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Response of monsoon precipitation in the Himalayas to global warming

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[1] Reconstruction of annual net accumulation using ice cores from the Dasuopu glacier reveals monsoon precipitation variability in the central Himalayas over the past three centuries. We found that the broad features of the snow accumulation are reverse to the Northern Hemisphere temperature reconstruction over the past 300 years. On average, a 0.1°C change in Northern Hemisphere temperature is associated with about 100 ± 10 mm change in snow accumulation in the Dasuopu ice core. Especially during the period 1920–1995 the snow accumulation in the Dasuopu ice core decreased about 500 mm while Northern Hemisphere temperature increased about 0.5°C, which contrasts with previous studies that indicate an increase of summer monsoon precipitation in High Asia is a consequence of global warming. For the period 1900–1995 Indian monsoon precipitation in the Himalayas, Nepal, Bangladesh and northern India highly correlate with the thermal contrast between the Tibetan Plateau and the tropic Indian Ocean. Although the Tibetan Plateau has experienced statistically significant warming until to the early 1960s, the linear warming trend on the Tibetan Plateau is still less than that in the tropical Indian Ocean during the period 1900–1995, suggesting a decreasing thermal contrast between the Tibetan Plateau and the tropical Indian Ocean. We infer that transportation of water vapor from the tropical Indian Ocean to the Himalayas is decreasing as a result of the decreasing thermal contrast between the Tibetan Plateau and the tropical Indian Ocean.

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1. Introduction

[2] The Asian summer monsoon has a significant impact on human activities and ecosystems in Asia and it also plays an important role in the global climate system. It has been thought that land-sea heating contrast is a fundamental mechanism driving the summer monsoon circulation [*Fu and Fletcher*, 1985; *Meehl*, 1994; *Li and Yanai*, 1996; *Bansod et al.*, 2003]. These results showed the greater the temperature gradient between land and sea, the more intense the Asian summer monsoon. Meanwhile, some studies have suggested an increase in monsoon precipitation with global temperature increases [*Meehl and Washington*, 1993; *Meehl et al.*, 1996; *Hulme et al.*, 1998], which is consistent with the basic principle that the monsoon intensifies as a result of the strengthening land-ocean thermal contrast as a result of global warming [*Meehl*, 1994; *Anderson et al.*, 2002]. The IPCC reported that it is likely that the warming associated with increasing greenhouse gas concentrations will cause an increase in Asian summer monsoon variability and changes in monsoon strength [*Intergovernmental Panel on Climate Change*, 1996, 2001]. However, there is no statistically significant trend in Indian Monsoon Precipitation (IMR) for India as a whole [*Pant and Kumar*, 1997]. Trends since 1979, the period of strongest reported surface warming, do not indicate any change in monsoon circulation [*Chase et al.*, 2003]. Though the 1990s have been the warmest decade of the millennium in most parts of the world, the IMR variability has decreased drastically rather than increased [*Kripalani et al.*, 2003a]. In last 150 years there are areas in India with decreasing trends of precipitation and there are also areas with increasing trends [*Kumar et al.*, 1992; *Sontakke and Singh*, 1996]. For example, over the period 1901–1995 monsoon precipitation in Nepal, Bangladesh and Northeast India, respectively, has decreased about 19%, 9% and 6% relative to the average [*Duan et al.*, 2004]. This discrepancy suggests there are still many gaps in our understanding of the monsoon variability. This may be a possible reason for the moderate success in monsoon forecasting [*Pallava*, 2002; *Webster et al.*, 1998].

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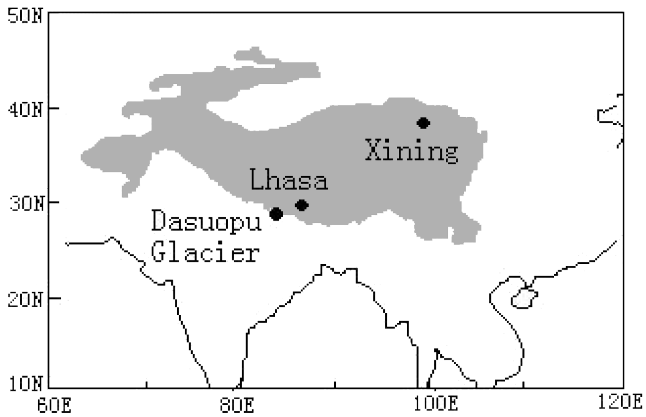

Figure 1. Location of Dasuopu glacier, Lhasa and Xining meteorology station. The shaded part is Tibetan Plateau.

[3] Some studies show that the Himalayas and the Tibetan Plateau play an important role in the evolution of the boreal summer monsoon [e.g., *Flohn*, 1957; *Ye*, 1981; *Yanai et al.*, 1992; *Yanai and Li*, 1994; *Ye and Wu*, 1998; *Bansod et al.*, 2003]. The strong (weak) monsoon years are associated with positive (negative) tropospheric temperature anomalies over Tibetan Plateau [*Fu and Fletcher*, 1985]. A recent study showed that the well-documented negative relationship between winter snow in Himalayas and IMR seems to have changed to a positive relationship because of global warming [*Kripalani et al.*, 2003b], suggesting the relationship between snow cover and monsoon precipitation are complex over southern Asia. Thus a better understanding of the spatial and temporal variability of precipitation in the Himalayas is vital to improve our understanding of Asian monsoon dynamics.

[4] Although considerable work has been done on variability of climate and particularly precipitation in south Asia [*Webster et al.*, 1998; *Yasunari*, 1990; *Meehl*, 1994; *Li and Yanai*, 1996; *Singh and Sontakke*, 2002; *Yanai and Li*, 1994, and references therein], little is known about monsoon precipitation in Himalayas. The reason is that the instrumental meteorological record on Tibetan Plateau only extends back into the late 1950s, which prevents us from understanding whether human activities are perturbing the Tibetan Plateau climate system and whether 20th century climate trends fall outside the natural range of past variability. Thus, to extend climate investigation back beyond 1950 on the Himalayas, natural archives of climate must be used. Moreover, decadal variations of Indian monsoon precipitation can be resolved by using the instrumental records, however, there are still gaps in understanding about centuries-long trends in monsoon precipitation variability in Southern Asia, especially in Himalayas, for the instrumental monsoon precipitation was only extended back to 1850s [*Sontakke and Singh*, 1996; *Mooley and Parthasarathy*, 1984; *Parthasarathy et al.*, 1994]. The prolonged monsoon precipitation from natural archives is essential to determine monsoon precipitation variability on century timescales.

[5] Previous studies have shown that changes in the monsoon precipitation over hundreds of years can be reconstructed using annual snow accumulation from the Himalayas [*Thompson et al.*, 2000; *Duan et al.*, 2004]. The present work aims to explore the variability of monsoon precipitation in the Himalayas as a result of global warming by using the extended annual net accumulation data. Also discussed is the effect of surface temperature of the Tibetan Plateau and the tropical Indian Ocean on monsoon variability. In addition, the relationship between the horizontal temperature gradient between the Tibetan Plateau and the tropical Indian Ocean and the intensity of the Asian summer monsoon is examined.

2. Data Acquisition

[6] In 1997, three ice cores were extracted from the Dasuopu glacier (28°23′N, 85°43′E) (Figure 1) in the Central Himalayas. The snow deposited at the core site (with elevation of 7200 m above sea level) is controlled by monsoon circulation in summer and the ice cores have the potential to provide valuable information on monsoon variability [*Thompson et al.*, 2000; *Wang et al.*, 2002]. Snow accumulation at the core site is thought to occur most often during the summer months, and the reconstructed snow accumulation time series over the past 300 years provides a strong record of South Asian Monsoon variability in the Himalayas at centennial and multidecadal timescales [*Thompson et al.*, 2000; *Duan et al.*, 2004]. Contemporary comparison shows variation in the Dasuopu snow accumulation is in phase (out of phase) with that in monsoon precipitation of Northeast India, Nepal and Bangladesh (West peninsula India and East Peninsula India) at centennial and multidecadal timescales. The results show the reconstructed snow accumulation provides a strong record of South Asian Monsoon variability in the northeast Indian subcontinent over the past 300 years at centennial and multidecadal timescales, suggesting we can examine the monsoon variation over a longer perspective [*Duan et al.*, 2004]. In this paper, we will make use of the snow accumulation time series covering the period 1700–1995 to detect monsoon variability in the Himalayas under the influence of global warming.

[7] On the basis of a fixed and well distributed network of 306 rain gauge stations over India, monsoon precipitation in Indian has been developed by giving proper area-weighting [*Parthasarathy et al.*, 1994]. *Sontakke and Singh* [1996] developed an algorithm to construct regional fields of monthly precipitation by merging gauge data and six subdivision monsoon precipitation regimes were divided into North West India, North Central India, North East India, West Peninsular India, East Peninsular India and South Peninsular India. We averaged monsoon precipitation of the North West, North Central and North East India as the monsoon precipitation index of northern India, and that of West, East and South Peninsula as the index of southern India. Monsoon precipitation covering the period 1901 to 1995 in Nepal and Bangladesh have also been used, which are developed by interpolating directly from station observations [*New et al.*, 2000].

[8] To explore the potential linkages between temperature variations and monsoon precipitation, the Northern Hemisphere temperature [*Mann et al.*, 1999; *Mann and Jones*, 2003], sea surface temperature (SST) in the Indian Ocean and surface air temperature over Tibetan Plateau are also used. The SST data in Indian Ocean were used on a 5° × 5° grid [*Rayner et al.*, 2003]. The SST used in this paper is defined as the annual mean over the domain from 60°E to 90°E and from 20°S to 20°N. Most meteorological stations

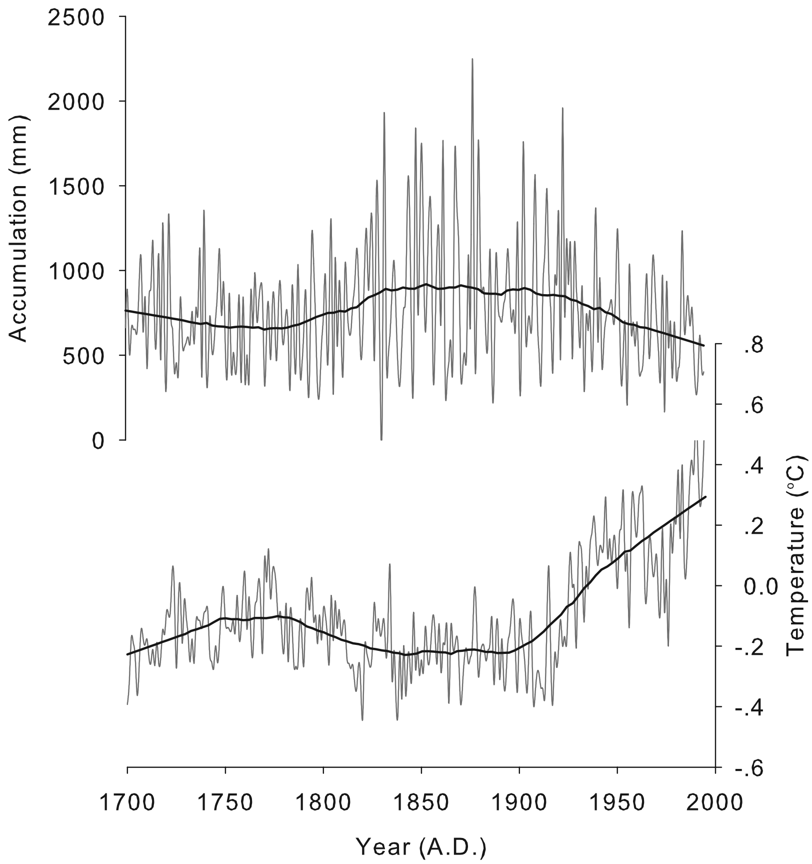

Figure 2. Time series of snow accumulation for the Dasuopu ice core and of Northern Hemisphere temperature [*Mann et al.*, 1999]. Solid curves denote century timescale trend.

on the Tibetan Plateau were not established until the early 1950s, with the exception of a few observational records collected before the 1930s. Temperature reconstructions for the entire Tibetan Plateau during 1955–1996 are based on observational temperature data from 97 stations with elevations over 2000 m [*Liu and Chen*, 2000]. The temperature reconstruction was also extended backward to 1901 with the EOF method dependent on the temperature relationship between Tibetan Plateau and Northern Hemisphere [*Liu et al.*, 1998]. In this study, temperature reconstruction in India and Nepal are also used [*New et al.*, 2000], which can be downloaded from http://www.cru.uea.ac.uk.

3. Relationship Between Snow Accumulation in the Dasuopu Ice Core and the Northern Hemisphere Temperature

[9] The snow accumulation reconstruction from the Dasuopu ice core in the central Himalayas for the last 300 years shows pronounced multidecadal variations superimposed on the long-term variations (Figure 2). The snow accumulation is directly considered as monsoon precipitation in the high Himalayas, and it highly correlates with summer monsoon precipitation in northeast India, Nepal and Bangladesh [*Duan et al.*, 2002, 2004]. The snow accumulation time series show that the strongest monsoon in Himalayas was in 1830–1920, while the weakest monsoon periods occurred in 1700–1830 and 1920–1995. Since 1830 the decreasing rate of the monsoon precipitation is not steady, with a brief increase occurring between 1880 and 1920. In addition to the recent decrease, there is a broader, century-long increase in monsoon precipitation that occurred between 1750 and 1830.

[10] We compared the monsoon precipitation record with the reconstructed Northern Hemisphere temperature change [*Mann et al.*, 1999] and found that the broad features of the monsoon index are the reverse of the temperature reconstruction. The comparison clearly shows that a negative correlation exists between the two records, with a correlation coefficient of -0.22 at the 95% confidence level ($n = 295$). A 5-year unweighted running mean was applied to both records, giving a coefficient of -0.41 at the 99% confidence level. Thus contemporary records demonstrate that decreasing monsoon precipitation in the Himalayas is connected to warming in Northern Hemisphere and visa versa.

[11] Both the high-resolution snow accumulation and temperature profiles show four distinct features over the past 300 years (Figure 2). First, a slight decrease in monsoon precipitation correlated with a slight increase in temperature between 1700 and 1770. Second, from 1770 to 1850 monsoon precipitation increased about 300 mm, while the Northern Hemisphere temperature decreased about 0.3°C. Third, an interval of generally the highest monsoon precipitation is observed between 1850 and 1920, and correlates with the lowest temperature period during the past 300 years. Fourth, a long-term gradual decrease in monsoon activity starting at around 1920 is indicated by a sharp shift in snow accumulation from ~900 mm in the

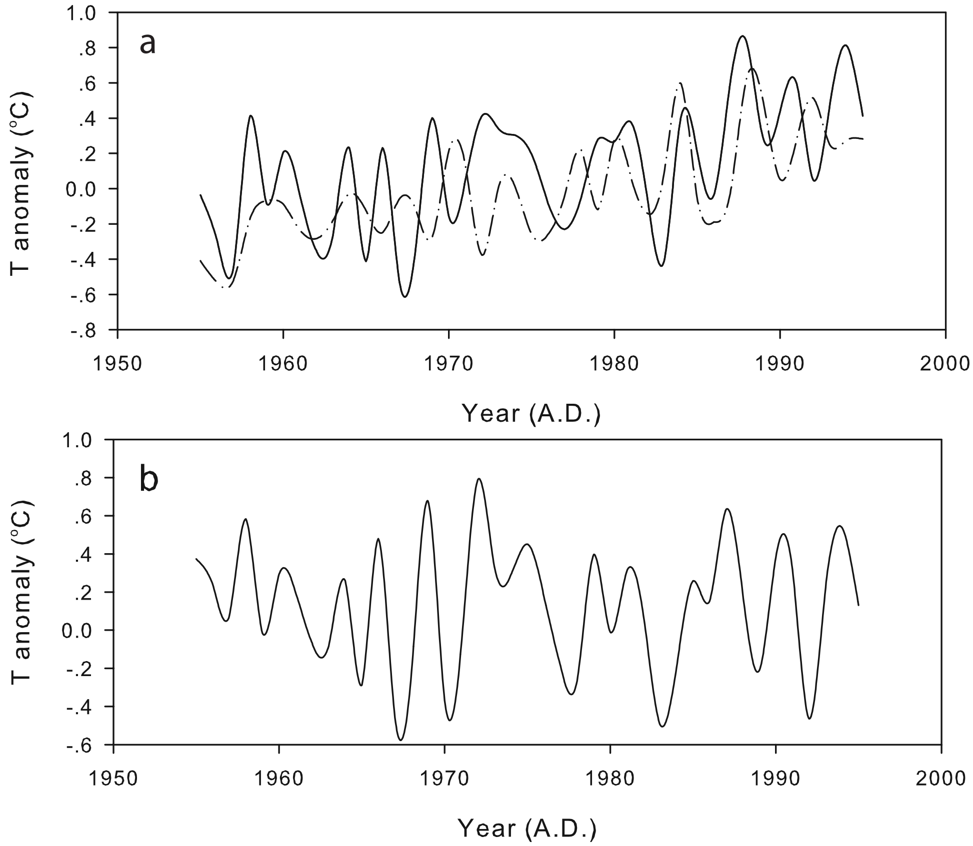

Figure 3. (a) Annual averaged time series of mean surface temperature anomalies in the Tibetan Plateau (black line) and tropical Indian Ocean (gray line) from 1955 to 1996. (b) Surface temperature anomaly difference between the Tibetan Plateau and the tropical Indian Ocean.

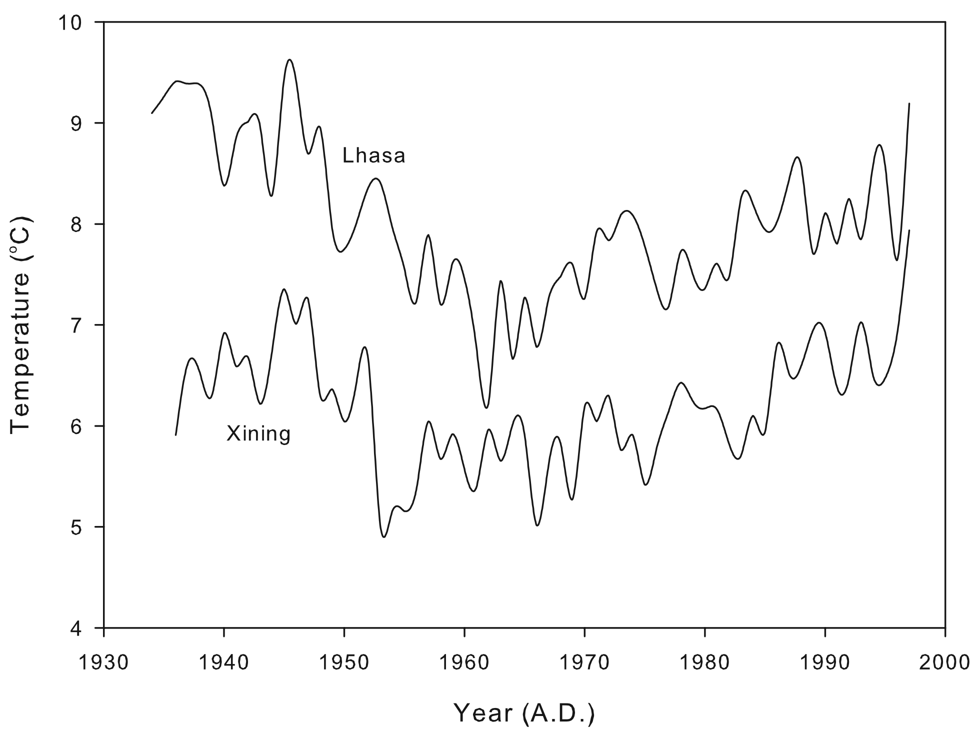

Figure 4. Time series of annual surface temperature in Xining (36°37′N, 101°46′E, 2262 m a.s.l.) and Lhasa (29°40′N, 91°8′E, 3650 m a.s.l.).

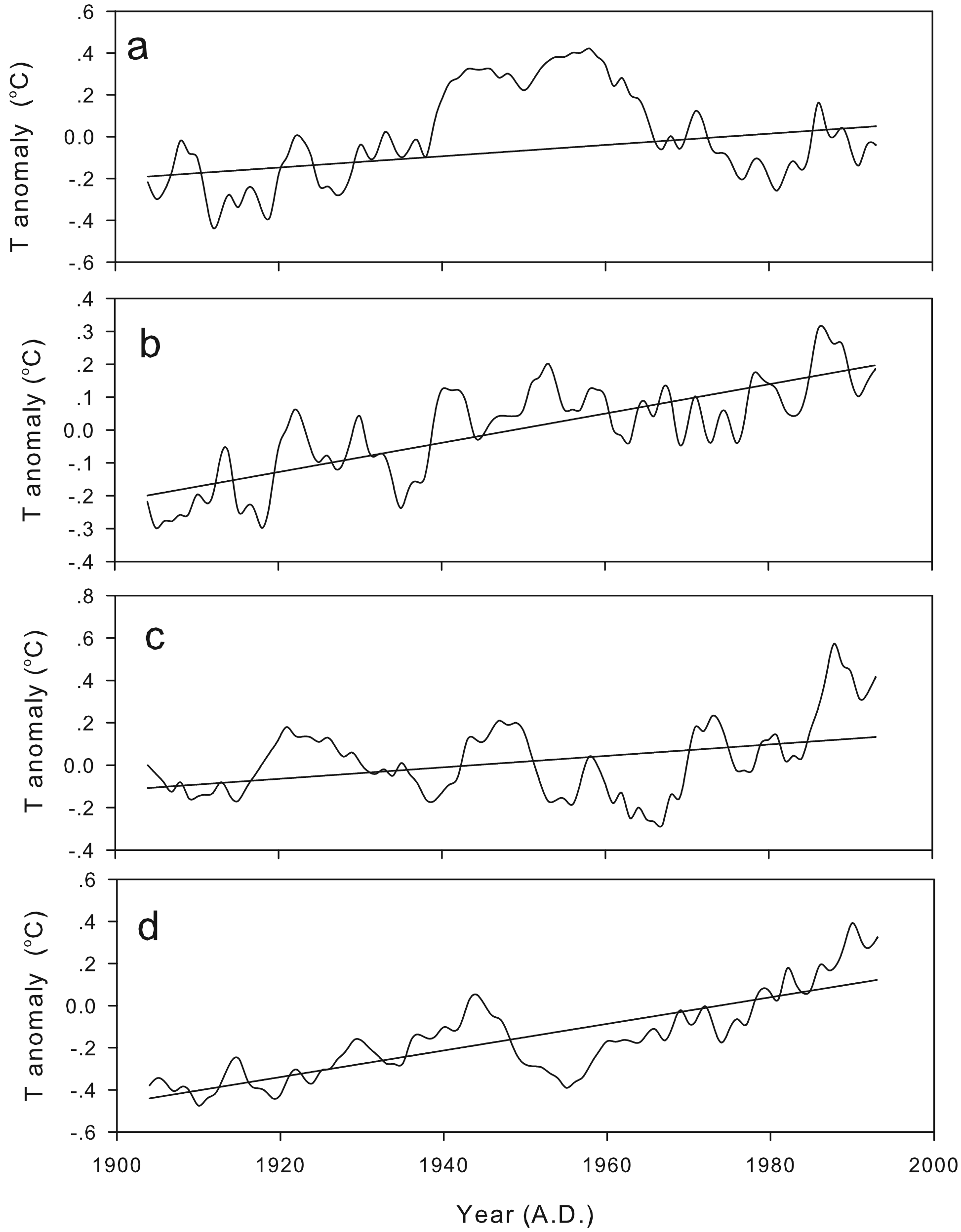

Figure 5. Reconstructions of 5-year running mean annual temperature anomaly for (a) Nepal, (b) India, (c) Tibetan Plateau and (d) tropic Indian Ocean. The straight lines are linear trends of temperature reconstructions.

1920s to ~400 mm in the 1990s, during a period of a rapid increase in global temperature of about 0.5°C from 1920 to 1995. The corresponding regression coefficient is about -1000 ± 100 mm $(°C)^{-1}$, indicating that on average a 0.1°C change in Northern Hemisphere temperature is associated with about 100 ± 10 mm change in the net snow balance in the Dasuopu ice core.

4. Snow Accumulation in Dasuopu Ice Core and Thermal Contrast Between the Tibetan Plateau and the Tropical Indian Ocean

[12] Since the monsoon is to a large degree a thermally driven large-scale circulation between land and ocean, it is logical to expect that any large-scale thermal anomaly may have its influence on the monsoon variability. Previous studies emphasize that variation in the Indian monsoon is closely linked to the greater heat capacity of the ocean relative to the surrounding landmasses and the Tibetan Plateau plays an important role in the evolution of the boreal summer monsoon [*Yanai et al.*, 1992; *Yanai and Li*, 1994; *Webster et al.*, 1998]. We logically expect that the variability of monsoon precipitation in the Himalayas should correspond with the thermal contrast between the Tibetan Plateau and the Indian Ocean.

4.1. Temperature Variations on the Tibetan Plateau and in the Tropical Indian Ocean Over the Past Century

[13] Analyses of the instrumental temperature series show that the majority of the Tibetan Plateau has experienced

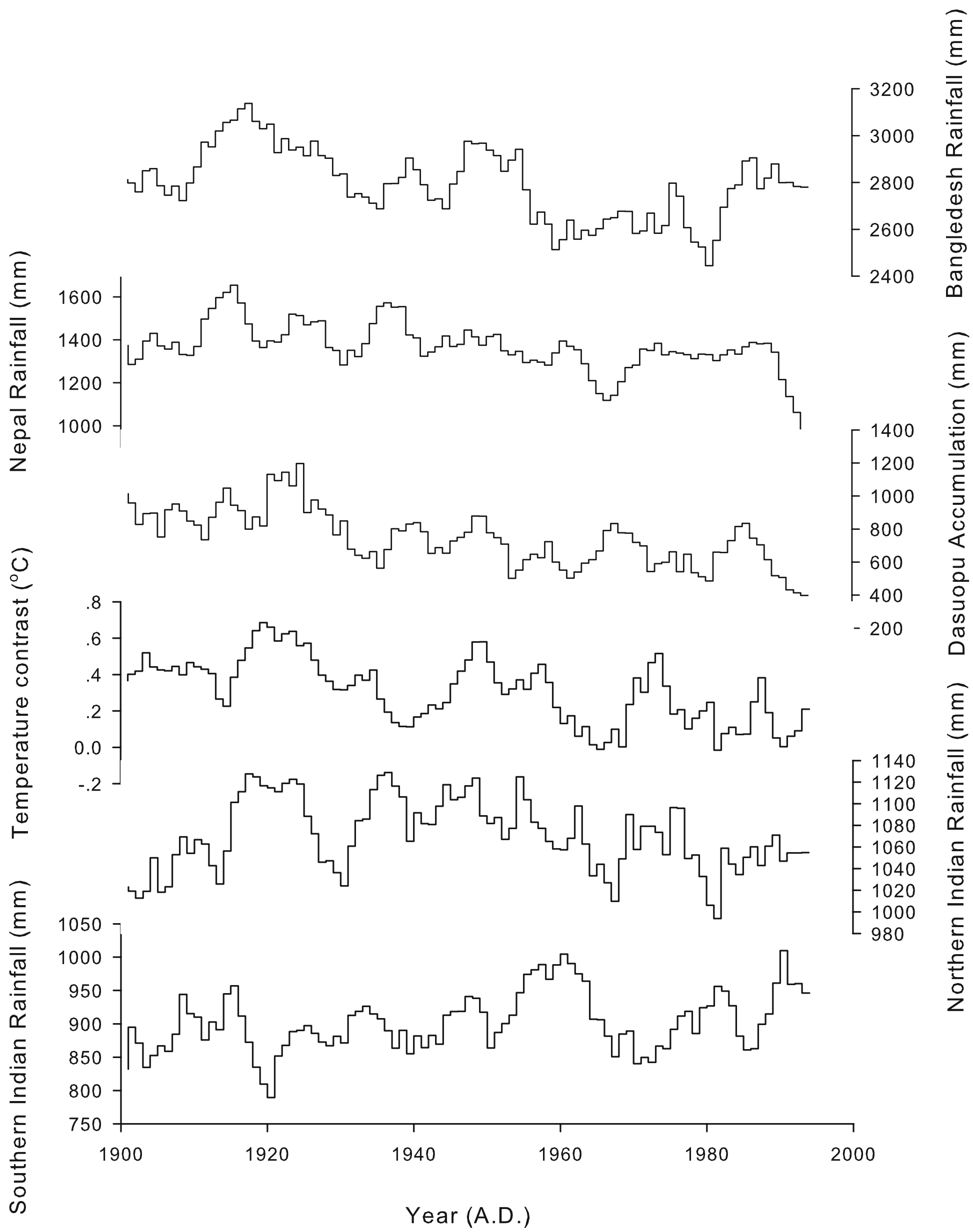

Figure 6. The 5-year running mean of monsoon rainfall in Bangladesh, Nepal, Himalayas, northern India and southern India and the thermal contrast between tropical Indian Ocean and Tibetan Plateau.

statistically significant warming since the mid-1950s. As shown in Figure 3a, the linear rates of temperature increase over the Tibetan Plateau during the period 1955–1996 are about 0.16°C/decade [*Liu and Chen*, 2000], which is comparable to that of the tropical Indian Ocean. Figure 3b shows the temperature difference between the Tibetan Plateau and the tropical Indian Ocean, indicating that there is not an apparent upward or downward trend of the temperature difference, and suggesting the thermal contrast between the Tibetan Plateau and the tropical Indian Ocean is steady over the past 50 years.

[14] On the Tibetan Plateau, the longest instrumental temperature records at five stations began in the 1930s, in which the best records are from Lhasa (29°40′N, 91°8′E, 3650 m a.s.l.) and Xining (36°37′N, 101°46′E, 2262 m a.s.l.), the two biggest cities on the Tibetan Plateau (Figure 1). Figure 4 demonstrates the annual mean surface temperatures in both Xining and Lhasa have experienced substantial fluctuations during the last six decades. A warm period exists during most of the 1930s and 1940s, with a general cooling from the late 1940s to the mid-1950s, and a statistically significant warming trend starting from the mid-1950s. The above temporal change characteristics of Xining and Lhasa are regarded as a plausible representation of those in the entire central and eastern Tibetan Plateau during the last 63 years [*Liu and Chen*, 2000]. Unlike the Northern Hemisphere temperature reconstructed by Mann [*Mann and Jones*, 2003], the recent warming in the central and eastern Tibetan Plateau did not reach the level of the 1940s warm period until the late 1990s [*Liu and Chen*, 2000].

[15] Figure 5 demonstrates the extended temperature variations on Tibetan Plateau, India and Nepal as well as

SST in tropical Indian Ocean. For the tropical Indian Ocean, there is a general warming from 1900s to the mid-1940s, a cooling from late 1940s to mid-1950s and a statistically increasing trend since the mid-1950s [*Kripalani and Kumar*, 2004]. Both the Tibetan Plateau and India show warm periods in 1920s and 1940s and a warming trend since 1960s. In summary, Figure 5 shows an intense warming trend for SST in the tropical Indian Ocean during 1900–1995, but does not show intense warming trends for the Tibetan Plateau until the mid-1960s. Figure 5 even shows a cooling trend for Nepal over the past 50 years. On the basis of the linear trend equations of the temperature time series in Figure 5, SST in the tropical Indian Ocean has increased about 0.6°C during the period of 1900–1995, which is much larger than the temperature increase in the Tibetan Plateau (0.3°C), India (0.45°C) and Nepal (0.3°C) in spite of the same warming linear trend in both the Tibetan Plateau and the tropical Indian Ocean since mid-1960s.

4.2. Impact of Thermal Contrast Between the Tibetan Plateau and Indian Ocean on Snow Accumulation in Dasuopu Ice Core

[16] We defined the thermal contrast index between the Tibetan Plateau and the Indian Ocean as identified by *Fu and Fletcher* [1985]. The thermal contrast index between the Tibetan Plateau and the tropical Indian Ocean is defined as the departure from the mean of the difference between the land surface temperature of the Tibetan Plateau and the surface temperature of the tropical Indian Ocean. The index covering the period 1901–1995 describes the variation in large-scale thermal contrasts for the Tibet-Indian Ocean oscillation. Figure 6 shows comparisons among Monsoon precipitation in Himalayas, Nepal, Bangladesh, northern India, southern India, and the thermal contrast as defined above. At the decadal timescale, a good agreement exists between variation of the monsoon precipitation in Himalayas and Tibet temperature ($r = 0.32$, $p = 95\%$), including strong monsoon periods corresponding to high temperatures on the Tibetan Plateau during the 1920s, 1940s, 1970s and late 1980s. However, at century timescale, monsoon precipitation in Himalayas, as well as monsoon precipitation in northern India and Nepal, does not agree well with Tibetan Plateau temperature, and instead demonstrates a good anticorrelation with Indian Ocean surface temperature. On the other hand, monsoon precipitation reconstruction in Himalayas is in strong agreement with the thermal contrast index at both decadal and long-trend timescales, suggesting that variation of monsoon precipitation in the Himalayas is mainly controlled by the thermal contrast between the Tibetan Plateau and Indian Ocean.

[17] The trend in all-India precipitation in last 130 years, although positive, is small and statistically insignificant [*Parthasarathy et al.*, 1994]. However, the regional and year-to-year variability is large. For example, over last century, the trend of precipitation in the southern and central Indian subcontinent is positive, while that in northern Indian subcontinent (including Nepal, Bangladesh and the Himalayas) is negative. This means the long trend of monsoon precipitation in southern India is not well connected to the thermal contrast between the tropical Indian Ocean and the Tibetan Plateau. The warmer Indian Ocean enhances evaporation, transports water vapor to the southern parts of India; however the decreasing thermal contrast between the Tibetan Plateau and the tropical Indian Ocean inhibits the transport of water vapor toward the Himalayas.

5. Conclusions

[18] The reconstructed annual net accumulation from ice cores provides a history of monsoon variability in Himalayas. A 300-year snow accumulation record from Dasuopu ice core in the central Himalayas reveals a strong anticorrelation between the monsoon precipitation in the central Himalayas and the Northern Hemisphere temperatures. It is also found that the reconstructed monsoon precipitation is linked with the thermal contrast between the Tibetan Plateau and the Indian Ocean. In contrast to what has been found in earlier studies indicating that the South Asian summer monsoon is increasing as a consequence of global warming, our finding shows decreasing trends of monsoon precipitation in Himalayas, northeast India, Nepal and Bangladesh over the last century. We also find that the temperature contrast between the Tibetan Plateau and the Indian Ocean does not relate to the all India monsoon precipitation variation. The warmer Indian Ocean enhances evaporation, transports water vapor to the southern parts of India; however the decreasing thermal contrast between the Tibetan Plateau and the tropical Indian Ocean inhibits the transport of water vapor toward the Himalayas. More research needs to be undertaken in order to improve our understanding of monsoon variability.

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