GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L16209, doi:10.1029/2004GL020015, 2004

Low-frequency of southern Asian monsoon variability using a 295-year record from the Dasuopu ice core in the central Himalayas

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Received 17 March 2004; revised 12 May 2004; accepted 20 July 2004; published 25 August 2004.

[1] A better understanding of the spatial and temporal variability of rainfall in the Himalayas should be extremely important to improve our understanding of Asian monsoon dynamics. There is little that is understood about rainfall variability at the high Himalayas with elevation over 7000 m a.s.l. Here a high-resolution snow accumulation record from a well dated Dasuopu ice core from central Himalayas reflects low-frequency variability of monsoon precipitation over the last 295-year. MultiDecadal to centennial variations in the Dasuopu snow accumulation (DSA) are in-phase (out-of-phase) with that in monsoon rainfall of northeast Indian, Nepal and Bangladesh (southern India) over the period 1901–1995. The record shows the monsoon in central Himalayas had weakened in 18th century and strengthened throughout much of 19th and early 20th century, and then weakening again from early 1920s to the present. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1827 Hydrology: Glaciology (1863); 1854 Hydrology: Precipitation (3354); 1863 Hydrology: Snow and ice (1827). **Citation:** Duan, K., T. Yao, and L. G. Thompson (2004), Low-frequency of southern Asian monsoon variability using a 295-year record from the Dasuopu ice core in the central Himalayas, *Geophys. Res. Lett.*, *31*, L16209, doi:10.1029/2004GL020015.

1. Introduction

[2] There are growing concerns over the monsoon rainfall variability in monsoon area. Specifically, changes in rainfall induced by the monsoon variability could severely impact human activities and ecosystems in this area. However, modeling results to forecast the monsoon rainfall have been made with only moderate success [*Pallava*, 2002]. One reason is that although in India considerable work has been done on variability of climate and particularly rainfall [*Webster et al.*, 1998; *Yasunari*, 1990; *Meehl*, 1994; *Li and Yanai*, 1996; *Singh and Sontakke*, 2002; *Yanai and Li*, 1994, and references therein], the nature of the climate variability over other parts of Indian monsoon regime, such as Himalayas, is not as well documented until to recent. A better understanding of the spatial and temporal variability of rainfall in the Himalayas should be extremely important to improve our understanding of Asian monsoon dynamics. Recent studies have shown that large rainfall amounts on the order of 300–400 cm yr^{-1}, can fall along the south-facing slopes of the Himalayas [*Barros et al.*, 2000; *Barros and Lang*, 2003; *Shrestha*, 2000; *Lang and Barros*, 2002]. Studies also have shown that the climatology of Himalayan rainfall variability differs markedly from the rest of the Indian subcontinent [*Shrestha*, 2000]. A few other studies have examined orographic effects on precipitation in the Himalayas [*Barros et al.*, 2000; *Barros and Lang*, 2003; *Shrestha*, 2000; *Lang and Barros*, 2002; *Singh et al.*, 1995; *Seko*, 1987], but generally on time-scales spanning from several days to 2–3 years. In Indian plain and river valleys in Nepal, monsoon rainfall is recovered and studied extensively [*Shrestha*, 2000; *Kripalani et al.*, 1996; *Pathasarathy et al.*, 1994, and references therein]. But all these studies were based mostly on meteorological network with elevation lower than 4500 m a.s.l., leaving gaps in understanding and quantifying precipitation over Himalayas ridges with elevation over 7000 m a.s.l.

[3] A major cause of the lack of studies on precipitation variability on the high elevation in Himalayas is the remoteness of the region, and the resultant lack of meteorological data. Fortunately, this data gap can be addressed with high-fidelity paleoclimate records from annually resolved ice core record recovered from high elevation glaciers in the Himalayas. In 1997, three ice cores were extracted at a high site (with elevation more than 7000 m a.s.l.) from the Dasuopu glacier (28°23′N, 85°43′E) (Figure 1) on the south central rim of the Himalayas. Those ice core records of dust and chloride concentrations have been proposed as a proxy to study variability in the South Asian Monsoon [*Thompson et al.*, 2000].

[4] Here, we present a 295-year proxy record of snow accumulation from the Dasuopu ice core (hereafter DSA). Then the relationship between DSA and monsoon rainfall in Indian monsoon regime over the last century is discussed. Last singular spectrum analysis (SSA) [*Vautardm et al.*, 1992] is applied to the DSA time series in order to separate and describe oscillatory modes. SSA can decompose a short, noisy time series to allow explaining trends, periodic oscillations and noise.

2. Data Acquisition

[5] Himalayas mark the boundary between the Indian Monsoon and continental climate of central Asia. Dasuopu glacier (28°23′N, 85°43′E) (Figure 1) with elevation over 7000 m in central Himalayas ridges, receive most of the

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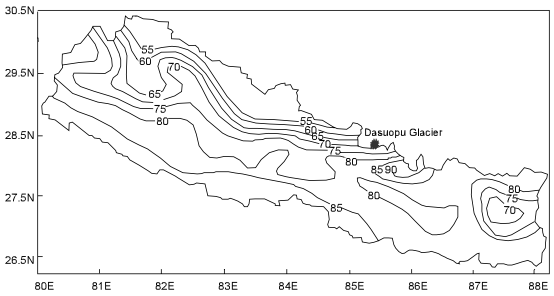

Figure 1. Percentage of monsoon rainfall compared to annual rainfall in Nepal [After *Shrestha*, 2000]. Black dot shows the Dasuopu ice core site.

moisture from Indian subcontinent and thus records summer monsoon rainfall. A meteorological survey was made on Dasuopu glacier during the period Sep. 3–Oct. 1, 1997 as three ice cores were being drilled on the glacier. The results show snowfall with south wind occurred every one-two days during Sep. 3–Sep. 22, 1997, while little snowfall with strong west wind appeared during Sep. 22–Oct. 1. Snow pit and stake surveys show snow accumulation in the region is sufficiently high as to allow for the recovery of annually resolved snow accumulation time series. On Dasuopu glacier site, snowfall is as high as 1000 mm (water equivalent) and annually resolved snow accumulation time series has been recovered from the ice cores using various stratigraphic tracers [*Thompson et al.*, 2000]. The annual snow accumulation time series from Dasuopu ice core C1 and C2 are agreement during the period 1700 to 1995 [*Thompson et al.*, 2000]. Here, we will make use of the Dasuopu snow accumulation time series from the ice core C2 covering the period 1700 to 1995.

[6] *Pathasarathy et al.* [1994] prepared monthly, seasonal and annual rainfall series of all-India for the years 1871–1993, based on a fixed and well distributed network of 306 raingauge stations over India, by giving proper area-weighting. *Sontakke and Singh* [1996] developed an algorithm to construct regional fields of monthly precipitation by merging gauge data and six subdivision monsoon rainfall regimes were divided into North West India, North Central India, North East India, West Peninsular India, East Peninsular India and South Peninsular India, which were classified by empirical orthogonal function (EOF) and cluster analyses of the summer monsoon rainfall of the period AD 1871–1995 of 306 rain gauges. In this paper we also use the average monsoon rainfall in Nepal and Bangladesh covering the period 1901 to 1995, which were interpolated directly from station observations [*New et al.*, 2000].

3. Results and Discussion

3.1. Coupling Between DSA and South Asian Monsoon Rainfall

[7] The DSA is a relatively simple proxy for precipitation in the site. In general, glacier accumulation depends not only on the snowfall but also on the ablation on the glacier. At the core site, however, one would expect the ablation can be neglected for the very high elevation (7200 m a.s.l.) and very cold temperature (annual mean temperature is −16°C). A key issue is whether DSA can be interpreted in terms of South Asian Monsoon rainfall. Previously study revealed that the Dasuopu ice core site is sensitive to fluctuations in the intensity of the South Asian Monsoon. Reductions in monsoonal intensity are recorded by dust and chloride concentrations [*Thompson et al.*, 2000]. At the larger scale, the monsoon onset is associated with monsoon depressions from the Bay of Bengal that moved close enough to the Himalayas to cause the observed upslope flow from the winds on their eastern flank [*Lang and Barros*, 2002]. The onset of the monsoon manifested itself as a gradual increase in total column moisture and convective instability, and a weakening of middle- and upper-tropospheric westerly winds. The daytime upslope flow aids the formation of convection at higher elevations, leading to the secondary peak in rainfall there [*Barros and Lang*, 2003]. Analysis of the raingauge data also shows that even at altitudes as high as 4,000 m the cumulative monsoon rainfall is comparable to the highest amount recorded in the Indian subcontinent [*Barros et al.*, 2000]. During the period as the ice cores were being drilled in September, 1997, it was observed that western wind dominated at the core site in the morning and southern wind dominated in the afternoon. In the afternoon clouds rose along the south slope of the Himalayas and generally produced snowfall at the core site, while at the base camp with elevation of 5800 m a.s.l. northern to the core site was clear. The site of base camp was suggested in rainshadow. This observation is coincidence with that of Barros [*Barros and Lang*, 2003], who observed that during daytime diurnally forced upslope and upvalley flow aids the formation of convection at high elevation. Overall, it appears that snowfall at the core site is related strongly with monsoon activities. On the other hand, rainfall analysis also shows that summer monsoon is more active in the southern part of Nepal but in the high Himalayas and Trans-

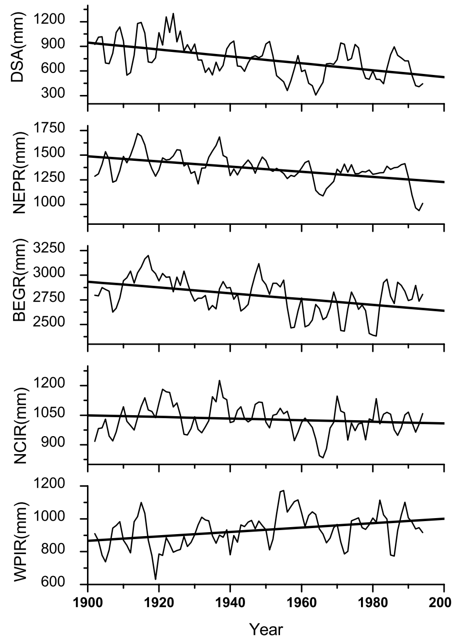

Figure 2. The 3-year running mean time series and trend statistics of: Dasuopu glacier accumulation (DSA); Nepal rainfall (NEPR), Bangladesh rainfall (BENR), north central Indian rainfall (NCIR) and west peninsular Indian rainfall (WPIR).

Table 1. The Correlation Coefficients Between DSA and Rainfall in Other Monsoon Regimes Over the Period 1901–1995[a]

	Nepal	Bangladesh	Northeast India	North Central India	West Peninsula India	East Peninsula India
DSA	**0.46**	**0.36**	0.22	0.23	−**0.36**	−0.31
DSA1	**0.57**	**0.58**	**0.41**	0.3	−**0.61**	−**0.42**

[a] Bold correlations are significant at 95% level. Note that the correlation coefficient in DSA and DSA1 lines are calculated with the annual and 3-year running mean, respectively.

Himalayan region other weather systems like western disturbance are also as effective as monsoon in giving rainfall [*Shrestha*, 2000]. Figure 1 depicts the spatial distribution of percentage of monsoon rainfall with respect to annual rainfall [*Shrestha*, 2000]. Because of lack of observed seasonal rainfall data at the core site, we can not figure out how much percentage of monsoon rainfall with respect to annual rainfall at the core site with elevation of 7000 m a.s.l. However, according to the position of the core site in the Figure 1, we estimated that about 60% of the annual rainfall at the core site is attributed to summer monsoon season. While on the basis of the present analysis over Nepal and Indian as a whole, about 80% of the annual rainfall is attributed to summer monsoon. This suggests that DSA is in potential to record some characteristic of monsoon rainfall. This interpretation is agreement with that monsoon rainfall in Bangladesh, Nepal and Northeast India, located directly south of the Himalayas, is positively correlated with DSA from 1901 to 1995 on decadal to centennial scales (Figure 2). Thus, DSA reflects the low-frequency variability of South Asian Monsoon in central Himalayas.

[8] Table 1 gives the correlation coefficients between DSA and monsoon rainfall in different regions. DSA has a strong positive correlation with monsoon rainfall in Northeast India, Nepal and Bangladesh, while it has a strong negative correlation with monsoon rainfall in West Peninsula India and East Peninsula India, suggesting monsoon rainfall in central Himalaya ridges is in phase with monsoon rainfall in north Indian subcontinent, and out of phase with that in southern subcontinent on the time scale over decadal time scales.

[9] Table 2 gives some characters of monsoon rainfall in different monsoon regions during the period 1901 to 1995. Over the last 100-year, the mean rainfall over the Himalaya ridges is as high as 738 mm, which is even higher than that in Northwest India. From Table 2 we can see a great deal of monsoon variability from region to region. There is a strong decreasing trend in the monsoon rainfall in Himalayas, Nepal, Bangladesh and Northeast India, while there is a strong increasing trend in West Peninsula India (Figure 2). Over the period 1901–1995, DSA and monsoon rainfall in Nepal, Bangladesh and Northeast India, respectively, have decreased about 45%, 19%, 9% and 6% relative to the average, while monsoon rainfall in West Peninsula India and East Peninsula India have increased about 12% and 11%. In summary, we can draw two conclusions from Table 2. The first is monsoon rainfall shifted from increasing to decreasing along the direction from the south-west subcontinent to the north-east subcontinent over the period 1901–1995. Secondly there exists a clear tendency of the monsoon rainfall trends to decrease at the Himalaya ridges. For example, monsoon rainfall at Himalaya ridges, on average, corresponds to mean linear rates of about −40 mm/decade during the period of 1901–1995. In this sense, the Himalayas can be regarded as one of the most sensitive areas to monsoon climate. The 20th century decreasing in monsoon rainfall in Himalayas is of great interest and need to be understood. This could be important in understanding the high elevation response of precipitation to global climate change in the 21st century.

Table 2. Mean Values and Linear Trend of Monsoon Rainfall in Different Regions Over the Period of 1901–1995[a]

Site	Mean (mm)	Linear Rate (mm/decadal)
DSA	738	−39.4 ± 11.8
Nepal	1360	−26.9 ± 8.1
Bangladesh	2791	−28 ± 8.4
Northeast India	1450	−9.7 ± 2.9
North Central India	1029	−2.9 ± 0.9
Northwest India	687	8.3 ± 2.5
West Peninsula India	929	12.7 ± 3.8
East Peninsula India	853	2.4 ± 0.7
South Peninsula India	926	1.8 ± 0.5

[a] Note that the linear rate errors are dependent on that typical raingauges have errors on the order of 30% on average.

[10] In Indian subcontinent, a well instrumental monsoon rainfall record is not more than 150 years, which really limits our understanding of monsoon rainfall variability over the longer term. As discussed above, DSA is an excellent proxy of South Asian Monsoon rainfall and is in phase with that in northern Indian subcontinent. Thus, DSA provides an excellent way to extend the low-frequency variability of South Asian Monsoon rainfall record back to AD 1700. Figure 3 shows the variability of 295-year DSA and 140-year monsoon rainfall in Northeast India. The correlation coefficient of the over lap of DSA and Northeast India rainfall is 0.56, indicating the DSA represents as a strong index of monsoon variability at the low-frequency.

3.2. Variability of 295-Year DSA

[11] Figure 4 shows the values of the DSA with a 3-year running mean applied. Interannual fluctuations clearly

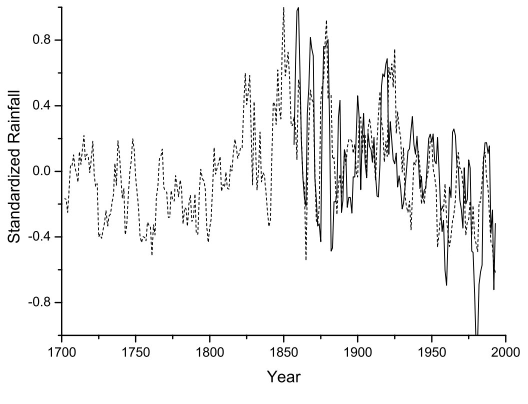

Figure 3. The 3-year running mean time series of the DSA (dotted line) and Northeast India rainfall (solid line).

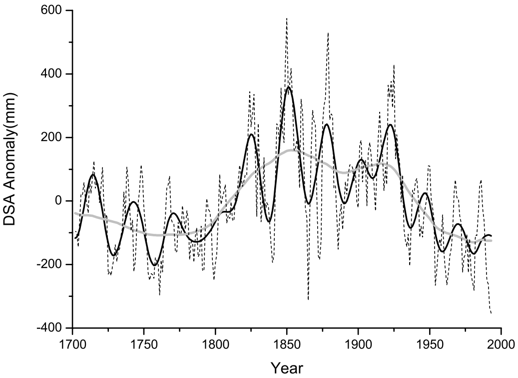

Figure 4. The original 3-year running mean time series (dotted line) of the DSA, reconstructed secular trend (gray line) and 26-year oscillation + trend (black solid line).

dominate the DSA. However, lower-frequency variability in the DSA is also apparent, with a sharp increase around the 1850s. To isolate the lower-frequency features, we apply SSA to the 3-year running mean time series. As the lowest frequency estimated by Fast Fourier Transform (FFT) is 25.6 years, the window width of 30 years is used in SSA. The results show that the first leading PC represents a long-term trend, the second and third PCs represent a 26-year oscillation. The long-term oscillation explains 37.8% and the 26-year oscillation accounts for 24.8% of the total variance of the time series, and both of them are clearly separated from the remaining PCs (Figure 4). The residual time series show interannual and interdecadal oscillations at the period of 9-year, 12-year, 7-year and 4-year, describing 17%, 8%, 4% and 4% of total variance respectively.

[12] The trend variability of DSA (gray line) over the period of 1700–1995 in Figure 4 shows that south Asian monsoon in the north Indian subcontinent, including the central Himalayas, Bangladesh, Nepal and Northeast India, had weakened in 18th century, then strengthened between the early 19th century to 1920's, after that it has weakened from early 1920 to the present.

4. Conclusions

[13] The relatively short length of most instrumental climate records restricts the study of South Asian monsoon variability, and it is therefore essential to extend the record into the past with the help of proxy dada. Here we presented a 295-year snow accumulation record from an ice core at a height of 7000 m above sea level—from central Himalayas. This record shows features that are closely linked with the south Asian monsoon for the period of instrumental data availability. Contemporary comparison shows variation in the DSA is in-phase (out-of-phase) with that in monsoon rainfall of Northeast India, Nepal and Bangladesh (West peninsula India and East Peninsula India) at centennial and multidecadal time-scales. The results show the reconstructed DSA provides a strong record of South Asian Monsoon variability in the northeast Indian subcontinent over the past 300 years at centennial and multidecadal time scales, suggesting we can examine the monsoon variation over a longer perspective. Over the period 1700–1995, the central Himalayas has suffered a weakening monsoon in 18th century, then a strengthening monsoon between began of the 19th century to early in the 20th century, following as a weakening monsoon from early 1920 to the present. The decrease in the linear rates of the monsoon rainfall in Himalayas during 1901–1995 is about −28 mm to 50 mm/decade. This could be important in understanding the high elevation response of precipitation to global climate change in the 21st century.

[14] **Acknowledgments.** This research was supported by Chinese NSF (40121101, 90102005 and 40101006), Chinese Academy of sciences (KZCX1-10-02 and KZCX2-301), and the Innovation Fund of Chinese Academy of Sciences (210506). Thanks for Mitchell, T. D., Hulme, M., and New, M. providing the rainfall data in Nepal and Bangladesh.

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