′435.3″ E), approximately 100 km to the northwest of the Tanggula 2005 ice core presented here (Fig. 1), provided a comparison for the time period 1935–2003. In addition, a 14 m ice core from the Tanggula Mtns (33°04′ N, 92°05′ E) previously presented by Yao et al. (1995) provided a comparison for the time period 1940–1990 (Yao et al., 1995). A significant isotope-temperature correlation was found for the Mt. Geladaindong ice core (elev. 5720 m a.s.l.) based on comparison with records from five meteorological stations in the vicinity (Kang et al., 2007). However, relatively more depleted summer isotope ratios in the Geladaindong core revealed impacts from monsoon moisture (Zhang et al., 2007b), demonstrating the relationships at multiple temporal scales suggested by Yu et al. (2008). In this paper, we focus on Tanggula 2005 (subsequently referred to as TGL05) δ^{18}O variability for the time period 1935–2004. Results are compared to ground-based temperature records to evaluate the relative importance of temperature and depleted monsoon moisture at this study location.

2 Methods

A 33 m depth ice core was retrieved in August, 2005 from the Longxia Zailongba Glacier, located in the south-central Tanggula Mtns, using an electro-mechanical drill. The core (subsequently referred to TGL05) was in excellent condition and lacked brittle ice zones. Core sections were transported frozen to Lanzhou and processed at 5 cm resolution for geochemical analysis. Oxygen isotope ratios were determined at the Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research. Analysis was performed using the classical headspace equilibration technique (Epstein and Mayeda, 1953) with a Finnigan Delta Plus MAT 253 isotope ratio mass spectrometer. Sample vials were auto-flush-filled with 0.3% CO_2 in He_2 and analyzed after equilibration with a GasBench II/GC PAL interfaced with continuous-flow IRMS. Sample isotope ratios were measured as the average of five peaks per sample and are reported in standard delta notation (δ) vs. Vienna Standard Mean Ocean Water (V-SMOW). Analytical δ^{18}O precision for the upper 17 m (n=327) was 0.09‰, based on maximum deviation of external standards for all runs.

Temperature data from two stations (Figs. 1a and 2) was used for comparison with ice core results. One station is located to the north of the drill site (Tuotuohe), while the other station is to the southwest (Amdo). Meteorological station locations and general information is listed in Table 1. In order to evaluate possible monsoon influence on the TGL05 ice core δ^{18}O ratios, annual average isotope ratios were compared to the average monsoon precipitation (JJAS) in N. India (Sontakke et al., 2008) for the period 1935–2004. The precipitation sum of the four homogenous rainfall regions north of 21° N (North Mountainous India, Northwest India, North Central India, and Northeast India) defined by Sontakke et al. (2008) was used since these monsoon-impacted regions are directly adjacent to the TP (Fig. 1a).

3 Results

The TGL05 ice core was retrieved from above the annual snow line in the upper glacier accumulation zone, and did not display any signs of annual melt. The upper 17 m presented here depicts the time period from 1935 to 2005, based on the layer-counted annual peaks in major ions (Zheng et al., 2009). The established depth-age scale was verified from the depth of maximum β-activity corresponding to the 1963 Northern Hemisphere maximum in atmospheric tritium, which was within ±1 yr of the layer-counted age. Isotope ratios did not show well-preserved annual variation consistent with peaks in seasonal ion concentrations (Fig. 3), indicating annual isotope signals preserved in the TGL05 ice core did not exhibit significant temperature dependant seasonal variability typical for continental locations. Lower δ^{18}O was usually related to lower SO_4, which should be the summer case for monsoon impacted regions. Average annual accumulation for the represented time period was 261 mm water equivalent (w.eq.) yr-^{1}, as determined from the ratio of the annual layer thickness to the flow-modeled thickness multiplied by the surface accumulation rate, a method previously outlined by Henderson et al. (2006).

Due to the low annual accumulation preserved in the ice core, seasonal separation of δ^{18}O ratios was not possible with the 5 cm sampling resolution employed. Therefore, annual average δ^{18}O isotope ratios were determined for the period 1935–2004; summary statistics are listed in Table 2. Results are presented in Fig. 4 with comparison to annual δ^{18}O ratios from prior results of Kang et al. (2007) for the Geladaindong ice core, and to average JJAS temperatures recorded at Tuotuohe and Amdo stations. In comparison to the Geladaindong ice core (Fig. 4a), a greater amount of interannual variability was preserved in the TGL05 ice core (Fig. 4b). Difference in the two records is most apparent prior to 1970. Despite similar elevations, isotope ratios are generally 2–3‰ lower in the TGL05 ice core prior to 1960, after which time ratios generally increase until peaking in the early- to mid-1960s. Subsequent to 1970, a general trend of increasing isotope ratios is present in both cores. Greatest increase in the TGL05 ice core ratios is observed for the period 1994–2004 (Fig. 4b), while maximum increase in the Geladaindong ice core began slightly earlier (Fig. 4a). The general trends in the TGL05 ice core isotope ratios are in agreement with previous results from a 14 m ice core (Yao et al., 1995), approximately 5 km to the south. Both cores revealed lowest ratios prior to the mid-1950s, increasing to an early- to mid-1960s maximum, and further increase subsequent to 1970. The minimum ratios in the TGL05 ice core from the late-1960s to the early-1970s are also in agreement with results reported by Yao et al. (1995).

Average annual δ^{18}O ratio in the TGL05 ice core increased from −13.7‰ for the period 1935–1969 to −12.6‰ for the period 1970–2004, a significant increase at the α=0.01 level. Since the mid-1950s, the TP has undergone warming which has exceeded Northern Hemisphere warming (Liu and Chen, 2000). To investigate the degree to which increasing isotope ratios in the TGL05 ice core reflect increasing temperatures, annual average ratios were compared to average JJAS temperatures recorded at two meteorological stations in the vicinity. Tuotuohe and Amdo stations both show consistent temperature variations for the respective recording times, with the greatest increase in JJAS temperatures observed since the mid-1980s (Fig. 4c). Average JJAS temperatures were used for comparison since these months accounted for 83–86% of the total annual precipitation during their respective recording times (Fig. 2). The timing of temperature increase at the two meteorological stations is earlier than the δ^{18}O increase observed in the Geladaindong and in the TGL05 ice cores. Both the annual average and 5-yr running means in the TGL05 ice core were compared with isotope-temperature correlations in the Geladaindong ice core (Kang et al., 2007), for the similar time periods. Resulting correlations between isotope ratios and average JJAS temperature are presented in Table 3 for both cores. Although no significant correlation between the TGL05 ice core and either station was observed on an annual basis, the lack of correlation between the 5-yr smoothed average δ^{18}O ratio and 5-yr smoothed JJAS average station temperature is more revealing, given the consistent variation of the 5-yr running mean temperatures at the two stations (Fig. 4c). Instead of the increasing positive δ^{18}O-JJAS temperature correlations found in the Geladaindong ice core for the 5-yr running means, correlations in the TGL05 core became more negative (Table 3). Although the negative correlations are not statistically significant ($p>0.10$), the lack of agreement between TGL05 ice core isotope ratios and average JJAS temperatures (Fig. 5) indicate limited use of the TGL05 ice core for temperature reconstruction, and suggests other controlling factors, such as contribution of depleted monsoon moisture arriving with the southern monsoon, have had a greater influence on the preserved isotopic ratios.

A comparison was made with the amount of N. India monsoon precipitation (Sontakke et al., 2008) to investigate possible influence of monsoon moisture. A significant correlation was revealed between δ^{18}O ratios and N. India precipitation, on both an annual average basis ($r=-0.37$, $p<0.01$) and for the 5-yr running means ($r=-0.72$,

$p < 0.001$). Figure 6 demonstrates a good general agreement between δ^{18}O variability and the amount of N. India precipitation on an annual and a long-term basis. Since the isotope ratios in Fig. 6 are plotted with a reversed scale, peaks in N. India precipitation are identified with greater isotopic depletion. A general decrease in N. India precipitation since the 1960s can be observed in Fig. 6, consistent with the increase in ice core isotope ratios (Fig. 4b). A scatterplot of the 5-yr running mean TGL05 ice core δ^{18}O ratios and N. India precipitation illustrates the significant correlation and exhibits a negative slope characteristic of monsoon moisture (Fig. 7). Results indicate years with greater amount of N. India precipitation were typically associated with greater isotope depletion in the TGL05 ice core. However, given the low annual accumulation (<300 mm w.eq. yr^{-1}), the authors acknowledge minimal monsoon influence on the overall amount of moisture. Vuille et al. (2008) suggested that an isotope-monsoon relationship may exist even in areas where monsoon variability does not affect local precipitation, due to increased rainout and distillation processes during transport. Results provide a first assessment of monsoon contributions to isotope ratios in this ice core, and additional analysis of δD will provide further quantification of monsoon moisture transport and interactions in the central TP.

4 Conclusions and discussion

Annual average δ^{18}O ratios were determined for the upper 17 m depth of an ice core from the Tanggula Mtns, representing the time period 1935–2004. The TGL05 ice core revealed lower annual δ^{18}O ratios and greater interannual variability compared to the Geladaindong ice core. Lower isotope ratios were most apparent prior to the mid-1950s, although both cores revealed increasing trends since the 1970s. Temperature dependence was previously established for the Geladaindong ice core by Kang et al. (2007). However, the TGL05 ice core did not reveal significant correlation between isotope ratios and JJAS temperature during the same time period. The lack of correlation between stable isotopes and station temperatures suggests limited application of isotopes as a paleo-thermometer for the TGL05 ice core. Contrasting results from the two study locations provides further evidence that the Tanggula Mtns exist at the boundary between westerly- and monsoon-dominated moisture to the north and south, respectively. Despite the relatively close geographic proximity, differences highlight the spatially variable nature of ice core δ^{18}O ratios within the central TP. and indicates different moisture sources, transport, and climatic conditions are impacting the two locations despite the. Good agreement between the TGL05 ice core isotope record and a shallow ice core 5 km to the south (Yao et al., 1995) indicate these cores were more impacted by depleted monsoon moisture compared to the Geladaindong ice core, 100 km to the northwest. Significant negative correlation between TGL05 ice core δ^{18}O ratios and N. India precipitation provides evidence that the southeastern Tanggula Mtns may receive depleted moisture during the maximum extent of the Indian Summer Monsoon. The relationship between δ^{18}O ratios and N. India precipitation amount exhibited a significant negative slope that would be expected for an area impacted by monsoon moisture, although influence on actual amount of precipitation appears minimal. Results are in accordance with previous research (Vuille et al., 2008) suggesting an area upstream from monsoon moisture, such as the central TP, may experience isotopic influences from transport and distillation processes without significant impact on the amount of moisture. Although the main moisture may be blocked in the southern TP by the Himalayas, these results provide further evidence that the impact of monsoon circulation on δ^{18}O ratios in precipitation extends beyond the southern TP and includes portions of the central and eastern Plateau as well. A negative correlation between precipitation amount and δ^{18}O ratios in the Tanggula Mtns at 5000 m a.s.l. was previously reported by Ohata et al. (1994). Future analysis of δD will provide a means to quantitatively describe moisture sources, transport distances, and continental recycling at this study location. Additional ice cores from the central TP are needed in order to increase the spatial coverage of glacio-geochemical records and to further document interactions of westerly and monsoon circulation systems.

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Table 1. Meteorological station summary data. P_T is average total precipitation, T_A is average annual temperature, and T_M is average monsoon (JJAS) temperature.

Station	Time Period	Latitude	Longitude	Elev (m a.s.l.)	P_T (mm)	T_A (°C)	T_M (°C)
Tuotuohe	1957–2004	34°13′ N	92°26′ E	4533	278	−4.1	5.8
Amdo	1966–2004	32°21′ N	91°06′ E	4800	440	−2.8	6.4

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Table 2. δ^{18}O summary statistics (‰) for the upper 17 m ice core depth, representing the time period 1935–2004.

n	327
max	−5.9
min	−18.1
median	−13.0
mean	−13.2
σ	1.8

Table 3. Correlations between δ^{18}O ratios and average JJAS station temperatures for annual and 5-yr running means in the TGL05 ice core, and for the Geladaindong ice core (Kang et al., 2007). Reported values are from 1966–2003 for Amdo station, 1958–2003 for Tuotuohe station.

		Tuotuohe	Amdo
Annual average	TGL05	0.03	–0.04
	Geladaindong	0.23	0.32
5-yr smoothed	TGL05	–0.09	–0.15
	Geladaindong	0.57	0.78

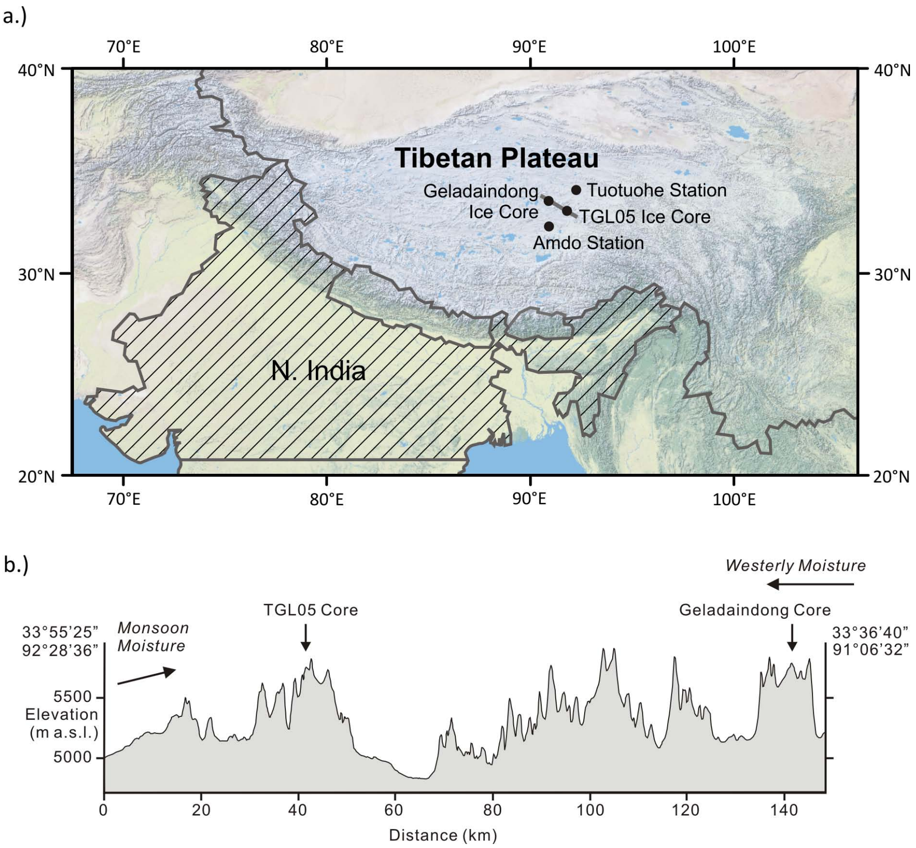

Fig. 1. (a) Ice core and meteorological station locations. Grey line indicates elevation profile used for **(b)**. Approximate region of N. India precipitation (Sontakke et al., 2008) shown with hatched fill. Borders are shown for reference only and are not meant to denote true political boundaries. (b) Elevation profile sketch from SE to NW within the Tanggula Mtns.

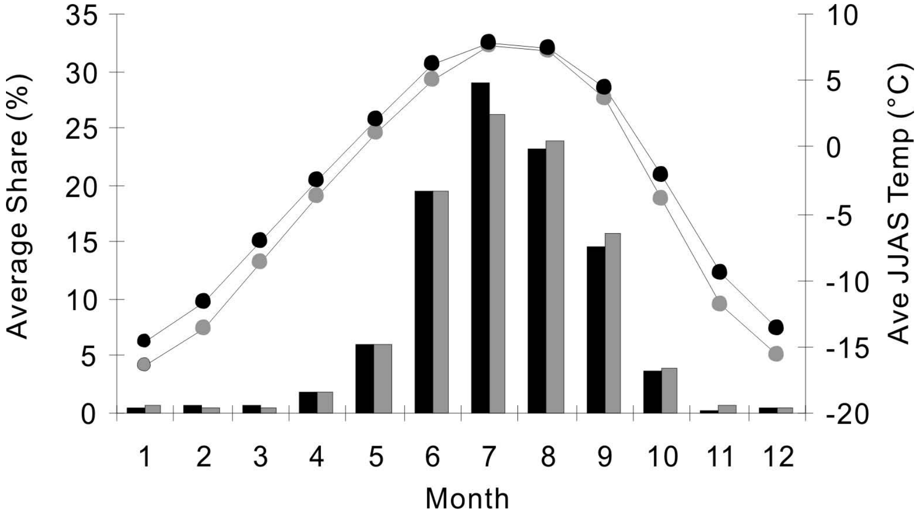

Fig. 2. Monthly distribution of precipitation (bars) and temperature (lines) for Tuotuohe (in black) and Amdo (in grey) meteorological stations.

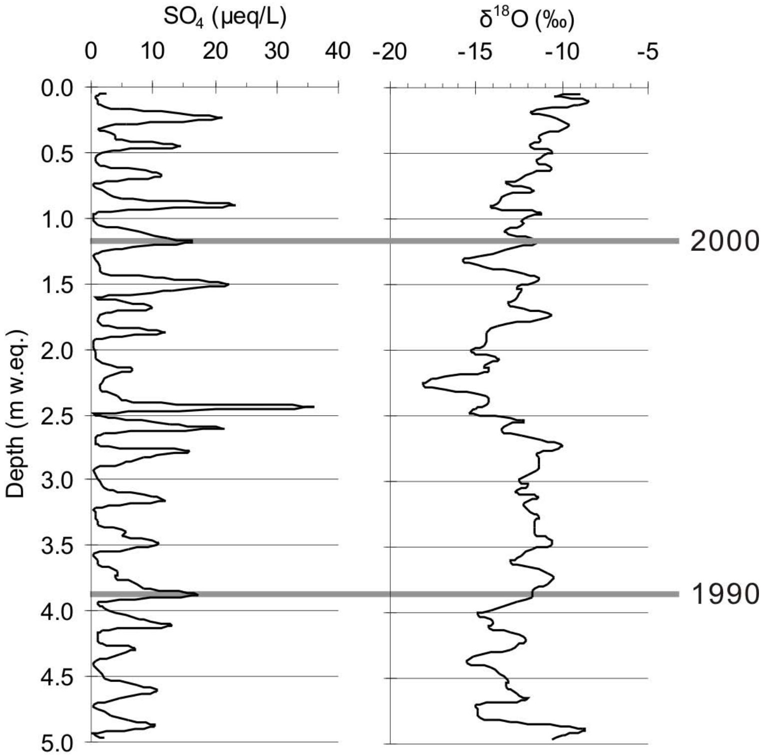

Fig. 3. High-resolution sulfate and δ^{18}O profiles for the upper 5 m w.eq. depth.

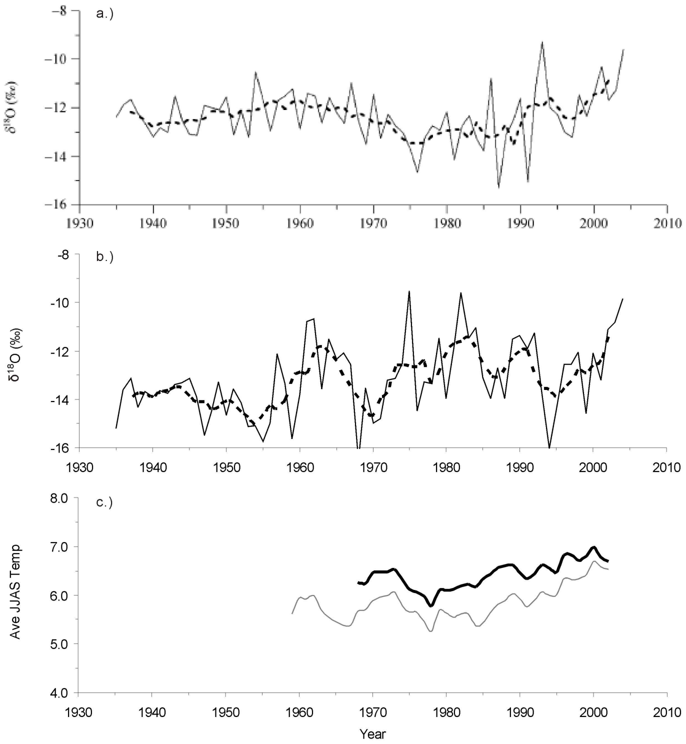

Fig. 4. **(a)** δ^{18}O ratios from the Geladaindong ice core, 1935–2003 (Kang et al., 2007). **(b)** δ^{18}O ratios the TGL05 ice core, 1935–2004. Annual averages are depicted with solid lines, 5-yr running means with dashed lines. **(c)** JJAS average temperatures recorded at Tuotuohe (black line) and Amdo stations (grey line).

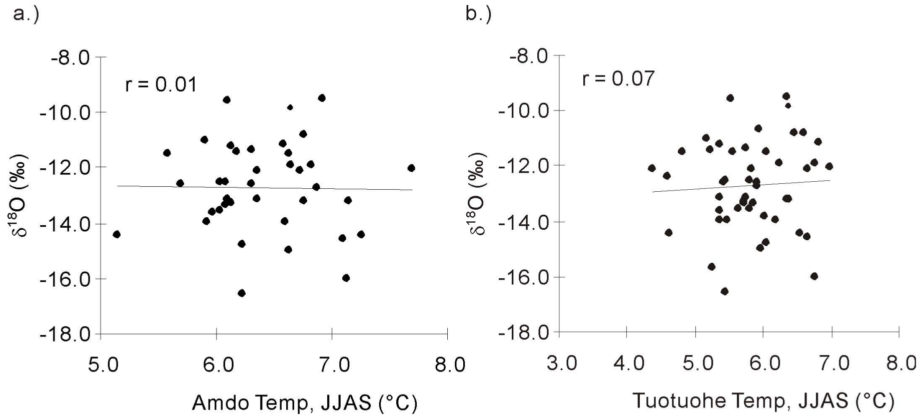

Fig. 5. Scatterplot of annual δ^{18}O ratios and average JJAS temperature recorded at Amdo (1966–2004) and Tuotuohe (1957–2004) meteorological stations.

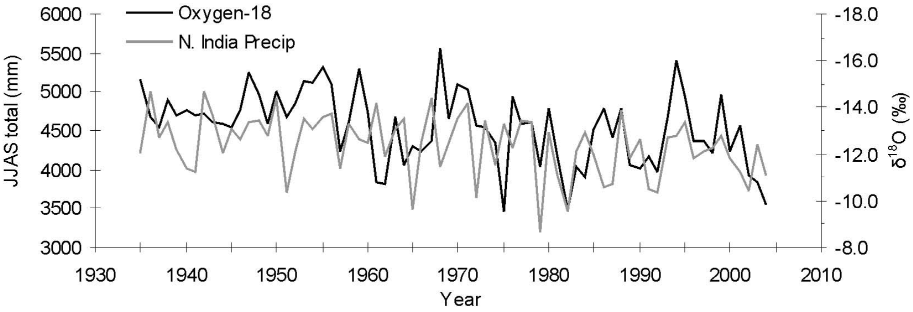

Fig. 6. Annual average δ^{18}O variability plotted with N. India monsoon rainfall (Sontakke et al., 2008). Note the reversed isotope scale.

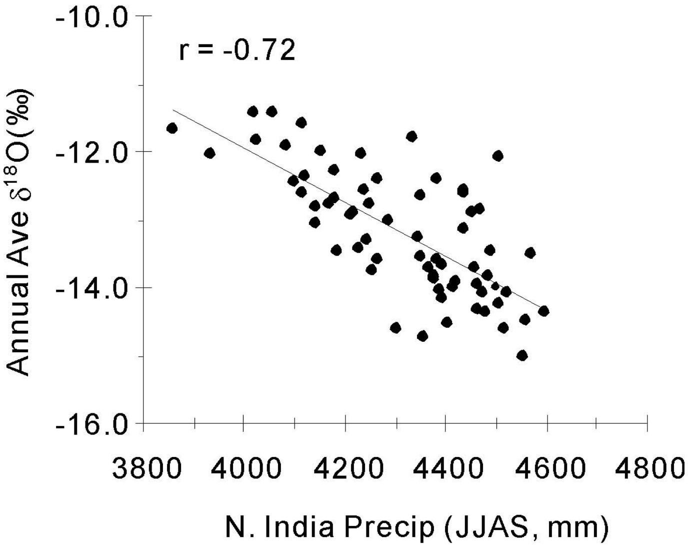

Fig. 7. Scatterplot of 5-yr running mean annual δ^{18}O ratios and total N. India precipitation, 1935–2004.