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COLLABORATIVE RESEARCH: A Glaciochemical Record of Natural and Anthropengic Environmental Change in the Northwestern North American Arctic

Karl J. Kreutz
Principal Investigator; University of Maine, Orono, karl.kreutz@maine.edu

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Principal Investigator: Kreutz, Karl J.
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Title:
COLLABORATIVE RESEARCH: A Glaciochemical Record of Natural and Anthropengic Environmental Change in the Northwestern North American Arctic

Project Participants

Senior Personnel

Name: Kreutz, Karl
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Osterberg, Erich
Worked for more than 160 Hours: Yes
Contribution to Project:
Field work, ice core processing, sample analysis

Name: Wanamaker, Alan
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research assistant

Name: Vogan, Nathan
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research assistant

Name: Birkel, Sean
Worked for more than 160 Hours: Yes
Contribution to Project:
Computer programming

Undergraduate Student

Name: Von Hasseln, Zachary
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research assistant

Name: Mondrick, Alex
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research assistant

Name: Bastien, Stephan
Worked for more than 160 Hours: Yes
Contribution to Project:

Field research assistant

Name: Scofield, Marcienne
Worked for more than 160 Hours: No
Contribution to Project:
Laboratory assistant

Technician, Programmer

Name: Introne, Douglas
Worked for more than 160 Hours: Yes
Contribution to Project:
Stable isotope analyses

Name: Handley, Michael
Worked for more than 160 Hours: Yes
Contribution to Project:
Trace element analyses, ice core processing

Name: Waskiewicz, Michael
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research assistance

Other Participant

Research Experience for Undergraduates

Organizational Partners

University of New Hampshire

Geological Survey of Canada

Columbia University Lamont Doherty Earth Observatory
Collaborating with Dr. T. Kenna on radionuclide measurements in the Eclipse ice cores

University of Ottawa
Collaborating with Drs. P. Johnson and L. Copeland on glaciological and meteorological measurements in the St. Elias Mountains

University of Alberta
Collaborating with Dr. G. Holdsworth on meteorological and glaciological data from the St. Elias mountains

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:
see attached research and education activities file

Outreach Activities:
see attached research and education activities file

Journal Publications

Kreutz, Wake, Yalcin, Introne, and Fisher, "Meteorological controls on summer fresh snow isotope ratios, Eclipse Icefield, St. Elias Mountains", Annals of Glaciology, p. , vol. , (2004). Submitted

Kreutz, K., Wake, C., Yalcin, K., Introne, D., and Fisher, D., "Late Holocene North Pacific climate based on Eclipse Icefield ice core isotope data", Geophysical Research Letters, p. , vol. , ( ). in prep

Osterberg, E., Handley, M., Sneed, S., Mayewski, P.A., and Kreutz, K.J.,, "A continuous ice core melter systems with discrete sampling for major ions, trace metals,
and stable isotopes", Environmental Science and Technology, p. , vol. , (2006). Accepted

Fisher, D.A., Wake, C.P., Kreutz, K.J., Yalcin, K., et al, "Stable isotope records from Mouth Logan, Eclipse ice cores and nearby Jellybean Lake. Water
cycle of the North Pacific over 2000 years and over five vertical kilometers: sudden shifts and
tropical connections", Geographie physique et Quaternaire, p. , vol. 58, (2006). Accepted

Yalcin, K., C.P. Wake, and S.I. Whitlow, K. J. Kreutz, "A 1000 year record of forest fire activity from Eclipse Icefield, Yukon, Canada.", The Holocene, p. 200, vol. 16, (2006). Published

Yalcin, K., C.P. Wake, K.J. Kreutz, and S. Whitlow, "Seasonal and spatial variability in snow chemistry at Eclipse Icefield, Yukon Territory, Canada", Annals of Glaciology, p. , vol. 43, ( ). Accepted

Yalcin, K., C.P. Wake, K.J. Kreutz, S. Whitlow, and M.S. German, "Ice core evidence for a second volcanic eruption around 1809 in the Northern Hemisphere", Geophysical Research Letters, p. , vol. , (2006). Accepted

Yalcin, K., C.P. Wake, J.E. Dibb, K.J. Kreutz, and S. Whitlow, "Relationships between aerosol and snow chemistry at King Col, Mt. Logan Massif, Yukon", Atmospheric Environment, p. , vol. , (2006). Submitted

Books or Other One-time Publications

Web/Internet Site

URL(s):
http://climatechange.umaine.edu/
Description:

Other Specific Products

Contributions

Contributions within Discipline:

We expect that the trace element techniques developed at UMaine as part of this project, particularly the continuous melting system with nickel melt head and ICP-MS analyses, will represent a valuable contribution to the glaciochemical community.

Contributions to Other Disciplines:

Trace element analyses, particularly iron, made in the Eclipse ice core will be valuable to the oceanographic community. Also, the detailed calibration work done with chemical and meteorological data as part of this project will be valuable for the general climatological community.

Contributions to Human Resource Development:

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Book

Any Product

Contributions: To Any Human Resource Development

Contributions: To Any Resources for Research and Education

Contributions: To Any Beyond Science and Engineering

A Glaciochemical Record of Natural and Anthropogenic Environmental Change in the Northwestern North American Arctic
NSF Award No.: OPP-0136146 (UNH); OPP-0136005 (UMaine)

UNH-UMaine - Report of Activities - May 2002 to April 2003

ICE CORE DRILLING PRGRAM– MAY/JUNE 2002

During May/June 2002 we recovered a 345 m ice core from the Eclipse Icefield (3100 m)(Figure 1) in the St. Elias mountains in south-western Yukon Territory. We also drilled three shallow cores (130 m, 40 m and 20 m). Given the local accumulation rate of 1.4 meters water equivalent, we expect the 345 m ice core will provide a high resolution record extending back thousands of years.

The upper 62 meters of the deep core (Core 2) was recovered using the Geological Survey of Canada (GSC) ultra-clean ice drilling system powered by photovoltaic panels and gel cell batteries. The ultra-clean barrel and head are made of commercially pure titanium and the cutters of carbide. To further reduce the potential contamination of the core, the inner barrel accommodates a high density polyethylene (HDPE) sleeve that extends into the cutter head. As the ice core is drilled it only touches the cutter head and is then extruded directly into the precleaned HDPE sleeves. After the core was removed from the core barrel (still in its polyethylene sleeve) the ends were sealed with polyethylene caps. A new precleaned polyethylene sleeve was then inserted into the core barrel for the next drill run. All core handlers wore clean gear (non-particulating suits and clean gloves), and at all times the firn/ice cores were isolated from potential sources of contamination (e.g., camp stoves, aircraft and generator exhaust). The sealed HDPE tube served as a transport tube, minimizing core handling, improving core quality, and making trace metal analysis at the parts-per-trillion level possible.

All cores were transported frozen to the freezers at UNH. In addition to the ice core drilling field work, we also performed several other field research activities designed to enhance the interpretation of the ice core records including:

- a detailed radio echo sounding survey of the entire region to define bedrock topography and aid in developing glacier flow models. These data will assist in dating the lower sections of the 345 m core.
- collection of snow samples for major ion, stable isotope and trace element analysis from four 4 m deep snowpits (representing approximately one year of snow accumulation).
- collection of samples from five separate fresh snowfall events for major ion and stable isotope analysis to define summertime glaciochemical and stable isotope signals.

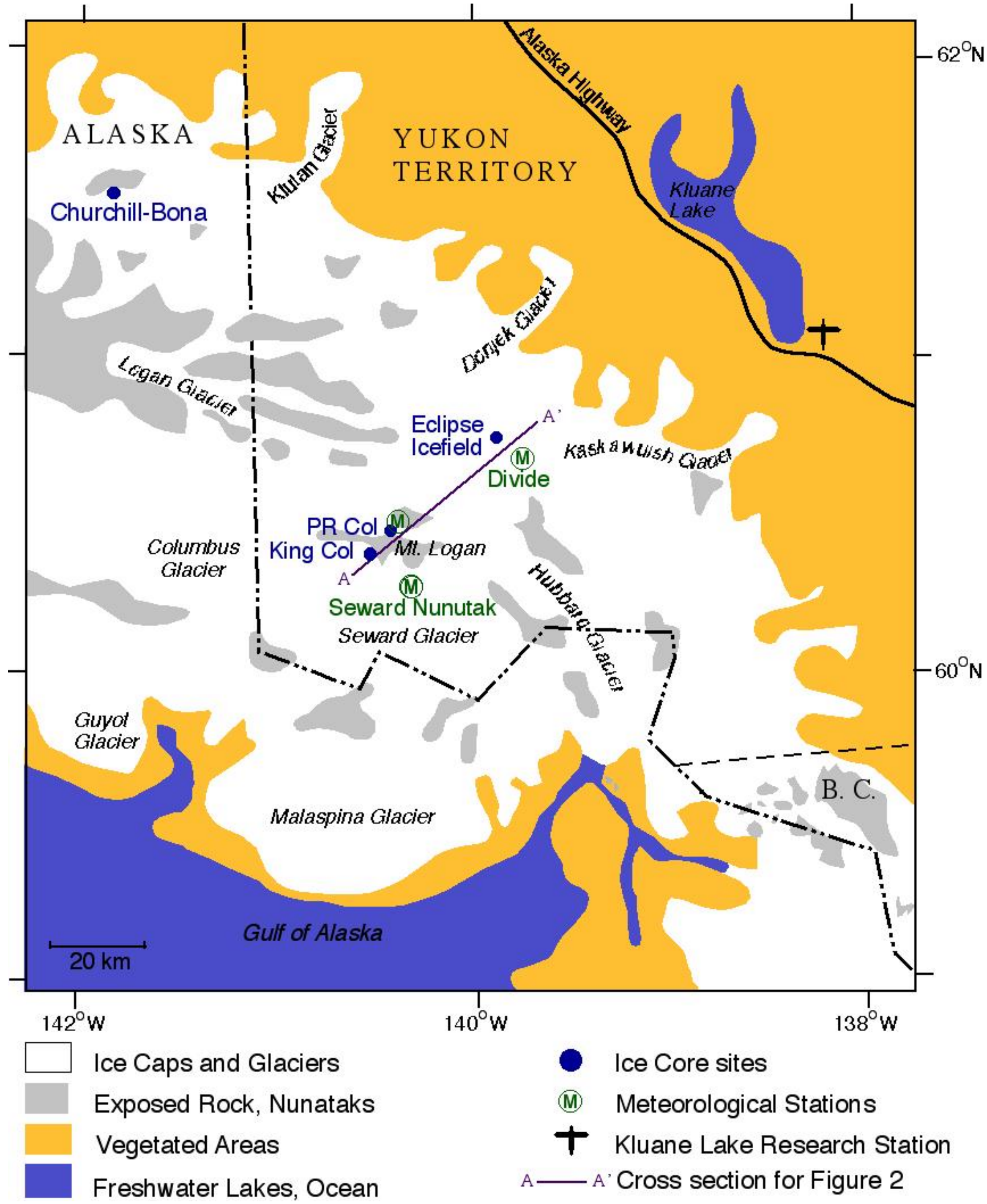

Figure 1. Location map in the St. Elias mountain range for the Eclipse icefield as well as other ice coring sites and meteorological stations.

• collection of borehole temperature data (Figure 2). Temperature at 340 m in the borehole (very close to bedrock) was –8°C indicating the Eclipse Icefield is frozen to the bed. There is also a section or relatively cold ice from approximately 100-300 m (about 80-200 years old). This section of cold ice likely represents snow that accumulated during a locally or regionally cold period of the Little Ice Age.

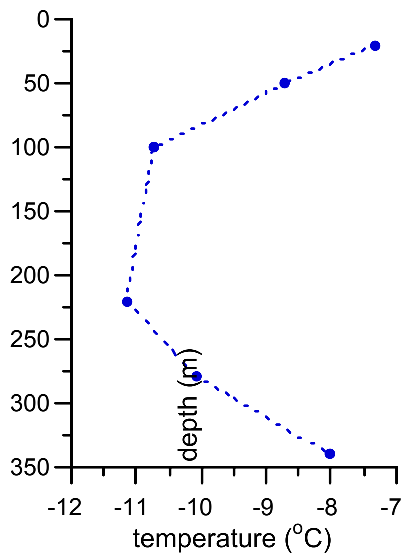

Figure 2. Borehole temperature versus depth for the Eclipse Icefield.

• in conjunction with the GSC, automatic weather stations (AWS) were installed at Prospector-Russel Col (5340 m), Seward Nunutak (2000m), and Divide (2500 m) (Figure 1 to investigate lapse rates and variations in snow accumulation over a range of elevations as well as to compare stable isotope/major ion signals preserved in fresh snow and snowpit samples with meteorological data. This data will be used to calibrate the ice core major ion and stable isotope record.

In addition to the Eclipse Icefield cores, ice cores were recovered from two other glaciers in the St. Elias Mountains as part of a collaborative ice core drilling project in the region during the 2002 field season (Figure 1). The GSC recovered a 187 m surface-to-bedrock core from Prospector-Russell Col at an elevation of 5300 m on the summit plateau of Mt. Logan. A 220 m core was recovered by the National Institute for Polar Research in Tokyo team from King Col at an elevation of 4135 m on the Mt. Logan Massif. Several additional institutions (University of Copenhagen, University of Washington, University of Alaska, Arctic Institute of North America, Hokkaido University, and University of Ottawa) will be involved in the analysis and interpretation of the ice cores.

Annual accumulation rates are substantially different between the sites (Prospector-Russell Col , 0.32 m water equivalent (we); King Col 1.0 m we; and Eclipse Icefield 1.38 m we). As a result, the Prospector-Russell Col site should provide the longest record, with Last Glacial Maximum ice encountered about 3.5 m above bedrock. The King Col core will provide a higher resolution Holocene record, while the Eclipse Icefield core will provide an even higher resolution record covering several thousand years. The elevational transect covered by the three sites allows for an unprecedented look into climate change in the region at different levels in the troposphere. Previous work on ice cores from the summit of Mt. Logan by Gerald Holdsworth and colleagues indicate that the Prospector-Russell Col core should provide a record of temperature and atmospheric chemistry in the free troposphere. Glaciochemical records developed from a 160 m core recovered from Eclipse Icefield by UNH in 1996 indicate that this site provides a more detailed record of anthropogenic emissions and volcanic eruptions, as well as a closer connection with surface temperature and pressure records. All of the cores will be analyzed for stable isotopes, major ions, microparticles, volcanic dust, and trace elements. The cooperative nature of the effort will lead to an improved understanding of changes in climate and atmospheric chemistry through the mid to upper troposphere and, along with another ice core recently recovered from Churchill-Bona in south-eastern Alaska, should provide a rich and multi-layered contribution to our understanding Holocene climate change and recent atmospheric pollution deposition in the North Pacific region.

In addition to the scientific objectives completed during 2002, three students participated in the field work. Kaplan Yalcin, a PhD student at UNH funded through the grant research assistantship, was centrally involved in all field preparations and logistics. Kaplan continues to lead the ice core processing effort at UNH and will be involved with interpetation of the results. Through a supplement to the grant provided by the Office of International Science and Engineering, two undergraduate students also participated in the field work: Alex Mondrick, UMaine Geological Sciences junior, and Stephane Bastien, University of Ottawa Geography senior. The two undergraduates have continued their collaboration after the field season by particpating in ice core processing in Ottawa, and by being involved in sample analysis and initial interpretations.

To date, public outreach activites associated with the project have included several school group tours to laboratory facilities, information dissemination on UNH/UMaine websites, and interviews with local broadcast (e.g., New Hampshire Public Television, New Hampshire Public Radio; Maine Public Radio) and print media.

LABORATORY ANALYSIS

During the summer of 2002, an undergraduate student – Tom Daigle – worked at UNH measuring ice core density and melt layers in the Eclipse Icefield cores. The density measurements indicate the firn-ice transition occurs at approximately 50 m (Figure 3). The melt percent results indicate an increase in melting has occurred over the past 30 years (Figure 4), consistent with the recent increase in the rate at which glaciers are retreating in the region (Arendt et al., 2002). A manuscript is currently being prepared for submission to *Journal of Glaciology.*

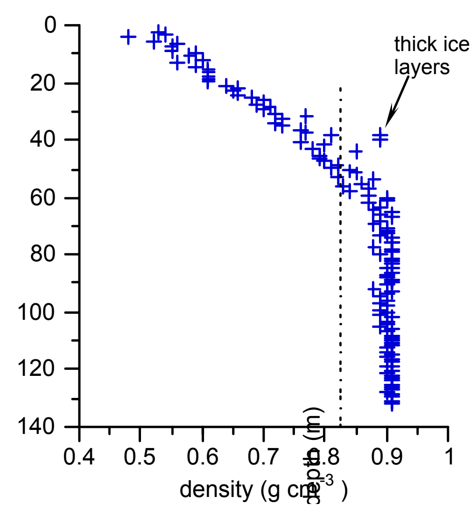

Figure 3. Density versus depth in Core 3 from the Eclipse Icefield.

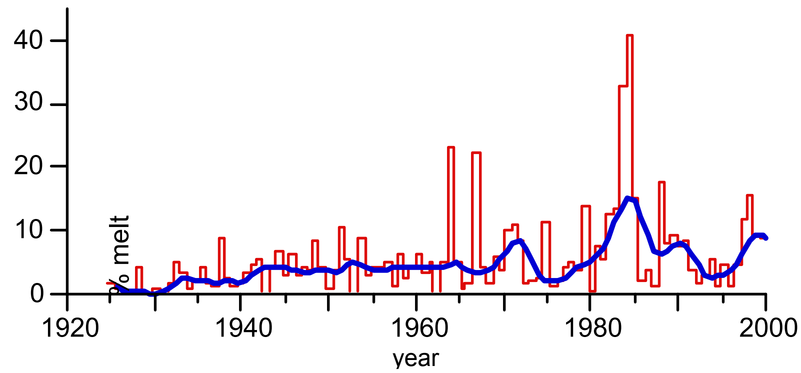

Figure 4. Melt percent measured in Core 3 (130 m long) recovered from the Eclipse Icefield in the spring of 2002. Dating is preliminary and good to approximately ± 5 years. Red line is the raw melt percent per meter; blue line is a robust spline smooth of the raw data.

Samples from Core 3 over a depth range from 48-65 m water equivalent depth have been melted and filtered through cation exchange filters to determine ^{137}Cs activity via gamma spectrometry. Initial results show a peak from 49-50 m (water equivalent depth) and a secondary peak at 57 m w.e. (Figure 5) that we interpet as representing fallout from the 1963 and 1954 periods of extensive atmospheric nuclear weapons testing, respectively. This corresponds to an average annual accumulation rate of approximately 1.3 m w.e., consistent with the snow accumulation rate over the past 40 years measured on the 160 m core recovered from the Eclipse Icefield in 1996 (Wake et al., 2002; Yalcin and Wake, 2001; Yalcin et al., 2002).

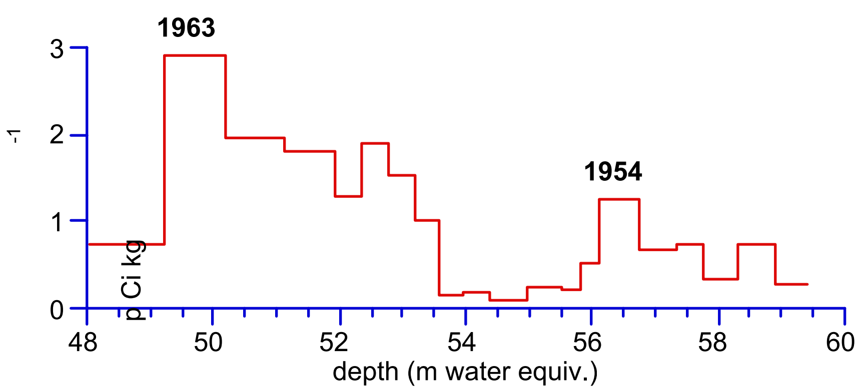

Figure 5. ^{137}Cs profile from core 3. The 1963 and 1954 peaks represent fallout from increased atmospheric nuclear weapons testing during those years.

All of the cores are stored in the freezer at UNH where we are currently processing them for major ion and stable isotope samples. To date we have processed all of Core 3 (130 m) and have completed processing of one third of the Core 2 (345 m). We are currently analyzing major ions and stable isotopes on core 3 and expect to have all of core 2 analyzed for major ions and stable isotopes by the end of the summer 2003. Initial results (Figure 6) indicate that oxygen isotopes and sodium display strong seasonal signals that will be used to establish a depth-age relationship for the core. Samples for mercury are also currently being processed for analysis by Daniel Cossa in France. We will begin processing samples for trace metal analysis from core 2 during the spring/summer of 2003.

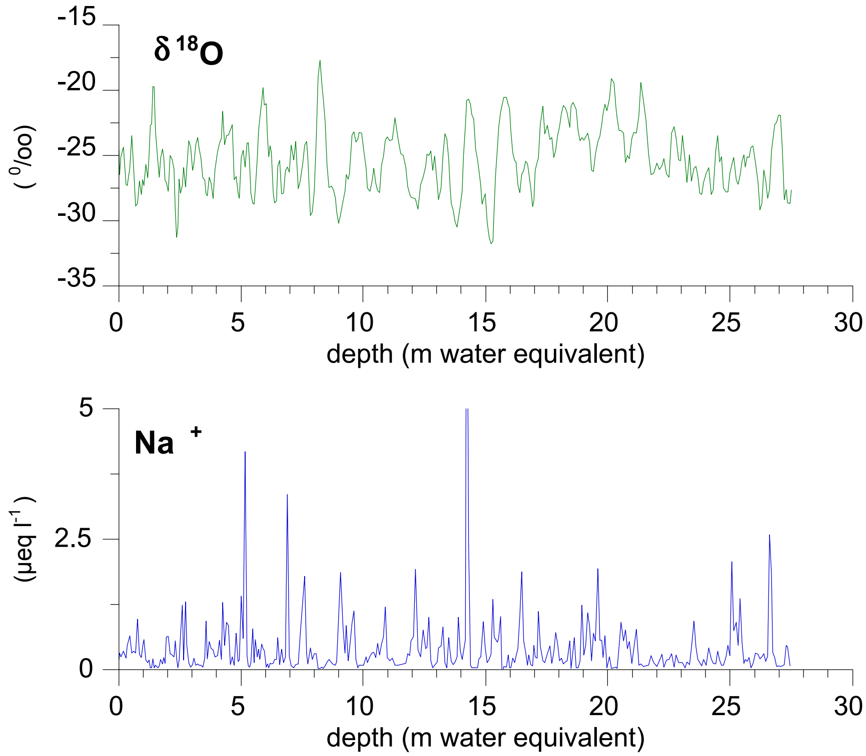

Figure 6. Oxygen isotope and sodium profiles from the upper 30 m of Core 3. Note the strong seasonal signals in both profiles.

References:

Arendt, A., K. Echelmeyer, W. Harrison, C. Lingle and V. Valentine. Rapid wastage of Alaska glaciers and their contribution to rising sea level. Science 297. 382-386, 2002.

Wake, C., Yalcin, K. and Gundestrup, N. (2003) The climate signal recorded in the oxygen isotope, accumulation, and major ion time-series from the Eclipse Ice Core, Yukon Territory. *Annals of Glaciology* 35, 416-422.

Yalcin, K. and C.P. Wake. (2001) Anthropogenic signals recorded in an ice core from Eclipse Icefield, Yukon Territory, Canada. *Geophy. Res. Lett.* 28, 4487-4490

Yalcin, K., C.P. Wake and M. Germani. A century of North Pacific volcanism in an ice core from Eclipse Icefield, Yukon Territory, Canada. *J. Geophys. Res.*. Vol. 108 No. D1, 10.1029/2002JD002449, 2003.

A Glaciochemical Record of Natural and Anthropogenic Environmental Change in the Northwestern North American Arctic
NSF Award No.: OPP-0136005 (UMaine)

UMaine - Final Report- July 2006

1. RESEARCH AND EDUCATIONAL ACTIVITIES:

1.1 Project Goals

The primary objective of this effort was to develop a continuous, high-resolution (event to seasonal), multi-parameter record of natural and anthropogenic environmental change over the last several hundred years through detailed chemical analysis (major ions, stable isotopes, trace elements, rare earth elements) of an ice core from the Eclipse Icefield in the St. Elias mountains in the south-western Yukon. The glaciochemical record developed provides detailed depositional histories of a wide variety of Arctic contaminants and provide unique chemical tracers to help identify source regions and transport pathways of contaminants to the Arctic and how these have changed with time. Furthermore, the low elevation Eclipse site (3100 m) site provides valuable information needed to place the paleoclimate record for the Holocene developed from Prospector-Russell Col (5300 m) ice core on Mt. Logan in the context of regional environmental change in the northwestern North American Arctic by linking chemical changes in the free troposphere to changes in the mid and lower troposphere.

1.1 Ice Core Drilling and Field Program - Summer 2002

During May/June 2002 we recovered a 345 m ice core (core 2) from the Eclipse Icefield (3100 m)(Figure 1) in the St. Elias mountains in south-western Yukon Territory. We also drilled three shallow cores (130 m [core 3], 40 m [core 4] and 20 m core 2]). Given the local accumulation rate of 1.4 meters water equivalent, we expect the 345 m ice core will provide a high resolution record extending back thousands of years.

The upper 62 meters of the deep core (Core 2) was recovered using the Geological Survey of Canada (GSC) ultra-clean ice drilling system powered by photovoltaic panels and gel cell batteries. The ultra-clean barrel and head are made of commercially pure titanium and the cutters of carbide. To further reduce the potential contamination of the core, the inner barrel accommodates a high density polyethylene (HDPE) sleeve that extends into the cutter head. As the ice core is drilled it only touches the cutter head and is then extruded directly into the precleaned HDPE sleeves. After the core was removed from the core barrel (still in its polyethylene sleeve) the ends were sealed with polyethylene caps. A new precleaned polyethylene sleeve was then inserted into the core barrel for the next drill run. All core handlers wore clean gear (non-particulating suits and clean gloves), and at all times the firn/ice cores were isolated from potential sources of contamination (e.g., camp stoves, aircraft and generator exhaust).

The sealed HDPE tube served as a transport tube, minimizing core handling, improving core quality, and making trace metal analysis at the parts-per-trillion level possible.

All cores were transported frozen to the freezers at UNH. In addition to the ice core drilling field work, we also performed several other field research activities designed to enhance the interpretation of the ice core records including:

- a detailed radio echo sounding survey of the entire region to define bedrock topography and aid in developing glacier flow models. These data will assist in dating the lower sections of the 345 m core.
- collection of snow samples for major ion, stable isotope, and trace element analysis from four 4 m deep snowpits (representing approximately one year of snow accumulation).
- collection of samples from five separate fresh snowfall events for major ion and stable isotope analysis to define summertime glaciochemical and stable isotope signals.

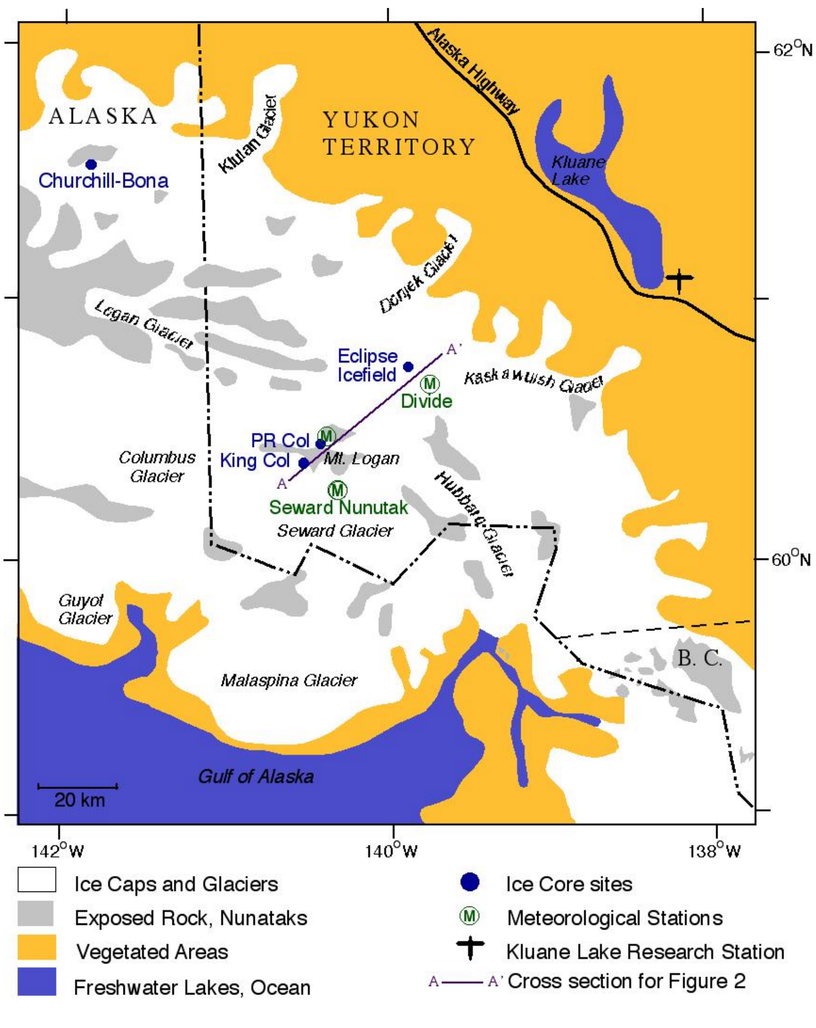

Figure 1. Location map in the St. Elias mountain range for the Eclipse icefield as well as other ice coring sites and meteorological stations

• collection of borehole temperature data (Figure 2). Temperature at 340 m in the borehole (very close to bedrock) was –8°C indicating the Eclipse Icefield is frozen to the bed. There is also a section or relatively cold ice from approximately 100-300 m (about 80-200 years old). This section of cold ice likely represents snow that accumulated during a locally or regionally cold period of the Little Ice Age.

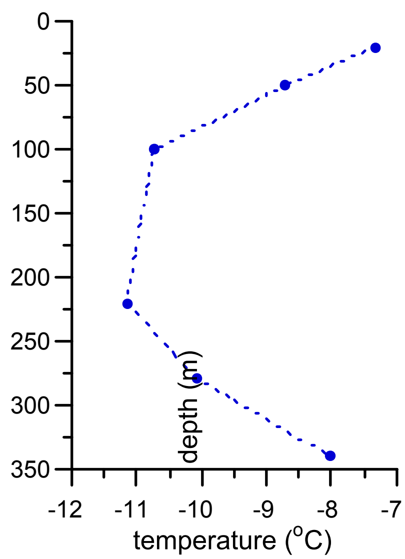

Figure 2. Borehole temperature versus depth for the Eclipse Icefield.

• in conjunction with the GSC, automatic weather stations (AWS) were installed at Prospector-Russel Col (5340 m), Seward Nunutak (2000m), and Divide (2500 m) (Figure 1) to investigate lapse rates and variations in snow accumulation over a range of elevations as well as to compare stable isotope/major ion signals preserved in fresh snow and snowpit samples with meteorological data. This data will be used to calibrate the ice core major ion and stable isotope record. We have revisited the Divide site in the summers of 2003, 2004, 2005, and 2006 to raise up the AWS and to dig snowpits to collect samples from the previous years snow for stable isotope, major ion, and trace element analysis.

In addition to the Eclipse Icefield cores, ice cores were recovered from two other glaciers in the St. Elias Mountains as part of a collaborative ice core drilling project in the region during the 2002 field season (Figure 1). The GSC recovered a 187 m surface-to-bedrock core from Prospector-Russell Col at an elevation of 5300 m on the summit plateau of Mt. Logan. A 220 m core was recovered by the National Institute for Polar Research in Tokyo team from King Col at an elevation of 4135 m on the Mt. Logan Massif. Several additional institutions (University of Copenhagen, University of Washington, University of Alaska, Arctic Institute of North America, Hokkaido University, and University of Ottawa) will be involved in the analysis and interpretation of the ice cores.

1.2 Ice Core Processing, Analysis and Dating

Two of the Eclipse 2002 ice cores (345 m [core 2] and 130 m [core 3])) have been analyzed continuously for major ions and stable isotopes (except for the top 60 m of the 345 core that was drilled with the titanium barrel for trace metal analyses) and along select sections for Cs^{137} activity and volcanic glass composition (Table 1). A sampling resolution of 10- 15 cm was used for the portion of core 2 from 0 - 200 m water equivalent (w.e.) depth and all of core 3, yielding around eight samples per year. Annual layer thinning required resampling of the lower third of core 2 at higher resolutions (beginning at 6 cm per sample, decreasing to 2 cm per sample by 254 m w.e. depth) to obtain an annually dated record to 1450 A.D. This portion of the core was resampled continuously for stable isotopes and around select high sulfate horizons for major ions.

Table 1. Summary of chemical analyses on Eclipse 2002 cores 2 and 3.

Analysis	Species	Analysis method	n
major ions	Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}	ion chromatography	3600
stable isotopes	$\delta^{18}O$ and δD	mass spectrometry	7200
radioactivity	^{137}Cs	gamma spectrometry	69
volcanic glass	SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O	electron microprobe	11
Trace elements	>25 elements	ICP-MS	492

All ice core processing for stable isotopes and major ions was performed in a clean bench in a freezer at the UNH Climate Change Research Center (CCRC) using established techniques for ultra-clean sample preparation. Prior to core sampling, a description of the visible stratigraphy (the location and thickness of ice layers) and density measurements were made on each of the approximately one-meter core sections. Above the firn/ice transition, core was scraped on an acrylic lathe system under a laminar flow bench using a titanium scraper so that all surface and sub-surface contamination from the drilling process is removed. Below the firn/ice transition, samples were cut into 3 x 3 cm pieces 10 cm long and the middle of the samples melted out using a custom made melter used to sample the GISP2, Penny, Devon, and Eclipse 1996 ice cores. Blanks (artificial core made by freezing 18mohm Milli-Q water) were processed frequently in the same manner as the core to ensure samples are uncontaminated by core processing. All samples were placed in LDPE bottles cleaned by successive soaking and rinsing in 18mohm Milli-Q water. Sample aliquots (5 ml) were taken for major ion and stable isotope analysis. The remaining sample volume was archived for future measurements.

Samples were analyzed for major ions (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, $C_2O_4^{2-}$) via ion chromatography using a 0.5 ml sample loop in a dedicated laboratory at the Climate Change Research Center. The cation system used a CS12A column with CSRS-ultra suppressor in auto suppression recycle mode with 20 mM MSA eluent. The anion system used an AS11 column with a CSRS-ultra suppressor in auto suppression recycle mode with 6 mM NaOH eluent. Stable isotope samples were analyzed at the University of Maine Stable Isotope Laboratory with a Multiprep CO_2 equilibration system coupled to a VG SIRA mass spectrometer for $\delta^{18}O$ (precision ± 0.05‰) and a Eurovector Cr pyrolosis unit coupled to a GV Isoprime mass spectrometer for δD (precision ± 0.5‰).

The chronology of the Eclipse ice cores is based on the counting of annual layers as delineated by summer maxima in $\delta^{18}O$ and δD and winter maxima in sodium concentrations (Figure 3). Age control on the chronology established via annual layer counting is provided by the 1986, 1963 and 1961 ^{137}Cs reference horizons (Figure 4) as well as volcanic reference horizons (e.g., Katmai 1912; Tambora 1815; Laki 1783, Kuwae 1453) developed through statistical analysis of the high- resolution sulfate record. In some cases (Redoubt 1989, Katmai 1912, Kuwae ~1453), these identifications have been independently verified using tephrochronology (Figure 5). Dating error is estimated based on the number of independently dated reference horizons (radioactivity, volcanic eruptions), and ranges from +/- one year between 2002 and 1912 and between 1815 and 1783, +/- two years between 1912 and 1815, and perhaps as much as +/- five years between 1783 and 1453 due to the lack of independently dated horizons in this interval.

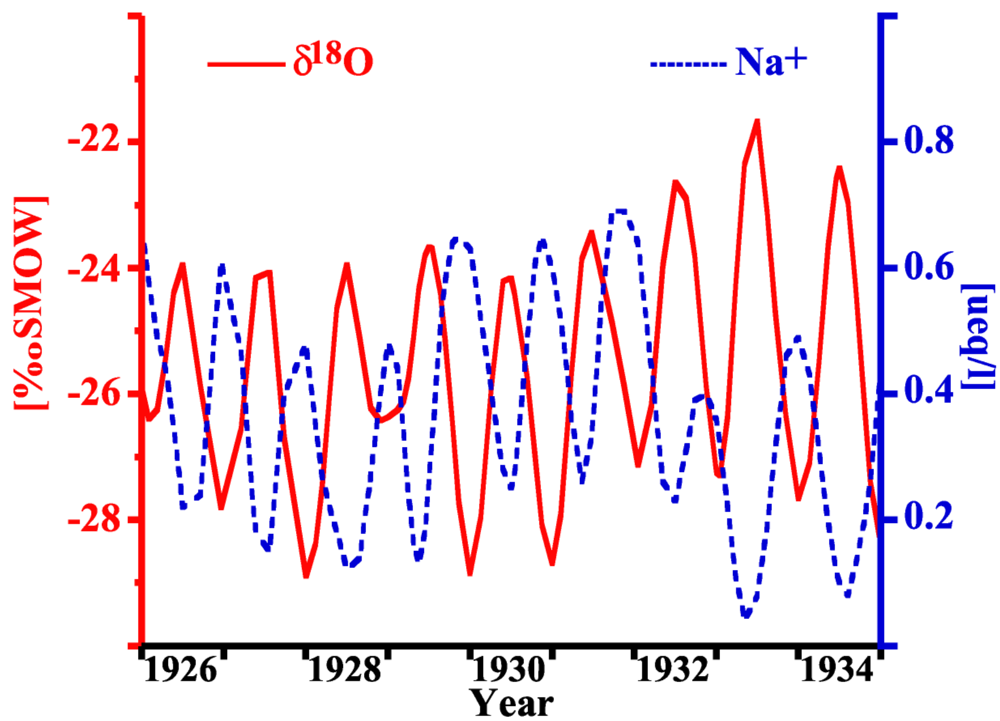

Figure 3. Seasonal signals in the smoothed □^{18}O and Na^+ records from the Eclipse 2002 Core 3 ice core.

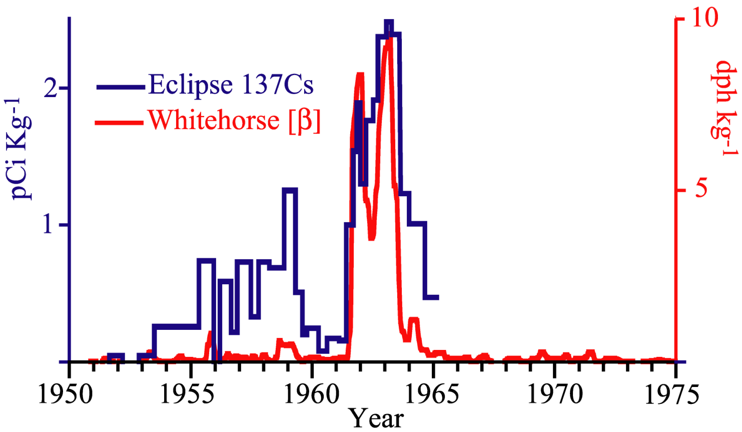

Figure 4. Comparison of Eclipse ice core ^{137}Cs profiles with real- time aerosol samples from Whitehorse, Yukon Territory, shows clear identification of the 1963 and 1961 radionuclide peaks from atmospheric nuclear weapons testing.

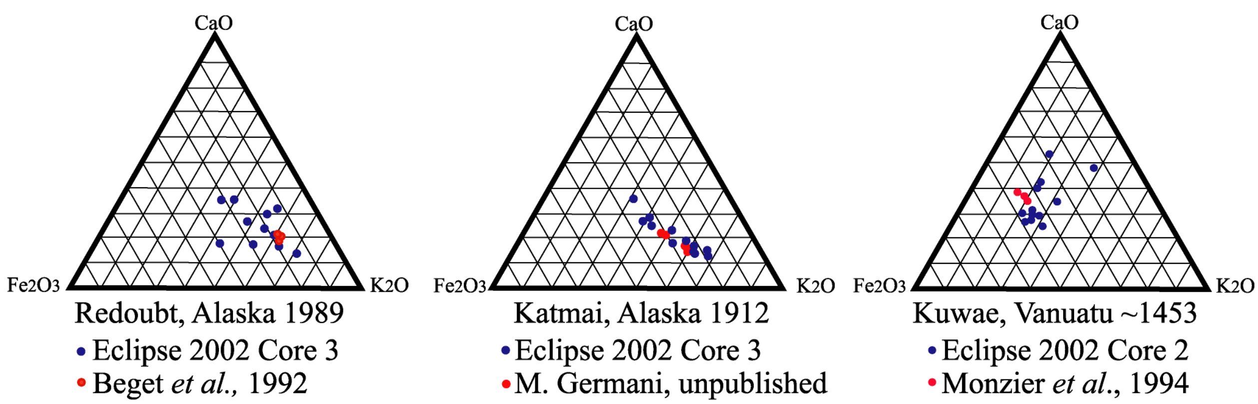

Figure 5. Ternary plots of CaO vs. Fe_2O_3 vs. K_2O in individual glass shards from the Eclipse ice cores (blue circles) and in reference tephras analyzed by other investigators (red circles).

1.3 Trace Element Analysis

We have recently completed analysis of trace elements on the 60 m section of core 2 drilled with the Geological Survey of Canada's ultra-clean titanium barrel. Core processing for trace elements was completed at the University of Maine during April 2005 on a custom nickel head melter and fractional flow collector allowing collection of co-registered samples for stable isotopes, major ions, and trace elements (Osterberg et al., 2006). This system has been tested and proven to be clean at the parts-per-trillion level and is also being used to sample the new ice core from Prospector-Russell Col on Mt. Logan. We are also in the process of analyzing large- volume snowpit samples collected during the 2002, 2003, 2004, 2005, and 2006 field seasons for trace elements to investigate seasonal signals. Samples were analyzed using a Finnigan Element2 ICP-MS at the University of Maine for major elements (S, Fe, Al), trace elements (As, Cd, Cu, Mn, Ni, Pb, Se, V, Zn), and rare earth elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu).

1.4 Presentations and Education Activities:

<u>AGU Presentations</u>

Kreutz, K.J., C. P. Wake and K. Yalcin (2004) Signal-to-Noise Ratios and Climate Records from the Eclipse Icefield Ice Cores. *Eos Trans. AGU, 85*(47), Fall Meet. Suppl., Abstract PP21A-1364.

Wake, C P, Yalcin, K, Kreutz, K J, Mayewski, P A, Fisher, D, Holdsworth, G. (2004) Why Drill More than One Ice Core? Paleoclimate Reconstruction along a Vertical Transect in the Saint Elias Mountains. *Eos Trans. AGU, 85*(17), Jt. Assem. Suppl., Abstract A43C-02 INVITED.

Yalcin, K., C.P. Wake, S.I. Whitlow, and K.J. Kreutz (2004) Forest Fire Signals Recorded in Ice Cores from Eclipse Icefield, Yukon Territory, Canada, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract PP23C-06.

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<u>Other Professional Presentations:</u>

Kreutz, K.J., Wake, C.P., Yalcin, K., Fisher, D.A., and Introne, D.S., Meteorological controls on summer fresh snow isotope values, Eclipse Icefield, St. Elias Mountains, *International Glaciological Society Symposium on Arctic Glaciology*, Geilo, Norway, August 23-27, 2004.

Fisher, D.A., Bourgeois, J., Demuth, M., Koerner, R.M., Parnandi, M., Sekerka, J., Zdanowicz, C., Zheng, J., Wake, C., Yalcin, K., Mayewski, P.A., Kreutz, K.J., Osterberg, E., Dahl-Jenssen, D., Goto-Azuma, K., Holdsworth, G., Steig, E., Ruper, S., and Waskiewicz, M., Mount Logan ice cores: the water cycle of the North Pacific in the Holocene, American Geophysical Union Fall Meeting, San Francisco, December 13-17, 2004.

Kreutz, K.J., Wake, C.P., Yalcin, K., Fisher, D., and Introne, D. (2005), Synoptic meteorological controls on summer snow and ice core stable isotopes, Eclipse Icefield, St. Elias Mountains, International Glaciological Society Symposium on High Elevation Glaciers and Climate Records, 5-9 September, Lanzhou, China.

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Yalcin, K., C.P. Wake, and S.I. Whitlow, K. J. Kreutz (2005) Seasonal and spatial variability in snow chemistry at Eclipse Icefield, Yukon, Canada. International Glaciological Society Symposium on High Elevation Glaciers and Climate Records, 5-9 September, Lanzhou, China.

Yalcin, K., C. Wake, K.J. Kreutz, D.A. Fisher, J.E. Dibb and S. Whitlow (2006) Glaciochemical records from Eclipse icefield, St. Elias Mountains, Yukon, Canada. North Pacific Climate Workshop, March 1-3, Institute of Ocean Science, Sidney, BC. (conference web site: http://ess.nrcan.gc.ca/extranet/npw/)

Other Educational Activities:

Use the Eclipse ice core record for teaching about ice cores and climate change in classes at UMaine (ERS200: Earth Systems; ERS527: Isotope Geology)

Use the Eclipse ice core record in numerous presentations in classrooms and invited presentations to environmental and educational organizations, as well as laboratory tours

Gave interviews on Maine Public Radio (Maine Things Considered; January 6, 2003)

Involved several graduate (3) and undergraduate (3) students in field work (ice core drilling in 2002, and visits to the Divide site in 2003, 2004, 2005, and 2006 to service AWS stations); collected data will result in at least two M.S. theses (Vogan, in prep. 2006, Gross, in prep 2006)

Several graduate (1) and undergraduate (2) students have been involved in computer software development and laboratory analysis as part of this project

A Glaciochemical Record of Natural and Anthropogenic Environmental Change in the Northwestern North American Arctic
NSF Award No.: OPP-0136005 (UMaine)

UMaine - Final Report- July 2006

2. MAJOR FINDINGS FROM THE ECLIPSE ICE CORES

The major findings from our research have been presented at several professional meetings – especially the AGU – and in papers that have already been published, or are in press or in review. Many of the results were also discussed in Kaplan Yalcin's dissertation (Yalcin, 2005). Below we provide a brief summary of our major findings.

2.1 Seasonal and spatial variability in snow chemistry

Samples collected from four snowpits at Eclipse Icefield, Yukon Territory, Canada, were analyzed for stable isotopes and major ions to assess seasonal and spatial variability in snow chemistry. Accumulation since the end of the 2001 summer season over the 0.1 km^2 area sampled ranges from 0.77 to 1.16 m water equivalent, with snowpit stratigraphy and chemical records demonstrating the low accumulation at Pit 3 is due to an under-representation of winter snowfall at that site. Chemical concentrations are independent of accumulation, while up to 44% of the variance in chemical flux can be explained by a linear relationship with snow accumulation rate. Summer- winter variations are evident in the major ion records and can broadly be divided between sea-salt species (Na^+, Cl^-) that peak in late fall-winter, and dust (Ca^{2+}, Mg^{2+}, K^+) and other species (NH_4^+, NO_3^-, SO_4^{2-}, $C_2O_2^{2-}$) that peak in late spring-summer. The average variance or signal common to all four snowpits identified by empirical orthogonal function analysis ranges from 49% of the total variance for Na^+ and Cl^- to as high as 80% of the total variance for SO_4^{2-}. Species present as coarse mode particles (Na^+, Cl^-, Ca^{2+}, Mg^{2+}) display more spatial variability than do species present mainly in accumulation mode aerosols (SO_4^{2-}, NH_4^+) or in the gas phase (NO_3^-) (Figure 6).

An poster on this topic was presented at the Fall 2005 International Glaciological Society Symposium on High Elevation Glaciers and Climate Records in Lanzhou, China and a paper detailing these results has been accepted for publication in the *Annals of Glaciology*, volume 43 (Yalcin et al., in press).

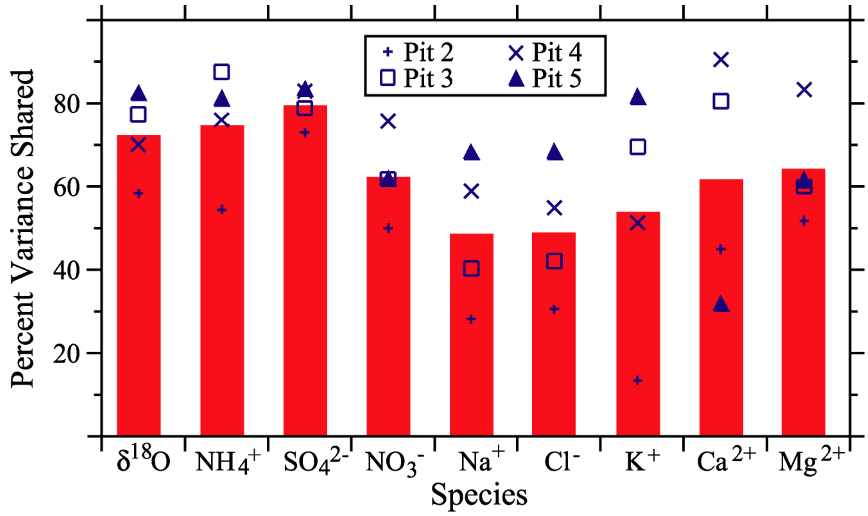

Figure 6. Graphical summary of snowpit EOF analysis. The percent variance explained by EOF 1 is plotted for each snowpit according to the legend at the top of the figure. The total variance explained is represented by size of the bar for each species.

2.2 Record of Forest Fire Activity in Alaska and the Yukon

A one thousand year record of forest fire activity has been developed using three annually- dated ice cores from Eclipse Icefield, Yukon Territory, Canada. Forest fire signals were identified as NH_4^+ residuals above a robust spline and using an EOF analysis which identified a chemical association in the NH_4^+, $C_2O_4^{2-}$, and K^+ records similar to that observed in forest fire plumes. These statistical techniques yielded similar records of forest fire activity, although the EOF analysis provides more conservative identification of forest fire signals. Comparison of forest fire signals in the Eclipse ice cores with the record of annual area burned in Alaska and the Yukon demonstrates that 80% of high fire years in Alaska and 79% of high fire years in the Yukon are identifiable as NH_4^+ concentration residuals in at least one core from Eclipse Icefield, although any individual core records between 33 and 67% of these events. The Eclipse ice cores record high fire activity in the 1760s, 1780s, 1840s, 1860s, 1880s, 1890s, 1920s to 1940s, 1970s, and 1980s (Figure 5). Peak fire activity occurred in the 1890s, possibly reflecting anthropogenic ignition sources associated with the large influx of people to the Yukon during the Klondike Gold Rush. Periods of low fire activity are evident during the 1770s, 1810s to 1830s, 1850s, 1950s, and 1960s. Extending our proxy of fire activity to 1000 A.D. using annual ammonium concentrations from our one core that extends back this far provides evidence of high fire activity from 1240 to 1410 coincident with the waning stages of the Medieval Warm Period.

Our results are compared and contrasted with other ice core proxies of forest fire activity from 20D and Summit, Greenland, and Mt. Logan, Yukon (Whitlow *et al.*, 1994; Taylor *et al.,* 1996; Savarino and Legrand, 1998). Somewhat surprisingly, the Eclipse record correlates best with the records from Greenland, with periods of high and low fire activity synchronous in eastern and northwestern North America. This correlation between Eclipse and Greenland breaks down during periods of pioneer land clearing for agriculture in eastern North America that are well recorded in Greenland but for which no evidence is seen in the Eclipse ice core since it is located upwind of the regions affected. Furthermore, both the Eclipse and Summit, Greenland ice cores provide evidence of high fire activity during the later part of the Medieval Warm Period between about 1200 and 1400 A.D. The apparent uniqueness of the Mt. Logan forest fire source region suggests that Mt. Logan records primarily Siberian forest fires, suggesting the new ice cores from Mt. Logan could be used to develop a record of forest fire activity in Siberia where documentary evidence of fire activity is essentially non-existent prior to the advent of remote sensing technologies. A talk was given on these results at the Fall 2004 AGU Meeting in San Francisco (Yalcin et al., 2004) and a paper has been accepted for publication in the journal *The Holocene* (Yalcin et al., 2006).

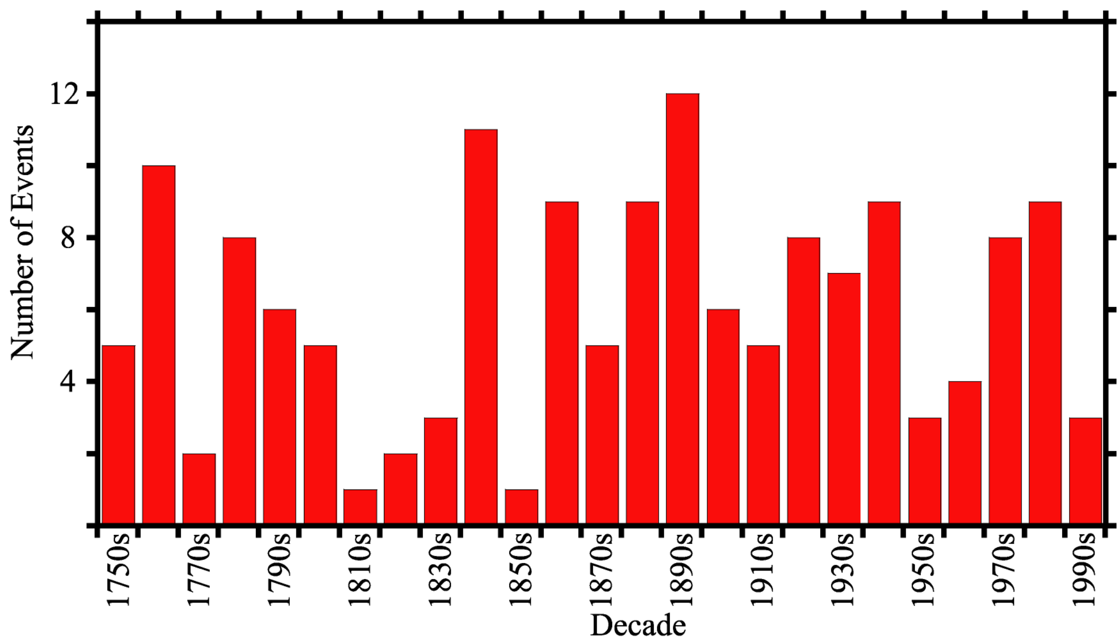

Figure 7. Reconstruction of forest fire activity since 1750 using the Eclipse ice cores as number of fire events recorded per decade. Post 1900, the bar represents the average number of events recorded in the three ice cores.

2.3 Evidence for a Second Volcanic Eruption Around 1809

A volcanic sulfate signal seen in ice cores from both polar regions six years prior to Tambora is attributed to an unknown tropical eruption in 1809 (e.g., Cole-Dai et al., 1991). Recovery of dacitic tephra from the 1809 horizon in an ice core from Eclipse Icefield, Yukon Territory, Canada with a chemical composition distinct from andesitic 1809 tephra found in Antarctic ice cores indicates a second eruption in the Northern Hemisphere at this time (Table 2). Sulfate flux calculations suggest this eruption contributed little additional sulfate to circum- Arctic ice cores, and therefore had negligible climatic significance. The 1809 tephra found in Antarctica is statistically indistinguishable from 1835 eruption products of Cosiguina Volcano, Nicaragua, leading to the suggestion that an 1809 eruption of Cosiguina is the source of the bipolar 1809 volcanic signal. Although a refined estimate of sulfur production incorporating exsolved sulfur gases demonstrates Cosiguina eruptions can release sulfur in sufficient quantities to perturb climate, the March 1809 date for an eruption of Cosiguina is now regarded as spurious due to a lack of geologic evidence. The source volcano responsible for the bipolar 1809 volcanic signal remains unknown. A paper detailing this research has been accepted for publication in Geophysical Research Letters (Yalcin et al., in press).

Table 2. Major oxide composition of 1809 ice core tephras. Compositions given as weight %, recalculated to a sum of 100%, where n is the number of samples analyzed. Values are means for the specified number of samples, with the standard deviation in parentheses.

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	n	Reference
1809 Eclipse	64.56	1.14	16.06	4.25	1.12	3.54	6.61	2.69	10	This work
	(1.10)	(0.20)	(0.67)	(0.78)	(0.49)	(0.73)	(0.77)	(0.26)		
1809 South Pole	59.74	0.83	15.66	7.84	2.33	5.40	4.22	3.08	8	Palais *et al*., 1990
	(1.40)	(0.16)	(1.75)	(1.84)	(0.92)	(0.91)	(0.74)	(1.37)		
1809 Dome C	59.45	0.67	16.43	9.00	2.83	5.44	4.14	2.05	13	De Angelis *et al*.,
	(1.63)	(0.24)	(0.51)	(0.27)	(0.73)	(0.82)	(0.52)	(0.40)		1985

2.4 Ice Core Paleovolcanic records from the St. Elias Mountains

Prior work has demonstrated that a record of regionally significant volcanic eruptions in the North Pacific is available from Eclipse Icefield, Yukon Territory, Canada. The acquisition of two new cores from Eclipse Icefield during the 2002 field season allows us to extend the record of North Pacific volcanism another five hundred years and assess the variability in volcanic signal preservation using the three ice core records now available from Eclipse Icefield. In addition, a paleovolcanic record is developed using the ice core record from the Northwest Col of Mount Logan covering the period 1690 to 1980. The Eclipse (3017 m elevation) and Logan (5340 m elevation) records are compared to assess vertical gradients in volcanic sulfate loading between the lower and middle troposphere. Non- sea – salt sulfate residuals above a robust spline and empirical orthogonal function (EOF) analysis were used to identify volcanic sulfate signatures (Yalcin et al., 2003). When possible, these signals were then matched to the historical record of volcanism to identify specific eruptions. Some of these identifications have been independently verified by means of tephrochronology, including Katmai (1912) and Kuwae (~1453). The largest North Pacific eruptions, such as Katmai 1912 (VEI 6) and Ksudach 1907 (VEI 5), as well as some moderate-sized eruptions (i.e., Redoubt 1989; VEI 3), are consistently recorded in each of the available cores. Meanwhile, other moderate to large eruptions, such as Bezymianny 1956 (VEI 5), are not recorded in any of the cores. Recent large tropical eruptions such as Pinatubo and El Chichon do not appear to be recorded at Eclipse, possibly due to anthropogenic sulfate deposition obscuring the volcanic sulfate signal from distant eruptions (Yalcin and Wake, 2001). However, older tropical eruptions such as Krakatau 1883, Tambora 1815, Unknown 1809, Cosiguina 1835, and Kuwae ~1453 are clearly recorded. A talk was given on these results at the May 2004 AGU General Assembly in Montreal, and a manuscript has been submitted to the *Journal of Geophysical Research* (Yalcin et al., in review)

2.5 Stable Isotope Records from Eclipse Icefield

Research efforts to understand the physical processes controlling isotope fractionation, and hence interpret time-series isotope records from the Eclipse ice cores, focus on three distinct time scales. First, fresh snow samples collected during the 2002 field season on Eclipse show a wide range of $\delta^{18}O$ values (~10‰), suggesting that on event timescales differences in synoptic atmospheric patterns play a large role in determining snow isotope ratios. Second, on longer timescales (seasonal to annual), we have maintained an automatic weather station (AWS) with a sonic snow depth sounder at the Divide site (~5km to the SW of Eclipse) from 2002 to 2006 (and plan to continue to keep this station in operation). This station provides a unique opportunity to correlate time-series snow chemistry of known age (Fig. 3) with local and regional-scale meteorological data. University of Maine students are re-visiting the Divide site during summer 2006, and in conjunction with GSC and University of Ottawa colleagues will download AWS data and collect snowpit samples. Once these samples are analyzed, isotop data will be correlated with meteorological data to better understand seasonal-annual isotope controls, and publication is planned in the *Journal of Glaciology*. Third, on interannual to decadal timescales, we intend to use established statistical analysis techniques to interpret the Eclipse ice core isotope records in terms of regional-scale (e.g., Gulf of Alaska/North Pacific, and

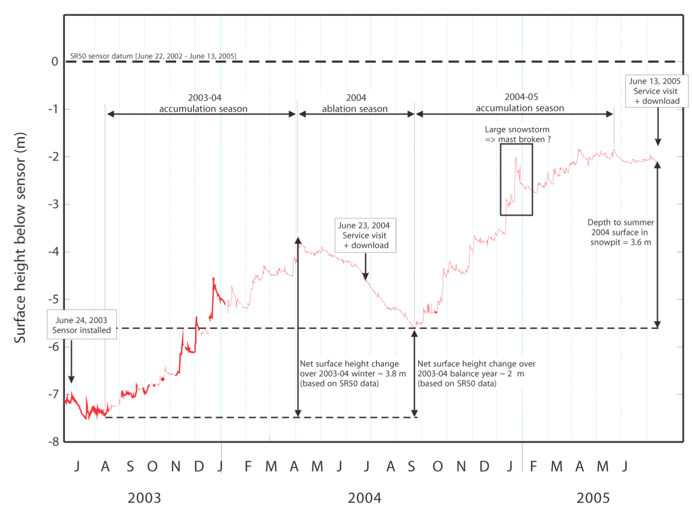

Figure 3. Time series of snow surface height changes at the Divide site measured by AWS depth sounder (Vogan et al. ,in prep).

tropical/extratropical) climate variability. An initial effort, using simple comparison of Eclipse and Mt. Logan isotope records along with intermediate complexity isotope models, has identified a potentially large North Pacific climate shift around 1850AD that may be linked to changes in El Nino-Southern Oscillation frequency (Fisher et al., 2006). We are currently preparing a paper on the 1000 year stable isotope record (Fig. 4) that will be submitted to *Geophysical Research Letters* in the fall of 2006. The highlights of the record are 1) a classic Medieval Warm Period/Little Ice Age isotope signal, if the isotope data are interpreted primarily in terms of temperature, and 2) potentially higher MWP temperatures relative to the past century at this latitude and elevation in the North Pacific. We are also planning to write a second paper dealing solely with the high-resolution Eclipse isotope record that we expect to submit to the *Journal of Geophysical Research*.

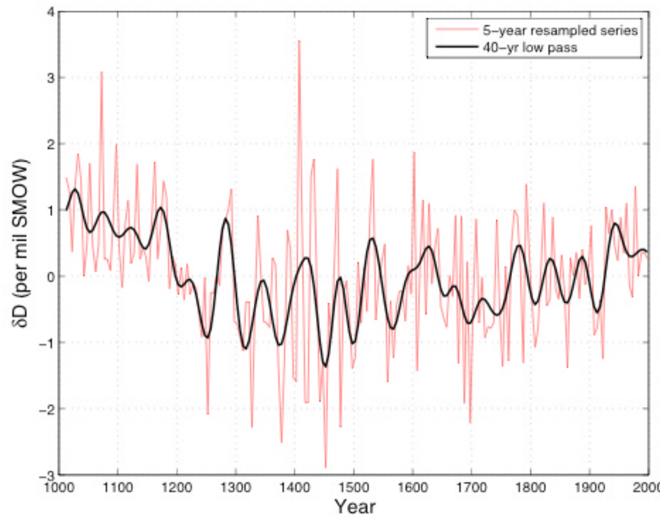

Figure 4. Full 1000 year isotope record from the Eclipse Icefield Core 2.

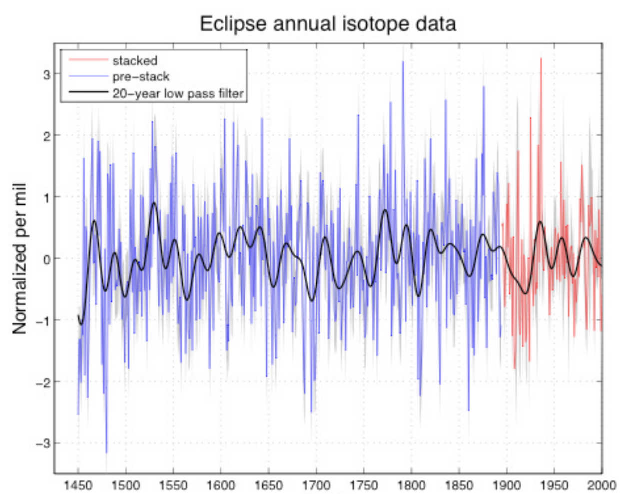

Figure 5. 550-year annual isotope record from Eclipse ice cores.

2.6 Ice Core Accumulation Records

Three annually dated ice cores from Eclipse Icefield, Yukon, Canada provide records of net accumulation spanning the last 100 to 500 years. Annual layers become progressively thinner with depth in the Eclipse ice cores, requiring reconstruction of original annual layer thicknesses by correcting for ice creep. An empirical approach was used that is based on the observed layer thicknesses from annual layer counting of the Eclipse ice cores. Accumulation records are highly reproducible with 73% of the signal shared between the three cores. The accumulation time-series shows considerable decadal scale variability that can be related to climate regimes that characterize the North Pacific. For example, periods of high accumulation are noted from 1470-1500, 1540-1560, and 1925-1975. Periods of low accumulation are observed between 1500-1540, 1680-1780, and 1875-1925. The strongest multi-year drop in accumulation is seen between 1979 and 1984, although there are isolated years with lower accumulation. This drop in accumulation is possibly related to the 1977 regime shift in the Pacific Decadal Oscillation. However, PDO regime shifts are not always reflected in the accumulation time series, implying a non-linear response or modulation by other modes of climate variability such as ENSO. Its is noteworthy that the Eclipse accumulation time series is out of phase with the accumulation time series from nearby Mount Logan on all time scales for reasons to be investigated. The results of this research were presented at the fall 2005 AGU meeting (Yalcin et al., 2005).

2.7 Melt Percent Records

Melt percent measures in ice cores provides a valuable record of summer temperatures (Fig. 6). Here we compare the record from the 1996 core with the 2002 core 3. Increased melt percent over the past 50 years in both records matches a wide regional temperature increase of 2°C measured at meteorological stations much closer to sea level. The warming trend is also consistent with a thinning measured in several Alaskan glaciers over the past 50 years (Arendt et al., 2002). More detailed analysis of daily summer temperature records will be useful for comparing the mid troposphere warming recorded in the melt percent records with summer temperatures measured in the lower troposphere. A paper is currently being prepared for submission to Journal of Glaciology (Wake et al., in prep).

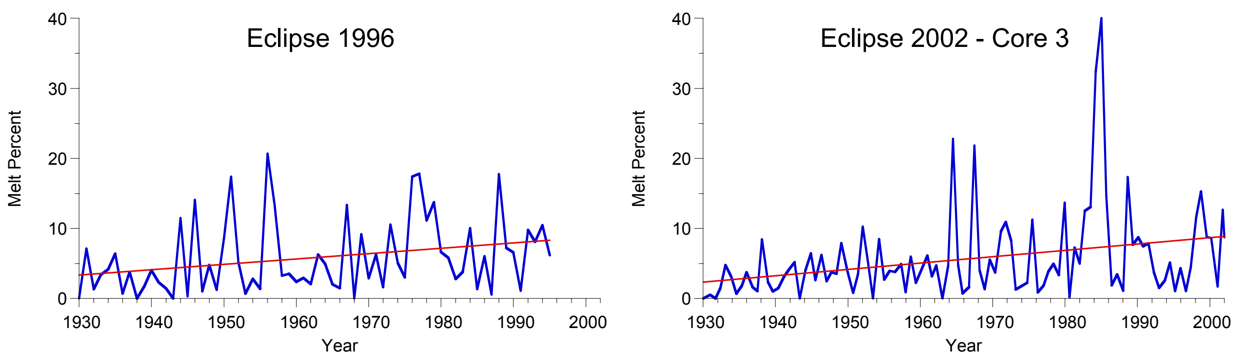

Figure 6 . Melt percent records from the 1996 and 2002 cores showing warming trend in summer temperatures over the past 70 years.

2.8 Trace element record

Trace element data from Eclipse 2002 core 2 reveals significant changes in the chemical composition of the North Pacific atmosphere over the past 40 years. In particular, we note the likely impact of both local and long-range anthropogenic impacts on Pb concentrations (Fig. 7). Much of the trace element data (e.g., rare earth element concentrations) support the input of locally-derived dust to the Eclipse Icefield, however comparison with trace element data from the PR Col core recovered near the summit of Mt. Logan suggests input of anthropogenic pollution from Asia (Osterberg et al., in prep.). Interestingly, the change in background Pb concentrations at the summit appears much earlier (1970's) than at Eclipse (mid-1990's), and may reflect the effects of transport processes at different elevations in the North Pacific region. We are working on comparisons of snowpit data from the Eclipse and Divide sites, seasonal trace element signals in the Eclipse ice core, and comparisons of meteorological and emissions data to the Eclipse ice core data (Gross et al., in prep.).

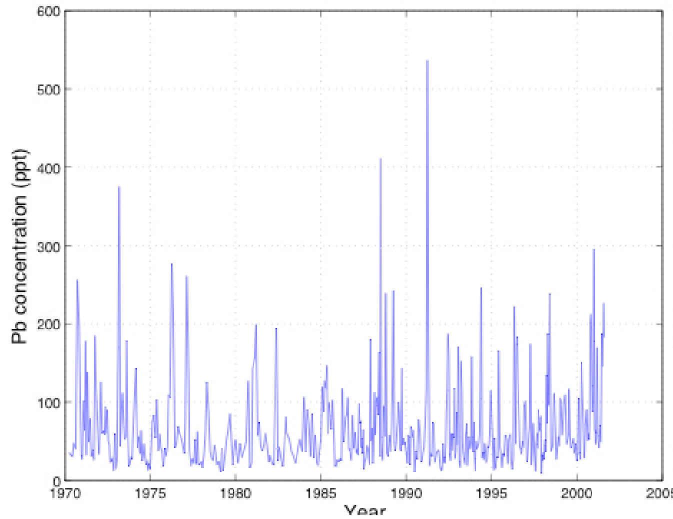

Figure 7. Pb data from the Eclipse Icefield core 2.

Papers, Abstracts, Dissertations, and Theses Resulting Directly from this Grant

Papers:

Kreutz, K.J., Wake, C.P., Yalcin, K., Introne, D., and Fisher, D. (in prep), Late Holocene North Pacific climate based on Eclipse Icefield ice core isotope data, Geophysical Research Letters.

Wake, C.P., T. Daigle, K. Yalcin, and K.J. Kreutz (in prep.) Ice Core Melt Percent Record of Recent Summer Warming in the St. Elias Mountains, Yukon. J. Glaciology.

Yalcin, K., C.P. Wake, K.J. Kreutz, M.S. Germani, and S. Whitlow (in review) Ice core paleovolcanic records from the St. Elias Mountains. J. Geophys. Res.

Yalcin, K., C.P. Wake, J.E. Dibb, K.J. Kreutz, and S. Whitlow (in review) Relationships between aerosol and snow chemistry at King Col, Mt. Logan Massif, Yukon, Canada Atmospheric Environment.

Yalcin, K., C.P. Wake, K.J. Kreutz, S. Whitlow, and M.S. German (in press) Ice core evidence for a second volcanic eruption around 1809 in the Northern Hemisphere. Geophysical Research Letters.

Yalcin, K., C.P. Wake, K.J. Kreutz, and S. Whitlow (in press) Seasonal and spatial variability in snow chemistry at Eclipse Icefield, Yukon Territory, Canada. Annals of Glaciology 43.

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Yalcin, K., C.P. Wake, K.J. Kreutz, M.S. Germani, and S.I. Whitlow (2004) North Pacific Volcanism in Three Ice Cores from Eclipse Icefield, Yukon Territory, Canada, Eos Trans. AGU, 85(17), Jt. Assem. Suppl., Abstract A43C-04.

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Yalcin, K. Glaciochemical records of environmental change from the St. Elias Mountains, Yukon Territory, Canada. Ph.D. Dissertation, University of New Hampshire, Durham, NH. 2005.

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