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Ice core precipitation record in central Tibetan plateau since AD 1600

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Abstract

Lack of reliable long-term precipitation record from northern Tibetan Plateau has constrained the understanding of precipitation variation in this region. An ice core drilled from the Puruogangri Ice Field on central Tibetan Plateau in the year 2000 helped reveal the precipitation variations since AD 1600. Analysis of the annual accumulation data presented precipitation changes from AD 1600, indicative of wet and dry periods in the past 400 year in the central Tibetan Plateau. Accordingly, the 18th and 20th centuries experienced high precipitation period, whilst the 19th century experienced low precipitation period. Such a feature was consistent with precipitation recorded in ice cores from Dunde and Guliya Glaciers, northern Tibetan Plateau. Besides, the results also pointed to consistency in precipitation-temperature correlation on the northern Tibetan Plateau, in a way that temperature and precipitation were positively correlated. But this feature was contrary to the relationship revealed from Dasuopu ice cores, southern Tibetan Plateau, where temperature and precipitation were negatively correlated. The north-south contrast in precipitation amount and its relationship with temperature may shed light on the reconstruction of Asian monsoon since AD 1600.

1 Introduction

Palaeoclimate has been reconstructed in the study of global change, to understand climate system in the past, to assess current climate thereupon and hence forecast future climate changes. Both temperature and precipitation are important factors in climate system. Yet in such regions as mid-low latitudes where ecology and water resources are vulnerable to climate changes, variation of precipitation may exert bigger influence on local climate and environment. In comparison with temperature, however, precipitation data was far lacking in climate modeling (Hulme, 1994) or forecasting of future climate (Hulme et al., 1999b). To acquire reliable precipitation data of the past is thus imperative. The problem, however, is that precipitation shows wider range

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of variation than temperature spatially, as more factors are attached to precipitation, indicating more difficulties in acquiring precipitation record.

Palaeoclimatology on the Tibetan Plateau has been conducted using ice core record, tree ring nucleus and limnology cores (Thompson et al., 1986, 1998; Yao et al., 1996, 1999; Duan et al., 2002; Shao et al., 2004; Zhang et al., 2004). Precipitation record recovered from proxies as tree ring nucleus and stalagmite is high in resolution, yet due to the complex process for meteoric water stored therein to translate into scientific record, a proportion of raw data got inevitably lost. For example, precipitation series have been established through analysis of tree rings (Shao et al., 2004; Sheppard et al., 2004; Achim et al., 2004) drilled from low-elevated regions on the bordering regions of the Plateau. Given the arboreal physiological processes, they failed to demonstrate the long-term trend in precipitation variation. In comparison, precipitation record recovered from ice cores is more direct and reliable, as glaciers are formed by layering accumulation of precipitation in the form of snow or ice, thus retaining the past atmospheric precipitation in a rather stable state. Due to snow ablation, wind scouring, and snow evaporation, however, not all glaciers truly record past precipitation. The error thus caused by snow accumulation and factual precipitation is neglectable as is trivial enough to have little effect on glacier recorded snow accumulation and precipitation change.

Given the limited spatial and temporal range of precipitation, regional feature represented by single meteoro-station precipitation record was far less significant than that by temperature record. More data about precipitation were therefore necessary for a holistic understanding of the precipitation over the Tibetan Plateau. On the other hand, meteoro-stations on the northern Tibetan Plateau were of limited number, with recorded time scale less than 50 years. The importance of ice cores as natural precipitation recorder was highlighted, as snow accumulation thus shed light on the features of precipitation occurrence on the region.

In the past two decades, ice cores have been drilled consecutively in Dasuopu of the Himalayas, Guliya of Mt. Kunlun and Dunde of Mt. Qilian, and ice accumulation record has been recovered to represent regional precipitation (Yao et al., 1990, 1996; Duan et al., 2002). But these ice cores mainly locate in the margins of the Tibetan Plateau, leaving the central Tibetan Plateau as a blind point in terms of glacial and climatic change study.

In 2000 and then 2002, an ice core drilling project was carried out on the Puruogangri Ice Field (89°00′–89°20′ E, 33°44′–34°03′ N, 5620–5860 m a.s.l.; Fig. 1) in the central Tibetan Plateau, which consisted of several ice caps with a total area of 423 km^2 and ice storage of 52.52 km^3 (Yao, 2000). Research found that it had retreated nearly 70 m since Little Ice Age (LIA), loosing an area of 24.2 km^2 (Pu et al., 2002), and presenting a unique combination of lakes, ice dunes and the Gobi desert around the glaciers (Yao, 2000). This paper would be engaged in the analysis of Puruogangri ice core by presenting its precipitation record since AD 1600.

2 Data and methods

Analysis of nearly 50-year precipitation record in the Tuotuohe Meterological Station (TMS, 92°26 E, 34°13′ N, 4533 m a.s.l.), a nearby station to Puruogangri, revealed the central Tibetan Plateau as a semi-arid region, with temperature of −16.67° as the January mean temperature and 7.46° as the July mean. Its annual precipitation was 273 mm, with the precipitation in the summer half (May–September) year accounting for 92.2% of the total. There was only about 10-m precipitation from November to April the next year, indicating winter in the central Tibetan Plateau as extremely cold and arid. Mean temperature observed at the Puruogangri drilling site from 3 to 27 October 2000 was −14.7°. Yet from the TMS record, the annual mean temperature at the top of the Ice Field was −14.8° based on the lapse rate. Hence, mean temperature of the Puruogangri in Jan was −27.3°, and that in July was −4.1°, both too low to introduce intense snow melting.

Three ice cores were drilled on the 6000 m-elevated site, respectively measuring 118.6 m, 152 m, and 214.7 m in length. This paper would present our results based on the analysis of the ∼214 m-long ice core.

Precipitation reconstruction is based on glacial accumulation calculation. Snow falling on the Puruogangri Ice Field got accumulated annually, presenting a layering structure of annual precipitation record. The ice core was described in detail immediately after it got extracted from the glacier. All dust layers were visible and thus noted down. Like that in the Dunde Glacier, the dust was also brought from the Mid-Asia depression by the Westerlies during the transition of winter and early next spring (Husar et al., 2001; Gao et al., 1992). Precipitation record at the TMS indicated summer as a wet season with most of the precipitation events, whilst transitional period of winter and early next spring as an arid one. Accordingly, dust layers were obvious between two clear ice layers formulated from summer snowfall, and could thus help point out the annual snow accumulation. In the Puruogangri ice core, annual dust layers coincided with the presence of micro-particle peaks. Ice core recorded oxygen isotopes also showed clear seasonal oscillations, indicative of annual snow accumulation. Hence dust layers can help identify the time series of the cores.

In addition, there was another reference layer for ice core dating, which is the β peak produced by thermo-nuclear explosion in the former Soviet Union in 1961. Test result thereupon was consistent with the 1963 layer from dust layer counting, confirming the accuracy of ice core dating with dust layers, as well as the reliability of ice core time series established thereupon. Dust layer counting led exactly to AD 1600 by the top 104 m, with annual layer as 27 cm in depth and dating error as ∼10 yr.

Due to slow ice flow and considerable annual snowfall on the Puruogangri Ice Field, dust layers in the ice core were clear, and dating errors by dust-layer-counting were trivial. The length between the first year and the consecutive one thus indicated the second layer thickness. Analogically, the annual layer thickness of the top 107 m was obtained. Admittedly, however, they can't, given new snow compression and ice flow, truly reflect snow amount originally falling on the ice surface. As has been indicated by the material continuity equation that, glacier flow speed was vertically proportional to annual snow accumulation (snow layer thickness), and can be deduced from annual layer thickness with depth. Accordingly, factual snow layer thickness on the ice surface, i.e. annual snow accumulation, can be retrieved. Combined with the ice density, the annual snow layer thickness can be translated into annual net accumulation (Bolzan, 1985; Reeh et al., 1988; Gao et al., 1992; Yao, 2000; Husar et al., 2001; Li et al., 2002; Pu et al., 2002; Achim, 2004).

Alpine glaciers over the Tibetan Plateau penetrate into the free atmosphere, resulting in precipitation record representative of precipitation spatial distribution. Theoretically, meteoric water in the past can be securely stored in the form of snow accumulation on the cold and flat ice surface. Precipitation recovered from ice cores was therefore more direct than that from tree rings or limnology sediment cores, and simpler for the explanation of ice core accumulation. But in fact, taking local geomorphology and wind scouring into consideration, snow accumulation recovered from ice cores does not equate with factual precipitation. Rather, it can only be regarded as a good approximation. Recent study of alpine glacier suggested 67% accuracy of ice core recovered snow accumulation to factual precipitation (Hardy, 2003). Regarding the Puruogangri ice core, however, accumulation loss by evaporation and wind scouring was neglectable given the extremely low temperature and gentle surface on the ice field top. Thus the error between reconstructed annual accumulation from Puruogangri ice core and factual precipitation was no more than 10%, and the error in the 10-yr mean was no more than 5%.

Tuotuohe Meteorological Station (TMS) meteorological record witnessed the consistency between 1956–2000 snow accumulation on the ice field and precipitation in the Tuotuohe region (Fig. 2). The correlation coefficient between these yearly records reached 0.45 with 95% confidence level. If calculated for 5-year running average, both records present as high a correlation coefficient as 0.76 with 99% confidence level. The mean precipitation recorded at TMS in 1965–2000 was 274 mm annually, whilst the mean annual accumulation recovered from Puruogangri ice core was 440 mm. To understand the extra snow accumulation on the ice field, it should be noted that, relative humidity within the 400 hPa range on the Tibetan Plateau increased with rising elevation before decreasing (Yao et al., 1995), and Puruogangri Ice Field was about 1700 m higher than the TMS in elevation.

Trend analysis of precipitation change on the Puruogangri ice field in the past 400 years (Fig. 3) found evident fluctuations with remarkable wet and dry periods. To further verify the precipitation changes, we applied Cramer's test to assess snow accumulation at a 31-year running mean. The statistics (t) reflected the comparison between the 31-year running mean and the whole serial mean. If t value turned out to be positive, precipitation was considered to be high. If it was negative, on the other hand, precipitation was low (Fig. 3a). In general, the central Tibetan Plateau experienced two high precipitation periods in the past 400 years, respectively in 1580–1777 and 1912–1999, and one low precipitation period in 1777–1912. Precipitation in 1640–1690, in particular, was as high as 460 mm, capping the wettest period; whilst precipitation in the entire 19th century was the lowest with 299 mm in mean.

3 Discussions

On the northern Tibetan Plateau, a number of precipitation series have been retrieved using different proxies. Among them, there are accumulation data recorded in the Guliya ice core (Yao et al., 1996) and the Dunde ice core (Yao et al., 1990), as well as Delingha precipitation data reconstructed from tree rings in Qinghai (Shao et al., 2004). Comparison among the Guliya, Dunde and Puruogangri ice cores recorded snow accumulation showed consistency in precipitation variation along the west-east transect on the northern Tibetan Plateau (Fig. 4). Specifically, all experienced high precipitation period from the mid-17th century to the end-18th century, the low one from the end-18th century to the early-20th century, and a high one again 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 in 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).

In the entire 20th century, again, the region experienced a high precipitation period as that in the 18th century, under the milieu of global warming. Such positive correlation between temperature and precipitation is opposite to snow accumulation revealed in Dasuopu ice core on the southern Plateau. As has been shown in the Dasuopu ice core, however, the Himalayan region was 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). Such a N-S contrary variation feature of precipitation in the centennial time scale was consistent with the inverted phase of N-S precipitation on the Plateau revealed in meteorological data (Nitta et al., 1996; Liu et al., 1999). This is probably associated with westerly anomalies in mid-low latitudes caused by NAO, inducing concomitant strengthening or weakening of the N-S trough over the Tibetan Plateau by changing the westerly circulation dynamics on the Plateau (Liu et al., 1999). The Dunde ice core (Davis et al., 2005) has indicated the land surface process as determining Dunde precipitation on annual and centennial time scale; though on the decadal scale, SST strongly affected the ice core recorded precipitation. Hence, the precipitation in the central Tibetan Plateau is featured by regional convective process, whilst the long-term trend of precipitation on the southern Tibetan Plateau is dominated by the ocean process, 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, witnessing such worries that temperature rise would surpass natural variation scale, or even more serious in the way that it would induce precipitation change. Regarding accumulated snow and permafrost, warming could lead to snow ablation and permafrost thawing, which would in turn change the geomorphology and the regional climate at large. With global warming, alpine glaciers are estimated to lose 1/3 or even 1/2 of their total in the future 100 years, and 1/4 of glacier would be melted away by 2050 (Orelemans et al., 1992). Under the condition that warming continues and precipitation decreases, Kotlyakov et al. (1991) assessed the glacial retreat trend in central Asia, and found intensification in snow ablation and glacier retreat. Undeniably, climate has been continuously warming in the past centuries. Yet to accurately evaluate and forecast glacier variation on the Plateau region, change in precipitation is of significant importance. Puruogangri Ice Field retreating has been continuing since the LIA. However, precipitation amount since AD 1600 on the Ice Field showed no decreasing (Fig. 3), suggesting temperature rise as the main driving force for glacier retreat present there.

4 Conclusions

Puruogangri Ice Field, the largest in the Tibetan Plateau, helps in understanding glacier and climate variation of the region. With the deep ice core drilled on the ice field in 2000, precipitation in the central Tibetan Plateau since AD 1600 was reconstructed, presenting the 18th century as a high precipitation period, the 19th a low precipitation period and the 20th a high one again. Such ice core recorded precipitation data is consistent with those in Dunde and Guliya ice cores, yet contrary to that in the Dasuopu ice core in the Himalayas, reflecting a N-S inverted phase of precipitation variation. In summary, precipitation is positively correlated with temperature on the northern Tibetan Plateau, whilst negatively correlated with temperature on the southern Tibetan Plateau.

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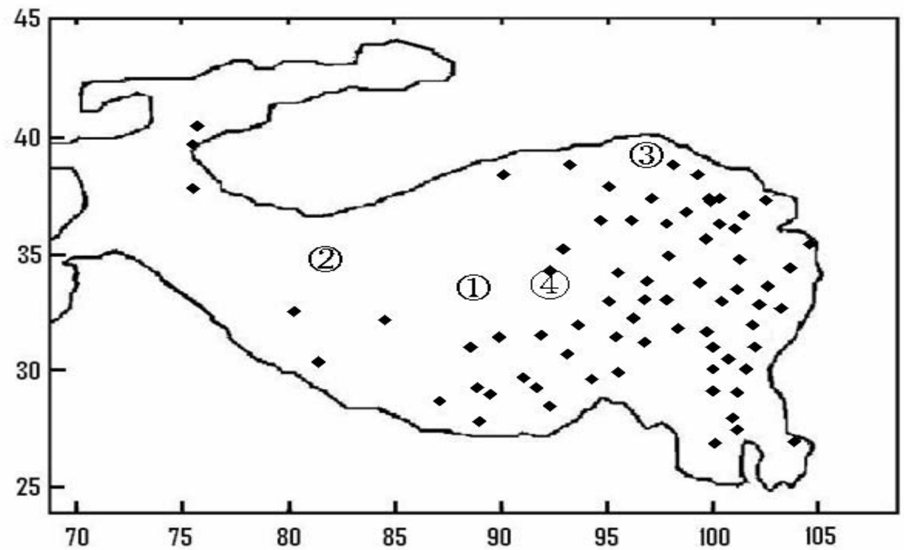

Fig. 1. Distribution of the ice coring sites on the Tibetan Plateau. Dots indicate meteoro-stations around the Plateau; numbers are the sites of the ice cores discussed in the paper.

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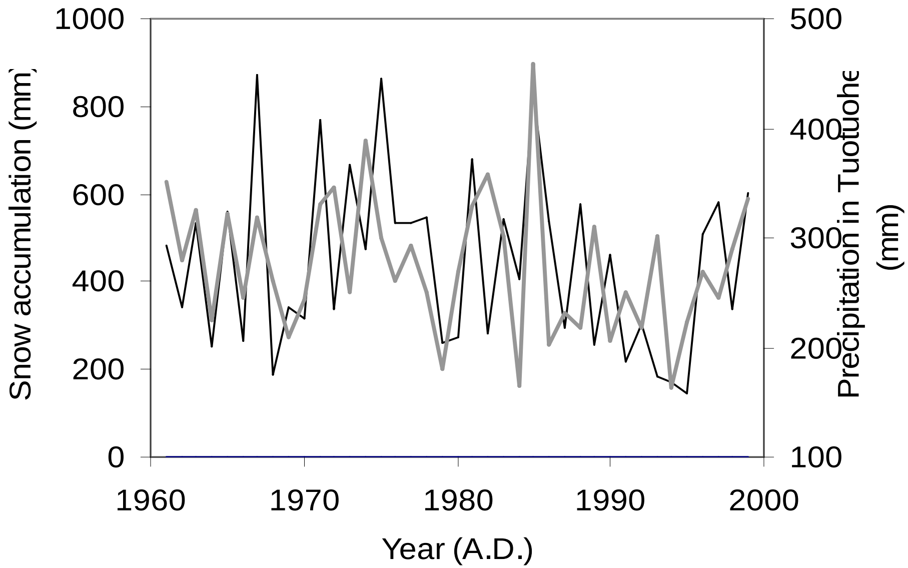

Fig. 2. Yearly comparison between Puruogangri ice core accumulation (black line) and TMS precipitation record (grey line).

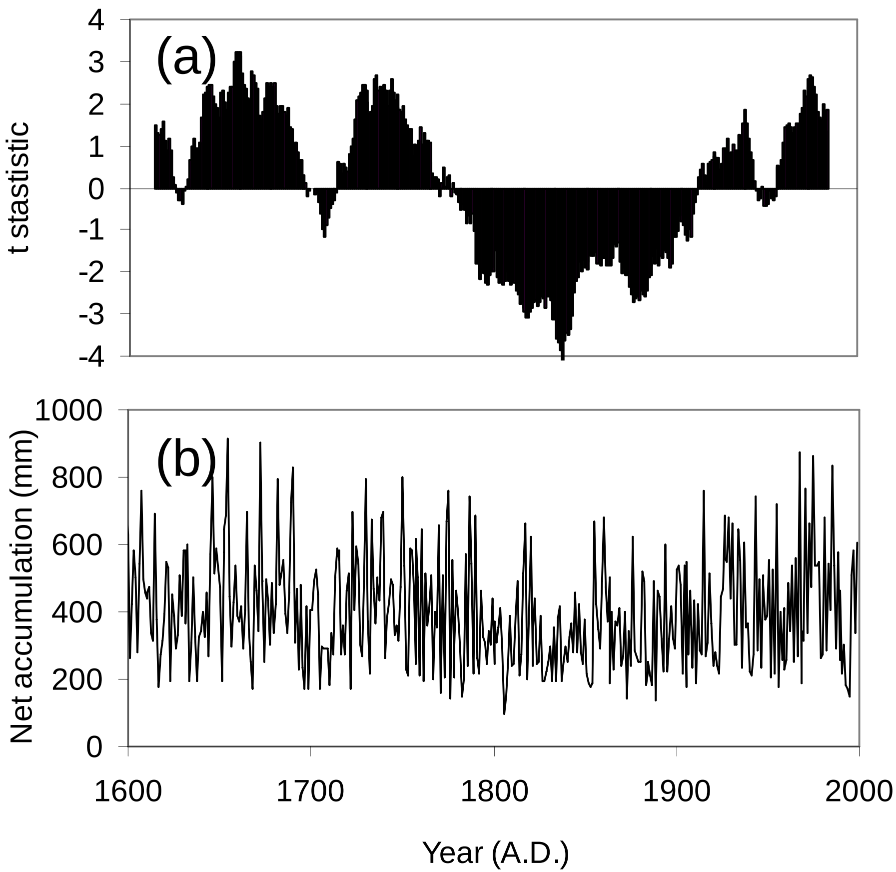

Fig. 3. **(a)** Cramer's test verification, *t* indicates relationship between 31-year running mean and the whole serial mean; **(b)** Puruogangri ice core yearly accumulation record since AD 1600.

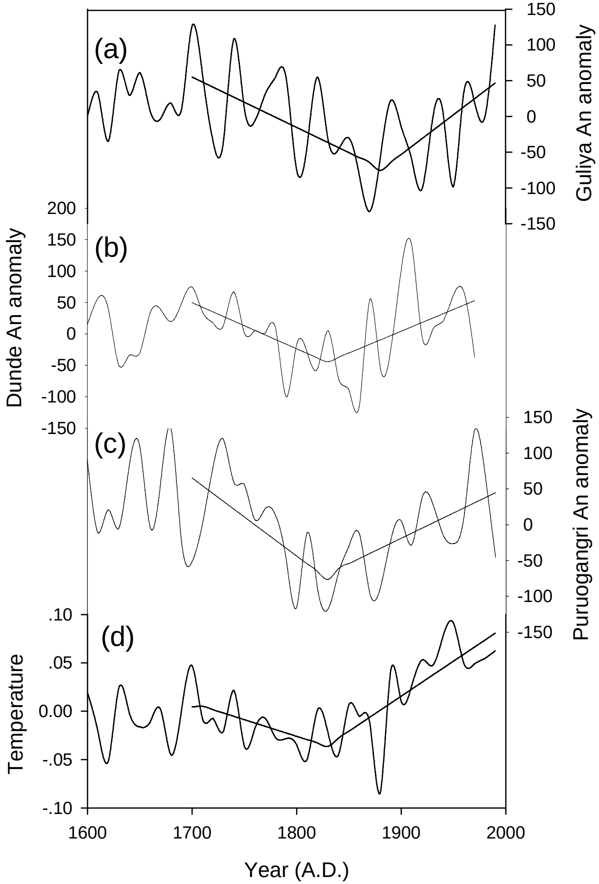

Fig. 4. Decadal changes of precipitation based on glacial accumulation reconstructed from Guliya ice core **(a)**, Dunde ice core **(b)**, and Puruogangri ice core **(c)**. The decadal temperature reconstructed by the composition of δ^{18}O from Puruogangri, Guliya and Dunde ice core **(d)**. The thick lines are linear trends of precipitation and temperature reconstructions.