Correlation between precipitation and temperature variations in the past 300 years recorded in Guliya ice core, China

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ABSTRACT. The Guliya ice cap, on the crest of the Kunlun Shan, central Asia, is an ideal site for acquiring ice cores for climate-change studies. Detailed analyses of the precipitation index (glacier accumulation) and the temperature proxy ($\delta^{18}O$) recorded in the Guliya ice core since 300 years BP show that precipitation correlates with temperature in this region. Climate conditions in the Guliya region since 300 years BP can be separated into three periods: warm and wet from AD 1690 to the end of the 18th century; cold and dry from the 19th century to the 1930s; and warm and wet again since the 1940s. During this period, the climate exhibits just two phases: warm/wet and cold/dry. Comparison of the temperatures and the precipitation recorded in the Guliya ice core shows that variations of temperature and precipitation in the region correlate quite well. However, changes in the precipitation regime appear to lag behind those of the temperature by 20–40 years. We believe this results from the larger heat capacity of the ocean relative to that of the land. Hence, ocean temperatures and corresponding evaporation rates change more slowly than do continental conditions. Additionally, however, positive feedback processes, such as increasing temperatures and precipitation improving vegetation, moisture retention and, hence, local convective precipitation probably play an important role. In this paper, we explain how the timescale of evolving vegetation and the feedback mechanism between precipitation and the temperature could help explain why the changes in precipitation lag those of temperature by 20–40 years over long periods. Taking this time lag into account, we should be able to predict future precipitation trends, based on observed temperature trends.

1. INTRODUCTION

Ice cores play an important role in paleoclimate studies, being unparalleled in resolution and types of climate and environmental information that can be extracted (Dansgaard, 1997; Kreutz and others, 1997; Thompson and others, 1998, 2000; Fischer and others, 1999; Petit and others, 1999). Because the Tibetan Plateau is sensitive to climate changes (Yao and others, 1995b; Feng and others, 1998; Liu and Chen, 2000; Gou and others, 2006), ice-core studies there are particularly important for examining past climate and environment changes.

The Guliya ice cap, west Kunlun Shan, Qinghai–Tibetan Plateau, is the deepest polar-type ice cap in central Asia, with an area of 376 km^2 (Yao and others, 1997). Three ice cores with respective lengths of 308.7, 93.2 and 34.5 m were successfully taken at 6200–6700 m a.s.l. on the ice cap (35°17′ N, 81°29′ E) (Thompson and others, 1995; Yao and others, 1995a) and the longest one reached the bedrock. The 308.7 m ice core at 6200 m a.s.l. was drilled (Fig. 1) using an electromechanical drill in a dry borehole to 200 m and a thermal drill with an alcohol–water mixture from 200 m to bedrock (308.6 m). The ice temperatures in the borehole are –15.6°C, –5.9°C and –2.1°C, corresponding to depths of 10 m, 200 m and the bottom, respectively. The core contained no hiatus, and the visible horizontal layers were evident throughout the core. Measurements of mass balance in 1990 and 1991 indicate that the ice cap receives ~200 mm w.e. a^{-1} of accumulation (Thompson and others, 1997; Yao and others, 1997). Thompson and others (1995, 1997) and Yao and others (1996) described in detail the field and laboratory methods used in climatic and environmental studies of the Guliya ice core. Numerous papers have described the Guliya ice core and the information extracted from it (e.g. Yao and others, 1994a, 1995a, 1996; Thompson and others, 1995, 1997; Yang and others, 2000, 2006a,c). This paper examines the relationship between temperature and precipitation over the past 300 years, based on the upper part of the 308.7 m length ice-core record, and suggests mechanisms that could explain the observed relationship.

2. RELATIONSHIP BETWEEN TEMPERATURE AND PRECIPITATION RECORDED IN THE GULIYA ICE CORE

Much work on the Qinghai–Tibetan Plateau has proved that there is a positive relationship between $\delta^{18}O$ and temperature (Yao and others, 1995a, b, 1996). Variation of $\delta^{18}O$ values in the Guliya ice core has been used as a proxy for historical temperature changes over the Qinghai–Tibetan Plateau. Net snow accumulation reflects total precipitation onto the ice cap and can be measured in the Guliya ice core. The core site lies high in the accumulation area of the

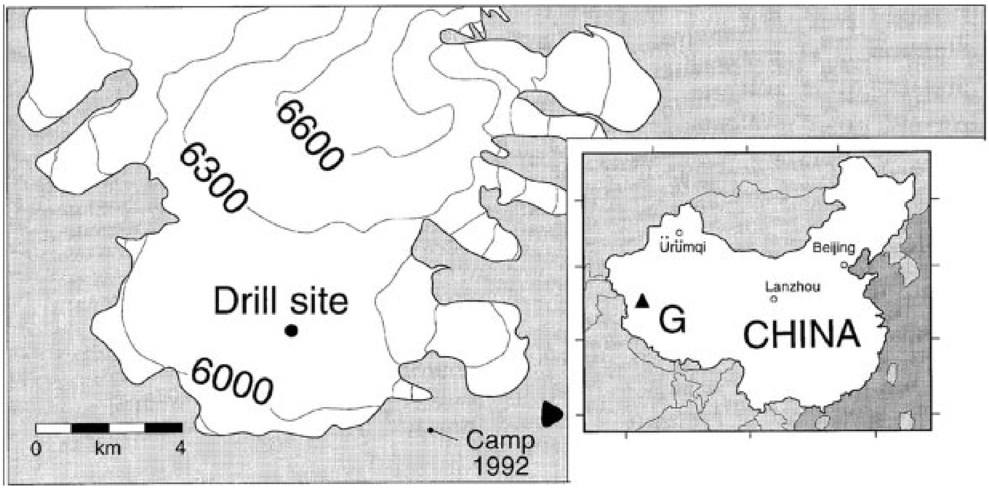

Fig. 1. The location of the Guliya (G) ice cap and the site where the 308.6 m Guliya ice core was drilled. Drill site elevation 6200 m a.s.l. (after Thompson and others, 1997).

glacier. For most glaciers, snow and ice thicknesses measured well into the accumulation zone closely mirror actual total precipitation. Because little snow melts high on the Guliya ice cap, we use the net accumulation as the total precipitation (Yao and others, 1996). The accumulation on Guliya ice cap was measured by means of (1) accumulation stakes, (2) visible stratigraphy in pits and (3) insoluble particulate beta and tritium horizons (Thompson and others, 1995). The precipitation on Guliya ice core is estimated from the net accumulation. As shown by Yao and others (1996), net accumulation on this ice cap closely approximates actual precipitation.

Figure 2 shows the yearly δ^{18}O and net accumulation recorded in the Guliya ice core for the past 300 years. In order to examine the relationship between temperature and precipitation, Yang and others (2000) applied the cumulative anomaly method, plotting the running total of the yearly differences between each year's value and the long-term mean. This method clearly displays long-term trends. Applied to climatic time series, the cumulative anomaly indicates periods where negative anomalies predominate (downward slopes on the cumulative anomaly curve) and periods where positive anomalies predominate (upward slopes on the cumulative anomaly curve). Thus, cumulative anomaly curves indicate changing trends over time. The general slope of the cumulative anomaly, rather than its position relative to the zero, indicates the trend. Figure 3 shows the cumulative anomalies of δ^{18}O and net accumulation recorded in Guliya ice core from AD 1690 to 1991. Figure 3 demonstrates that over the period of this study the climate in the Guliya region exhibits only two dominant phases: warm when conditions are wet, and cold when conditions are dry. Since 300 years BP, the climate in the Guliya region can be separated into three periods: warm and wet from AD 1690 to the end of the 18th century; cold and dry from the 19th century to the 1930s; and warm and wet again from the 1940s to the present (Fig. 3).

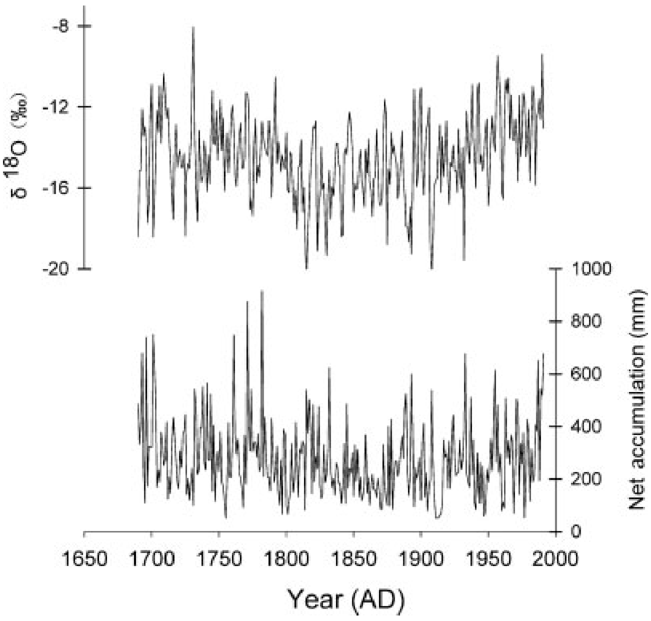

Fig. 2. Yearly δ^{18}O and net accumulation values recorded in the Guliya ice core for the past 300 years.

Adjusting for a lag time of about 30 years, Figure 3 also highlights the similarity in variation of the trends of cumulative anomalies between temperature and precipitation. The correlation coefficient reaches around 0.8 ($p < 0.001$) when the variation of the cumulative anomaly of the net accumulation lags behind that of the temperature by about 20–40 years. When we take into account the lag in precipitation relative to the temperature, even small fluctuations in the secular changes appear to be very consistent between temperature and precipitation. The cross-correlation analysis of the temperature and precipitation yields the highest correlation coefficient ($R = 0.97$, $p < 0.001$) when precipitation lags by 28 years.

Our study also used the 11 year moving average of the temperature and precipitation to illustrate the relationship between temperature and precipitation (Fig. 4), and we calculated the lag correlation coefficients for the 11 year averages (Fig. 5). Figure 5 again shows the best correlation when the precipitation lags behind temperature by about 20–40 years. The highest correlation coefficient was attained ($R = 0.57$, $p < 0.001$) when precipitation lagged temperature by 29 years.

These data pose the question why temperature and precipitation should be correlated in this manner. In other

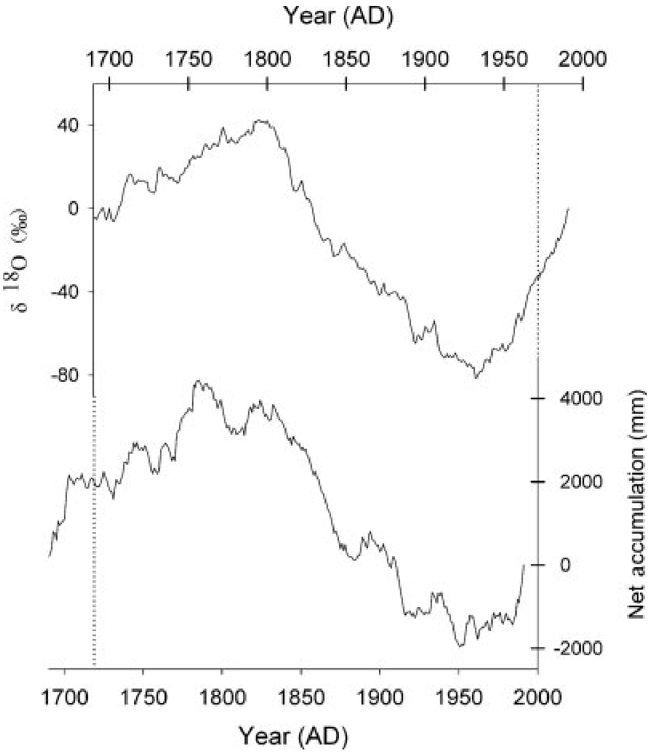

Fig. 3. The cumulative anomalies (the running total of deviations from the mean) of $\delta^{18}O$ and net accumulation recorded in the Guliya ice core during AD 1690–1991, displayed with displaced time axes (28 years) to illustrate the phase lag between similar oscillations.

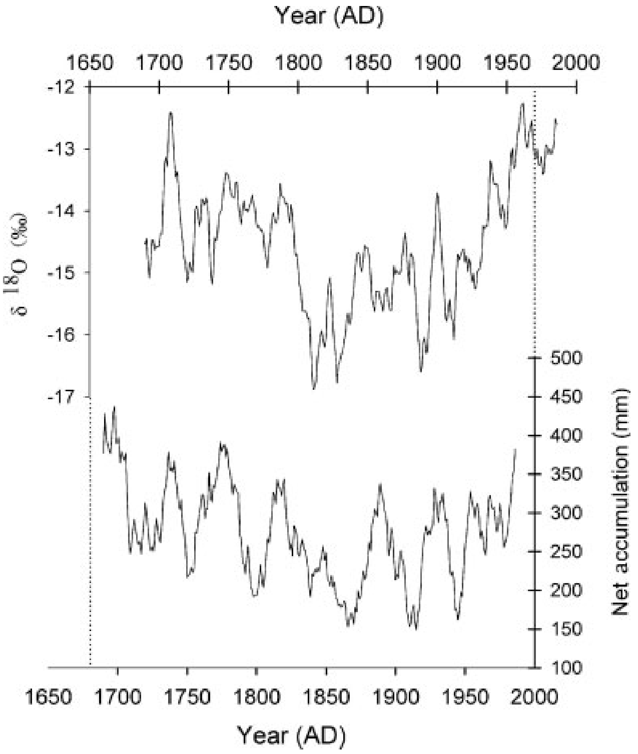

Fig. 4. The 11 year moving average of $\delta^{18}O$ and net accumulation recorded in the Guliya ice core over the past 300 years, displayed with displaced time axes (29 years) to illustrate the phase lag between similar oscillations.

words, why are variations of precipitation so sensitive to the temperature changes and what mechanisms can explain the 20–40 year time lag of precipitation behind temperature?

3. DISCUSSION

Yao and others (1996) considered various mechanisms involving evaporation and transport of moisture from the ocean to the plateau. They recognized that the lag effect between variations of precipitation and temperature could relate to the large specific heat of the ocean, preventing a rapid response to external heating or cooling. This effect causes ocean temperatures to lag changes in the air temperature. Because ocean evaporation intensity depends on the ocean temperature, and precipitation depends on evaporation (and transport), precipitation will also lag behind the temperature changes.

The monsoon provides a linkage. The Indian monsoon strength is related to the temperature difference between ocean surface and the Tibetan Plateau (Duan and others, 2002). When the climate warms, temperatures on the land and ocean surface increase and evaporation from the ocean surface strengthens. Transport of water vapor to the Tibetan Plateau intensifies, increasing precipitation over the plateau. When the climate cools, temperatures on the land and ocean surface decrease and evaporation from the ocean surface weakens. Water-vapor transport to the Tibetan Plateau diminishes and precipitation on the plateau decreases. Even for moisture from local convective clouds, climate warming increases precipitation because local convective activity intensifies, and climate cooling has the opposite effect (Yao and others, 1994b).

Additional factors may contribute to the lag of precipitation variations behind temperature changes. The following feedback processes should also be considered. When climate starts warming, the temperature on land will increase first, due to the difference in heat capacity between land and ocean. Because of its geographical position and sensitivity to climate change, Tibetan Plateau temperatures should increase particularly rapidly. Then the heat difference between land and ocean increases and the monsoon intensifies, which in turn intensifies water-vapor transport from ocean to the Tibetan Plateau. Previous studies (e.g. Yao and others, 1995a) have noted that moisture sources in the

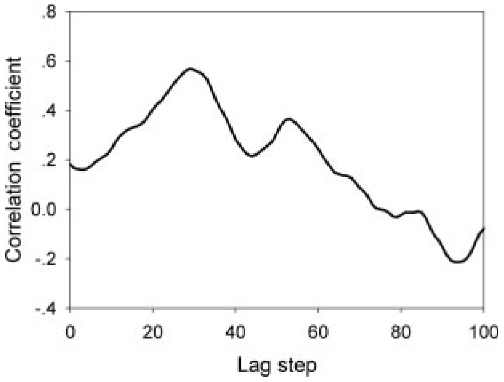

Fig. 5. The lag correlation coefficient between the net accumulation and the temperature. Data used for calculation are 11 year moving average from AD 1690 to 1990 (Fig. 4). Each lag step represents 1 year and the peak in the correlation coefficient (0.57) corresponding to the 29 year lag step.

Bay of Bengal, the Arabian Sea and local convective water vapor all influence precipitation on glaciers from the Guliya ice cap to the Tanggula mountains. These three moisture sources are closely related to the strength of the monsoon. When climate warms, precipitation on the Tibetan Plateau increases. As precipitation increases, the surface soil moisture also increases. The summertime climate on the Tibetan Plateau is relatively warm. Such warm/wet climate conditions benefit vegetation growth and water storage capacity, and decrease the runoff. Considering the water balance, enhanced land surface moisture along with high temperatures should increase evaporation and the local convective precipitation. In fact, because of the plateau's geographical position, local convective activities are very strong in summer and local convective precipitation occurs frequently. The local convection recycles water vapor from the ocean continuously, and thus local convective precipitation contributes a large percentage (46.86% at least in the central Tibetan Plateau) of the total precipitation (Yang and others, 2006b).

When the climate cools, temperatures on the plateau cool first (due to the difference in heat capacity between land and ocean), the heat difference between land and ocean decreases and the monsoon weakens. Moisture transport from the ocean decreases and the precipitation on the plateau decreases. This causes the surface moisture to decrease. When it is cold over the Tibetan Plateau, the cold/dry conditions cause the vegetation to diminish. The water storage capacity of the Tibetan Plateau declines and runoff increases. The water balance changes, with reduced surface moisture and lower temperatures decreasing evaporation and lowering the percentage of the local convective precipitation. Precipitation on the Tibetan Plateau then further decreases through this positive feedback process. The expansion or diminution of vegetation in response to changing temperature and precipitation conditions is not instantaneous and requires some time for the vegetative response. This response time, coupled with associated temperature and precipitation processes, may contribute to lag of precipitation behind temperature by 20–40 years.

4. CONCLUSIONS

The Guliya ice cap is an ideal site for acquiring ice cores for climate-change studies. The analysis of net accumulation and temperature proxy ($\delta^{18}O$) data covering the past 300 years archived in Guliya ice cores shows that precipitation correlates well with temperature. Over a long time period, positive precipitation anomalies correspond to positive temperature anomalies, and vice versa. However, changes in the precipitation regime lag behind changes in temperature by about 20–40 years. Likely reasons for this lag include differences between the specific heat of the oceans and the land, but other mechanisms also appear to be involved. A lag in the precipitation response following changes in temperature may arise from the slow warming of the ocean surface and its effect on evaporation. However, at the same time a slow vegetation response to temperature and precipitation affects retention of soil moisture, which in turn feeds back by affecting precipitation. Because variations in temperature precede those of precipitation, future trends in precipitation might be predictable based on current observations of variations of temperature trends.

ACKNOWLEDGEMENTS

We thank the two referees for valuable and constructive criticism. This research was jointly supported by the National Key Basic Research Program (2005CB422000), the Chinese National Science Foundation (40201012, 40571036), the National Natural Science Foundation of China (NSFC) Innovation Team Project (40121101), the Century Program of the Chinese Academy of Sciences (2004401), the Chinese Postdoctoral Science Foundation (20040350410), and the Talent Program of the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences.

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