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Climate of the Past

Precipitation record since AD 1600 from ice cores on the central Tibetan Plateau

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Abstract. Lack of reliable long-term precipitation record from the northern Tibetan Plateau has constrained our understanding of precipitation variations in this region. We drilled an ice core on the Puruogangri Ice Field in the central Tibetan Plateau in 2000 to reveal the precipitation variations. The well dated part of the core extends back to AD 1600, allowing us to construct a 400-year annual accumulation record. This record shows that the central Tibetan plateau experienced a drier period with an average annual precipitation of ∼300 mm in the 19th century, compared to ∼450 mm in the wetter periods during 1700–1780 and the 20th century. This pattern agrees with precipitation reconstructions from the Dunde and Guliya ice cores on the northern Plateau but differs from that found in the Dasuopu ice cores from the southern Plateau The north-south contrasts in precipitation reconstruction reveals difference in moisture origin between the south Tibetan Plateau dominated by the Asian monsoon and the north Tibetan Plateau dominated by the continental recycling and the westerlies.

1 Introduction

Studies of global change reconstruct palaeoclimate in order to understand climate systems in the past, interpret the current climate in context, and thereby help forecast future climate changes. Both temperature and precipitation are important factors in the climate system. Yet in the mid-low latitudes, where ecology and water resources are particularly vulnerable to climate changes, variations in precipitation may exert an especially great influence on the local climate and environment. In comparison with temperature, however, we lack long-term precipitation data necessary for accurate climate modeling (Hulme, 1994) and future climates forecasting (Hulme et al., 1999). Consequently, acquiring reliable precipitation data for the past is imperative. Precipitation, however, shows greater spatial variability than temperature, as more factors affect precipitation, posing more difficulties in acquiring representative precipitation records.

Palaeoclimates on the Tibetan Plateau have been investigated using ice cores, tree rings and lake cores (Thompson et al., 1986, 1998; Yao et al., 1996, 1999; Duan and Yao, 2002; Shao et al., 2004; Zhang et al., 2004). Precipitation reconstructions from proxies such as tree and stalagmite rings provide high time resolution; yet due to the complex processes for their storage of meteoric water, translating the raw data into precipitation amounts is extremely difficult. Nevertheless, several researchers have established precipitation time series through analysis of tree rings from low-elevation regions bordering the Plateau (Shao et al., 2004; Sheppard et al., 2004; Achim et al., 2004). Given the arboreal physiological processes, those series failed to demonstrate any long-term trend in precipitation amounts. In comparison, precipitation records recovered from ice cores provide more direct and reliable data, as glaciers are formed by accumulating layers of precipitation as snow. This process retains the past atmospheric precipitation in a rather stable state. Because of snow ablation, wind scouring, and sublimation, however, not all glaciers accurately record past precipitation. If the snow loss caused by snow ablation, wind scouring, and snow sublimation is small compared with the total, the annual snow accumulation on the glacier approximately equals the real annual precipitation.

Given the spatial and temporal variations of precipitation, single meteorological stations represent regional

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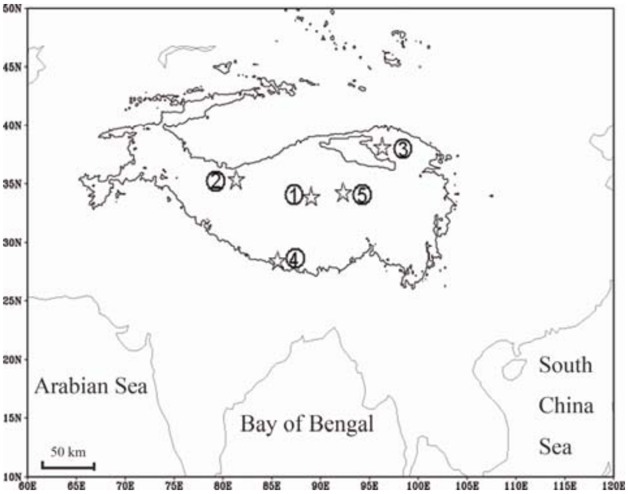

Fig. 1. Location of the Puruogangri ice core (1), Guliya ice core (2), Dunde ice core (3), Dasuopu ice core (4) and Tuotuohe meteorological station (5). The highlighted area represents the Tibetan Plateau.

precipitation less significantly than they do to temperature. We therefore need more data about precipitation for a holistic understanding of the Plateau precipitation system. On the other hand, few meteorological stations exist on the northern Tibetan Plateau with instrumental data for more than 50 years. As natural precipitation recorders, glaciers on the Tibetan Plateau play an important role in reconstructing the palaeoclimate.

Over the past two decades, we have drilled ice cores in the Dasuopu glacier in the Himalayas, the Guliya glacier in the Kunlun mountains, and the Dunde glacier in the Qilian mountains. The resulting annual ice accumulation records reflect the regional precipitation (Yao et al., 1990, 1996; Duan and Yao, 2002). But these ice coring sites lie mainly at the margins of the Tibetan Plateau, leaving a gap in our understanding of climate changes in the central Tibetan Plateau.

The Puruogangri Ice Field (89°00′–89°20′ E, 33°44′–34°03′ N, 5620–5860 m; Fig. 1) in the central Tibetan Plateau was surveyed in 2000. The area consists of several ice caps with a total area of ∼423 km^2 and ice storage of ∼52.5 km^3 (Yao, 2000). The glacier retreated nearly 70 m and lost an area of ∼24.2 km^2 since the Little Ice Age (Pu et al., 2002). Three ice cores were drilled at a 6000 m elevation site on the glacier, to depths of 118.6 m, 152 m, and 214.7 m. The following interpretations result from our analysis of the ∼214 m-long ice core.

This paper puts forward a reconstruction of snow accumulation (net balance) from the Puruogangri ice core and discusses the history of dry/wet variability in the north central Tibetan Plateau over the last 400 years. We then discuss the wet/dry variations on the northern Tibetan plateau, using the net snow accumulation recorded in the Puruogangri ice core, together with similar records from the Dunde and Guliya ice cores. We conclude by discussing the relationship between reconstructions of precipitation and temperature.

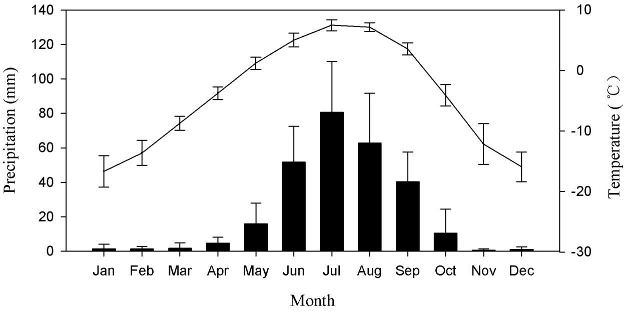

Fig. 2. Monthly temperature (line) and precipitation (bar) with one stand deviation at the Tuotuohe meteorological station.

2 Data and methods

Analysis of the nearly 50-year precipitation record from the Tuotuohe Meteorological Station (TMS; 92°26′ E–34°13′ N, 4533 m), a station near Puruogangri, reveals the central Tibetan Plateau as a semi-arid region, with a mean January temperature of ∼−16.7°C and mean July temperature of ∼7.5°C (Fig. 2). The annual precipitation was 273 mm (all precipitation values given in water equivalent), with the precipitation in the summer half year (May–September) accounting for over 92% of the total. Less than 10 mm precipitation fell from November to the following April, indicating extremely cold and arid winters on the central Tibetan Plateau. The mean of the temperatures we observed at the Puruogangri drilling site from October 3rd to the 27th in 2000 was −14.7°C. Using the TMS instrumental temperatures, adjusted for the lapse rate, we estimate the mean annual temperature at the Ice Field to be −14.8°C.

Snow falls on the Puruogangri Ice Field and accumulates annually, recording annual precipitation in a layered structure. The Puruogangri ice core was described in detail immediately after extraction from the glacier. Dust layers are clearly visible along the ice core. Those dust layers in the Puruogangri ice cores, as well as in the Dunde ice cores, were deposited on the glacier during the late winter/early spring as westerly low-pressure systems carry dust from central Asia (Husar et al., 2001; Gao et al., 1992). Precipitation records at the TMS show summer to be a wet season with most of the precipitation events. To the contrary, arid conditions prevail during the transition period from winter till early next spring. Accordingly, dust layers are conspicuous between the two clear ice layers resulting from successive summer snowfalls, and these help in delineating the annual snow accumulation. In the Puruogangri ice core, annual dust layers coincide with the presence of micro-particle peaks. As a result, the strong

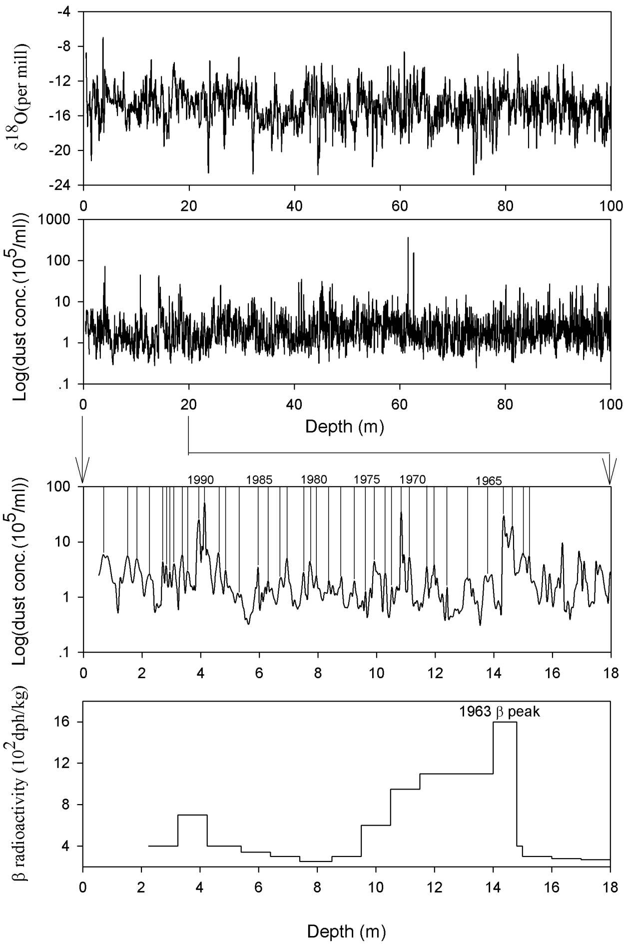

Fig. 3. The variations of δ^{18}O and dust concentrations with depth in the upper 100 m section of the Puruogangri ice core. Also the dust concentration and β radioactivity with depth in the first 18 m of the core are shown as an example of dating. The dashed vertical lines show the identification of annual layers.

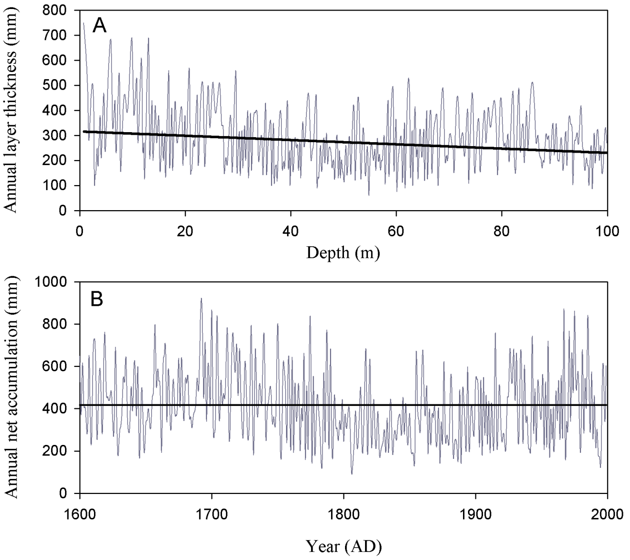

Fig. 4. Glacial accumulation reconstruction from the Puruogangri ice core: **(a)** Variations of annual layer thickness with depth and its linear trend (black line) in the first upper 100m in the Puruogangri ice core. **(b)** Variations of annual net accumulation for the years 1600 to 2000. The horizontal black line shows the average precipitation of the 20th century.

seasonally dust concentrations can be used to identify the time series of the cores. Figure 3 shows the seasonal variations of dust concentration and δ^{18}O with depth in the Puruogangri ice core, as well as dashed vertical lines indicating the identification of annual layers.

Another reference layer also exists for ice core dating, which is the β radioactivity peak produced by a nuclear explosion in the former Soviet Union in 1963 (Fig. 3). The results of this dating method coincides with the 1963 layer from counting dust layers, supporting the accuracy of ice core dating with dust layers, and affirming the reliability of ice core time series established on that basis. Dust layer counting found exactly 1600 AD at the core-depth of 104 m, with the average annual layer thickness of 27 cm.

Due to slow ice flow and considerable annual snowfall on the Puruogangri Ice Field, dust layers in the ice core are distinct, and we therefore believe dating errors from the dust-layer-counting to be insignificant. The distance between the first year layer and the next one thus indicates the second layer thickness. By this means, we determined the annual layer thicknesses of the upper 107 m (Fig. 4a). Of course, the annual layer thickness does not provide directly the snow amount originally fallen on the ice surface because new snow compresses and ice flows. The annual snow accumulation record was constructed for Puruogangri ice core using a flow model (Eq. 1) (Bolzan, 1985; Reeh, 1988), which we also applied to the Guliya and Dunde ice cores.

$$L(Z) = b\left(1 - \frac{Z}{H}\right)^{1-p} \tag{1}$$

In Eq. (1), Z is the corresponding ice equivalent depth for the calculation, b is the measured annual layer thickness; H is the depth of the glacier at the core site which is ~260 m measured by a radar echo sounding; p is the thinning parameter which is determined to be 0.54 by requiring the age to be 37 years at β peak 14.5 m and 400 years at 107.6 m obtained from layer counting (Thompson et al., 2006). Because the topography of platform where the ice core was recovered is flat and the ice layers are horizontal, p is applied to the model with only consideration of vertical deformation, other factors such as horizontal deformation are not considered. Then the reconstructed annual net accumulation is shown in Fig. 4b.

Alpine glaciers over the Tibetan Plateau penetrate into the free atmosphere, yielding ice cores that provide continuous precipitation records representative of the spatial distribution

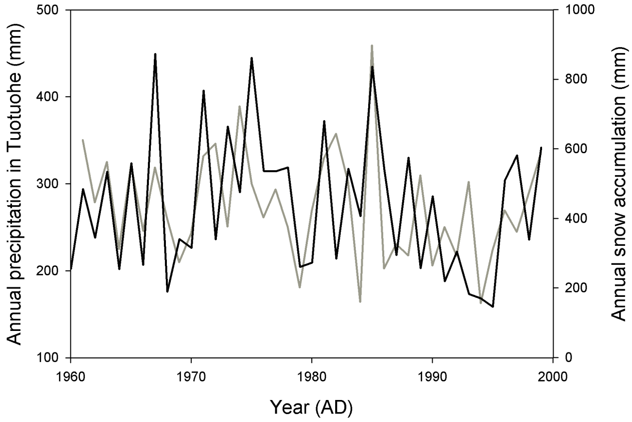

Fig. 5. Year-by-year comparison of Puruogangri ice core accumulations (black line) and Tuotuohe station instrumental precipitation records (grey line).

of the precipitation. Theoretically, old meteoric water can be securely stored in the form of snow accumulated on the cold and flat ice surface. Ice cores therefore provide more direct records of precipitation than do tree rings or lake sediment cores, and can be more simply interpreted. But in fact, taking local geomorphology and wind scouring into consideration, snow accumulation recovered from ice cores does not equate accurately with precipitation. Rather, it can only be regarded as a good approximation. Recent studies of alpine glaciers suggest a 67% accuracy of ice core recovered snow accumulation to original precipitation (Hardy, 2003).

In Fig. 5 we compare the precipitation record measured at the TMS with the reconstructed snow accumulation from the Puruogangri core for the period from 1961–1999. The comparison clearly shows that a positive correlation exists between the two records (r^2=0.45 at a 95% confidence level). The mean annual precipitation recorded at Tuotuohe during 1965–2000 was 274 mm, while the mean annual accumulation recovered from Puruogangri ice core was 440 mm. To understand the extra snow accumulation on the ice field, we note that relative humidity within the 400 hPa range on the Tibetan Plateau increases with elevation before decreasing (Yao et al., 1995), and Puruogangri Ice Field is about 1700 m higher than the TMS.

Because of the long time series, we applied a 31-year running mean to the reconstructed annual accumulation in the Puruogangri core for the past 400 years, indicating distinct precipitation fluctuations with remarkable wet and dry periods. In general, the central Tibetan Plateau experienced two high precipitation periods in the past 400 years, 1580 to 1777 and 1912 to 1999, and one low precipitation period, 1777 to 1912. Between 1640 and 1690 precipitation was as high as 460 mm, the wettest of the wet period. The entire 19th century was relatively dry, with a mean of only 299 mm of precipitation.

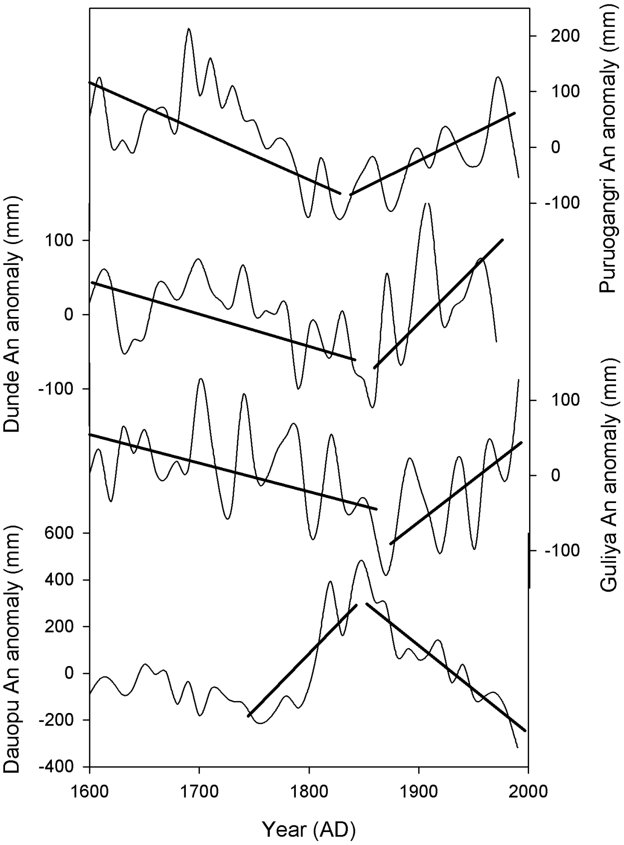

Fig. 6. Decadal changes of precipitation based on glacial accumulation reconstructed from Puruogangri ice core, Dunde ice core, Guliya ice core and Dasuopu ice core. The thick lines are linear trends of accumulation in different periods.

3 Discussions

On the northern Tibetan Plateau, several precipitation reconstructions have been made using different proxies. Among them, Yao et al. (1996) collected and interpreted data recorded in the Guliya ice core; Yao et al. (1990) presented a similar analysis of the Dunde ice core; and Shao et al. (2004) reconstructed precipitation data from tree rings at Delingha in Qinghai Province. Comparisons among recorded snow accumulations from the Guliya, Dunde and Puruogangri ice cores show consistent variations in precipitation along the west-east transect of the northern Tibetan Plateau (Fig. 6). Specifically, all three sites experienced high precipitation periods from the mid-17th century to the end of the 18th century, a low precipitation period from the end of the 18th century to the early 20th century, and another period of high precipitation since the early 20th century. Studies (Yao et al., 1995, 1991) have indicated that the high precipitation period in the 18th century on the northern Tibetan Plateau coincided with a relatively warm period of the past 500 years. Moreover, the low precipitation period in the 19th century coincided with a cold period on the Tibetan Plateau (Yao et al., 1995, 1991). The region experienced high precipitation throughout the entire 20th century, similar to that in the 18th century, during a time of gradual global warming. This positive correlation between temperature and precipitation contrasts with snow accumulation record from the Dasuopu ice core on the southern Plateau. The Dasuopu ice core shows the Himalayan region to have been warm with low precipitation in the 18th century, cold with high precipitation in the 19th century, and warm with low precipitation again in the 20th century (Yao et al., 2000). These opposite trends in precipitation in the north versus the south on the centennial time scale conform to the inverted phase of N-S precipitation on the Plateau revealed in meteorological data (Nitta et al., 1996; Liu et al., 1999). This probably relates to westerly anomalies in mid-low latitudes caused by the North Atlantic Oscillation (NAO), inducing accompanying strengthening or weakening of the N-S trough over the Plateau by changing the westerly circulation dynamics of the region (Liu et al., 1999). The Dunde ice core (Davis et al., 2005) indicates that land surface processes determine the Dunde precipitation on annual and centennial time scales; though on the decadal scale, sea surface temperature strongly affects precipitation recorded on the ice core. Hence, regional convective processes affect precipitation in the central Tibetan Plateau, whereas ocean processes dominate the long-term trend of precipitation on the southern Plateau, as was shown by the temperature and humidity recorded in the Dasuopu ice core (Duan et al., 2001).

The past century is considered as the warmest one in the past millennium, which gives rise to worries that temperature rise might surpass the range of natural variations, which could induce even more serious precipitation changes. Warming could lead to increased snow ablation (reducing accumulated snow) and permafrost thawing, which would then change the geomorphology and the regional climate at large. Oerlemans et al. (1992) estimates that global warming will cause alpine glaciers to lose 1/3 or even 1/2 of their total mass in the next 100 years, and that 1/4 of glaciers could melt away by 2050. Under the condition that warming continues and precipitation decreases, Kotlyakov et al. (1991) assessed the trends of glacial retreat in central Asia, and found intensification of snow ablation and glacier retreat. Undeniably, climate has been continuously warming in the past centuries. Furthermore, changes in precipitation play a very significant role in accurately evaluating and forecasting glacier variations on the Plateau. The retreat of the Puruogangri Ice Field has been continuing since the Little Ice Age (Pu et al., 2002). However, the amount of precipitation on the Ice Field since 1600 showed no decrease, suggesting that temperature rise may be the main driving force for the present glacier retreat in this area.

4 Conclusions

Studies of the Puruogangri Ice Field, the largest on the Tibetan Plateau, advance our understanding of glacial and climatic variations of the region. With the deep ice core drilled on the Ice Field in 2000, this study reconstructed precipitation on the central Tibetan Plateau since AD 1600, and found the 18th century to have been a high precipitation period, the 19th century a low precipitation period, and the 20th century a high one again. These ice core recorded precipitation data are consistent with those from the Dunde and Guliya ice cores. However, records from the Dasuopu ice core in the Himalayas provide opposite correlations, reflecting a phase reversal from north to south of these precipitation relationships.

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