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A New Mt. Logan Ice Core Record - Change in Climate and Chemistry of the Atmosphere for the North Pacific

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Title:
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Project Participants

Senior Personnel

Name: Mayewski, Paul
Worked for more than 160 Hours: Yes
Contribution to Project:
Project oversight

Name: Zielinski, Gregory
Worked for more than 160 Hours: Yes
Contribution to Project:
Volcanic event oversight and comparison with other Arctic records.

Name: Kreutz, Karl
Worked for more than 160 Hours: Yes
Contribution to Project:
Comparison with Eclipse ice core recore to infer elevation related variability and isotope oversight.

Name: Kurbatov, Andrei
Worked for more than 160 Hours: Yes
Contribution to Project:
Processing oversight and volcanics.

Post-doc

Name: Kang, Shichang
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on ice core - meteorology calibration papers.

Name: Yan, Yuping
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on ice core - meteorology calibration papers.

Graduate Student

Name: Osterberg, Erich
Worked for more than 160 Hours: Yes
Contribution to Project:
PhD thesis research includes processing, analysis, and interpretation

Undergraduate Student

Technician, Programmer

Name: Sneed, Sharon
Worked for more than 160 Hours: Yes

Contribution to Project:
Laboratory supervision - IC

Name: Handley, Michael
Worked for more than 160 Hours: Yes
Contribution to Project:
laboratory supervision - ICPOES and ICPMS

Name: Introne, Douglas
Worked for more than 160 Hours: Yes
Contribution to Project:
Laboratory oversight for isotopes.

Other Participant

Research Experience for Undergraduates

Organizational Partners

Canadian Geological Survey
Organized field program, installed AWS on site, provided ice core drill.

University of New Hampshire
Share ice core records from lower elevation sites adjacent to Mt. Logan.

National Institute of Polar Research
Share ice core data from site near Mt. Logan at lower elevation.

University of Alaska Fairbanks Campus
Field expenses through IARC support generated through a joint proposal between Candaian Geological Surbey and University of Maine.

University of Washington
University of Washington is collaborating by providing stable isotope measurements on some core sections and as an intercalibration.

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
Advances in Ultra-Clean Continuous Melter Technology:
Our continuous melter system has been used successfully for the past 3 years in sampling ice and firn cores from Antarctica and Asia for the 8 major ions (Na+, K+, Mg2+, Ca2+, Cl-, NO3-, SO42-, MSA) with a concentration resolution of 1 ppb (1 mg/l). Through extensive testing and iterative procedural changes over the past year, we have made major advances to our continuous melter system in order to measure an additional 33 trace elements at concentration resolutions of 10 ppq (10 pg/l) to 1 ppt (1 ng/l) depending on the element (trace elements measured: Al, Fe, Zn, Pb, Cd, Cu, Co, Ti, Ba, Bi, Cr, Sr, V, Sn, Sb, U, Cs, Mn, As, Se, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu). All trace element concentrations are measured with our recently acquired Finnigan ELEMENT 2 inductively coupled plasma mass spectrometer. Our focus has been on consistently obtaining procedural blank values from the melter system for all measured elements below 10% of their average concentrations in the core. The following changes have been made to our melter system in order to meet this goal:
1. New Melthead Design: Through collaboration with the Advanced Manufacturing Center at the University of Maine, we developed a new

melthead design that can be easily dissected for cleaning between melting sessions. This aluminum melthead is capable of melting both firn and ice, and can be customized to accommodate cores of varying dimensions. We have also collaborated with the University of Maine Laboratory for Surface Science and Technology to coat the melthead with Zirconium Oxide and thereby eliminate any transfer of the foundation metal (Aluminum) into the samples. Our tests indicate that a melthead fabricated from pure Nickel is also suitable for collecting trace metal samples, and we may use a Nickel head in future melting of the Mt. Logan PR Col core.
2. New Melter Clean Room: We have relocated our continuous melter system to a dedicated positive-pressure clean room with Class 1000 filtered air.
3. Advances in Sample Resolution: We have enhanced the maximum resolution for continuous sampling to 1 cm ice/sample. This will allow us to increase the time period over which we can obtain sub-annual sampling.
4. New Sample Preparation and Handling Procedures: We have developed new procedures to eliminate trace element contamination during sample storage and measurement. The new procedures maintain our ability to preserve an archive of each sample for future chemical measurements of both major and trace elements should they become desirable.
Data Obtained to Date:
1. Glaciochemical: We have melted meters 2-9 & 115-116 and analyzed the samples for the major ions and trace elements listed above. Preliminary oxygen isotope measurements have been completed on the entire core by Geological Survey of Canada collaborators.
2. Electrical Conductivity: Measured on the entire length of core by Geological Survey of Canada collaborators.
3. Density: Density measurements have been completed on meters 2-50.
4. Stratigraphy: Visual stratigraphy has been completed on meters 2-50.
Plan for Year 2:
With the advancements to the continuous melter system completed, we are continuing to melt the remainder of the PR Col core (175 m) with a sample resolution of 1-2 cm/sample. Melting and sampling of the core will be completed by September 2004. Dating of the core will be accomplished by counting annual layers in the glaciochemical data and ice flow models in the older ice, constrained by absolute time markers including known volcanic eruptions and atmospheric nuclear testing horizons. Major ions, stable oxygen isotopes and volcanic tephra will be measured in each sample, and all samples from the anthropogenic period will be analyzed for trace elements as well. Trace elements will be measured in pre-anthropogenic samples (throughout the remainder of the core) at a lower sample resolution than the major ions. These data will be evaluated using multivariate statistical analyses and compared with instrumental climate records to determine proxy records of climate variability throughout the Holocene. Existing proxies for the strength of the autumntime Aleutian Low and summertime Pacific High pressure centers (Kang et al., in press), combined with new proxies such as Kara Sea atmospheric pressure, will allow us to investigate the variability of atmospheric circulation during the Holocene.

Mt. Logan PR Col Ice Core Progress Report 2004-2005

Advances in Ultra-Clean Continuous Ice Melter with Discrete Sampling:
We have continued to modify the UMaine high-resolution, continuous ice core melter system since the last progress report. A melter head composed of pure Nickel proved to be superior in cleanliness to zirconium-coated aluminum, and is now used exclusively for all ice melting. The UMaine melter system is unique because the ice core meltwater is not directly channeled to online instruments for continuous flow analyses (e.g. Sigg et al., 1991; Rothlisberger et al., 2000; Huber et al., 2001; McConnell et al., 2002; Knusel et al., 2003), but rather discrete, co-registered samples are taken at a regular interval (0.5 cm/sample or greater) for major ion, trace element and stable isotope measurements. Continuous melting with discrete sampling is advantageous over melter systems with online analyses for several reasons. With discrete sampling, an archive of each sample remains after initial analyses, allowing for additional chemical measurements (including trace element isotope ratios) should they become desirable, or should they become necessary because of an instrument malfunction during the initial analysis. Discrete samples can be scanned for longer intervals and in replicate, which lowers detection limits and increases measurement precision. Discrete samples can also be frozen and analyzed off-site, enhancing the potential range of analyses that can be performed and expanding capabilities for collaboration with other research teams. The physical separation of the analytical instruments (IC, ICP-MS and IRMS) from the ice core melter system reduces the complexity of the system, decreasing the potential for costly difficulties during ice melting. Should an instrument require maintenance or repair, the other instruments and the ice melting system can continue operating, reducing the total ôdown timeö.
Before continuing with the PR Col melting, we conducted a series of experiments on the melter system to test the accuracy and repeatability of the chemistry data that are created by it. A series of deionized water samples passed through the entire melter system provided method detection limits similar to or lower than all previously published detection limits for ice core melter systems and manual ice core processing techniques (e.g. Boutron and Batifol, 1985; Barbante et al., 1999; McConnell et al., 2002; Knusel et al., 2003). Two consecutive meters of ice from the GISP2 B core (meters 100-102; ~1675 A.D.; Meese et al., 1997) were cut into ôparallelö 4.5x4.2 cm slabs and melted to demonstrate the reproducibility of chemical measurements made with the system. These samples were analyzed at UMaine for the same suite of elements that we are measuring on the Mt. Logan PR Col core, specifically Na+, K+, Mg2+, Ca2+, Cl-, NO3-, SO42- and MSA on our IC, and Al, Fe, S, Zn, Pb, Cd, Cu, Co, Ti, Ba, Bi, Cr, Sr, V, Sb, U, Cs, Mn, As, Tl, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu on our ICP-MS. The following results were found:
1. All chemical series closely match (Figure 1, 2) with minor dfferences between the parallel slabs due to natural chemical variability within the

ice itself, and the non-uniform distribution of small particles (Knusel et al., 2003).
2. There is no relationship between concentration levels and core breaks for any of the elements.
3. Even when chemical concentrations do not exactly match for a particular sample due to natural variability, the patterns of high and low intervals are nearly identical in the parallel slabs (Figures 1, 2).
4. High-resolution (2 cm/sample) IC data from the UMaine system match the original GISP2 IC data analyzed in 1991 (Figure 4).
5. Different elements with the same likely source (i.e. dust, sea-salt, etc.) strongly co-vary as would be expected. For example, sea-salt proxies Na and Cl are highly correlated, as are dust proxies such as Al and Fe.
6. Rare earth elements, which are valuable dust source tracers, all show a similar pattern as would be expected because of their small mass range and uniform transport properties (Kreutz and Sholkovitz, 2000). Their ratios, however, reveal distinct patterns most likely indicative of their source region and transport history. The UMCoM system is the first ice melter system to measure rare earth element concentrations.
7. Elements measured on both the IC and ICP-MS have a correlation of $R2>0.88$, confirming the co-registration of IC and ICP-MS samples.

Lastly, the ability of the melthead to provide a clean sample by separating the outer portion of the core from the pristine, inner portion of the core was tested by melting a series of ice cores sideways at extremely high resolution (3 mm/sample). These experiments proved that contamination from the drilling and processing procedures only contaminate firn up to 6 mm into the core (Figure 3). Contamination is even less pervasive in ice. Our melthead is consequently designed so that it always removes >6 mm of firn or ice from the outside of the core.

The above data and results were presented at the 2004 Fall Meeting of the American Geophysical Union (see list of posters below), and are currently in the process of being published (see list of in preparation publications below).

2005 Mt. Logan Expedition:
In May-June of 2005, Erich Osterberg participated in a field expedition to Mt. Logan in order to extend the PR Col record to present, install three weather stations at various elevations on Mt. Logan to aid in the interpretation of ice core data, and collect snow samples from discrete storms to better understand their behavior and chemical signature. This expedition was in cooperation with Gerald Holdsworth of the University of Calgary, and funded in part by National Geographic. The team successfully installed weather stations at 3000 and 4000 m on Mt. Logan, and 3000 m at Eclipse Icefield. Two 15 m PICO auger cores were collected at King Col (4000 m) and a further 10 m core was collected at Eclipse Dome. Four 2-m snowpits were sampled at 500 m elevation intervals along the Mt. Logan ascent route, along with an additional 2-m pit at Eclipse Icefield, to examine the change in chemistry with altitude. A very large storm was also sampled at several elevations on the mountain. This same storm, however, prevented the team from reaching the PR Col core site on the summit plateau as originally planned.

Data Obtained to Date:
1. Glaciochemical: We have melted meters 2-100, 115-116 & 156-159 of the 186 m core, for a total of 4,900 samples. Sample resolution is approximately 3.5 cm firn/sample at the top of the core, decreasing steadily with depth to 1.7 cm ice/sample below the firn ice transition. All of the samples were analyzed by IC for the major ions, and meters 2-20, 97-99, 115-116 & 156-159 have been analyzed for the suite of trace elements listed above by ICP-MS. Preliminary oxygen isotope measurements were completed on the entire core by Geological Survey of Canada collaborators. Oxygen isotope samples are being prepared for the University of Washington (Eric Steig) and the University of Copenhagen for analysis.
2. Electrical Conductivity: Measured on the entire length of core by Geological Survey of Canada collaborators.
3. Density: Density measurements have been completed on meters 2-50.
4. Stratigraphy: Visual stratigraphy has been completed on meters 2-186.
5. Dating: A preliminary timescale has been developed in cooperation with the Geological Survey of Canada based on oxygen isotope data and glaciochemical data.
6. Volcanic Events: We are developing a database of North Pacific volcanic eruptions spanning the Holocene using published data and reports. This database will be invaluable for interpreting volcanic eruptions identified in the glaciochemical timeseries, and will aid in confirming the timescale.

Plan for Year 3:
Melting the remaining 80 m of core will be completed by the end of July 2005, and chemical analyses of the remaining samples will be completed by December 2005. Dating of the core will be accomplished by counting annual layers in the glaciochemical data and ice flow models in the older ice, constrained by absolute time markers including known volcanic eruptions and atmospheric nuclear testing horizons. Major ions, trace elements, oxygen isotopes and volcanic tephra will be measured in each sample. The entire core will include ~8000 samples, with over 40 different chemical species analyzed in each sample, resulting in an unprecedented glaciochemical dataset. These data will be evaluated using multivariate statistical analyses and compared with instrumental climate records to determine proxy records of climate variability throughout the Holocene. Existing proxies for the strength of the autumntime Aleutian Low and summertime Pacific High pressure centers (Kang et al., in press), combined with new proxies such as Kara Sea atmospheric pressure, will allow us to investigate the variability of atmospheric circulation during the Holocene. Trace element data spanning the last two centuries will reveal any pollution in the free

troposphere due to industrial activities. Prior to the industrial period, trace element data may be a proxy for volcanic activity. During all periods, the trace element data, and particularly the REE data, will be used as dust source tracers.

Workshops:
In early March, 2006, Erich Osterberg presented results from the Mt. Logan ice core at the North Pacific Climate Workshop in Sidney, British Columbia, hosted by the Canadian Institute of Ocean Sciences. The workshop was attended by researchers developing marine, terrestrial, and glaciological proxies of paleoclimate in the North Pacific region, an helped to develop some of the interpretations discussed here. In August, 2005, a workshop was held at the Geological Survey of Canada to discuss and develop the timescale for the PR Col core.

Publications:
Erich Osterberg, Mike Handley, Sharon Sneed, Paul Mayewski, Karl Kreutz. A continuous ice core melter system with discrete sampling for major ion, trace element and stable isotope analyses, Environmental Science and Technology, in press.

David Fisher, C. Wake, K. Kreutz, K. Yalcin, E. Steig, P. Mayewski, L. Anderson, J. Zheng, S. Rupper, C. Zdanowicz, M. Demuth, M. Waszkiewicz, D. Dahl-Jensen, K. Goto-Azuma, J.B. Bourgeois, R. M. Koerner, J. Sekerka, E. Osterberg, M. B. Abbott, B. P. Finney, S. J. Burns, Stable Isotope Records from Mount Logan and Eclipse Ice Cores and Nearby Jellybean Lake ; Water Cycle of the North Pacific over 2000 years and Over 5 Vertical Kilometers; Sudden Shifts and Tropical Connections, in press.

Erich Osterberg, Paul Mayewski, Mike Handley, Sharon Sneed, Dave Fisher, Karl Kreutz, submitted to Science. An ice core record of Asian Pb, Bi and As pollution in the North American free troposphere.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Cameron Wake, Kaplan Yalcin, Sharon Sneed, Mike Handley, in preparation. Globally synchronous intensification of circulation during the onset of the Little Ice Age.

Erich Osterberg, David Fisher, Paul Mayewski, Karl Kreutz, Sharon Sneed, Mike Handley, in preparation. North Pacific Holocene

Andrei Kurbatov, Erich Osterberg, Paul Mayewski, Mike Handley, Sharon Sneed, David Fisher, Karl Kreutz, in preparation. North Pacific explosive volcanic time series and trace metal budget over the past 2000 years.

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

Preliminary Results:
1. Preliminary analysis of the stable oxygen isotope ratios suggests that the PR Col core extends through the Holocene and into the last deglaciation. An initial timescale based on stable isotope and electrical conductivity data suggests that annual resolution of the glaciochemical data will be possible for the most recent 1000-2000 years, with decadal resolution for the remainder of the Holocene and centennial resolution for the Glacial/Holocene transition.
2. Principal component analyses of glaciochemical data from the top 7 m of the PR Col core reveal a strong annual signal dominated by dust and sea-salt elements, though these two primary signals appear to have different seasonal timing. Preliminary results suggest that the majority of sea-salt is deposited during the autumn when the Aleutian Low pressure center is strongest due to intense cyclonic activity in the Gulf of Alaska, while the majority of dust is deposited in spring when extra-tropical cyclones create dust storms in the Chinese and Mongolian deserts. The annual signal is resolvable at 115 m depth, estimated to be ~400 years old based on the preliminary timescale.
3. A very strong linear correlation has been found between annual mean Ca^{2+} concentration (proxy for dust) on the summit of Mt. Logan and springtime atmospheric pressure over the Kara Sea in polar Asia from 1948 to 1979 ($r=-.69$, $p<0.0001$). The Mt. Logan Ca^{2+} data are from the NW Col ice core, and atmospheric pressure data is from the NCEP/NCAR Reanalysis. The Kara Sea appears to be a region of cyclogenesis in the spring, spawning storms that entrain dust from the Gobi and Taklamakan Deserts and transport it across the Pacific Ocean. A dramatic example of this process was observed first hand in May 2001 by the PR Col ice core drilling team while on Mt. Logan. Satellite aerosol measurements confirm the Asian source region of the 2001 dust event and other smaller events during the 1990s. Rare Earth Element concentrations from dust events in the top 7 m of the PR Col core have a normalized pattern characterized by Gadolinium enrichment, similar to the REE pattern measured in Asian loess samples from the Gobi and Taklamakan Deserts and ice cores from the Tien Shan Mountains (Kreutz and Shokolvitz, 2000). Low dust concentrations in the top 7 m (representing background dust or perhaps a local source) have a contrasting REE pattern characterized by Terbium enrichment. Initial results also suggest that individual dust events can be clustered into a limited number of groups with different REE patterns, encouraging our efforts to differentiate specific dust source regions by their trace element signature.
4. Glaciochemical analyses also reveal that the uppermost 7 m of the PR Col core (representing 1990-1998) are enriched in Uranium and Cesium, and possibly several other metals including Cadmium and Lead, relative to the continental crust. Uranium is more enriched in the background (low) dust relative to the high dust events, supporting an interpretation that elevated concentrations are due to anthropogenic

nuclear mining and atmospheric testing rather than natural enrichment of a dust source region. Analysis of the U and Cs concentrations from the 1950Æs and 1960Æs, during which atmospheric nuclear testing was active, will elucidate the role of these activities in contaminating the free troposphere. Nitrate and sulfate concentrations also appear elevated compared with pre-anthropogenic values from the NW Col core, however the new timeseries is not yet long enough to determine the statistical significance of the rise.

Preliminary Results 2004-2005:
1. Preliminary analysis of the stable oxygen isotope ratios suggests that the PR Col core extends through the Holocene and into the last deglaciation. Our prelimary timescale suggests that annual resolution of the glaciochemical data will be possible for the most recent 1000-2000 years, with decadal resolution for the remainder of the Holocene and centennial resolution for the Glacial/Holocene transition.
2. Principal component analyses of glaciochemical data from the top 20 m of the PR Col core reveal a strong annual signal dominated by dust and sea-salt elements, though these two primary signals appear to have different seasonal timing. Preliminary results suggest that the majority of sea-salt is deposited during the autumn when the Aleutian Low pressure center is strongest due to intense cyclonic activity in the Gulf of Alaska, while the majority of dust is deposited in spring when extra-tropical cyclones create dust storms in the Chinese and Mongolian deserts. A second, smaller dust peak also appears in the autumn along with the sea-salt peak. The annual signal is resolvable at 115 m depth, estimated to be ~400 years old based on the preliminary timescale.
3. A very strong linear correlation has been found between annual mean Ca2+ concentration (proxy for dust) on the summit of Mt. Logan and springtime atmospheric pressure over the Kara Sea in polar Asia from 1948 to 1979 ($r=-.69$, $p<0.0001$). The Mt. Logan Ca2+ data are from the NW Col ice core, and atmospheric pressure data is from the NCEP/NCAR Reanalysis. The Kara Sea appears to be a region of cyclogenesis in the spring, spawning storms that entrain dust from the Gobi and Taklamakan Deserts and transport it across the Pacific Ocean. A dramatic example of this process was observed first hand in May 2001 by the PR Col ice core drilling team while on Mt. Logan. Satellite aerosol measurements confirm the Asian source region of the 2001 dust event and other smaller events during the 1990s. Rare Earth Element concentrations from dust events in the top 7 m of the PR Col core have a normalized pattern characterized by Gadolinium enrichment, similar to the REE pattern measured in Asian loess samples from the Gobi and Taklamakan Deserts and ice cores from the Tien Shan Mountains (Kreutz and Shokolvitz, 2000). Low dust concentrations in the top 7 m (representing background dust or perhaps a local source) have a contrasting REE pattern characterized by Terbium enrichment. Initial results also suggest that individual dust events can be clustered into a limited number of groups with different REE patterns, encouraging our efforts to differentiate specific dust source regions by their trace element signature.
4. Glaciochemical analyses also reveal that the uppermost 20 m of the PR Col core are enriched in Uranium and Cesium, and possibly several other metals including Cadmium and Lead, relative to the continental crust. Uranium is more enriched in the background (low) dust relative to the high dust events, supporting an interpretation that elevated concentrations are due to anthropogenic nuclear mining and atmospheric testing rather than natural enrichment of a dust source region. Analysis of the U and Cs concentrations from the 1950Æs and 1960Æs, during which atmospheric nuclear testing was active, will elucidate the role of these activities in contaminating the free troposphere.
5. Some volcanic eruptions are characterized by elevated heavy metal concentrations (including Bi, Cu, Pb, Zn, Sb) along with the typical rise in sulfate and chloride. We anticipate that the heavy metal signature of volcanic events will be dependent on their distance from the core site, the explosiveness of the event, and the composition of the source magma.

2005-2006 Mt. Logan PR Col Ice Core Final Report

see attached pdf for figures referred to below.

Data Obtained to Date:
1. Glaciochemical: We have melted all 186 m of the Mt. Logan PR Col core using the continuous ice core melter system with discrete sampling developed as part of this project (Osterberg et al., 2006). Sample resolution is approximately 3.5 cm firn/sample at the top of the core, decreasing steadily with depth to 1.7 cm ice/sample below the firn ice transition. To prevent seasonal biasing, sample resolution was increased to 4.5 cm/sample between 125 and 170 m depth (~500 BP û 2000 BP). All of the samples have been analyzed by IC for the major ions (Na+, K+, Mg2+, Ca2+, Cl-, NO3-, SO42- and MSA), and by ICP-MS for trace elements (Al, Fe, S, Zn, Pb, Cd, Cu, Co, Ti, Ba, Bi, Cr, Sr, V, Sb, U, Cs, Mn, As, Tl, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb, Lu). A second slab of the core was sampled and analyzed for stable water isotopes (δ18O) by the Geological Survey of Canada. Co-registered samples for stable isotope analyses from the continuous melter system have been sent to the University of Copenhagen for analysis. The glaciochemical data has sub-annual resolution (up to 20 samples/year) for the top 500 years, annual resolution for the top 1000 years, bi-annual resolution for the top 1500 years, 5-year resolution back to 2500 years BP, 10-year resolution back to 4500 years BP, 20-year resolution to 6000 YBP, 30-year resolution back to 13,000 YBP, and 50-year resolution for the remainder of the record to ~16,000 YBP.
2. Electrical Conductivity: Measured on the entire length of core by Geological Survey of Canada collaborators.
3. Density: Density measurements have been completed on meters 2-50.
4. Stratigraphy: Visual stratigraphy has been completed on meters 2-186.
5. Dating: A preliminary timescale has been developed in cooperation with the Geological Survey of Canada based on oxygen isotope data and

glaciochemical data.
6. Volcanic Events: We are developing a database of North Pacific volcanic eruptions spanning the Holocene using published data and reports. This database will be invaluable for interpreting volcanic eruptions identified in the glaciochemical time series, and will aid in confirming the timescale. We have collected ice samples from intervals characterized by large volcanic events (marked by elevated SO42-, Cu, Bi, Pb, As, Tl, and Cd) for tephra particle analysis by microprobe.

Timescale:
The glaciochemical data confirm that the PR Col ice core record encompasses the Holocene and deglacial transition period, including the Younger Dryas and Bolling-Allerod (Figure 1). The deglacial period is marked by depleted stable isotope values, and elevated (by several times) sea-salt and dust concentrations relative to the Holocene, similar to other ice cores records spanning this period. The timescale has been developed over the past year in conjunction with David Fisher and his colleagues at the Geological Survey of Canada. Sub-annual sampling for the top ~500 years (5-25 samples/year) reveals seasalt and dust concentration peaks in the spring and fall when cyclogenesis is most intense in the Gulf of Alaska, representing a robust framework for annual layer counting. The top 500 years of the timescale, in particular, are confirmed by identifying major (VEI>4) historical volcanic eruptions (marked by elevated SO42-, Cu, Bi, As, Tl, and Cd) from primarily Alaskan and Kamtchatkan volcanoes. The Katmai eruption in Alaska in 1912, the largest 20th century volcanic eruption in the world, provides an indisputable marker to constrain the portion of the record that overlaps with the instrumental record, providing robust, calibrated paleoclimate proxies (see below). A Nye-based ice flow model provides the basis for the timescale over the remainder of the Holocene. Major eruptions at 1259 AD and 800 AD, which are well dated from other Northern Hemisphere ice cores, help to constrain the timescale below 1500 AD. The sharp transition into the deglacial period is used to temporally constrain the bottom of the record, using a transition age from the annual layer-counted GISP2 ice core. The Mt. Logan PR Col record is the longest ice core record from the North Pacific, and the longest high-resolution record of atmospheric trace element deposition in the world. The uncertainties in the timescale range from 0.5 years for the top 100 years, to over 500 years in the middle of the Holocene where the record is the least constrained by volcanic eruptions. Gas age measurements are currently underway at the University of British Columbia, Canada in an effort to further constrain the middle-late Holocene record.

Results from this Research:
1. High-resolution trace metal time series from the PR Col record show dramatic increases in the concentration and crustal enrichment factor of Pb, Bi and As beginning simultaneously in the late 1960s and early 1970s and continuing to rise through the 1990Æs (Figure 2), attributed to Asian (primarily Chinese) industrial activities (Osterberg et al., submitted). Interestingly, sulfate and nitrate concentrations in the PR Col record do not show any anthropogenic trend similar to the 1980 NW Col core (Mayewski et al., 1990), but a rising trend in nitrate and sulfate has been documented in the Eclipse ice core record and attributed to Eurasian anthropogenic sources (Yalcin and Wake, 2001). The co-registered measurement of a large suite of dust and volcanic species allows any natural contribution (from dust and volcanic activity) to the trace metal flux to be removed from the PR Col record, revealing the anthropogenically-dominated Pb, Bi and As signal over the past three decades. Comparison of the anthropogenic trace metal data to total Sulfur and CO2 emission time series from industrial countries confirms that ChinaÆs history of industrial expansion matched the timing and magnitude of the Pb, Bi and As pollution seen on Mt. Logan. This signal is dramatically different from the North American and European trace metal record from Greenland ice cores, which show a much earlier onset of pollution in the late 19th century, and a steady decline in anthropogenic metal concentrations since the late 1960Æs owing to the phasing out of leaded gasoline (Boutron et al., 1991; Rosman et al., 1993). The PR Col data represent the first record of Asian anthropogenic metal emissions impacting the North American atmosphere. A smaller rise in Pb concentrations at the turn of the century may represent European emissions. The differences between the Logan and Greenland metal pollution records may represent differences in transport efficiency of trace metals vs. dust, as both regions have the same dust source areas in the East Asian deserts (Gobi and Takla Makan). One major advantage of the new continuous melting system developed for this project is the preservation of an archive of each sample. We have applied for funding to perform lead stable isotope analyses on the archives of anthropogenically enriched samples to confidently constrain the pollution source (e.g. Rosman et al., 1993; Vallelonga et al., 2003).
2. The annually averaged seasalt aerosol time series from the 2001 PR Col core (using Na+ concentrations) shows a statistically significant correlation with the intensity of the Aleutian Low and North Pacific High in NCAR/NCEP reanalysis models, similar to the record at NW Col (Kang et al., 2003). A period of lower average Na+ concentration corresponds to the cold phase of the PDO from 1947-1976 (Mantua et al., 1997) associated with a weaker Aleutian Low. Comparison of the Mt. Logan record of Aleutian Low intensity to the atmospheric circulation intensity records from Eclipse Icefield (Wake et al., 2002), Siple Dome (Kreutz et al., 1997, 2000) and GISP2 (Mayewski et al., 1997; OÆBrien et al., 1997) over the past ~2000 years reveals a pattern of steady intensification at both poles in the Pacific basin (Logan and Siple Dome) beginning at ~1200 AD, in contrast to the abrupt jump in intensification recorded in Greenland by GISP2 at ~1400 AD (Figure 3). The Siple Dome and Logan records show a great deal of similarity even on decadal timescales, and suggest that the ramp up of circulation intensity associated with the ôLittle Ice Ageö (LIA) is a global signal, and the abrupt LIA signal in Greenland may be due to another external forcing factor, such as sea-ice extent, that enhances the Greenland signal (Osterberg et al., in prep.). Interestingly, all three ice core records suggest that both hemispheres are still in LIA circulation patterns, even though temperature records show a warming since the late 19th century.
3. Annually averaged dust aerosol time series, as recorded by Mt. Logan Al and Fe concentrations, show a very strong inverse correlation to spring sea level pressure over the Gobi and Takla Makan deserts in China and Mongolia in NCEP/NCAR reanalysis models (rmax= -0.6,

p<0.0005; Figure 4). The inverse correlation suggests that as pressure over Asian deserts decreases (due to increased cyclonic activity), dust concentration in the North Pacific increases. The Mt. Logan Al record represents 75% of the total variance in sea-level pressure over 5-year averages, providing a robust proxy of atmospheric circulation over Asia extending well beyond the instrumental record (Figure 5). The proxy record shows that the early-mid 20th century was associated with the most intense circulation (and largest trans-Pacific dust transport) over the last 500 years (Figure 5). The correlation is not as robust for Ca2+ and Mg2+ time series owing to their partial source contribution from marine aerosols, highlighting the advantage of high-resolution trace metal data for atmospheric proxy records. The correlation of Mt. Logan dust with springtime geopotential height over Asian dust source regions supports the hypothesis that Asia is the dominant dust source for the North American free troposphere, particularly during spring when extratropical cyclones descend from Siberia and entrain dust to heights exceeding 9 km (e.g. Zhao et al., 2004). Normalized Rare Earth Element (REE) patterns from PR Col dust are similar to those from Greenland ice and Asian dust (Biscaye et al., 1997; Bory et al., 2003), and significantly different from those of Antarctic ice and Patagonia dust (Basile et al., 1997; Smith et al., 2003), further supporting the interpretation of a dominantly Asian dust source for Mt. Logan. These data also support the Asian source for order-of-magnitude Pb, Bi and As enrichment in the North Pacific free troposphere as discussed above. PR Col REE patterns display inter-annual variability potentially related to climatically-controlled changes in source region (changing circulation or precipitation patterns). We have applied for additional funding to analyze Sr isotope ratios in Mt. Logan meltwater archive samples to elucidate the time-varying locations of the source regions and further constrain our paleoclimatic interpretations.

4. Comparison of the Mt. Logan stable isotope record to the dust and sea-salt aerosol record over the Holocene reveals millennial-scale climate events (>3ë δ18O amplitude) in the North Pacific associated with depleted δ18O and enhanced aerosol concentrations at ~2.5, 4.2,6, 7.5, 8.2, 9 and 10 kyr BP (Figure 1). Hydrological model simulations suggest that the stable isotope record from the PR Col site does not represent a classical paleotemperature record, but rather a record of changing moisture sources (Fisher et al., in press). Depleted δ18O is associated with a more meridional flow with more southerly moisture sources, while enriched δ18O is associated with a more zonal flow from proximal sources in the North Pacific. The Holocene climate shifts are interpreted as expansions (zonal flow) and contractions (meridional flow) of the polar vortex following similar arguments developed from the GISP2 record (Mayewski et al., 1997). The most recent shift was in the early 19th century (~1820 AD) when there was a switch to the modern (meridional) flow regime. Thus, the LIA ramp-up in circulation intensity beginning at ~1200 AD (during a zonal flow regime according to the Mt. Logan stable isotope record) is contrary to the general Holocene pattern in the PR Col record (Fisher et al., in review).

5. Large volcanic eruptions (VEI>4) are consistently characterized by elevated heavy metal concentrations (including Bi, Cu, Pb, Cd, As, Tl) along with the typical rise in sulfate and chloride. This provides a more robust glaciochemical method for identifying eruptions in ice cores and developing time series of volcanic eruptions for the North Pacific (Kurbatov et al., in prep.). The heavy metal signature of volcanic events identified from the historical record is dependent on the distance of the source volcano from the core site. This supports the interpretation of anthropogenic trace metal data that trace metals have different transport efficiency than other aerosols, preferentially falling out closer to the source site owing to their high molecular weight. Although metal enrichments have been documented in ice cores for select eruptions in the past (e.g. Vallelonga et al., 2003), this is the first record of consistent metal enrichment from volcanic eruptions, providing the ability to constrain the relative source strengths of dust and volcanic activity to the atmospheric trace element budget. Our records suggests that in the North Pacific, explosive volcanic eruptions contribute 1.5-5 times the amount of Pb, Cu, Bi, As, and Tl than crustal dust, while quiescent degassing volcanoes contribute 6-20 times the amount of those metals than crustal dust (Kurbatov et al., in prep.)

References in this report:

Basile, I., Grousset, F.E., Revel, M., Petit, J.R., Biscaye, P.E., Barkov, N.I., 1997. Patagonian origin of glacial dust deposited in East Antarctica (Vostok and dome C) during glacial stages 2, 4 and 6, Earth and Planetary Science Letters 146, 573-589.

Biscaye, P. E., Grousset, F.E., Revel, M., Van der Gast, S., Zielinski, G.A., Vaars, A., Kukla, G., 1997. Asian provenance of glacial dust (stage 2) in the Greenland Ice Sheet Project 2 ice core, Summit, Greenland, Journal of Geophysical Research 102, 26,765û26,781.

Bory, A., Biscaye, P.E., Grousset, F.E., 2003. Two distinct seasonal Asian source regions for mineral dust deposited in Greenland (NorthGRIP), Geophysical Research Letters 30, 1167.

Boutron, C.F., Gorlach, U., Candelone, J.P., Bolshow, M.A., Delmas, R.J., 1991. Decrease in anthropogenic lead, cadmium and zinc in Greenland snows since the late 1960s, Nature 353, 153-156.

Kang, S.; Mayewski, P.A.; Yan, Y.; Qin, D.; Yao, T.; Ren, J., 2003. Dust records from three ice cores: relationships to spring atmospheric circulation over the Northern Hemisphere, Atmospheric Environment 37, 4823-4835.

Kreutz, K., Mayewski, P., Meeker, L., Twickler, M., Whitlow, S., Pittalwala, L., 1997. Bipolar changes in atmospheric circulation during the Little Ice Age, Science 277, 1294-1296.

Kreutz, K., Mayewski, P., Pittalwala, L., Meeker, L., Twickler, M., Whitlow, S., 2000. Sea level pressure variability in the Amundsen Sea region inferred from a West Antarctic glaciochemical record, Journal of Geophysical Research Atmospheres 105, 4047-4059.

Mayewski, P.A., Lyons, W.B., Spencer, M.J., Twickler, M.S., Buck, C.F. and Whitlow, S., 1990. An ice core record of atmospheric response to anthropogenic sulphate and nitrate, Nature 346, 554-556.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S.I., Yang, Q., Lyons, W.B., and Prentice, M., 1997. Major features and forcing of high latitude northern hemisphere atmospheric circulation over the last 110,000 years, Journal of Geophysical Research 102, 26345-26366.

OÆBrien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S. and Whitlow, S.I., 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core, Science 278, 1251-1256.

Rosman, K.J.R., Chisholm, W., Boutron, C.F., Candelone, J.P., Gorlach, U., 1993. Isotopic evidence for the source of lead in Greenland snows since the late 1960s, Nature 362, 333-334.

Smith, J., Vance, D., Kemp, R.A., Archer, C., Toms, P., King, M., Zarate, M., 2003. Isotopic contrains on the source of Argentinian loess û with implications for atmospheric circulation and the provenance of Antarctic dust during recent glacial maxima, Earth and Planetary Science Letters 212, 181-196.

Vallelonga, P., Candelone, J.P., Van de Velde, K., Curran, M.A.J., Morgan, V.I., Rosman, K.J.R, 2003. Lead, Ba and Bi in Antarctic Law Dome ice corresponding to the 1815 AD Tambora eruption: an assessment of emission sources using Pb isotopes, Earth and Planetary Science Letters 211, 329-341.

Wake, C., Yalcin, K., Gundestrup, N., 2002. The climate signal recorded in the oxygen isotope, accumulation and major ion time series from the Eclipse ice core, Yukon Territory, Canada, Annals of Glaciology 35, 416-422.

Yalcin, K., Wake, C.P., 2001. Anthropogenic signals recorded in an ice core from Eclipse Icefield, Yukon Territory, Canada, Geophysical Research Letters 28, 4487-4490.

Zhao, C., Dabu, X., Li, Y., 2004. Relationship between climate factors and dust storm frequency in Inner Mongolia of China, Geophysical Research Letters 31, L01103.

Training and Development:

Laboratory procedures and data resulting from this project are a major component of Erich Osterberg's PhD dissertation and have been included in our graduate courses.

Outreach Activities:

Presentation of results at local to regional meetings and K-12.

Workshops:

In July-August, 2005, a workshop will be held at the Geological Survey of Canada to discuss the timescale for the PR Col core based on the latest glaciochemical data. In October 2005, a workshop is planned to synthesize the results from the PR Col, King Col and Eclipse ice cores. Researchers from the University of Maine, the Geological Survey of Canada, the University of New Hampshire, the University of Washington, and the Japanese National Institute of Polar Research are expected to attend.

Presentations and Posters:

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Andrei Kurbatov, Greg Zeilinski, 2003. New Mt. Logan Summit Ice Core: High-Resolution Record of North Pacific Holocene Climate Variability, University of Maine Department of Earth Sciences Presentation.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Greg Zielinski, Andrei Kurbatov, Mike Handley, Sharon Sneed, 2003. Subannual-Decadal Holocene Climate Record from a New Mt. Logan Summit Ice Core, Saint Elias Mountains, Yukon, Poster presented at the workshop on the Interplay of Collisional Tectonics and Late Cenozoic Glacial Climate in Alaska and the northeastern Pacific Ocean, May 5, 2003.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Andrei Kurbatov, Greg Zeilinski, 2003. New Mt. Logan Summit Ice Core: High-Resolution Record of North Pacific Holocene Climate Variability, 2003 J. Louis Agassiz Symposium presentation.

Erich Osterberg, Paul Mayewski, Karl Kreutz, Greg Zielinski, Andrei Kurbatov, 2003. Mt. Logan PR Col Chemistry: Progress, Preliminary Results and Future Plans, 2003 St. Elias Ice Core Workshop Presentation, July 15, 2003.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Sharon Sneed, Mike Handley, 2004. Determining Dust Sources and Related Climate Signals in Mt. Logan Ice Cores, 2004 J. Louis Agassiz Symposium presentation.

Erich Osterberg, Mike Handley, Sharon Sneed, Paul Mayewski, Karl Kreutz, David Fisher, 2004. An Ice Core Melter System for Continuous Major and Trace Chemical
Analyses of a New Mt. Logan Summit Ice Core, EOS Trans. AGU, 85(47), Fall Meeting Supplement

Workshops:
In early March, 2006, Erich Osterberg presented results from the Mt. Logan ice core at the North Pacific Climate Workshop in Sidney, British Columbia, hosted by the Canadian Institute of Ocean Sciences. The workshop was attended by researchers developing marine, terrestrial, and glaciological proxies of paleoclimate in the North Pacific region, an helped to develop some of the interpretations discussed here. In August, 2005, a workshop was held at the Geological Survey of Canada to discuss and develop the timescale for the PR Col core.

Presentations and Posters:
Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Andrei Kurbatov, Greg Zeilinski, 2003. New Mt. Logan Summit Ice Core: High-Resolution Record of North Pacific Holocene Climate Variability, University of Maine Department of Earth and Environmental Sciences Presentation.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Greg Zielinski, Andrei Kurbatov, Mike Handley, Sharon Sneed, 2003. Subannual-Decadal Holocene Climate Record from a New Mt. Logan Summit Ice Core, Saint Elias Mountains, Yukon, Poster presented at the workshop on the Interplay of Collisional Tectonics and Late Cenozoic Glacial Climate in Alaska and the northeastern Pacific Ocean, May 5, 2003.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Andrei Kurbatov, Greg Zeilinski, 2003. New Mt. Logan Summit Ice Core: High-Resolution Record of North Pacific Holocene Climate Variability, 2003 J. Louis Agassiz Symposium presentation.

Erich Osterberg, Paul Mayewski, Karl Kreutz, Greg Zielinski, Andrei Kurbatov, 2003. Mt. Logan PR Col Chemistry: Progress, Preliminary Results and Future Plans, 2003 St. Elias Ice Core Workshop Presentation, July 15, 2003.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Sharon Sneed, Mike Handley, 2004. Determining Dust Sources and Related Climate Signals in Mt. Logan Ice Cores, 2004 J. Louis Agassiz Symposium presentation.

Erich Osterberg, Mike Handley, Sharon Sneed, Paul Mayewski, Karl Kreutz, David Fisher, 2004. An Ice Core Melter System for Continuous Major and Trace Chemical
Analyses of a New Mt. Logan Summit Ice Core, EOS Trans. AGU, 85(47), Fall Meeting Supplement, Abstract PP21A-1365.

Erich Osterberg, Andrei Kurbatov, Paul Mayewski, Karl Kreutz, David Fisher, Sharon Sneed, Mike Handley, 2005. Sub-annual ice-core record of major ion and heavy metal variability and sources in the North Pacific free troposphere, Mt. Logan, Yukon, Canada, Eos Trans. AGU, 86(52), Fall Meeting Supplement, Abstract PP31C-08.

Erich Osterberg, Paul Mayewski, Karl Kreutz, David Fisher, Mike Handley, Sharon Sneed, Kaplan Yalcin, Cameron Wake, Major ion and trace element record of Asian dust flux, Aleutian Low Intensity, and anthropogenic pollution from the Mt. Logan summit ice core. North Pacific Climate Workshop. Canadian Institute of Ocean Sciences, Sidney, British Columbia, Canada. March 1 to 3, 2006.

Erich Osterberg, Paul Mayewski, David Fisher, Karl Kreutz, Sharon Sneed, Mike Handley, Andrei Kurbatov, An ice core record of Holocene climate change, trans-Pacific dust flux, and anthropogenic pollution in the North Pacific: Mt. Logan, Yukon, Canada, 2006 J. Louis Agassiz Symposium presentation.

Journal Publications

Kang, S. mayewski, P.A., Yan, Y., Qin, D., Yao, T. and Ren, J., "Dust records from three ice cores: Relationship to Spring atmospheric circulation over the Northern Hemisphere.", Atmospheric Environment, p. 4823, vol. 37, (2003). Published

Fisher D.A., Zdanowicz C, Demuth M, Waskiewatski, M , Bourgeois J B, Koerner R M, Zheng J , Sekerka, J., Yalcin, Wake. C. Kreutz, K., Mayewski, P. A., Osterberg, E., Dahl-Jensen D. Anderson, L., Abbott, M.B., Finney, B.P., Steig, E., and Rupper. S, "Stable isotope records from Mount Logan and Eclipse Ice Cores and nearby Jelly Bean Lake:The water cycle of the North Pacific spanning 2000 years and 5400 vertical meters; Sudden regime shifts and tropical connections.", Science, p. , vol. , ( ). Submitted

Osterberg, E., Mayewski, P.A., Fisher, D. and Kreutz, K., "A 290-year dust proxy record of Kara Sea atmospheric pressure and Asian cyclogenesis from Mt. Logan, Yukon.", Geophysical Research Letters, p. , vol. , ( ).

Mayewski,P.A., Maasch, K., Yan, Y., Kang, S., Meyerson, E., Sneed, S., Kaspari, S., and Dixon, D., Osterberg, E., Morgan, V., van Ommen, T., and Curran, M., "Solar forcing of the polar atmosphere: Data, mechanism and Implications", Annals of Glaciology, p. , vol. , ( ). Accepted

Erich Osterberg, Mike Handley, Sharon Sneed, Paul Mayewski, Karl Kreutz, "A continuous ice core melter system with discrete sampling for major ion, trace element and stable isotope analyses", Environmental Science and Technology, p. , vol. , ( ). Accepted

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

Results from this Research:

1. High-resolution trace metal time series from the PR Col record show dramatic increases in the concentration and crustal enrichment factor of Pb, Bi and As beginning simultaneously in the late 1960s and early 1970s and continuing to rise through the 1990Æs, attributed to Asian (primarily Chinese) industrial activities. Interestingly, sulfate and nitrate concentrations in the PR Col record do not show any anthropogenic trend similar to the 1980 NW Col core, compared to a rising trend in nitrate and sulfate has been documented in the Eclipse ice core record and attributed to Eurasian anthropogenic sources. The co-registered measurement of a large suite of dust and volcanic species allows any natural contribution (from dust and volcanic activity) to the trace metal flux to be removed from the PR Col record, revealing the anthropogenically-dominated Pb, Bi and As signal over the past three decades. Comparison of the anthropogenic trace metal data to total Sulfur and CO2 emission time series from industrial countries confirms that ChinaÆs history of industrial expansion matched the timing and magnitude of the Pb, Bi and As pollution seen on Mt. Logan. This signal is dramatically different from the North American and European trace metal record from Greenland ice cores, which show a much earlier onset of pollution in the late 19th century, and a steady decline in anthropogenic metal concentrations since the late 1960Æs owing to the phasing out of leaded gasoline. The PR Col data represent the first record of Asian anthropogenic metal emissions impacting the North American atmosphere. A smaller rise in Pb concentrations at the turn of the century may represent European emissions. The differences between the Logan and Greenland metal pollution records may represent differences in transport efficiency of trace metals vs. dust, as both regions have the same dust source areas in the East Asian deserts (Gobi and Takla Makan). One major advantage of the new continuous melting system developed for this project is the preservation of an archive of each sample. We have applied for funding to perform lead stable isotope analyses on the archives of anthropogenically enriched samples to confidently constrain the pollution source.

2. The annually averaged seasalt aerosol time series from the 2001 PR Col core (using Na+ concentrations) shows a statistically significant correlation with the intensity of the Aleutian Low and North Pacific High in NCAR/NCEP reanalysis models, similar to the record at NW Col. A period of lower average Na+ concentration corresponds to the cold phase of the PDO from 1947-1976 associated with a weaker Aleutian Low. Comparison of the Mt. Logan record of Aleutian Low intensity to the atmospheric circulation intensity records from Eclipse Icefield, Siple Dome (Antarctica) and GISP2 (Greenland) over the past ~2000 years reveals a pattern of steady intensification at both poles in the Pacific basin (Logan and Siple Dome) beginning at ~1200 AD, in contrast to the abrupt jump in intensification recorded in Greenland by GISP2 at ~1400 AD. The Siple Dome and Logan records show a great deal of similarity even on decadal timescales, and suggest that the ramp up of

circulation intensity associated with the ôLittle Ice Ageö (LIA) is a global signal, and the abrupt LIA signal in Greenland may be due to another external forcing factor, such as sea-ice extent, that enhances the Greenland signal. Interestingly, all three ice core records suggest that both hemispheres are still in LIA circulation patterns, even though temperature records show a warming since the late 19th century.
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Contributions to Other Disciplines:

Proxy atmospheric circulation reconstructions covering the last ~10,000 years of value to climatology and meteorology to enhance instrumental climate base (~100 years).
Documentation of Asian source Pb and S emission histories compared to North American and European series.
Documentation of abrupt climate change onset over the Pacific (north and south) vs North Atlantic during the last 1000 years.

Contributions to Human Resource Development:

Reconstruction of Asian source anthropogenic pollution histories for Pb and S; major Asian-North Pacific atmospheric circulation features; and phasing of abrupt climate change events in Pacific vs Atlantic.

Contributions to Resources for Research and Education:

New high resolution, continuous, trace element contamination-free sampling system developed by PhD student (Erich Osterberg) in this project is now being used by graduate students in our Institute and being purchased by ice core analysis laboratories in Canada, Japan, and India.

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Book
Any Web/Internet Site
Any Product
Contributions: To Any Beyond Science and Engineering

Fig. 1 GISP2 Parallel Sticks Tests
Unpublished data by Erich Osterberg, Paul Mayewski, Karl Kreutz, Mike Handley & Sharon Sneed

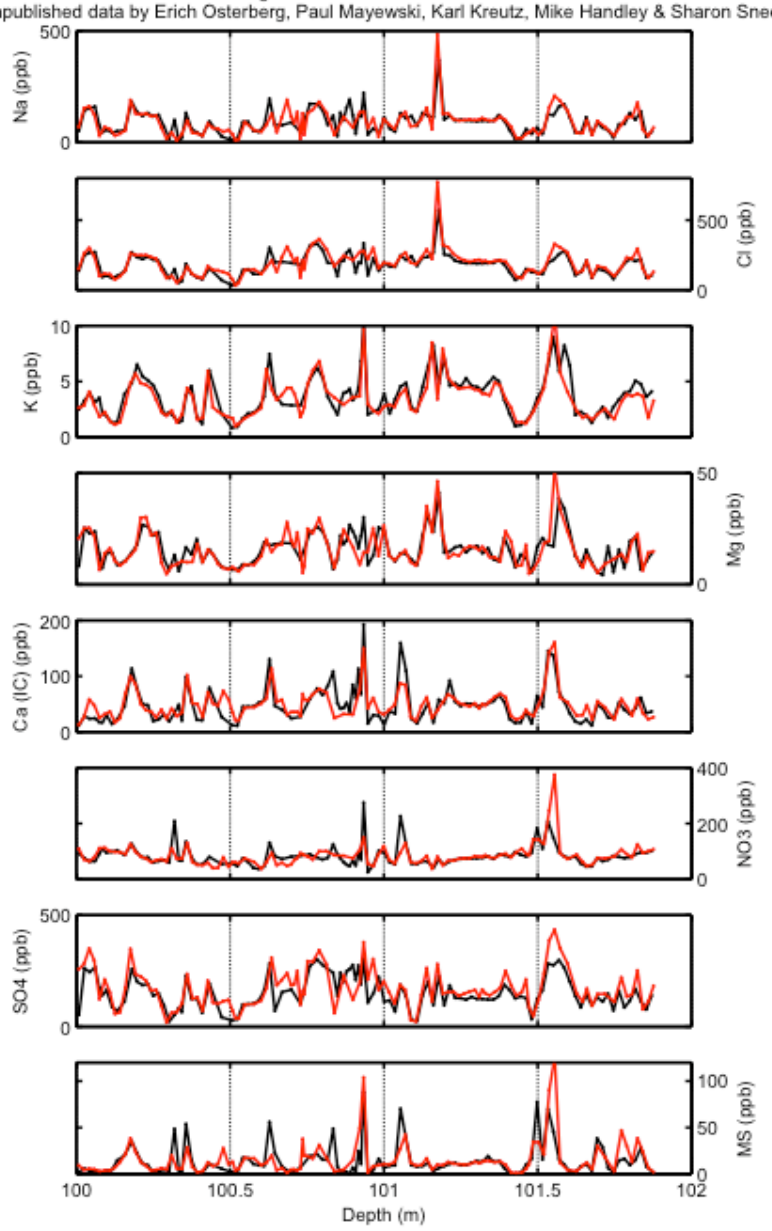


Fig. 2 GISP2 Parallel Sticks Tests
Unpublished data by Erich Osterberg, Paul Mayewski, Karl Kreutz, Mike Handley & Sharon Sneed

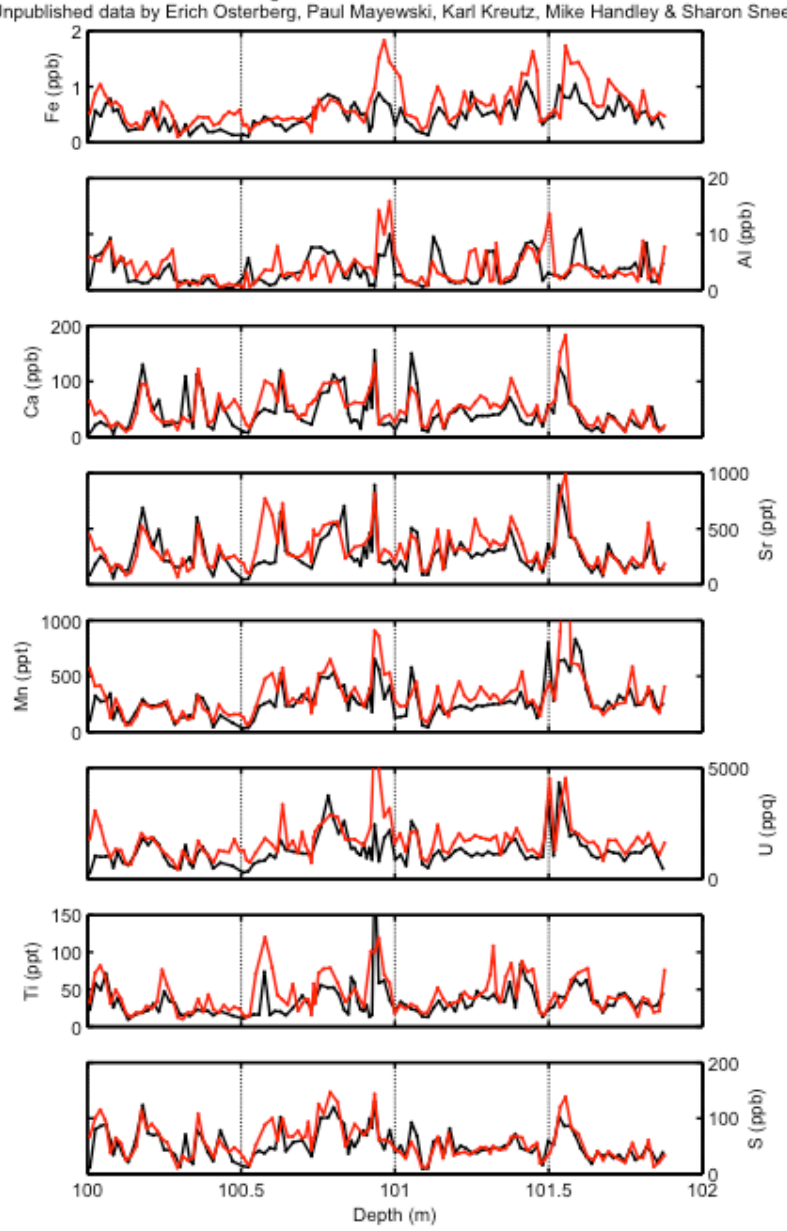


Figure 3. Concentration cross-sections from the Mt. Logan PR Col core. Only the outer 3-6 mm is contaminated.

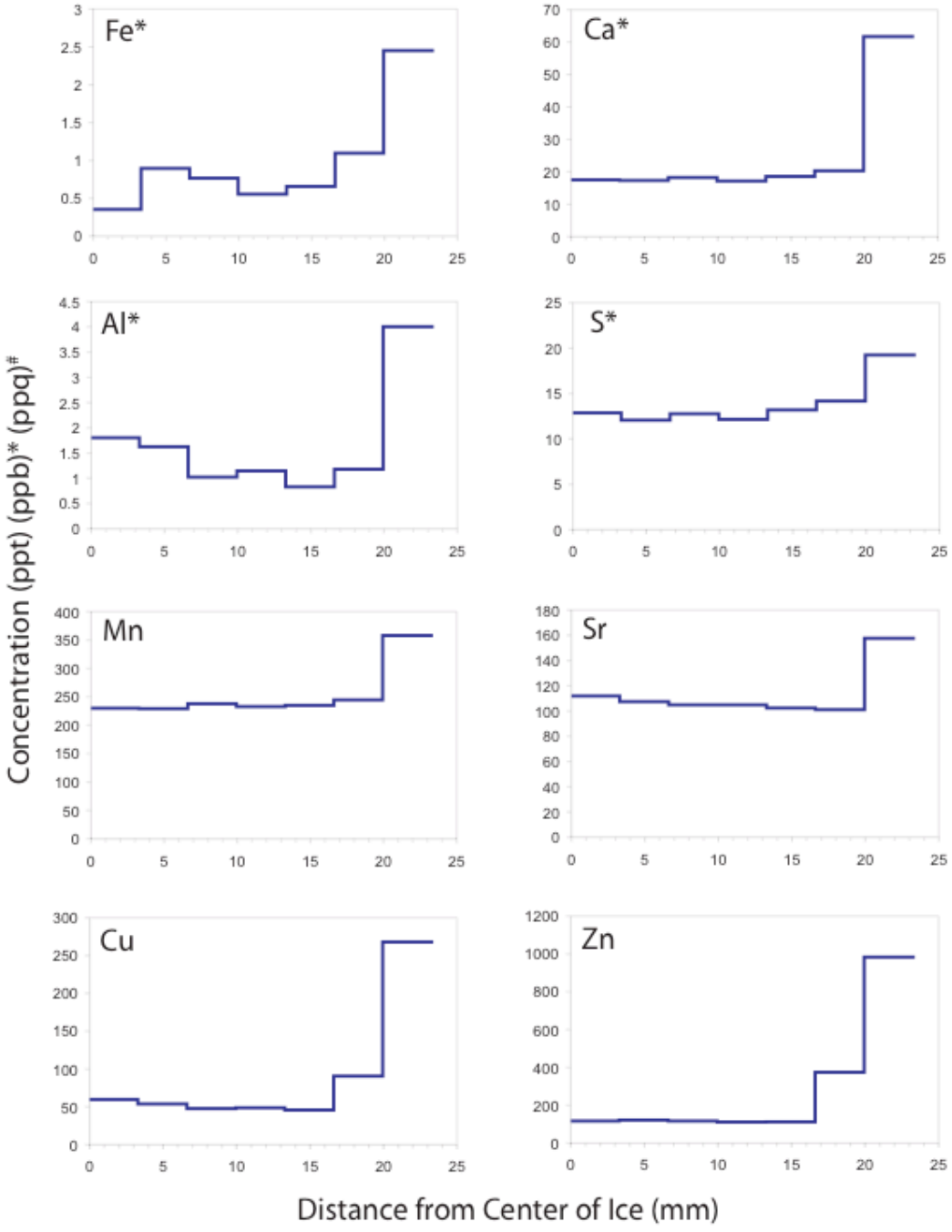
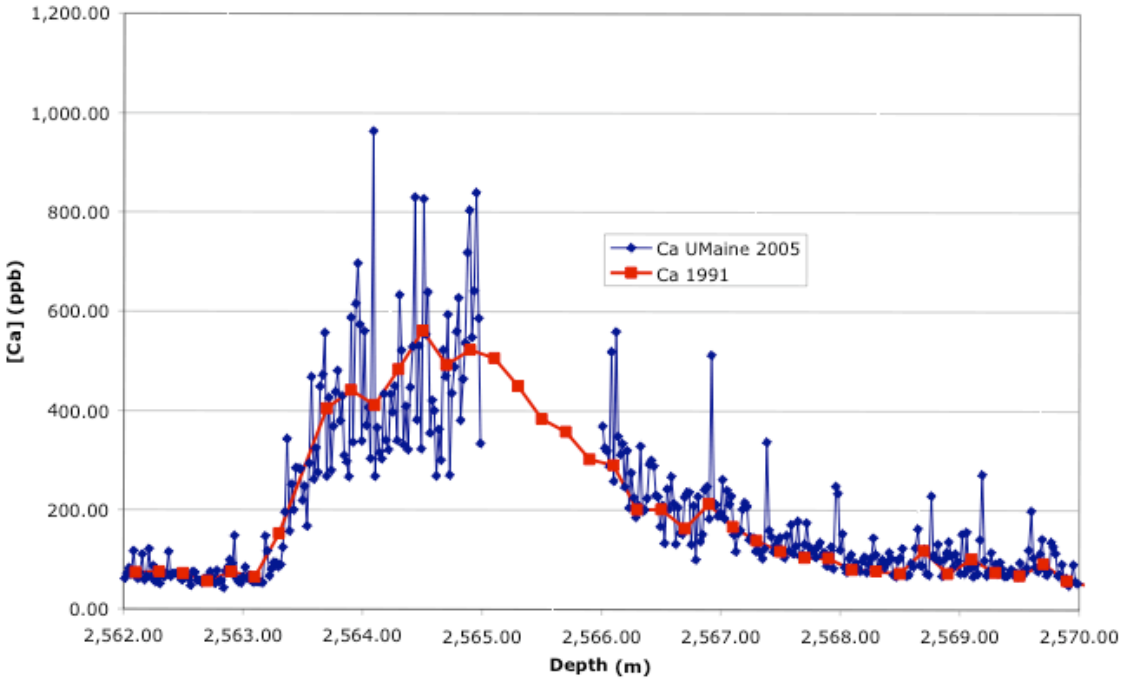


Figure 4. Comparison of original GISP2 IC data (20 cm/sample) to new high-resolution data collected on the UMaine melter system (2 cm/sample)



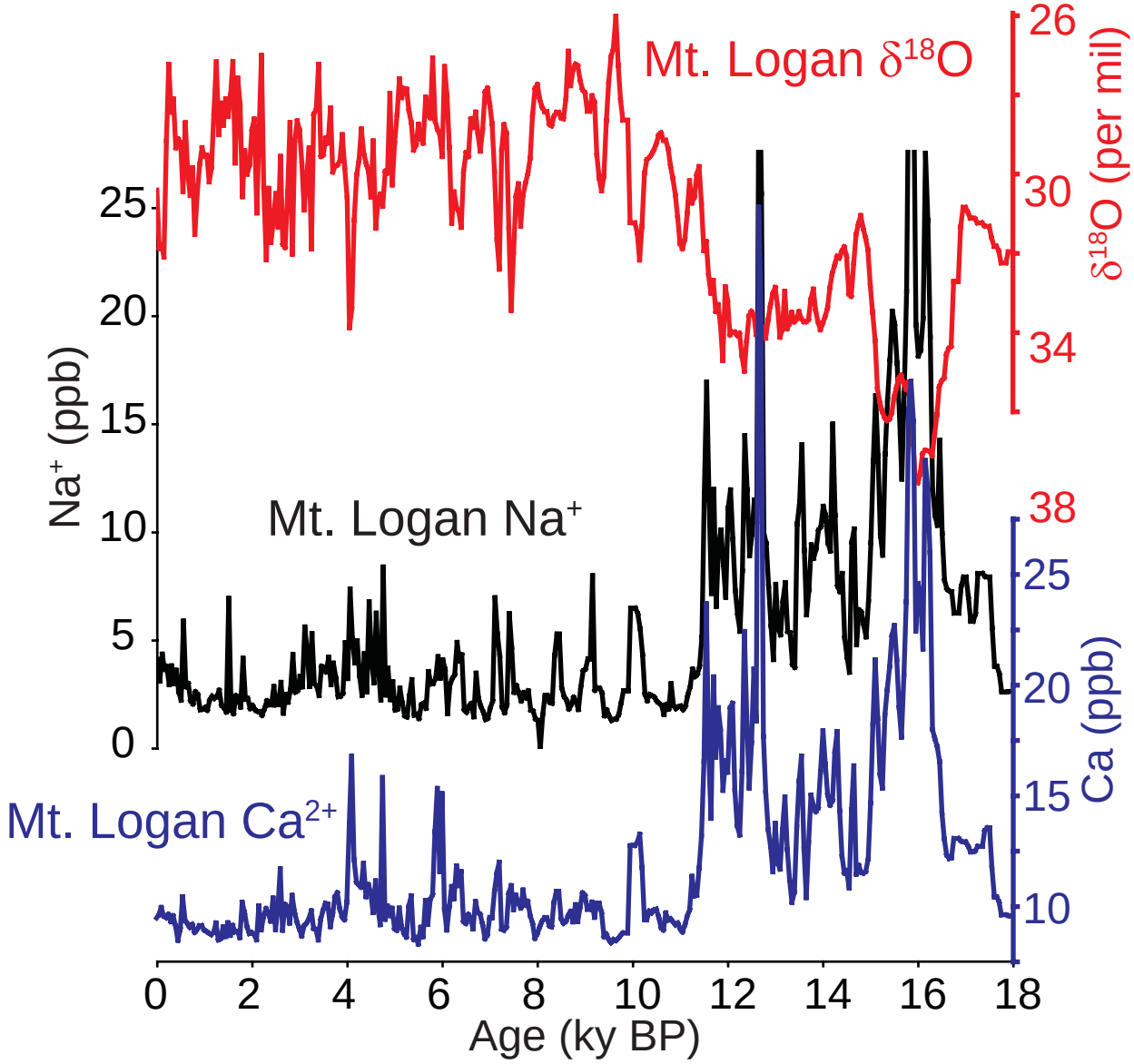


Figure 1. Mt. Logan PR Col stable isotope, calcium and sodium time series spanning the Holocene and deglacial periods, showing climate events associated with depleted oxygen isotopes and enriched aerosol concentrations.

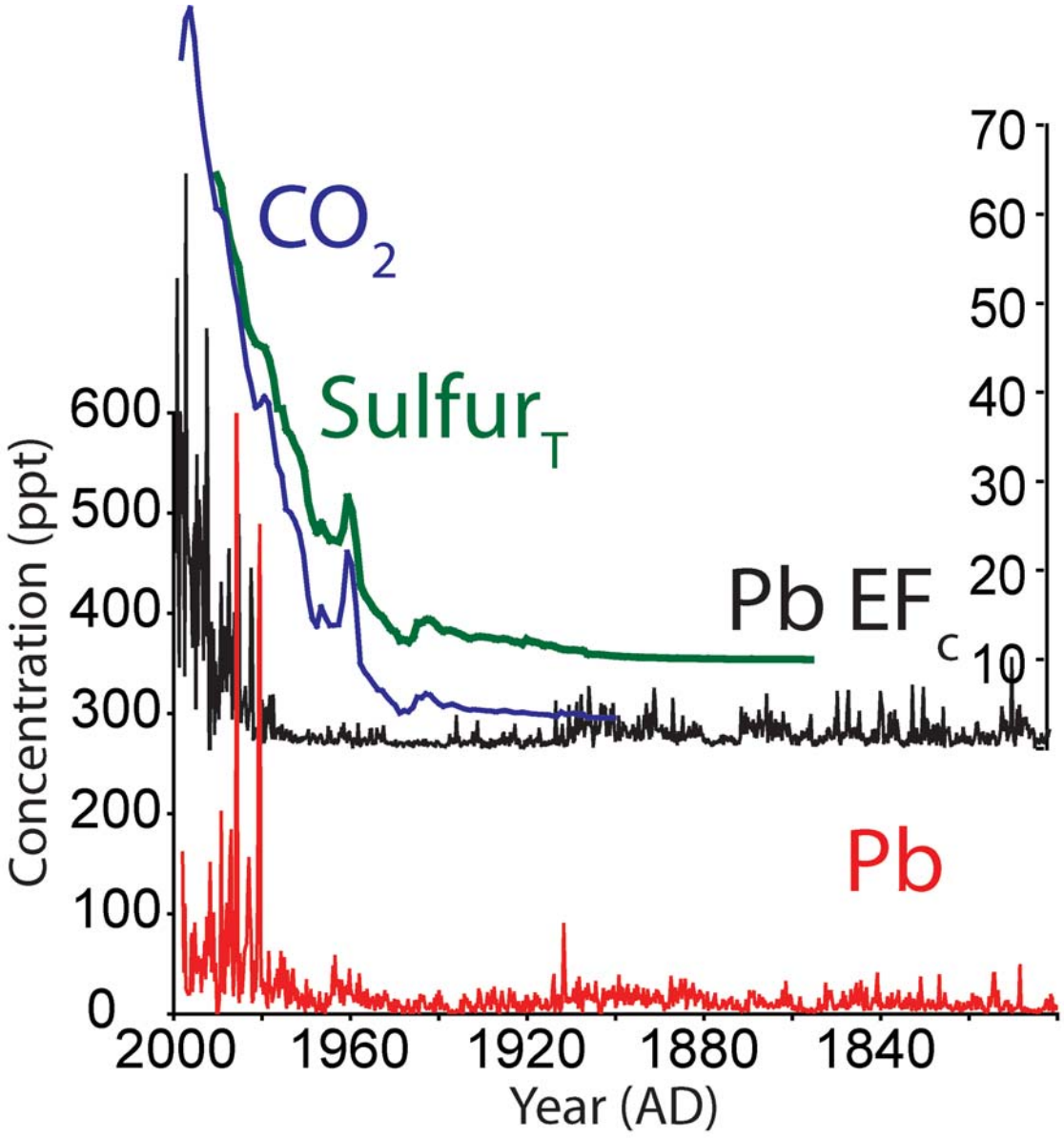


Figure 2. Lead concentration (red) and crustal enrichment factor (black) from the Mt. Logan PR Col core compared to Chinese anthropogenic sulfur and CO2 emissions since 1800. Note the similar timing of the Pb increase to the sulfur and CO2 increase, strongly implicating China as the source of the metal pollution.

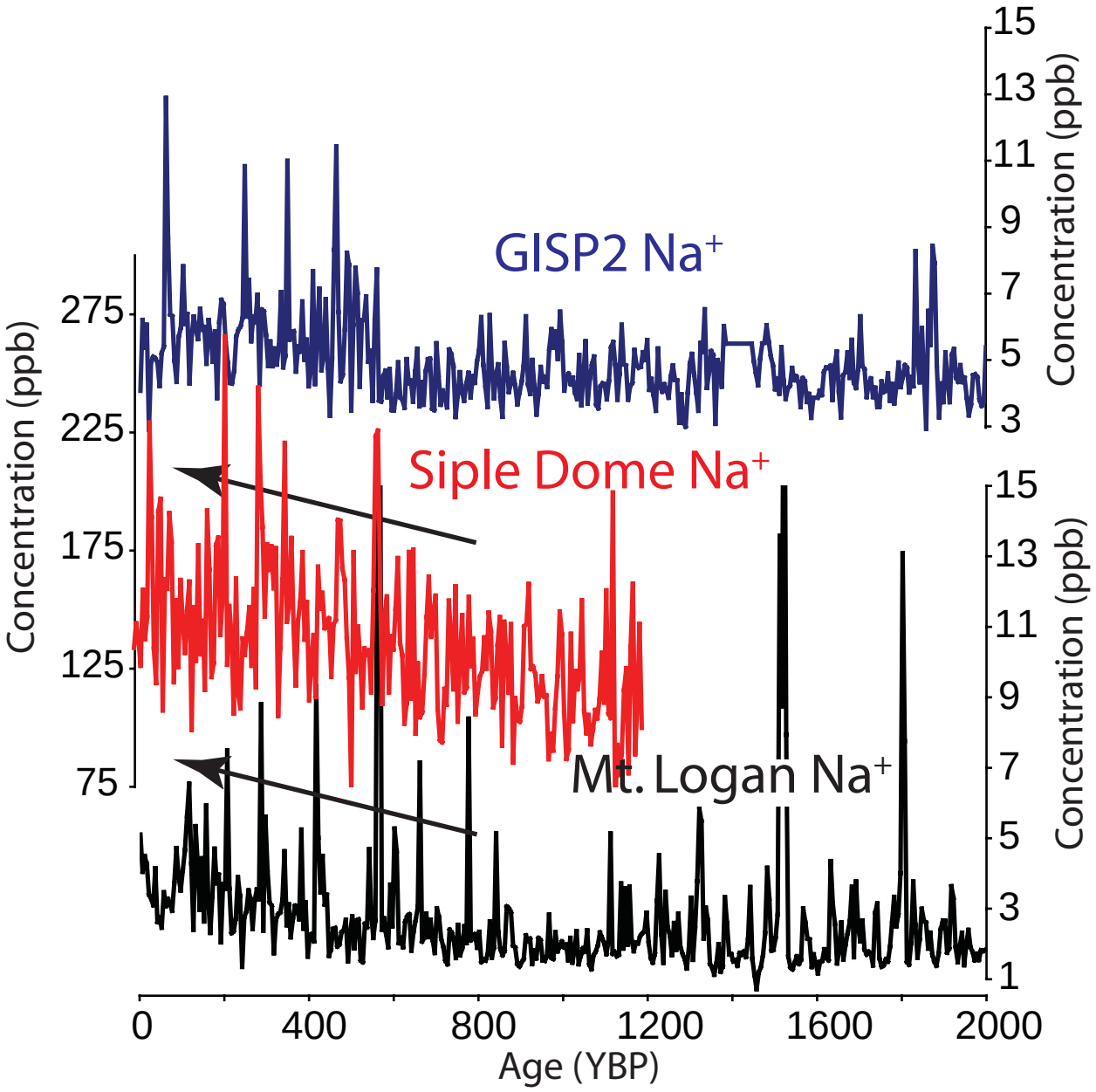


Figure 3. Sea salt aerosol (Na+) records from the GISP2, Siple Dome and Mt. Logan ice cores. The Mt. Logan and Siple Dome records show a steady intensification of atmospheric circulation beginning ~1200 AD, while GISP2 shows a sudden shift at ~1400 AD. These records suggest that there was a global intensification of circulation since the onset of the Little Ice Age, but that another factor (sea-ice?) modified and accentuates the signal at Greenland.

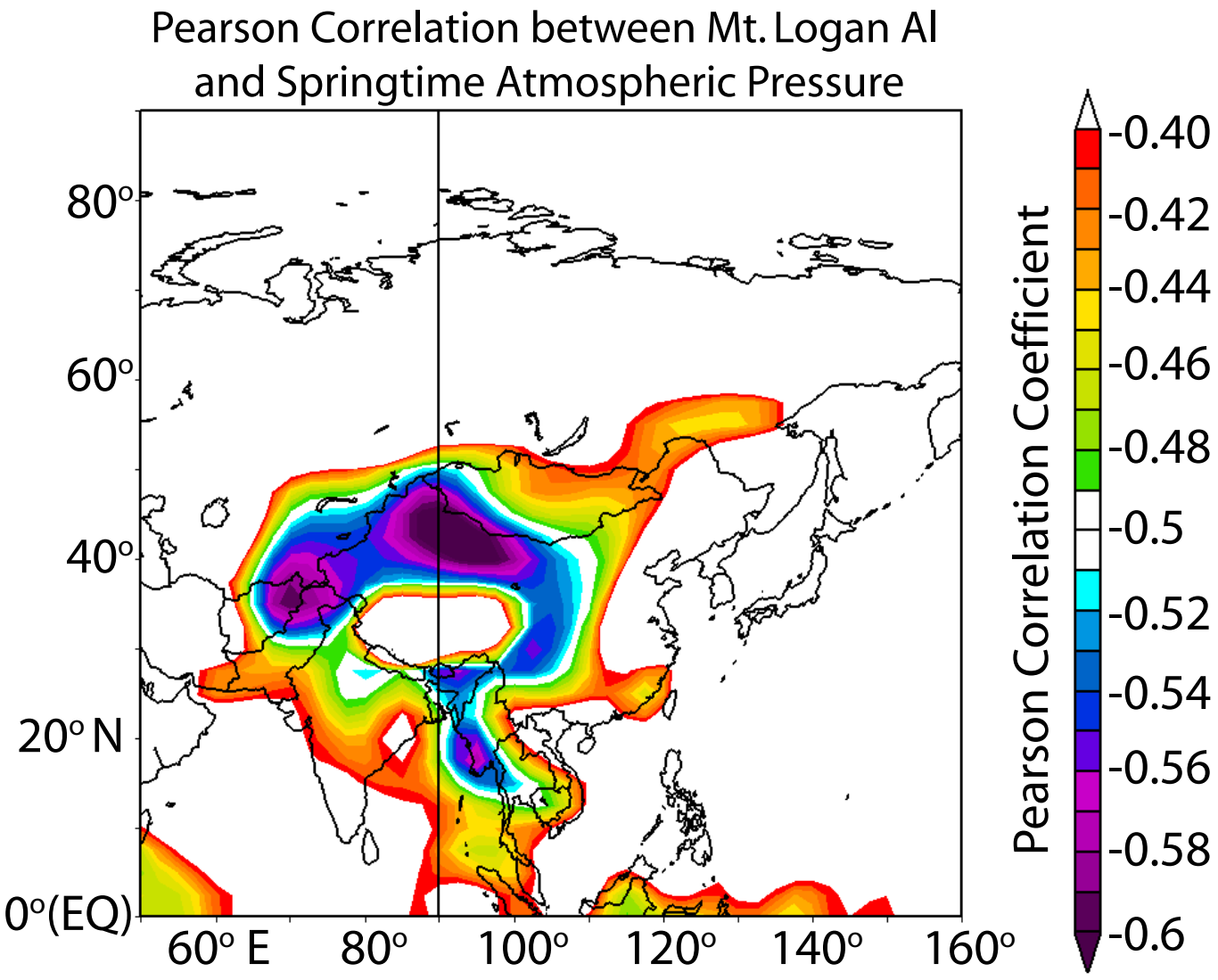


Figure 4. Pearson correlation coefficient between annual Mt. Logan Al concentration and springtime (April, May, June) atmospheric pressure in the NCEP/NCAR reanalysis model from 1948-1998. The strong negative correlation over the Gobi and Takla Makan deserts China and Mongolia suggest that stormier times are associated with enhanced dust transport to Mt. Logan. This correlation is the basis for the Mt. Logan proxy record of atmospheric pressure shown in Figure 5.

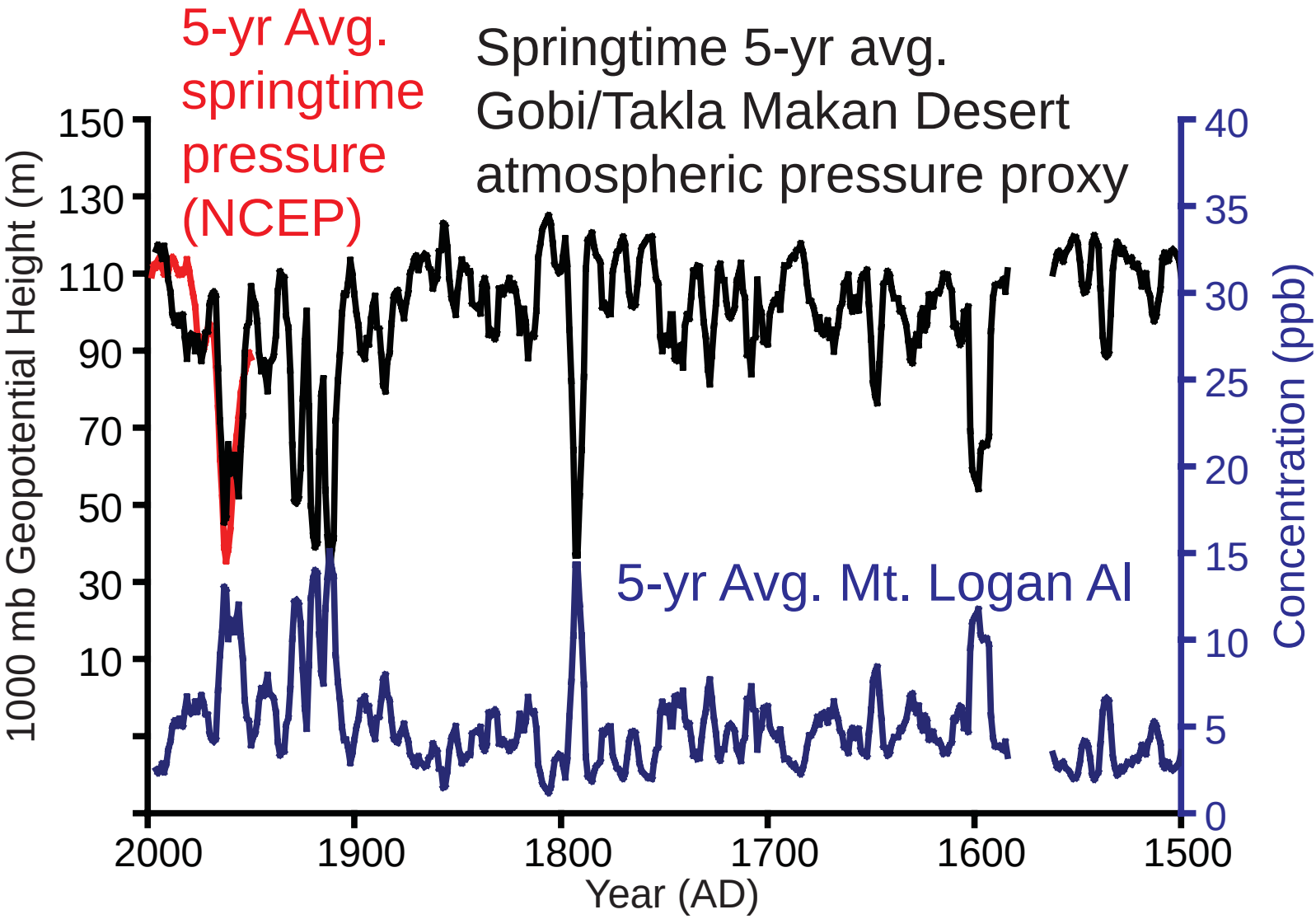


Figure 5. Mt. Logan proxy for atmospheric pressure (circulation intensity) over the Gobi and Takla Makan deserts in China and Mongolia, which are major dust soruce areas for the Northern Hemisphere. The proxy record was calibrated using NCEP/NCAR reanalysis pressure data centered over the desert areas for the months of April, May and June (springtime) each year. Spring is when Asian dust storms are most intese, capable of entraining large volumes of dust across the Pacific.