5-2013

Investigating the Controls on Surface Snow δ18O Values in the Coastal Northeast Pacific: Implications for Paleoclimate Interpretations

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INVESTIGATING THE CONTROLS ON SURFACE SNOW $\delta^{18}O$ VALUES IN THE COASTAL NORTHEAST PACIFIC: IMPLICATIONS FOR PALEOCLIMATE INTERPRETATIONS

by

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A Thesis Submitted in Partial Fulfillment
of the Requirements for a Degree with Honors
(Earth and Climate Science; Anthropology)

The Honors College

University of Maine

May 2013

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Abstract

Stable water isotope ratios ($\delta^{18}O$ and δD) in snow pit (Juneau Icefield) and fresh snow (Eclipse Icefield) samples are included in a compilation of all available snow isotope data from coastal Alaska, and used to evaluate observed isotope shifts in regional paleoclimate records. I compiled existing isotope data in coastal Alaska (primarily the Saint Elias Range) in order to better understand the elevation dependence of stable atmospheric water isotope ratios in the region. The values that make up the compilation are reflective of multiple fractionation regimes associated with synoptic scale cyclonic events, described using the Cyclone-Water Isotope Model (Holdsworth and Krouse 2002). Using this Cyclone-Water Isotope Model as a link between high frequency spatial and temporal variability, fresh snow data characterizing five different events within a 17 day time span from the Eclipse Icefield were analyzed for $\delta^{18}O$ values. Average isotope values among these five events vary by as much as 8‰. Meteorological conditions over the domain are investigated with NCEP Climate Forecast System Reanalysis (CFSR), and show that events with more depleted $\delta^{18}O$ are associated with systems that have higher pressure and a zonal (northern) moisture source, whereas events with less depleted $\delta^{18}O$ are related to events with lower pressure and a more significant component of southern moisture. These observations of event-based meteorological controls on $\delta^{18}O$ variability shed light on paleoclimate interpretations of shifts in the isotopic record seen in the Mount Logan ice core and Jellybean Lake sediment core at around A.D. 800 and A.D. 1840. The findings in the paper support Fields et al. (2010) in the interpretation that the shift to lower $\delta^{18}O$ values seen in the isotopic record is caused by a transition to a more zonal (northern) moisture source paradigm.

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1. Introduction

Paleoclimate reconstructions derived from the isotopic analysis of ice cores have become a powerful tool for those attempting to understand past climatic parameters. This method has been utilized extensively in places such as Antarctica and Greenland (Dansgaard 1993; Steen-Larsen et al. 2011), and is a result of research into stable water isotope behavior within the hydrologic cycle (Dansgaard 1964; Gat 1996; Bradley 1999). Isotopic records gathered from ice cores, e.g., the EPICA Dome C (Antarctica), and GISP2 in Greenland serve to provide a record of past climate; portraying a paleorecord of parameters such as seasonal temperature relationships, circulation characteristics, and persistent weather patterns (Dansgaard 1993; Steen-Larsen et al. 2011; Kuettel et al. 2012). These data types are generated as a result of studying the patterns and ratios of stable atmospheric water isotopes. The evaporation and condensation of water fractionates stable water isotopes (oxygen and hydrogen), creating a situation where weather systems preferentially precipitate ^{18}O and Deuterium (D) (Dansgaard 1964; Gat 1996; Bradley 1999). This means that ^{18}O and D decrease in the precipitate at a fairly constant rate distally, predicted by Rayleigh distillation models (Bradley 1999; Galewsky 2009). A reverse fractionation process occurs with evaporation, where the lighter isotopes of oxygen and hydrogen are preferentially evaporated, leaving a water source rich in the heavier isotopes, and vapor depleted in the heavier isotopes (Gat 1996; Bradley 1999; Galewsky 2009). These ratios between the light and heavy isotopes of water (denoted as $\delta^{18}O$ and δD for oxygen and hydrogen respectively) that serve as the tools for paleoclimate reconstruction. The general linearity of the simple Rayleigh distillation model is fit to observations of isotopic values in ice cores and snow pits in order to characterize the variability in the data sets. For instance, in a purely linear relationship and simplified hydrologic cycle where moisture travels directly from equator to pole, a relatively cold Northern Hemisphere would afford low $\delta^{18}O$ and δD values in a Greenland ice core, whereas a relatively warm Northern Hemisphere would afford the opposite (Dansgaard 1964; Dansgaard et al. 1993). The reason stable water isotopes can be used to evaluate paleoclimate is because of their semi-predictable fractionation

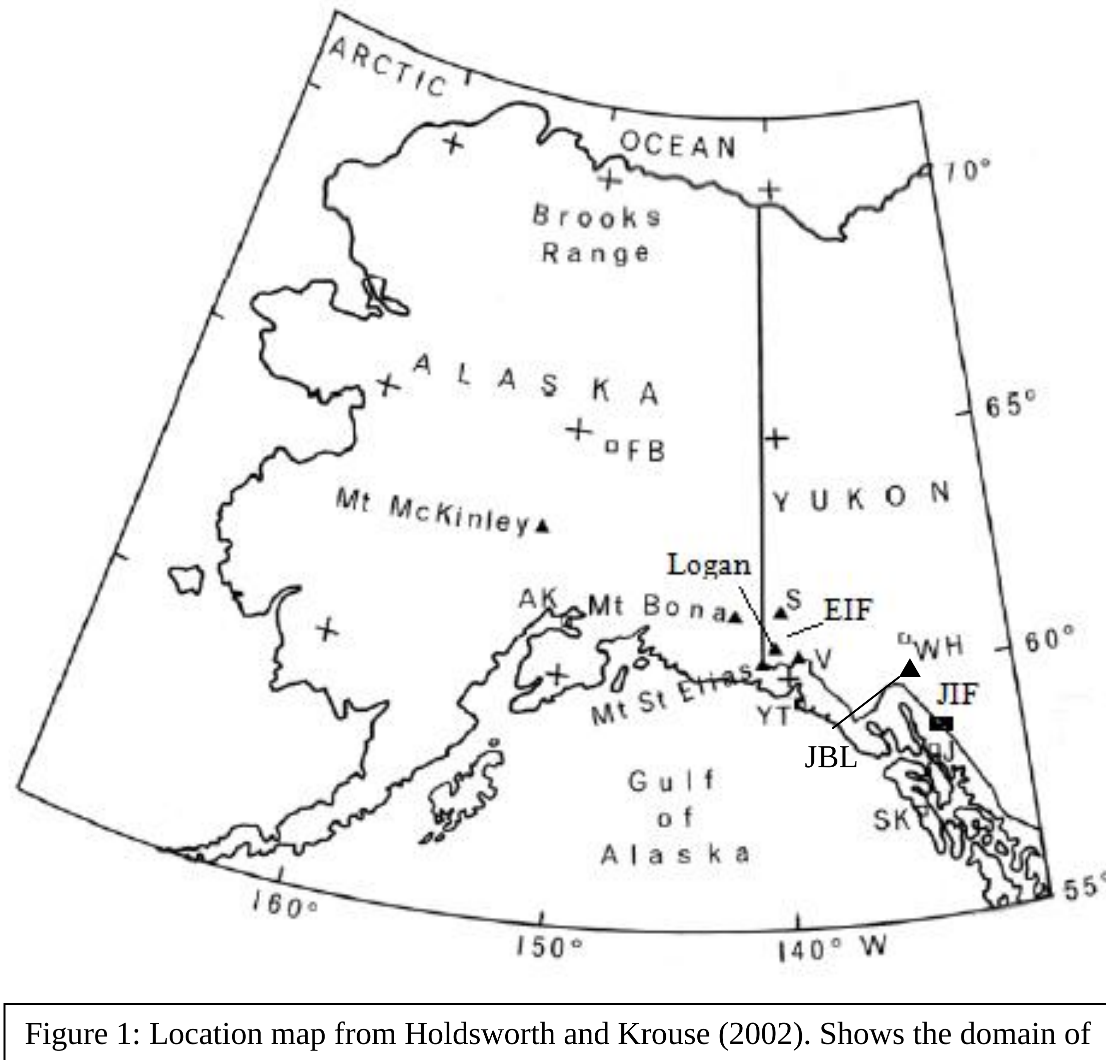


Figure 1: Location map from Holdsworth and Krouse (2002). Shows the domain of interests with site labeled: Juneau Icefield (JIF), Eclipse Icefield (EIF), Mount Logan (Logan), Yakutat (YT), Whitehorse (WH), Jellybean Lake (JBL) Mount Steele (S).

behaviors.

There has, however, been research that has shown breaks from this simple Rayleigh distribution, having implications in the evaluation of isotopic ice core data in areas of high relief and multi-latitudinal moisture influence (Holdsworth 2001; Holdsworth 2008; Galewsky 2009; Steen-Larsen et al. 2011). With new data being put forth on the high frequency variability of isotopic values on short temporal scales, controls on event based isotopic values can be utilized to characterize low frequency variability within ice cores (Steen-Larsen et al. 2011). Steen-Larson et al. (2011) notice an event based discontinuity in fractionation patterns based on moisture source regions, and similarly Holdsworth (2008) suggest that cyclonic events in the North Pacific are characterized by two different fractionation regimes in lower and upper boundaries that are indicative of a storm event that draws moisture from two different regions. In regions like the Saint Elias/southern Yukon, the complexity of the isotope signal does not necessarily relate to temperature, but may instead be more closely linked to persistent weather patterns (moisture source). The example presented in this paper is the interpretation of stable isotope records from Mount Logan and Jellybean Lake (Figure 1), addressing a shift to more depleted $\delta^{18}O$ values around A.D. 1840. The competing hypotheses consider meteorological controls to be the driving force of this change. Fields et al. (2010) believe that this shift in $\delta^{18}O$ values stems from storm systems having a more zonal (northern) moisture source, whereas Fisher et al. (2004) interprets this shift to represent the introduction of more southern moisture sources. Gaining a better understanding of these anomalies and controls within short (event based) time scales will provide insight on the interpretation of long term isotopic variability when analyzing ice cores. With this, more accurate paleoclimate reconstructions can be produced from ice cores within the domain of this study.

Also important to the interpretations of isotopic records in this region is the spatial (vertical) variability of $\delta^{18}O$ that has been shown to occur in areas of high elevation/relief (Holdsworth and Krouse 2002). The distribution of the stable water isotope ratios is distorted when analyzing measurements transecting certain altitudes (Holdsworth 2001) and also under certain weather conditions, latitudes, and surface terrain (Galewsky 2009). Data collected in Holdsworth (2008) displays a stepping trend at altitudes of 5-7km that are not consistent with flat level fractionation research, and a nonlinear atmospheric model implemented in Galewsky (2009) shows variation in the isotope ratios of precipitation caused by the effects of stratified atmospheric regimes of moisture source and temperature. These anomalies can be, in part, characterized by a difference in fractionation regimes, whether it is different among events, or different within vertical atmospheric layers of a single event (Holdsworth 2008; Steen-Larsen et al. 2011). Research shows that discrepancies among fractionation regimes correlate to differences in event and event boundary moisture sources (Holdsworth 2008; Steen-Larsen et al. 2011). This creates an important link between spatial and temporal isotopic variability, which is key in understanding the big picture of isotopic complexity in the region.

In order to get an understanding of more complex fractionation behavior related to multiple parameters such as moisture source and relief, a case study was conducted in the Pacific Northwest (coastal Alaska). In late July 2011, snow pit samples were collected from the Juneau Icefield for isotopic analysis. Fifteen pits in total were sampled in order to transect an elevation gain from 4400 feet to 5800 feet in elevation (100ft of relief between each pit) (Figure 2). These data, along with fresh snow data from the Eclipse Icefield and other data $\delta^{18}O$ sets derived within the same domain (e.g. the Saint Elias Mountain Range) are compiled and represent observed data from the region, characterizing regional fractionation behavior and variability. The spatial (altitudinal) variability within the compilation is viewed with regard to the Cyclone-Water Isotope Model developed in Holdsworth and Krouse (2002), and is an important indicator of controls on event based and fractionation that could be analogously related to long term interpretation. Meteorological parameters from the NCEP Climate Forecast System Reanalysis (CFSR) model is used in order to relate potential controls on event based isotope values to fresh snow data collected at the Eclipse Icefield for five events in

Figure 2: Southwestern half of the Juneau Ice Field. Sample transect highlighted in red, starting at 4400ft and ending at 5800ft near the top of Snowdrift Peak

the 2002 field season. Identifying moisture sources using precipitable water and precipitation rates, while also examining changes in pressure, show a correlation to the significant variation among the isotope values of the five different events. The recognition of these controls on event based isotopic variability gleamed from the fresh snow isotopic data of five different events may inform current debates (Fisher et al. 2004; Fields et al. 2010) regarding lower frequency isotopic variability in ice cores in the Coastal Northwest Pacific. Project objectives were to:

- Collect snow pit samples from the Juneau Icefield
- Utilize event based fresh snow samples from the Eclipse Icefield
- Create a compilation of $\delta^{18}O$ values in the coastal Northeast Pacific
- Compare the fresh snow samples from Eclipse to the meteorological data that characterized the different snow events
- Use the compilation, fresh snow data, and meteorological data to address opposing hypotheses (Fisher et al. 2004; Fields et al. 2010) regarding interpretations of the regions paleo-isotopic record.

2. Background

2.1 The Cyclone-Water Isotope Model

Models have been developed over to explain the altitudinal variation of stable atmospheric water isotope ratios ($\delta^{18}O$ and δD) in the Coastal Northwest Pacific (Figure 3). Understanding this spatial relationship is important in the study of atmospheric water isotope ratios and their role in paleoclimate studies. Holdsworth and Krouse (2002) link the existence of this altitudinal discontinuity to the formation, structure, and behavior of synoptic-scale polar-front cyclone events. These cyclonic systems are thought to contribute most of the precipitation experienced in the Saint Elias region (Holdsworth and Krouse 2002) and >85% of the air mass associated with the region is estimated to be contributed by Pacific sources (Bryson and Hare 1974).

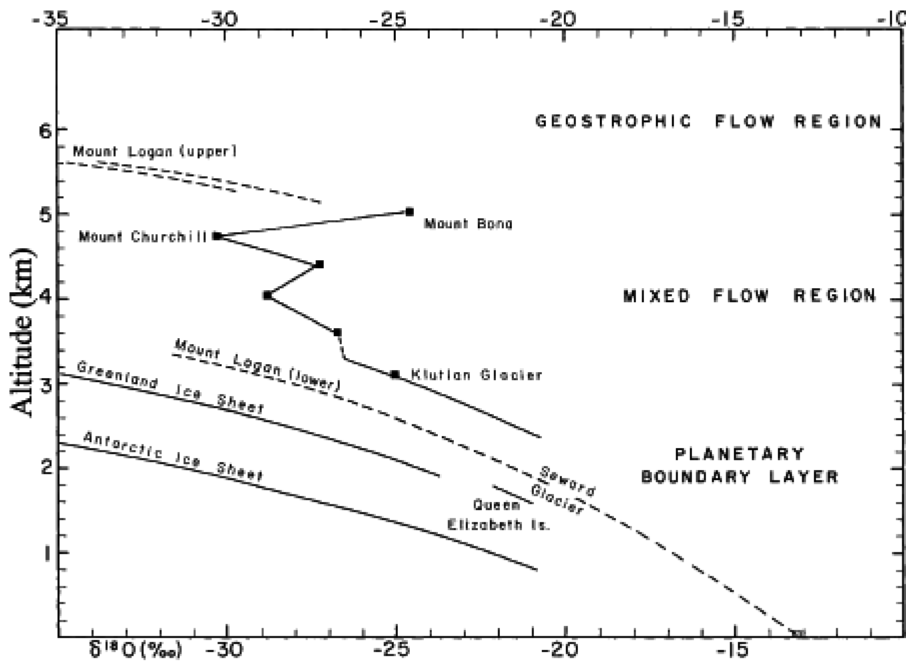


Figure 3: $\delta^{18}O$ variation with altitude at Mount Bona, with the three fractionation regions of the Cyclone-Water Isotope Model outlined. From Holdsworth and Krouse (2002).

Cyclones get occluded along the coast of Alaska due to the significant change in relief (Putnins 1966; Holdsworth and Krouse 2002). Within the occlusion processes, the cold front overtakes the warm front in cyclone formation and warm, moist air from low latitudes is forced up as the cold air passes at low levels. The occlusion process may cause an atmospheric structure that is reflected in the vertical distribution of $\delta^{18}O$ values observed in snow pits and ice cores in the Saint Elias range (McBean and Stewart 1991; Holdsworth and Krouse 2002; Newell and Zhu 1994). While a cyclone is stalled on the coastline, the cold front is able to overtake the warm front, resulting in warm moist air from low latitudes around 22^{o} to be lofted as an upper layer over the warm-front zone, and the northern cold air to be transported as a lower layer (Holdsworth and Krouse 2002). In the middle of these sub-horizontally stratified layers is the warm-front zone, being comprised of a mixture of air (moisture) from both the upper and lower layers (Holdsworth and Krouse 2002). The lower layer air mass (comprising the Planetary Boundary Layer (PBL)) has origins north of the polar front where the body water source is often colder than 12°C, and has a short trajectory to its deposition in the Saint Elias range (Holdsworth and Krouse 2002). The upper layer air mass has a much

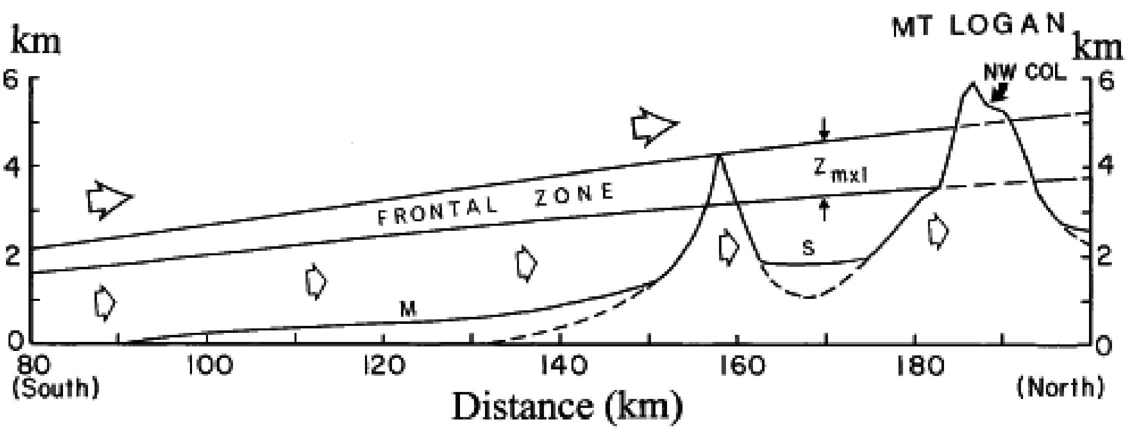


Figure 4: Schematic diagram of the three atmospheric layers associated with a frontal zone extending into the Saint Elias Mountains. The NW Col drill site is mark on Mt. Logan. Wind shear between the upper (southwestern velocity) and lower (southern velocity) layers generate flow of one air mass into the other which produces the middle mixed layer observed in spatial stable isotope data. From Holdsworth and Krouse 2002.

longer tract from low latitudes, and originates from water sources that are often >20°C (Holdsworth and Krouse 2002). These two layers, being characterized by different moisture transport trajectories and source water temperatures, are expected to create two different fractionation regimes arriving in altitudinal bands in the Saint Elias range (Holdsworth and Krouse 2002; Newell and Zhu 1994). The middle layer is thought to be a mixture of moisture from the upper and lower regimes, and so its isotopic signature is derived from the two sources (Holdsworth and Krouse 2002). This leads to trends of fractionation in the mixing layer to be variable (Holdsworth and Krouse 2002). The Cyclone-Water Isotope Model proposes that the main factor of the vertical distribution of $\delta^{18}O$ in areas of high elevation and high relief is the structure of the atmosphere during the precipitation events rather than post-depositional changes (Holdsworth and Krouse 2002).

2.2 The Moisture-Switch Hypothesis

The analysis of time series climate records from the St. Elias range by Fisher et al. (2004) suggest that the $\delta^{18}O$ values in this region are more indicative of source moisture as opposed to a viable tool for temperature reconstruction. Synchronous shifts in the $\delta^{18}O$ record at Jellybean Lake (JBL) (800 m asl/1650 m asl) and the PRCol site on Logan (5340 m asl) occurring around A.D. 1840 and A.D. 800 have been examined and modeled by Fisher et al. (2004) by switching the combination of source moisture for these sites. Two regimes emerge to explain these shifts in the record. The first regime is defined by a zonal moisture source, where moisture that arrives in the St. Elias range is derived from a relatively isolated North

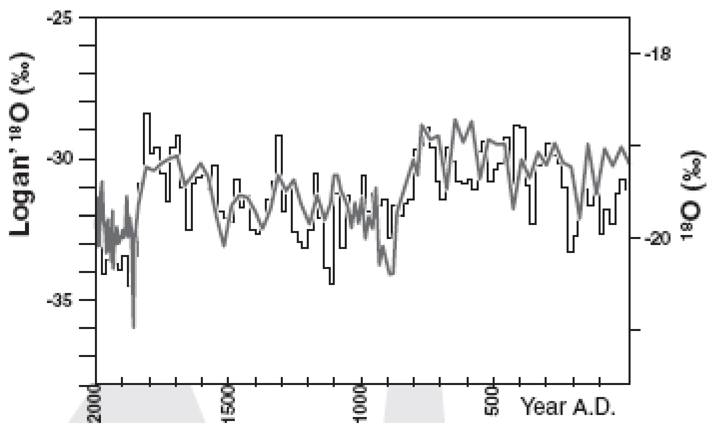


Figure 5: From Fisher et al. (2004). Shows the synchronous shifts (depletion) at A.D. 800 and A.D. 1840 in the isotopic record from Mount Logan (left scale) and Jellybean Lake (right scale).

Pacific reservoir comprised of a more southern polar front (Fisher et al. 2004; Mayewski et al. 1994). The second regime is defined as the modern-like moisture source dynamic, where multi-latitude sources are considered (Fisher et al. 2004). The modern source regime is described in event form by Holdsworth and Krouse (2002). Fisher et al. (2004) suggest that a zonal moisture source regime dominated precipitation in the St. Elias range pre-A.D. 1840, and then was abruptly changed to a modern source regime. This shift is marked in the $\delta^{18}O$ record at sites occupying varying elevations, showing more depleted $\delta^{18}O$ values at JBL and PRCol, with no shift recorded in the Eclipse record (Fisher et al. 2004). A deepening of the Aleutian Low, where vapor is drawn from more southern latitudes, contributing to a more distal depletion of $\delta^{18}O$ values, is the proposed mechanism for the more depleted $\delta^{18}O$ values post-A.D. 1840 (Fisher et al. 2004).

2.3 GCM-Based Analysis

In Fields et al. (2010), an isotopically-equipped general circulation model (GCM) is run in order to better understand isotopic records taken from the St. Elias region. In contrast to the model presented by Fisher et al. (2004) that designates the abrupt depletion of $\delta^{18}O$ values at A.D. 1840 being caused by more southern moisture sources (greater distal diminution), the GCM suggests that depleted $\delta^{18}O$ is associated with a weaker Aleutian Low (AL), where a weaker southern moisture signal exists (Fields et al. 2010). This opposite interpretation of the $\delta^{18}O$ record draws support from other climate reconstruction proxies, such as tree-ring sampling (D'Arrigo et al. 2005), which show effects of a weakening AL during the mid 19^{th} century (Fields et al. 2010). The relationship between a Deeper AL and warmer temperatures within Alaska and much of the American Northwest (Mock et al. 1998; Trenberth and Hurrell 1994; Fields et al. 2010) does not fit with the Fisher et al. (2004) interpretation of abrupt $\delta^{18}O$ depletion. The reduction of isotopic depletion along a longer southerly trajectory is suggested to be caused by a number a factors including reduced rainout, enhanced evaporation recharge, and/or weaker fractionation due to warmer environment (Fields et al. 2010). The GCM shows that the primary controls on $\delta^{18}O$ are thought to be strengthened in the cooler season, whereas the warmer seasons experience a weakening of these controls/relationships (Fields et al. 2010). Furthermore, Kelsey et al. (2012) uses seasonal averaged geopotential height grids (500 hPa) to examine stacked time series of accumulation and stable isotope values of the Eclipse ice cores. The record was divided into warm and cold seasons, as well as extreme highs and extreme lows in accumulation and isotopic values in order to investigate common anomalous flow patterns in the region (Kelsey et al. 2012). Findings indicate that the lowest $\delta^{18}O$ values (accompanies with lowest accumulation) are related to a more zonal height pattern in the North Pacific (Kelsey et al. 2012), supporting Fields et al. (2010) interpretation of greater fractionation occuring from more zonal sources. This potentially affects the way these isotope records should be analyzed in the future when attempting to determine circulation controls on $\delta^{18}O$ (Fields et al. 2010; Kelsey et al. 2012), and could hold implications to prior examinations of the data.

3. Methods

3.1 Juneau Icefield

The Juneau Icefield spans from about 58°24'50.16"N to 59°28'16.49"N and 134°43'48.24"W to 133°53'53.78"W, containing over 40 large valley glaciers. I was involved in the Juneau Icefield Research Program both as a field student, and as an independent researcher, securing logistics regarding my research on the Icefield with the program. The criteria for selecting the snow pit sites involved maximizing the vertical distance in order to distinguish potential trends in the vertical stable isotope distribution. A transect line was established with a SW/NE strike, and the pits were oriented along this line. The line itself crossed an altitude of 4400 feet (1431 m) to 5800 feet (1768 m), as this was the largest altitude gain available with the highest peak altitude, which was logistically able to be sampled (Figure 2). The sampling occurred on the northwest branch of the Taku Glacier (paralleling the Taku Range), ending near the summit of Snowdrift Peak (6000 ft; 1829 m); The horizontal distance of the sample line was approximately 5 km. All samples were collected on July 19th, 2011.

In preparation for the field season, 150 air-tight plastic sample bottles (200 mL) were rinsed three times with 18mΩ Milli-Q, and then subsequently dried prior to shipment to the field. Sample collection consisted of 15 one meter deep pits, with each pit being sampled 10 times. Personnel used pre-cleaned polycarbonate scrapers to collect each sample. The ten samples for each pit were taken in vertical profile on a pristine wall, each sample accounting for a 10 cm vertical layer (starting from the top). Ice layers were not included in the samples, and only the surrounding snow was incorporated into the corresponding sample. Each sample bottle was filled and appropriately labeled. After collection, the samples were kept within a cooler until transported to a freezer within the University of Maine Stable Isotope Laboratory for analysis. These samples did experience some melting before reaching the freezer within the Stable Isotope Laboratory, but remained in the sealed bottled until sampling. δD values were determined using a Eurovector Pyro HD coupled to a Micromass Isoprime mass spectrometer. Data are reported in standard delta (δ) notation ($\delta D(‰) = [R_{sample}/R_{standard} - 1] * 1000$) versus SMOW.

3.2 Eclipse Icefield

Samples were collected during each fresh snow events (total of five) that occurred on the Eclipse Icefield (60°51'39.84"N and 139°47'31.72"W; 3010 masl) during a field season that lasted from 10 May 2002 to 09 June 2002 (Kreutz, unpublished data). A 100 m x 100 m square grid surrounding the ice core drill site was established, and fresh snow and snow pit sampling was conducted at each of the grid corners. For each of the five snow events, five fresh snow samples were collected at each grid corner using 60 ml LDPE bottles. Sampling and isotope analysis procedure followed those described in the section above, save for that the samples remained frozen until immediately prior to isotope analysis.

3.3 Isotope Data Compilation Methods

A comprehensive literature review was undertaken in order to compile all known $\delta^{18}O$ data sets in the Southern Yukon-Saint Elias region. This amalgamation of varying time series is geared to gain a better understanding of the vertical distribution of stable atmospheric water isotope ratios in the Saint Elias region, as well as higher frequency spatial and temporal variability. Also included in the compilation are the data from the

Juneau and Eclipse Icefields. This is to gain insight on whether the two regions can be related by controls on the elevation and temporal dependence of both event based and long term $\delta^{18}O$ values. All references, locations, and data spans are listed in Appendix 1.

3.4 Climate Forecast System Reanalysis Methods

I examined these fresh snow samples from the Eclipse Icefield in terms of the meteorological conditions under which they were produced over the Eclipse Icefield site. The meteorological conditions are recreated within the relevant time interval using outputs from NCEP Climate Forecast System Reanalysis (CFSR) databases. This reanalysis output captures the five different fresh snow events ranging from May 16th to June 5th 2002 in order to investigate the controls on high frequency variability in atmospheric stable water isotope ratios. Temperature, specific humidity, pressure, planetary boundary layer height, precipitable water, and wind velocity fields for May and June 2002 over the domain of interest were extracted. The model output obtained for every six-hour time period, with a 36 km horizontal grid resolution. Points are located over the coordinates of Yakutat and the Eclipse Core site location (59.79^{o}N,-140.27^{o}W; 60.56^{o}N,-139.79^{o}W). Yakutat was chosen as it provides a near sea-level location to observe atmospheric structure outside the area of high relief. This is done to identify any meteorological changes that occur with topographical changes. These changes may highlight and be related to observed changes in fresh snow isotopic variability, providing a better understanding of the isotope values of precipitation associated with the areas synoptic scale cyclonic events.

4. Results

4.1 Juneau Icefield Data

Isotope data collected from the Juneau Icefield are shown in figure 6. The data represent spatial isotopic variation base on sub-annual pit averages. There is a general trend that shows isotope values increasing with gain in elevation. A t-test on the slope

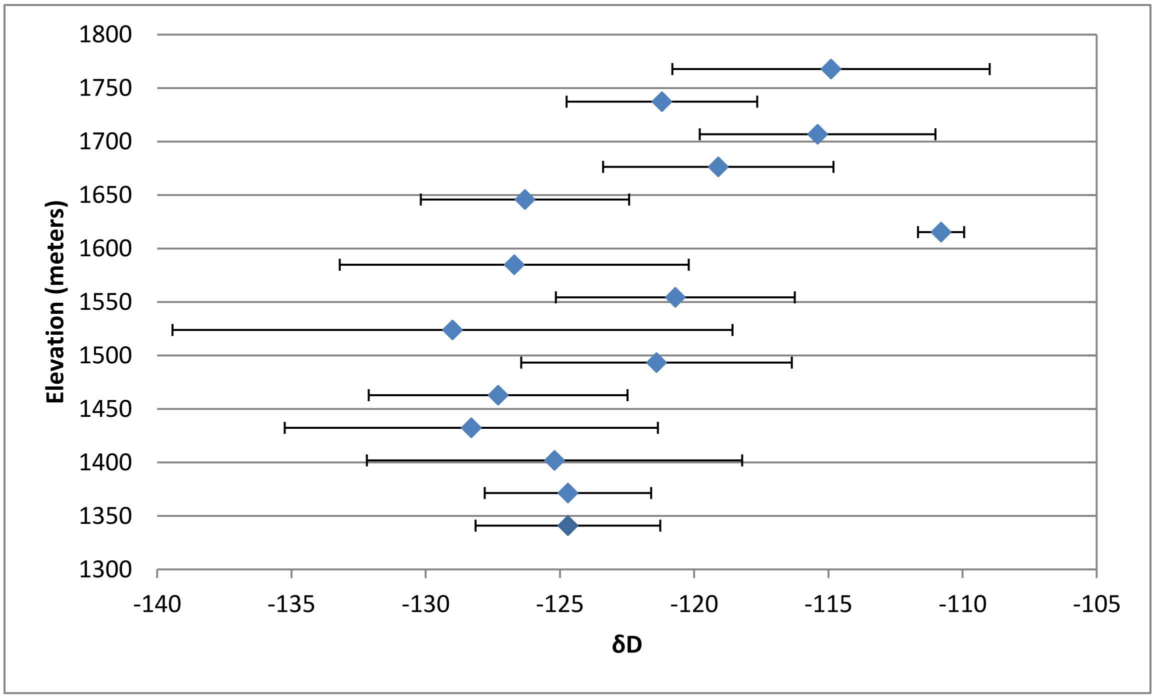


Figure 6: Average δD values of each pit on the Juneau Icefield plotted at their respective elevations. Error bars represent 1 standard deviation from the mean of the 10 samples.

coefficient of a simple regression confirms that a statistically significant positive relationship exists between δD and elevation (*p* value close to 0). Pit 10 (just above 1600 meters) is an outlier in this data set, and also holds the smallest standard deviation of the individual pits. Most pits hold a high standard deviation, indicative of sizable isotopic variation within each pit. Because each of the 10 samples per pit are representative of 10 cm vertical layer, the isotopic variability is representative of a vertical profile. These variations could represent isotopic differences that accompany individual storm events, or changes via post depositional alteration such as snow pack melting and refreezing (Zhou et al. 2008). Sampling of the pits was biased by the omission of ice layers. The degree in which melting water percolation and refreezing effects a snowpack is not yet agreed on (Moran et al. 2011), but the potential exists that excessive melting would lead to more negative $\delta^{18}O$ values of the surrounding snow (Moran et al. 2011). Pits within the Juneau data set may experience varying amounts of melt, and therefore may be exposed to varying degrees of post depositional isotopic change. Excluding ice layers in sampling does not address the potential degrees of isotopic alteration per pit.

4.2 Eclipse Icefield Isotope Data

The data collected from the five fresh snow events on the Eclipse Icefield site are displayed in figure 7. The $\delta^{18}O$ values vary by as much as 8‰ within a 17 day time span, indicating event based temporal variation, and so signifying high frequency controls on the isotopic values. Mean values for each event range from -18.96‰ to -26.94‰. Samples were taken soon after snowfall had stopped, assuring that post-depositional effects (such as evaporation/sublimation) on isotopic composition at each location were kept to a minimum. Samples were collected carefully in order to not mix fresh snow with prior events, and wind speeds through the duration of sample collections were low, giving confidence that there was no significant mixing of fresh and preserved snow. The samples remained frozen until analysis, so isotopic enrichment due to evaporation prior to analysis is an unlikely source of error. A one way analysis of error (ANOVA) test is used to evaluate the hypothesis that isotope values at each corner of the grid within a particular event are representative of the same population (i.e. mean values are not statistically different). For each event, the *p* values indicate that there is no difference in the spatial $\delta^{18}O$ values, suggesting samples within the grid are representative of

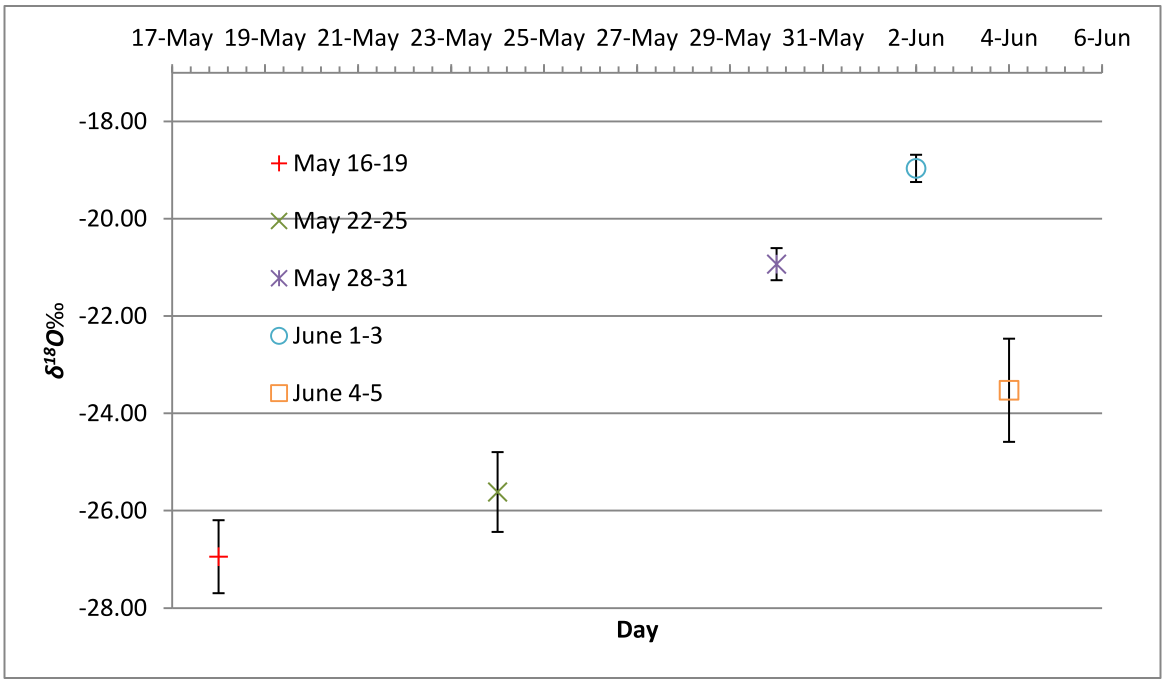


Figure 7: Eclipse Icefield fresh snow $\delta^{18}O$ values for each event collected in 2002.

individual events as a whole (Table 1). A second ANOVA analysis is used to confirm that there is a statistically significant difference among the five fresh snow events (Table 1).

	Mean (‰)	1σ (‰)	n	Thickness (cm)	ss	df	MS	F	Prob>F
					Variance within fresh snow events				
19-May	-26.94	0.75	20	5	4.86	3	1.62	4.54	0.018
25-May	-25.61	0.82	19	5	7.18	3	2.39	7.37	0.003
31-May	-20.93	0.33	20	5	0.74	3	0.25	3.04	0.060
3-Jun	-18.96	0.28	20	6.5	0.83	3	0.28	6.46	0.005
5-Jun	-23.52	1.06	21	8.5	6.99	3	2.33	2.79	0.072
					Variance among fresh snow events				
All Events					854.69	4	213.67	424.22	0

Table 1: Statistical information for the fresh snow events on the Eclipse Icefield. Columns are as follows: (1) mean (2) standard deviation of $\delta^{18}O$ values for each individual fresh snow event (3) number of samples collected for each event (five samples at each of four grid points per event) (4) fresh snow layer thickness for each event. Columns for ANOVA analysis are as follows: ss (sum of squares), df (degrees of freedom), MS (mean squares = ss/df), F statistic, and *p* value. Two separate ANOVA tests are presented: one test comparing mean values for each grid location within a particular snow event (upper); and a second test comparing mean values among all five fresh snow events (Bottom row).

4.3 Isotope Data Compilation

In order to get a better understanding of the spatial and temporal controls on $\delta^{18}O$ values with regard to elevation in the Saint Elias Range and South Yukon, data was compiled into a compilation plot of measured $\delta^{18}O$ values (Figure 8). An anomaly in simple fractionation is observed as $\delta^{18}O$ values tend to reach a stepping or vertical trend at approximately 3000 meters asl continuing to approximately 5000 meters asl, where fractionation returns to a more simple fractionation scheme (discontinuous from the below 3000 meter regime). The isotopic record is not simply related to temperature in these instances where the fractionation pattern becomes complex. The elevation at which linked data sets (lines) reach this stepping trend may vary because of the varying site locations. With this data alone, both high frequency spatial and temporal variability in $\delta^{18}O$ values are underrepresented in the coastal Northwest Pacific, and event based variability in $\delta^{18}O$ values has yet to be thoroughly accounted for. Further knowledge on the controls of high frequency, event driven $\delta^{18}O$ variability will lead to a better understanding of long term (low frequency) variability seen in sediment and ice cores as described by Fields et al. (2010) and Fisher et al. (2004).

The Juneau Icefield data is added to this plot by converting the measured δD values to $\delta^{18}O$ values by dividing the δD values by 8. Because both isotopic values of

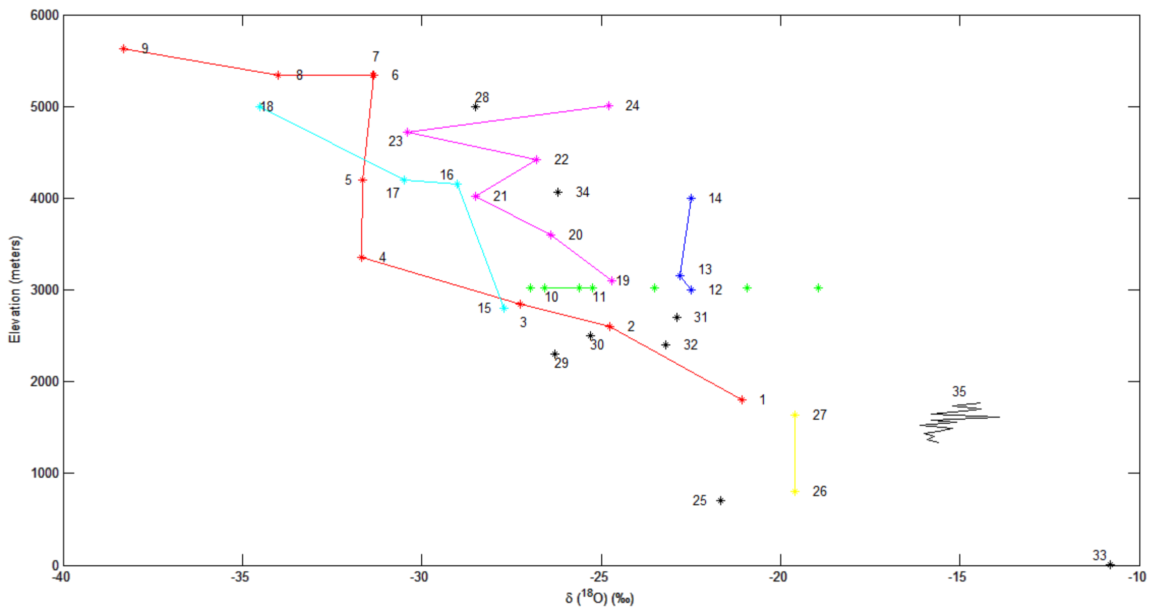


Figure 8: Compilation plot of $\delta^{18}O$ values in the coastal Northwest Pacific. Plot contains a variety of data, from fresh snow to decadal averages of ice cores. Points and type of data are listed in appendix 1. Unlabeled green points represent the fresh snow data from the Eclipse Icefield. Connected lines indicate horizontal spatial relation and data sets previously shown as elevation transects.

hydrogen and oxygen were not measured, and deuterium excess of the site is unknown, this conversion represents a coarse estimate (Gat 1998). The Juneau data is equally as important in the context of the rest of the regional isotopic data as it is in portraying internal variability. This is because the data do not have the vertical spatial range to cover the anomalous fractionation schemes described in the Cyclone-Water isotope model.

4.4 CFSR Data

Temperature, pressure, specific humidity, precipitable water, planetary boundary layer height, and wind velocities were the fields included in the CFSR output over the specified duration and domain. Temperature, specific humidity and wind velocities are examined in 3-dimensions with outputs at 1000mb, 900mb, 850mb, 600mb, and 250mb,

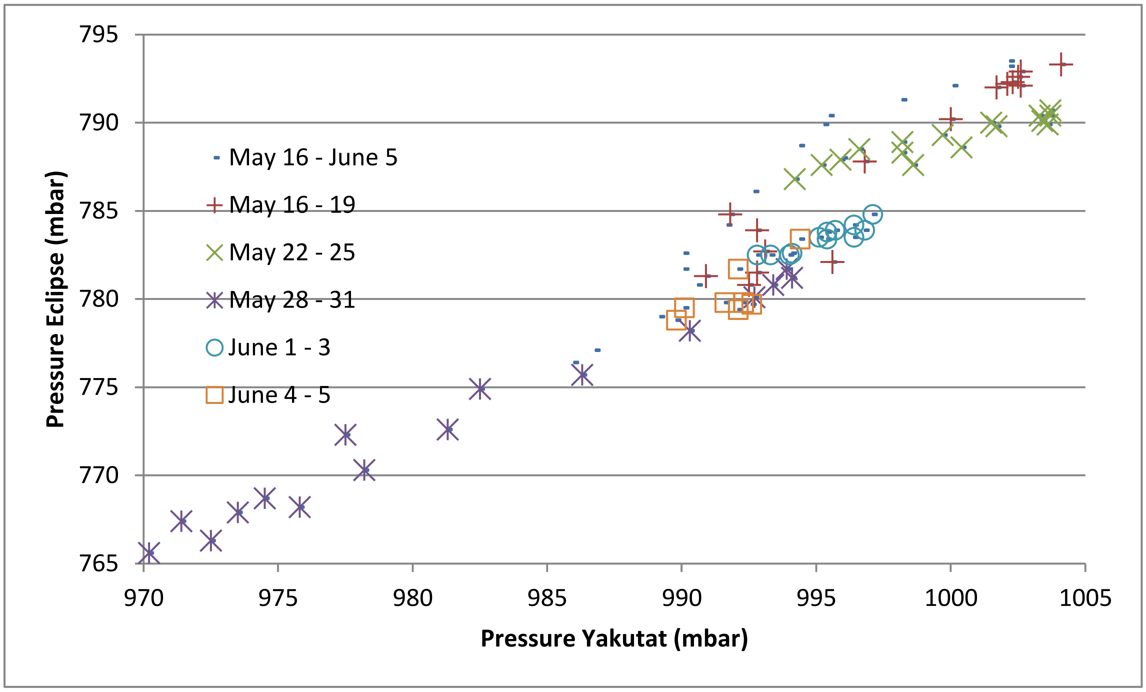
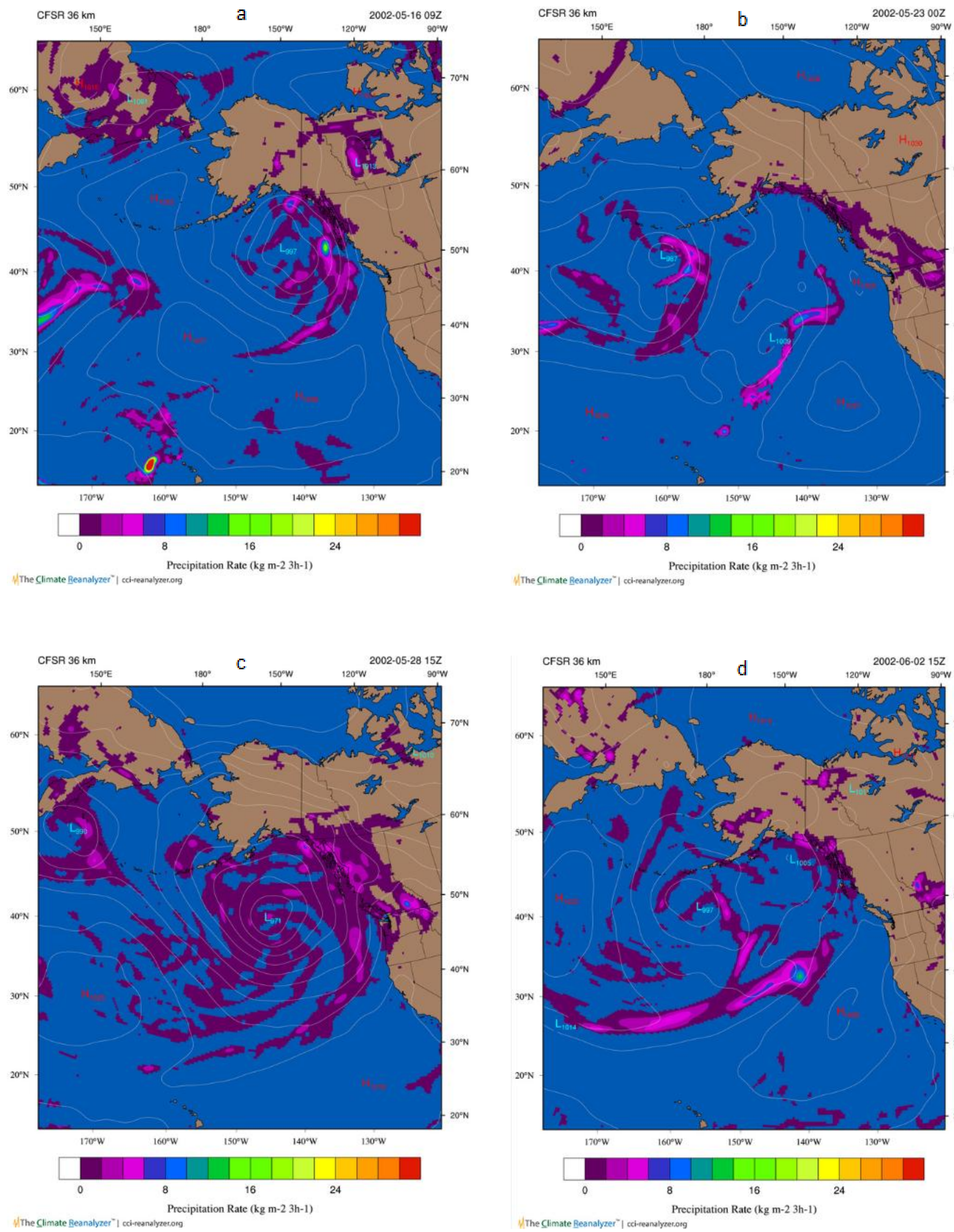


Figure 9: Pressure plot generated from the CFSR output comparing pressures at Yakutat to pressures at the Eclipse site during each of the five events.

while the rest of the fields represent surface values. The pressure CFSR output for May-June of 2002 appears to relate the best to the observed $\delta^{18}O$ of the five snow events. The lower $\delta^{18}O$ values of the first two events (confined within the dates of May 16th to May 25th) are related to higher pressure values, both in Yakutat and over the Eclipse site. There is a sizable drop in pressure of approximately 25-30 mbar between May 28th and May 31st (Figure 5), aligning with observed frontal activity and measured pressure data noted during the field campaign (Kreutz unpublished data). During this drop in pressure and after the front has passed (but lower pressures persist), the recorded $\delta^{18}O$ values for the latter three events are significantly higher. The pressure outputs at the Eclipse site within this time period are supported by a larger scale view of low/high pressure systems within the Pacific domain as it relates to the Eclipse site. Using CFSR, images were created depicting precipitation and precipitable water within the larger view of the Pacific system. These relate what is observed and interpolated at Eclipse to the larger meteorological system. This is particularly important in addressing the idea of moisture source being a dominant control on regional $\delta^{18}O$ values. Figures 10 and 11 show precipitation rate and precipitable water respectively in a bounded domain of 18N-75N and 120W-180W including much of the Northeastern Pacific Ocean. The images representing the first two events show a lesser influence of more southern moisture in the Eclipse region. In these cases, southern high pressures are interacting farther north, and the low pressure system that characterize both the first and second event seem to be composed of a more zonal moisture source. In fact, the second event seems to be the remnant low pressure system that produced the first event around the 16^{th} of May. The low proceeds down the coast of North America (to around 40^{o}N) and moisture is fed back into the Eclipse region. Conversely, the three latter events are associated with deep seated low pressure systems that gather moisture from as far south as 22^{o}N. The last event may appear to be unlike the other two in its category, however, moisture is pinched between southeast and northwest moving high pressure systems feeding the low pressure system which allows for moisture to be drawn in from equally low latitudes. The trend of source moisture and deepness of the low pressure systems can also be seen in the precipitable water images, illustrating the location and strength of moisture flow for each event.


CFSR 36 km
a
2002-05-16 09Z
CFSR 36 km
b
2002-05-23 00Z
CFSR 36 km
c
2002-05-28 15Z
CFSR 36 km
d
2002-06-02 15Z
Precipitation Rate (kg m-2 3h-1)
0
8
16
24
The Climate Reanalyzer | cci-reanalyzer.org

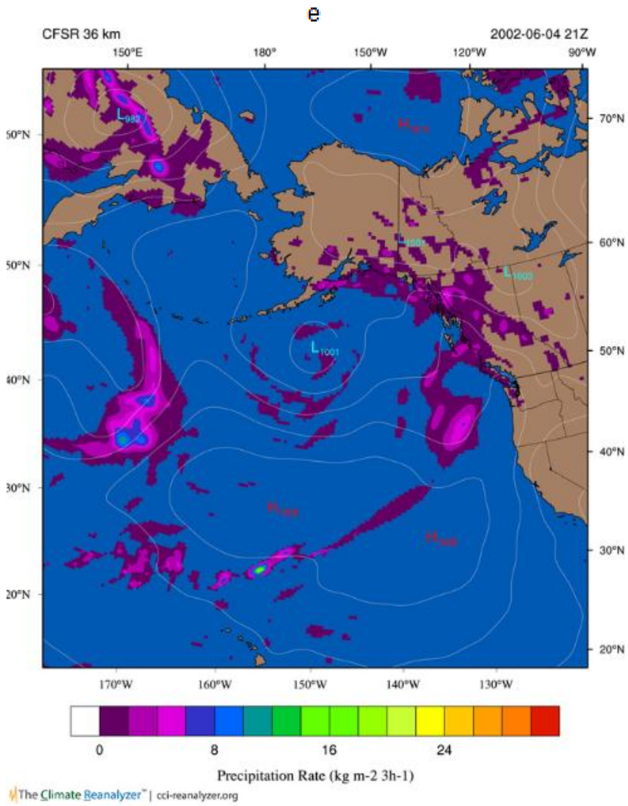
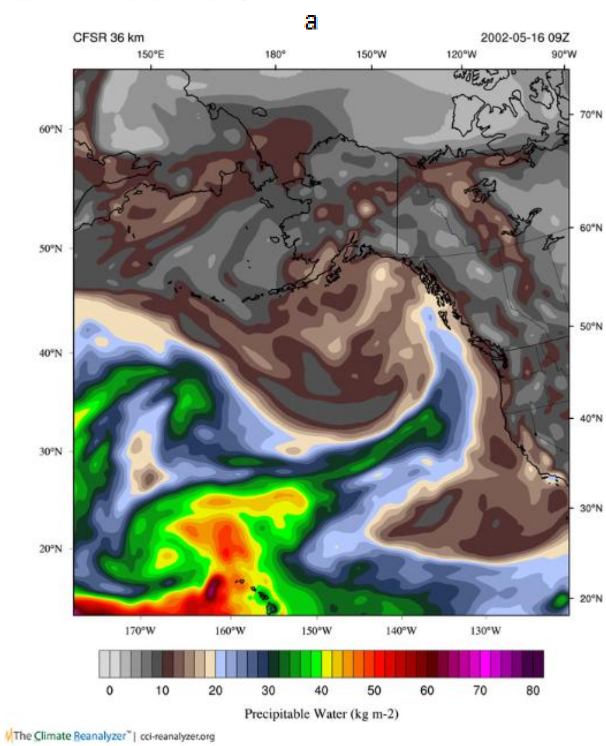
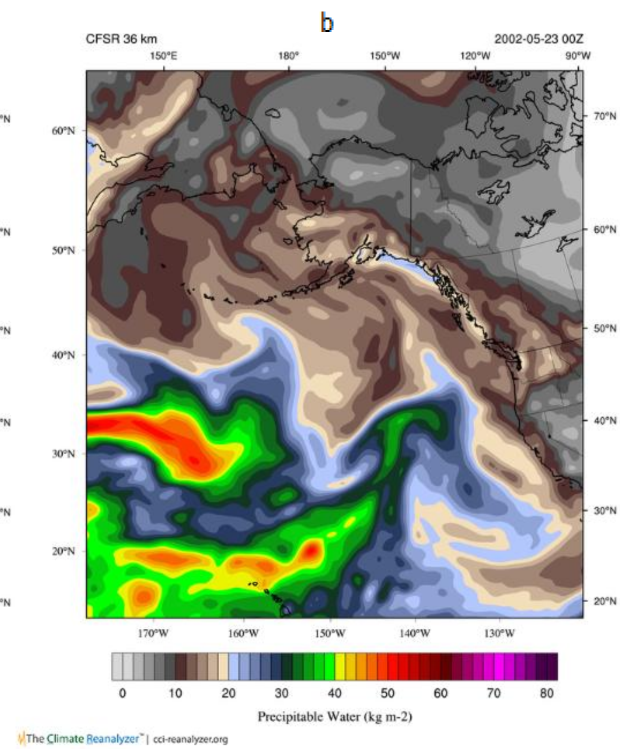
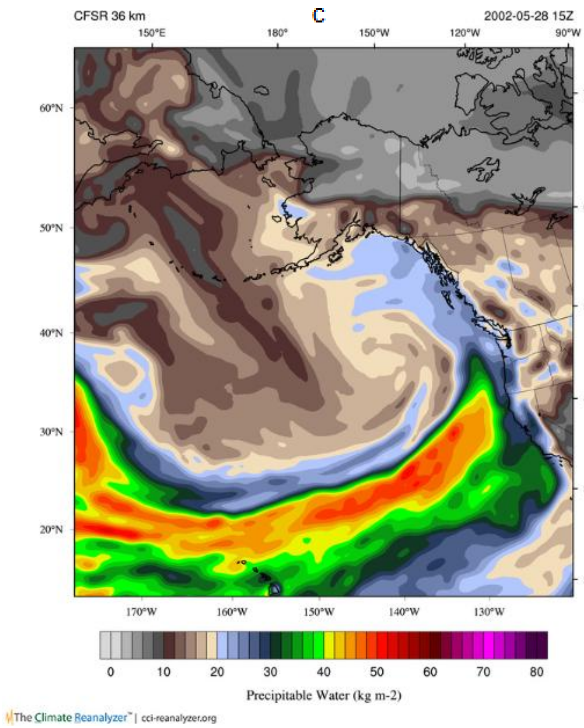
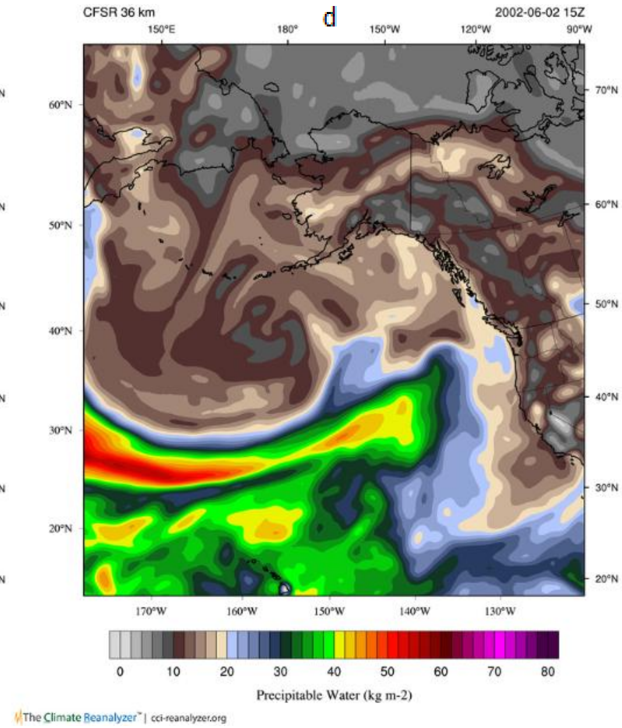


Figure 10: Images of precipitation rates for each of the five events are shown. (a) May 16th 9Z (b) May 23rd 0Z (c) May 28th 15Z (d) June 2nd 15Z (e) June 4th 21Z. Images are meant to give the orientation of pressure systems over the domain and show the paths of moisture that cause precipitation over the Eclipse site. (a) is a shallow seated low pressure system while (b) is its remnant system. (c-e) are deeper seated low pressure systems that are able to draw moisture from farther south.









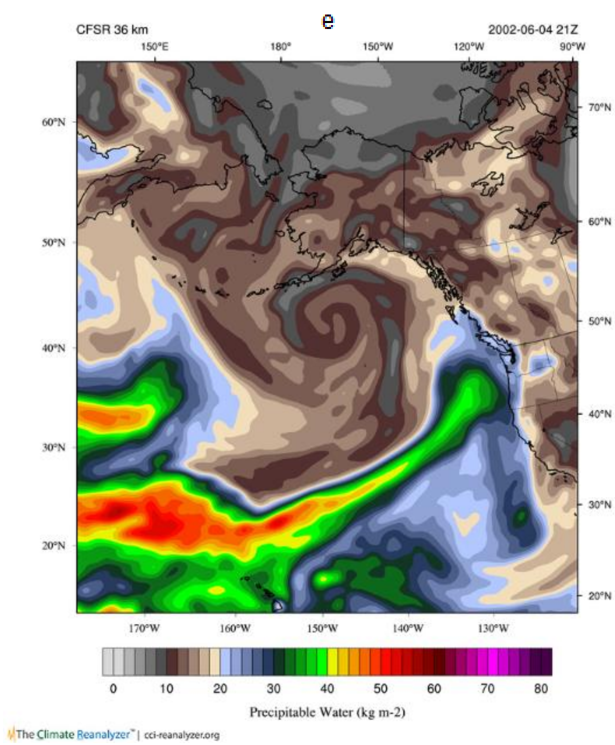


Figure 11: Images of precipitable water for each of the five events are shown. (a) May 16th 9Z (b) May 23rd 0Z (c) May 28th 15Z (d) June 2nd 15Z (e) June 4th 21Z. Moisture paths and low pressure relationships are easily seen. (a) and (b) experience little contribution of precipitable water from south of 40^{o}N. (c-e) low pressure systems press and draw from as far south as 22^{o}N, and create a noticeable structure in more southern precipitable water bands.

5. Discussion

My results from the compilation suggest that $\delta^{18}O$ values in the coastal Northwest Pacific experience spatial variability and complexity associated with the long term impact of the Cyclone-Water Isotope Model presented by Holdsworth and Krouse (2002). Juneau Icefield data set was added to the plot in order to investigate spatial resolution and its relationship to the data sets taken approximately 150 miles to the north. The Juneau data represent high vertical resolution, but fail to record an elevation where the altitudinal anomaly is recorded in the Saint Elias domain. The Juneau data set, however, is included as a higher frequency spatial (vertical) $\delta^{18}O$ record, and is an important contribution to the expansion of the knowledge of atmospheric water stable isotope ratios in the coastal Northwest Pacific. Though the Juneau data does not provide positive examples of the tested anomaly related to the Cyclone-Water Isotope Model (Holdsworth and Krouse 2002), it is useful in that it can better characterize a higher spatial resolution fractionation scheme at the lower elevations. More data will be needed from this domain in order to cover all the complexities of fractionation seen within fresh snow samples and snow pits, representing the short term variability of stable atmospheric water isotope ratios, and in sediment and ice cores, representing lower frequency (long term) variability.

The concept of the Cyclone-Water Isotope Model is not only important in discerning spatial variability in $\delta^{18}O$ values, but also holds implications on temporal variation as well, specifically event based inconsistencies as it relates to sources of moisture and associated fractionation regimes. The differences in $\delta^{18}O$ values of fresh snow samples collected from the five different events at the Eclipse site suggest meteorological controls that adhere to high frequency variability. My results from the CFSR indicate that the $\delta^{18}O$

values observed for the five events are related to moisture source of each storm, and in this instance have a connection to pressure. The data, although limited in its scope due to the lack of fresh snow samples taken within the domain, shows that the events less depleted of $\delta^{18}O$ are associated with systems containing larger southern components, representative of deeper seated (more southerly) low pressure systems. In contrast, the more depleted $\delta^{18}O$ events are related to more zonal systems that do not draw moisture from as far south. These results connect well with the GCM-based analysis presented by Fields et al. (2010) suggesting that depleted $\delta^{18}O$ is associated with a weaker Aleutian Low (AL), where a weaker southern moisture signal exists. It would be beneficial to gather event based data in the cooler season and compare them to these findings, as Fields et al. (2010) find in their model that primary controls on $\delta^{18}O$ values are strengthened in the cooler seasons and weakened in the warmer. These finding oppose the original ideas presented by Fisher et al. (2004), suggesting that a more southern component would lead to greater extents of distal fractionation, and so be associated with more depleted $\delta^{18}O$ values. More fresh snow samples from the coastal Northwest Pacific at various locations and elevations are needed in order to solidify spatial and high frequency variability of $\delta^{18}O$ values.

With a better understanding of event based controls on $\delta^{18}O$ values, interpretation of low frequency shifts such as the ones observed in the PRCol ice core and Jellybean Lake sediment core around A.D. 800 and A.D. 1840 (Fisher et al. 2004; Fields et al. 2010) can be better represented. $\delta^{18}O$ values of fresh snow samples coupled with synoptic scale meteorological observations may be useful in gaining higher resolution analyses on the controls of event based systems as they relate to the Cyclone-Water Isotope model. I suggest that fresh snow samples be collected at elevations above 5000 meters, below 3000 meters, and in between (representing upper, lower, and mixing fractionation regimes respectively) for single events to better characterize the atmospheric structure and associated $\delta^{18}O$ values of these cyclone events. Examination of both spatial and temporal high frequency controls of $\delta^{18}O$ values can be used as an analog to better understand isotopic paleoclimate records.

6. Conclusion

$\delta^{18}O$ values collected from fresh snow events on the Eclipse Icefield during the 2002 field campaign show signs of high event based variability in isotopic composition within a short period of time (17 days). Reconstructed meteorological conditions characterizing each of the five events show that the differences in $\delta^{18}O$ are related to moisture source and pressure. The more depleted $\delta^{18}O$ values are associated with systems that have a more zonal (northern) moisture source, while less depleted $\delta^{18}O$ values were produced by events that are comprised of a larger southern moisture source (as far as 22^{o}N). Also, lower $\delta^{18}O$ values are accompanied by higher pressure systems, while higher $\delta^{18}O$ are associated with lower pressure systems. These findings support Fields et al. (2010) interpretation of a low frequency isotopic shift in both an ice and sediment core taken from Mount Logan and Jellybean Lake respectively, and are contrary to interpretations suggested in Fisher et al. (2004) hypothesizing that a more significant southern moisture component would lead to more negative $\delta^{18}O$ values in coastal Alaska due to a greater extent of distal fractionation. These findings also have implications towards the Cyclone-Water Isotope Model which can be observed in the compilation of data gathered throughout the Saint Elias region. This model provides an link between high frequency spatial and temporal controls on $\delta^{18}O$ values. A better understanding of the meteorology associated with $\delta^{18}O$ variability will lead to a better understanding of the vertical spatial variability caused by cyclonic events with distinct atmospheric structures (fractionation regimes caused by different moisture sources on an event basis). The Juneau data set adds to the isotopic knowledge of the coastal Pacific Northwest, where more data, especially fresh snow, is needed in order to better understand high frequency controls on $\delta^{18}O$. These high frequency controls can then be used analogously to better interpret lower frequency shifts in the isotopic record, providing a better understanding of regional paleoclimate.

Acknowledgements

Travel cost for the field work on the Juneau Icefield was generously supported by the Churchill Exploration Fund at the University of Maine. I thank Bradley Markle and Seth Campbell for their assistance in the field in logistics and the collection of samples; and many thanks the all the JIRP members who generously gave their time to help me in the field. Isotope analysis and lab assistance from Douglas Introne is gratefully acknowledged. The assistance of Sean Birkel in getting meteorological output fields from the CFSR is appreciated.

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8. Appendix

Location (Site)	Reference	Data Type	Elevation (meters)	$\delta^{18}O$
Steward	(Holdsworth et al. 1988)	3 year average (Core/Pit Samples)	1800	-21
Kaskawulsh	(Holdsworth et al. 1988)	4 year average (Core/ Pit Samples)	2600	-24.8
Quintino Sella	(Holdsworth et al. 1988)	Annual average (Pit Samples)	2850	-27.3
Logan King T	(Holdsworth et al. 1988)	Annual average (Pit Samples)	3360	-31.7
Logan King C	(Holdsworth et al. 1988)	Annual average (Pit Samples)	4200	-31.6
Logan NW Col	(Holdsworth et al. 1988)	Annual average (Pit Samples)	5340	-31.3
Logan Core Ave	(Moore et al. 2002)	Decadal average (Core)	5340	-31.3
Logan PR Col	(Holdsworth and Krouse 2002)	Annual averages (Pit Samples)	5343	-34
Logan AINA PK	(Holdsworth et al. 1988)	Annual averages (Pit Samples)	5630	-38.3
Eclipse Pit	(Holdsworth et al. 1988)	Annual averages (Pit Samples)	3017	-26.6
Eclipse Core Ave	(Yalcin et al. 2007)	Decadal Average (Core)	3017	-25.2
Strickland 1	(Krouse et al. 1977)		3000	-22.5
Strickland 2	(Krouse et al. 1977)		3150	-22.8
Strickland 3	(Krouse et al. 1977)		4000	-22.5
SUN1 (Steele 1)	(Holdsworth and Krouse 1991)		2800	-27.7
SLC (Steele 2)	(Holdsworth and Krouse 1991)		4150	-29
ST2 (Steele 3)	(Holdsworth and Krouse 1991)		4200	-30.5
ST3 (Steele 4)	(Holdsworth and Krouse 1991)		5000	-34.5
Klutlan Glacier	(Holdsworth and Krouse 2002)		3100	-24.7
KG2	(Holdsworth and Krouse 2002)		3600	-26.4
KG3	(Holdsworth and Krouse 2002)		4020	-28.5
B-C Col	(Holdsworth and Krouse 2002)		4420	-26.8
Churchill	(Holdsworth and Krouse 2002)		4720	-30.4
Bona	(Holdsworth and Krouse 2002)		5005	-24.8
Whitehorse	(GNIP)	Recorded Average	702	-21.7
JBL 1 (800)	(Fisher et al. 2004)	(Sed Core average)	800	-19.6
JBL 2 (1640)	(Fisher et al. 2004)	(Sed Core average)	1640	-19.6
"Football Field"	(cited within Fisher et al. 2004)		5000	-28.5
"Rusty Glacier"1	(Fisher et al. 2004)		2300	-26.3
"Rusty Glacier" 2	(Fisher et al. 2004)		2500	-25.3
"Divide"	(cited within Fisher et al. 2004)		2700	-22.9
Unknown	(cited within Fisher et al. 2004)		2400	-23.2
Yakutat	(Holdsworth and Krouse 2002)		9	-10.8
	(Jouzel et al. 1987)			
Mount Wrangell	(Holdsworth and Krouse 2002)		4068	-26.2
	(C.S. Benson unpublished data)			

Appendix 1: Data used in the compilation plot (Figure 7).

*Data type left blank represents taken from paper as presented (no manipulation)

Authors Biography

Matthew Koehler was born in Nashua, NH, on November 22nd, 1990. He grew up in Saco, Maine with a family consisting of a mother, stepfather, father, and two sisters. He attended undergraduate school at the University of Maine, Orono to attain a B.S. in Earth and Climate Sciences and a B.A. in Anthropology.