Monsoon Variability in the Himalayas under the Condition of Global Warming

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Abstract

An ice core-drilling program was carried out at the accumulation area of Dasuopu glacier (28°23'N, 85°43'E, 7100 m a.s.l.) in the central Himalayas in 1997. The ice core was analyzed continuously for stable isotopes ($\delta^{18}\text{O}$), and major ions throughout the core. Cycles indicated by $\delta^{18}\text{O}$, cations were identified and counted as seasonal fluctuations as annual increment from maximum to maximum values. Reconstructed 300-year annual net accumulation (water equivalent) from the core, with a good correlation to Indian monsoon, reflects a major precipitation trend in the central Himalayas. The accumulation trend, separated from the time series, shows a strong negative correlation to Northern Hemisphere temperature. Generally, as northern hemisphere temperature increases 0.1°C, the accumulation decreases about 80 mm, reflecting monsoon rainfall in the central Himalayas has decreased over the past decades in the condition of global warming.

1. Introduction

Agriculture, industry and hydroelectric power in south Asia are heavily dependent on the performance of the summer (June to September) monsoon rainfall, which provides 75 to 90 per cent of the annual rainwater over most parts of the area. A weak monsoon year generally corresponds to low crop yields. And strong monsoon usually produces abundant crops, although too much rainfall may produce devastating floods. However, modeling efforts to

forecast the monsoon have been made with only moderate success (Webster and others 1998). A long series of reliable data for large contiguous spatial domains is not available except for India, which limits our ability to determine the rainfall patterns in the monsoon regions. Previously published results suggest that variation of south Asian monsoon is closely linked to the greater heat capacity of the ocean relative to the surrounding landmasses (Fu and Fletcher 1985; Li and Yanai 1996). On short time scales, variations in the strength of the South Asian monsoon have been explained by changes in internal boundary conditions, such as increasing tropical sea surface temperatures (Tourre and White 1995), variations in Eurasian snow cover (Sirocko et al. 1993; Barnett et al. 1988;

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Hahn and Shukla 1976; Dickson et al. 1984), and linkages with the El Niño-Southern Oscillation (ENSO) (Charles et al. 1997; Webster et al. 1998; Cole et al. 2000).

Some studies show that the Himalayas and the Tibetan plateau play an important role in the evolution of the boreal summer monsoon (Ye 1981; Yanai and others 1992, 1994). Flohn (1957) suggested that the seasonal heating of the elevated surface of the Tibetan plateau, and the consequent reversal of the meridional temperature and pressure gradients, trigger the large-scale change of the general circulation over Asia and the monsoon burst over the Indian subcontinent. The strong (weak) monsoon years are associated with positive (negative) tropospheric temperature anomalies over Tibetan plateau (Fu and Fletcher 1985). However, analysis of how these relations vary, particularly on decadal and longer time scales, is hampered by the limited instrumental precipitation record in the Tibetan plateau, especially in the Himalayas, which rarely spans more than the past few decades. Therefore, it is significance to detect monsoon precipitation variability on secular time scales in the Himalayas in order to improve the understanding of monsoon variability. This data gap can be addressed with high-fidelity paleoclimate records from long-record ice cores recovered from carefully selected, high elevation glaciers in the Himalayas.

The Himalayas contain the largest glacier mass outside the polar region. On the high mountains in the Tibetan Plateau, snow accumulates year by year and glaciers form. So glaciers continuously record the chemical and physical nature of the Earth's atmosphere. Ice cores drilled from carefully selected sites often provide the records of the past climate change with seasonal, annual, decadal and centennial resolutions. Over the last two decades high-quality ice core records have been obtained from the Tibetan Plateau and records of accumulation and $\delta^{18}\text{O}$ in the cores have been demonstrated as good indexes for precipitation and temperature on the Plateau (Yao et al. 1991, 1992, 1997, 1999; Thompson et al. 1997). All these ice core records have shown local, regional and large-scale climate variations. Data from these cores have indicated a long perspective of the Tibetan Plateau's climate. These

Fig. 1. The location of the Dasuopu Glacier

also demonstrate considerable natural variability during the present climate epoch, including a number of climate extremes such as the so-called "Little Ice Age".

In this paper we present a 300-year proxy record of precipitation from the central Himalayas, Tibet, which allows us to examine the long-term precipitation variability in the Himalayas and its relationship with Northern Hemisphere temperature.

2. Sampling and analysis

Three ice cores were recovered by an electromechanical drill in the accumulation area of Dasuopu glacier ($28^{\circ}23'\text{N}$, $85^{\circ}43'\text{E}$) (Fig. 1), Himalayas, between August and October 1997. The first core (C1) was 159.9 m long, and was drilled at 7000 m above sea level (a.s.l.) down the flow line from the top of the col, and two cores (C2 and C3), 149.2 and 167.7 m long, respectively, were drilled to bedrock 100 m apart on the col at 7200 m a.s.l. Visible stratigraphy showed no hiatus features in any of the cores. The sites are influenced seasonally by summer monsoon and westerly winds, suggesting most of the annual precipitation on Dasuopu falls during the summer, and the greatest aerosol entrainment occurs from mid-February through late May (Thompson et al. 2000).

The C2 was brought (in a frozen state) to the Lanzhou Institute of Glaciology and Geocryology. C3 was brought (also frozen) to the Byrd Polar Research Center in America, and C1 was split between the two institutes. All cores were analyzed over their entire lengths for oxygen isotopic ratio ($\delta^{18}\text{O}$), chemical composition, and dust concentration. The results presented here are from C2, which was cut into

Fig. 2. Variations of $\delta^{18}\text{O}$ (black line) and Ca^{2+} (gray line) with depth in the Dasuopu ice core and ice core dating

4110 samples for $\delta^{18}\text{O}$ and major ions (Cl^- , SO_4^{2-} , NO_3^- , Na^+ , K^+ , Mg^{2+} , Ca^{2+}) analyses. Borehole temperatures were -14°C at 10 m depth and -13°C at the ice-bedrock contact, demonstrating that the Dasuopu glacier is frozen to its bed.

At the col of Dasuopu, the annual snowfall between 1996 and 1997 is as high as 2500 mm a^{-1} in snow thickness (1000 mm w.e. a^{-1}), as determined by snow pit and shallow core studies, and by the measurement of a 12-stake accumulation network established during a reconnaissance survey in July 1996. Meteorology observation had also been making at the core site (7100 m a.s.l.) while the cores had been drilling during August 15 to October 3 in 1997. The maximum temperature was below 0°C and no surface snow melting was detected during the observation period at the site. Therefore the annual net accumulation record in the Dasuopu ice core is expected to provide a well-dated precipitation history with high resolution in the Himalayas.

In the monsoon region the peaks of $\delta^{18}\text{O}$ and ions in the rainfall appear in the dry stage of spring (Wushiki 1977; Zhang 2001; Muradkani 1987; Luo and Yanai 1983). Thus the high annual accumulation allows preservation of distinct seasonal cycles in $\delta^{18}\text{O}$, and ions which make it possible to reconstruct an annual record for the upper part of the cores. Then the core is dated by counting annual peaks of $\delta^{18}\text{O}$ with reference of peaks of Ca^{2+} (Fig. 2). A time-depth relation for the cores was established using the well-preserved seasonal fluctuations of $\delta^{18}\text{O}$ and ion. The snow in one layer, (in Fig. 2 one layer is the thickness from one $\delta^{18}\text{O}$ peak to next $\delta^{18}\text{O}$ peak), falls in one year. It turned

out the depth of 114 m of the core extended back to 1700 A.D. for obvious annual variation. Below this horizon, annual layers are thinned and stretched as new snow accumulates continually and the ice flows outward from the center, which made annual resolution of the records impossible. The annual layer counting was verified at 35.5 m and 42.2 m by the location of a 1963 and 1953 beta radioactivity horizon produced by the 1962 and 1952 atmospheric thermonuclear tests (Picciotto and Wilgain 1963). Due to high accumulation, low temperature and strong seasonality, these time estimates carry little uncertainty. Although the thickness of an annual layer can be easily measured throughout the Dasuopu ice core by counting the gaps between two peaks of $\delta^{18}\text{O}$, the layer thickness do not directly represent the snowfall thickness originally deposited at the glacier surface. Because these layers are thinned and stretched as new snow accumulates and the ice flows outward from the center, the layer thickness must be rectified in order to recover original snowfall deposited on the glacier surface. The vertical velocity of the glacier is proportional to the accumulation rate and the vertical velocity can be easily obtained from the change in layer thickness (Bolzan 1985; Reeh 1988). Then the depth-age relation for the upper 114 m establishes an annually precise age model (Thompson and others 1982). Following the model, annual accumulation (water equivalent) of the core can be reconstructed (Fig. 3 and Fig. 4) by the relationship between accumulation and velocity (Bolzan 1985; Reeh 1988). Moreover, as mentioned above, the peaks of $\delta^{18}\text{O}$ and ions appear in the dry stage of spring (Wushiki 1977; Zhang 2001), so accumulation recovered in the core represents precipitation from spring to spring. Most of the annual precipitation on Dasuopu falls during the summer monsoon season (June through August), suggesting accumulation from spring to spring is almost equal to precipitation in the monsoon season.

3. Results and discussion

The 300-year accumulation record indicates fluctuations in the intensity of the South Asian Monsoon in the Himalayas that is interpreted as a good correlation between the record and precipitation in India (Sontakke et al. 1996),

Fig. 3. Five-year running means of accumulation (line 1) from the Dasuopu glacier are significantly correlated with Northeast India monsoon precipitation (line 2) since 1860

close to the Himalayas. Empirical orthogonal function (EOF) analysis was applied on the accumulation record and the summer (June through September) precipitation for all India, and for Indian regions (Sontakke et al. 1996) to identify the spatial feature difference between precipitation in the central Himalayas and in Indian regions (Duan et al. 2002a). The result showed in the EOF1 associations the accumulation of the Dasuopu ice core, and precipitation in northeast Indian are positively correlated, and anti-correlated with that in central India and all-India, reflecting the regional distribution of monsoon rainfall. A linear regression between accumulation in the Dasuopu ice core, and precipitation in northeast India, yields a correlation coefficient 0.3 at the 95% significant level during 1860–1995 A.D. The Dasuopu ice core accumulation record represents conditions at a single location, and a dating error of just 1 year may affect the statistical correlation. Therefore, a 5-year mean was applied to both records, giving $R = 0.58$ (sig. = 99%) (Fig. 3).

In the EOF2 associations accumulation in the Dasuopu ice core is positively correlated with precipitation in northern India, and negatively correlated with that in southern India. Based on these associations, distinct climatic regimes in monsoon precipitation with main changes around the year 1930 are identified (Duan et al. 2002b). The period 1850–1930 is characterized by more wet years over the Himalayas and Northeast India and by drier years over southern and central India, while

Fig. 4. Power spectral of accumulation series of the Dasuopu ice core

the period 1930–1995 is characterized by drier years over the Himalayas and Northeast India, and by wetter years over central India (Duan et al. 2002a). This suggests that the precipitation climatology of the Himalayas and its foothills behave differently from the southern part of the subcontinent, and the all-India average precipitation record does not provide a valid representation of the entire subcontinent, especially of the Tibetan Plateau.

Oscillatory characteristics in the accumulation record of the Dasuopu ice core are detected by spectral analyses. Figure 4 shows significant peaks at periods close to 5.1, 7.9, 9.1, 14.2 and 26 years in the accumulation time series during 1700–1996. These periods are in agreement with the global temperature peaks (Ghil and Vautard 1991). This may suggest the accumulation variation in the Dasuopu ice core connects to temperature variability.

To identify common trends and features related to broad-scale climate variability, the accumulation record of the Dasuopu ice core is compared with the 300-year northern hemisphere temperature (Mann et al. 1999) (Fig. 5A). The comparison clearly shows that a negative correlation exists between the two records, with a correlation coefficient -0.22 at 95% confidence level ($n = 295$). A 5-year unweighted running mean was applied to both records, giving coefficient -0.41 at 99% confidence level. Thus, contemporary records demonstrate that decreasing accumulation in the Dasuopu ice core connects to warming in northern hemisphere and visa versa. For example, in the last century, accumulation in the Dasuopu ice core has decreased by 425 mm

Fig. 5. (A) Variations of the Dasuopu accumulation (black line), and the North hemisphere temperature (Mann et al. 1999) (gray line) over the past 300 years. (B) The trends, separated from two signals, show a negative relationship between accumulation in the Dasuopu glacier (black line), and north hemisphere temperature (gray line)

from early 20th to late 20th century, while north hemisphere temperature has increased about 0.5°C. The corresponding regression coefficient is about $-800 \pm 100 \text{ mm}(\text{°C})^{-1}$, indicating that on average a 0.1°C change in north hemisphere temperature is associated with about 80 mm change in accumulation in the Dasuopu ice core.

To reveal the secular signals, low-passed filtered (>60 years) is applied to the two records. The extracted secular signals are illustrated in Figure 5B. The low-passed components capture 31% of the accumulation variance, and 78% of the temperature. The accumulation low-passed time sequences displays fluctuations with peaks near 1854 and 1915, with trough near 1890, while the temperature low-passed time sequences displays fluctuations with peaks near 1875, with trough near 1840 and 1900. It seems that there is a negative correla-

tion between the precipitation and the temperature with variation of temperature lead that of precipitation around 15 years. These characteristics, visible in Fig. 5, are supported by cross-correlation between precipitation and temperature, suggesting that precipitation in the Himalayas will continuously decrease in future decades due to the Global warming in the past decades.

Figure 5B also shows clearly the variability trend of the accumulation record in the Dasuopu ice core in the last 300 years, suggesting South Asian Monsoon in the Himalayas had weakened in the 18th century, then strengthened strongly during 1795–1850, again moderately weakened during 1850–1875 and strengthened during 1875–1920, after that it has weakened from early 1920 to the present.

Model studies suggest an increase (5–15%) in monsoon precipitation with global temperature increases (Meehl et al. 1993, 1996). This is consistent with the basic principle of the monsoon increase in the strengthening land-ocean thermal contrast as a result of global warming (Meehl 1994). It is the case that the average Indian monsoon rainfall has increased slightly over the past decades. However, rainfall in some parts of India such as the Northwest Peninsular India and Northeast India has decreased over the past decades (Sontakke 1996). Monsoon trough is assumed to result in transport of moisture to the Himalayas. Generally as monsoon trough locates in central Indian, the rainfall is above normal over central India and below normal over northern India and foothills of the Himalayas. While as monsoon trough shifts to the Himalayas side, the rainfall is above normal over northern India and foothills of the Himalayas and below normal over central India. A recent study concluded that increase in temperature over the last few decades have led to changes in atmospheric circulation that have resulted in a decrease in moisture flux to the Tibetan plateau (Qin et al. 2000). We assume increased temperature makes the monsoon trough easier to stay over central Indian. This assumption is consistent with the monsoon rainfall pattern over the last decades. The past decades is characterized by drier years over the Himalayas and Northeast India, and by wetter years over central India. The results presented here are probably hardly

conclusive. There seems to need additional research in this area for the Himalayas is the headwaters of such important rivers as the Indus and the Ganges. According to IPCC reports (Houghton 1992), a global temperature will increase of 0.1–0.2°C/10a, which will lead to decreasing rainfall in the Himalayas. If this is the case, there will be not enough precipitation to match the melting volume of glaciers on the Himalayas. Then the glaciers on the Himalayas, including our studying site, will have been continual retreating, decreasing accumulation and negative mass balance. The Himalayan glaciers continue to dissolve in the future. The rivers originated in the Himalayas will get low in summer because of the most vulnerable portions of the glaciers is gone.

4. Summary

The reconstructed annual accumulation record in the Dasuopu ice core from the central Himalayas provides evidence of a significant South Asian Monsoon variability in the Himalayas over the past 300 years, which is interpreted as a good correlation between the accumulation record in the Dasuopu ice core and monsoon precipitation record in Northeast India and in Nepal. This suggests monsoon variability in the Himalayas can be examined in a longer perspective. The 300-year accumulation record showed that South Asian Monsoon in the Himalayas had weakened in 18th, then strengthened between 1795–1850, weakened again between 1850–1875 and strengthened during 1875–1920, after that it has weakened from early 1920 to the present.

There exists a strong anti-correlation between the accumulation record in the Dasuopu ice core and Northern Hemisphere temperature. The results demonstrate that decreasing accumulation in the Dasuopu ice core connects to warming in the Northern Hemisphere and visa versa. In a case of Northern Hemisphere mean temperature 0.1°C increases, the accumulation decreases 80 mm and vise versa. Over the past century, north hemisphere temperature has increased about 0.5°C, while accumulation in the Dasuopu ice core has decreased by 400 mm, which really reflects that monsoon precipitation in the central Himalayas has decreased in the global warming over the past decades.

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