Ice core evidence of rapid air temperature increases since 1960 in alpine areas of the Wind River Range, Wyoming, United States

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[1] Site-specific transfer functions relating delta oxygen 18 ($\delta^{18}O$) values in snow to the average air temperature (T_A) during storms on Upper Fremont Glacier (UFG) were used in conjunction with $\delta^{18}O$ records from UFG ice cores to reconstruct long-term trends in air temperature from alpine areas in the Wind River Range, Wyoming. Transfer functions were determined by using data collected from four seasonal snowpacks (1989–1990, 1997–1998, 1998–1999, and 1999–2000). The timing and amount of each storm was determined from an automated snowpack telemetry (SNOTEL) site, 22 km northeast of UFG, and ~1060 m in elevation below UFG. Statistically significant and positive correlations between $\delta^{18}O$ values in the snow and T_A were consistently found in three of the four seasonal snowpacks. The snowpack with the poor correlation was deposited in 1997–1998 during the 1997–1998 El Niño Southern Oscillation (ENSO). An ultrasonic snow-depth sensor installed on UFG provided valuable insights into site-specific storms and postdepositional processes that occur on UFG. The timing of storms recorded at the UFG and Cold Springs SNOTEL sites were similar; however, selected storms did not correlate. Snow from storms occurring after mid-October and followed by high winds was most susceptible to redeposition of snow. This removal of lower temperature snowfall could potentially bias the $\delta^{18}O$ values preserved in ice core records to environmental conditions reflecting higher air temperatures and lower wind speeds. Transfer functions derived from seasonal snow cover on UFG were used to reconstruct T_A values from $\delta^{18}O$ values determined from two ice cores collected from UFG. Reconstructed air temperatures from the ice core data indicate an increase in T_A of ~3.5°C from the mid-1960s to the early 1990s in the alpine areas of northwestern Wyoming. Reconstructed T_A from the ice core records between the end of the Little Ice Age (LIA), mid-1800s, and the early 1990s indicate a T_A increase of ~5°C. The historically reconstructed T_A values from the UFG were significantly higher than the global average observed during the 20th Century but were in agreement with T_A increases observed at selected, high-altitude and high-latitude sites in other parts of the world. Additional research is required to determine if part of the observed trend toward heavier $\delta^{18}O$ values in ice from the UFG since the LIA (and increased T_A) is due to an increased proportion of snowfall from southerly storm tracks and moisture sources, as seems to have been the situation in 1997–1998. *INDEX TERMS:* 1854 Hydrology: Precipitation (3354); 1827 Hydrology: Glaciology (1863); 1040 Geochemistry: Isotopic composition/chemistry; *KEYWORDS:* climate change, glaciology, Wind River Range, Wyoming, stable isotopes

1. Introduction

[2] Oxygen isotopic ratios ($\delta^{18}O$) in ice cores have been used extensively to reconstruct past climate trends. *Covey and Haagenson* [1984] and *Charles et al.* [1994] demonstrated that the $\delta^{18}O$ composition of precipitation might depend strongly on storm trajectories and moisture sources; however, most midlatitude and high-latitude isotopic data sets contain a positive correlation to average air temperature (T_A). *Lorius et al.* [1990] show a positive correlation between trends in $\delta^{18}O$ values in ice cores from polar regions to variations in greenhouse gases since the last glacial maximum, 18,000 years before present. Borehole temperature profiles measured in central Greenland indicate $\delta^{18}O$ values provide good proxy indicators of long-term T_A during the past 500 to 600 years [*Cuffey et al.*, 1994]. On the basis of selected Global Circulation Model (GCM) results, *Jouzel et al.* [1997] concluded that ice core isotopic

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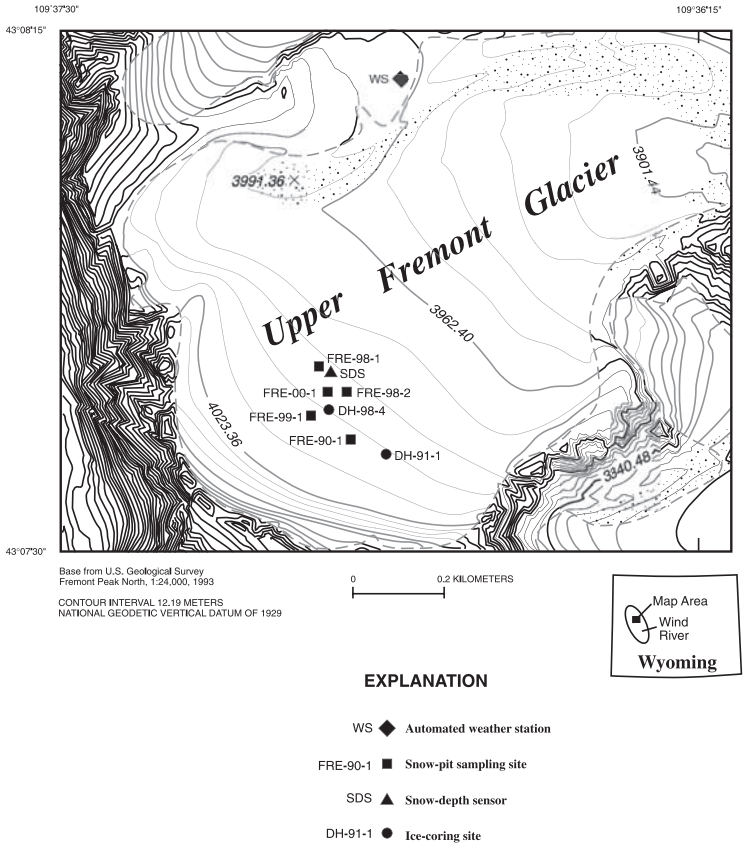

Figure 1. Location of meteorological station, snow-pit sampling sites, snow-depth sensor, and ice-coring sites, Upper Fremont Glacier, Wind River Range, Wyoming.

records can be used to interpret local temperature changes in polar regions.

[3] Recent investigations have documented positive correlations between the site-specific $\delta^{18}O$ values in snow and ice to the site specific T_A during snow accumulation events in polar regions. For example, *Thompson et al.* [1994] found positive correlation between recent (1958–1989) air temperatures and $\delta^{18}O$ values in ice core samples collected on the Antarctica peninsula. *Shuman et al.* [1995] found positive correlations between $\delta^{18}O$ values in shallow snow pits and daily microwave brightness temperature records in the vicinity of the Greenland Ice Sheet Project II (GISP2). Current research by *Stichler et al.* [2001] indicates that sublimation may modify the stable isotope values in snow at high-elevation sites in the tropics. On the basis of this research, postdepositional processes that may change the $\delta^{18}O$ values in snow include diffusive mixing of water vapor within the firn layer and sublimation at the surface of the snowpack.

[4] To date (2001), only limited observations link the $\delta^{18}O$ values in ice and snow samples to on-site air temperature at high-altitude, midlatitude, and low-latitude ice-coring sites. *Davis et al.* [1995] found a positive correlation between increasing air temperature and $\delta^{18}O$ value in snow deposited since the early 1970s in an ice core collected from the Huascaran Ice Cap in Peru. Similar results have been reported by *Yao et al.* [1996] between recent air temperature records and $\delta^{18}O$ values from three ice cores collected in northern Tibet. Furthermore, *Yao et al.* [1996] reported the first development of transfer functions between $\delta^{18}O$ values in recent precipitation and the T_A during storms in northern Tibet. The research by *Yao et al.* [1996] is one of the few studies that has developed transfer functions for nonpolar ice-coring locations. More recent research by *Yao et al.* [1999] has indicated that the impact of temperature change on the isotopic content of precipitation is better at higher elevation (>4200 m) sites in China.

[5] Detailed $\delta^{18}O$ data from snow-pit samples combined with site-specific meteorological and snow-accumulation data from Upper Fremont Glacier (UFG) (Figure 1) provides the opportunity to develop a transfer function between $\delta^{18}O$ and T_A at a high-altitude, nonpolar ice-coring site in the continental United States. If a site-specific transfer function can be developed at the UFG site, continuous ice cores collected to bedrock in 1991 and 1998 can be used to reconstruct long-term changes in T_A at this remote, high-altitude site. Carbon 14 ages of insect legs in the lower parts of both cores, and core stratigraphy, indicate that ~280 years of record are available for temperature reconstruction [*Naftz et al.*, 1996; *Schuster et al.*, 2000]. Chemical and isotopic analyses of ice from both cores indicate the preservation of historical records of environmental change, including above-ground nuclear weapons testing, air temperature, volcanic eruptions, and the chemical quality of atmospheric deposition [*Naftz et al.*, 1991; *Naftz*, 1993; *Naftz et al.*, 1996; *Cecil and Vogt*, 1997; *Schuster et al.*, 2000].

[6] The objective of this paper is to determine a site-specific $\delta^{18}O/T_A$ transfer function for the UFG. If successful, this UFG $\delta^{18}O/T_A$ transfer function will then be used in

conjunction with $\delta^{18}O$ records from the UFG ice cores to reconstruct trends in T_A in alpine areas of the Wind River Range during the past 200 years.

2. Background Glaciological Data

[7] Background glaciological data on UFG were collected from 1990 to 1991 [*Naftz and Smith*, 1993]. Radio echo sounding [*Watts and England*, 1976; *Trombley*, 1986] was used to determine ice thickness and bedrock topography. Ice thickness ranged from 60 to 172 m in the upper half of the glacier during 1990. The 10-m borehole temperatures (4-day equilibration period) indicated that the ice is at the pressure melting point (0 ± 0.4°C). Annual ablation (including snow, firn, and ice) measured during 1990–1991 averaged 0.93 m/yr. Densification processes proceed rapidly at the site, with densities exceeding 8.5×10^2 kg/m^3 at depths 14 m below the surface. Ice velocity decreases in a downslope direction, ranging from 0.8 to 3.1 m/yr during the monitoring period. Mean air temperature monitored on UFG from 11 July 1990 to 10 July 1991 was −6.9°C. Snow-pit sampling at the site indicated preservation of the annual $\delta^{18}O$ signature during the initial summer melt season followed by dampening of the signal in subsequent melt seasons [*Naftz*, 1993; *Naftz et al.*, 1993]. A detailed age-depth profile for UFG was determined using continuous electrical conductivity measurements (125,000 data points) on the ice core collected in 1991 [*Schuster et al.*, 2000] in combination with carbon 14 age dating of insect parts found in the lower part of this core [*Naftz et al.*, 1996]. On the basis of these data, ice from the bottom of the 1991 ice core (162 m below the surface) was probably deposited as snow prior to 1710 A.D.

3. Methodology

3.1. Data Collection

[8] Site-specific air temperature on UFG was monitored with an automated weather station (WS) installed in a boulder field ~100 m to the north of UFG at an altitude of 3960 m (Figure 1). Sensor height was 2 m above land surface and it was shielded with a RM Young 12 plate grill radiation shield. The temperature sensor was factory calibrated and was periodically checked for accuracy at the field site with a handheld digital thermocouple probe. The WS was operated from July 1990 through August 1991 and from September 1997 through March 2001. Relative humidity, wind speed and direction, and solar radiation (bandwidth) also were measured each minute and compiled into hourly averages. Changes in snow depth on UFG were continuously monitored with a Judd snow-depth sensor installed on UFG at an altitude of 3990 m in September 1997 (Figure 1). The ultrasonic depth sensor was suspended on a horizontal bar above the snow surface and emitted a sonic signal. The travel time for the sonic pulse to the snow surface and return were measured, and the distance to the surface was calculated after correcting for air temperature effects on the speed of sound. Additional snow accumulation, cumulative precipitation, and air temperature data used in this research were obtained from the Cold Springs snowpack telemetry (SNOTEL) site located ~22 km northeast of UFG at an altitude of 2940 m. The Snow Survey Branch of the Natural Resources Conservation Service operates the Cold Springs SNOTEL site. SNOTEL stations are fully automated and unattended with air temperature sensors, cumulative precipitation gages, and snow pillows. Snow pillows are sheet metal bladders filled with an antifreeze solution connected to a pressure transducer that measures snow-water equivalent. Data transmission occurs daily using a meteor-burst telemetry system [*Serreze et al.*, 1999].

[9] Snow samples were collected on UFG from vertical trench faces of snow pits. Ten to 20 cm of snow were composited in precleaned, 500-mL Nalgene wide-mouthed sample bottles. Snow density was determined by collecting snow at 10-cm intervals from trench faces in 250- or 1000-cm^3 samplers and weighing the samples on a portable electronic balance. Ice core samples from UFG were collected according to methods outlined by *Naftz et al.* [1996].

3.2. Sample Processing and Analysis

[10] The ice core samples were melted according to strict protocols to minimize sample contamination. Ice cores were subsampled by using a bandsaw operated in walk-in freezers (air temperature between −10° and −24°C). The sections were split lengthwise with one split being archived for future research. The surface ice from each subsample was scraped away with a stainless steel microtome. Each ice sample was thoroughly rinsed with ultrapure (18.0 megohm) deionized water and placed in a prerinsed and covered plastic container. Each sample was allowed to melt at room temperature for ~1 hour (or until ~15 mL of meltwater had accumulated). After this period the sample was rinsed in the accumulated meltwater, and the melt was discarded to eliminate any remaining isotopic signature from the rinse water. The remaining sample was allowed to melt in the covered plastic container at room temperature. After complete melting, the samples were filtered (0.45 μm), placed in a glass vial, sealed with a polyseal cap and coated with ParaFilm. The snow samples were processed in a similar manner, except they were not scraped or rinsed with ultrapure deionized water and the initial meltwater was not discarded. Because of the remote location of the study site, snow samples collected during the summer months could not be kept frozen during transport to the trailhead. Summer snow samples were allowed to melt in thick-walled plastic bottles with tape sealed lids to eliminate isotopic exchange with outside air.

[11] The $\delta^{18}O$ value of each sample was determined by using the method developed by *Epstein and Mayeda* [1953] at the U.S. Geological Survey Stable Isotope Laboratory in Menlo Park, California, and reported relative to Standard Mean Ocean Water (SMOW) in per mill notation. Tritium concentration was determined by electrolytic enrichment/liquid scintillation counting [*Thatcher et al.*, 1977] at the U.S. Geological Survey Tritium Laboratory in Menlo Park, California.

4. Results and Discussion

4.1. Transfer Function From SNOTEL Data

[12] Because UFG is a remote, high-altitude site, it is not possible to physically collect snow samples from individual storms for $\delta^{18}O$ analysis. Instead, the site was visited one to two times per year. During each site visit, continuous snow samples were collected and snow density measurements were made from pit faces that exposed the cumulative

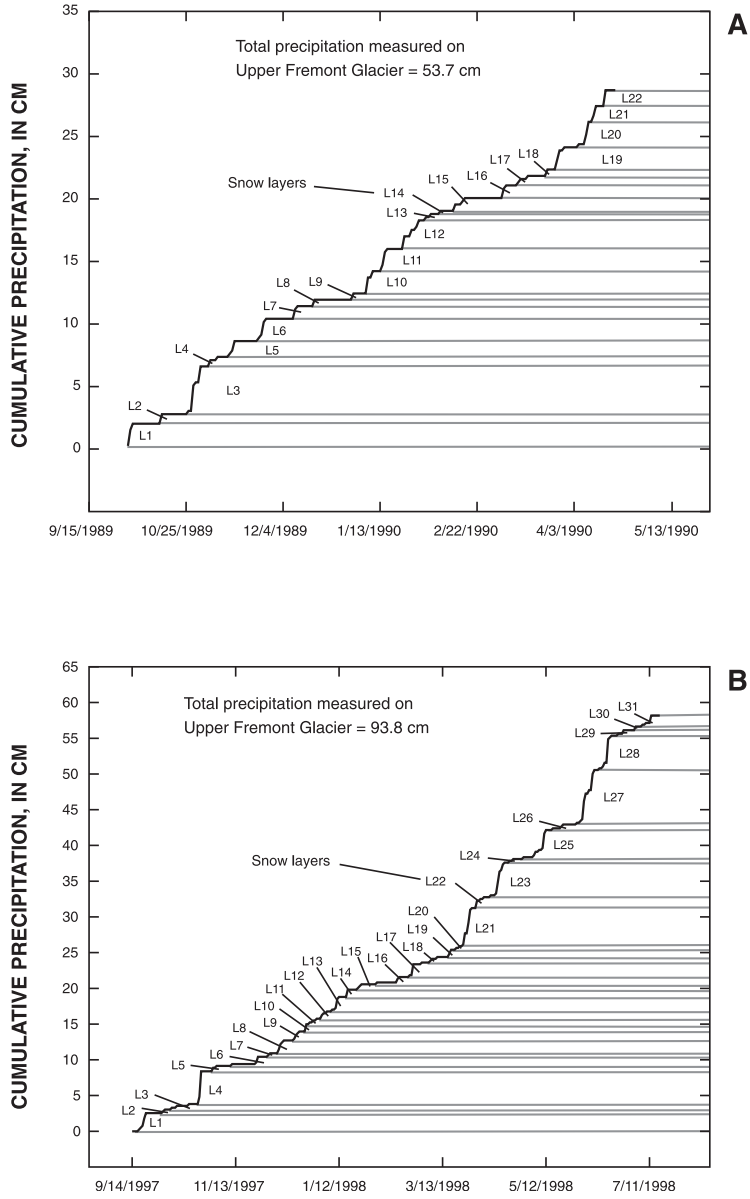

Figure 2. Cumulative precipitation events recorded at the Cold Springs SNOTEL site in the Wind River Range, Wyoming, from (a) 1 October 1989 through 20 April 1990, (b) 14 September 1997 through 17 July 1998, (c) 1 September 1998 through 21 July 1999, and (d) 1 October 1999 through 3 May 2000.

seasonal snowpack. Transfer functions between $\delta^{18}O$ in the snowpack and T_A were determined from data collected during four seasonal snowpacks (1989–1990, 1997–1998, 1998–1999, and 1999–2000).

[13] The cumulative precipitation and snow pillow data from the Cold Springs SNOTEL site were used to determine the timing and amount of each snow accumulation event on UFG. The cumulative precipitation measured in the UFG snow pits and the Cold Springs SNOTEL site was standardized to identify the approximate location and timing of each accumulation event. This method of determining the timing and relative amounts of accumulation events on UFG relied on the following assumptions: (1) snow redeposition and melting was minimal after each accumulation event; (2) the same storms impact both sites with the same relative intensities; and (3) all precipitation on the UFG is in the form of snow and therefore accumulates and can be used as a proxy for cumulative precipitation. None of these assumptions were valid 100% of the time.

[14] Cumulative precipitation measured at the SNOTEL site varied significantly from 24.9 cm in May 2000 to 77.2 cm in July 1999 (Figure 2). Because the periods of record are different for each year, direct comparisons of seasonal cumulative precipitation amounts are not possible. The largest accumulation events generally occurred between the months of March and June (Figure 2) for the 2 years with snow-pit records extending into July (1998 and 1999). Cumulative precipitation measured from snow pits on UFG during the same time periods ranged from 69 to 189 percent of the cumulative precipitation measured at the Cold Springs SNOTEL site. The 1998–1999 seasonal snowpack included the only snow pit containing less cumulative

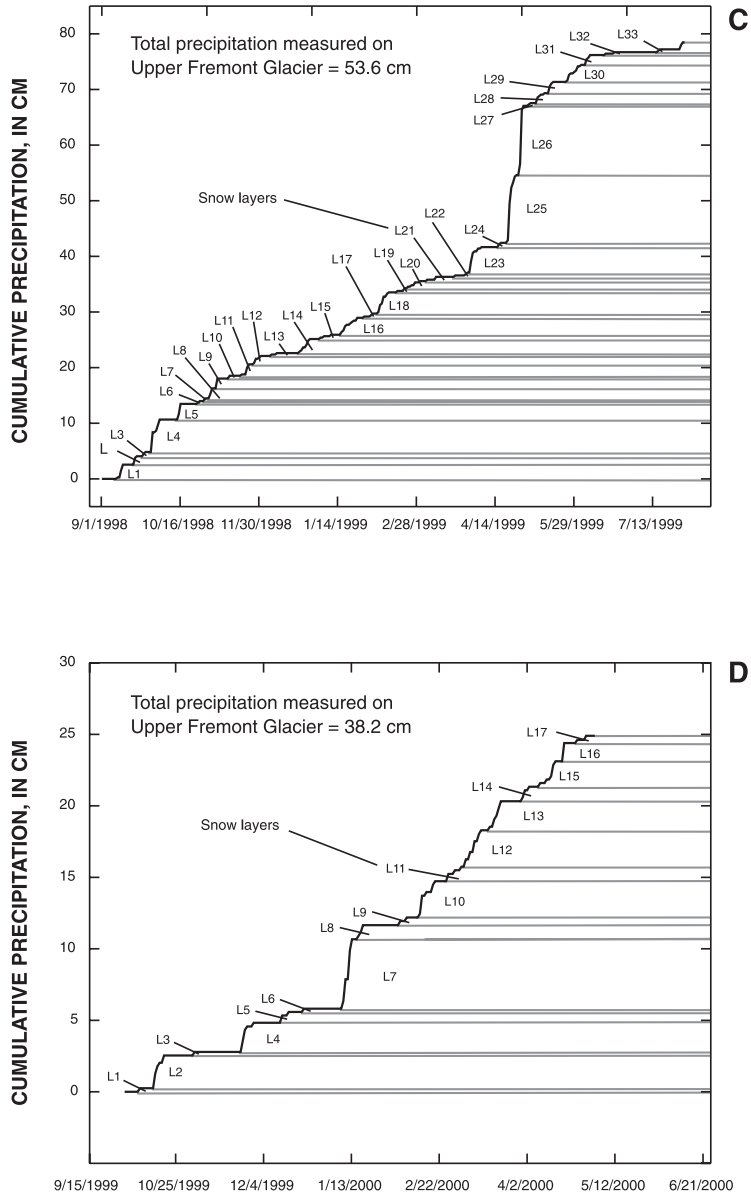

Figure 2. (continued)

precipitation at UFG than the Cold Springs SNOTEL site. The reason for this anomaly is unknown; however, one possible cause could be the substantial amount of snowfall that occurred in a short time period during April 1999 (layers 25 and 26, Figure 2c). More than 31% of the cumulative precipitation measured at the Cold Springs SNOTEL site from 1 September 1998 to 17 July 1999, occurred during an 11-day period in April 1999. Localized occurrence of storms at the Cold Springs SNOTEL site or substantial wind removal of the snow deposited during this 11-day event could substantially decrease the cumulative precipitation measured on UFG, resulting in the lower than expected cumulative precipitation relative to the SNOTEL site.

[15] Hourly T_A measured adjacent to UFG was used to determine the T_A during each accumulation event during the 1997–1998, 1998–1999, and 1999–2000 seasons. A weather station was not installed adjacent to UFG until July 1990. Daily T_A for the 1989–1990 accumulation period was estimated from the regression equation developed between air temperature at the Cold Springs SNOTEL site and the UFG glacier during a period of dual measurements from 11 July 1990, through 28 July 1991 (Figure 3a). The positive correlation between daily T_A measured adjacent to UFG and the Cold Springs SNOTEL site was excellent (coefficient of determination (R^2) = 0.946, $p < 0.0001$, $n = 383$). This same technique was used to estimate daily T_A adjacent to UFG during mid-June to mid-July 1998 and from mid-April to mid-July 1999, when the air temperature sensor adjacent to UFG was not operating properly. The regression equation used for these estimates was based on 264 days of dual temperature records recorded at both sites from 1 October 1997 through 21 June 1998 (Figure 3b). The positive correlation between daily T_A measured adjacent to UFG and the Cold Springs SNOTEL site during the

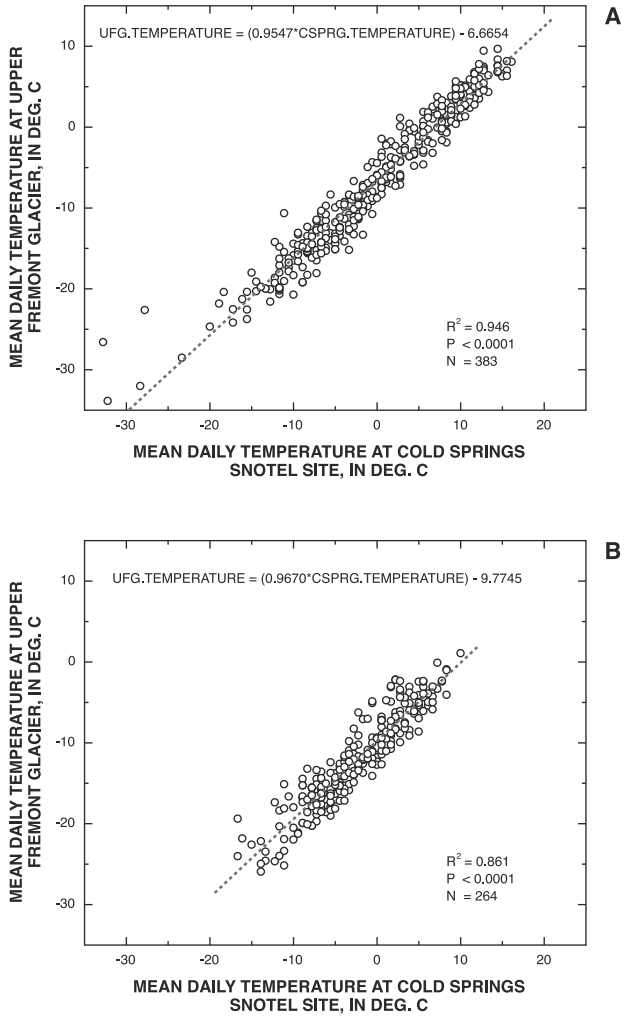

Figure 3. Regression equations developed between mean daily air temperature at the Cold Springs SNOTEL (CSPRG) site (altitude = 2940 m) and Upper Fremont Glacier (UFG) (altitude is 3960 m) from (a) 11 July 1990 through 28 July 1991 and (b) 1 October 1997 through 21 June 1998, Wind River Range, Wyoming.

1997–1998 period of record was also statistically significant ($R^2 = 0.861$, $p < 0.0001$, $n = 264$).

[16] Snow samples were collected from snow pits on UFG during April 1990, March 1998, July 1998, July 1999, and May 2000. Each snow sample represented a 10- to 20-cm depth composite. The $\delta^{18}O$ value was determined for each sample composite. The bottom of each snow pit, recognized by a distinctive firn/ice layer, corresponds to the first snowfall event of each accumulation period, and usually occurred in mid-September to early October. Snow density profiles for each snow pit were converted to cumulative precipitation. The cumulative precipitation data from the snow pits was standardized to equal the cumulative precipitation data from the Cold Springs SNOTEL site. This standardizing procedure allowed for a direct comparison between accumulation events recorded at the SNOTEL site with the snow pits sampled on UFG. The standardized snow accumulation events from each snow pit were then assigned a layer number (L1, L2, etc.) corresponding to a specific date range for a snow accumulation event recorded at the Cold Springs SNOTEL site (Tables 1–5). Individual accumulation events were composited to reduce the number of layers during each accumulation season. Each accumulation period was then assigned a mean air temperature on the basis of measured air temperature on UFG (15 days before to 15 days after the accumulation period midpoint, $n = 31$) and measured $\delta^{18}O$ values in snow pits excavated on UFG (fraction of standardized sampled snowpack corresponding to the accumulation period recorded at the Cold Springs SNOTEL site) (Tables 1–5).

[17] The $\delta^{18}O$ and air temperature data for each snow pit were plotted to determine if a positive linear relation between $\delta^{18}O$ and T_A exists at the UFG coring site (Figure 4). With the exception of the data collected during the 1997–1998 season, there is a significant and positive linear correlation between $\delta^{18}O$ and T_A values for each accumulation period (Figure 4). As expected, the lowest $\delta^{18}O$ values coincide with the lowest measured air temperatures. Large variations in mean air temperatures were observed during the 4-year study, ranging from a low of −18°C to a high of 2°C.

[18] Both of the UFG snow pits sampled in 1998 (March and July) record a series of accumulation events with anomalously heavy $\delta^{18}O$ signals relative to the local air temperature measured on UFG (Figure 4). Both snow pits, FRE-98-1 and FRE-98-2, display a strong trend in heavier isotopic composition beginning in early December 1997 and continuing through February 1998. The amplitude of $\delta^{18}O$ values in FRE-98-2 is higher than in FRE-98-1; however, this is probably due to the smaller sampling intervals used when sampling FRE-98-2 (10-cm composites) compared to FRE-98-1 (20-cm composites).

[19] It is probable that the anomalously heavy $\delta^{18}O$ found in early December 1997 thru February 1998 in snow pits FRE-98-1 and 2 are related, in large part, to changes in moisture sources related to the El Niño-Southern Oscillation (ENSO) episode that began to strongly influence weather patterns over the region in early 1998. Analysis of daily 700 mbar height anomalies over the Northern Hemisphere (not shown) indicated that storms impacting UFG from 11 November 1997 through 3 December 1997, originated in the Gulf of Alaska. Precipitation from these storms contained normal $\delta^{18}O$ values and air temperatures for this time of year (Figure 4).

[20] In contrast, storms impacting UFG from 8 December 1997 through 5 January 1998 and from 17 January 1998 through 25 January 1998 were derived from source areas over the subtropical Pacific Ocean, following the long westerly trajectories characteristic of many ENSO winters [*Dettinger et al.*, 1998]. These storms did not have the strong connections to polar air masses that characterized the earlier storms in November 1997 and the first few days of December 1997. Snow-pit samples during both of these latter time periods (8 December 1997 through 5 January 1998 and 17 January 1998 through 25 January 1998) contained anomalously heavy $\delta^{18}O$ values (Figure 4) indicating a change in moisture source area and storm track from northern path moisture sources to more southerly moisture paths and sources [*Cayan*, 1990; *Dettinger and Cayan*, 1992]. Although the different moisture source during the ENSO events can explain the overall heavier isotopic signature

Table 1. Mean Air Temperature, Percent of Cumulative Precipitation, and Mean $\delta^{18}O$ Value for Each Accumulation Period From October 1989 to April 1990 in Snow Pit FRE-90-1, Upper Fremont Glacier, Wyoming[a]

Layer	1989–1990 Accumulation Periods	Mean Air Temperature, °C[b]	Percent of Cumulative Precipitation	Mean $\delta^{18}O$, per mill
L1	1–3 Oct.	−5.36[c]	7.08	−16.05
L2	15 Oct.	−6.15	2.65	−17.07
L3	26–31 Oct.	−8.32	13.27	−17.06
L4	4–7 Nov.	−8.92	2.65	−16.65
L5	12–14 Nov.	−10.29	4.42	−16.65
L6	24–27 Nov.	−11.06	6.19	−16.80
L7	9–10 Dec.	−14.47	3.54	−20.35
L8	17 Dec.	−13.94	1.77	−20.35
L9	2 Jan.	−13.39	1.77	−20.35
L10	8–10 Jan.	−13.66	6.17	−20.40
L11	14–16 Jan.	−14.88	6.20	−25.15
L12	23–29 Jan.	−15.85	7.96	−26.61
L13	1–3 Feb.	−17.15	1.77	−27.05
L14	7 Feb.	−17.14	0.9	−27.05
L15	13–17 Feb.	−15.49	3.54	−25.48
L16	5–6 March	−11.20	3.54	−24.15
L17	11–15 March	−11.88	2.65	−21.71
L18	23 March	−10.75	1.77	−21.25
L19	27–30 March	−10.29	6.21	−20.10
L20	5–9 April	−8.51	7.09	−19.82
L21	11–12 April	−7.44	4.43	−15.76
L22	16 April	−7.73	4.43	−16.10

[a]Mean air temperature: mean daily air temperature 15 days before to 15 days after the midpoint of each accumulation period; $\delta^{18}O$, delta oxygen 18; C, Celsius.
[b]Site-specific air temperature data from weather station on Upper Fremont Glacier missing. Mean values reconstructed using air temperature measured at Cold Springs SNOTEL site.
[c]Mean based on less than 31 values because temperature record at Cold Springs SNOTEL site did not start until 30 September 1989.

observed in the snow falling on UFG, the lack of a positive correlation between the $\delta^{18}O$ in snow and the local temperature cannot be explained with the existing data.

[21] Transfer functions between $\delta^{18}O$ and T_A were developed for each of the five snow pits (Figure 4). The R^2 values for the three data sets not impacted by the ENSO events (1989–1990, 1998–1999, and 1999–2000) were statistically significant ($p < 0.0001$). The slopes of the regression equations for the three transfer functions ($\delta^{18}O/T_A$) ranged from 0.435 to 0.943 and appear to be related to the length of

Table 2. Mean Air Temperature, Percent of Cumulative Precipitation, and Mean $\delta^{18}O$ Value for Each Accumulation Period from September 1997 to March 1998 in Snow Pit FRE-98-1, Upper Fremont Glacier, Wyoming[a]

Layer	1997–1998 Accumulation Periods	Mean Air Temperature, °C	Percent of Cumulative Precipitation	Mean $\delta^{18}O$, per mill
L1	18–22 Sept.	−2.98[b]	9.80	−14.56
L2	2–3 Oct.	−4.82	1.96	−14.56
L3	7–17 Oct.	−6.97	2.94	−20.09
L4	23–24 Oct.	−9.30	17.65	−23.34
L5	31 Oct. to 2 Nov.	−11.24	2.94	−24.18
L6	11–26 Nov.	−13.58	4.90	−24.18
L7	2–3 Dec.	−14.06	1.96	−21.58
L8	8–11 Dec.	−14.44	6.86	−19.53
L9	17–20 Dec.	−14.74	4.90	−19.53
L10	24 Dec.	−15.74	3.93	−20.50
L11	26–30 Dec.	−15.98	2.94	−20.71
L12	2–5 Jan.	−16.75	3.93	−20.71
L13	8–12 Jan.	−17.02	7.84	−19.34
L14	17 Jan.	−17.11	3.93	−18.78
L15	23–25 Jan.	−15.92	2.94	−18.85
L16	3–16 Feb.	−15.28	3.92	−21.06
L17	22 Feb. to 1 March	−18.02	7.84	−21.06
L18	6–10 March	−16.79	2.94	−18.46
L19	17–18 March	−14.43	3.93	−16.41
L20	21–23 March	−13.44	1.96	−16.41

[a]Mean air temperature: mean daily air temperature 15 days before to 15 days after the midpoint of each accumulation period; $\delta^{18}O$, delta oxygen 18; C, Celsius.
[b]Mean based on less than 31 values because temperature record on Upper Fremont Glacier did not start until 13 September 1997.

Table 3. Mean Air Temperature, Percent of Cumulative Precipitation, and Mean $\delta^{18}O$ Value for Each Accumulation Period From September 1997 to July 1998 in Snow Pit FRE-98-2, Upper Fremont Glacier, Wyoming[a]

Layer	1997–1998 Accumulation Periods	Mean Air Temperature, °C	Percent of Cumulative Precipitation	Mean $\delta^{18}O$, per mill
L1	18–22 Sept.	−2.98[b]	4.26	−14.07
L2	2–3 Oct.	−4.82	0.85	−15.71
L3	7–17 Oct.	−6.97	1.28	−19.43
L4	23–24 Oct.	−9.30	7.66	−17.92
L5	31 Oct. to 2 Nov.	−11.24	1.28	−19.62
L6	11–26 Nov.	−13.58	2.12	−21.02
L7	2–3 Dec.	−14.06	0.85	−21.02
L8	8–11 Dec.	−14.44	2.98	−18.08
L9	17–20 Dec.	−14.74	2.12	−16.26
L10	24 Dec.	−15.74	1.71	−15.48
L11	26–30 Dec.	−15.98	1.28	−14.92
L12	2–5 Jan.	−16.75	1.71	−14.92
L13	8–12 Jan.	−17.02	3.40	−17.62
L14	17 Jan.	−17.11	1.71	−19.02
L15	23–25 Jan.	−15.92	1.28	−18.96
L16	3–16 Feb.	−15.28	1.71	−17.42
L17	22 Feb. to 1 March	−18.02	3.40	−17.42
L18	6–10 March	−16.79	1.28	−17.22
L19	17–18 March	−14.43	1.71	−17.18
L20	21–23 March	−13.44	0.85	−17.18
L21	25–30 March	−12.63	8.94	−18.01
L22	2–6 April	−13.38	2.55	−18.43
L23	10–18 April	−12.62	8.09	−19.67
L24	21–23 April	−10.47	0.85	−20.92
L25	29 April to 12 May	−7.50	6.81	−22.21
L26	16–22 May	−6.84	1.28	−21.70
L27	30 May to 9 June	−4.61	14.89	−17.59
L28	12–19 June	−3.31[c]	8.09	−18.84
L29	22–26 June	−1.62[c]	1.71	−18.46
L30	3 July	0.66[c]	0.85	−18.46
L31	7–12 July	2.37[c]	2.55	−18.46

[a]Mean air temperature: mean daily air temperature 15 days before to 15 days after the midpoint of each accumulation period; $\delta^{18}O$, delta oxygen 18; C, Celsius.

[b]Mean based on less than 31 values because temperature record on Upper Fremont Glacier did not start until 13 September 1997.

[c]Daily mean air temperature on Upper Fremont Glacier calculated from corresponding air temperature at Cold Springs SNOTEL site by using the regression equation shown in Figure 3.

record sampled by each snow pit. For example, snow pit FRE-90-1 (Figure 4f) has the highest slope (0.943) corresponding to the shortest seasonal record length (snow pit sampled on 20 April 1990). In contrast, snow pit FRE-99-1 (Figure 4i) has the lowest slope (0.435), which corresponds to the longest seasonal record length (snow pit sampled on 17 July 1999). The 3 May 2000, sampling date for snow pit FRE-00-1 (Figure 4j) has an intermediate record length relative to snow pits FRE-90-1 and FRE-99-1, which results in an intermediate slope of 0.688. It is likely that the lowest slope (0.435) observed in snow pit FRE-99-1 results from snow deposited from mid-May through mid-July on UFG. As observed by *Yao et al.* [1999], convective cloud droplets and reevaporation cycles are characteristic of late spring and summer precipitation events and could result in significant decreases in $\delta^{18}O/T_A$ slopes compared to nonconvective winter precipitation events. Removal of snowfall events occurring after 15 May 1999 from the data set (Figure 4i) results in a $\delta^{18}O/T_A$ slope increase from 0.435 to 0.614.

4.2. Transfer Function From Depth Sensor Data

[22] The transfer functions developed by using storm occurrence and amount data from the Cold Springs SNOTEL site do not account for possible localized effects occurring on UFG. These localized effects may include wind erosion, redeposition of snow from previous storm events, or significant differences in the relative timing and magnitude of storms impacting UFG relative to the Cold Springs SNOTEL site.

[23] An ultrasonic snow-depth sensor was installed on UFG in September 1997 (Figure 1) to measure the timing, amount, and significance of wind redistribution of localized storm events on UFG. The depth sensor was programmed to record snow depth every 60 min. Because of technical difficulties, the period of operation for the snow-depth sensor was limited (13 September 1997 to 18 December 1997, and 17 September 1998 to 25 January 1999). The partial records obtained from the snow-depth sensor provided valuable insights into postdepositional processes that may occur at high-altitude coring sites. These postdepositional processes were significant in developing transfer functions between $\delta^{18}O$ and T_A.

[24] During the two periods of snow-depth sensor operation the timing and relative amounts of daily snow accumulation occurring at the UFG and Cold Springs SNOTEL sites were compared (Figures 5 and 6). The precipitation amounts could not be directly compared between the sites because the depth sensor measures snow depth, whereas the

Table 4. Mean Air Temperature, Percent of Cumulative Precipitation, and Mean $\delta^{18}O$ Value for Each Accumulation Period From September 1998 to July 1999 in Snow Pit FRE-99-1, Upper Fremont Glacier, Wyoming[a]

Layer	1998–1999 Accumulation Periods	Mean Air Temperature, °C	Percent of Cumulative Precipitation	Mean $\delta^{18}O$, per mill
L1	10–13 Sept.	1.23	3.28	−14.50
L2	20–21 Sept.	−1.71	1.96	−14.50
L3	25–26 Sept.	−3.24	0.99	−14.50
L4	30 Sept. to 4 Oct.	−4.81	7.56	−15.00
L5	15–16 Oct.	−7.24	3.61	−16.43
L6	26–27 Oct.	−10.86	0.65	−16.43
L7	30 Oct.	−11.64	0.65	−16.43
L8	2–3 Nov.	−11.69	2.29	−16.43
L9	6 Nov.	−12.76	2.29	−16.72
L10	13 Nov.	−13.65	0.65	−21.57
L11	20–24 Nov.	−14.74	2.62	−21.57
L12	27 Nov. to 1 Dec.	−13.90	1.96	−21.57
L13	7–10 Dec.	−16.95	0.65	−21.57
L14	23–29 Dec.	−17.49	3.28	−21.57
L15	4–10 Dec.	−16.69	0.98	−21.57
L16	16–25 Dec.	−16.25	3.94	−22.22
L17	29 Jan. to 3 Feb.	−16.93	0.98	−24.99
L18	6–12 Feb.	−16.89	4.92	−24.99
L19	17–21 Feb.	−17.41	0.94	−24.99
L20	23 Feb. to 2 March	−16.51	1.67	−24.99
L21	6–11 March	−14.46	0.98	−24.99
L22	22–29 March	−13.71	1.29	−24.99
L23	31 March to 6 April	−14.06[b]	5.91	−23.42
L24	16–17 April	−13.00[b]	0.98	−22.19
L25	21–26 April	−11.14[b]	15.78	−20.99
L26	28–30 April	−10.76[b]	16.11	−18.95
L27	3–4 May	−10.26[b]	0.65	−19.09
L28	8–12 May	−8.89[b]	2.29	−19.09
L29	15–17 May	−8.13[b]	2.62	−19.09
L30	25 May to 2 June	−5.87[b]	3.94	−19.09
L31	5–7 June	−3.94[b]	2.29	−19.09
L32	16–21 June	−2.18[b]	0.65	−19.09
L33	16–17 June	2.37[b]	0.65	−19.09

[a]Mean air temperature: mean daily air temperature 15 days before to 15 days after the midpoint of each accumulation period; $\delta^{18}O$, delta oxygen 18; C, Celsius.

[b]Daily mean air temperature on Upper Fremont Glacier calculated from corresponding air temperature at Cold Springs SNOTEL site by using the regression equation shown in Figure 3.

Table 5. Mean Air Temperature, Percent of Cumulative Precipitation, and Mean $\delta^{18}O$ Value for Each Accumulation Period From October 1999 to May 2000 in Snow Pit FRE-00-1, Upper Fremont Glacier, Wyoming[a]

Layer	1999–2000 Accumulation Periods	Mean Air Temperature, °C	Percent of Cumulative Precipitation	Mean $\delta^{18}O$, per mill
L1	8 Oct.	−5.60	1.02	−16.28
L2	15–19 Oct.	−5.36	9.18	−15.81
L3	2 Nov.	−5.19	1.02	−15.00
L4	24–29 Nov.	−12.64	8.16	−16.84
L5	12–15 Dec.	−14.63	3.06	−17.56
L6	22 Dec.	−16.09	0.92	−21.94
L7	9–13 Jan.	−15.72	19.49	−23.42
L8	16–18 Jan.	−17.37	3.98	−20.21
L9	4–7 Feb.	−15.39	2.14	−21.47
L10	13–20 Feb.	−14.32	10.20	−21.72
L11	26 Feb. to 3 March	−14.82	4.08	−21.68
L12	5–12 March	−14.61	10.20	−21.75
L13	16–21 March	−14.48	8.16	−19.14
L14	31 March to 3 April	−12.02	4.08	−17.95
L15	8–15 April	−12.27	7.14	−16.29
L16	19 April	−7.50	5.12	−11.83
L17	25–29 April	−7.74	2.05	−11.83

[a]Mean air temperature: mean daily air temperature 15 days before to 15 days after the midpoint of each accumulation period; $\delta^{18}O$, delta oxygen 18; C, Celsius.

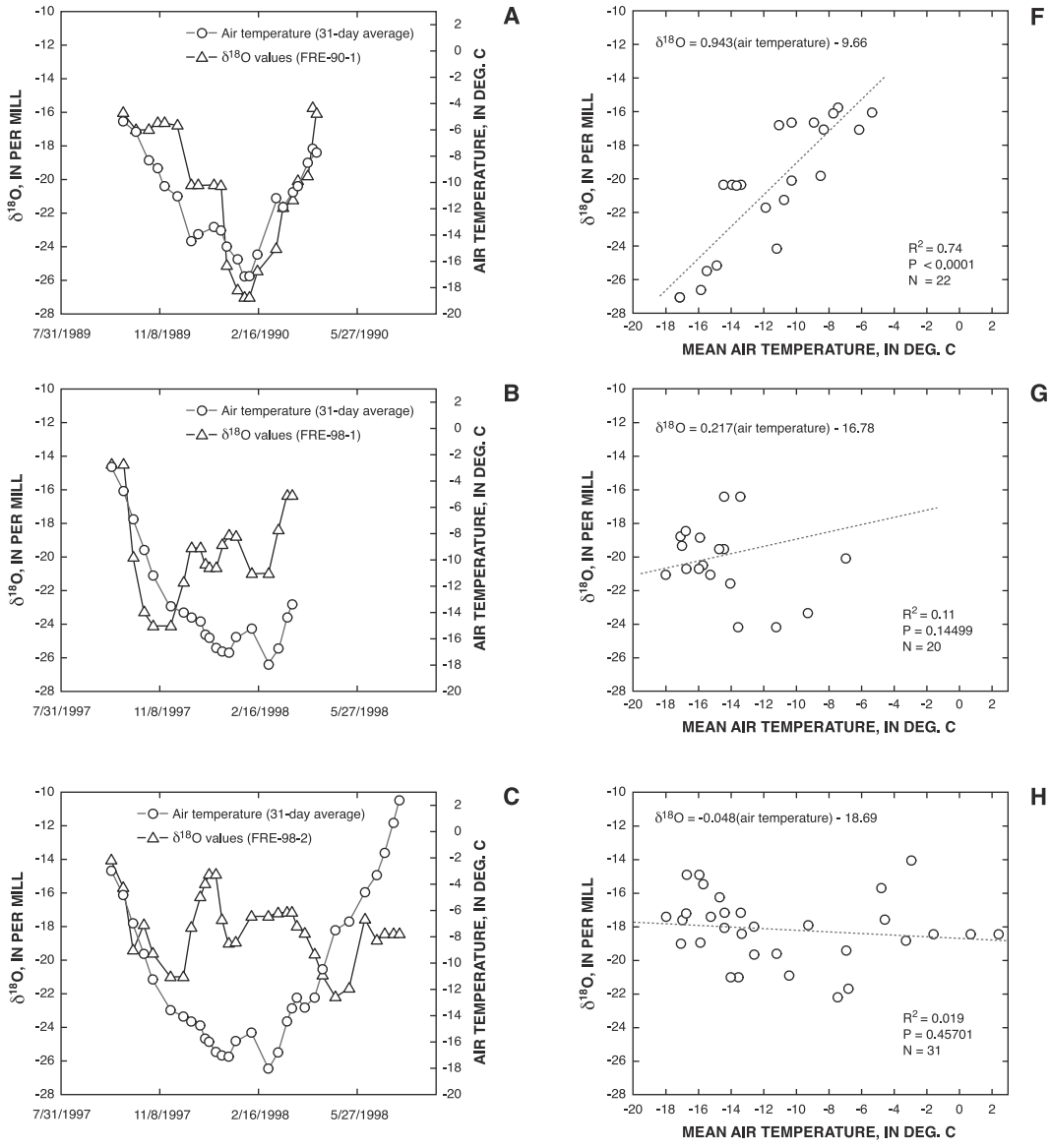

Figure 4. Weighted mean $\delta^{18}O$ values from snow-pit samples in relation to air temperatures measured before, during, and after the recorded snowfall events in UFG snow pits (a) FRE-90-1, (b) FRE-98-1, (c) FRE-98-2, (d) FRE-99-1, and (e) FRE-00-1, Upper Fremont Glacier, Wyoming. Linear trends between mean air temperature and weighted mean $\delta^{18}O$ values are from snow-pit samples collected at pits (f) FRE-90-1, (g) FRE-98-1, (h) FRE-98-2, (i) FRE-99-1, and (j) FRE-00-1.

SNOTEL sensor measures water equivalent. There is general agreement between the timing of accumulation events between the UFG and Cold Springs SNOTEL sites; however, there appear to be specific storm events that occur at one site and not the other. For example, from 19 November 1997 through 21 November 1997 a storm on UFG was detected by the snow-depth sensor, whereas no measurable precipitation was recorded at the Cold Springs SNOTEL site. The duration of selected storm events is also different between sites. For example, snow accumulation was recorded on UFG continuously from 5 November 1998 through 9 November 1998; however, at the Cold Springs SNOTEL site, measurable precipitation was only recorded on 6 November 1998. The extended duration of accumulation events recorded on UFG may be the result of redeposition of snow by wind after a snowfall event. Wind redeposition is more likely at UFG because of the high altitude (above timberline) of the site relative to the Cold Springs SNOTEL site, which is relatively sheltered (below timberline).

[25] Removal and (or) settling of snow after initial deposition also can be inferred from snow-depth sensor data. Changes in snow depth during 1997 and 1998–1999 are shown in Figure 7. The continuous monitoring of snow depth on UFG indicates that selected accumulation events may have been completely removed after deposition, probably by wind (Figure 7). For example, accumulation events that occurred between 26 October 1998 and 8 November 1998 may have been subsequently removed by wind. The depth sensor data do not allow for a clear separation

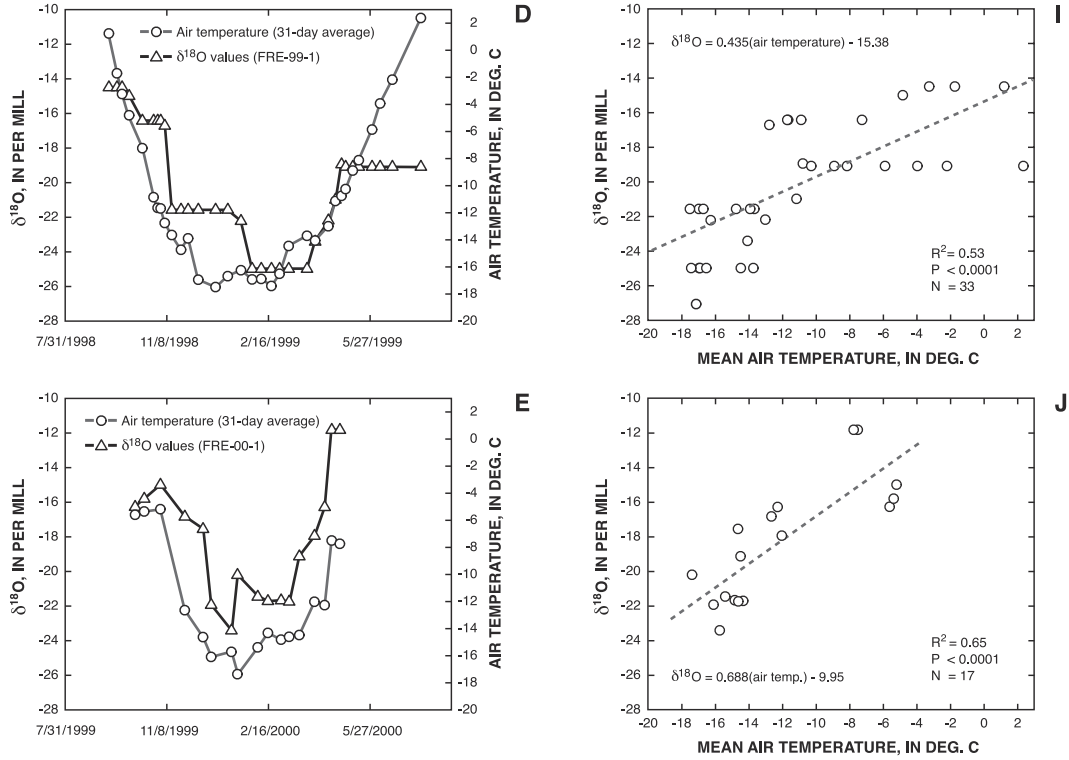

Figure 4. (continued)

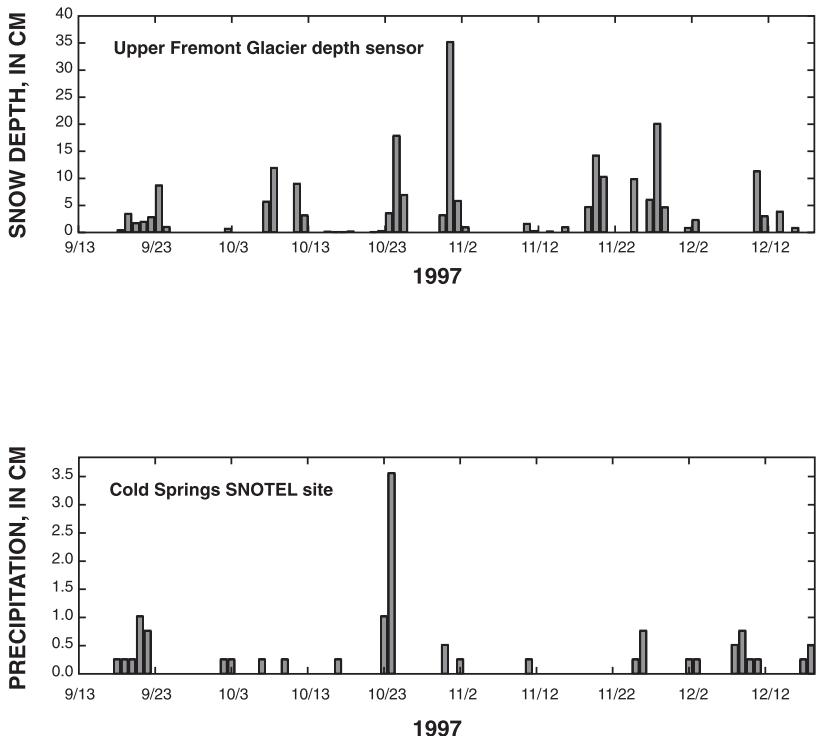

Figure 5. Daily snow accumulation recorded at the (top) Upper Fremont Glacier, Wyoming, snow-depth sensor and daily precipitation recorded at the (bottom) Cold Springs, Wyoming, SNOTEL site from 13 September to 18 December 1997.

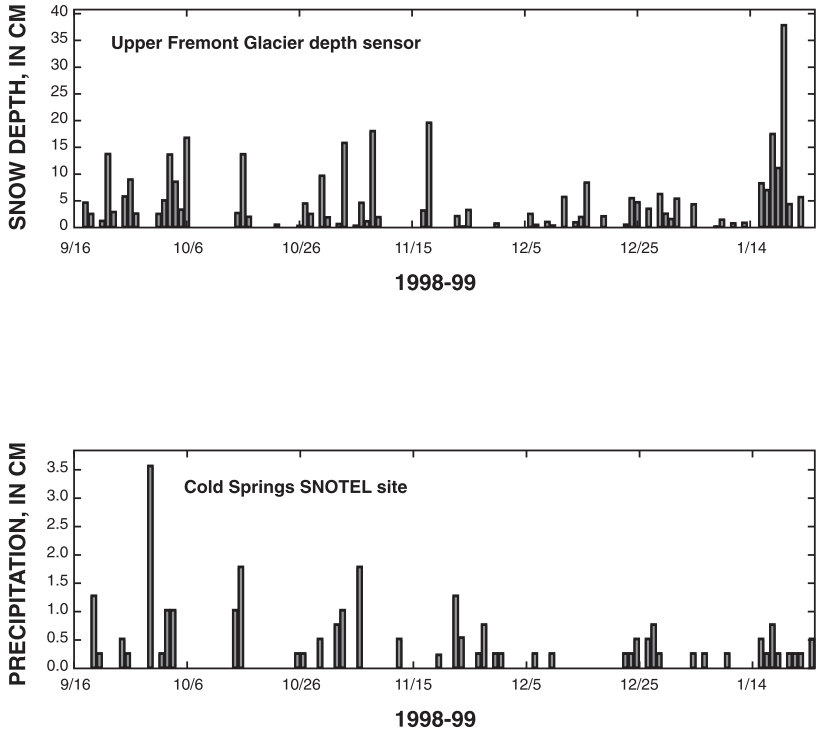

Figure 6. Daily snow accumulation recorded at the (top) Upper Fremont Glacier, Wyoming, snow-depth sensor and daily precipitation recorded at the (bottom) Cold Springs, Wyoming, SNOTEL site from 17 September 1998 to 25 January 1999.

between snow depth decreases caused by removal or settling; however, the return of the snow depth to prestorm measurements is probably dominated by wind removal processes.

[26] A comparison of measured wind speed and snow depth on UFG during 1998–1999 provides insight into conditions promoting wind removal of snow (Figure 8). In this example, early season snowfall occurring from mid-September through mid-October is not subject to substantial wind removal (Figure 8), although wind speed is elevated after the snowfall events. Higher air temperatures during the early season may result in denser snow that is less vulnerable to wind removal. After mid-October, high winds that occur immediately after accumulation events cause substantial snow removal. Lower temperatures during this period likely result in a less dense snow that is more vulnerable to wind removal. High wind speeds that occur between accumulation events do not appear to cause significant snow removal (Figure 8), probably because of the development of a wind or sun crust on the snow surface. On the basis of these observations, accumulation events that occur in mid-winter or during lower air temperatures may be more susceptible to wind removal, potentially biasing the $\delta^{18}O$ values toward periods of higher air temperatures (early or late season snowfall).

[27] Snow-depth sensor data were used to develop a transfer function between $\delta^{18}O$ and T_A for the partial accumulation records during the 1997 and 1998–1999 seasons (Figure 9). Snow accumulation layers not removed by wind at the site were designated L1 through L4 for both years of record (Figure 7). Each accumulation layer measured by the depth sensor was assigned a mean air temperature based on the measured air temperature at UFG (15 days before to 15 days after the accumulation period midpoint, $n = 31$). A settled snow depth of 0.5 times the measured depth of each layer was assumed to determine the corresponding sample depth of each accumulation event in snow pits FRE-98-1 and FRE-99-1. The transfer function developed from accumulation data from the snow-depth sensor on UFG ($R^2 = 0.77$, $p = 0.0042$) is in general agreement with transfer functions developed from accumulation records from the SNOTEL site 22 km away. Unlike the SNOTEL data, a positive correlation between T_A and $\delta^{18}O$ was obtained with the data from FRE-98-1 because the snow-depth sensor data did not extend past 18 December 1997, which was before the potential ENSO signals were recorded in the UFG snowpack.

[28] Longer-term snow-depth sensor records are needed before a reliable evaluation of the quality of transfer functions using the different methods can be made. The local properties of the data used to develop both sets of transfer functions should enhance the predictive power of the equations to reconstruct T_A trends using $\delta^{18}O$ values in ice cores from UFG.

4.3. Applications of Transfer Function to Climate Reconstruction

[29] Trends in $\delta^{18}O$ values were compared between the two ice cores collected from UFG in 1991 and 1998 (Figure 10). Both ice cores were collected at an altitude of 4000 m above sea level and were separated by ~200 m in distance (Figure 1). Precise chronology cannot be assigned

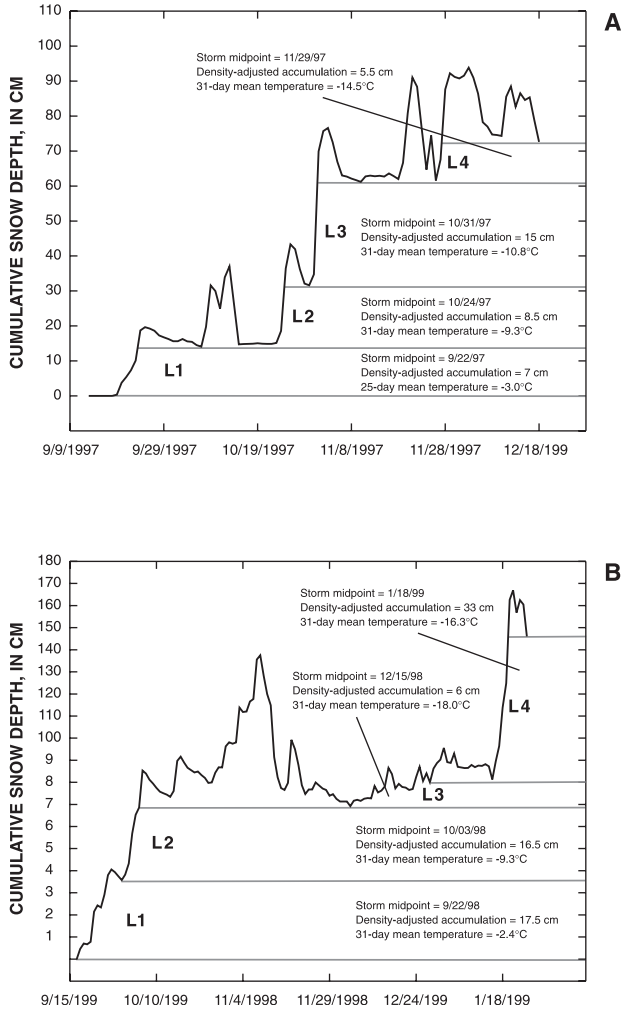

Figure 7. Cumulative snow depth and average air temperature during possible accumulation periods during (a) 1997 and (b) 1998–1999 on Upper Fremont Glacier, Wyoming. Snow layers designated as L1 through L4.

to specific sections of the core; however, approximate age dates of the upper 40 m of the core can be determined by the relative location of the highest concentrations of tritium in each ice core, presumably caused by the 1963 peak in aboveground nuclear testing. The tritium concentration spike in the DH98-4 ice core is ~1.5 m deeper than the tritium concentration spike in the DH91-1 ice core (Figure 10). This offset is probably a result of additional snow deposited on UFG between the 1991 and 1998 collection periods and small-scale differences in snow accumulation and retention between the two sites.

[30] Values of $\delta^{18}O$ in the upper 40 m of both ice cores show similar trends after accounting for the different collection dates, sampling densities, and small-scale variability in snow accumulation. For example, the peak tritium concentration in each core coincides with a sharp increase in $\delta^{18}O$ values (Figure 10). Another example is the sharp decline in $\delta^{18}O$ values that approach −20 per mill ~2 to 3 m below each peak in tritium concentration. These and other similarities in the $\delta^{18}O$ record from both cores indicate that a lower-resolution, annual climatic signal has been

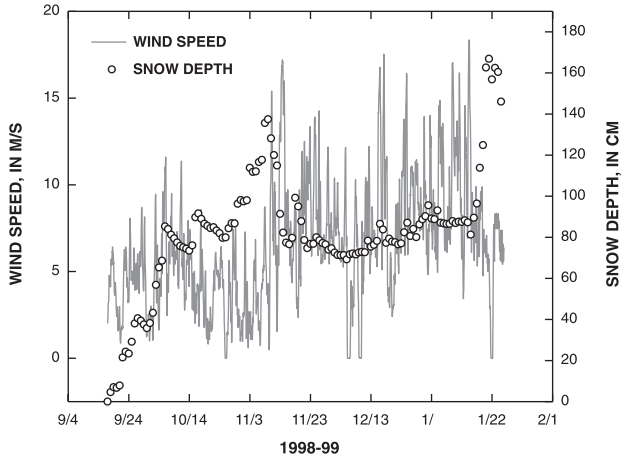

Figure 8. Hourly wind speed (5-hour running mean) and daily snow depth measured on Upper Fremont Glacier, Wyoming, from September 1998 through January 1999.

preserved in UFG. Seasonal climatic signals are not observed in the $\delta^{18}O$ values from the upper 40 m of the ice core records from UFG, probably as a result of a damping effect resulting from summer melting [*Wagenbach*, 1989; *Naftz*, 1993].

[31] A statistically significant ($p < 0.0001$) isotopic enrichment is observed in the top 40 m of both ice cores, indicating a warming trend in T_A (Figure 10). On the basis of the location of the tritium peak, ~40 years (early 1950s to early 1990s) is represented in both cores (the top 6.27 m of the DH 98-4 ice core was not sampled). The slopes of both trend lines (0.044 and 0.039) are similar to the range of $\delta^{18}O$ enrichment slopes (0.022 to 0.040) observed in ice core samples collected on three ice caps in Northern Tibet representing the period from 1960 to 1990 [*Yao et al.*,

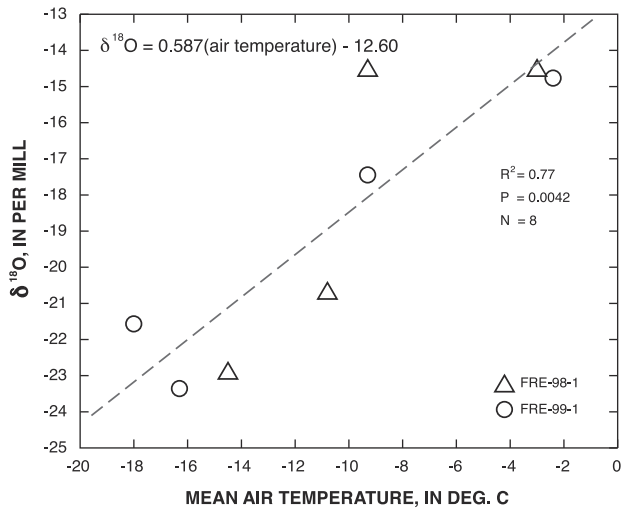

Figure 9. Linear trend between mean air temperature and weighted average $\delta^{18}O$ values from snow-pit samples collected during March 1998 (FRE-98-1) and July 1999 (FRE-99-1), Upper Fremont Glacier, Wyoming. Data from the snow-depth sensor (Figure 1) were used to determine amount and timing of accumulation events.

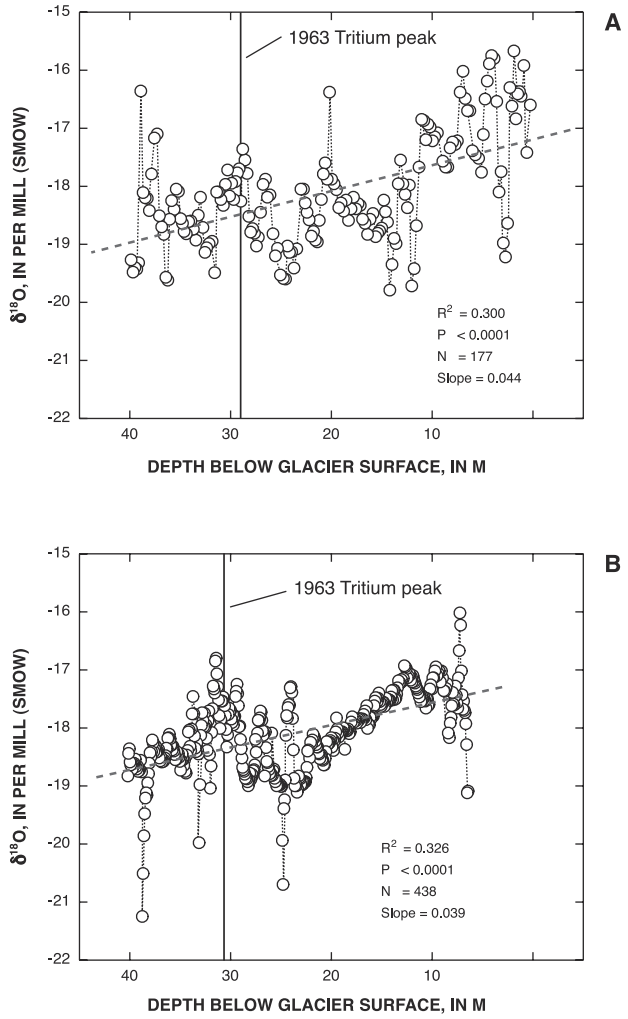

Figure 10. The $\delta^{18}O$ values measured in the upper 40 m of two ice cores collected from UFG: (a) DH91-1, ice core collected August 1991 and (b) DH98-4, ice core collected July 1998 and corresponding linear trend lines.

1996]. A summary transfer function (Figure 11) combining the data from snow pits FRE-90-1, FRE-99-1, FRE-00-1, and the snow-depth sensor data was used ($R^2 = 0.526$, $p < 0.001$, $n = 80$) to reconstruct trends in air temperature on UFG. A sharp increase in reconstructed T_A begins at ~25 m below the surface (mid to late 1960s) and continues to about the top of the sampled core (6.2 m below the surface), which roughly equates to the mid-1990s period (Figure 11). On the basis of this temperature reconstruction an average temperature increase of ~3.5°C has occurred since the mid-1960s in the alpine areas of northwestern Wyoming. This increase is much larger than the observed global mean temperature increase of ~0.7°C during the entire 20th Century. The reconstructed temperature increase from UFG is comparable to the temperature increase of +6°C for areas of Alaska from 1963 to 1998 [*Hileman*, 1999]; +2°C for sites in the European Alps since the early 1980s [*Haeberli and Beniston*, 1998]; +2.2°C at a high-altitude site in central Asia from 1962 to 1990 [*Mikhalenko*, 1997]; and +4°C in the western Arctic during the 20th Century [*Sin'kevich*, 1991]. The ice core data indicate that UFG and adjacent alpine areas in the Wind River Range, Wyoming, may be warming at much faster rates than the global average.

[32] In contrast to the reconstructed temperature increase at the UFG site, an instrumental temperature record from a high-altitude (3048 m) forested site at Niwot Ridge in northern Colorado indicates a statistically significant decrease in mean annual temperature of 1.0°C from 1953 to 1994 [*Williams et al.*, 1996]. Knowledge of the long-term climatic characteristics of high mountain regions are limited by sparse station networks and short records that seldom exceed 100 years [*Williams et al.*, 1996]. Local climate in alpine areas is often significantly different from regional and global conditions and the course grid GCM cannot simulate climate change in these areas. The mechanism causing the different trends in air temperature observed at the Niwot Ridge and UFG sites is not known.

[33] The significance of the recent temperature increases in areas surrounding UFG is given additional support by comparing them with information obtained from deeper sections of the 1991 ice core (Figure 11). Previous studies [*Naftz et al.*, 1996; *Schuster et al.*, 2000] indicate that the ice core section from ~102 to 150 m below the surface corresponds to snow deposited during the Little Ice Age (LIA) from ~1740 to 1860 A.D. The mean $\delta^{18}O$ value in ice from this section of the core is −19.85 per mill (n = 248). The mean $\delta^{18}O$ value during the LIA corresponds to a mean air temperature of −11.5°C (Figure 11). This value is ~5°C lower than the reconstructed T_A values from the near-surface sections of the 1998 ice core. Site-specific tree ring chronologies also support the cooling trends observed during this time period. Selected tree cores collected 2 km from UFG consistently showed a sustained period of reduced radial growth beginning ~1790 A.D. and continuing until ~1840 A.D. [*Naftz*, 1993]. This reduction in radial

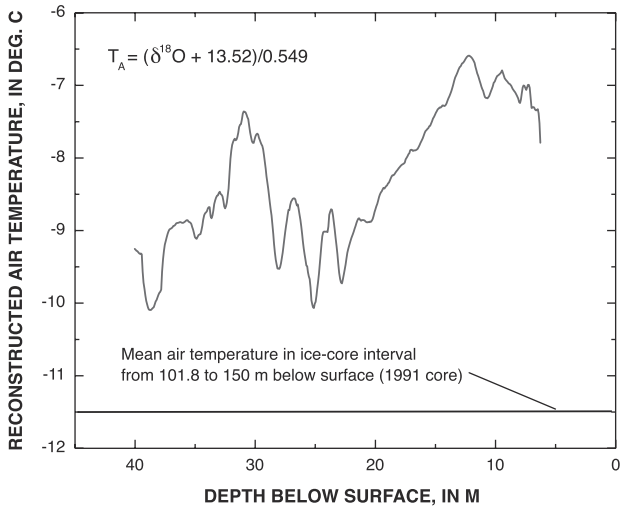

Figure 11. Reconstructed air temperature trends (20-sample running mean) during approximately 1950–1995 obtained from $\delta^{18}O$ values from the ice core collected during 1998, Upper Fremont Glacier, Wyoming. A composite transfer function using data from FRE-90-1, FRE-99-1, FRE-00-1, and depth sensor was used to reconstruct T_A values.

growth probably reflects a prolonged period of cooler summer temperatures that reduced the growing season in this alpine region.

[34] Changing trends in moisture sources and storm tracks may explain part of the shift toward heavier $\delta^{18}O$ values in recent sections of the UFG ice core. As discussed previously, relatively heavy $\delta^{18}O$ values were deposited on UFG during parts of the 1997–1998 accumulation cycle. The heavier isotopic signals corresponded to a distinct shift to more southerly storm moisture paths and sources. If the ratio of southern to northern storm paths impacting the Wind River Range has increased since the LIA, then part of the observed shift to heavier $\delta^{18}O$ values cannot be attributed to an increased T_A. *Dettinger et al.* [1994] have documented an increase in southerly storm tracks impacting the Sierra Nevada Range between 1947 and 1993. Additional research is required to determine if this shift to more southerly storm tracks is also impacting the Wind River Range.

5. Conclusions

[35] Transfer functions between $\delta^{18}O$ values measured in snow samples and T_A (31-day mean) were derived from data collected from four seasonal snowpacks (1989–1990, 1997–1998, 1998–1999, and 1999–2000) deposited on UFG. The timing and amount of each accumulation event on UFG was derived from an automated SNOTEL station ~22 km northeast of UFG. Except for the 1997–1998 snowpack, probably impacted by ENSO events, statistically significant and positive correlations between $\delta^{18}O$ values in the snow and T_A were consistently found. Large variations in T_A were observed during the four seasonal accumulation cycles ranging from a low of −18°C to a high of +2°C.

[36] Partial records obtained from an ultrasonic snow-depth sensor (13 September 1997 to 18 December 1997 and 17 September 1998 to 25 January 1999) provide valuable insights into postdepositional processes that likely occur on UFG and other high-altitude ice-coring sites. The timing of accumulation events at UFG and the Cold Springs SNOTEL site were similar; however, selected localized storm events did not correlate well between the two sites. Because of lower temperatures, snow accumulation events followed by high winds on UFG were partly or completely removed after deposition. Accumulation events occurring after mid-October were found to be more susceptible to wind removal, potentially biasing the $\delta^{18}O$ values preserved in ice core records toward environmental conditions reflecting higher air temperatures and lower wind speeds. A transfer function between $\delta^{18}O$ and T_A was determined from using the snow-depth sensor data. This transfer function accounted for the accumulation events removed by wind and had a similar slope (0.587) to the transfer functions developed from the Cold Springs SNOTEL data (slopes ranging from 0.435 to 0.943). Transfer functions developed by using site specific snow accumulation and removal data may be more accurate in reconstructing T_A values at high-altitude ice-coring sites.

[37] Two ice cores from different locations on UFG were collected in 1991 and 1998. The $\delta^{18}O$ values in ice samples from both cores indicate a statistically significant isotopic enrichment in the top 40 m, indicative of a warming trend in T_A from the early 1950s to the early 1990s. A summary transfer function developed from site-specific air temperature and $\delta^{18}O$ values in snow deposited on UFG was used to reconstruct T_A from the ice core data. Reconstructed temperatures from ice core $\delta^{18}O$ values indicate a T_A increase of approximately +3.5°C from the mid-1960s to the early 1990s in the alpine areas of northwestern Wyoming. The same transfer function was applied to the mean $\delta^{18}O$ value at a depth of 102 to 150 m in the 1991 UFG ice core and indicated a T_A increase of approximately +5°C between the end of the LIA (mid-1800s) and the early 1990s. The historically reconstructed air temperatures from the UFG ice cores were substantially higher than the global average observed during the 20th Century, but in agreement with temperature increases observed at selected, high-altitude and high-latitude sites. Additional research is required to determine if part of the observed trend toward heavier $\delta^{18}O$ values in ice from the UFG since the LIA is due to an increased proportion of snowfall from southerly storm tracks and moisture sources.

[38] **Acknowledgments.** The U.S. Department of Energy, Idaho National Engineering, and Environmental Laboratory provided funding for this study. Logistical support provided by the National Outdoor Leadership School, Hawkins and Powers Aviation, Oregon Army National Guard, and John Mionczynski (Wind River Pack Goats) during the fieldwork was outstanding. Jay Kyne with the Polar Ice Coring Office, Lincoln, Nebraska, supervised the ice-coring operations. Assistance from Skip Shoutis (U.S. Forest Service, Lander, Wyoming) and Ray Nation (Bureau of Indian Affairs, Fort Washakie, Wyoming) in accessing the study sites is appreciated. Field efforts by study team members M. Abbott, T. Mcling, F. Hall, J. Green, R. Rowland, B. Stolp, R. Williams, B. Bowers, R. Irvine, and G. Clarke were outstanding. The manuscript was improved significantly with technical reviews by B.A. Kimball, J.W. Ball, and two anonymous reviewers. Disclaimer: Use of brand names in this article is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

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