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Temperature changes on the Tibetan Plateau during the past 600 years inferred from ice cores and tree rings

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ABSTRACT

The climatological signal of $\delta^{18}O$ variations preserved in ice cores recovered from Puruogangri ice field in the central Tibetan Plateau (TP) was calibrated with regional meteorological data for the past 50 years. For the period AD 1860–2000, 5-yearly averaged ice core $\delta^{18}O$ and a summer temperature reconstruction derived from pollen data from the same ice core were compared. The statistical results provide compelling evidence that Puruogangri ice core $\delta^{18}O$ variations represent summer temperature changes for the central TP, and hence regional temperature history during the past 600 years was revealed. A comparison of Puruogangri ice core $\delta^{18}O$ with several other temperature reconstructions shows that broad-scale climate anomalies since the Little Ice Age occurred synchronously across the eastern and southern TP, and the Himalayas. Common cold periods were identified in the 15th century, 1625–1645 AD, 1660–1700 AD, 1725–1775 AD, 1795–1830 AD, 1850–1870 AD, 1890–1920 AD, 1940–1950 AD, and 1975–1985 AD. The period 1725–1775 AD was one of the most prolonged cool periods during the past 400 years and corresponded to maximum Little Ice Age glacier advance of monsoonal temperate glaciers of the TP.

1. Introduction

The reconstruction of long and high-resolution climatic series spanning the past centuries and millennia is important for understanding natural climate variations at those timescales and for estimating the anthropogenic influence on the climate system. The Tibetan Plateau (TP), one of the Earth's most imposing geomorphic features, is a climatically very important region due to its influence on large-scale atmospheric circulation patterns over Asia, including the summer monsoon over South Asia and the South China Sea (Ding, 1992; Li and Yanai, 1996; Webster et al., 1998). During the past decades, a great number of paleoclimatic records covering the last centuries were derived from ice cores (Davis et al., 2005; Liu et al., 1998; Thompson et al., 1993, 2000, 2003, 2006a,b; Wang et al., 2006; Yao et al., 1997; Yao, 2002, 2006), tree rings (Bräuning, 1999; Bräuning and Mantwill, 2004; Cook et al., 2003; Zhang et al., 2003a,b; Shao et al., 2005; Fan et al., 2008, 2009; Gou et al., 2006, 2008; Sheppard et al., 2004; Liu et al., 2006a,b; Esper et al., 2002, 2003a; Treydte et al., 2006), lake sediments (Herzschuh et al., 2006; Wu et al., 2001; Zhang et al., 2003a,b; Zhang et al., 2004; Liu et al., 2006a,b; Zhao et al., 2007, 2008; Zhao and Herzschuh, 2009) and glacier fluctuations (Bräuning, 2006; Yang et al., 2007) on the TP and adjacent areas (Yang et al., 2003; Ge et al., 2007; Wang et al., 2007). However, it is difficult to compare the results obtained from different proxy data due to lack of calibration models, different time resolution and limited temporal and spatial representation. In addition, the prominent topography on the TP strongly modifies regional atmospheric circulation patterns. Yang et al. (2003) attempted an integrated analysis of various proxy records for the past two millennia with a time resolution of 50 years, and suggested that the TP experienced well defined climatic episodes such as the warm intervals during A.D. 800–1100 and A.D. 1150–1400, the cool "Little Ice Age" between A.D. 1400 and 1900, and an earlier cold period between the 4th and 6th centuries. Due to the low resolution (50 years) of these temperature composites, however, it was not possible to reveal multi-year and decadal-scale climatic events of the TP for the "pre-instrumental" periods.

In this study, we concentrate on decadal to inter-decadal temperature variations during the past 600 years to assess how unusual the warming in the 20th century is in the context of the Little Ice Age. The proxy data we use include a $\delta^{18}O$ series from an ice core drilled on the central Tibetan Puruogangri ice field and several tree-ring series with a time resolution of 5 years (Fig. 1 and Table 1). We first analyze the climatological significance of ice core proxy records by examining correlation between annual ice core $\delta^{18}O$ and instrumental meteorological observations for the recent 50 years. Then we compute the correlation of 5-year average $\delta^{18}O$ with a pollen-based summer

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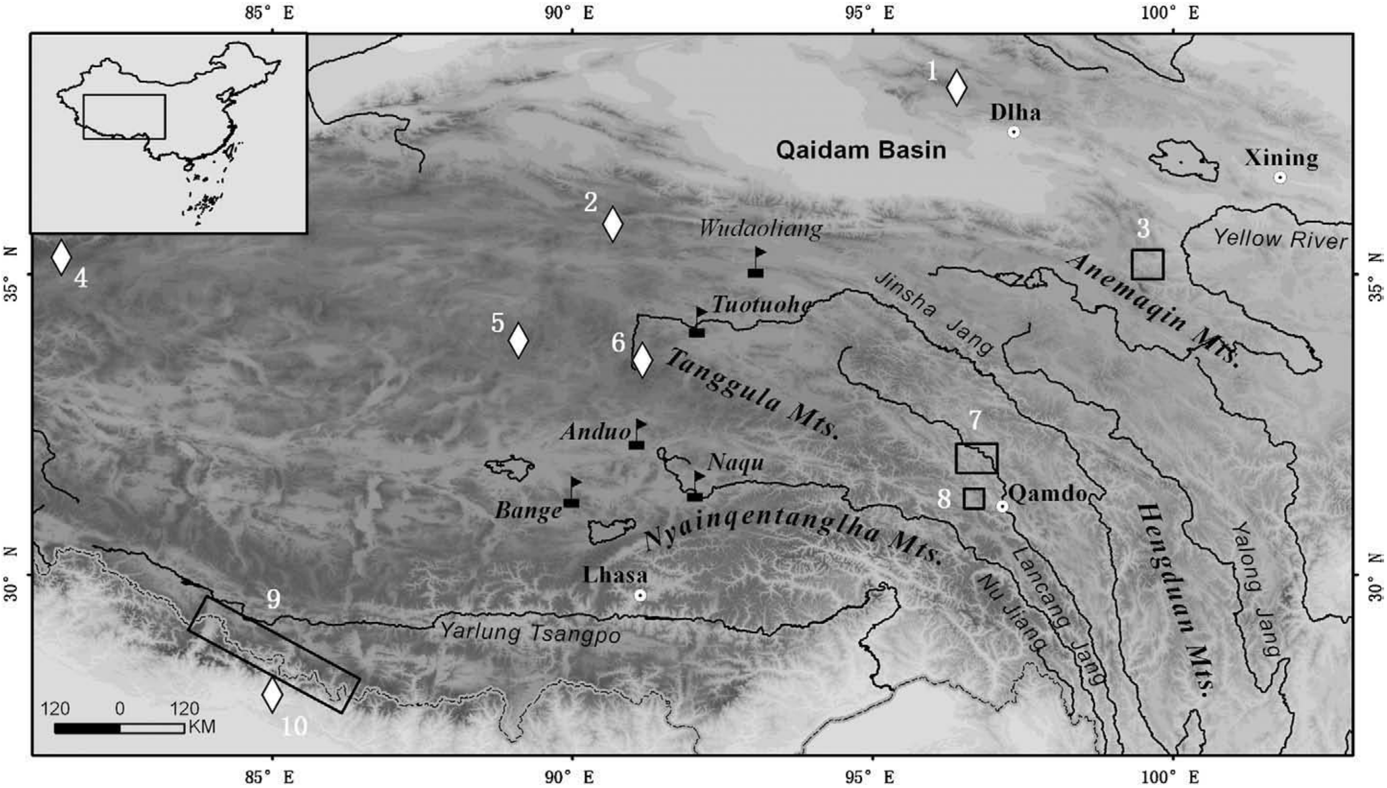

Fig. 1. Map showing the study site of Puruogangri ice cap and other proxy sites mentioned in the text. 1) Dunde ice core; 2) Malan ice core; 3) Anemaqin Shan tree rings; 4) Guliya ice core; 5) Puruogangri ice core; 6) Guoqu ice core; 7) Nangqian tree rings in the source region of the Yangtze River; 8) Qamdo tree rings; 9) Nepal tree rings; 10) Dasuopu ice core.

temperature reconstruction derived from the same ice core for the past 140 years. Finally, we compare different proxy temperature records including ice cores, tree rings and glacier fluctuations from different parts of the TP and reveal characteristics of temperature variations during the last 600 years.

2. Ice cores and study area

The Puruogangri ice field (33°44′–34°44′N, 88°20′–89°50′E), situated in the Tanggula Mountains in the central TP, has an area of 422.6 km^2 and an elevation of 5500–6500 m (Yi et al., 2002; Yao et al., 2006). Shifting sand dunes several tens of meters high occur close to the western part of the ice field. During the late winter/spring, strong westerly winds sweep across the desert surface and deposit dust particles on the ice surface, which buried by subsequent snow results in visible dust layers in ice cores. The mean annual surface temperature on the Puruogangri ice field is about −6 °C, and summer temperature is estimated to be close to 0 °C (Li et al., 2006). Total annual precipitation in this region is estimated to be only 150–200 mm (Shen et al., 2006), with 70–80% of the annual precipitation falling as snow during the summer season (Thompson et al., 2005).

Three ice cores were first retrieved in 2000 in the northern part of the Puruogangri ice field (referred to Nc1, Nc2, and Nc3), from which physical and chemical parameters were studied (Thompson et al., 2006a,b; Yao et al., 2006). Another 80 m ice core (33°53′N, 89°06′E, 5900 m asl) from the southern part of the ice field (referred to as Sc) was recovered in 2004. The upper 34.24 m of this core covering the past 140 years were analyzed for ice core δ^{18}O and pollen content. The timescale was established based on seasonal variations of δ^{18}O in combination with counting of visible annual dust layers (Yang et al., 2008a,b). First, we calibrated the annually resolved δ^{18}O record from core Sc with climate data of the past 50 years. Then, we compared this series with a temperature reconstruction based on the ice core pollen data and δ^{18}O records with a 5-year resolution derived from cores Nc1 and Nc2 (Thompson et al., 2006a,b) for the past 140 years to recover temperature history for the past 600 years.

Table 1
Characteristics of proxy data series recovered from the Tibetan Plateau.

Site no. in Fig. 1	Proxy series	Proxy type	Lat. N	Long. E	Elev. (m)	Series length	Time resolution	First autocorrelation on decadal scale	Source
1	Dunde	Ice core δ^{18}O	38°06″	96°24″	5325	1400–1980	Decadal	0.42	Thompson et al., 2006a,b
2	Malan	Ice core δ^{18}O	35°50″	90°40″	5680	1400–2000	Decadal	0.68	Wang et al., 2006
3	Anemaqin Shan	Tree-ring widths	34°47″	99°47″	3600–3700	1400–2000	Annual	0.35	Gou et al., 2008
4	Guliya	Ice core δ^{18}O	35°17″	81°29″	6200	1400–1990	Decadal	0.16	Thompson et al., 2006a,b
5	Puruogangri	Ice core δ^{18}O	33°53′	89°06	5900	1400–1990	Decadal	0.09	Thompson et al., 2006a, b
6	Guoqu	Ice core δ^{18}O	33°34″	91°10″	5720	1935–2004	Decadal	0.10	Kang et al., 2007
7	Nangqian	Tree-ring widths	32°12′	96°29′	4010–4330	1624–2002	Annual	0.32	Liang et al., 2008
8	Qamdo	Tree-ring widths	31°	97°	4350–4400	1400–2000	Annual	0.66	Bräuning and Grießinger, 2006
9	Nepal	Tree-ring widths	28°	85°	1830–3630	1550–1980	Annual	0.42	Cook et al., 2003
10	Dasuopu	Ice core δ^{18}O	28°″	85°	6900	1400–1990	Decadal	0.56	Thompson et al., 2000