Influence of variations in NAO and SO on air temperature over the northern Tibetan Plateau as recorded by $\delta^{18}O$ in the Malan ice core

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[1] An isotopic ($\delta^{18}O$) enrichment trend from 1887 to 1998 recorded in the Malan ice core from the northern Tibetan Plateau indicates that temperatures there have warmed in the past century. Statistical analyses suggest that the annual $\delta^{18}O$ in this ice core largely reflects air temperature variations in the warm season. Statistically significant modest to weak correlations were found between the annual $\delta^{18}O$ and the North Atlantic Oscillation (NAO) index from May through October and the Southern Oscillation (SO) index from August through November, respectively. A multivariate linear regression shows that when combined, the NAO and SO account for 55% of the total variance in $\delta^{18}O$ over the past century. Moreover, the correlations between $\delta^{18}O$ and the NAO and the SO vary over the study period, as might be expected due to changes in the strength and amplitude of the NAO and SO over the past century. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1827 Hydrology: Glaciology (1863); 4870 Oceanography: Biological and Chemical: Stable isotopes; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* Tibetan Plateau, Ice core, NAO, ENSO, Climate change. **Citation:** Ninglian, W., L. G. Thompson, M. E. Davis, E. Mosley-Thompson, Y. Tandong, and P. Jianchen, Influence of variations in NAO and SO on air temperature over the northern Tibetan Plateau as recorded by $\delta^{18}O$ in the Malan ice core, *Geophys. Res. Lett.*, *30*(22), 2167, doi:10.1029/2003GL018188, 2003.

1. Introduction

[2] El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are two strong internal phenomena in the global climate system, that can influence hemispheric and global climate [*Diaz and Markgraf*, 2000; *Jones et al.*, 2001]. The contribution of ENSO to global air temperature variations in the past 150 years is ~10–30% [*Jones*, 1988; *Privalsky and Jensen*, 1995]. NAO's climatic effects have been extensively studied as it is an important source of climate variability not only in Europe [*Hurrell*, 1995; *Castro-Diez et al.*, 2002], but also over much of the Northern Hemisphere [*Thompson and Wallace*, 2001]. *Hurrell* [1996] showed that in recent decades the NAO accounts for 31% of the total variance in winter surface temperatures north of 20°N. Unfortunately, the short and scarce meteorological records over the northern Tibetan Plateau make it difficult to examine the influence of ENSO and the NAO on climate variability in that region. Here, the Malan ice core $\delta^{18}O$ record is used to investigate the extent to which ENSO and the NAO may influence air temperature variations over the northern Tibetan Plateau (TP).

2. Data and Method

[3] The Malan ice cap (35°50′N, 90°40′E), with an area of 195 km^2 and a summit elevation 6056 m a.s.l., is located in the Kunlun Mountains. In 1999 a 102-meter ice core was drilled at 5680 m a.s.l. where the 10-meter borehole temperature was about −6.5°C. The core was returned frozen to the Key Laboratory of the Ice Core and Cold Regions Environment of the CAS where $\delta^{18}O$ was measured by Gas Stable Isotope Ratio Mass Spectrometry (MAT-252). The upper 24 meters were annually dated using seasonal $\delta^{18}O$ variations and annual visible dust layers. The resulting 112-year proxy climate record contains $\delta^{18}O$ variations that exhibit ~8 and 5-year periods that may reflect changes in forcing by both the NAO and ENSO, respectively [*Wang et al.*, 2003].

[4] To explore the potential linkages between NAO and ENSO variations and the Malan $\delta^{18}O$ record, linear regression was employed. Monthly NAO indices reflecting

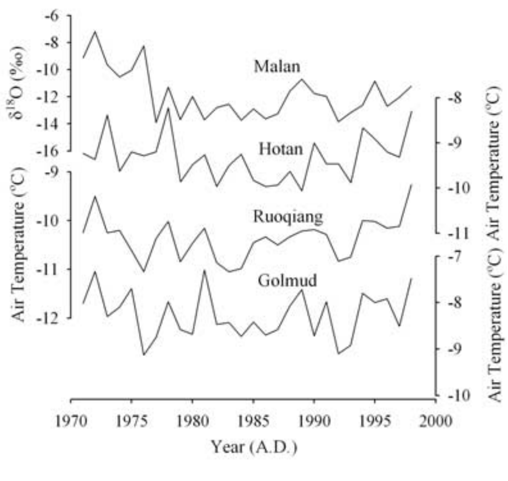

Figure 1. Variations in the mean annual $\delta^{18}O$ in the Malan ice core and 500 hPa air temperatures for the summer half year (May–October) at Hotan, Ruoqiang and Golmud meteorological observation stations for the past 30 years.

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Table 1. Correlation coefficients between malan annual $\delta^{18}O$ and monthly NAO indices (1887 to 1998)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual	May–Oct.
Yearly data	−0.030	0.030	−0.039	−0.066	0.223[a]	0.271[b]	0.129	0.216[a]	0.113	0.213[a]	0.035	−0.090	0.238[a]	0.415[b]
5-yr r.m. data	−0.201	−0.033	−0.133	−0.168	0.378[a]	0.596[b]	0.309	0.419[a]	0.240	0.520[b]	0.090	−0.125	0.455[a]	0.721[b]

[a]5% Significance level.
[b]1% Significance level. Note the degrees of freedom for the filtered time series are calculated using *Trenberth*'s [1984] method.

meridional shifts in the subpolar low and subtropical high pressure systems in the North Atlantic, provide a measure of the strength of the westerlies. The NAO index used here is based on differences in sea level pressure between Ponta Delgada, Azores and Akureyri, Iceland [*Rogers*, 1984]. The ENSO phenomenon, a coupled atmosphere-ocean mode of interannual climate variability, is characterized by the Southern Oscillation Index (SOI), defined as the normalized pressure difference between Tahiti and Darwin, Australia [*Ropelewski and Jones*, 1987].

3. Results and Discussion

[5] Although $\delta^{18}O$ in ice cores is commonly used as a proxy for air temperature, and a strong positive correlation was found between contemporaneous measurements of $\delta^{18}O$ in precipitation samples and air temperature from an array of meteorological stations over the northern part of the TP [*Yao et al.*, 1996], it is instructive to illustrate the climatological significance of $\delta^{18}O$ in the Malan core. As more than 80% of the annual precipitation arrives in the summer half year over the TP [*Qiao and Zhang*, 1994], annual mean $\delta^{18}O$ values should reflect primarily summer air temperatures. As temperatures are now warming more strongly with altitude [*Liu and Chen*, 2000], it is more appropriate to compare the annual $\delta^{18}O$ variations with variations in 500 hPa air temperatures than with surface temperatures measured at low-altitude meteorological stations around the drilling site. Figure 1 reveals that during the past three decades, $\delta^{18}O$ and the summer half-year (May to October, henceforth called summer or warm season) air temperatures have varied similarly. As expected, $\delta^{18}O$ and winter half-year temperatures are dissimilar (not shown). Considering disturbance by drifting snow, the correlation coefficients were calculated between the 3-year running means (r.m.) of $\delta^{18}O$ and 500 hPa summer air temperatures. The correlation coefficients at Hotan (37°08′N, 79°56′E), Ruoqiang (39°02′N, 88°10′E) and Golmud (36°25′N, 94°54′E) are 0.502, 0.456 and 0.531, respectively, and are all significant at the <10% level. This suggests that (1) the Malan $\delta^{18}O$ record provides a realistic index of 500 hPa air temperature; (2) mean annual $\delta^{18}O$ provides a reasonable proxy for summer air temperatures; and (3) $\delta^{18}O$ variations, to some extent, reflect variations in air temperature over a large area of the northern TP.

[6] To identify more precisely when NAO and SO might exert the largest influence on mean annual $\delta^{18}O$, correlation coefficients were calculated between the annual $\delta^{18}O$ and each monthly index of both the NAO and the SO. The results (Table 1) show that variations in the annual $\delta^{18}O$ were significantly related to variations in the summer (May–October) NAO. Over the entire period (1887 to 1998) variations in $\delta^{18}O$ associated with the summer NAO index account for ∼52% of the total variance (based on 5-year r.m.). Variations in the annual $\delta^{18}O$ are related to the intensity of the SO in the late summer and autumn (August–November), although only 8% of the total variance in $\delta^{18}O$ was explained (Table 2). These correlation coefficients suggest the likelihood of a linkage between the annual $\delta^{18}O$ in the Malan ice core and the warm season NAO and SO indices, consistent with the fact that most of the precipitation over the TP falls during the summer. The positive correlations between the annual $\delta^{18}O$ and the warm season NAO and SO indices suggest that summer temperatures may be warmer (colder) over the northern TP when either the NAO or SO summer index is positive (negative). Thus, the influence of NAO and SO on atmospheric circulation, particularly the westerlies, might influence climatic variability over the northern TP. Using NCEP/NCAR reanalysis data, the westerlies over the middle latitudes in Asia were found to be stronger when either the NAO or SO conditions are more positive (Figure 2). *Thompson and Wallace* [2001] noted that incursions of colder air from the north might decrease when the westerlies are strong. This may explain in part why the temperatures over the northern TP are warm in years with more positive NAO and SO indices.

[7] The Malan ice cap is located on the northern margin of the region that is affected by the contemporary Asian monsoon and this likely produces a linkage between the SO and air temperature variations at Malan. Many studies have shown significant correlations between the Indian monsoon strength and SOI [*Rasmusson and Carpenter*, 1983; *Kakade and Dugam*, 2000]. The Indian Monsoon tends to weaken (strengthen) during years of low (high) SOI, i.e., during strong El Niño (La Niña) conditions. When the Indian monsoon is strong, warm moist air is transported much further north (e.g., to the vicinity of Malan). It may be by this linkage that ENSO affects air temperatures over the northern TP.

[8] Figure 3 illustrates the annual $\delta^{18}O$ in the Malan ice core, the NAO index (May–October), and the SO index (August–November) from 1887 to 1998. The increasing trend (enrichment) in $\delta^{18}O$ demonstrates that warm season

Table 2. Correlation Coefficients Between Malan Annual $\delta^{18}O$ and Monthly SO Indices (1887 to 1998)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual.	Aug.–Nov
Yearly data	−0.069	−0.068	0.034	0.007	0.016	−0.027	−0.022	0.123	0.067	0.125	0.154	0.023	0.042	0.136
5-yr r.m. data	−0.257	−0.071	0.098	−0.038	0.055	−0.019	−0.016	0.330[a]	0.159	0.194	0.271	0.115	0.095	0.285[a]

[a]10% Significance level.

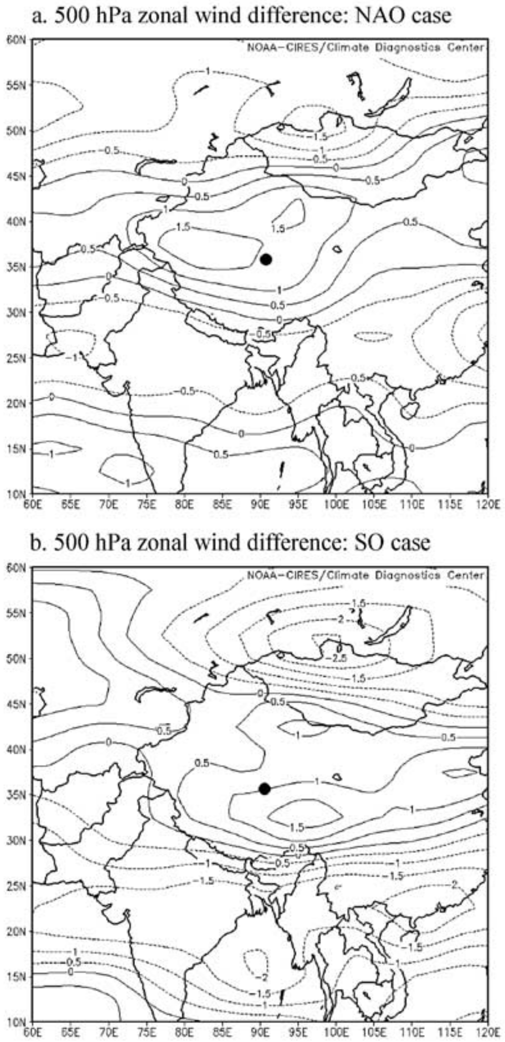

Figure 2. (a) Differences between mean zonal winds (m/s) at the 500 hPa level in strongly positive and strongly negative NAO years (May–October) from 1948 to 1998. Strongly positive (1953, 1954, 1961, 1963, 1967) and strongly negative (1949, 1952, 1957, 1958, 1960, 1968, 1976, 1987, 1993, 1995, 1997) NAO years are those with index anomalies exceeding $\pm 1\sigma$. (b) Differences between the 500 hPa mean zonal winds (m/s) for strongly positive and negative SO index years (August–November) from 1948 to 1998. Strongly positive (1950, 1955, 1956, 1964, 1970, 1971, 1973, 1975, 1988, and 1998) and negative (1951, 1965, 1977, 1982, 1991, 1994, 1997) SO years are those with index anomalies exceeding $\pm 1\sigma$. Source: NCEP/NCAR reanalysis zonal wind data, available at http://www.cdc.noaa.gov; Black dot shows the Malan ice core drilling site.

air temperatures over the northern TP have increased in the past century, consistent with the warming of globally averaged surface temperatures. To explore the potential influence of both NAO and SO on the $\delta^{18}O$ variations, multivariate linear regression is applied to their 5-year r.m. data sets. The statistical results (Table 3) for a regression model using both NAO and SO indices as independent

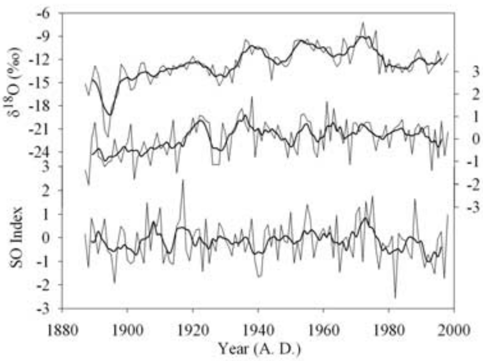

Figure 3. Variations in annual $\delta^{18}O$ from Malan ice core (top), NAO index from May through October (middle) and the SO index from August through November (bottom) from 1887 to 1998. Thin lines are yearly data and thick lines are 5-year r.m.

variables show that they explain 55% of $\delta^{18}O$ variance, and that the leading regression coefficient is associated with the NAO index.

[9] A time transgressive relationship has been reported between climate variability and the NAO and ENSO [*Kumar et al.*, 1999; *Lu and Greatbatch*, 2002]. To explore the changing correlations over climatological time scales, sliding correlations between $\delta^{18}O$ and the NAO and SO are computed using a window-length of 31 years that was chosen to approximate the standard climatological mean. The results (Figure 4) show that the correlation coefficients between $\delta^{18}O$ and the NAO were statistically significant before the 1940s, but less significant thereafter. The correlation coefficients between $\delta^{18}O$ and SO were significant before the 1910s and after the end of the 1950s but less significant and even changing sign, from ~1910 to ~1960. The transient nature of the relationships between Malan $\delta^{18}O$ and the NAO and SO indices likely reflects the interplay between the large scale pressure systems that dominate both the Atlantic and Pacific Ocean basins. From 1911 to 1950, the ENSO trend was characterized by decreasing amplitude and longer periodicity [*Kumar et al.*, 1999], as is evident in Figure 3. Not surprising, the correlation coefficients between $\delta^{18}O$ and SO were less significant and even changed sign over this period. The strength of the NAO (May–October) increased before the 1930s, when the correlation coefficients between $\delta^{18}O$ and the NAO were strongly significant, but since then the NAO strength has decreased (Figure 3), and contemporaneously

Table 3. Summary Statistics From the Multivariate Regression Using NAO (May–October) and SO (August–November) Indices as Independent Variables and the Malan Annual $\delta^{18}O$ as the Dependent Variable

Regression Coefficient	Estimate	Standard Error	*t*-Statistic	Probability of Larger $\lvert t \rvert$
NAO	3.06	0.29	10.53	<0.0001
SO	1.04	0.37	2.82	0.0057
$R^2 = 0.55$				

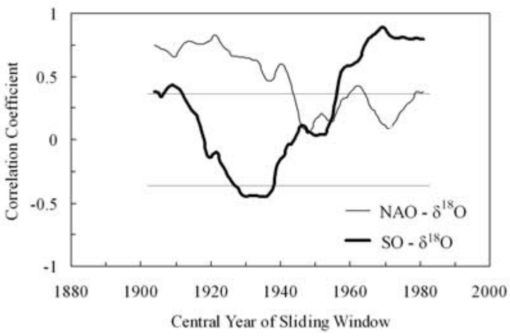

Figure 4. 31-year sliding correlations between (i) the Malan annual δ^{18}O and the NAO index from May through October (thin curve) and (ii) the Malan annual δ^{18}O and the SO index from August through November (thick curve). Parallel lines (at ±0.36) indicate correlations significant at the 5% level.

the correlation coefficients between δ^{18}O and the NAO index were weak.

4. Conclusions

[10] Recently interest has increased in the potential impacts of the NAO and ENSO on climate variability. The δ^{18}O history from the Malan ice core is used as a proxy for summer air temperatures over the northern Tibetan Plateau. A statistical approach reveals that from 1887 to 1998, the Malan δ^{18}O time series and the NAO (May–October) and SO (August–November) indices are related. Using both the NAO and SO indices as predictors, multiple regression suggests that 55% of the total variance of δ^{18}O can be explained, although the influence of NAO is much stronger. These results suggest that variations in warm season air temperatures over the northern Tibetan Plateau have been influenced by the strength of both the NAO and SO during the past century. The mechanism linking temperatures over the northern Tibetan Plateau and these two climate oscillations is most likely via changes in the strength of westerlies and the Indian monsoon. These relationships are shown to change over multi-decadal time scales and the transient nature of the correlations undoubtedly reflects changes in the strength and amplitude of the NAO and SO and the interplay between them. The extent to which the NAO and SO have influenced atmospheric circulation on longer time scales requires further study facilitated by longer proxy histories and a better understanding of the processes responsible for NAO and SO variability.

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