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Annual Accumulation in the Mt. Nyainqentanglha Ice Core, Southern Tibetan Plateau, China: Relationships to Atmospheric Circulation over Asia

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Abstract

Annual accumulation records covering the period A.D. 1952–1998 were reconstructed using a 29.5-m ice core from the col of the Lanong Glacier (5850 m a.s.l.) on the eastern saddle of Mt. Nyainqentanglha, southern Tibetan Plateau. Using NCEP/NCAR Reanalysis data, we explore the relationships between this ice-core accumulation record and primary components of the climate system. Linear correlation analysis between annual accumulation and climate components for the 47-yr overlap period indicates that annual accumulation variations are closely correlated with sea-surface and 500-mb air temperature over the North Indian Ocean and atmospheric circulation (surface pressure and geopotential height) over Asia ($r > 0.34$, $P < 0.01$). An intensification of atmospheric circulation and increase of sea-surface and air temperatures, resulting in intensified moisture availability and moisture transport, have been a major cause for the increase of ice-core accumulation over the Mt. Nyainquentanglha region since the 1980s.

Introduction

Several deep ice cores retrieved from the Tibetan Plateau have been used to reconstruct paleoclimate histories since the Last Glacial period (Thompson et al., 1989, 1997, 2000; Yao and Thompson, 1992; Yao et al., 2002; Qin et al., 2000, 2002). Recent studies investigating the relationships between ice-core records and atmospheric circulation suggest that variations of major ion concentrations in a Mt. Everest ice core are closely correlated with the winter Mongolian High and summer Mongolian Low over Asia (Kang et al., 2002, 2003), indicating that glaciochemical records from ice cores can be used as proxies for reconstructing history of past atmospheric circulation. Ice-core accumulation records from the Tibetan Plateau enable precipitation history to be reconstructed (Yao et al., 2000; Yang et al., 2006). Since precipitation is largely driven by the Indian Monsoon in the southern Tibetan Plateau (Kang et al., 2000), ice-core accumulation records from this region provide information about Indian Monsoon variability (Duan et al., 2002). Since the 1950s, ice-core accumulation records indicate a general decline in the Himalayan region, and an increase in the central and northern Tibetan Plateau (Duan et al., 2002; Hou et al., 2002), indicating regional differences in trends of Tibetan Plateau precipitation (Yao et al., 2000; Wei et al., 2003).

South and central Asian climate is influenced by polar air masses originating in the Arctic, continental air masses originating over central Asia, and equatorial-maritime air masses originating in the Pacific and Indian Oceans (Bryson, 1986). The Tibetan Plateau plays a central role in the climatology of this region. It blocks mid-latitude westerlies and splits the jet into two currents that flow south and north of the plateau (Fig. 1). A complete reversal of weather patterns occurs from summer to winter. In summer, low pressure over the plateau induces a supply of moist and warm air from the Indian and Pacific Oceans to the continent (summer monsoon). In winter, high pressure drives cold and dry air moving out of the plateau (winter monsoon) (Bryson, 1986; Tang, 1998).

Mt. Nyainqentanglha, located in the southern Tibetan Plateau (Fig. 1), places it under the influence of both the Indian Monsoon and the continental climate of central Asia. An ice-core record from Lanong Glacier on the eastern saddle of Mt. Nyainqentanglha (30°24.5′N, 90°34.2′E, 5850 m a.s.l., above the influence of the boundary layer) (Fig. 1), offers a unique opportunity to describe and understand change in climate and chemistry of the atmosphere over Asia. Here we present an ice-core accumulation record from Mt. Nyainqentanglha, and investigate the relationships between the ice-core record and primary components of the climate system over Asia using NCEP/NCAR Reanalysis data. The main purpose of the present work is to understand the relationships between ice-core records and atmospheric circulation over Asia, in order to further reconstruct the changing history of atmospheric circulation.

Methods

During July 1999, a 29.5-m ice core was retrieved from the col of Lanong Glacier on Mt. Nyainqentanglha. The ice core was kept frozen during transport from the coring site to a freezer at the University of Maine, U.S.A., and sectioned at 3.5- to 4-cm intervals (total of 791 samples) in the lab. Once scraped, samples were placed into pre-cleaned high density polyethylene containers for analysis of major ions and stable isotopic ($\delta^{18}O$ and δD)

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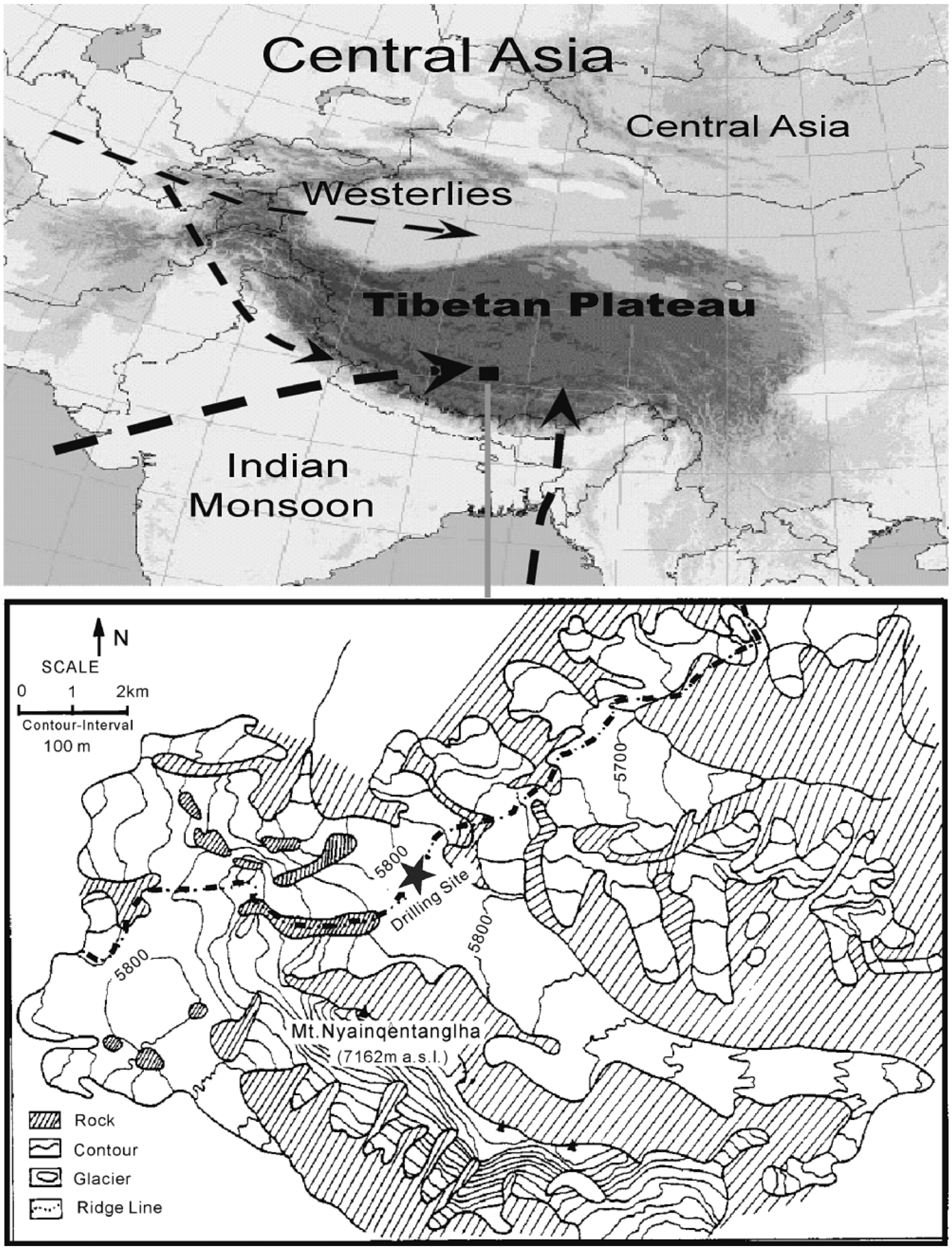

FIGURE 1. Map of the Tibetan Plateau (upper panel), showing schematic trajectories of westerlies and Indian summer monsoon. Black square shows location of lower map. Lower panel shows location of the ice-core site on Mt. Nyainqentanglha, southern Tibetan Plateau.

composition. Meanwhile, scraped ice chips were collected for ^{137}Cs measurements. Hydrogen isotope ratios (δD) were measured via Cr reduction with a Eurovector elemental analyzer coupled to a Micromass Isoprime mass spectrometer (±0.5‰ precision; Morrison et al., 2001) at the Climate Change Institute, University of Maine. All data are reported in standard delta (δ) notation relative to Standard Mean Ocean Water (SMOW). The ^{137}Cs samples were filtered through cation exchange filters and analyzed by a gas-flow proportional counter at the Department of Physics, University of Maine.

Distinct seasonal variations in stable isotope ratios and chemical species in snow over the higher mountains in the southern Tibetan Plateau are reported by several researchers (e.g., Wushiki, 1977; Mayewski et al., 1984; Wake and Stievenard, 1995; Aizen et al., 1996; Kang et al., 2000; Thompson et al., 2000; Tian et al., 2001). In the southern Tibetan Plateau, which is mostly influenced by the Indian Monsoon during summer, annual variations of $\delta^{18}O$ (or δD) values are controlled by the amount effect, with more negative (i.e. lighter) $\delta^{18}O$ values representing summer monsoon precipitation and less negative $\delta^{18}O$ values appearing in other seasons (Wake and Stievenard, 1995; Aizen et al., 1996; Kang et al., 2000; Tian et al., 2001). The distinct seasonal cycles shown in the δD record from the Mt. Nyainqentanglha ice core (Fig. 2) allows us to perform the ice-core dating. Annual layer counting was done by identifying seasonal cycles of δD and verified by ^{137}Cs peaks from known horizons from nuclear bomb testing (1963 and 1958) and the Chernobyl accident (1986) (United Nations, 1993; Eichler et al., 2000) (Fig. 2). We counted 47 annual layers in the 29.5-m ice core, indicating that our record spans the time period A.D. 1952–1999 with a resolution of 17 samples per year.

During summer, melting on the snow-pack surface occurs at the coring site, which produces water that percolates down and refreezes in the colder snow layers below. When the core was drilled in July, there was 40 cm surface snow. Thus, we consider that the formation of ice from snow was accomplished in one year. Research by Pfeffer and Humphrey (1996) suggests that ice layers created during the cycle of summer melting and subsequent

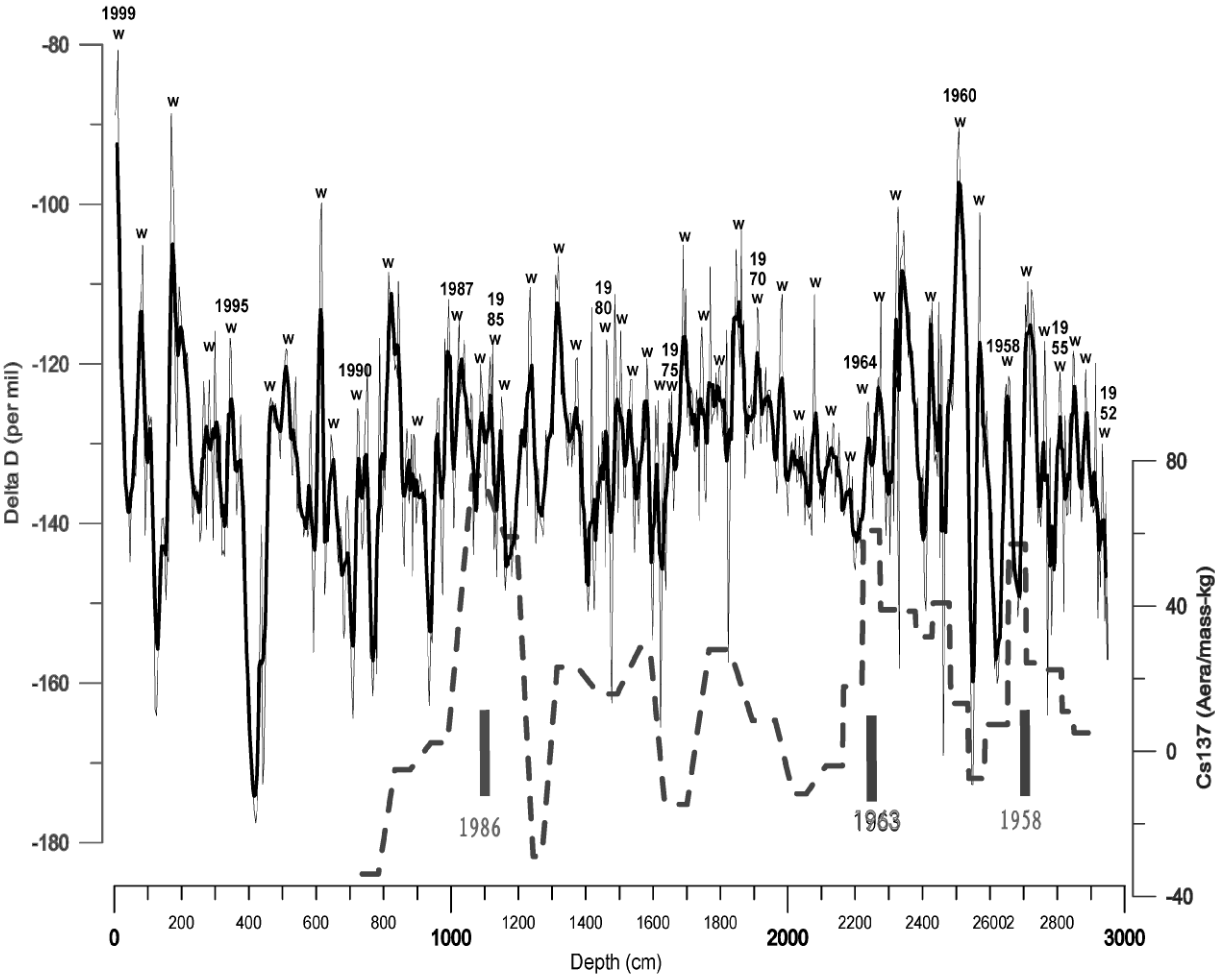

FIGURE 2. Dating for the Nyainqentanglha ice core. The thin and thick lines are the original sampled and 5-point running average values for δD, respectively. The dashed line represents Cesium 137 values used as reference markers. Winter seasons inferred from high δD values indicated with w.

refreezing have the potential to preserve annual signals in an ice-core record by providing physical barriers to stable isotope migration. Since the Nyainqentanglha core still has obvious seasonal signals for δD and air bubbles, we suggest that the summer percolation of melting water does not strongly affect climate records, allowing record preservation.

Annual accumulation and δD values for the past 47 yr were calculated based on the annual layers (Fig. 3). We focus on the annual ice-core accumulation record in this report. During the last 47 yr, the average annual accumulation is 517 mm (water equivalent) at the coring site, which is slightly higher than that at Dangxiong (400 mm) and Lhasa (432 mm). Since the 1950s, there is an increasing trend in annual accumulation with a dramatic increase occurring in the late 1980s. The interannual and interdecadal variations of the Nyainqentanglha accumulation are consistent with changes in precipitation noted from meteorological stations presented by Wei et al. (2003), although the increase in accumulation since the late 1980s is greater in the ice core than the meteorological record. The lower annual accumulations during the 1970s also agree with the dry period reported by others (Lin and Wu, 1986; Wei et al., 2003).

The NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis are obtained by assimilating past data into a state-of-the-art analysis/forecast model system (Trenberth, 1995; Kalnay et al., 1996; Simmonds and Keay, 2000). The database has been enhanced with many sources of observations that were not available in real time operations, and the product is regarded as one of the most complete, physically consistent meteorological datasets (Simmonds and Keay, 2000). The NCEP/NCAR reanalysis archive is provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (Web site: http://www.cdc.noaa.gov). It contains monthly averaged analyses

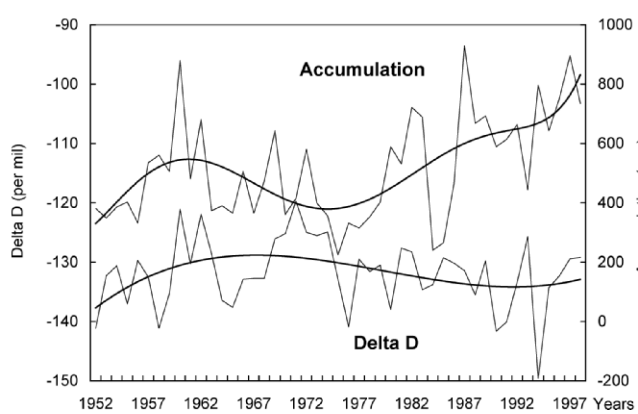

FIGURE 3. Variations of annual accumulation (water equivalent) and annual δD (averaged by value of raw samples in one year) in the Nyainqentanglha ice core. The thick lines are a polynomial regression.

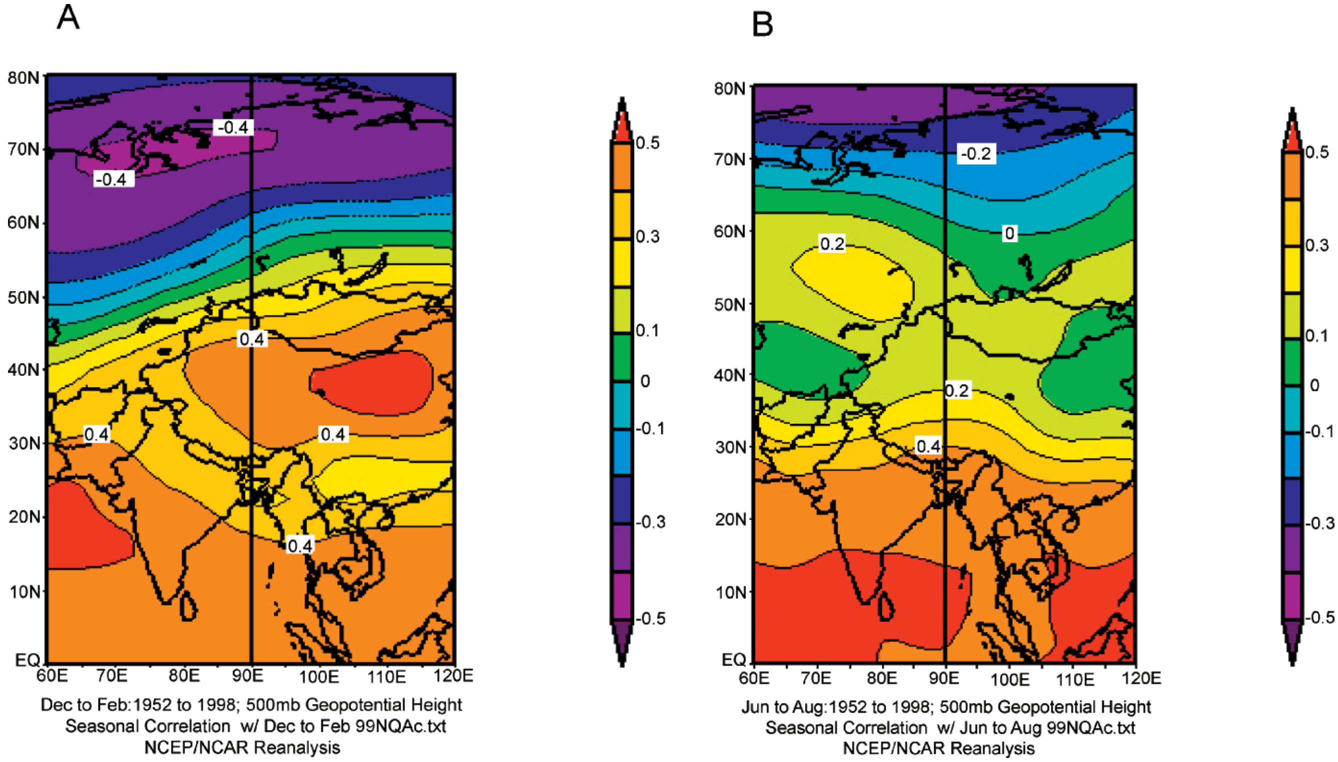

FIGURE 4. Spatial correlation patterns between annual accumulation from the Nyainqentanglha ice core and DJF (A) and JJA (B) 500-mb geopotential height during the period 1952–1998, plotted as correlation coefficients with a contour interval of 0.1.

(reported every 6 h from 0000UTC) on a 2.5 latitude-longitude grid, at 17 standard pressure levels as well as surface and boundary level variables for the period 1948–2003.

In order to investigate potential associations between ice-core accumulation and primary components of the climate system, we use available NCEP/NCAR instrumented/modeled meteorological data to compare with our accumulation records, demonstrating that the Nyainqentanglha annual accumulation record is closely correlated with geopotential height, surface air pressure, sea-surface temperature (SST), and 500-mb air temperature over Asia.

Results and Discussion

RELATIONSHIPS BETWEEN ANNUAL ACCUMULATION AND ATMOSPHERIC CIRCULATION

There is a significant ($r > 0.34$, $P < 0.01$) positive correlation between the Nyainqentanglha annual accumulation and seasonal mean 500-mb geopotential height for both winter (DJF) and summer (JJA) over central and southern Asia, especially in the regions of Tibetan Plateau/central China (during winter) and North Indian Ocean (during summer) (Fig. 4A, B). During winter, a negative relationship exists between annual accumulation and 500-mb geopotential height in the Siberian region (Fig. 4A). The Nyainqentanglha accumulation is also positively correlated with surface pressure over the Tibetan Plateau, and negatively correlated in the Siberian region during winter (DJF) (Fig. 5). Comparisons between annual accumulation and the time series of geopotential height and surface pressure averaged from the most correlated areas show the detailed relationships (Fig. 6). Periods of higher geopotential height and winter surface pressure in the Tibetan Plateau and decreased Siberian pressure coincide with increased Nyainqentanglha accumulation during the past 47 yr (Fig. 6). Lower accumulation during the 1970s and 1984 correspond well to lower winter and summer geopotential height over Asia during these periods and lower winter surface pressure over the Tibetan Plateau with high values in the Siberia (Fig. 6).

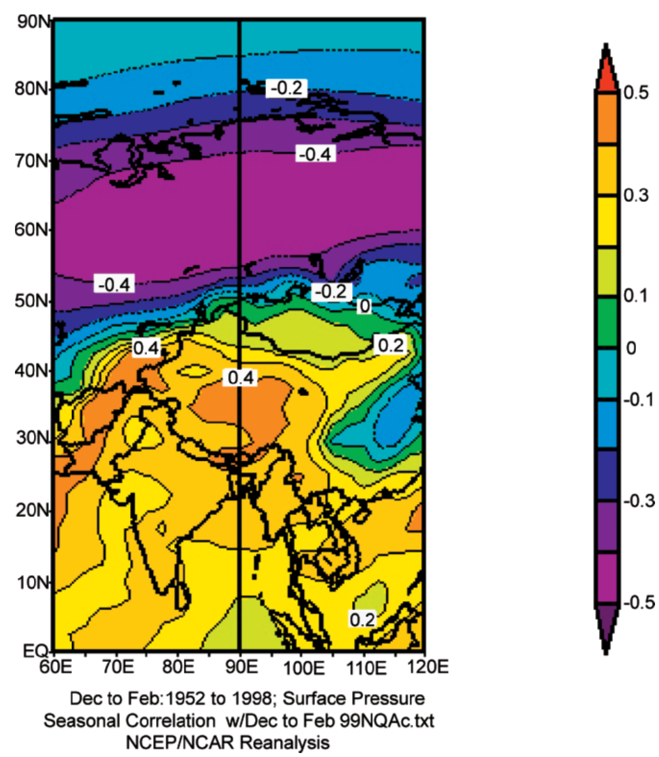

FIGURE 5. Spatial correlation patterns between annual accumulation from the Nyainqentanglha ice core and DJF surface pressure during the period 1952–1998, plotted as correlation coefficients with a contour interval of 0.1.

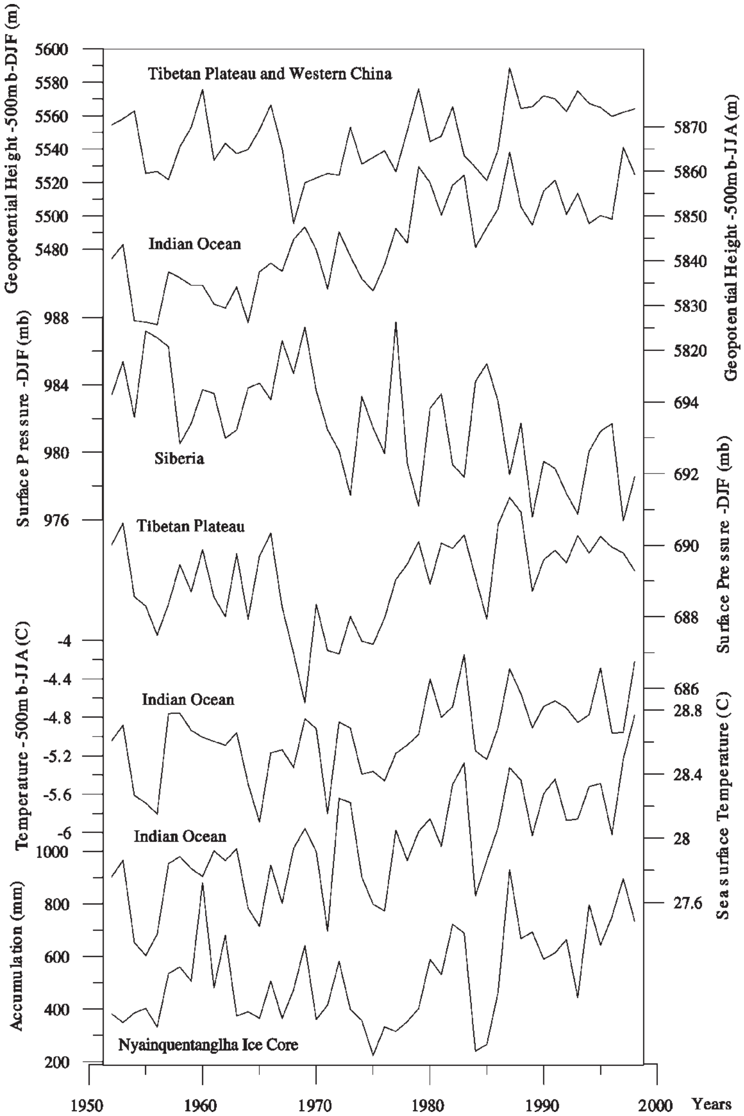

FIGURE 6. Nyainqentanglha annual accumulation compared with annual sea-surface temperature, summer 500-mb air temperature and summer geopotential height over the North Indian Ocean, winter surface pressure in the Tibetan Plateau and Siberia, and winter geopotential height over the Tibetan Plateau and central China.

Geopotential height and surface pressure are major components of atmospheric circulation. An increase in winter geopotential height over the Tibetan Plateau may enhance the winter Tibetan High (Tang, 1998). Meanwhile, both increased winter Tibetan Plateau surface pressure and decreasing Siberia surface pressure may also strengthen the Tibetan High (Tang, 1998). An enhanced Tibetan High is often accompanied by intensified winter atmospheric circulation over Asia resulting in more precipitation and high temperature over the Tibetan Plateau (Tang, 1995). Increased summer geopotential height over the north Indian Ocean may cause steeper pressure gradients from the south to the north during the summer monsoon season, enhancing the transport of moisture from the Indian Ocean to the Tibetan Plateau (Lin and Wu, 1990). Therefore, increasing geopotential height in summer and winter, as well as winter surface pressure over central and south Asia in the last 47 yr, results in intensification of atmospheric circulation over Asia, and strengthening of moisture transport into the Tibetan Plateau. Using strong associations between the atmospheric circulation and the Nyainqentanglha accumulation record, a longer ice-core record from the Nyainqentanglha site could be used to reconstruct atmospheric circulation farther back through time.

RELATIONSHIPS BETWEEN ANNUAL ACCUMULATION AND TEMPERATURE

Significant ($r > 0.34$, $P < 0.01$) positive correlations exist between the Nyainqentanglha accumulation record and SST and summer (JJA) 500-mb air temperature in the North Indian Ocean during the past 47 yr (Fig. 7). Comparisons between interannual variations in annual accumulation and the SST/air temperature time series averaged from the most correlated area in the North Indian Ocean reveal notable coherence, especially since 1965 (Fig. 6). A previous study of the relationship between summer Indian Monsoon rainfall and SST around northern Australia–Indonesia found that warm SST is generally associated with a strong monsoon, whereas, a weak monsoon is usually accompanied and preceded by low SST (Nicholls, 1995). Similar close associations exist between SST of the Indian Ocean and precipitation in the Tibetan Plateau (Jia and Zhou, 2003). When spring SST has a positive anomaly in the Indian Ocean, especially in the Arabian Sea regions, precipitation is high in the southern Tibetan Plateau during summer (Jia and Zhou, 2003). Generally, warmer SST enhances evaporation over the Indian Ocean and supply more moisture for transport to the Tibetan Plateau by the summer Indian Monsoon (Lin and Wu, 1990).

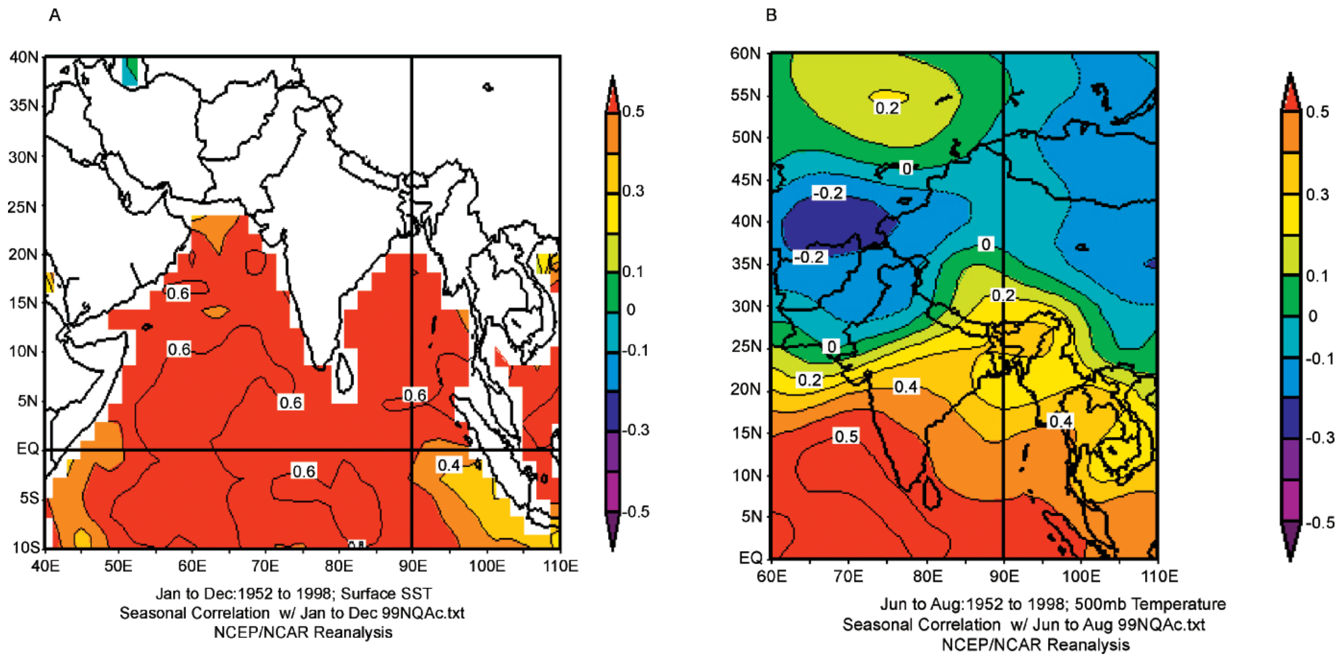

FIGURE 7. Spatial correlation patterns between annual accumulation from the Nyainqentanglha ice core and annual sea-surface pressure (A) and JJA 500-mb air temperature (B) during the period 1952–1998, plotted as correlation coefficients with a contour interval of 0.1.

Figure 8 illustrates relationships between Nyainqentanglha accumulation and other components of the climate system over Asia. Although the majority of precipitation is coming in during the monsoon season over the Tibetan Plateau (Kang et al., 2000), recent study suggests that winter and spring precipitation may also have a contribution in the mountain regions (Tian et al., 2005). Therefore, annual accumulation record is related to both summer and winter atmospheric circulation. During the winter, annual accumulation is most strongly connected with surface pressure and geopotential height over the Tibetan Plateau and nearby regions, reflecting the continental climate system that dominates the region in winter (Bryson, 1986; Tang, 1998). Changes in winter surface pressure and geopotential height may strengthen/weaken winter atmospheric circulation, causing changes in precipitation over the Tibetan Plateau (Tang, 1995). During the summer monsoon season, annual accumulation is more closely connected with geopotential height, SST and air temperature over the Indian Ocean, consistent with the summer Indian Monsoon that prevails over the southern Tibetan Plateau. Variations in geopotential height affect the strength of the Indian summer monsoon, and combined with varying moisture availability that is dependent on SST over the Indian Ocean, yield the fluctuations in precipitation in southern Tibetan Plateau. Enhanced moisture in response to increasing SST as well as strengthened transport of moisture, caused by intensification of atmospheric circulation, may explain of the additional annual accumulation in the Nyainqentanglha region since the 1980s. Although the mechanism of these connections needs further study, the close relationships noted between ice-core accumulation and climate components over Asia offer promise for future climate reconstructions utilizing longer ice-core records.

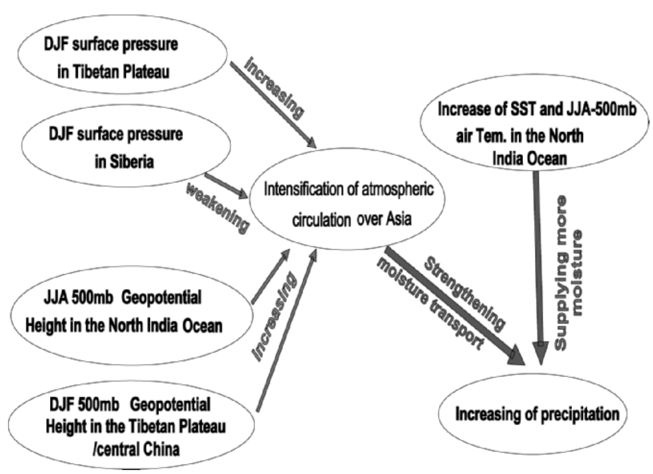

FIGURE 8. Illustration of relationships between precipitation on Mt. Nyainqentanglha region and other components of the climate system over Asia.

Conclusions

Reconstruction of annual accumulation from the Nyainqentanglha ice core reveals details of the variability in precipitation over high-elevation regions in the southern Tibetan Plateau. Interannual and interdecadal variations in Nyainqentanglha accumulation are consistent with changes in precipitation measured from meteorological stations (Wei et al., 2003). However, increasing levels of annual accumulation in the Nyainqentanglha record are more dramatic than those from station precipitation data since the 1980s. Linear correlation analysis between annual accumulation and climate components for the 47 yr period indicates that variations of annual accumulation are closely correlated with SST and 500-mb air temperature over the North Indian Ocean and atmospheric circulation (surface pressure and geopotential height) over Asia. Intensified atmospheric circulation and higher sea-surface and air temperatures since the 1980s enhance moisture transport to the Nyainquentanglha region, resulting in increasing annual accumulation in the Mt. Nyainquentanglha ice-core record. Associations between atmospheric circulation and the Nyainquentanglha accumulation record found in this study can be applied to future studies utilizing longer ice-core records to reconstruct atmospheric circulation farther back in time.

Acknowledgments

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