The Mount Logan (Yukon) ice cores: A time window into northwest Pacific climate variability

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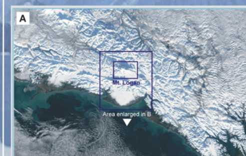
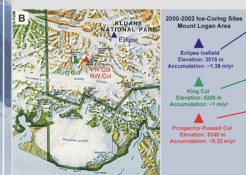
Introduction

In the summers of 2001 and 2002, scientists from the Geological Survey of Canada (GSC), Japan's National Institute for Polar Research (NIPR), the University of New Hampshire (UNH), and University of Maine (UMaine) recovered several ice cores on or near the Mount Logan massif (max. elevation 5959 m asl) in the St. Elias Mountain range of south-western Yukon (map **A**, below). The GSC recovered a 187 m core to bedrock from Prospector-Russell (PR) Col (5340 m) on the high plateau of Mt. Logan. A 220 m core was recovered by the NIPR team from King Col (4200 m) also on the Mt. Logan massif, while the UNH-UMaine team recovered a 345 m core from Eclipse Icefield (3015 m), some ~45 km from Mt. Logan (map **B**, below). The elevational transect covered by the three sites allows for an unprecedented look into climate change in the northwest Pacific region at different levels in the troposphere.





▲ (**A**) MODIS satellite image showing the Mount Logan massif and the surrounding region; (**B**) Location map of the three sites from which ice cores were drilled in 2001-2002. The modern snow accumulation for each site is indicated. Northwest Col (NW Col) = site of the 1980 coring effort (NHRI).

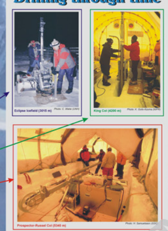
Vertical contrasts

Previous work on ice cores from the summit of Mt. Logan by G. Holdsworth and colleagues (Env. Canada NHRI Expedition, 1980) indicate that the PR Col core should provide a record of temperature, snow accumulation, atmospheric composition and circulation patterns in the free troposphere. A preliminary chronology for the core based on measurements of oxygen isotope ratios ($\delta^{18}O$, see text panels below) indicate that the climate record at this site covers the entire Holocene period (i.e., the last ~11,500 years), with an expected temporal resolution varying from annual (top of core) to centennial (bottom).

Glaciochemical records developed from a 160-m core recovered from Eclipse icefield in 1996 by C. Wake and colleagues (Univ. of New Hampshire) indicate that this site will provide a more detailed record of atmospheric pollution and volcanic eruptions (acidic fallouts), as well as closer connections with surface temperature and pressure records from regional weather stations. Because it was drilled from an area of high snow accumulation, but with a significant horizontal ice flow component, it is expected that the Eclipse icefield will deliver a shorter (< 5000-yr long), but higher-resolution climate record than the PR Col core. The King Col core, drilled at 4200 m, should provide a record of intermediate resolution but possibly shorter than the Eclipse icefield core.

Because the three coring sites span an elevation range of over 2000 m, they will provide a unique opportunity to investigate changes in the vertical structure of the atmosphere in relation to climatic changes over at least part of the Holocene period. Another surface-to-bedrock ice core was also drilled in 2002 from Mount Bona-Churchill in nearby Alaska by a team from the Byrd Polar Research Centre (Ohio State University).

Drilling through time



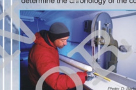
▲ Ice-core drilling operations during the Mount Logan international glaciological expedition. More than 900 m of cores were recovered from three sites, including three surface-to-bedrock cores at Prospector-Russel (PR) Col, King Col and on the Eclipse icefield.

The considerable differences in climatic conditions encountered in the Mount Logan massif are well emphasized by time series of daily air temperature measurements made by a series of automated weather stations deployed in or near the massif during the 2001-2002 drilling campaigns (▶). PR Col site is located in the" dry firn zone" where surface temperatures are below zero throghout the year. King Col experiences a limited amount of surface metling and percolation during the brief subarctic Yukon summer. There is considerably more melt occurring 1000 m below on the Eclipse icefield, but previous investigations suggest that this melt does not affect isotopic and glaciochemical signals in the ice in a significant manner.

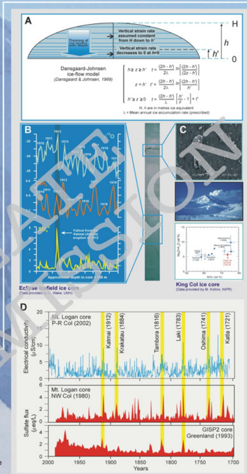
▼ Time series of air temperature (daily averages) recorded at three autostations deployed in the Mount Logan area during the 2001-2002 glaciological expedition.

Dating the Mt. Logan ice cores

The initial task facing us is to establish reliable chronologies for the Mount Logan suite of ice cores. This is an essential -and often time-consuming- step that must be taken before any definite climatic interpretation of the ice-core records can be formulated. Following the intensive 2001-2002 drilling campaigns, the Logan cores were sampled (below) and distributed between the various laboratories involved in Canada, the USA, Denmark and Japan. A combination of methods are being used to determine the chronology of the cores (see panel at right). These include theoretical (**A**) ice-flow modeling; (**B**) the use of (O/H) isotopic and glaciochemical variations in ice to identify annual layers; (**C**) the identification of volcanic ash layers that can be analyzed and matched to source eruptions of known age; and (**D**) cross-correlations with other, well-dated ice-core records from the Northern Hemisphere (e.g., the central Greenland deep ice cores GRIP and GISP2). A preliminary time scale for the PR Col core has been developed for the PR Col core, using $\delta^{18}O$ and electrical conductivity measurements (proxy for acidity). The initial interpretations discussed hereafter are founded on this preliminary chronology, and should therefore be considered speculative for the time being.



△ Sampling an ice core from Mt. Logan.

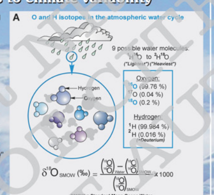


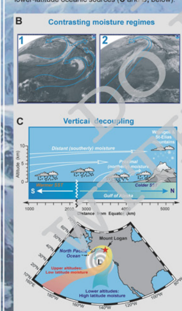
▲ A summary of various methods employed to establish the chronology of the Mt. Logan cores: (A) ice-flow modeling, (B) chemical stratigraphy, (C) identification of volcanic (tephra) time markers, and (D) correlation with other well-dated cores.

Isotopes in precipitation: Clues to climate variability

The ratio of stable O and H isotopes in precipitation is determined by several factors, including air temperature, distance from the oceanic moisture source, and conditions at the source (e.g., sea surface temperature (SST), rel. humidity, etc.). In polar regions, the ratio of oxygen isotopes in snow (expressed by $\delta^{18}O$ as departure from SMOW: see panel **A** at right) is largely controlled by the temperature at the time of precipitation. On Mount Logan however, we hypothesize that distance to the moisture source is the predominant factor affecting temporal variations of $\delta^{18}O$ in snow: The further away the source, the isotopically "lighter" the precipitation (more negative $\delta^{18}O$), and conversely.

The time series of $\delta^{18}O$ from the PR Col core suggests an alternance between two opposing regimes of moisture delivery to Mt. Logan (panel **B** below): Under regime **1**, moisture is drawn from the North Pacific Ocean, while under regime **2**, precipitation on Mount Logan can draw its source from as far as the equatorial Pacific Ocean. Furthermore there may exist a vertical "decoupling" between high and low elevations on Mt. Logan, such that low elevation sites (e.g., Eclipse) can be fed by local moisture while higher sites (e.g., PR Col) receive far-travelled moisture from lower-latitude oceanic sources (**C** and **D**, below).





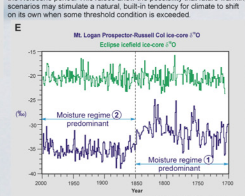
▲ (**B**) The proposed alternating regimes of moisture delivery to the Mt. Logan area as represented by two contrasting synoptic situations; (**C** and **D**) Conceptual diagram of the vertical "decoupling" between low and high elevation sites on Mt. Logan: Low elevations are fed by local moisture from the Gulf of Alaska, while higher elevations are fed by moisture from more distant, mid- to low-latitude sources.

▶ (**E**) Comparison between 300-yr time series of $\delta^{18}O$ measured in cores from PR Col (5340 m) and Eclipse icefield (3015 m), on or near Mt. Logan. The "regime shift" ca AD 1850 (see text) is evident in the PR Col $\delta^{18}O$ record, but is lacking from the Eclipse series, suggesting this lower elevation site is primarily fed from a "proximal", North Pacific moisture source and is unaffected by the changes affecting precipitation in the mid-troposphere.

Abrupt Climatic Shifts in the Holocene ?

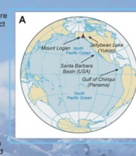
Preliminary examination of the PR Col $\delta^{18}O$ record reveals that the Holocene period was punctuated by abrupt "shifts", which are speculated to represent rapid changes between contrasting modes of large-scale atmospheric circulation affecting moisture delivery to the upper reaches of Mt. Logan (as shown in B). One such transition occurred ca AD 1850, which corresponds with the termination of the "Little Ice Age" cold interval (panel E, below). Remarkably, there is no sign of this 4 per mil shift in the $\delta^{18}O$ record from the Eclipse icefield core, drilled some 2000 below PR Col. This difference between the two records lends support to our hypothesis of an atmospheric "decoupling" between high and low elevation sites on Mt. Logan. PR Col receives moisture from distant, low-latitude oceanic sources and is therefore sensitive to changes in large-scale circulation that affect the mid-troposphere. The Eclipse icefield, on the other hand, is mostly fed from a relatively proximal North Pacific moisture source, and does not "see" the aforementionned large-scale changes. Data from the King Col core (4200 m high) will help verify these findings in the near future, and may allow to documnet changes in this atmospheric stratification over time.

The range of variability in the PR Col Holocene d O record far exceeds that in circumpolar ice cores (e.g., Greenland). It suggests that rapid shifts between contrasting, quasi-stable circulation / moisture regimes recur with century-scale frequency, and have been common throughout the Holocene period. This raises anew the possibility that future warming scenarios may stimulate a natural, built-in tendency for climate to shift on its own when some threshold condition is exceeded.



The Mount Logan ice-core record and Pacific climate teleconnections

If, as we postulate, our Mt. Logan PR Col $\delta^{18}O$ record is sensitive to changes in atmospheric moisture provenance (high vs low-latitudes), we should expect it to correlate with other moisture-sensitive proxy records from nearby (northerly) or distant (southerly) regions. To verify this, we compared the PR Col $\delta^{18}O$ record with various paleo-records that document changes in oceanic and atmospheric conditions at high and low latitudes in the eastern Pacific region during the Holocene (see location map in **A**▶).



On panel **B** (top right), the PR Col $\delta^{18}O$ record is correlated with a 2000-yr proxy record of meteoritic water $\delta^{18}O$ developed from a radiometrically-dated sediment core extracted from Jellybean Lake, in southwestern Yukon. The two records are in close agreement. The regime shift at AD 1850 is evident in both, as is an earlier shift ca AD 800, possibly related to the onset of the so-called Medieval Warm Period in Europe. The comparison suggests that the Yukon interior "sees" the moisture regime shifts documented in the Mt. Logan PR Col record, possibly because of the strongly contrasting $\delta^{18}O$ signatures in distant vs proximal precipitation feeding the Jellybean Lake catchment.

On panel **C** (middle right), we compare changes in deuterium excess (an isotopic indicator of water vapor provenance) in the PR Col ice core with a record of $\delta^{18}O$ variations measured in growth layers of a coral reef in the Gulf of Chiriqui, on the Pacific coast of Panama, in the inter-tropical convergence zone. Unlike other tropical coral reefs (e.g., Galapagos) where the $\delta^{18}O$ provides a proxy for sea surface temperatures, the $\delta^{18}O$ values in Chiriqui corals are more strongly affected by changes in the isotopic composition of the surface Ocean brought about by rainfall or evaporation (the "amount effect"). Higher rainfall in the gulf dilutes the surface Ocean with isotopically "lighter" waters, thereby shifting the $\delta^{18}O$ signature of coral growth layers toward lower (more negative) values. The opposite effect occurs with excessive evaporation. Thus, the Chiriqui record is primarily a proxy for the hydrological balance in the coastal (Pacific) region of Panama. Here again, we find a remarkably good agreement with the PR Col $\delta^{18}O$ record, with the AD 1850 regime shift clearly reflected in both records. This correlation reinforces our hypothesis that high elevations on Mt. Logan are fed by moisture originating from distant, low-latitude Pacific sources.

On panel **D** (bottom right) we compare the PR Col $\delta^{18}O$ record with changes in sea surface temperatures (SST) off the coast of California over the last 10,000 years, as reconstructed from surface-dwelling planktonic foraminifera (*G. Bulloides*) in a deep-sea core from the Santa Barbara basin. Note that the relationship between SSTs and $\delta^{18}O$ in foraminiferal shells is opposite to that between air temperature and $\delta^{18}O$ in precipitation, i.e. warmer SSTs are associated with "lighter" (more negative) $\delta^{18}O$ values in *G. Bulloides* shells. Again, the agreement with the PR Col record is remarkably good. The probable link between the PR Col and Santa Barbara basin records is to be found in the $\delta^{18}O$ composition of water vapor at the oceanic source: All other factors being equal, warmer SSTs (low foraminiferal $\delta^{18}O$) lead to a relative enrichment of light O and H isotopes in water vapor above the surface Ocean (i.e., lower $\delta^{18}O$ values).

Again one would point out the frequency, persistence, magnitude and suddenness of the $\delta^{18}O$ shifts throughout the Holocene period. The extreme shift (5 per mil) between 4000 and 5000 yr ago is noteworthy, as is an earlier shift ca 7500 yr ago. The Mt. Logan PR Col core is presently being re-sampled at the University of Maine at much higher resolution for further $\delta^{18}O$ and chemical analyses. This will allow us to further investigate the suddenness of the isotopic shifts observed in the preliminary record.

It appears from these comparisons that the Pacific region, as whole, is more climatically connected under moisture regime 2 periods. In an earlier conceptual framework, one would say that during colder periods in the Holocene, the Polar Front was located further south and thereby limited moisture sources feeding precipitation on Mt. Logan to the (relatively proximal) North Pacific waters (moisture regime 1 situation). The high resolution paleoceanographic records now being developed from sediment cores off coastal British Columbia (GSC Pacific, A. Dallimore) will be of extreme interest in relation to the Mt. Logan suite of ice cores. We anticipate that as new results emerge and are compared to our own, they will further illuminate the Holocene climate history of the northwest Pacific region.

For further reading....

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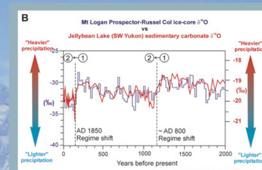

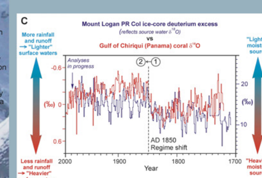

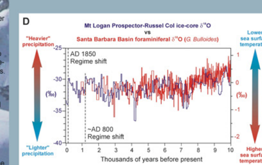

▲ Comparisons between the stable O isotope record of the Prospector-Russel (PR) Col ice core from Mount Logan, and various paleo-climatic proxy records (see map A for locations): (B) Jellybean Lake (SW Yukon), (C) Gulf of Chiriqui (Panama), and (D) Santa Barbara basin, western Pacific. Note the different time scales for each panel. Coloured arrows provide a first-order interpretation of the various proxies to facilitate comparisons. Data sources for records other than Mt. Logan are given on each panel. See main text for discussion.