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Accumulation Rates over the Past 500 Years Recorded in Ice Cores from the Northern and Southern Tibetan Plateau, China

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Abstract

Based on the Guliya, Dunde, and Dasuopu ice cores and direct observations, we investigated the spatial and temporal variations in precipitation on the Tibetan Plateau over the past 500 yr. The variations in accumulation rates showed significant periodicities of 12.7, 7.6, 6.2, 5.4, 4.4, and 2.1 yr in the Guliya ice core, 9.5, 6.8, 5.7, and 2.1 yr in the Dunde ice core, and 12.3, 7.5, 6.3, 5.3, and 2.4 yr in the Dasuopu ice core. The periodicities displayed in these three ice core records are similar and correspond to the periodicities of the Quasi-Biennial Oscillation, the Southern Oscillation, the North Atlantic Oscillation, and the sunspot cycle. However, the accumulation rate from the Guliya and Dunde ice cores exhibited a generally decreasing trend, while the records from the Dasuopu ice core show a generally increasing trend over the entire period of interest. Our study also indicates that there is a strong negative correlation between the accumulation rates in the ice cores from the northern and southern Tibetan Plateau, especially on climatological (multi-decadal or longer) time-scales. Modern meteorological observation data suggest that a dividing line between the northern and southern Tibetan Plateau with respect to variations in precipitation is located at ~32–33°N. This dividing line coincides with other atmospheric, geographical, geological, and geophysical discontinuities. This suggests that interactions among these phenomena might help to understand the spatial patterns of climate over the Tibetan Plateau.

Introduction

The worldwide retreat of many glaciers over the past few decades is regarded as an unambiguous sign of global warming (Dyurgerov and Meier, 2000; Oerlemans, 2005). However, it was found that many coastal glaciers in Norway began to advance in the 1990s, which was attributed to an increased snowfall in winters (Andreassen et al., 2005; Fealy and Sweeney, 2005). This suggests that the effect of precipitation, in addition to that of air temperature, on glacier mass balance should be considered when we consider glaciers to be indictors of climate change. Recent studies on the variations of glaciers on the Tibetan Plateau show that most glaciers have shrunk, but glaciers in some areas on the northern Tibetan Plateau have expanded over the past three decades (Liu et al., 2004; Shangguan et al., 2004). In order to explain this phenomenon, we need to investigate the characteristics of climate change in different areas of the Tibetan Plateau. We have found that over the past century the warm season air temperature variations over the southern part of the Tibetan Plateau have been different from that in the northern Tibetan Plateau (Wang et al., 2003; Wang, 2006). The spatial and temporal variations in precipitation are usually much more complicated than in air temperature, and precipitation variations play an important role in environmental changes (especially in arid and semiarid regions). The mean annual precipitation is less than 400 mm in most parts of the Tibetan Plateau except in the southeast part and in high mountains, and less than 200 mm in large parts of the northern Plateau (Ye and Gao, 1979). This dry climate results in desert formation in some areas of the Plateau, especially in the north. It is estimated that about 14% of the total area of the Tibetan Plateau is occupied by land that has experienced desertification, and the region is suffering from the intensification of this process (Li et al., 2001, 2004). Thus, investigation of the variations in precipitation can also help us to understand the causes of environmental changes in the Tibetan Plateau. In this paper, we try to study the spatial and temporal variations in precipitation across the Tibetan Plateau using ice core records, observation data and NCEP/NCAR (the National Centers for Environmental Prediction and the National Center for Atmospheric Research) reanalysis data.

Data and Methods

The high elevation of the Tibetan Plateau is instrumental in the development of its many glaciers, the presence of which provides us an opportunity to study suites of ice cores from across the Plateau. From these cores we can reconstruct records of past climatic and environmental changes which can help offset the scarcity of meteorological data.

Since the 1980s, we have drilled cores from the Dunde (38°06′N, 96°24.5′E, 5325 m a.s.l.), Guliya (35°17′N, 81°29′E, 6200 m a.s.l.), and Dasuopu (28°22.58′N, 85°42.94′E, 7000 m a.s.l.) ice caps (Fig. 1). These ice cores are in the Qilian Mountains, the western Kunlun Mountains and the Himalayan Mountains, respectively. Dunde and Guliya are located in the north, where climate is influenced mainly by the westerlies, while Dasuopu is in the Himalayas to the south, which is influenced by the Indian Monsoon in summertime and the southern branch of the westerlies in the winter. By using the seasonal characteristics of $\delta^{18}O$ and dust, the upper parts of these ice cores were dated, and the thicknesses of annual layers were obtained. Considering the

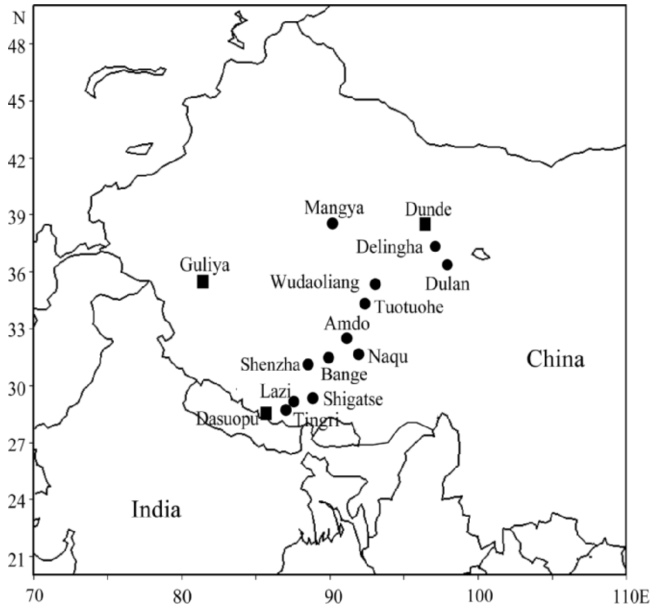

FIGURE 1. Locations of the Dunde, Guliya, and Dasuopu ice cores (black squares) and the selected meteorological stations (black circles) across the Tibetan Plateau.

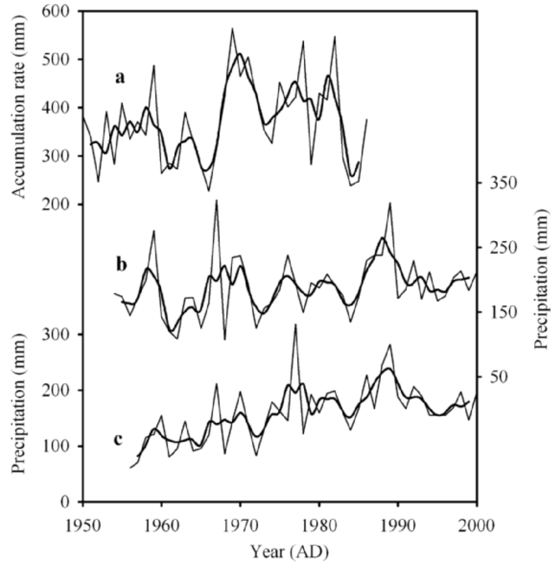

FIGURE 2. Comparison of the records of accumulation rates from the Dunde ice core (a) from 1950 to 1987 with precipitation variations at the Dulan (b) and Delingha (c) meteorological stations from 1955 to 2000.

thinning of annual layers with depth by ice deformation, we reconstructed the annual accumulation rates recorded in these ice cores using a two-parameter steady state flow model that takes into account the rapid thinning of layers near a glacier's flow divide (Bolzan, 1985; Reeh, 1988; Thompson et al., 1989, 1990, 1995, 1997, 2000; Yao and Thompson, 1992; Yao et al., 1997; Yang, 1989; Davis et al., 2005).

Sublimation and/or melting can reduce the ice accumulation rate; in fact some studies indicate that sublimation might be more vigorous on tropical glaciers than on polar glaciers (King et al., 2001; Stichler et al., 2001; Wagnon et al., 2003; Mölg and Hardy, 2004; Ginot et al., 2006). Unfortunately, direct knowledge of the extent of sublimation on Tibetan Plateau glaciers is lacking. However, a recent study showed that sublimation on snow cover in the non-mountainous areas of the central Tibetan Plateau was remarkable in wintertime (Ueno et al., 2007). In order to determine whether ice core accumulation rates could be regarded as proxies of precipitation on the Plateau, we can compare them with precipitation records from nearby meteorological stations. In the case of Guliya, we could not compare the ice-core record with direct instrumental measurements because there is a lack of meteorological stations within acceptable proximity. However, it has been found that there is a strong correlation between the Dasuopu accumulation-rate record and monsoon rainfall in north-central and northeast India (Duan et al., 2004; Davis et al., 2005). Figure 2 shows the similarities between the accumulation-rate record from the Dunde ice core since 1950 and the precipitation records from the nearby Delingha (37°22′N, 97°22′E, 2982 m a.s.l.) and Dulan (36°18′N, 98°06′E, 3192 m a.s.l.) stations. The correlation coefficients between the Dunde record and the Delingha and Dulan records are 0.421 and 0.552, respectively, of which the later one is significant at 10% level. Moreover, Figure 2 also illustrates that the annual accumulation rate at the high-altitude drilling site was larger than the annual precipitation at the lower elevations, which is consistent with general observations that precipitation is usually larger at high elevations than at low elevations in a mountainous regions. All these suggest that records of accumulation rates from the Tibetan ice cores are acceptable proxies for precipitation histories.

Figure 3a, 3b, and 3c show the reconstructed accumulation records since A.D. 1500 from the Dunde, Guliya, and Dasuopu ice caps, respectively. These provide the basic data for us to investigate the characteristics of the variations in precipitation in different climate regions across the Tibetan Plateau over centennial time scales. In order to detect whether there were pervasive influences of atmospheric phenomena (such as the Quasi-Biennial Oscillation, the Southern Oscillation, and the North Atlantic Oscillation) on the records of these accumulation

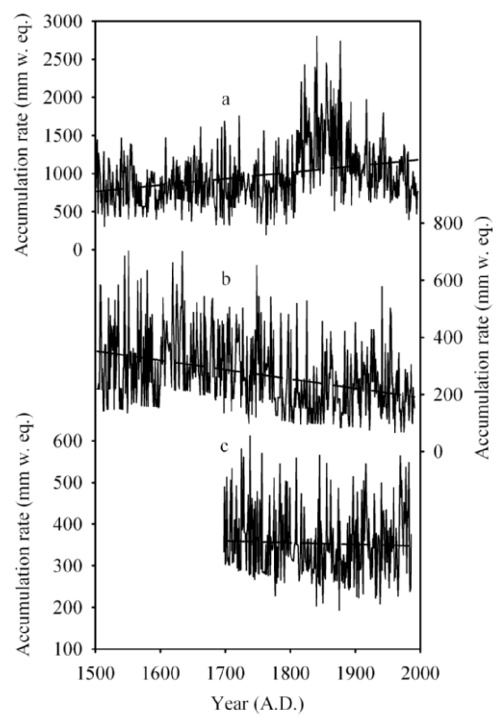

FIGURE 3. Yearly variations of the accumulation rates recorded since 1500 A.D. in the Dasuopu (a), Guliya (b), and Dunde (c) ice cores over the past 500 yr. The dashed lines represent their first order linear trends.

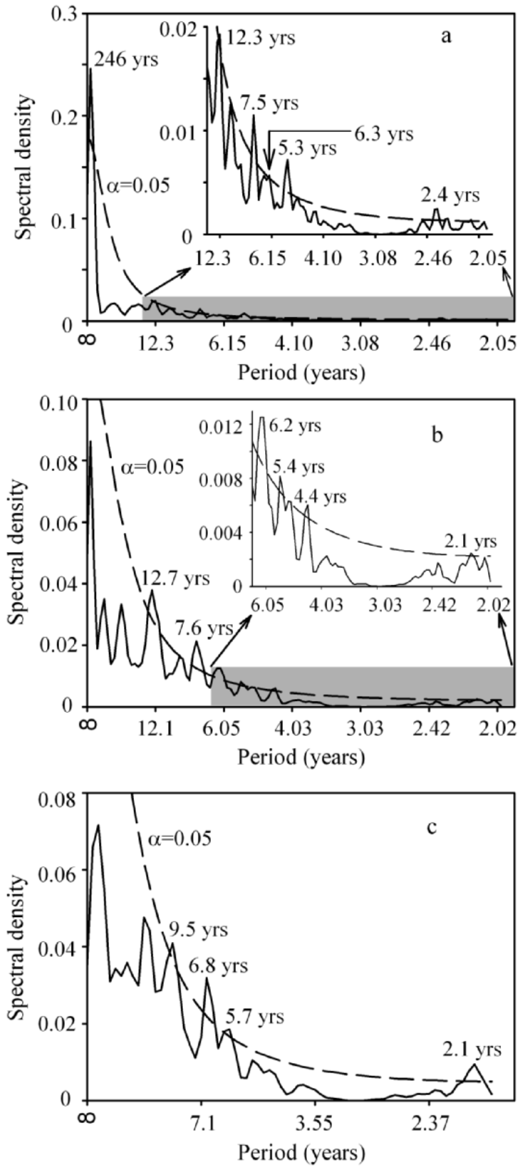

FIGURE 4. Spectral analyses of the accumulation-rate records in the Dasuopu (a), Guliya (b), and Dunde (c) ice cores over the past 500 yr. The dashed lines represent the 5% significance level (α = 0.05).

rates, we used power spectral method (Huang, 2000) to analyze the possible signals of the phenomena in the variations in the accumulation rates. In view of the paucity of meteorological stations within western Tibetan Plateau, we will focus our attention on the variations in precipitation over the northern and southern regions. Therefore, the records from an array of meteorological stations (see Fig. 1) from north to south were selected. We performed correlation analyses (Huang, 2000) on both the instrumental data and the ice-core records in order to ascertain the spatial and temporal characteristics of the variations in precipitation. Moreover, we used the NCEP/NCAR reanalysis data to further verify the results obtained from ice-core records and observation data.

Results and Discussion

Figure 4a, 4b, and 4c shows the results of the spectral analyses performed on the time series of accumulation rates from

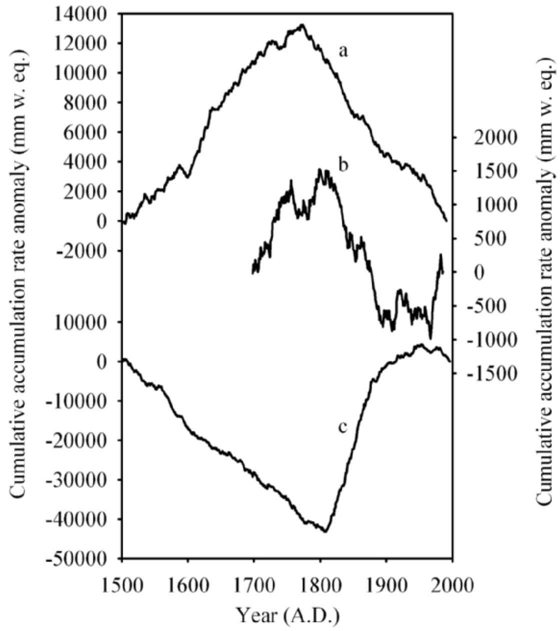

FIGURE 5. Cumulative accumulation rate anomalies in the Guliya (a), Dunde (b), and Dasuopu (c) ice cores since A.D. 1500.

the Dasuopu, Guliya, and Dunde ice cores, respectively over the past 500 yr. Significant periodicities of 12.3, 7.5, 6.3, 5.3, and 2.4 yr occur in the Dasuopu ice core, while periodicities of 12.7, 7.6, 6.2, 5.4, 4.4, and 2.1 yr occur in the Guliya core, and 9.5, 6.8, 5.7, and 2.1 yr in the Dunde core. The periodicities displayed in the three ice-core records are similar, and correspond to those of the Quasi-Biennial Oscillation (about 2.3 yr; Angell and Korshover, 1964), the Southern Oscillation (3 to 7 yr; Ropelewski and Jones, 1987), the North Atlantic Oscillation (about 7.6 yr; Rogers, 1984), and the sunspot cycle. Some studies also found signals of the Quasi-Biennial Oscillation, Southern Oscillation, and the North Atlantic Oscillation in precipitation variations in southern and eastern Tibetan Plateau (Zhu and Zhi, 1991; Liu and Hou, 1999; Yang et al., 2000; Zhou et al., 2001). These imply that atmospheric oscillations might influence precipitation across the whole Tibetan Plateau. In fact, although the Quasi-Biennial Oscillation, the Southern Oscillation, and the North Atlantic Oscillation are regional phenomena, they affect global climate (including temperature and precipitation) by modulating atmospheric circulation (Lau and Sheu, 1988; Yulaeva and Wallace, 1994; Brázdil and Zolotokrylin, 1995; Hurrell, 1995; Baldwin et al., 2001).

We note that the accumulation-rate records from the Guliya and Dunde ice cores exhibit a generally decreasing trend while the Dasuopu record shows an increasing trend over the entire study period (see Fig. 3). This phenomenon suggests that the secular trend in precipitation in the northern Tibetan Plateau is opposite to that in the south. In order to better recognize the patterns in variations of accumulation rates in these three ice cores, we calculated their cumulative anomalies (Fig. 5). Usually several steps should be taken for calculating a cumulative anomaly series. First, a long-term mean value must be computed for a time series data; then, the anomaly time series can be obtained by calculation of the deviations of individual values from the long-term mean; and finally, the cumulative anomaly series can be obtained by summing the anomalies through time. The epochs during which slopes of the cumulative anomalies increase/decrease are the epochs when most anomalies are positive/negative. Therefore,

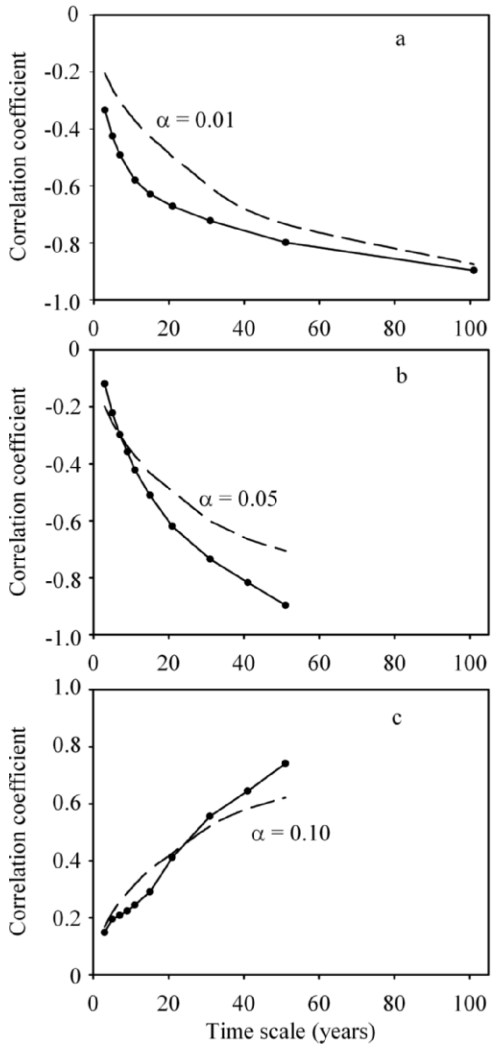

FIGURE 6. Correlation coefficients between the accumulation rates in the Guliya, Dunde, and Dasuopu ice cores on different time-scales. (a) Guliya vs Dasuopu; (b) Dunde vs Dasuopu; and (c) Guliya vs Dunde. The dashed lines represent the α significance level.

Figure 5a indicates that during the epoch from A.D. 1503 to 1771 the Guliya ice cap experienced high accumulation rates, while A.D. 1771 to 1991 was a period of low accumulation rates. Figure 5b illustrates that in the Dunde high accumulation rates occurred from A.D. 1698 to 1799 and from A.D. 1967 to 1986, and low rates occurred from A.D. 1799 to 1967. Finally, Figure 5c shows that low accumulation rates occurred in the Dasuopu record from A.D. 1500 to 1805 and from A.D. 1953 to 1996, and high accumulation rates from A.D. 1805 to 1953. Thus Figure 5 suggests that the variations in accumulation rates in the northern Tibetan Plateau have generally been opposite from that in the southern Tibetan Plateau over the last 500 yr.

Figure 6 shows the correlation coefficients between the accumulation rate time series from the three ice cores, which were calculated for various running averages. Recently, much attention has been paid on the spatial patterns of climate variability on the different time scales. If we take the years by which the running averages were computed as a time scale of interest, it can be seen from the Figure 6 that, on climatological (multidecadal or longer) time-scales the following pattern emerges. Accumulation rates in the Dasuopu ice core were significantly and negatively correlated with those in the Guliya and Dunde ice cores, and the record from the Guliya ice core was significantly and positively related with

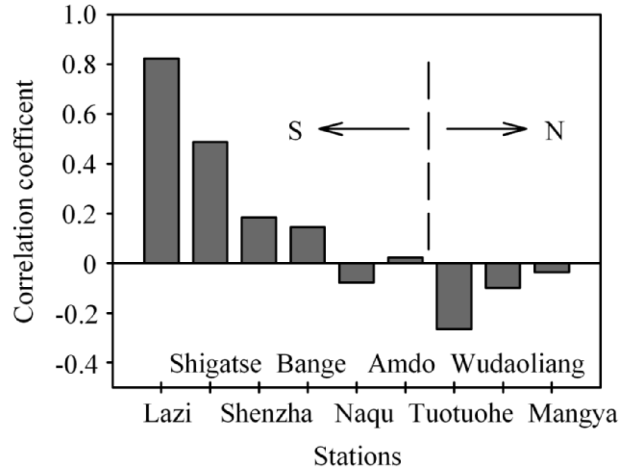

FIGURE 7. Correlation coefficients between annual precipitation from Tingri, the southernmost meteorological station, and each of the meteorological stations along the north-south transect shown in Figure 1.

that from the Dunde ice core. These further illustrate that the variations in accumulation rates in the northern Tibetan Plateau were opposite from that in the southern Tibetan Plateau on climatological time-scales.

We attempted to determine the location of the dividing line separating the precipitation climatology between the northern and southern Tibetan Plateau. In order to pursue this, we used the instrumental precipitation data from a north-south transect of meteorological stations (see Fig. 1) over the past four decades (Fig. 7). The sign of the correlation coefficient changes around Amdo meteorological station (32°21′N, 91°06′E), which is just located to the south of the Tanggula Mountains. This suggests that a climatological division between the northern and southern Tibetan Plateau, with respect to precipitation, is located ~32–33°N.

The scarcity and short-term nature of the meteorological records from the Tibetan Plateau inhibit our ability to investigate the spatial variations in precipitation over this whole region. These shortcomings can be compensated for in part by utilizing the NCEP/NCAR reanalysis data set (available at http://www.cdc.noaa.gov). Thus, we can verify whether there are opposite trends in precipitation over the southern and northern Tibetan Plateau on decadal time-scales. Figure 8a and 8b represents the differences between decadal means (1980s minus 1970s and 1990s minus 1980s, respectively) of surface precipitation rates, and Figure 8c and 8d shows similar differences in surface precipitable water (the water vapor content of a vertical column, which extends from the ground to the top of the atmosphere). These patterns clearly indicate that the variations in both surface precipitation rate and surface precipitable water in the southern Tibetan Plateau were opposite to that in the northern Plateau, and the dividing line was situated ~33°N. We calculate precipitation trend coefficients (defined as the correlation coefficient between the precipitation series and corresponding sequence of years) at each grid point in the area from 27.5°N to 40.5°N and from 77.0°E to 105.5°E, which encompasses the Tibetan Plateau, using University of Delaware air temperature and precipitation data (available at http://www.cdc.noaa.gov/cdc/data.UDel_AirT_Precip.html). The data are of high resolution (0.5 degree latitude × 0.5 degree longitude) and long duration (1950 to 1999). The spatial distribution of the precipitation trend coefficients illustrate that the precipitation trend coefficients are positive in most parts of the north while negative in most of the south (Fig. 9), which

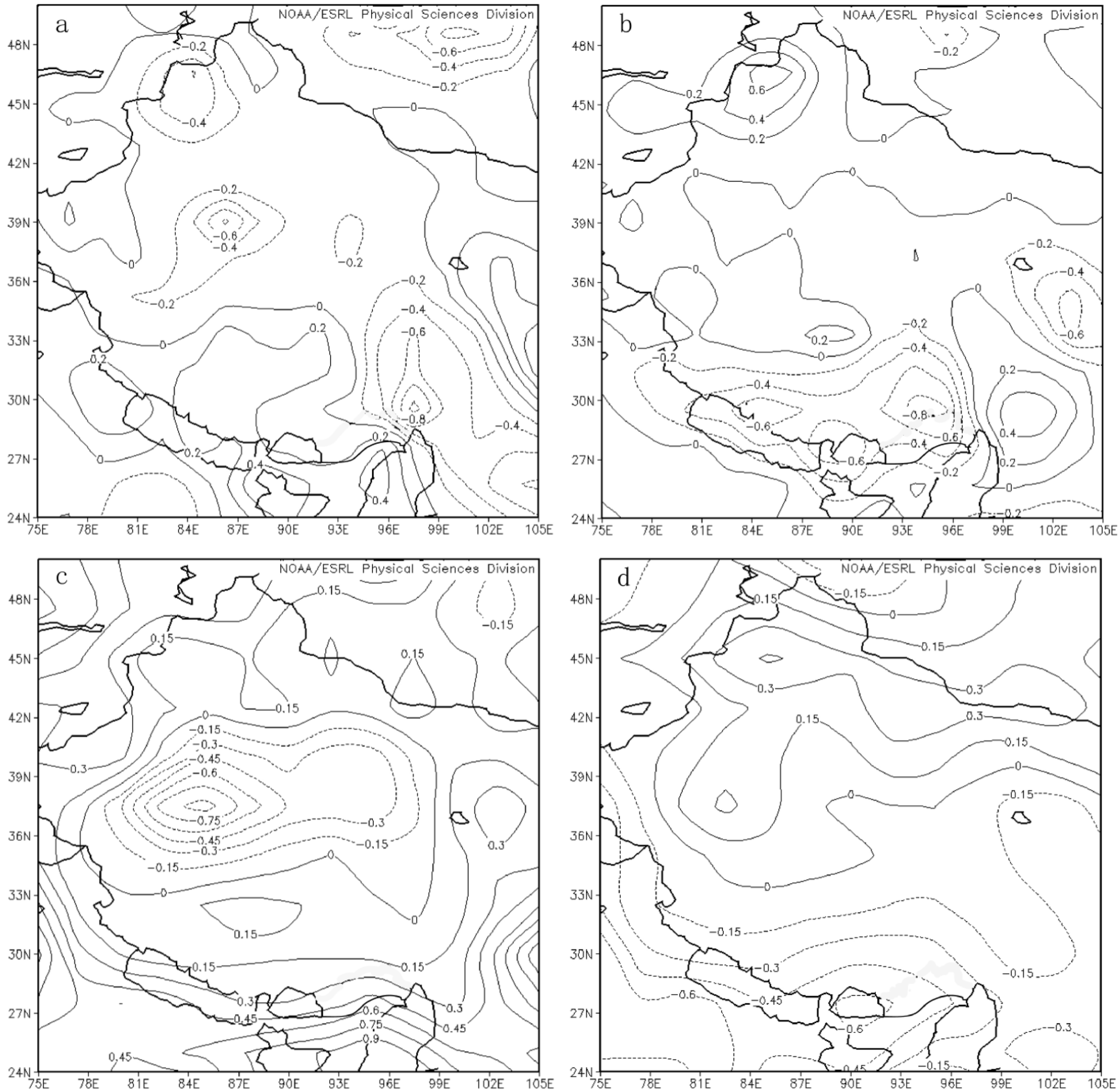

FIGURE 8. Contour maps illustrating the differences between the decadal means of surface precipitation rate (a, b) and surface precipitable water (c, d). All the data are available at http://www.cdc.noaa.gov. Panels a and c represent the patterns resulting from subtracting the 1970s means from 1980s means and panels b and d show the patterns resulting from subtracting the 1980s means from 1990s means. The contour interval for panels a and b is 0.2 mm d^{-1}, and the contour interval for panels c and d is 0.15 kg m^{-2}.

implies that precipitation generally increased in the north while decreasing in the south from 1950 to 1999. These further substantiate the above results derived from the ice core records and instrumental data.

It is not clear why the variations in precipitation in the northern Plateau region are opposite from those in the south. But it is very interesting that the location of the dividing line between them coincides with the location where many atmospheric, geographical, geological, and geophysical phenomena intersect. Examples of these are: the boundary between variations in the warm season air temperatures on decadal time-scales over the past century (Wang, 2006); the average position of the shear line activity (Qiao and Zhang, 1994); the northern limit of the influence of the Indian Monsoon (Qiao and Zhang, 1994); the southern limit of the continuous permafrost region (Zhou et al., 2000); the location of the Lake Bangong-Nu Jiang suture zone (Kong et al., 1996); the dividing line between the young (south side) and the old (north side) terranes (Kong et al., 1996); and the dividing line between the high (south side) and the low (north side) geothermal heat fluxes (Shen et al., 1992). These suggest that an important dividing line of climate, environment, and geophysics occurs across the Tibetan Plateau at ~32–33°N.

Conclusions

Precipitation variations, like temperature variations, can exert a strong influence on environmental changes. The environmental conditions in different regions of the Tibetan Plateau are

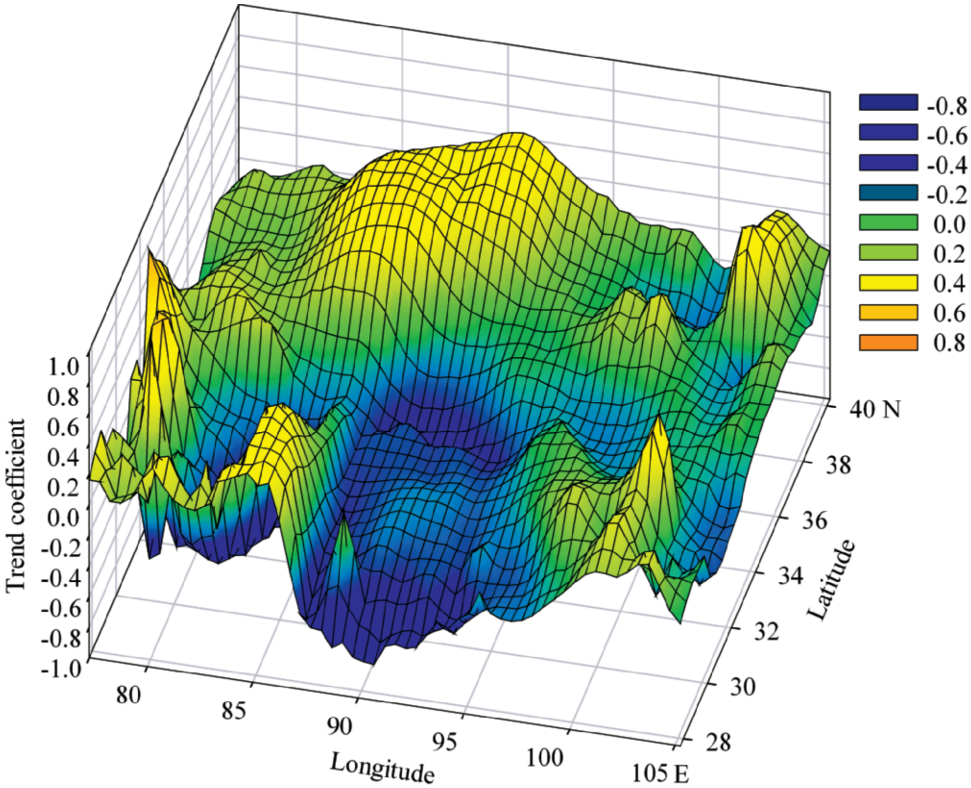

FIGURE 9. Spatial distribution of the precipitation trend coefficients during the period from 1950 to 1999.

distinctly different. Examining the spatial and temporal variations in precipitation over the Plateau can help us to better understand the past environmental changes in this high land. Through analyses of the records of accumulation rates from the Dasuopu, Guliya, and Dunde ice cores and of recent meteorological data, we find that over the past 500 yr precipitation in the largely dry northern Tibetan Plateau shows a generally decreasing trend, which is opposite to the precipitation trend in the south. Although the site of the Guliya ice core is far from that of the Dunde ice core, the accumulation rate records of these sites are significantly correlated on climatological (multidecadal) time-scales, which hints that the variations in precipitation in the northern Tibetan Plateau have been consistent over a large area. A climatological dividing line between the northern and southern Tibetan Plateau with respect to variations in precipitation appears to be located at ~32–33°N.

Acknowledgments

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