Changes in Atmospheric Circulation over the South-Eastern Tibetan Plateau over the last Two Centuries from a Himalayan Ice Core

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Fig. 1: The Eclipse ice core drill at 6500 m on the Far East Rongbuk Glacier with Mt. Everest in the background. Photo. C. Wake.

Introduction

Understanding climate change in central Asia is especially important given the role of the Tibetan Plateau in regional and global atmospheric circulation. Climate in the region is dominated by the Asian monsoon which provides summertime life sustaining rains for hundreds of millions of people. While long-term variability (thousands of years) of the Asian monsoon has been linked to changes in northern hemisphere insolation, shorter-term variability (years to decades) has been explained by changes within the climate system, such as variations in Eurasian snow cover, the El Niño-Southern Oscillation, and tropical sea-surface temperatures. More recently, model results have suggested the importance of anthropogenic forcing (e.g. greenhouse gas, landcover change) for the Asian monsoon.

Ice cores recovered from high elevation glaciers in the Himalaya contain high resolution records that can be used to document annual to century scale changes in the Asian monsoon. Here we document changes in atmospheric circulation over the past 200 years in the south-eastern Tibetan Plateau from the analysis of a multi-parameter major ion record developed from an ice core recovered from the Far East Rongbuk Glacier on the north side of Mt. Everest (Fig. 1).

Methods and Dating

In the spring of 1997 we recovered a 41 m ice core from the accumulation zone at an elevation of 6500 m on the Far East Rongbuk (FER) glacier (Fig. 1, 2). The cleaned core was cut into 0.04 m sections and analyzed for major ion concentrations (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}) and oxygen isotopes. A depth-age relationship for the FER firn/ice core was developed through the identification of reference horizons in the beta activity record due to atmospheric nuclear weapons testing in 1954 and 1963 coupled with spectral analyses of the major ion and $\delta^{18}O$ records and multiparameter annual layer counting. We counted 182 annual layers back through the entire 41 m ice core; our record spans the time period from 1815 to 1997. We estimate that the dating error from 1997 to 1954 is ± 2 years, and below 1954 may double to ± 4 years due to the lack of reference horizons in this section of the record.

Results and Discussion; Major Ion Chemistry

Seven of the eight major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}) show similar temporal variability (correlation coefficients among all seven ions is greater than 0.75) indicating that most of the major ion chemistry either has a common source (i.e., the arid and semi-arid dust producing regions on the northwestern margin of the Tibetan Plateau) or has separate sources that lie at a sufficient distance upwind that the major ions from different sources have time to become well mixed by the time they are deposited ensemble on the FER glacier. Previous work has shown that the spatial variation of snow chemistry in central Asia is controlled by the influx of dust from the arid and semi-arid regions in the northern and western Tibetan Plateau. A comparison of major ion chemistry from the FER glacier with data from Nangpai Gosum glacier over the last 20 years illustrates the importance of the Himalaya as a divide between dust-rich air masses to the north and relatively dust-free air masses to the south (Table 1). In addition, Na^+ and Cl^- concentrations in snow samples collected on the southern flank of Mt. Everest are approximately one-tenth and one-half those at FER glacier (Table 1) indicating that Na^+ and Cl^- do not originate from modern marine sources to the south, but from evaporite deposits in the arid regions of the northern and western Tibetan Plateau that are likely transported with calcium-rich desert dust to the FER glacier.

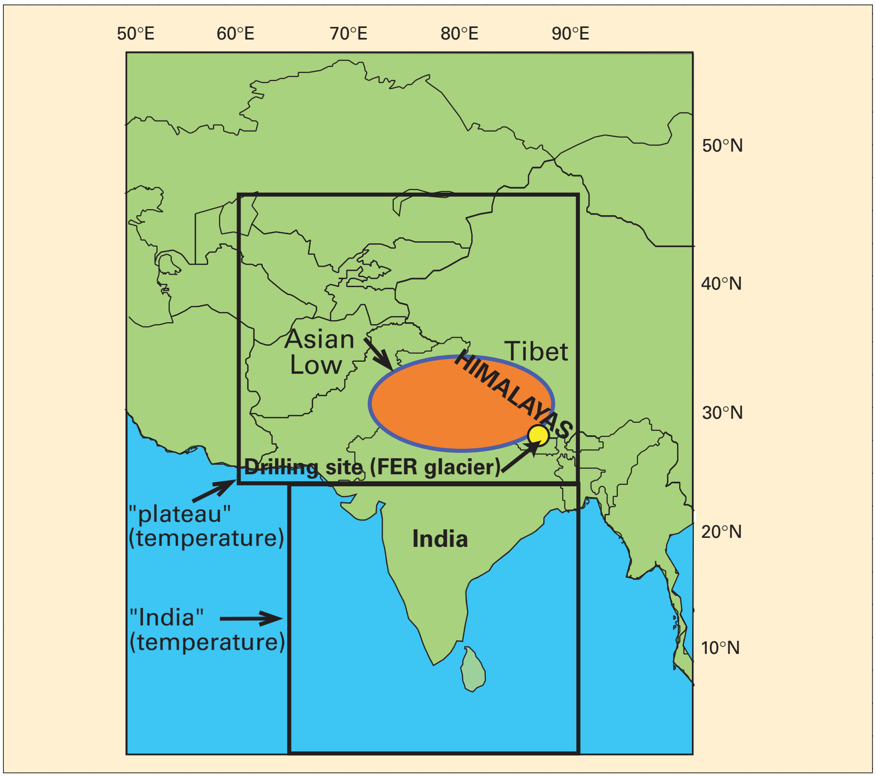

Fig. 2: Location map for the Far East Rongbuk (FER) glacier and areas for instrumental data used for comparison with the FER ice core record.

Comparison with Climate Records

To investigate the relationship between the glaciochemical ice core record and climate, we have compared the FER calcium record with seasonal or annual averages of regional temperature (Hansen et al., 1996), solar irradiance (Lean et al., 1995), the southern oscillation index (SOI), regional precipitation (Parthasarathy et al., 1992), and sea level pressure (Trenberth and Paolino, 1980) over the longest period of overlap of these records (i.e., 1899-1992).

While the traditional measure of the strength of the Asian summer monsoon is precipitation over a particular region (e.g., the All-India precipitation index), we have also developed a measure of regional summertime atmospheric circulation that estimates the strength of the summertime Asian Low using 5° x 5° global sea-level pressure (SLP) data following methods developed by Trenberth and Paolino (1980). For our Asian Low index, we have averaged the monthly SLP for June, July, and August within the region of 15° - 60° N and 40° - 136° E. The center of activity of the summertime Asian low from June through August commonly lies north of the Indian subcontinent within the region chosen for the Asian Low index (Fig. 2).

A direct comparison of the Asian Low index with All-India precipitation shows little correlation among the two variables. While precipitation is arguably the most societally important climatic variable in the region, it remains one of the most difficult parameters to measure and interpret over a broad region due to the difficulty of differentiating the influence of geographical factors on precipitation versus changes in circulation, and the spatial limitation of the precipitation data base which covers only a portion of the land area under the influence of the monsoon and none of the adjacent ocean (Webster and Yang, 1992). Furthermore, a comparison between precipitation fluctuations over the Himalaya and India does not show good agreement.

Comparison between the annualized FER calcium record and the climate variables mentioned above was accomplished using multivariate EOF analysis rather than repeated simple linear regressions because of its ability to assess joint behavior of several variates (i.e., major ions). The first EOF explains almost half of the variance in the SOI and approximately two-thirds of the variance in the regional temperature records (Table 2). The inverse relationship between the SOI and temperature in continental regions identified in EOF1 has previously been identified in several studies. EOF1 also reveals a positive relationship between solar variability and temperature in central Asia and India, reflecting the link between increases in solar irradiance and warmer climate. EOF2 is loaded on the Asian Low, FER calcium, and All-India precipitation. High calcium concentrations in the core correspond to a deeper summertime Asian low (i.e., lower sea-level pressure) (Fig. 3) and an increase in summertime precipitation. Webster and Yang (1992) show that strong monsoons (i.e., stronger Asian Low and more rain) are associated with a substantial increase in 200 mb zonal winds from 30° - 45° N in central Asia in DJF and MAM preceding the summer of the strong monsoon, while weak monsoons are associated with a decrease in these zonal winds in the two seasons preceding the weak monsoon. An increase in zonal winds over the desert regions in western Asia during a strong monsoon transports more dust eastward and result in higher ion concentrations in snow on the FER glacier, and vice versa during weak monsoons. The inverse relationship between the FER calcium record and the Asian Low is somewhat counter-intuitive as one might expect an increase in precipitation to decrease dust levels. However, this would only occur if the

Table 1: Median major ion concentrations (μeq kg^{-1}) for Far East Rongbuk (FER, n=80) and Nangpai Gosum (n=493) ice core samples over the past 20 years.

Species	FER	Nangpai Gosum
Ca^{2+}	8.61	0.21
NH_4^+	2.07	0.97
Mg^{2+}	0.77	0.05
Na^+	0.62	0.05
K^+	0.14	0.03
NO_3^-	1.30	0.24
SO_4^{2-}	0.81	0.05
Cl^-	0.52	0.26

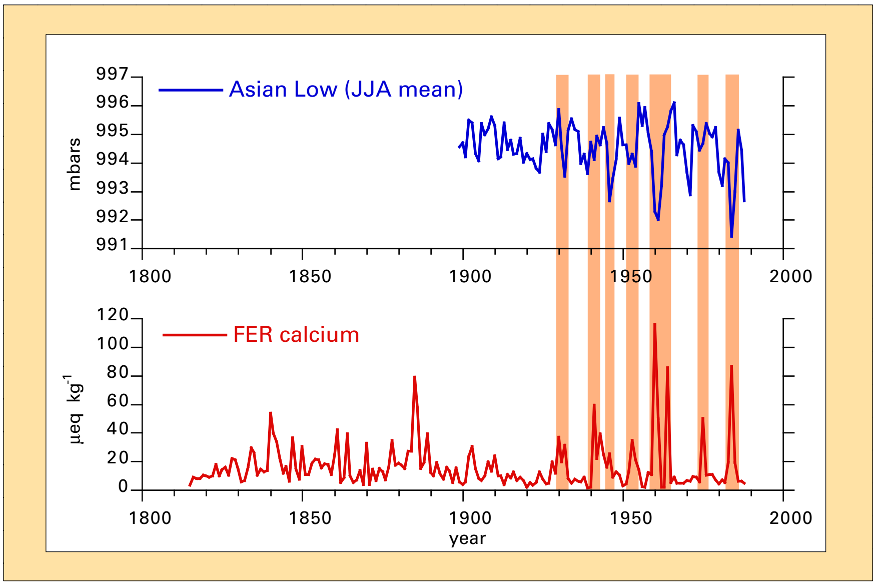

Fig. 3: Comparison of the Far East Rongbuk (FER) ice core calcium record and the Asian low index.

source of the dust was from the Indian subcontinent. Our spatial analysis of snow chemistry in central Asia (Table 1) indicates that the dust is actually derived from the arid regions of the western and northern margins of the Tibetan Plateau.

The direct relationship between FER calcium and the Asian Low is not strong (r = -0.31) but significant on the 99% level. However, the relationship becomes clearer once the effects of temperature, solar radiation, and ENSO on the strength of the Asian Low are accounted for, using multivariate EOF analysis. While not perfect, the FER ice core calcium record does provide a proxy record of summertime Asian monsoon circulation via the association between the summer monsoon and 200 mb zonal flow over central Asia, with higher FER calcium concentrations relating to a stronger monsoon. We therefore use the longer-term FER calcium record to interpret changes in atmospheric circulation in this region over the last 200 years. The interannual variability of the Asian Low, as evidenced in the sea level pressure records, has increased since 1940 with especially deep summertime lows occurring in 1871, 1946, 1960-61 and 1983 (Figure 3). The longer-term FER calcium record suggests that while the calcium spikes are not unique to the past 50 years, recent values are higher than in the past. This trend is not apparent in the precipitation record (Parthasarathy et al., 1987). Circulation models suggest an increase in the strength of summer monsoon circulation with increased global temperatures resulting from increased concentration of greenhouse gases. The trend toward deeper Asian Lows over the past 50 years suggested by our 200 year FER calcium record may represent an enhanced monsoon, forced by a recent increase in the atmospheric concentration of greenhouse gases. This would also imply an increase in the strength of westerly circulation (i.e., 200 mb zonal winds from 30° - 45° N in central Asia) in the 6 months period preceding the monsoon and increase in dust transport from the Tibetan plateau to the FER glacier.

Table 2: EOF associations between climatic variables and the Far East Rongbuk (FER) glacier calcium record for the period 1899-1991.

Parameter	EOF1 - clim (33.0%)	EOF2 - clim (21.9%)
Temperature "plateau"	62	0
Temperature "India"	75	-12
Solar activity	39	11
Southern Oscillation Index	-43	12
All-India summer precipitation	0	39
Asian Low	-16	-37
Far East Rongbuk Glacier Calcium	2	-39

Conclusions

The major ion chemistry of snow at the FER glacier is dominated by the influx of mineral aerosol derived from the western and northern regions of the Tibetan Plateau, supporting previous research. Through comparison of the FER calcium record with a variety of climate indices, we have documented a relationship between dust deposition it the Himalaya and the strength of the Asian Low. This relationship can be explained by a link with the upper level westerlies over the Tibetan plateau which are stronger in the winter/spring preceding a strong monsoon (Webster and Yang, 1992). This strengthened circulation would be responsible for an increase in dust deposition on the northern slope of the Himalaya. Our records suggest that there has been an increase over the past fifty years in the strength of the Asian Low. This is consistent with model results that suggest an increase in the strength of the Asian monsoon in a world warmed by greenhouse gases. While tentative, our results suggest ice core records provide a valuable contribution to documenting and understanding decadal-to-century scale variability of the Asian monsoon.

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