FOUR CENTURIES OF CLIMATIC VARIATION ACROSS THE TIBETAN PLATEAU FROM ICE-CORE ACCUMULATION AND $\delta^{18}O$ RECORDS

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1. INTRODUCTION

The Tibetan Plateau is an important component of the South Asian Monsoon system, but there are relatively few long, high-resolution records of precipitation and temperature variability from the Plateau itself. Only recently has it been recognized that the distribution and the chemistry of the precipitation across this large, elevated landmass is not uniform (*Araguás-Araguás et al.,* 1999; *Tian et al.,* 2001; *Liu and Lin.,* 2001). These studies have been based on data from precipitation and river water sample collection and analysis, and on patterns of meteorological and reanalysis data. Here, longer, high-resolution records of spatial and temporal variations of temperature and precipitation across the Tibetan Plateau since 1600 A.D. are presented from two ice cores. These ice-core sites are on the southern and northeastern edges of the Tibetan Plateau, thus providing wide spatial coverage (Figure 1).

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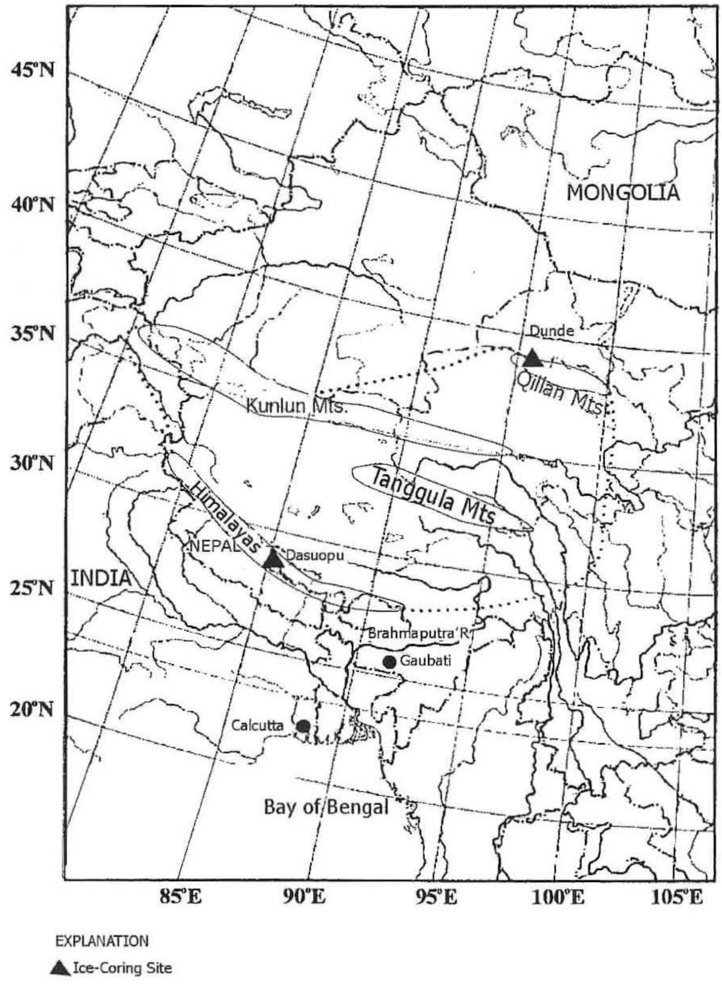

Figure -1. Map of western China and surrounding regions showing locations of the ice-core sites mentioned in the text and the mountain ranges in which they are located. The Tibetan Plateau is outlined by the dotted line.

In the boreal summer of 1987, three ice cores were drilled to bedrock on the Dunde ice cap (38° 06'N; 96° 24'E, 5325 masl) in the Qilian Mountains on the northeast edge of the Plateau. Ten years later, two cores were recovered to bedrock from the 7200 masl Dasuopu ice cap in the Himalayas (28° 23'N, 85° 43'E). The complete records of these cores and their climatic interpretations are presented in *Thompson et al.* (1989) and *Thompson et al.* (2000), respectively. They were analyzed for a variety of physical and chemical properties, including (but not limited to) oxygen isotopic ratios ($\delta^{18}O$) and reconstructed net balance (annual accumulation rate, or a_n). For the most recent parts of the records where seasonal stratigraphy was discernible, annual averages of $\delta^{18}O$ and a_n were calculated, resulting in high-resolution records of climatic variation that span several hundred years. The records from these ice-core sites are now compared with other climate records and with each other to assess the effects of temperature and precipitation on $\delta^{18}O$ values across the Tibetan Plateau, and to determine the spatial and high- and low-frequency temporal variations of temperature and precipitation since 1600 A.D., the extent of annual resolution for the Dunde record (for comparison Dasuopu is annually resolvable to 1440 A.D.).

2. SEASONALITY IN THE TIBETAN PLATEAU ICE CORES

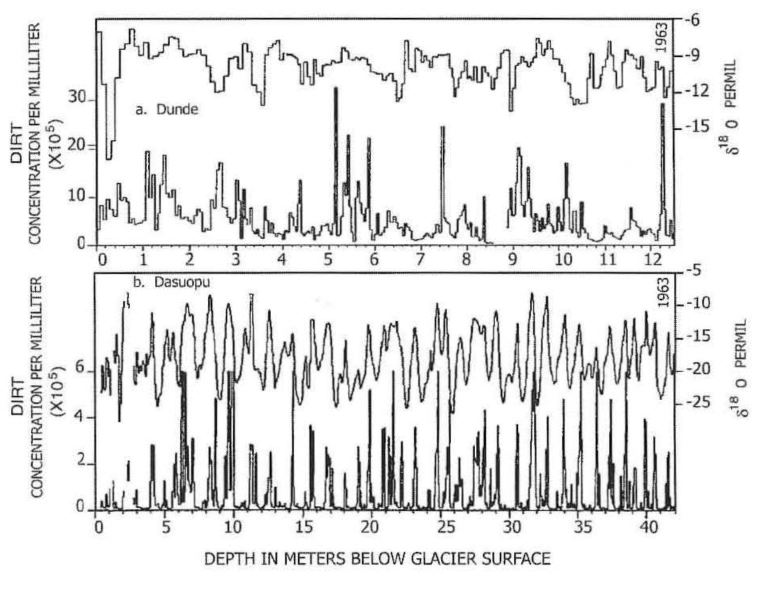

Figure -2. $\delta^{18}O$ and concentration data from the (a) Dunde and (b) Dasuopu ice cores back to the depth corresponding to 1963 in each core, which is the time horizon marked by the β-radioactivity peak in the Tibetan Plateau ice fields resulting from the Soviet Arctic thermonuclear tests.

Seasonal relationships between mineral dust concentration and $\delta^{18}O$ in these two ice-core records are shown in Figure 2. In the Dunde ice, more negative (^{18}O-depleted) $\delta^{18}O$ values are generally contemporaneous with high dust concentrations, which occur in late winter and early spring (*Davis*, 2002). The opposite relationship occurs in the Dasuopu record from the central Himalayas; i.e. the high winter/spring dust concentrations are concurrent with less negative (^{18}O-enriched) values in the core. Alternatively, during the monsoon season in the boreal summer, the precipitation that falls on the Dasuopu ice cap is more ^{18}O-depleted and contains fewer dust particles. Nevertheless, for both these ice fields, over 70 percent of the annual precipitation falls in the summer.

This dichotomy of seasonal δ^{18}O values between the north and the south was discussed by *Araguás-Araguás et al.* (1998). Using the database from the IAEA/WMO Global Network "Isotopes in Precipitation" that spans from 41 to 14 years in Asia, depending on the location, the spatial distribution of the seasonal differences in δ^{18}O shows a reversal between the two sides of the Plateau, with the dividing line at approximately 35°N. Using stable isotopes from a suite of river water and precipitation samples collected along a meridional transect on the Plateau, *Tian et al.* (2001) found a 15 permil decrease from north to south in summer values of δ^{18}O. According to Tian and his colleagues, the spatial patterns of the oxygen isotopes, along with the deuterium excess measured on these water samples, suggest that the Plateau can be divided into two regions of varying degrees of monsoon influence, with the Tanggula Mountains marking the border. South of this range to the Himalayas, the summer moisture is monsoon-derived, although recycled during its transport over the Indian subcontinent, and to the north the influence of the summer monsoon is greatly diminished.

2.1 δ^{18}O and accumulation records from Tibetan Plateau ice cores since 1600 A.D.

The δ^{18}O profiles from the Dunde and Dasuopu ice cores are shown in Figure 3a and 3b as five-year averages. The Northern Hemisphere temperature anomaly data of *Jones et al.* (1998), also calculated in five-year averages, are shown in Figure 3c. All the records are broadly similar, with gradually increasing trends until the middle of the 19th century, then a steeper positive slope toward the present. The δ^{18}O and the temperature anomalies peak in the middle 20th century, decrease slightly in the 1960s and 1970s, then increase toward the present.

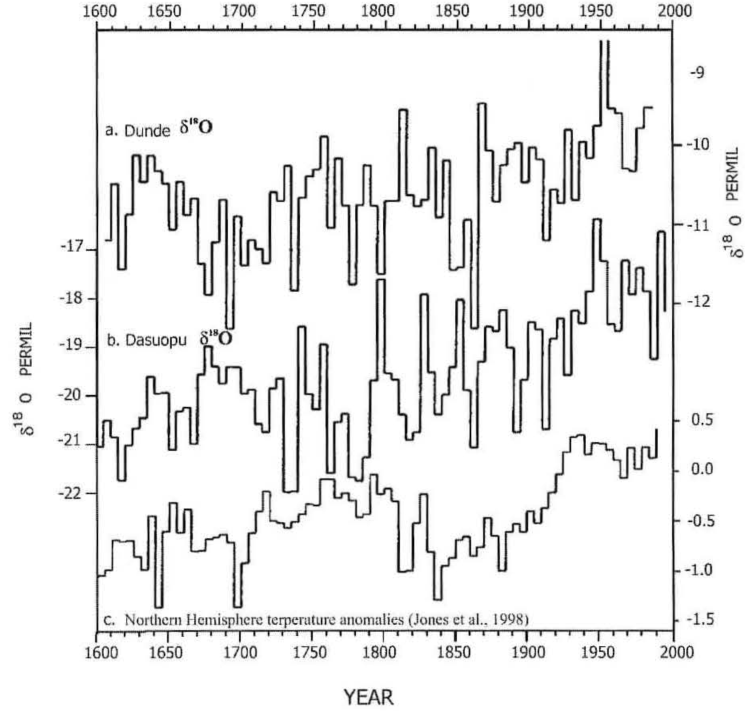

Figure -3. Five-year averages of $\delta^{18}O$ values from the (a) Dunde and (b) Dasuopu ice cores back to 1600 A.D. The Northern Hemisphere temperature record of *Jones et al.* (1998), also calculated as five-year averages, is shown in (c).

The reconstructed accumulation records from these sites are displayed in Figure 4. The Dunde data show wet periods from 1600 to about 1760 and about 1880 to the present, and lower accumulation between 1760 and 1880. The Dasuopu record, however, has an inverse accumulation profile, with much higher rates during the period of lowest values in the northern site. In fact, the correlation coefficient between Dunde and Dasuopu (5-year averages) is –0.57, significant at the 99 percent level. The spatial patterns of accumulation between the north and south sides of the Tibetan Plateau that are presented by these ice cores suggests that the region affected by the monsoons, in which the more isotopically depleted snow falls in the summer, has an opposite precipitation history to that in the north, where the seasonal relationships of $\delta^{18}O$ are also reversed.

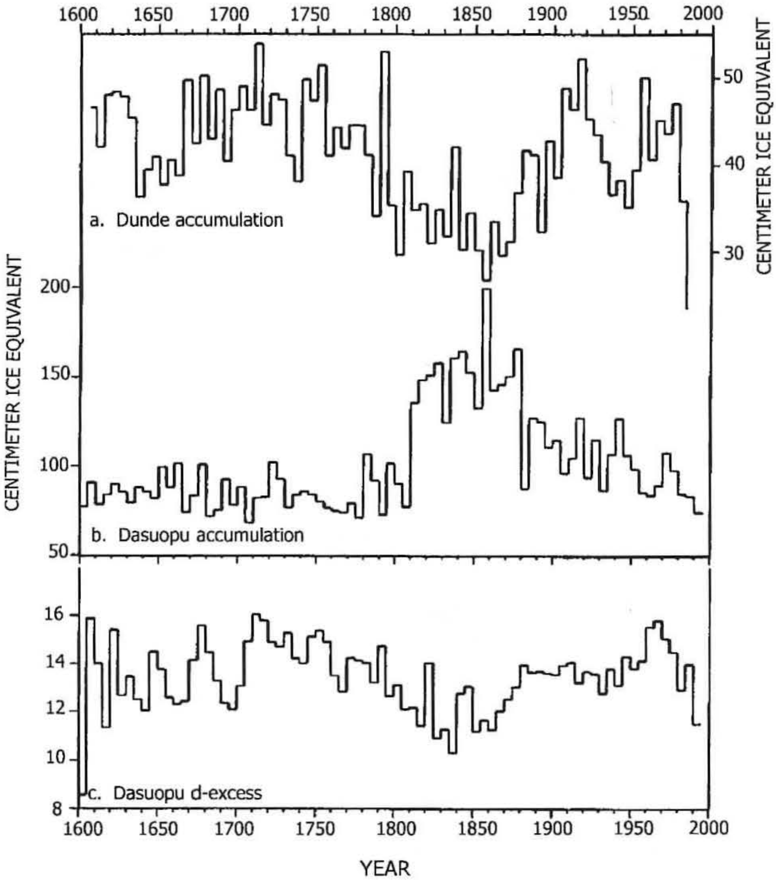

Figure -4. Five-year averages of accumulation from the (a) Dunde and (b) Dasuopu ice cores back to 1600 A.D. The Dasuopu d-excess, also calculated as five-meter averages, is shown in (c).

2.2 Temperature, precipitation and their influence on $\delta^{18}O$ in Tibetan precipitation

Currently, there is a debate over the atmospheric and hydrological parameters that control the stable isotopic composition of rain and snow in low latitudes, including the Tibetan Plateau. In the case of $\delta^{18}O$ in meteoric water in the northern part of Tibet, where the monsoon influence is weak or nonexistent, many believe that it is controlled mainly by temperature (*Araguás-Araguás et al.*, 1998; *Yao et al.*, 1996; *Thompson et al.*, 1989).

However, the controversy surfaces over the interpretation of stable isotopes in precipitation in the monsoon-dominated south. Because the summer precipitation in the Himalayas is more ^{18}O-depleted than in the winter, *Dahe et al.* (2000), *Shichang et al.* (2000), and *Tian et al.* (2001) credit the "amount effect" as being the dominant influence on the isotopic fractionation. In the regions of Asia that lie within the domain of the Indian and Southeast Monsoons, *Araguás-Araguás et al.* (1998) noticed an inverse correlation between mean monthly $\delta^{18}O$ in summer rainfall and the amount of precipitation. A simple explanation of the mechanism behind the amount effect in a monsoon regime is that the amount of precipitation is the controlling factor in the isotopic fractionation of oxygen according to the Rayleigh distillation model, since during precipitation the more ^{18}O-enriched water vapor will initially condense and precipitate out, leaving more ^{18}O-depleted water vapor behind to form the later condensate (*Dansgaard*, 1964). The longer a precipitation event occurs, the greater the amount of ^{18}O-depleted precipitation that falls. This applies to an air mass as it travels farther from its source such that progressively lower $\delta^{18}O$ condensate forms and precipitates as the vapor moves inland. However, since the fractionation process is not always at equilibrium and the water vapor and the condensate are not isolated from the environment, the controls on $\delta^{18}O$ in precipitation are more complex, especially in mountain regions. The ratio of ^{18}O to ^{16}O in alpine snowfall is also affected by temperature at the source and at the deposition site, vertical and horizontal transport pathways, and atmospheric circulation patterns (e.g. *Grootes et al.*, 1989; *Henderson et al.*, 2000; *Araguás-Araguás* et al., 2000; *Thompson*, 2001; *Bradley et al.*, 2003).

Taken together, the accumulation and oxygen isotope profiles from the Tibetan Plateau ice cores raise interesting questions about the influences of temperature and precipitation on stable isotopes. The $\delta^{18}O$ of the Dunde site should be controlled primarily by temperature, since it is located in a more continental climatic regime (*Araguás-Araguás et al.*, 1998; *Tian et al.*, 2001). The comparison between the Dasuopu and Dunde $\delta^{18}O$ records raises an issue: if the primary influence on the isotopic composition of snow in the north is temperature, while in the south it is monsoon intensity, why are the two records similar to each other? If the Dasuopu $\delta^{18}O$ record is a proxy for monsoon precipitation intensity and is strongly influenced by the "amount effect", then it should show an inverse relationship with its accumulation record. This would imply that the region of the Himalayas where Dasuopu is located has been experiencing progressively less snowfall since 1600 while the northeast Plateau region has been getting warmer. In fact, this has not been the case, as Figures 3b and 4b demonstrate. The most obvious disagreement occurred between 1810 and 1870, when the accumulation rate abruptly increased, but the $\delta^{18}O$ did not decrease. In fact, the Dasuopu $\delta^{18}O$

bears a much closer resemblance to the Northern Hemisphere temperature anomalies of *Jones et al.* (1998), which is discussed in *Thompson et al.* (2000) and is shown in Figure 3c. This presents a challenge to assertions about the role of the quantity of precipitation in the fractionation of oxygen in the Himalayan snow.

The Dasuopu profile in Figure 3b is assumed to be indicative of the monsoon season record of $\delta^{18}O$ variations on the basis that 70 percent or more of the annual precipitation falls in the summer season. To prove that this assumption is valid, the isotopic averages in the summer ice layers are compared with those in the annual layers. Because the accumulation is high and the rate of layer thinning is low in the upper 50 m of the Dasuopu ice cap, the annual cycles of $\delta^{18}O$ can be separated into summer and winter averages over the most recent decades. As Figure 5a shows, the annual averages of $\delta^{18}O$ in the Dasuopu record are reliable approximations of the monsoon averages, since the R^2 between these two time series between 1949 and 1996 is 0.90. When these monsoon season $\delta^{18}O$ values over this interval are compared with the annual accumulations (which are also closely related to the monsoon season amounts), the relationship between them, though present, is small ($R^2 = 0.09$, Figure 5b).

This is not to suggest that precipitation intensity in the Himalayas has no relationship to any stable isotope parameters. Deuterium was also measured in the Dasuopu ice samples, and from δH and $\delta^{18}O$, the deuterium excess (d-excess) was calculated. The d-time series shows an inverse relationship with the accumulation profile, particularly between 1800 and 1880 A.D., when the accumulation rate is high (Figure 4b,c). The d-excess ($d=\delta^2H-8\delta^{18}O$) is a measure of kinetic effects at both the source and the deposition of the moisture. It is lower when wind speeds are higher or when evaporation rates decrease at the source (*Merlivat and Jouzel*, 1979; *Jouzel et al.*, 1982; *Johnsen et al.*, 1989). In the Dasuopu ice core, the low d-excess that is contemporaneous with the high accumulation from 1810 to 1870 A.D is suggested by *Thompson et al.* (2000) to mean that the monsoon intensified greatly during this period.

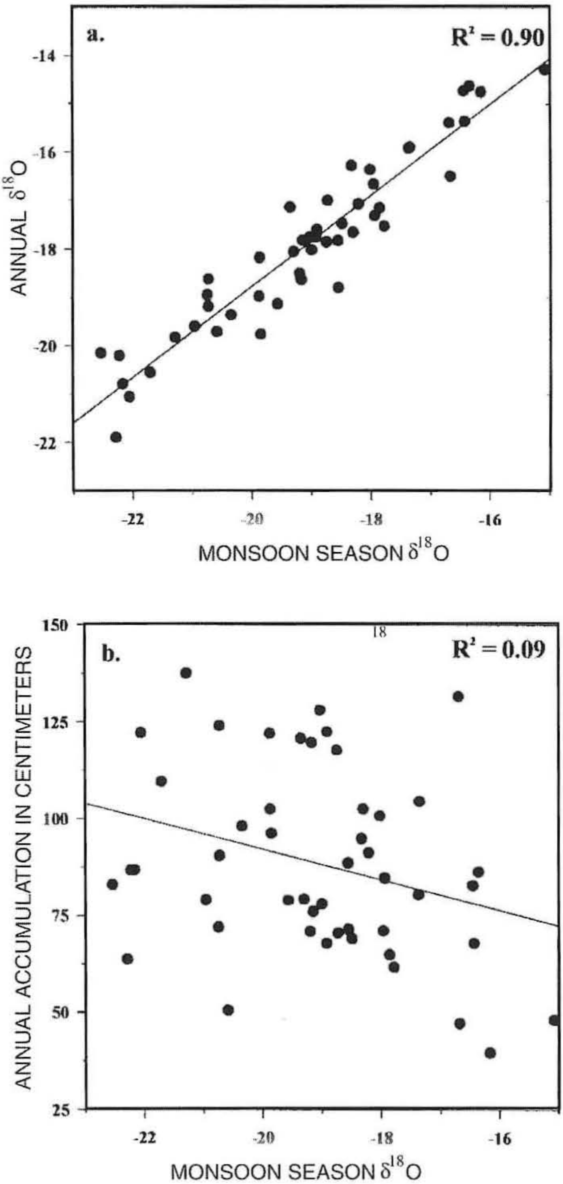

Figure -5. Regressions between (a) the average monsoon season $\delta^{18}O$ and the annual average $\delta^{18}O$ for the Dasuopu ice core from 1949 to 1996, and (b) the average monsoon season $\delta^{18}O$ and the annual accumulation for the Dasuopu core from 1949 to 1996.

3. PRECIPITATION SOURCES AND INFLUENCES

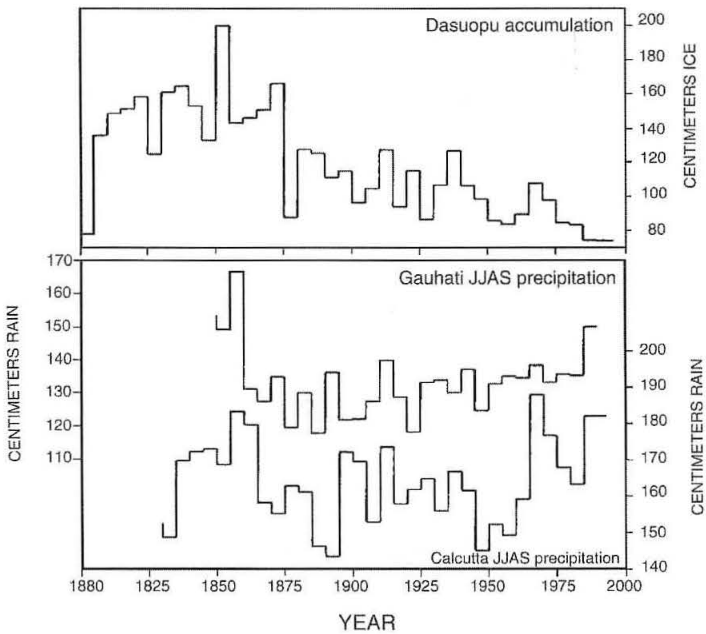

Figure -6. Dasuopu annual accumulation compared with rainfall amounts during June, July, August and September at Gauhati and Calcutta, India. All data are five-year averages. The Indian precipitation data is from the NOAA NCDC GCPS Monthly Station data set, available through the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu).

The averages of the annual accumulation rates over the last four centuries on the Tibetan Plateau ice caps have been highly variable, from as little as 40 cm of ice per year on Dunde, up to 97 cm on Dasuopu. As mentioned above, most of the annual snow budget (70 to 80 percent) falls on these sites in the summer, so the records of $\delta^{18}O$ and accumulation in Figures 3 and 4 can be considered as summertime climate histories. In the winter, the westerlies dominate at the 500 hecto Pascals (hPa) level throughout the Plateau, even along its borders, and the ice-core sites most likely receive their winter moisture from cyclonic activity that ultimately originates in the North Atlantic and travels through western and central Eurasia. Precipitation sources in the summer are more variable. The Himalayas, which are located well within the region of South Asian monsoon influence, receive their snow from the Indian Ocean through the Arabian Sea. *Lin et al.* (1990) and *Shrestha et al.* (2000) have noted two moisture trajectories over the Himalayas from the south: on the west side, water advects northward from the Arabian Sea over the Indian subcontinent, and the moisture for the eastern Himalayas travels from the Arabian Sea across India to the Bay of Bengal, then northward along the Brahmaputra River valley. The Dasuopu ice cap appears to be located close to the dividing point between these two regimes. Meteorological station records from Calcutta and Gauhati on the eastern edge of the Indian Peninsula (Figure 1) suggest increases in summer rainfall in the middle of the 19^{th} century as seen in the Dasuopu accumulation record (Figure 6), although after this time the ice core and station data show no significant correlations.

Tracking the summer sources of snow for the north Plateau is more complicated. The degree to which this region of Tibet is currently affected by the summer monsoon is uncertain. The Dunde ice cap is located in an area that *Winkler and Wang* (1993) assert is affected primarily by air masses that travel through Central Asia in the summer. *Tian et al.* (2001) have discovered that north of the Tanggula Mountains the river water chemistry (high $\delta^{18}O$ and d-excess) indicates that precipitation is the result of local convective activity resulting from continental moisture recycling.

There is evidence that the accumulation on the Dunde ice cap is linked to atmospheric processes in the North Atlantic. Similarities between the accumulation record, the July and August Icelandic Low sea level pressure variations since 1824, and the July and August North Atlantic Oscillation index since 1865 *(Hurrell*, 1995; *Jones et al.*, 1997) are illustrated in Figure 7. Although these data appear to agree broadly, the relationship of high accumulation/high Icelandic Low sea-level pressure (SLP)/low NAO index is not what one might expect if the North Atlantic is the summertime source of moisture for the northern part of the Plateau. *Liu* and *Yin* (2001) analyzed meteorological data from an array of stations to determine that the summer indices of the NAO are related to the precipitation patterns over the eastern Tibetan Plateau. During negative phases of the NAO, southerly winds in the southern Tibetan Plateau and northerly winds in the northern Tibetan Plateau are intensified, resulting in lower precipitation in the north and higher precipitation in the south. However, comparisons of Figures 4 and 7 show the opposite configuration in the case of Dunde and Dasuopu, that is, during periods of low July and August NAO indices (and high Icelandic Low SLP's), the accumulation rates over Dunde in the north increased, while on Dasuopu in the south they decreased.

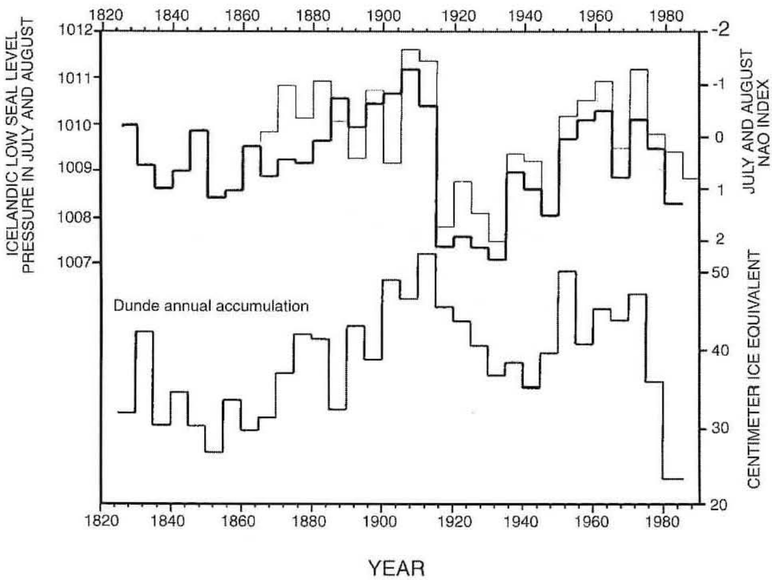

Figure -7. Relationship between the average of July and August Icelandic Low sea level pressure (heavy line), average July and August North Atlantic Oscillation Index (light line), and the annual accumulation from the Dunde ice core. All data are calculated as five-year averages.

An explanation for this may be provided by *Fu et al.* (1999), who noted that during summers of weakened westerlies from the North Atlantic to western Asia (which is a situation described by high NAO indices) the Asian monsoon troughs strengthen. This is more consistent with the Tibetan Plateau ice-core records; for example, the summertime Icelandic Low SLP was low (and the NAO was high) from the early to the middle 19th century, contemporaneously with the accumulation increase in Dasuopu which may have been caused by a strengthened monsoon. At the same time, the accumulation decrease in the Dunde record may have resulted from weakened cyclonic activity from the west. If these relationships between the ice cores and the North Atlantic summertime atmospheric conditions persist further back in the record, then these accumulation data from the north and south sides of the Tibetan Plateau may provide information on the variability of the summer NAO that spans several centuries.

3.1 Comparison of Tibetan Plateau precipitation histories with other proxy records

There are few high-resolution climate records that have been recovered from the Tibetan Plateau and surrounding regions. One source of information comes from tree rings, such as the composite of seven records from the Tibetan Plateau (*Wu*, 1995) that is shown in Figure 8, along with the Dunde accumulation record. The broad, low-frequency variations are similar between the two records, especially the middle 19th century low, the increases in the 20th century, and the most recent abrupt drop in precipitation. Unfortunately, *Wu* does not indicate from where on the Tibetan Plateau these records come, but a description by *Li* (1985) of a precipitation record that was reconstructed from a set of tree-ring chronologies from the east Tien Shan in northwest China indicates that the dry periods here were from 1685-1725, 1813-1890, and from 1927 to the end of the record. This generally agrees with the time series shown in Figure 8.

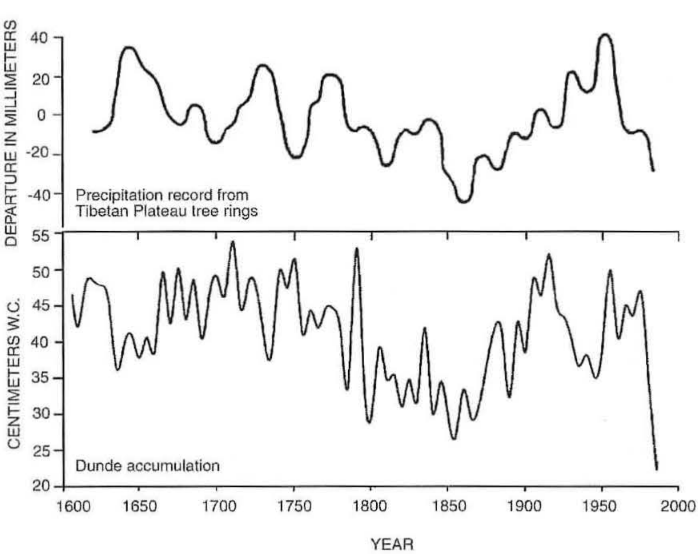

Figure -8. Comparison between the precipitation history from the Tibetan Plateau that was reconstructed from tree rings (*Wu*, 1995) and the five-year averages of the Dunde accumulation back to 1606 A.D. The tree-ring data are presented as departures from the mean of the latest 30 years.

A high-resolution marine record of monsoon intensity provides a much different scenario than that presented by the Dasuopu ice core. Increasing abundances of *G. bulloides* in shallow marine cores studied by *Anderson et al.* (2002) indicate that upwelling (and thus wind speed which is indicative of monsoon strength) has been intensifying since 1600 A.D. Since the middle of the 19th century this trend has been opposite to the Dasuopu accumulation profile. The marine record has broadly tracked the Northern Hemisphere temperature curves of *Mann et al.* (1998) and *Jones et al.* (1998), and the $\delta^{18}O$ record from Dasuopu. The link between the monsoon strength and these temperatures is made through the North Atlantic climate and its influence on the extent of Asian snow cover (*Overpeck et al.*, 1996), which in turn may affect the intensity of the South Asian Monsoon (*Barnett et al.*, 1988; *Vernaker et al.*, 1995). However, another scenario involves the strengthening of the tropical hydrology resulting from the increasing Northern Hemisphere temperatures. The increase in sea surface temperatures would lead to greater evaporation rates, which would introduce more moisture in the lower troposphere. Higher surface temperatures would also increase the thermal gradient between land and ocean in the summer, which drives the Asian monsoon system (*Hu et al.*, 2000).

4. CONCLUSIONS

The Tanggula Mountains, which span east-west across the Plateau at 32° to 33°N, mark the location of a precipitation transition between the north and south sides of the Tibetan Plateau. North of this latitude, the accumulation rate is low, ^{18}O-enriched precipitation falls in the summer (Figure 2, this paper; *Araguás and Araguás et al.*,1998), and the d-excess is high (*Tian et al.*, 2001). To the south, the annual accumulation is higher, the ^{18}O-enriched precipitation is deposited in the winter, and the d-excess is lower. In addition, the loading pattern of the first unrotated principle component of the summertime precipitation anomalies (*Liu* and *Yin*, 2001) are out of phase between north and south of approximately 33°N across the eastern part of the Plateau. Many investigators, such as *Tian et al.* (2001) and *Araguás* and *Araguás et al.* (1998) have concluded that the Tanggula Mountains are a barrier to the northward expansion of the influence of the South Asian Monsoon, while to the north recycled rainfall from continental precipitation processes dominate. *Araguás-Araguás et al.* (1998) noted that the line that separates the different characteristics of precipitation in the north and the south sides of the Plateau occurs at the summertime northernmost extent of the Intertropical Convergence Zone over this region.

The spatial and temporal comparisons of the stable isotope and accumulation records from the ice cores recovered from the north and the south of the "Tanggula transition" tend to agree with the stable isotope analyses of water and precipitation samples from across the region, and with the patterns of precipitation variations derived from meteorological station data. Several studies of the stable-isotope chemistry of the precipitation in the South Asian Monsoon region link the "amount effect" with the low summertime values of $\delta^{18}O$, at least on monthly time frames, but over semi-decadal and longer time scales the strongest links appear to be with atmospheric temperature. Currently, an ice core that was drilled in the Tangulla Mountains in 2000 is being analyzed in the same manner as the Dunde and Dasuopu cores, and it is hoped that the stable isotope and accumulation history from this region will help refine the northern extent of the monsoon influence over time.

In the final analysis, no single climate record will provide the complete picture of the history of so large, complex, and spatially variable a system as the South Asian Monsoon. Since the summer precipitation from this ocean-atmosphere interaction is so vital to such a large, densely populated region, it is important that more information be gathered and analyzed on its spatial and temporal patterns in order to help understand the processes that are responsible for the variability in these patterns. It is also important to be able to understand the effects of the recent warming on the intensity and distribution of the monsoon precipitation.

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