

The climate signal recorded in the oxygen isotope, accumulation, and major ion time-series from the Eclipse ice core, Yukon Territory

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ABSTRACT

The high accumulation rate, nearly complete preservation, and detailed chronology of the Eclipse ice core are well suited for comparison of the glaciochemical record with instrumental time-series of temperature, precipitation, and sea level pressure. Results of cross correlation analysis of instrumental temperature records with the Eclipse ^{18}O time-series reveals a significant positive relationship between summertime ^{18}O at Eclipse and summer (April-September) temperatures at both coastal and interior Alaskan sites. The results indicate that the Eclipse ^{18}O time-series provides a better proxy for regional temperature than does the ^{18}O time series from the Mt. Logan ice core record for which only negative correlations were found. Summer accumulation at Eclipse is only significantly correlated with summer precipitation at Haines Junction, YT, reflecting substantial regional variability in precipitation. The ^{18}O , accumulation, and glaciochemical time series also display significant correlations with the Northern Hemisphere sea level pressure data set, especially between annual variability in sulfate and nitrate deposition at Eclipse and the intensity of the wintertime Siberian High and Aleutian and Icelandic Lows. These results suggest that year-to-year variability in the deposition of pollutants at Eclipse can be linked to changes in atmospheric circulation while long-term trends can be explained by changes in source strength.

INTRODUCTION

Our understanding of natural climate variability over the past several hundred years and the identification of human induced climate change in the Arctic is hampered by the lack of long-term instrumental records from this region. To supplement the instrumental record and enhance our understanding of natural climate variability, multi-variate climate records can be developed through the collection and analysis of ice cores recovered from suitably located glaciers and polar ice caps. Preserved in glacial ice is a time-series of precipitation chemistry and dry deposition reflecting changes in temperature, precipitation, and atmospheric circulation. However, the exact links between the ice core records, the instrumental record, and other paleoclimate records are often unclear.

In contrast to the growing number of ice core records from Greenland and the eastern Canadian Arctic (e.g., Koerner and Fisher, 1990; Hammer and others, 1998; Fisher and others, 1998; Grunet and others, 2001), the ice core record from Mt. Logan had remained the only one recovered from northwest North America. The 103 m core was recovered in 1980 from an elevation of 5340 m on the summit plateau of Mt. Logan (60.35° N, 140.30° W) in the St. Elias Mountains, southwest Yukon Territory, Canada (Holdsworth and others, 1984; 1985). Unfortunately, the oxygen isotope record from Mt. Logan does not cross correlate well with regional instrumental records of temperature (Holdsworth and others, 1992) as the Mt. Logan ice core site samples primarily free tropospheric air masses with a distinctly different stable isotope fractionation history compared to air masses present at the lower elevation meteorological stations (Holdsworth and others, 1991). However, analysis of the accumulation time series from Mt. Logan shows strong correlation with instrumental precipitation records from Japan (Holdsworth and others, 1992). In addition, due to its location near the 500 mb height, the Mt. Logan record is uniquely situated for evaluating the extra-tropical response to ENSO (Moore and others, 2001).

To provide new insights on the temporal variability of precipitation chemistry and develop a broader array of proxy climate records for northwestern North America, a 160 m ice core was collected from Eclipse Icefield (Figure 1; 3017 m, 60.51° N, 139.47° W) in the St. Elias Range, southwestern Yukon Territory, Canada. The Eclipse site is 45 km northeast of and more than 2 km lower than the Mt. Logan drill site with an accumulation rate nearly five times greater. Due to its lower elevation, the Eclipse site samples distinctly different air masses from the Mt. Logan site, with different source inputs and transport histories (Holdsworth and others, 1988; Yalcin, 2001; Yalcin and Wake, in press.). The high accumulation rate and nearly complete preservation at the Eclipse site provides an excellent opportunity to compare the ice core record with instrumental time-series of temperature, precipitation, and sea level pressure and determine the extent to which the Eclipse ^{18}O and accumulation time-series can be considered a representative proxy for temperature, precipitation, and atmospheric circulation in the region.

METHODS

The 160 m firn/ice core was recovered from Eclipse Icefield in the summer of 1996 (Blake and others, 1998) and shipped frozen to UNH. The core was continuously sampled in 10 cm segments using stringent core processing techniques to ensure that samples were contamination free at the ng g^{-1} level. Blanks prepared on a frequent basis showed no contamination of samples during processing of the core. Samples were analyzed for major ions (Na^+ , NH_4^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , NO_3^- , SO_4^{2-}) using an ion chromatograph in a dedicated laboratory at the University of New Hampshire and for oxygen isotopes at the Department of Geophysics, University of Copenhagen, Denmark. A section of the core from 50 m to 76 m depth was analyzed for beta activity.

Analysis of the ice core beta activity profile and comparison with real-time precipitation measurements from Whitehorse, YT (Figure 2a) shows clear identification of the 1961 and 1963 beta activity peaks from atmospheric thermonuclear weapons testing. Average annual accumulation from 1963 to 1996 was 1.38 m water equivalent. Analysis of snowpit samples collected during the summer drilling season indicates that ^{18}O values are heavier (i.e., less negative) and Na^+ concentrations lower in summer snow. The seasonal variability of the that ^{18}O signal in snow at Eclipse (heavier in summer, lighter in winter) is similar to that recorded in Greenland snow (Dansgaard, 1964), suggesting that the temperature at which the snow forms in the atmosphere is the dominant control on the oxygen isotope ratio preserved at the Eclipse site. Sodium peaks generally occur during the winter, likely as a result of increased wind speeds. The ^{18}O and Na^+ relationship (Na^+ peaks coinciding with troughs in the ^{18}O record) are evident in the ice core record (Figure 2b). The consistent seasonal signals recorded in these two time-series provides the basis for the counting of annual layers and the identification of seasonal (summer and winter) layers in the ice core record. Control on the depth-age relationship developed via annual layer counting is provided by identification of nuclear weapons testing fallout and SO_4^{2-} reference horizons linked to known volcanic eruptions (Yalcin, 2001). While it is difficult to quantify the dating uncertainly, we estimate it to be no more than ± 1 year for the last 100 years based on our multi-parameter approach and high number of positively identified volcanic horizons. The annualized ice core time-series discussed in this paper are shown in Figure 3.

To compare the ice core record with a variety of meteorological variables, we collected instrumental time-series of monthly mean temperature and monthly precipitation from a range of stations surrounding the St. Elias Mountains (Table 1, Figure 1). These monthly time-series were converted to both annual (January to December) and seasonal (October to March; April to September) resolutions for comparison with our glaciochemical record on an annual and seasonal basis. Missing months in the instrumental records were filled in with the long-term average for that month; years with more than half the months missing were excluded from our analyses. Cross correlation analysis was performed individually between each instrumental record and the

Eclipse ice core record over the maximum period the records overlapped. This overlap ranged from 45 to 92 years for temperature records, and 37 to 92 years for the precipitation records. Instrumental data series shorter than 35 years were not used in our analysis.

We also developed a regional temperature record using data from all stations that had records extending from at least 1944 to 1989 (31 total). This was accomplished by running an EOF analysis on the annual, summer, and winter records. The first EOF (EOF1-Temperature) explains 71%, 54%, and 81% percent of the variability in the data for the annual, summer, and winter records, respectively. A similar analysis was performed on the precipitation data; however the first EOF explained at most 25% of the variability in the data and, due the high spatial variability in these precipitation, we have not used the precipitation EOF as a regional record. The Eclipse glaciochemical record was also compared with gridded ($5^{\circ} \times 5^{\circ}$) Northern Hemisphere sea level pressure (SLP) data over the period 1899-1995 (after Trenberth and Paolino, 1980). Seasonal SLP for winter (DJF) and summer (JJA) were compared with winter and summer records from the Eclipse ice core.

RESULTS and DISCUSSION

Eclipse $\delta^{18}O$ and instrumental temperature records

The results of cross correlation analysis of instrumental temperature and precipitation records with the Eclipse ^{18}O and net accumulation time-series are presented in Table 2. The most widespread significant positive correlations between the Eclipse ^{18}O and instrumental temperature occur during the summertime with stations that lie to the north-west, west, and south-east of the St. Elias range, including almost all sites in Alaska both coastal and inland (Figure 4 a and b). A similar pattern emerges for annual temperature records, albeit for only one-third of the stations represented by the summertime relationship. This annual signal is likely driven by the summertime relationship, as there are no significant positive relationship for the winter data. There also exists a significant positive correlation between "summer" EOF1-Temperature and the summertime ^{18}O record. There is no positive correlation with any station data (except Dawson) to the north-east for summer or annual data. The results indicate that summertime ^{18}O signals at Eclipse represent 10-15% of the temperature variability in a broad coastal region extending from Ketchikan to Kodiak, and to the interior of Alaska north of the Alaskan Range. The lack of a relationship with inland Yukon sites can be explained by the substantial climatic divide created by the St. Elias Mountains which rise to 2.5 km in just 60 km from the west coast of North America. In summer, the mountains act as a transition zone between the coastal maritime conditions and the adjacent continental regime to its east (Taylor-Barge, 1969). Temperatures are largely modified on the coastal side of the St. Elias Mountains, while the interannual range in temperatures is greater inland. While the ^{18}O /summer

temperature correlations are not spectacular, they are significant and indicate that the Eclipse summer stable isotope record offers a better temperature proxy for the nearby region than does the Mt. Logan record.

All of the correlation analyses were also done with a lag of plus and minus 1 year. None of the correlation coefficients discussed here improved with this lag, suggesting that our depth-age relationship is reasonably accurate.

Eclipse accumulation and instrumental precipitation records

There exists little relationship between the Eclipse accumulation record and regional precipitation records. While the positive correlation with Haines Junction is encouraging, the relatively short period of the Haines Junction record (1944-1980) limits the usefulness. Significant negative correlations exist with winter precipitation at inland stations in east central Alaska and Dawson, Yukon Territory, and with summer and annual precipitation at Talkeetna, Alaska. Our EOF analysis of regional precipitation records from 1945 to 1989 indicates that there is much greater spatial variability in precipitation trends compared to those for temperature, so it is not surprising that the Eclipse accumulation record does not display a signal that is representative of station data. In addition, the significant elevation gradient between the Eclipse site and lowland instrumental records may explain the limited usefulness of the Eclipse accumulation record as a proxy record for regional precipitation. In this case, local, orographic process may play a stronger role in controlling the amount of snowfall at Eclipse than regional climate variability. Or conversely, the station data reflects more local influences on precipitation and the Eclipse record provides a more regional signal.

Eclipse major ions and instrumental sea level pressure records

For reference, the mean SLP for the winter (DJF) for the period 1899 to 1995 is shown in Figure 5a. The semi-permanent high and low pressure cells for winter (Aleutian Low, Icelandic Low, Siberian High) are apparent. The ^{18}O , accumulation, and glaciochemical time series display significant correlations with the Northern Hemisphere SLP data set. Here we focus on the relationship between the relative strength of the Aleutian Low, Icelandic Low, Siberian High and sulfate and nitrate concentrations preserved in the Eclipse ice core since 1945. Since the 1940's there has been an increase in sulfate and nitrate deposition in the Arctic linked to increases in anthropogenic emissions from Eurasia (Barrie, 1985; Goto-Azuma and Koerner, 2001; Yalcin and Wake, in press). In addition, there is considerable year-to-year variability in sulfate and nitrate deposition (Figure 3) which is not the result of changes in source strength (annual anthropogenic emissions change by only a few percent at most), but may be related to changes in atmospheric circulation and/or processes which affect the formation, transport, and deposition of aerosols. To try and explain this year-to-year variability in terms of changes in

atmospheric circulation, we looked at the difference between pressure patterns for years of high winter sulfate and nitrate (the highest one-third of concentrations) versus low winter sulfate and nitrate (the lowest one-third of concentrations). Winter values were used as the majority of the increase in nitrate and sulfate over the last 50 years at Eclipse occurs in wintertime snow (Yalcin and Wake, in press). Higher sulfate and nitrate concentrations are characterized by a higher pressure over Siberia (SLP 2-4 mb higher; Figure 5 b and c). Higher sulfate concentrations are also linked with a stronger Aleutian low (SLP 4 mb lower; Figure 5b) while higher nitrate concentrations correspond to a stronger Icelandic Low (SLP 3 mb lower; Figure 5c). Note that these patterns of strengthening of the wintertime semi-permanent pressure cells by 2-4 millibars over the last 55 years shown in Figure 5 b and c are comparable to shifts in pressure associated with a changeover from a high to low index for the North Atlantic Oscillation and El Niño/Southern Oscillation. The increase in the SLP pressure over Eurasia, combined with decreased pressure in the region of the Aleutian low and the Icelandic low would encourage the transport of pollutants from Eurasia into north-western North American Arctic (e.g., Raatz and Shaw, 1984). The results indicate that the year-to-year variability in sulfate and nitrate deposition can be linked to changes in atmospheric circulation, while the longer-term trends are related to changes in source strength in Eurasia (Goto-Azuma and Koerner, 2001; Yalcin and Wake, in press).

CONCLUSIONS

The 100 year physical and chemical time-series developed from the Eclipse ice core provides a valuable new paleoclimate record for northwest North America. Comparison of the accumulation, ^{18}O , and major ion records with instrumental meteorological data indicates that there exists significant statistical relationships between the Eclipse glaciochemical time-series and regional instrumental temperature data and Northern Hemisphere SLP data.

Summertime ^{18}O signals at Eclipse represent 10-15% of the temperature variability in a broad coastal region extending from Ketchikan to Kodiak, and in the interior of Alaska north of the Alaskan Range. There exists little correlation between the Eclipse accumulation time-series and instrumental precipitation data, reflecting substantial spatial variability of precipitation across the region. Perhaps the most encouraging results come from the analysis of SLP and the Eclipse sulfate and nitrate records. Years of high sulfate and nitrate deposition at Eclipse are related to a strengthening of the wintertime semi-permanent pressure cells in the northern hemisphere (i.e., Aleutian Low, Icelandic Low, Siberian High), which would encourage the transport of air from northern Eurasia into the region, indicating that both changes in source strength of pollutants and changes in atmospheric circulation must be considered to explain the observed trends.

Small dating errors in the Eclipse ice core record may be influencing the results, although any dating error that may exist is not systematic through the entire record as the plus/minus lag analysis did not reveal any improved relationships. Noise in the Eclipse ice core time-series may also be affecting the result of comparison to climate parameters. Constructing a stacked isotope/major ion record using this core and cores collected in the near future from this region should improve correlations between the ice core and climate records by increasing the signal to noise ratio. This approach has been used with considerable success for stable isotope records by Fisher and others (1996) and White and others (1998).

Comparison of the Eclipse with Mt. Logan ice core records highlights the importance of collecting ice cores from a range of elevations; time-series developed from ice cores recovered from different elevations in the St. Elias Mountains provide unique records of environmental change. In this sense, the Eclipse ice core record, in addition to other snowpit and shallow core studies (Holdsworth and others, 1988; 1991), provide an elevational survey that identifies the need for collecting ice cores from a range of elevations to more fully understand environmental change in northwestern north America. This information should prove invaluable for interpreting the Holocene ice core record being developed from an ice core recently recovered from the Prospector-Russell Col on the summit plateau of Mt. Logan (Fisher, pers. Comm., 2001).

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Table 1. Monthly temperature and precipitation records from meteorological stations surrounding the St. Elias Range used in our analysis. Data obtained from the NOAA Global Historical Climate Network (GHCN). %miss indicates percent of missing data for the years listed.

Station	Lat. (N)	Long. (W)	Temperature			Precipitation		
			Begin	End	%miss	Begin	End	%miss
Kodiak, AK	57.75	152.50	1915	1996	1.8	1899	1990	4.0
Homer, AK	59.63	151.50	1932	1996	6.3	1932	1999	5.9
Kenai AK	60.52	151.25	1899	1996	37.8	N/A	N/A	N/A
Seward, AK	60.12	149.45	1908	1990	7.1	N/A	N/A	N/A
Valdez, AK	61.13	146.35	1917	1996	12.0	N/A	N/A	N/A
Cordova, AK	60.50	145.50	1909	1996	7.3	1942	1990	5.3
Haines, AK	59.24	135.44	1925	1990	3.8	1925	1981	6.3
Juneau	58.37	134.58	1943	1996	2.3	1899	1990	2.8
Annex Creek, AK	58.32	134.10	1917	1989	3.7	N/A	N/A	N/A
Sitka, AK	57.07	135.35	1899	1989	2.4	1842	1989	12.0
Little Port Walter, AK	56.39	134.66	1936	1990	1.5	N/A	N/A	N/A
Wrangell, AK	56.50	132.40	1917	1990	7.9	1917	1989	7.1
Ketchikan, AK	55.37	131.72	1910	1990	5.3	N/A	N/A	N/A
Bettles, AK	66.90	151.50	1944	1996	1.7	1944	1990	1.2
Tanana, AK	65.20	152.10	1905	1990	8.3	1903	1989	2.5
Puntilla, AK	62.10	152.75	1942	1990	8.2	1942	1981	14.4
Achorage, AK	61.17	150.02	1916	1996	1.5	1916	1990	1.6
Matanuska, AK	61.60	149.30	1917	1990	3.8	1917	1989	3.0
Talkeetna, AK	62.30	150.10	1918	1996	3.4	1918	1999	4.4
Mckinley Park, AK	63.70	149.00	1923	1990	3.4	1923	1989	5.8
Fairbanks Int'l, AK	64.82	147.87	1929	1996	3.7	N/A	N/A	N/A
Fairbanks Univ. AK	64.85	147.87	1904	1990	2.1	1905	1988	10.0
Ft. Greeley, AK	64.00	145.73	1941	1996	6.2	N/A	N/A	N/A
Gulkana, AK	62.15	145.45	1910	1996	34.5	1942	1999	2.0
Northway, AK	62.97	141.94	1942	1996	4.2	1942	1990	1.0
Eagle, AK	64.79	141.20	1899	1990	28.4	1899	1981	21.5
Dawson, YT	64.05	139.13	1897	1979	5.9	1897	1990	6.6
Haines Jet., YT	60.77	137.58	1944	1985	5.6	1944	1980	4.3
Mayo, YT	63.62	135.87	1924	1990	3.7	1925	1990	3.0
Ft. McPherson, NWT	67.40	134.90	1892	1977	30.6	1940	1977	41.0
Whitehorse, YT	60.72	135.07	1942	1995	10.3	1942	1990	1.0
Teslin, YT	60.17	132.73	1943	1989	11.3	N/A	N/A	N/A
Atlin, BC	59.57	133.70	1899	1947	29.7	1899	1990	31.0
Dease Lake, BC	58.42	130.00	1944	1990	3.9	1944	1990	7.3

Table 2. Correlation coefficients for ice core ^{18}O versus instrumental temperature records and ice core accumulation versus instrumental precipitation records. Only r values significant at the P=0.05 level for ^{18}O /temperature data and at the P=0.10 level for the accumulation/precipitation data are listed.

Station	years	r (^{18}O vs. temperature)			r (accumulation vs. ppt.)		
		winter	summer	annual	winter	summer	annual
Kodiak, AK	82	0.25		0.24	92		
Homer, AK	65	0.31			58		
Kenai AK	98				n/a		
Seward, AK	83	0.22			n/a		
Valdez, AK	80	0.27			n/a		
Cordova, AK	91				48		
Haines, AK	66				57		
Juneau	54	0.32			92		
Annex Creek, AK	73				n/a		
Sitka, AK	91				91		
Little Port Walter, AK	55	0.31			n/a		
Wrangell, AK	74	0.29			73		
Ketchikan, AK	81	0.34		0.23	n/a		
Bettles, AK	53	0.29			47		
Tanana, AK	86	0.28		0.27	87		
Puntilla, AK	49	0.30		0.31	40		
Achorage, AK	81	0.23			75		
Matanuska, AK	74	0.33		0.23	73		
Talkeetna, AK	79	0.29			71		
Mckinley Park, AK	68	0.24			67	-0.21	
Fairbanks Int'l, AK	68				n/a		
Fairbanks Univ., AK	87			0.30	84		
Ft. Greeley, AK	57				n/a		
Gulkana, AK	87	0.32			48		
Northway, AK	55	0.31			49	-0.37	
Eagle, AK	45	0.38			82	-0.18	
Dawson, YT	83	-0.30	0.24		94	-0.30	
Haines Jet., YT	42				37		0.28
Mayo, YT	67				64		
Ft. McPherson, NWT	71				72		
Whitehorse, YT	50				49		
Teslin, YT	47				n/a		
Atlin, BC	92		0.24		92		
Dease Lake, BC	47				n/a		
EOF1-Temperature	46		0.33		n/a		

FIGURE CAPTIONS

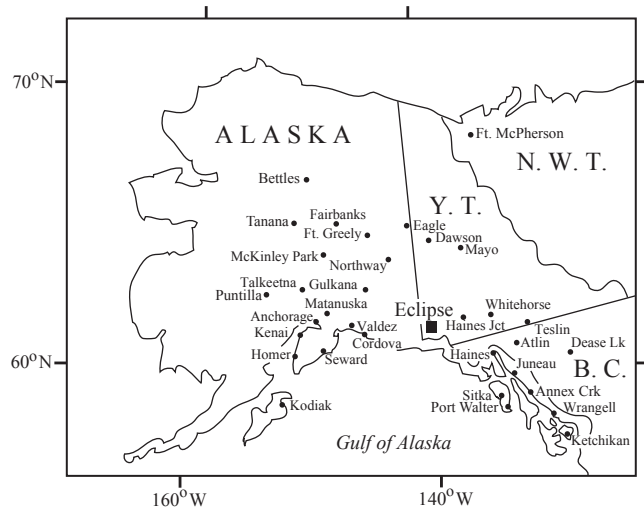
Figure 1. Location map for Global Historical Climatological Network meteorological stations whose data was used in this work (small black circles) and the Eclipse Icefield (large black circle).

Figure 2. Detail of glaciochemical records used to develop a depth-age relationship for the Eclipse core; (a) Beta activity record from the Eclipse ice core and from air samples collected at Whitehorse, Yukon Territory (after Holdsworth and others, 1984); and (b) seasonal signals in the ^{18}O and Na^+ records smoothed using a robust spline (Meeker and others, 1995).

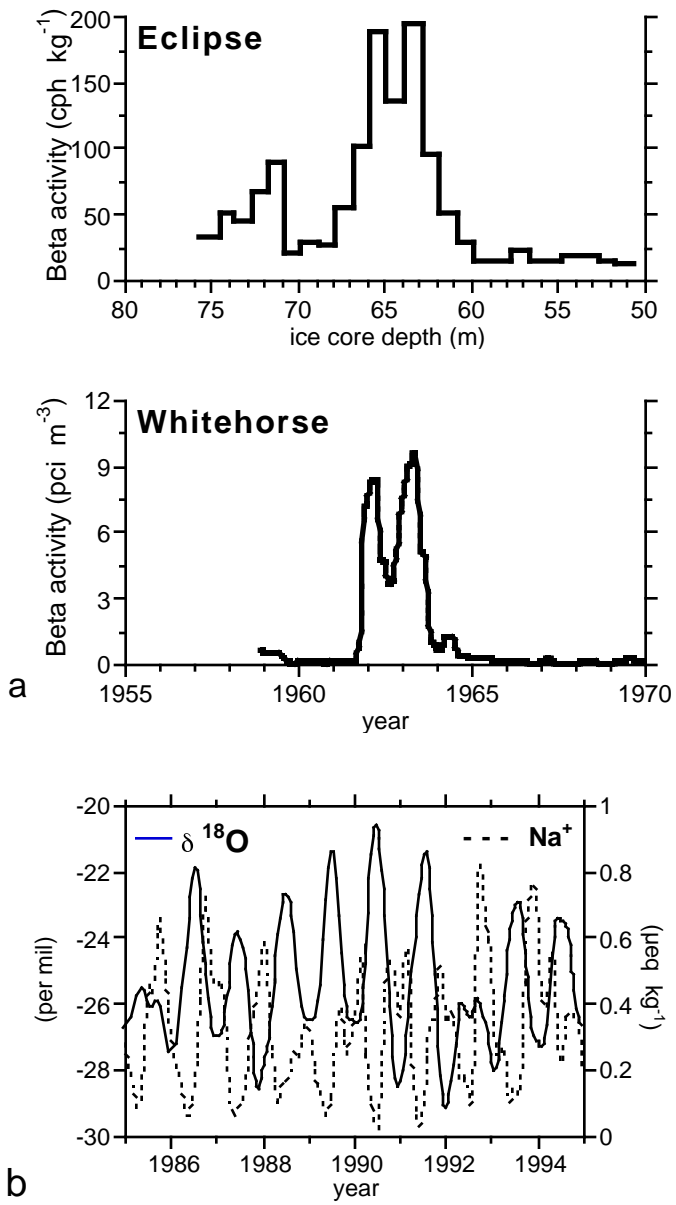
Figure 3. Annualized time-series developed from physical and chemical analysis of the Eclipse ice core.

Figure 4. Comparison of time-series of summertime Eclipse ^{18}O and "summer" (April-Sept) temperatures from meteorological stations that show a correlation coefficient greater than 0.3 with the ^{18}O record (cf. Table 3).

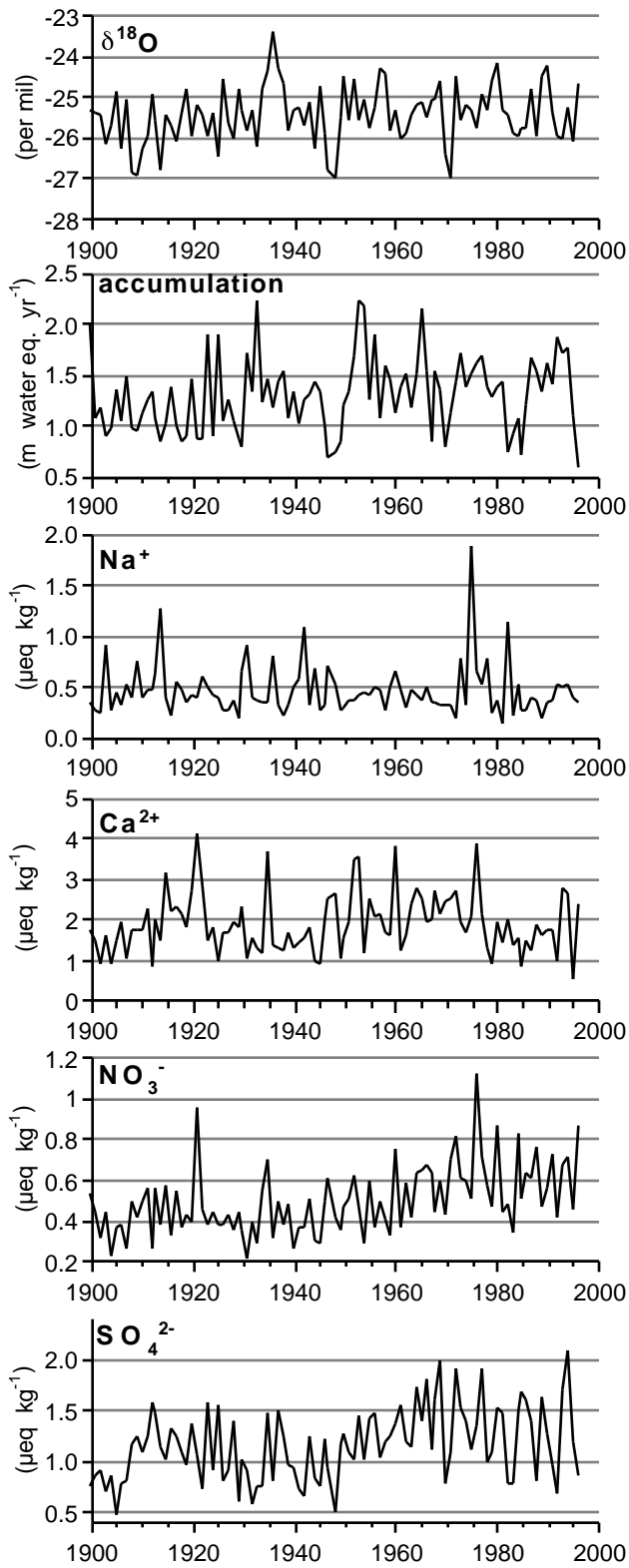
Figure 5. (a) Mean northern hemisphere sea level pressure in $5^\circ \times 5^\circ$ grid for winter (DJF)(after Trenberth and Paolino, 1980). The semi-permanent high and low pressure cells in winter (AL- Aleutian Low; IL-Icelandic Low; SH-Siberian High)) are noted; (b) mean sea level pressure anomaly from 1945-1995 for high sulfate winter concentrations (highest one third) minus low winter sulfate concentrations (lowest one third); and (c) same as figure b, but for nitrate.



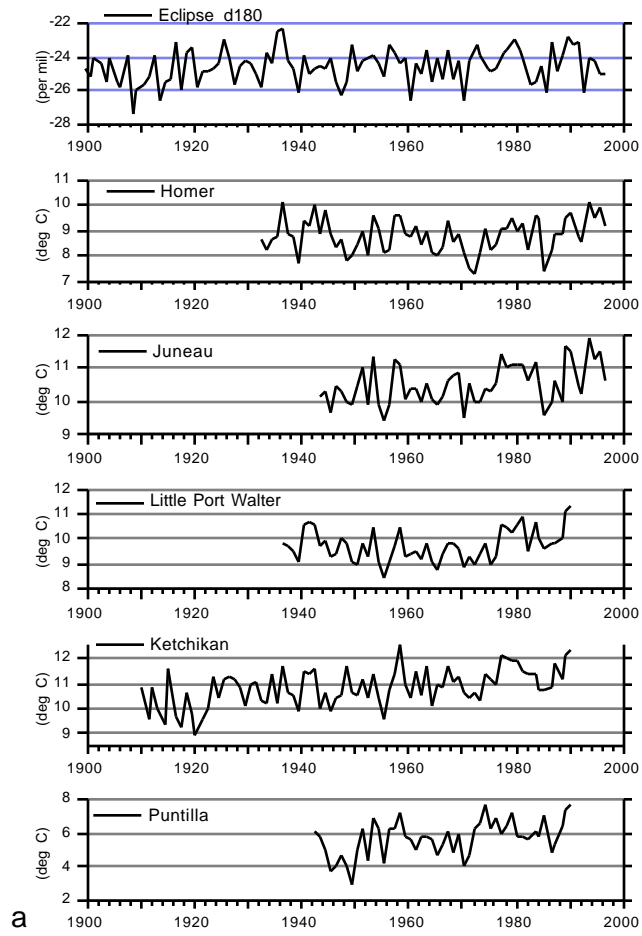
Wake and others
Figure 1



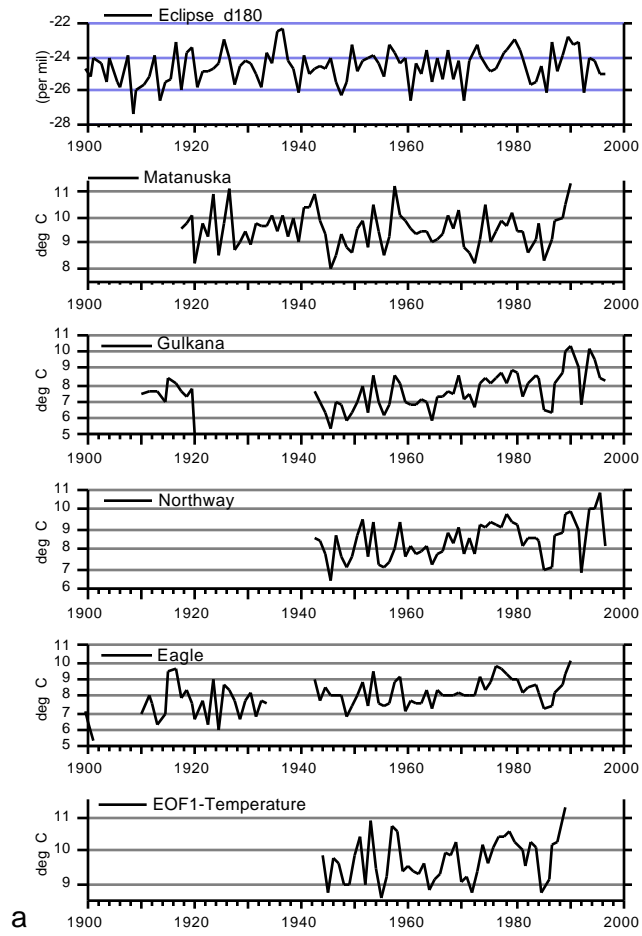
Wake and others
Figure 2



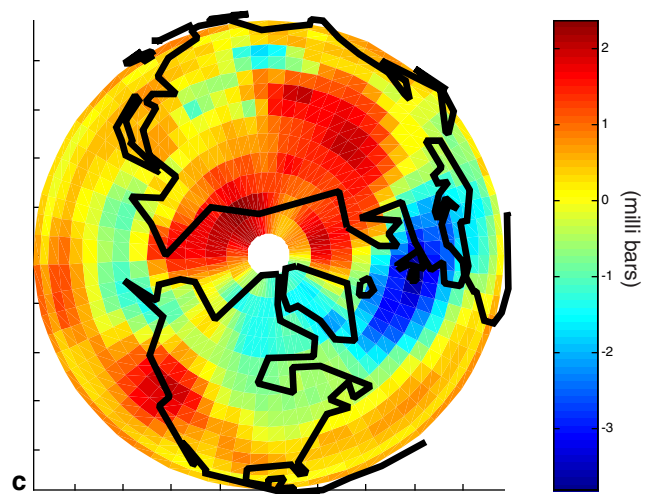
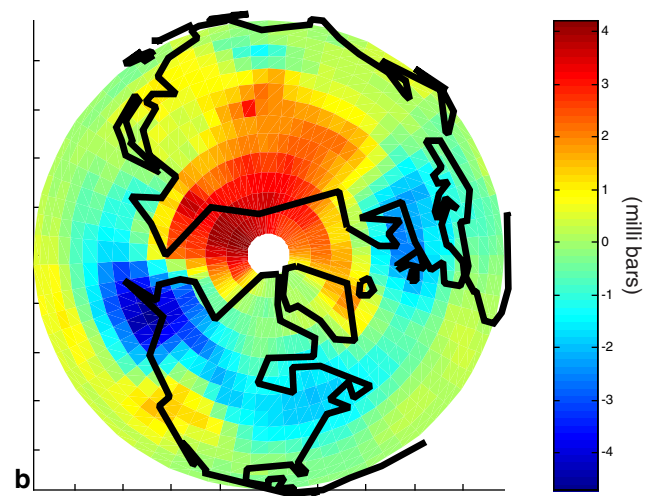
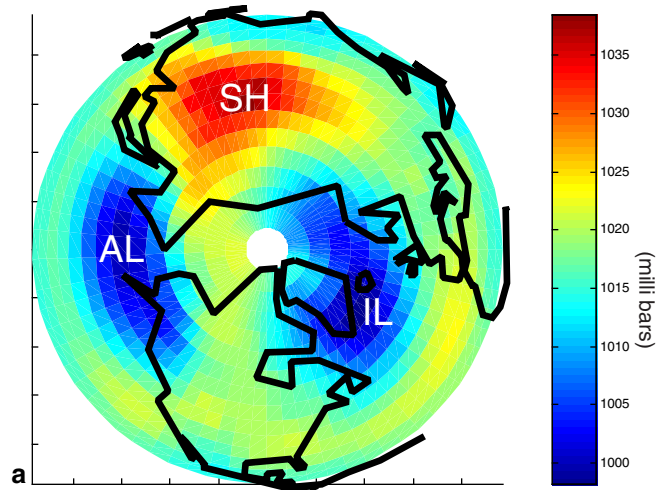
Wake and others, Figure 3



Wake and others
Figure 4a



Wake and others
Figure 4b



Wake and others
Figure 5