1989

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G. Holdsworth

H. R. Krouse

M. Nosal

M. J. Spencer

Paul Andrew Mayewski
University of Maine, paul.mayewski@maine.edu

ANALYSIS OF A 290-YEAR NET ACCUMULATION TIME SERIES FROM MT. LOGAN, YUKON

G. HOLDSWORTH
National Hydrology Research Institute, Saskatoon, Saskatchewan, Canada S7N 3H5

H.R. KROUSE AND M. NOSAL
University of Calgary, Calgary, Alberta, Canada T2N 1N4

M.J. SPENCER AND P.A. MAYEWSKI
Glacier Research Group, University of New Hampshire
Durham, New Hampshire 03824, USA

ABSTRACT A 102.5-m mechanically continuous firn and ice core sequence retrieved from the Northwest Col of Mt. Logan (latitude 60°30'N; longitude 140°35'W; site location 5340 m a.s.l.) in the Yukon Territory, Canada, has been analyzed continuously for stable isotopes, pH and liquid electrolytic conductivity. Specific sections of the core have been analyzed for total β-activity (0–22 m) and trace ion concentrations (across major volcanic events) in order to date the core. In the lower half of the core, nitrate and some other ionic species are used to identify annual increments except between AD 1693 and AD 1720 and between AD 1729 and AD 1735 where only average annual increments are given. Annual increments were converted to water equivalents, then corrected for ice flow thinning as well as for origin, since a significant net accumulation gradient exists across the borehole site. The time series was subjected to cross correlation analysis, using instrumental data for the last 80 years, and to spectral analyses, using a 250-year sequence.

INTRODUCTION

In 1980 a 102.5-m core sequence was retrieved from the Northwest Col of Mt. Logan (altitude 5340 m a.s.l., mean annual temperature –28.9°C). Further details are given in Holdsworth & Peake (1985) and Holdsworth *et al.* (1988).

In 1986, the sequence was updated to 1985. The base of the core is believed to correspond to about AD 1690 and thus the full time span covered by the firn and ice is over 290 years. However, two sections of the lowest part of the core cannot yet be resolved into annual increments and thus only the last 250 years have been subjected to spectral analyses. The upper half of the core has been analyzed in more detail and dated with greater accuracy than has the lower half, although hemispherically significant volcanic events occur there with a high frequency (about once every 20 years on average) down to AD 1693.

A handicap in annual increment identification below a depth of about 50 m (referenced to 1980) is the disappearance of seasonal oscillations in $\delta^{18}O$ where the amplitude is low and/or where the annual layer is thin (less than about 0.25 m water equivalent). In most cases nitrate and sodium concentration variations can be used to resolve annual increments. Less than 13% of the core is not resolvable into annual increments using the present methods and thus only average accumulation values are given over the intervals involved (bracketed by identifiable volcanic events).

Only the net accumulation time series has been analyzed in some detail so far since this has more meaning hydrologically than temperature, which is a parameter that may be obtained from the $\delta^{18}0$ (or δ *D*) data. However, it has been found that the $\delta^{18}0$ time series will be difficult to analyze in terms of a pure temperature signal because other processes are acting to produce variations in $\delta^{18}0$.

METHODOLOGY

Stable isotope chemistry

The core was initially cut at 10-cm intervals, decreasing to 2-cm intervals at the lower end, to ensure that, on average, about eight samples per annual layer were obtained. Analyses of oxygen isotopes were carried out on all samples in accordance with standard procedures (Dansgaard *et al.*, 1973). Figure 1 shows the $\delta^{18}0$ sequence plotted alongside a linear depth scale and a nonlinear time scale, which has been constructed using $\delta^{18}0$, β-activity and ion chemistry data. This sequence may easily be converted to a time series.

Radioactivity measurements

Total β-activity was measured from the surface to a core depth of 22 m (Holdsworth *et al.*, 1984). By comparing the firn core β-activity with the measured air and precip-

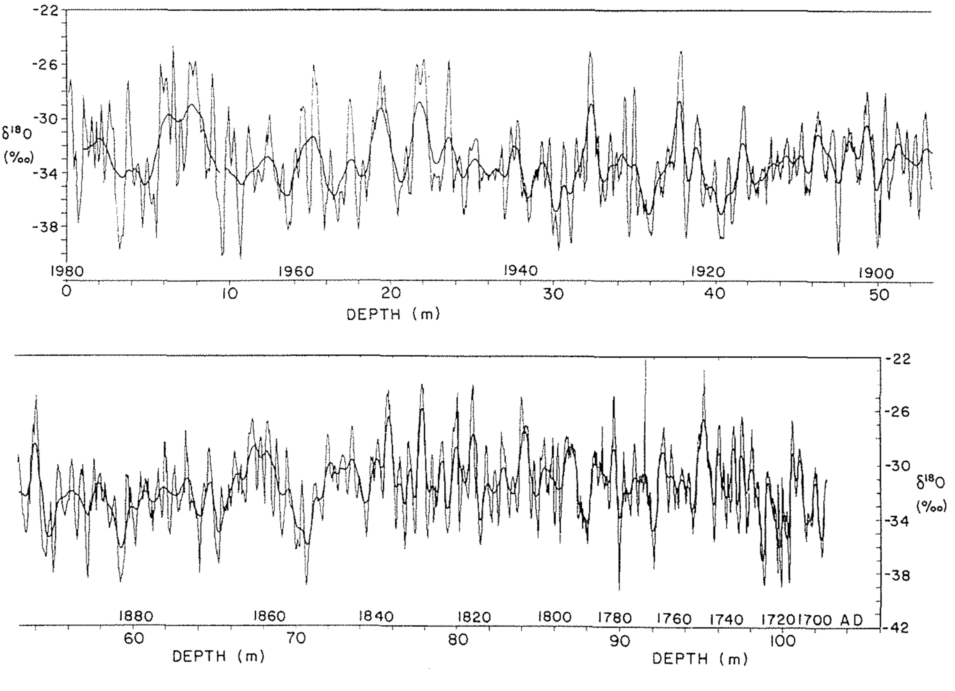

FIG. 1 $\delta^{18}0$ (‰) vs depth in the core. Nonlinear time scale is marked above the depth scale.

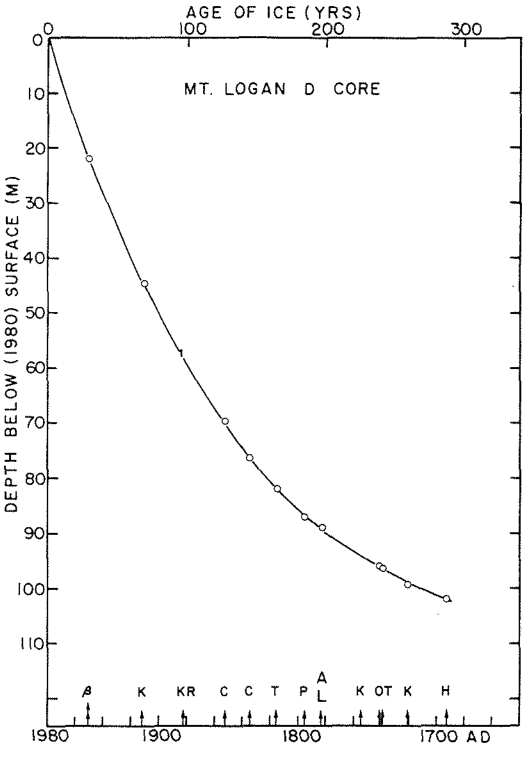

FIG. 2 Depth vs time scale plot for the Mt. Logan core. Volcanic events identified through the chemical signatures are marked by vertical arrows. The double arrow marks the end of the β-activity dating.

itation β-activity from the Yukon and Alaska, it was possible to date the core back to 1951, with an accuracy of about ± 0.25 year.

Ion chemistry

Following pH and conductivity measurements made on all samples, sequences through high conductivity and low pH points were analyzed for nitrate, sulfate and chloride concentrations to establish the presence of volcanic signals (Hammer, 1977). The expected positions of major volcanic signatures were approximately known by use of purely mechanical depth–time models. The gross depth–time scale is shown in Fig. 2.

Time plane tilt in the core

Thin glaze crusts, evidently corresponding to the wind/sun crusts developed on the distal faces of sastrugi, occur throughout the core. The tilt increases progressively from about 2° at the surface to about 32° at the base (102 m). The progressive tilt can be ascribed to ice flow dynamics being influenced by an asymmetrical bedrock profile and a displacement between topographic divide and the flow divide (Fig. 3). The tilt of the isochrons must be taken into account when computing the (net) accumulation values.

Firn and ice density

Determination of the depth-density profile was carried out over the entire core sequence by using weight and volumetric measurements made on selected segments of the core. Values of density carry an average error of ± 3 kg m^{-3}. The depth–

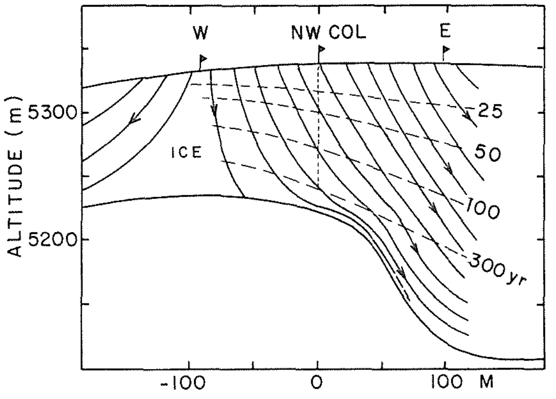

FIG. 3 Vertical cross section through the Northwest Col showing flow lines and time lines. Borehole is at central flag (Northwest Col).

density plot contains information that may be related to climate (Gow, 1968) and thus there is a check on its integrity. For example, during the AD 1925–1945 time interval there is a marked positive departure of density values from the smoothed curve or from a theoretical best fit (Ling *et al.*, 1987). This anomaly is explained both by the occurrence of higher temperatures in this interval and lower precipitation (deduced from this core). Such information disappears at the firn–ice transition, which occurs at about 65 m depth (density 825 ± 5 kg m^{-3}).

DATA REDUCTION

Computation of water equivalent

Once individual annual increments, $a_n(z)$, were defined using the isotopic and chemical indicators, the water equivalent of the layer was determined by multiplying these values by the corresponding density, $\rho_n(z)$, at depth z below the 1980 surface:

$$b_n(z) = a_n(z).\rho_n(z) \qquad (n = 1,2...) \quad (z \leq 65 \text{ m}) \tag{1}$$

where b_n is a water equivalent *net* accumulation value.

Correction for tilt of isochrons

The layer tilt, $\alpha_n(z)$, is a nonlinear function of depth (z). Values were taken from a smoothed curve fitted to the data and a corrected b_n value, b'_n, computed from:

$$b'_n(z) = b_n(z) \cdot \cos\alpha_n(z). \tag{2}$$

Correction for creep thinning of layers

The assumption is made that down to the firn–ice transition, densification is not yet influenced by long-term ice creep. At the firn–ice transition, grain compaction has become insignificant and crystal fabric is developing. Creep processes are beginning to become significant, because the base of the core is within 17 ±10 m of bedrock and the shear stresses at the base of the core are no longer small.

The vertical strain rate $\dot{\varepsilon}_z(z)$ was computed numerically from the time–depth curve. Because the derived $\dot{\varepsilon}_z(z)$ variation is consistent with recent numerical simulations of model glaciers, it is considered reliable. Furthermore, this is in itself a check on the integrity of the original time scale. If the annual layer thickness at the firn–ice transition is denoted by $a_n(0^*)$ and the annual layer thickness at z^* below the firn–ice transition by $a_n(z^*)$ then it can be shown (e.g., Holdsworth, 1984) that

$$a_n(0^*)/a_n(z^*) = [\exp\{\int_0^t \dot{\varepsilon}_z(z^*)\,dt\}]^{-1} \qquad (65 < z^* < 102 \text{ m}) \tag{3}$$

where t is time. Thus, a correction is applied with dimensionless values lying between 1.00 and 5.00. Next, the water equivalent value b'_n below the firn–ice transition is obtained from:

$$b'_n = a_n(0^*) \cdot \rho(0^*)$$

where $\rho(0^*)$ is the density at the firn–ice transition (825 kg m^{-3} ± 5 kg m^{-3}).

Correction for source of ice

As Fig. 3 shows, firn and ice occurring in the core have an origin that varies with depth. The flow line geometry is based on a two-dimensional finite element flow simulation that uses surface deformation data as input. The surface net accumulation gradient is known; therefore, a correction factor $C(z)$ was computed. Take $a_n(0)$ as the surface net accumulation rate at the top of the borehole. Take $a_n(x^*,0)$ as the value at distance x^* from the top of the borehole, and measured to the left of it. Then, at the point $(0,z)$ where the flow line starting at $(x^*,0)$ intersects the borehole

$$C(z) = a_n(0)/a_n(x^*,0). \tag{4}$$

Because $a_n(x^*,0) < a_n(0)$, $C(z) > 1$ (maximum 1.176).

The $C(z)$ profile was established for the core and the final corrected $b''_n(z)$ value obtained from

$$b''_n = b'_n(z) \cdot C(z). \tag{5}$$

Because we have established a relationship between depth (z) and time (t), it is then possible to derive the time series $b''_n(t)$. Figure 4 shows the final corrected time series.

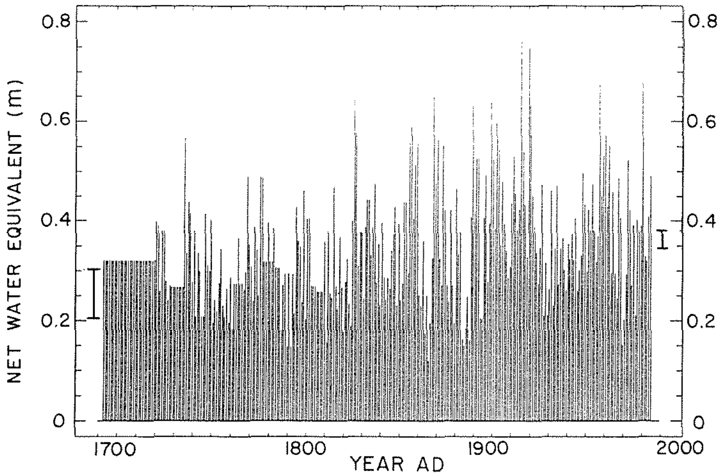

FIG. 4 Mt. Logan net accumulation time series (metres water equivalent): AD 1693–1985.

Data precision

The error on individual $b''_n(z)$ values is variable as a result of the different techniques that are used to delineate annual increments, $a_n(z)$, and as a result of the depth dependent corrections that are subsequently applied to the data. The estimated error on the mean b''_n (0.350 m) is ± 0.03 m. The standard deviation of the 250-year series is 0.12 m.

TIME SERIES ANALYSIS

A knowledge of the integrity of the "proxy" net Accumulation Time Series (ATS) is of crucial importance if it is to be used for hydrological purposes, such as reconstructing stream flows in order to extend such time series (Jones, 1984).

Correlation of ATS with instrumental data

A discovery that will be elaborated on in a separate paper is that the Mt. Logan ATS cross-correlates positively with a number of remote regionally averaged ATS values. These include the Steppes of the Soviet Union (cross-correlation coefficient $r = 0.3$), in which the ATS is for November to March precipitation (1891–1960) (Budyko, 1977). This latter series also has a significant cross-correlation with the total annual precipitation for the same region over the same time span. Other regions that cross-correlate with the Mt. Logan ATS are Japan (1889–1965) ($r = 0.5$), northern Scandinavia ($r = 0.3$) and certain parts of northwestern Canada ($r = 0.3$), but for shorter time series. These r values are significant at the 95% level and may be increased by further smoothing of the data.

These long range cross-correlations of the ATS are classed as teleconnections, and they suggested not only that the last 80 years of the Mt. Logan data are reliable but that the site (at the 50-kPa level) is uniquely situated for teleconnection studies. The results also suggest that the Mt. Logan net ATS is nearly linearly related to the total precipitation at the site.

Power spectral analyses

The ATS for Mt. Logan has been subjected to power spectral analysis by the Fourier Transform and the Fast Fourier Transform (FFT) methods (Bloomfield, 1976). In the future, the ATS will be subjected to additional spectral analyses by other methods. For the series AD 1736–1985, Fig. 5 shows one power spectrum in which prominent peaks occur at 3.8, 10.9 ± 0.5 and 21 ± 2 years.

The main series was then partitioned into two subseries: (a) AD 1736–1860 and (b) AD 1860–1985. By use of the same band width of the spectral window as before, the spectrum of the first subseries (a) yields prominent peaks at 3.8 and 10.9 ± 0.5 years. Other peaks correspond to about 15.5 and 36 years, the former also occurring on the spectrum of the main series. The second subseries spectrum has peaks at 3.8, 11 ± 0.5 and ~21 years, approximately those of the main time series. Without the correction given by equation 4, the FFT spectral analysis of the main series yielded peaks at 3.8, 10.9 ± 0.3, 15 ± 1, 22.2 ± 2 and 54 ± 8 years.

Comparison of results with other analyses

In an analysis of the 504 year Beijing ATS, Hameed *et al.* (1983) found, using the FFT method, prominent frequency peaks that corresponded to periods of 3.7 ± 0.2,

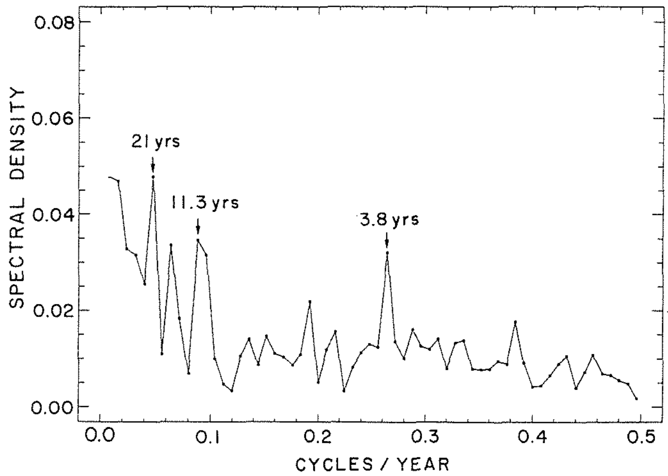

FIG. 5 Fourier transform power spectrum of Mt. Logan net accumulation time series from AD 1736–1985. Physically significant spectral peaks are marked.

9.9 ± 0.1, 18.7 and about 56 years, within the frequency span of our interest. The statistical significance of these peaks was not given, although they were all far above the white noise level. Clegg & Wigley (1984) pointed out the limitations of the above study by analyzing a larger number of records and by specifying the statistical significance of the results, which are favorable to the present ones.

First, the AD 1725–1979 Beijing power spectrum shows a statistically significant peak at 3.7 ± 0.1 years (but no others in the span of interest), restricted here to periods less than 60 years. Spectra for other stations near Beijing yielded fairly consistent peaks at from 3.5–3.8, and 10.3 ± 0.9 years. Other spectral peaks occurred at 20, 26, 27, 31, 37 years, but they were not spatially coherent. Currie (1984), using maximum entropy spectral analysis on western North American precipitation time series, found evidence of the 11-year cycle as well as the 18.6-year periodic component. This latter component may be responsible for some of the power represented by the ~15 and the 21 ± 2 year peaks seen in the Mt. Logan spectra for 1860–1985 and 1736–1985, although the latter peaks, also found by Hameed & Wyant (1982), may be induced by other mechanisms.

There are many other studies that support (and refute) the present results but in the search for cyclic components in the time series, it is certainly necessary to consider the suitability of the analytical technique employed (Bell, 1986; Ramachandra Rao & Durgunoglu, 1987; Chave *et al.*, 1987).

CONCLUSIONS

This preliminary analysis of the Mt. Logan net accumulation time series shows, firstly, that there is significant coherence between the last one-third of the series and instrumental precipitation time series for other specific regions of the northern hemisphere. This result is meaningful, provided the phenomenon of teleconnections is accepted. Secondly, spectral analyses indicate the presence of three main frequencies in the series that correspond to periods of about 3.8 years, about 11 years and about 21 years. Two of these periods may be associated with physical phenomena, viz: ENSO events (van Loon & Madden, 1981; van Loon & Rogers, 1981) and the sunspot cycle (Currie, 1984; Currie & Fairbridge, 1985). The third is not immediately resolvable on the basis of these results, and current knowledge. These collective results suggest that the precipitation on Mt. Logan is modulated in part by physical processes that also influence precipitation elsewhere in the northern hemisphere.

ACKNOWLEDGEMENTS We thank S. Fogarasi, B. McCarthy and R.S. Bradley for performing many cross-correlation analyses; D. Stolle for the results of a finite element simulation of the ice flow at the core site; and the Executive Director and staff of the Arctic Institute of North America, the University of Calgary, for providing facilities and for project support in the field. Many chemical analyses were carried out at the Water Quality Laboratory (Environment Canada), the Kananaskis Centre for Environmental Research (University of Calgary) and Monenco Analytical Laboratories (Calgary). The manuscript was express typed by Ruth Ast, Arctic Institute of North America.

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