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Isotope thermometry in melt-affected ice cores

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[1] A statistically significant relationship is observed between stable water isotopes (δ^{18}O) and melt amounts in a melt-affected firn core (SSummit) taken from the Prince of Wales Icefield, Ellesmere Island, Canada. By contrast, a low-melt firn core taken from a higher-elevation, higher-latitude location on the same icefield shows no relationship between these variables. We interpret this as evidence for meltwater-induced isotopic enrichment at SSummit. A percent melt–based correction slope is applied to isotopic values from SSummit. Uncorrected and corrected temperature records derived from the raw and corrected δ^{18}O values are compared to bias-corrected temperature data from the NCEP Reanalysis. Improvements are observed in the isotopic reconstruction of SSummit annual precipitation-weighted temperatures when we correct for meltwater enrichment, with a reduction from +0.6°C to 0.0°C in the mean annual error and a decrease in root-mean-square error from 1.8°C to 1.6°C. The correction factor appears to overcorrect isotopic modification during high melt years such as 1999, during which SSummit experienced nearly 70% more melt than the average from 1975 to 2000. Excluding 1999 data from the correction analysis results in a slight reduction in mean absolute error from 1.4°C to 1.3°C. These results suggest that melt-induced isotopic modification cannot be corrected in very high melt years.

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1. Introduction

[2] Records of stable water isotope ratios (δ^{18}O, δ^{2}H) in ice cores from the Greenland and Antarctic ice sheets have been used as high-resolution proxies for past air temperatures [*Dansgaard et al.*, 1993; *Petit et al.*, 1999; *Johnsen et al.*, 2001]. However, there is potential for the isotopic information contained in solid precipitation to be modified after deposition by various processes including wind scour [*Fisher and Koerner*, 1994], meltwater percolation [*Taylor et al.*, 2001; *Unnikrishna et al.*, 2002] and refreezing [*Zhou et al.*, 2008], erosive and depositional sublimation [*Friedman et al.*, 1991; *Stichler et al.*, 2001], and vapor diffusion [*Johnsen et al.*, 2000].

[3] The potential for meltwater percolation to affect the accuracy of paleoclimatic reconstructions derived from ice cores has been well summarized by *Koerner* [1997]. Known effects on ice core records include the reduction of seasonal isotopic signals [*Pohjola et al.*, 2002], isotopic enrichment [*Moran and Marshall*, 2009], the introduction of time gaps [*Koerner*, 1997], and the elution of chemical species [*Moore et al.*, 2005; *Kinnard et al.*, 2008]. Meltwater modification of seasonal isotopic signals has traditionally been minimized by drilling ice cores in regions that experience little or no summertime melt (e.g., central Greenland and interior regions of Antarctica). However, the desire to derive ice core records from areas that experience occasional periods of summertime melt motivates a more complete understanding of meltwater effects on isotopic ratios.

[4] *Pohjola et al.* [2002] and *Goto-Azuma et al.* [2002] investigate the effects of meltwater percolation on stable water isotopes from Arctic ice cores. Both studies acknowledge the reduction of seasonal isotopic values accompanying meltwater percolation; however, the similarity between annual δ^{18}O values from an ice core site and adjusted coastal values leads *Pohjola et al.* [2002] to conclude that there are no significant changes to mean annual isotopic values resulting from average melt values of 55%. These results are in contrast to work by *Goto-Azuma et al.* [2002], who found significant evidence of postdepositional modification of δ^{18}O signals resulting from melt. As a result of these findings, *Goto-Azuma et al.* [2002] limit the use of δ^{18}O signals to a combined δ^{18}O/melt record temperature proxy.

[5] Discrepancies between studies can be attributed to the complexity of factors at play in melt-affected ice core records. *Kaczmarska et al.* [2006] attribute the lack of relationship observed between melt features and δ^{18}O values in a coastal Antarctic ice core record to local differences in melt rate resulting from surface topography variations, local microclimate, snow surface morphology, and dating error.

[6] *Moran and Marshall* [2009] use data from repeat snowpit sampling sites along a low-elevation transect from 380 to 1000 m above sea level on the Prince of Wales (POW)

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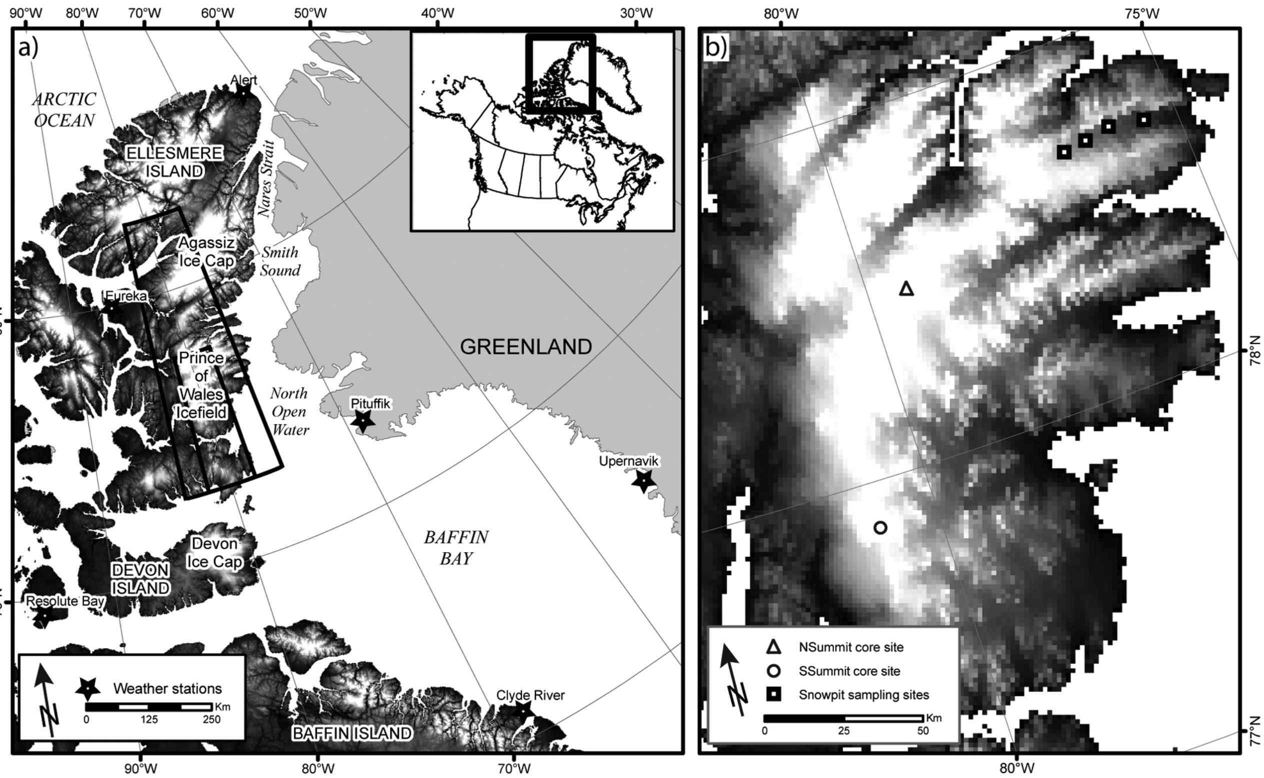

Figure 1. (a) Location of the Prince of Wales (POW) Icefield, Nunavut, Canada. The small and large solid boxes located about the POW Icefield represent the spatial extents of the NCEP-POW and NCEP-Icefield regions, respectively. The stars indicate surrounding Environment Canada and Greenland weather stations. (b) The Prince of Wales Icefield. The south and north icefield summits (SSummit and NSummit) are marked with a circle and a triangle, respectively. Low-elevation snowpit sampling sites used by *Moran and Marshall* [2009] are also shown (squares).

Icefield, Ellesmere Island, Canada to investigate the effects of meltwater percolation on seasonal isotopic signals. The amount of isotopic modification observed at the low-elevation snowpit sites is used to infer changes in isotopic values expected at a higher-elevation firn core site drilled on the same icefield. Even moderate amounts of summertime melt cause reductions in seasonal isotopic signals and enrichment of average isotopic values. Early in the melt season, reductions in isotopic amplitudes occur without a corresponding increase in mean δ^{18}O values, suggesting that isotopic modifications resulting during this period are dominated by internal snowpack processes (i.e., internal redistribution, with reductions in the amplitude of the annual cycle but without mass loss). However, as the amount of meltwater in the system increases, open-system processes, allowing mass exchange with the surrounding environment become increasingly important, and result in the enrichment of mean snowpit δ^{18}O values during the latter part of the study period. Because no meltwater is observed at the base of any of the snowpit sites, evaporation and sublimation are considered to be the dominant processes influencing mass loss from these sites.

[7] *Moran and Marshall* [2009] conclude that overestimation of annual temperatures from stable isotope data is likely to result from ice cores experiencing moderate to high amounts of melt. They propose corrections to melt-induced isotopic enrichments based on melt amount. Here we build on this work by correcting average annual isotopic values from two firn cores drilled on the POW Icefield using methods similar to *Moran and Marshall* [2009]. We compare the corrected and uncorrected temperature records to temperature data from the National Centers for Environmental Prediction (NCEP) Reanalysis [*Kalnay et al.*, 1996] spanning the same time frame.

2. Methods

[8] The POW Icefield, Ellesmere Island, has an area of 19,325 km^2, with a broad, gently sloping central plateau ranging in altitude from 1400 to 1730 m (Figure 1). Twenty meter firn cores were collected from the south (1350 m, 77.9°N, 80.8°W) and north (1727 m, 78.5°N, 79.4°W) summits of the icefield in the summers of 2002 and 2001, respectively (Figure 1b). These sites/cores are referred to as SSummit and NSummit.

[9] Both cores were drilled from the previous year's summer melt surface using a Kovacs Mark II coring system. The horizon from the end of the previous summer is easily recognized where there has been substantial melt; it is a dark (low-albedo), high-density ice crust which cannot be penetrated with a shovel. While this horizon can be more difficult to identify in regions with less melt, it is also apparent from stable isotope values in snowpit stratigraphies taken at the time of core collection. Detailed visual analysis of

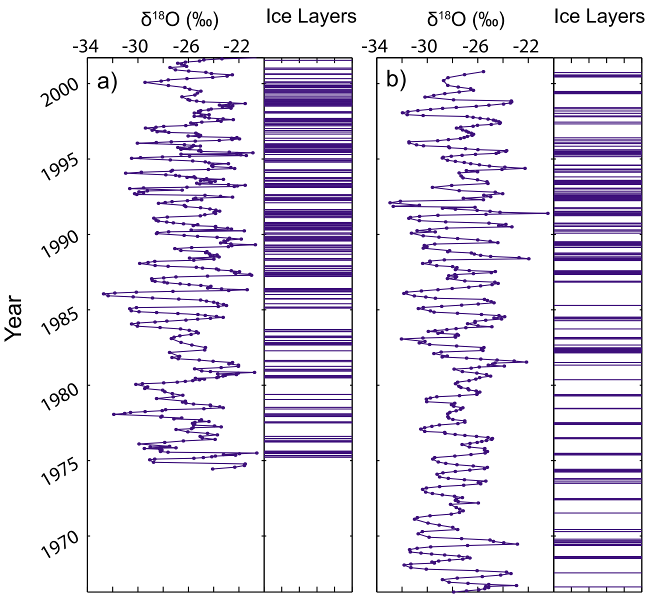

Figure 2. Prince of Wales (POW) firn core chronologies and ice layer locations. (a) The SSummit firn core spans 26 complete years from 1975 to 2000. (b) The NSummit firn core spans 33 complete years from 1967 to 1999. The chronologies were developed using annual layer counting of δ^{18}O signals. Ice thickness and location were derived from visual analysis.

stratigraphic features in the cores, including ice content and grain size, was performed at the University of Alberta. Gloves were worn at all times during core handling and cutting. Both cores were cut into 5 cm sections, which were then thawed and bottled for chemical and isotopic analysis.

[10] Analysis of δ^{18}O ratios for SSummit was performed at the Niels Bohr Institute, University of Copenhagen with a Finnigan MAT dual inlet Isotope Ratio Mass Spectrometer (IRMS), using CO_2 equilibration of water samples for approximately 6 h prior to analysis. These samples have an analytical error of ±0.05‰. NSummit water samples were analyzed for δ^{18}O ratios at the University of Calgary Stable Isotope Laboratory. δ^{18}O ratios were determined using CO_2 equilibration of water samples at 25°C with an analytical error of <0.2‰.

[11] Ion chromatography (IC) analysis was carried out at the University of Alberta using a Dionex ICS 2500 ion chromatograph with an AS18 column. Prior to laboratory analysis, core sections were opened in a cold room (−15°C), where ice chips remaining from the drilling process were removed using a clean microtome blade. Cores were then cut into discs with a band saw and placed in clean Ziploc© bags for storage.

[12] Various in-laboratory tests were taken to determine the effects on sample concentration of transferring sample from Ziploc bag to analytical vial. On the basis of these experiments we conclude that the key issues for sample handling are to (1) avoid use of filters and syringes and (2) minimize the extent of the surface touched by gloves during sample preparation. As a result, core discs were melted in the Ziplocs and poured directly into clean sample vials. Finally, for IC analysis, samples were poured directly from the sample vial into clean analytical vials. Tests on method cleanliness were carried out using deionized water, and give mean anion concentrations of 0.001, 0.02 and 0 μeq L^{-1} for Cl^-, SO_4^{2-} and NO_3, respectively. The instrument detection limits, defined as three times the standard deviation of repeat measurements of the lowest concentration detectable standard, are (μeq L^{-1}): SO_4^{2-} = 0.09, Cl^- = 0.10, NO_3 = 0.11, CH_3SO_{3-} = 0.08. Precision and accuracy are better than 7% for all anions.

[13] Annual layer counting of δ^{18}O and sulphate peaks was used in the development of both firn core chronologies. SSummit spans 26 complete years from 1975 to 2000, while NSummit, owing to its lower rates of accumulation, spans 33 complete years from 1967 to 1999 (Figure 2).

[14] SSummit has an average annual accumulation rate of 0.43 meters water equivalent per year (m w.e.yr^{-1}) and average annual δ^{18}O amplitudes of 6.4 ± 2.6‰. NSummit has an average annual accumulation rate of 0.31 m w.e.yr^{-1} and δ^{18}O amplitudes of 5.9 ± 2.1‰. The δ^{18}O amplitudes are large enough at both sites to allow identification of seasonal signals within the cores. SSummit has an average of 14.5 samples per annum, while NSummit has 11.1. Average annual percent and absolute melt amounts are 25.1% and 85 mm w.e.yr^{-1} for the 26 year SSummit record. Melt amounts at NSummit (9.3% and 29 mm w.e.yr^{-1}) are nearly a third of those observed at SSummit (Figure 2).

3. Data Analysis

[15] Plots of the annual density-weighted δ^{18}O values versus percent and absolute melt values for the two firn cores are shown in Figures 3a–3d. Statistically significant correlations are observed between both percent and absolute melt amounts and δ^{18}O values at SSummit (r = 0.70, 0.71; $p < 0.001$) (Figures 3a and 3b). This may be a noncausal correlation between warm years (with high mean annual δ^{18}O) and warm summers (with high melt), or it may indicate that meltwater percolation plays a significant role in enriching δ^{18}O values at this higher-melt site. There is no relationship between δ^{18}O values and melt amount at the lower-melt NSummit (Figures 3c and 3d).

[16] *Moran and Marshall* [2009] use two proxies for the correction of melt-induced isotopic modification, percent melt (calculated using the methods of *Fisher and Koerner* [1994]), and positive degree-day (PDD) values. Percent melt isotopic corrections are derived directly from the visual stratigraphies and density measurements. The PDD-isotope correction relies on the assumption that PDD values are a good predictor of snow and ice melt [*Braithwaite*, 1995].

[17] SSummit was equipped with a SP2000 temperature-relative humidity sensor from Veriteq Instruments Inc. for the summer of 2002, recording air temperature every 40 minutes. We measure a 2002 SSummit summertime (JJA) PDD total of 7.1°C d. NSummit was equipped with an automated weather station (AWS) recording hourly air temperature data from 1 June 2001 to 23 September 2002. JJA PDD totals of 25.0 and 1.0°C d are measured for summers 2001 and 2002 at NSummit, respectively. PDD values are calculated for each site as the sum of all temperatures above 0°C divided by the number of sample points per day [*Braithwaite*, 1995].

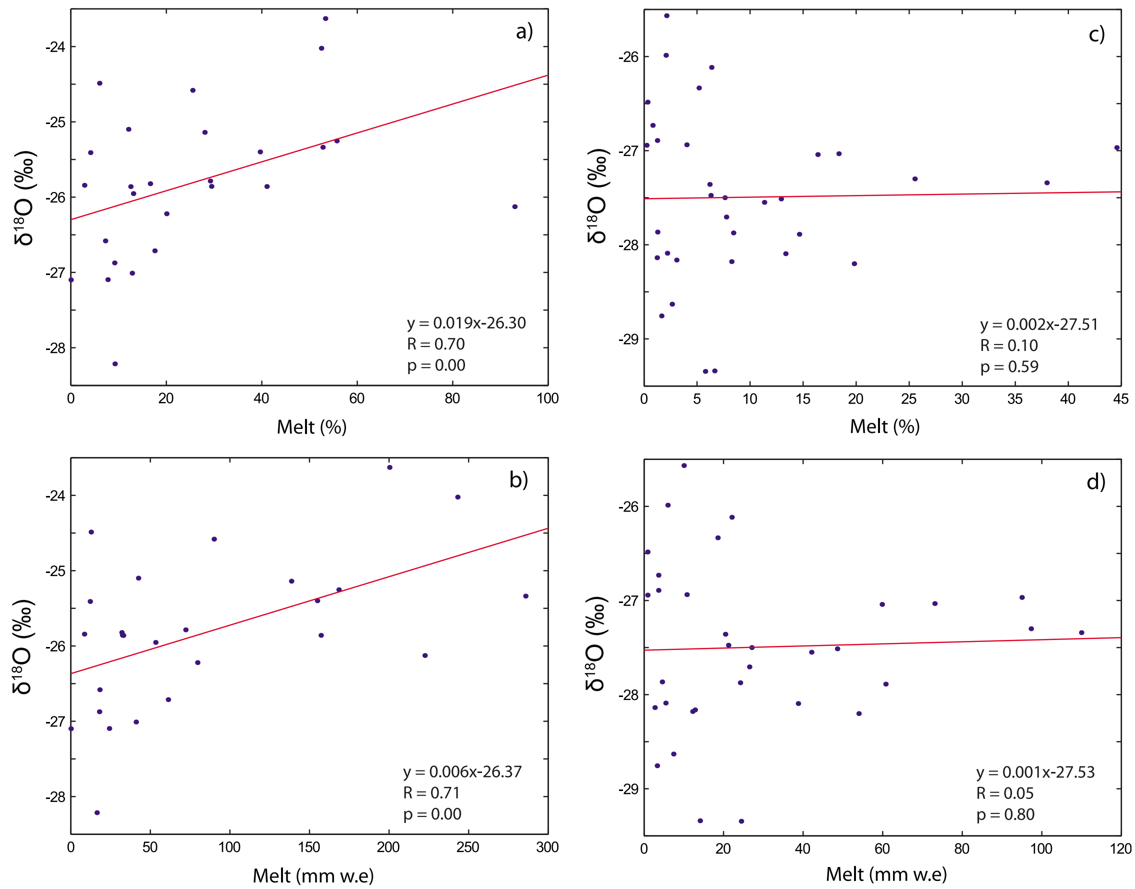

Figure 3. Annual density-weighted δ^{18}O values versus SSummit (a) percent and (b) absolute melt amounts and NSummit (c) percent and (d) absolute melt amounts.

[18] Mean summertime (JJA) temperatures (T_{JJA}) and positive degree-day (PDD) values for the 2002 SSummit data, and the 2001 and 2002 NSummit data, are correlated with four-times-daily surface, 700 mbar, and 850 mbar pressure level temperature from the NCEP Reanalysis data for the latitude-longitude grid cell centered over both sites (77.5°N, 80°W) in order to determine the data set most appropriate for the development of historical PDD records (Table 1). The latitude-longitude grid cell used in this analysis is referred to as NCEP-POW and is the same region used in subsequent analyses. The NCEP 850 mbar Reanalysis temperature data is chosen for historical PDD reconstructions because it provides the best correlation with recorded temperatures. However, as shown in Table 1 there is a systematic warm bias associated with the NCEP 850 mbar temperature data set. Removing this bias results in excellent agreement with JJA PDD values at both firn core sites. The North American Regional Reanalysis (NARR) data sets also correlate significantly (at the 99% confidence level) with T_{JJA} and PDD values from both SSummit and NSummit [*Moran and Marshall*, 2009; *Gardner et al.*, 2009]; however these Reanalysis data sets do not span the duration of the SSummit and NSummit firn core records. Data were smoothed using a 5-point moving average filter prior to analysis. For more information on the development of historical PDD values see *Moran and Marshall* [2009].

[19] Significant correlations are observed between historical PDD values and both percent and absolute melt values for both SSummit (r = 0.82 and 0.74, $p < 0.001$) and NSummit (r = 0.46 and 0.45, $p < 0.01$), indicating that PDD values are a reliable predictor of melt at both sites. The lower correlations between PDD values and melt amounts at NSummit may be due to the generally low PDD totals at the site, with the majority of heat energy (measured as PDD) devoted to warming the snowpack to the melting point rather than into driving melt.

[20] Because PDD values are significantly correlated with both percent and absolute melt amounts at both firn core sites, and because melt amounts produce statistically significant correlations with δ^{18}O values at SSummit, we proceed with correction of the annually averaged δ^{18}O values.

3.1. The δ^{18}O-T Slopes

[21] In order to derive temperatures from δ^{18}O values, a δ^{18}O-temperature relationship must be determined. Significant relationships are commonly observed between average annual δ^{18}O values and average annual surface and/or condensation-level temperatures for a site, particularly in polar regions [*Dansgaard et al.*, 1993; *Jouzel et al.*, 1997]. However, it is broadly acknowledged in the ice core literature that temperature estimates derived from ice cores are not representative of average annual temperatures for a site

Table 1. PDD and Firn Core Temperature Records and Correlations[a]

Data Set	T_{JJA} (°C)	*r*	PDD (°C d)
	NSummit 2001		
Measured T	−4.1	1.00	25.0
NCEP T_s	0.4	0.66	120.8
NCEP T_{850}	−0.9	0.86	109.7
NCEP T_{700}	−8.0	0.84	0.2
NCEP T_{850c}[b]	−4.0	0.86	22.1
	NSummit 2002		
Measured T	−6.0	1.00	1.0
NCEP T_s	0.3	0.58	92.4
NCEP T_{850}	−3.0	0.78	29.9
NCEP T_{700}	−10.3	0.73	0.0
NCEP T_{850c}[b]	−6.1	0.78	1.0
	SSummit 2002		
Measured T	−4.6	1.00	7.1
NCEP T_s	0.3	0.44	93.7
NCEP T_{850}	−3.0	0.57	29.9
NCEP T_{700}	−10.3	0.52	0.0
NCEP T_{850c}[b]	−4.6	0.57	7.5

[a]Mean summertime temperatures (T_{JJA}) and positive degree-day (PDD) values for the 2001 and 2002 NSummit measured data; 2002 SSummit measured data; and 4 times daily surface, 850 mbar, and 700 mbar pressure level temperature data (T_s, T_{850}, T_{700}) from the National Centers for Environmental Prediction (NCEP) Reanalysis for the latitude-longitude grid cell centered over both sites (77.5°N, 80°W). Correlation coefficients (*r*) between NCEP-derived T_{JJA} with measured SSummit and NSummit T_{JJA} for the same year are also reported. All data sets correlate at the 99% confidence interval.

[b]The bias-corrected NCEP 850 mbar temperature is used for historical PDD values at both sites.

[*Steig et al.*, 1994; *Jouzel et al.*, 1997; *Krinner et al.*, 1997], but are a reflection of air temperatures at the time of precipitation. We therefore calculate δ^{18}O-temperature slopes using both average annual temperatures and precipitation-weighted temperatures. Precipitation-weighted temperatures are calculated using

$$PWT = \frac{1}{P_A}\sum_{i=1}^{n} T_i P_i \qquad (1)$$

where P_A is the total annual precipitation, and T_i and P_i are the average temperature and total precipitation over time (i) [*Krinner and Werner*, 2003].

[22] The δ^{18}O-temperature (δ^{18}O-*T*) slope is defined as $d\delta/dT$, where δ stands for either δ^2H or δ^{18}O of the precipitation, and *T* is temperature (in this case average annual temperature or average annual precipitation-weighted temperature (*PWT*)) [*Jouzel et al.*, 1997]. Because analysis for this study assumes that summertime melt results in modification of the annual average isotopic values at a site, δ^{18}O-*T*(*PWT*) slopes are calculated using only the annual density-weighted δ^{18}O values for years with summertime PDD values <5°C d. We assume that when degree-day totals are low (i.e., PDD values <5°C d), there is little or no melt and hence negligible isotopic modification. NSummit has 13 such years, while SSummit has 2.

[23] The δ^{18}O-*T*(*PWT*) slopes are determined using correlations between the annually averaged density-weighted δ^{18}O values for the 15 low-PDD years and several prospective proxies, including the following.

[24] 1. Average annual temperature (*T*) and precipitation-weighted temperature (*PWT*) were calculated using daily-averaged temperature and precipitation data from four Environment Canada weather stations located within 1000 km of the POW Icefield and with data from 1966 to 2000. These stations are Eureka (EurekaST), Alert (AlertST), Resolute (ResoluteST), and Clyde River (ClydeST) (Figure 1a).

[25] 2. *T* and *PWT* were calculated using daily-averaged surface, 700 mbar, and 850 mbar temperatures and surface precipitation rate data from the NCEP Reanalysis. Data were extracted for two distinct regions: (1) the 2.5° NCEP grid cell most closely associated with SSummit and NSummit (NCEP-POW) (77.5°N, 80°W) and (2) a larger spatial area covering the POW Icefield and surrounding area (NCEP-Icefield) (77.5–80°N, 75–82.5°W). The abbreviated names are suffixed with S, 700, or 850 to indicate surface, 700 mbar, or 850 mbar pressure level data, respectively.

[26] 3. *T* was calculated using monthly-averaged data from Upernavik (UpernavikST), Greenland (WMO station 04211) [*Cappelen et al.*, 2006].

[27] 4. *T* was calculated using daily-averaged data from Pituffik (PituffikST), Greenland (WMO station 04202). These data are available from the NOAA NCDC Climate Data Online (http://cdo.ncdc.noaa.gov/CDO/).

[28] All data were smoothed using a 3-point moving average filter prior to analysis.

[29] Correlations between low-PDD δ^{18}O values and the different *T* and *PWT* records are reported in Table 2. Both

Table 2. Correlations of δ^{18}O Values With Various Temperature Records

Proxy Data Sets	*r*	*p*	Slopes/Regression Lines (‰ (°C)$^{-1}$)	R^2
EurekaST *T*	0.49	0.06	0.65	0.24
AlertST *T*	**0.63**	**0.01**	**0.90**	**0.39**
ResoluteST *T*	0.42	0.12	0.50	0.17
ClydeST *T*	0.07	0.81	0.07	0.00
PituffikST *T*	0.40	0.14	0.61	0.15
UpernavikST *T*	0.38	0.16	0.43	0.15
NCEP-POWS *T*	*0.54*	*0.04*	*0.64*	*0.30*
NCEP-POW700 *T*	*0.57*	*0.03*	*1.00*	*0.32*
NCEP-POW850 *T*	0.45	0.10	0.67	0.20
NCEP-IcefieldS *T*	*0.58*	*0.02*	*0.78*	*0.34*
NCEP-Icefield700 *T*	*0.60*	*0.02*	*1.16*	*0.36*
NCEP-Icefield850 *T*	0.41	0.13	0.64	0.17
EurekaST *PWT*	0.48	0.07	0.19	0.23
AlertST *PWT*	−0.11	0.70	−0.09	0.01
ResoluteST *PWT*	*−0.52*	*0.05*	*−0.25*	*0.27*
ClydeST *PWT*	−0.38	0.16	−0.29	0.15
NCEP-POWS *PWT*	**0.75**	**<0.01**	**0.49**	**0.56**
NCEP-POW700 *PWT*	**0.73**	**<0.01**	**0.54**	**0.53**
NCEP-POW850 *PWT*	**0.75**	**<0.01**	**0.63**	**0.56**
NCEP-IcefieldS *PWT*	**0.78**	**<0.01**	**0.51**	**0.60**
NCEP-Icefield700 *PWT*	**0.70**	**<0.01**	**0.60**	**0.49**
NCEP-Icefield850 *PWT*	**0.73**	**<0.01**	**0.67**	**0.53**

[a]Correlation coefficients (*r*) and probabilities (*p*) from correlations of low-PDD density-weighted annual average δ^{18}O values with (1) annual average temperature (*T*) and precipitation-weighted temperature (*PWT*) from Environment Canada weather stations (suffixed with ST); (2) surface (S), 700 mbar (700), and 850 mbar (850) *T* and *PWT* from two spatial areas in the NCEP Reanalysis grid; and (3) *T* data from the Pituffik and Upernavik, Greenland, weather stations (also suffixed with ST). Values significant at the 95% and 99% confidence intervals are shown in italics and bold, respectively. Slopes and regression line statistics (‰ (°C)$^{-1}$) are also given for all *T* and *PWT* data sets.

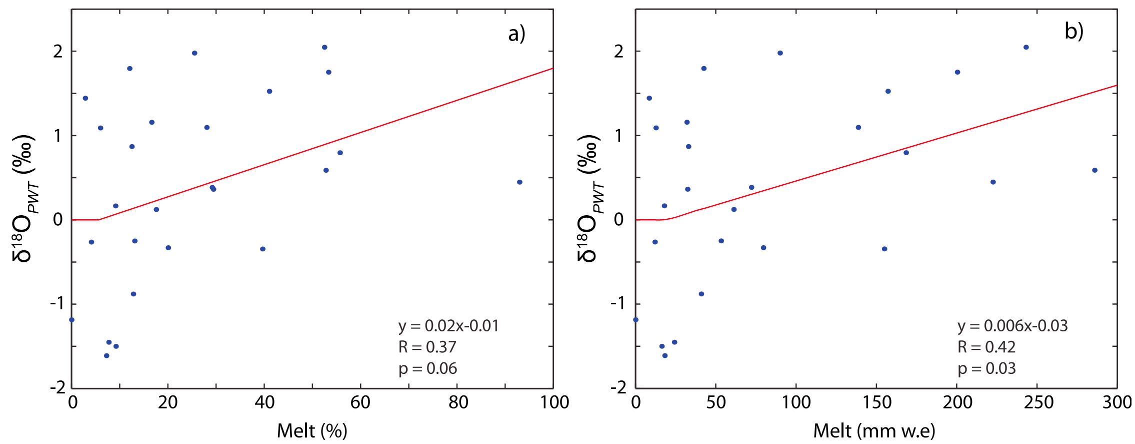

Figure 4. Plots of precipitation-weighted temperature-corrected δ^{18}O values ($\delta^{18}O_{PWT}$ values) versus (a) percent and (b) absolute melt amounts for SSummit. The fitted line in each plot represents the correction factor for each melt scenario; no correction is performed at percent melt values <5% and absolute melt values <14.3 mm w.e.

the surface and 700 mbar pressure level NCEP-POW T and NCEP-Icefield T data sets correlate significantly with the low-PDD δ^{18}O values at the 95% confidence interval. The Environment Canada AlertST T data set is the only temperature data set significant at the 99% confidence level. All six NCEP-derived *PWT* data sets correlate significantly with the low-δ^{18}O values at the 99% confidence level.

[30] Temporal δ^{18}O-*T*(*PWT*) slopes are produced by regressing the low-PDD δ^{18}O values against the *T*(*PWT*) data sets (Table 2). Because of the improvements observed between correlations of the low-PDD δ^{18}O values with *PWT* relative to T, we use only δ^{18}O-*PWT* slopes for the remainder of our analysis.

[31] There is little difference in predictive power (R^2) for the different NCEP PWT-based models, and all are significant at the 99% confidence interval. We opt to work with the 700 mbar pressure level data, because it is closest to the condensation-level temperatures for both firn core sites. In addition, the broader spatial area represented by the NCEP-Icefield data set may be more regionally applicable and less susceptible to the poor resolution of the icefield topography in the NCEP Reanalysis, so we expect it to provide a more robust measure of the regional δ^{18}O-*PWT* slope. We therefore adopt NCEP-Icefield700 PWT as our reference model.

[32] In order to address the potential errors associated with the derivation of a δ^{18}O-*PWT* slope using δ^{18}O values from two different sites on the POW Icefield, we bias-correct the NCEP-Icefield700 *PWT* data set using average annual precipitation-weighted temperatures for each firn core site. Bias corrections are calculated by comparing average annual precipitation-weighted temperatures from all available in situ temperature data for each site against the NCEP-Icefield700 Reanalysis data for the same years. Similar to estimations of historical PDD values, *PWT* biases are assumed to remain constant over time.

[33] The precipitation-weighted temperature biases are used to calculate δ^{18}O-*PWT* slopes that account for precipitation-weighted temperature differences between the two sites. Bias correction of the δ^{18}O-NCEP-Icefield700 *PWT* slope increases the slope from 0.60‰ (°C)$^{-1}$ to 0.63‰ (°C)$^{-1}$.

3.2. Isotopic Corrections for Melt Effects

[34] A significant relationship is observed between melt amounts and δ^{18}O values at SSummit (Figures 3a and 3b). However, because of the relationship between summertime temperature and melt (reflected here as the significant relationship between melt and PDD values), it is necessary to remove the temperature signal from δ^{18}O values before determining if melt remains a significant predictor of δ^{18}O values.

[35] *PWT* signals are removed from the δ^{18}O values for both SSummit and NSummit using the bias-corrected NCEP-Icefield700 *PWT* regression line developed for each site. We refer to the *PWT*-corrected δ^{18}O values as $\delta^{18}O_{PWT}$ values.

[36] Figures 4a and 4b show $\delta^{18}O_{PWT}$ values from SSummit plotted against the percent and absolute melt amounts. The statistical relationship between percent and absolute melt amount and $\delta^{18}O_{PWT}$ values at SSummit is weakly significant (p = 0.06, 0.03), indicating that melt amount explains some of the variance in $\delta^{18}O_{PWT}$ values at the site. Based on these results, we proceed with correction of meltwater-induced isotopic enrichment at SSummit. Because these relationships are not observed at NSummit, we limit correction to the SSummit δ^{18}O record.

[37] *Moran and Marshall* [2009] use isotopic modification melt thresholds for their percent and absolute melt-based correction factors. These thresholds are used as a parameterization of two main physical processes, (1) the initial amount of sensible heat required to warm the snowpack to the melting point and (2) the minimum amount of meltwater required to be present within the snowpack to produce measurable changes to isotopic values resulting from percolation, evaporation, and fractionation processes.

[38] There is likely to be an additional threshold at the opposite end of the melt spectrum where melt values obliterate the seasonal isotopic values and the meltwater-induced fractionation exceeds correction using the methods proposed here. While we do not have the data available to determine the upper melt threshold, later in the analysis we estimate a range over which we believe the maximum melt threshold is likely to occur.

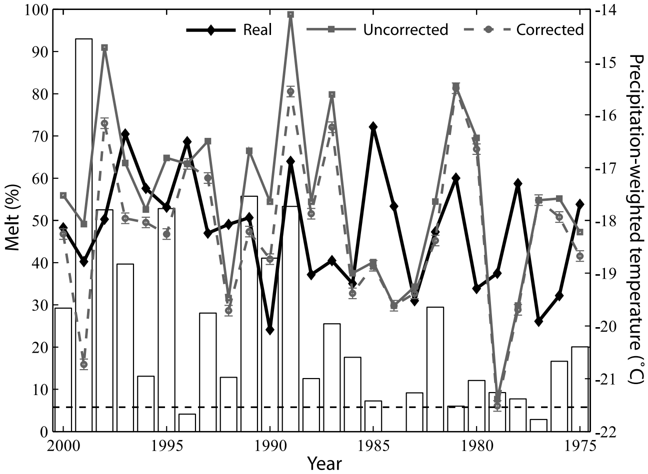

Figure 5. SSummit uncorrected and corrected precipitation-weighted temperature plotted against real *PWT* (NCEP-Icefield700 *PWT*). The bars represent percent melt amounts for SSummit. The straight dashed line indicates the 5% isotopic-modification threshold.

[39] Regression lines resulting from the $\delta^{18}O_{PWT}$ values versus percent and absolute melt amount represent the isotopic modification resulting from melt. Using the 5% isotopic modification threshold of *Moran and Marshall* [2009], we calculate a percent melt correction factor of 0.02‰ (% melt)$^{-1}$ (Figure 4a). This slope is slightly lower than the percent melt correction slope of 0.03‰ (% melt)$^{-1}$ reported by *Moran and Marshall* [2009] in a study of early melt season isotopic modification at four low-elevation snowpit sites on the POW Icefield. The earlier study is based on direct measurements of isotopic modification during melt, through repeat snowpit analysis, and is therefore independent of the methods and estimates derived here.

[40] *Moran and Marshall* [2009] also report absolute melt-based corrections. These corrections are given as a function of PDD (0.08‰ (PDD)$^{-1}$) and have a 2.5°C d isotopic modification threshold. Degree-day factors (DDF), measured as millimeter water equivalent per day per degrees Celsius (mm w.e.d^{-1} °C^{-1}), are used to relate PDD values to total melt, and allow the ‰(PDD)$^{-1}$ correction factor to be converted to ‰(mm w.e.)$^{-1}$. *Braithwaite* [1995] reports snow DDF values ranging between 3.0 and 5.7 mm w.e.d^{-1} °C^{-1} for Arctic snowpacks. These DDF values result in absolute melt-correction factors ranging between 0.030 to 0.014‰ (mm w.e.)$^{-1}$, with isotopic modification thresholds of 7.5 and 14.3 mm w.e. Using the isotopic modification threshold of 14.3 mm w.e., we calculate an absolute melt correction slope of 0.006‰ (mm w.e.)$^{-1}$ (Figure 4b). This slope falls well outside of the range of absolute melt correction values reported by *Moran and Marshall* [2009]. As a result the remainder of our analysis uses only the percent melt correction.

4. Results

[41] In order to evaluate the corrections to melt-affected isotopic data, we compare temperature records derived from these data against NCEP Reanalysis data spanning the same timeframe. The NCEP Reanalysis data set used in the development of the δ^{18}O-*PWT* slope, NCEP-Icefield700 *PWT*, is used as our proxy for actual or "real" temperature. Figure 5 shows uncorrected and percent melt–corrected *PWT* data sets plotted versus NCEP-Icefield700 *PWT* for SSummit.

[42] Three measures are used to evaluate the errors in the uncorrected and percent melt–corrected *PWT* (PWT_{unc}, PWT_c) data sets relative to the real *PWT* data set. These are (1) mean annual error, (2) mean absolute error, and (3) root-mean-square (RMS) error. Results of these analyses are reported in Table 3. We also compare the mean *PWT* across the entire record ($\overline{PWT}$).

[43] All model error statistics improve with the correction of isotope-based temperature reconstructions (PWT_c) (Table 3). Mean model error is reduced from an average of +0.6°C for $\overline{PWT}_{unc}$ to 0.0°C for $\overline{PWT}_c$. Model RMS error decreases from 1.8°C with PWT_{unc} to 1.6°C with PWT_c.

[44] The δ^{18}O-*PWT* slopes significant at the 99% confidence level range between 0.49‰ (°C)$^{-1}$ and 0.67‰ (°C)$^{-1}$ (Table 2). Sensitivity tests using this range of δ^{18}O-*PWT* slopes show no change in melt-based correction factors (i.e., the percent melt–based correction factor has a consistent value of 0.02‰ (% melt)$^{-1}$). The average error in *PWT* reconstructions for individual years is ±0.1°C.

5. Discussion

[45] We focus our analysis on the precipitation-weighted temperatures because of the significant improvements observed between annual average temperatures and precipitation-weighted temperatures for all NCEP data sets (Table 2). Precipitation weighting of Environment Canada station temperature data sets did not improve the relationship with

Table 3. Real, Uncorrected, and Corrected Temperature Records[a]

	Ref Model	Ref Model[b]
	Real	
Real $\overline{PWT}$ (°C)	−18.2	−18.2
Variance (°C^2)	1.2	1.2
	Uncorrected	
Uncorrected $\overline{PWT}$ (°C)	−17.6	−17.6
Variance (°C^2)	2.7	2.8
Mean annual error(°C)	0.6	0.6
Mean absolute error (°C)	1.6	1.6
RMS error (°C)	1.8	1.9
	Corrected	
Corrected $\overline{PWT}$ (°C)	−18.2	−18.1
Variance (°C^2)	2.2	2.0
Mean annual error (°C)	0.0	−0.1
Mean absolute error (°C)	1.4	1.3
RMS error (°C)	1.6	1.6

[a]The two columns show precipitation-weighted temperature (*PWT*) reconstructions calculated with and without 1999 data (both referred to as Ref Model). The rows are broken into three sections. The first section gives the mean *PWT* ($\overline{PWT}$) and variance calculated from NCEP-Icefield700 *PWT*, which is considered the real *PWT* for the site. In addition to the mean and variance of the uncorrected and corrected *PWT* values, the second and third sections report mean annual error, mean absolute error, and root-mean-square (RMS) error of these data sets compared with the real *PWT* data set.

[b]Calculations exclude 1999 data.

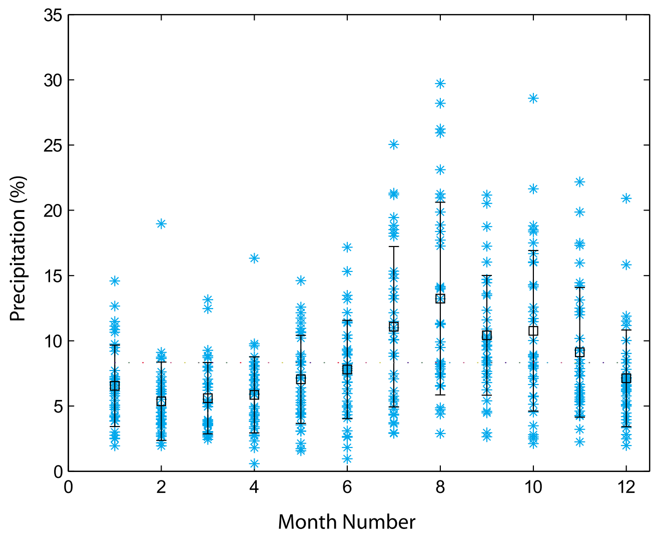

Figure 6. Percent precipitation values calculated for each month from 1965 to 2000 using NCEP daily average surface precipitation rate reanalysis data for the NCEP-Icefield spatial extent. The monthly mean and standard deviation are also shown.

low-PDD δ^{18}O values. Precipitation weighting of these stations was done using site-specific precipitation data and the null result indicates that precipitation at these sites does not occur with the same frequency or seasonality as precipitation on the POW Icefield.

[46] Because we do not have a continuous record of snow depth on the POW Icefield, precipitation weighting of NCEP *T* data sets was done using NCEP surface precipitation rate data. We suggest that correlation of precipitation-weighted temperatures with low-PDD δ^{18}O values is an effective means of determining whether the NCEP precipitation rate data reflects the seasonality of precipitation on the POW Icefield. If the precipitation record did not represent the seasonality of precipitation in our study region then no improvement in the relationship would be observed with its implementation (as is the case with the Environment Canada station data). This is not the case with the NCEP *T* data, which all show marked improvement in their relationship with low-PDD δ^{18}O values after precipitation weighting.

[47] The POW Icefield sits adjacent to the North Open Water (NOW) polynya (Figure 1a), an area of open water or much reduced sea-ice cover bounded by the coasts of Ellesmere Island and Greenland and the latitudes 76°N and 78.5°N [*Ingram et al.*, 2002]. The proximity of the NOW polynya to the POW Icefield influences both the seasonality and amount of precipitation on the POW Icefield [*Koerner*, 1979], as precipitation on the POW Icefield generally originates from the south in Baffin Bay or regions of the North Atlantic and is transported from southeast to northwest across the icefield [*Serreze et al.*, 2000].

[48] Figure 6 shows monthly percent precipitation values derived from the NCEP daily average surface precipitation rate data for the NCEP-Icefield region from 1965–2000. The highest monthly precipitation values are observed in August, a period commonly associated with ice-free water conditions in the Baffin Bay region [*Ingram et al.*, 2002] (Figure 6). Average bias-corrected NCEP-Icefield700 $\overline{PWT}$ for SSummit is −18.2°C, 3.3°C warmer than the annual temperature for the region. The warmer average annual precipitation-weighted temperatures with respect to average annual temperatures on the icefield are an indication of the summer/fall bias observed in the precipitation in the region.

[49] Multivariate regression analysis is performed on SSummit $\delta^{18}O_{PWT}$ values. The bias-corrected NCEP-Icefield700 *PWT* explains approximately 14% of the adjusted variance in $\delta^{18}O_{PWT}$ at this site with an additional 12% explained by percent melt (adjusted R^2 = 0.26, p = 0.01, F = 5.4).

[50] Because summertime melt modifies the annual average isotopic values at a site, we use a subset of years with minimal melt effects to establish the temporal δ^{18}O-*PWT* relationship for the icefield. As a result, the temporal δ^{18}O-*PWT* slope used to reconstruct SSummit *PWT* is developed using low-PDD δ^{18}O values from both firn core sites; 13 of the 15 values are from NSummit. In combining these data, we make the assumption that the two sites have the same δ^{18}O-*PWT* relationship. The sites are close together (approximately 75 km apart) and subject to the same air masses and precipitation regimes, so the assumption of a regional-scale δ^{18}O-*PWT* relationship seems reasonable. There is insufficient low-PDD δ^{18}O data to allow the development of a site-specific SSummit δ^{18}O-*PWT* slope, so we cannot test this assumption.

[51] While the temporal δ^{18}O-*PWT* slope is (1) developed using the NCEP-Icefield precipitation-weighted temperature record which covers a larger area than the NCEP-POW data set and is therefore thought to be more representative of regional temperatures and (2) bias-corrected to account for precipitation-weighted temperature differences between the two sites, the slope is not developed for SSummit specifically. As a result, it is not expected to explain as much of the variance at this site as would be expected from a locally calibrated δ^{18}O-*PWT* slope.

[52] The enrichment of isotopic values within a snowpack is commonly attributed to the preferential removal of light isotopes from the snowpack via erosive sublimation [*Stichler et al.*, 2001], evaporation [*Moser and Stichler*, 1975], and meltwater runoff [*Árnason*, 1969; *Taylor et al.*, 2001]. Runoff from an ice column may occur if the column is fully wetted (i.e., the melt index is 100%) [*Pohjola et al.*, 2002]. This is not the case at SSummit, which is located in the accumulation zone of the POW Icefield, and has an annual average melt index of 25%. Isotopic enrichment at SSummit is therefore attributed to the preferential loss of light isotopes from the snowpack via evaporation and erosive sublimation during the melt season.

[53] NSummit has average melt values of 9.3% or 29 mm w.e.yr^{-1} for the 33 year record (Figure 2a). This percent melt value translates into average annual isotopic enrichments of 0.1‰, which is below the δ^{18}O analytical measurement error of ±0.2‰ for that record. The relatively small isotopic changes are an indication that melt is not the dominant postdepositional factor affecting isotopic values at this site. This result is consistent with the lack of a statistically significant relationship between melt amounts and δ^{18}O values there.

[54] SSummit, with average melt values of 25.1% and 85 mm w.e.yr^{-1} over the 26 year record, experiences melt

rates more than 2.5 times those observed at NSummit (Figure 2b). These melt amounts result in average percent melt isotopic modifications of 0.6‰ at SSummit, well above the analytical error of 0.05‰ for this site. Use of the percent melt–based correction factor on SSummit $\delta^{18}O$ values results in improved prediction of *PWT* temperature values at the site, and decreases the model mean error from +0.6°C to 0.0°C (Table 3).

[55] The percent melt–based correction factor overcorrects isotopic modification in high melt years. This is particularly evident in 1999, which has an annual melt amount of 93%, 37% higher than the next highest melt year (Figure 5). If the 1999 data are removed from the melt-based correction analysis, the model mean error increases slightly (from a difference of 0.6°C to a difference of 0.7°C), but results in a slight decrease in the model absolute mean error (from 1.4°C to 1.3°C) (Table 3). While we do not have the data necessary to determine the upper limit of applicability for the percent melt–based correction factor, results from this analysis indicate that it lies between the 1999 percent melt value of 93% and the next highest annual percent melt amount of 56%.

[56] After removal of *PWT* from the SSummit $\delta^{18}O$ values, a percent melt slope of 0.02‰ (% melt)$^{-1}$, with a 5% melt threshold is derived for the site. This slope is slightly lower than the 0.03‰ (% melt)$^{-1}$ correction factor measured from melt-induced isotopic modification at lower elevations on the icefield [*Moran and Marshall*, 2009]. The SSummit percent melt slope given in this analysis is calculated using annual data spanning 26 complete years, by contrast the percent melt slope presented by *Moran and Marshall* [2009] is based on early melt season data from only 1 year. We therefore attribute differences in the percent melt slopes resulting from the two studies to be a result of differences in the temporal records over which the slopes are calculated. Inaccuracies in both the derivation of melt fractions and the firn core chronology may also play a role in the lower percent melt slope observed at SSummit. Given the potential factors affecting the calculation of percent melt slopes between the two studies, the similarity between slopes indicates that meltwater effects may be relatively consistent across the icefield and independent of temperature, at least for moderate amounts of melt.

6. Conclusion

[57] A $\delta^{18}O$-T slope is developed for the POW Icefield using both average annual temperature and precipitation-weighted temperature. Only one average annual temperature data set correlates with low-PDD $\delta^{18}O$ values at the 99% confidence level, while six precipitation-weighted temperature data sets correlate at this level. These results demonstrate the importance of accounting for the seasonality of precipitation to the POW Icefield. Because of the significant improvement in correlations between low-PDD $\delta^{18}O$ values and precipitation-weighted temperatures, temperature correction of $\delta^{18}O$ values is done using only the $\delta^{18}O$-bias-corrected NCEP-Icefield700 *PWT* slope.

[58] No relationship is observed between melt amounts and temperature-corrected $\delta^{18}O$ values from the low-melt site, NSummit. These results are in contrast to $\delta^{18}O$ values from the lower-elevation, higher-melt SSummit site, where percent melt explains 12% of the variance in $\delta^{18}O$ values after the removal of the temperature signal from the isotopic ratios. Correction of melt-induced isotopic enrichment using the percent melt correction factor results in consistent improvements to the prediction of precipitation-weighted temperatures at SSummit and reduces mean annual error from 0.6°C to 0.0°C.

[59] The percent melt–based correction factor overcorrects isotopic modification in high melt years. This is particularly evident in 1999, which was an extremely high melt year at SSummit, with an annual melt value more than 35% higher than the next highest melt year. We interpret the overcorrection of isotopic values during high melt years as an indication of the upper melt correction threshold. Removal of the 1999 data from the melt correction analysis results in a slight reduction in the model absolute mean error. Based on these results, we estimate the upper limit of the percent melt–based correction factor to lie between percent melt values of 56% and 93%. Beyond this, isotopic stratigraphy and mean isotopic values are excessively modified and correction may not be possible.

[60] The authors recognize the limited number and spatial scope of the data sets tested. The relative consistency of melt-based correction factors derived by *Moran and Marshall* [2009] using early melt season data from four low-elevation snowpit sites on the northern transect of the POW Icefield with melt-based correction factors from SSummit is nevertheless encouraging, and suggests that melt-induced isotopic modification is a temperature-independent process. However, further analysis is required to determine the applicability of these correction factors to firn/ice core records outside of the POW Icefield region. The application of this analysis to a longer ice core record allowing the development of a locally derived temporal $\delta^{18}O$-T slope is expected to improve the predictive ability of these corrections. This analysis, therefore, serves as the first step in recognizing and correcting melt-induced isotopic enrichment using physically based melt parameters derived from firn core records.

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