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Decadal-centenary glacier mass changes and their variability, Jasper National Park of Canada, Alberta, including the Columbia Icefield region

M.N. Demuth and G. Horne

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Summary

Geological Survey of Canada Open File 8229 presents an analysis of recently documented glacier volume and longitudinal profile changes to illustrate the decadal-centenary variability of mass change for a broad sample of study glaciers in Jasper National Park including those in the Columbia Icefield region. The results generally reflect large-scale regional glacier mass balance variability observed since the mid-20th century though, notably, the study glaciers are undergoing negative annual mass changes at a rate equal to or greater than thrice that of their long-term annualized centenary value (i.e., since c. 1841). While the general pattern of glacier mass loss since the mid-20th century appears to be influenced, in part, by shifts in the regime of the Pacific North American circulation pattern, it is noted that for the study glaciers and for other glaciers in southwestern Canada, the northwest Pacific and globally, mass change values over the last several decades and into early 21st century are exhibiting higher variability including several instances of record mass gains.

This is an important result because glacier fluctuations and climate change are nearly always discussed by non-specialists in terms of the archetypal *less glacier mass = warmer climate*; and while this paradigm is true at the scale of climate cycles, Ice Ages and the glacial and interglacial periods within them, a more variable state of glacier nourishment, wastage and melt under the influences of a more variable, non-stationary climate system - a finger print of human-induced climate change - within the response times of typical mountain glaciers (order 1-100 a), will have implications on assessing their role on the functioning and health of related ecosystems.

Under fiscal pressures, many monitoring-based scientific efforts are being asked to reduce their measurement networks both spatially and even temporally. Under climatic conditions that manifest increasing variability in the functioning of related systems at multiple scales, it is prudent to do quite the opposite by building observing partnerships and thereby increasing observing system density and measurement frequency. Such an effort can be fortified, in part, by developing novel approaches to observing and interpretation as detailed herein.

Geological Survey of Canada *Water for Life 2010-2015* base camp on the Columbia Icefield plateau. The view is c. southeast towards Mount Castleguard (centre) and a portion of the Mount Alexandra massif (far right). The pyramidal bulk of Mount Forbes is in the distance. Selena Raven Cordeau photograph, 2011-April-29.

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INTRODUCTION

Changes in the mass of glaciers in many of Canada's Arctic and alpine regions play a significant role in regional and global sea-level change (f.ex., UNEP/WGMS, 2010; Van Wychen et al., 2014; Zemp et al., 2015) and modulate mountain runoff that impacts natural and human system functioning (f.ex., for Canada's western Cordillera, see Moore and Demuth, 2001; Demuth et al., 2008; Comeau et al., 2009; Moore et al., 2009; Marshall et al., 2013). Employing its Reference Glacier-Climate Observing System (Appendix A), the Geological Survey of Canada (GSC) issues data reports and research on the state of Canada's glaciers. These efforts, in part, contribute to Canada's international commitments towards the goals of the United Nations Framework Convention on Climate Change.

As it concerns protected areas generally and Canada's system of National Parks and Reserves specifically, medium to long-term (10-100 year) change in the glacier cover configuration has landscape, public safety, visitor experience and ecological significance. Such changes will modify the thermal and hydraulic properties of streams and rivers derived from glacier melt and wastage which, in turn, exert a significant regulation of water quality for highly adapted biota, as well as influencing stream morphometry and related habitats (Petts et al., 2006). Further, glaciers are significant to the distribution of grazing and predator species; their presence generating strong katabatic wind flow which helps to reduce insect harassment of ungulate populations. Glaciers that flow over significant topographic barriers may also provide travel corridors for wildlife and humans between valleys that are preferentially sought out during seasonal fluctuations in the weather (f. ex., Demuth et al., 2014).

A key measure of glacier health is its annual "mass balance". Records documenting the inter-annual mass balance of glaciers in Jasper National Park are, to date, still relatively short. As these inter-annual data series continue to be developed through cooperative work between JNP and the GSC, decadal-centenary perspectives from companion earth observation, in-situ measurements and modelling can provide important temporal context with which to examine variability. Using recently documented glacier volume and longitudinal profile changes, this report details the decadal-centenary variability of mass change for selected glaciers in Jasper National Park including those in the Columbia Icefield region.

1. Definitions - Quantifying Glacier Fluctuations

The fluctuation of a glacier under the influence of climate (precipitation, air temperature, solar radiation and cloud cover) can be described using various measures and metrics associated with its geometry (length, area and thickness), flow, surface facies expressions/glaciological zones, and mass change (*Figure* 1).

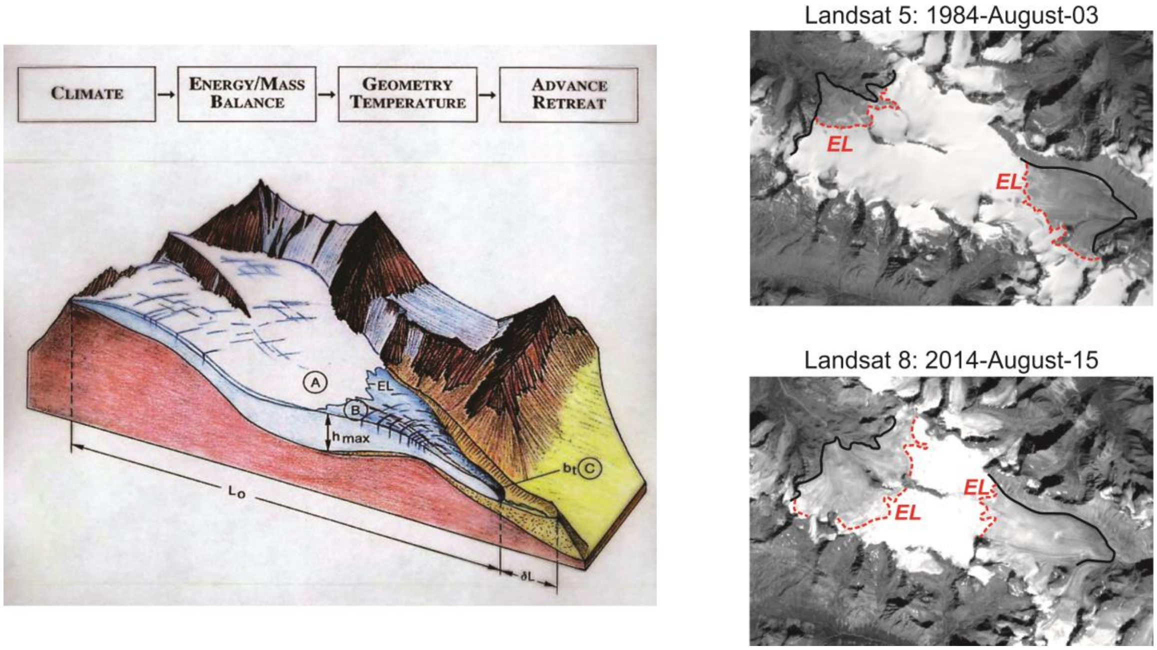

*FIGURE 1 A TYPICAL ALPINE GLACIER FEATURES NET ACCUMULATION AND NET ABLATION ZONES DIFFERENTIATED BY AN EQUILIBRIUM LINE (**EL**). ABOVE THE EL LAY THE SNOW AND FIRN FACIES OF THE ACCUMULATION AREA Ⓐ; BELOW IT THE ICE FACIES OF THE ABLATION AREA Ⓑ. LATE-SUMMER LANDSAT IMAGES OF THE BRINTNELL-BOLOGNA ICEFIELD IN NAHANNI NATIONAL PARK RESERVE ILLUSTRATE CONTRASTING FACIES CONFIGURATIONS AND ACCUMULATION AREA SIZES (DEMUTH AND EDNIE, 2016).*

1.1 Geodetic Mass Change

Changes in a glacier's mass[1] is the net result of mass being added and taken away by the processes of accumulation and ablation respectively. Accumulation can result from precipitation, condensation, drift snow or avalanching; while ablation results from melt,

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[1] Mass change is the relevant quantity when assessing glacier fluctuations in a water resources or sea-level change context.

sublimation, or avalanching (commonly ice calving from the glacier margins). In regions where these processes are primarily driven by climatic factors such as air temperature, precipitation, solar radiation and cloud cover, the measurement of mass change provides a high-confidence, integrated indicator of the climate.

There are several methods and conventions for estimating the mass change of a glacier. Three dominant methods are employed: i) traditional, *glaciological*, *direct*; ii) geodetic*,* *cartographic*, *topographic*; and iii) mass flux divergence (refer to Cogley et al., 2011 and Demuth and Ednie, 2016). The geodetic method is briefly reviewed next.

Glacier mass ($\boldsymbol{M}$) change over time ($\boldsymbol{t}$) can be written as:

$$\frac{\partial \boldsymbol{M}}{\partial \boldsymbol{t}} = \frac{\partial (\boldsymbol{\rho V})}{\partial \boldsymbol{t}}$$

(EQN. 1)

where $\boldsymbol{\rho}$ is the density and $\boldsymbol{V}$ is the volume. Integrated with respect to time, *equation* 1 becomes simply:

$$\Delta \boldsymbol{M} = \Delta \boldsymbol{\rho V} + \Delta \boldsymbol{V \rho}$$

(EQN. 2)

where $\boldsymbol{\rho}$ is the bulk density of the glacier including its firn area, and $\boldsymbol{\Delta\rho}$ is the change in the average density over the time interval being considered.

After Huss (2013), *equation* 2 can be rewritten as:

$$\Delta \boldsymbol{M} = \left[\frac{\Delta \boldsymbol{\rho V}}{\Delta \boldsymbol{V}} + \boldsymbol{\rho}\right] \Delta \boldsymbol{V}$$

(EQN. 3)

From a practical point-of-view, when two digital elevation models of a glacier are available for the beginning and end of a time period (typically 5-10 years) and compared (or “differenced”; see *Figure* 2), the observed volume change can be converted to a mass change using a lumped conversion factor $\boldsymbol{F}$ which accounts for density variations over the glacier surface:

$$\Delta \boldsymbol{M} = \boldsymbol{F}\, \Delta \boldsymbol{V}$$

(EQN. 4)

$\boldsymbol{F}$ essentially lumps together $\boldsymbol{\Delta\rho}$, $\boldsymbol{\rho}$ and $\boldsymbol{V}$ in *equation* 3 - variables that are extremely difficult to quantify individually (see Huss, 2013 and references therein).

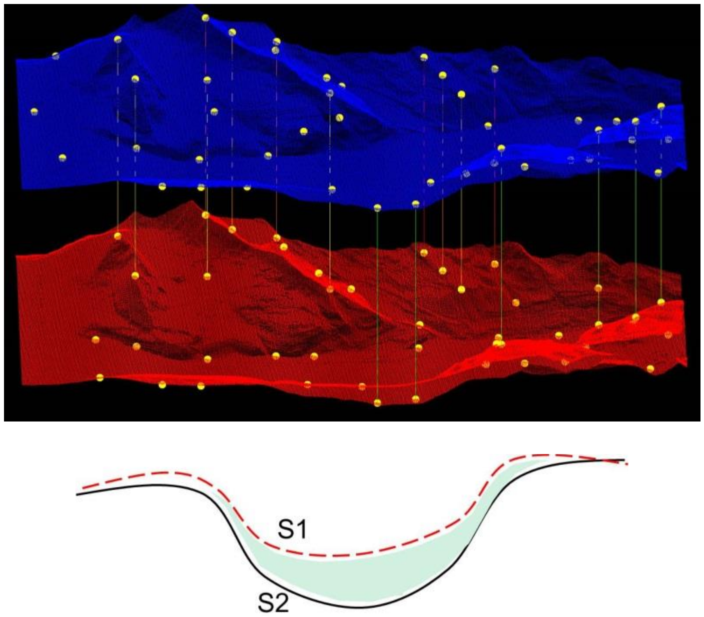


FIGURE 2 VOLUMETRIC CHANGE FROM THE RIGID ALIGNMENT OF TWO 3-DIMENSIONAL SURFACES OR DIGITAL ELEVATION MODELS.

The conversion factor $\boldsymbol{F}$, however, is not simple, nor is it necessarily constant because of the addition and removal of low density firn, and alterations in the rate of firn densification, depending on whether there is net accumulation or ablation occurring (see also Fischer, 2011). Clearly, though, when the glacier's surface facies configuration is comprised entirely of ice, the density conversion is simple.

From the literature, where the study glaciers have all had some degree of firn coverage, practitioners have typically used an "*average-density-of-volume-change"* value of 850 kg m^{-3}. Others have used zonally variable conversion factors by examining the facies configurations at the start, during and end of the time period under consideration. As an example, the surface facies configurations in evidence for the Bologna Glacier, NT (*Figure* 1 inserts: 1984; 2014) clearly illustrate where significant changes in the distribution of surface density would need to be taken into account when applying the geodetic method.

A somewhat simpler but complimentary approach from a data collection and geomatics point-of-view is to exploit changes in the longitudinal profile of the glacier surface. This approach is described next.

1.2 LONGITUDINAL PROFILE CHANGE PARAMETERIZATION

As glaciers continually adjust their thickness distribution and area-wise extents by dynamic flow towards new equilibrium configurations they may create lateral moraines and trim lines of various configurations and morphologies. Many of these features can be exploited, with requisite cautions, to estimate, at least at the reconnaissance level of certainty, the previous size and extent of the glacier. Moreover, glacier topography and mapping products may be available dating back to the early period of formal glaciological investigation in a particular region - for Canada, c. early-mid 1900s (Ommanney, 2002). These information sources, whether inferred or directly observed are the foundation for parameterizing the longitudinal profile changes of glaciers; and from these, reconnaissance values of their long-term (centenary) average annual mass balances.

As reviewed in Demuth and Ednie (2016), Schwitter and Raymond (1993; henceforth "S-R") exploited the notion that the pattern of elevation change along the length of a glacier, fueled by retreat from a previous configuration, f.ex., its Neoglacial maximum, to present, can be parameterized in terms of a longitudinal *profile shape factor* $\boldsymbol{f}$.

The value of $\boldsymbol{f}$ reflects the degree to which thickness change is distributed over the glacier length. For $\boldsymbol{f} \rightarrow 0$, the thickness change is localized at the terminus; $\boldsymbol{f}$ = 0.5 implies a near linear distribution from zero at the head of the glacier to some maximum value at the glacier terminus; $\boldsymbol{f}$ = 1.0 indicates the changes are distributed evenly. In essence, $\boldsymbol{f}$ is the ratio of the average thickness change to the local thickness change at the contemporary terminus:

$$\boldsymbol{f}(\boldsymbol{t}) = \langle \Delta\boldsymbol{h}(\boldsymbol{x},\boldsymbol{t})\rangle \,/\, \langle \Delta\boldsymbol{h}(\boldsymbol{l_0},\boldsymbol{t})\rangle$$

(EQN. 5)

where $\Delta\boldsymbol{h}$ is the thickness change relative to a reference glacier geometry with length $\boldsymbol{l_0}$, and $\Delta\boldsymbol{h}(\boldsymbol{x},\boldsymbol{t})$ is the width-averaged thickness change at time $\boldsymbol{t}$ along the glacier length $\boldsymbol{x}$ running from 0 at the head, to $\boldsymbol{l}$ at the terminus (*Figure* 3). The numerator represents the average thickness change over the length of the glacier ($0 \leq \boldsymbol{x} \leq \boldsymbol{l_0}$) while the denominator is the thickness change at the terminus of the reference glacier configuration. With the simplification of uniform width, the volume change from the reference configuration is:

$$\Delta\boldsymbol{V}(\boldsymbol{t}) = \boldsymbol{f}(\boldsymbol{t})\Delta\boldsymbol{h}(\boldsymbol{l_0},\boldsymbol{t})\boldsymbol{l_0}\boldsymbol{w} \qquad \textit{(EQN. 6)}$$

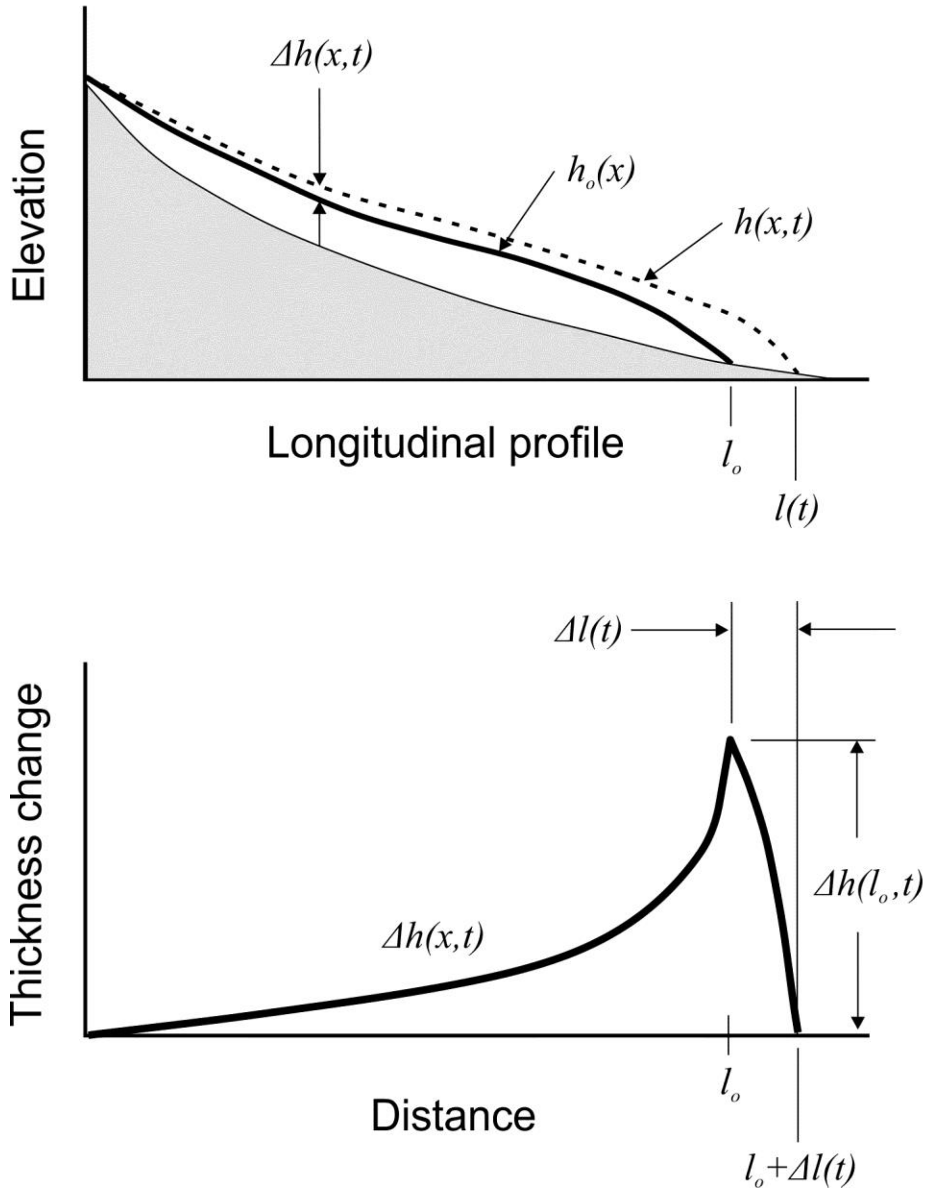


FIGURE 3 DEFINITION OF QUANTITIES IN EQUATIONS 4 AND 5. ADAPTED FROM SCHWITTER AND RAYMOND, 1993.

S-R's work synthesized actual observations of changes in geometry with data available at that time, and from them examined the actual range of ***f*** values. Data sources used by S-R (1993; page 585) represent sites, for intervals since the *Neoglacial* maximum, in the European Alps and Washington, U.S.A.; and several additional glaciers from the southern Canadian Rockies and Interior Ranges for other intervals where topographic maps were available. The mean value of $\boldsymbol{f}$ derived from S-R's observations is 0.28 (standard deviation 0.102).

Recalling that $\boldsymbol{f}$ reflects the distribution of thickness change over the glacier length, we write, as an approximation to *equation* 6, the mean centenary-scale annual mass change as:

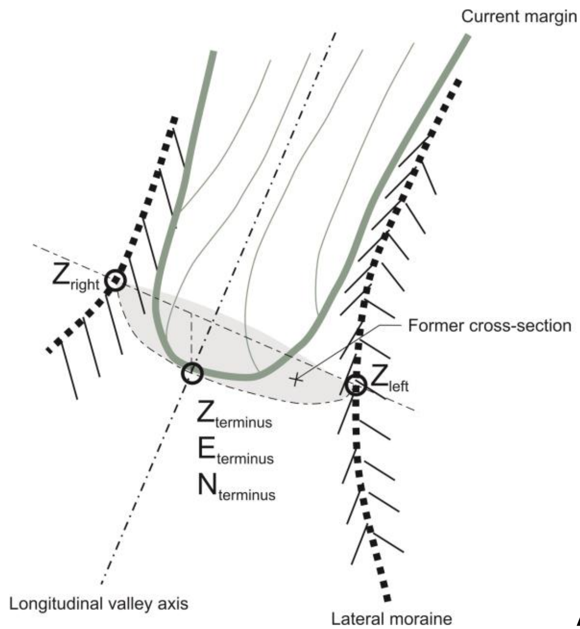
$$\langle \dot{\boldsymbol{M}} \rangle \approx \boldsymbol{f}\ \Delta \boldsymbol{h}(\boldsymbol{l_0})\ /\ \Delta \boldsymbol{t} \qquad \textit{EQN. 7}$$

where $\Delta \boldsymbol{h}(\boldsymbol{l_0})$ is the thickness change at the contemporary terminus with reference to the morphological feature defining the Neoglacial stage of the glacier at the same valley cross-section (*Figure 4*); and $\Delta \boldsymbol{t}$ is the time between the date of observing the contemporary terminus and the estimated date of the morphological impression of the Neoglacial stage.

Referring to *Figure* 4, the field measurements required to determine $\Delta \boldsymbol{h}(\boldsymbol{l_0})$ in *equation* 7 are simple, though acquiring them may be both difficult and hazardous. Further details can be found in Demuth and Ednie (2016) and Horne (2017).

Demuth and Ednie (2016) present several cautions; one in particular applies equally to employing the longitudinal profile change parameterization technique and the geodetic technique for determining mass change – namely, that both the climate and a particular glacier are always changing and never in steady state – implying that there will be complexities in the manner that thickness and volume changes occur in time and space for the glacier under examination.

If we constrain ourselves to examining volume and longitudinal profile changes since the Neoglacial maximum stage, however, we could reasonably state that the glaciers under consideration have, over c. 100 years, transitioned from the influences of a climate that was relatively favourable to glacier growth to one more favourable to glacier shrinkage; and have done so over time periods greater than the individual glacier *response time* – the time between a climatically-induced step change in the mass balance and the glacier's asymptotic approach to a new steady-state configuration. Demuth and Ednie (2016; pages 15-16) reiterate several other cautions for implementing the "$\boldsymbol{f}$-parameter" approach in particular.



$$\Delta h(l_0) \approx \left[\frac{Z_{right} + Z_{left}}{2}\right] - Z_{terminus}$$

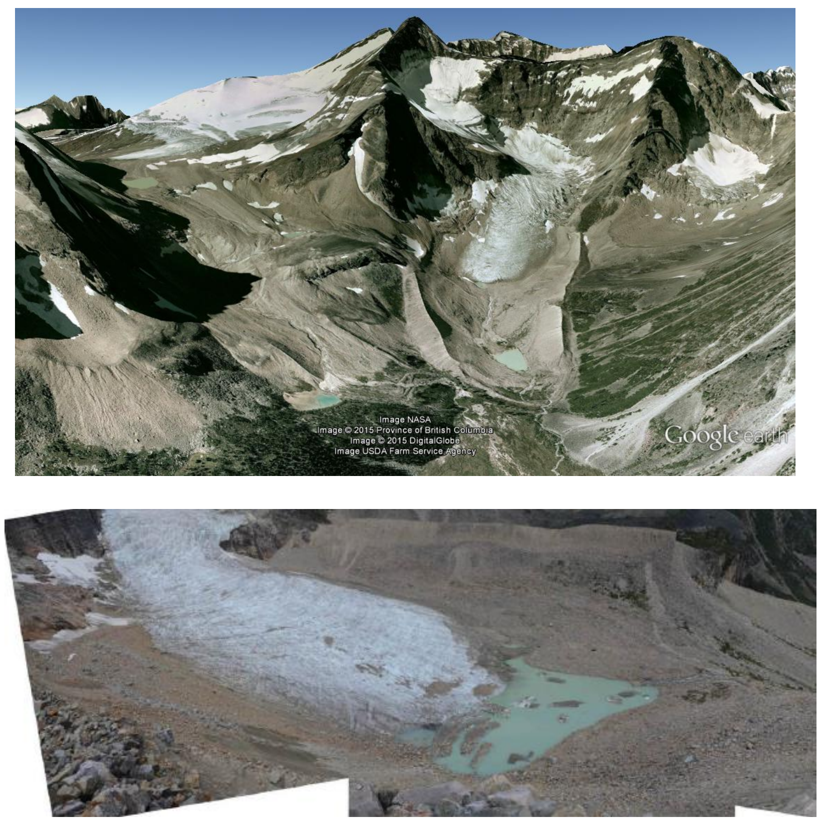


FIGURE 4 THICKNESS CHANGE MEASUREMENT SCHEMATIC AT THE CONTEMPORARY TERMINUS. EXAMPLE SHOWN IS THE PARAPET GLACIER IN JASPER NATIONAL PARK. PHOTO IS TAKEN FROM THE RIGHT-HAND LITTLE ICE AGE MORAINE CREST; $\boldsymbol{\Delta h(l_0)}$ *≈ c. 100 m. GREG HORNE PHOTOGRAPH, AUGUST 23, 2013.*

2. Study Region – Jasper National Park and the Columbia Icefield

Jasper National Park (JNP) is the largest protected area of the numerous National and Provincial Parks that form the "Canadian Rocky Mountain Parks" (a UNESCO World Heritage Site). JNP occupies a total area of c. 11,000 km^2, and exhibits a wide diversity of flora and fauna that reside in three dominant *life zones* or landscape units – montane, subalpine and alpine. The large altitudinal range within JNP is the main agent of variability as it concerns the differences in biodiversity between these units, though local terrain characteristics can create local micro-climates and ecological niches. Several major river systems of the Arctic Ocean Drainage Basin originate in JNP. They include the Athabasca and Smokey Rivers. The Brazaeu River flows into the North Saskatchewan River as part of the Nelson Drainage Basin (Hudson's Bay). See http://www.pc.gc.ca/eng/pn-np/ab/jasper/index.aspx for additional information.

JNP is situated in a region where its bounding western slopes are influenced by the humid inter-mountain climates of British Columbia's eastern interior; and the majority of its territory by the dry, continental influences of the Rocky Mountain eastern slopes. *Upslope* conditions, however, can arise – resulting in episodic but heavy precipitation as air masses, associated with cyclonic activity tracking to the south and east of the region, are subject to orographic enhancement and resulting upper-level divergence.

The region is founded by folded and faulted Palaeozoic sedimentary bedrock, giving rise to an extensive network of benches that support several large icefields and numerous valley and mountain glaciers. In several instances, the icefields nourish outlet valley glaciers. A history of end-moraine building and down-valley over-deepening has created numerous proglacial lakes and paternoster lake sequences; all revealed by a general recession of glaciers in the region since the *Neoglacial* maximum (c. 1841; Luckman and Osborne, 1979). Luckman (2017) provides an excellent overview of the landforms associated with the region's numerous glacier forefields.

A significant landscape feature of Jasper National Park is the Columbia Icefield. Details on its natural history can be found in Sandford (2016). Briefly, the Columbia Icefield is situated in the Park Ranges of the Canadian Rocky Mountains at 52.17° N latitude and 117.32° W longitude (*Figure* 5). The area of the Columbia Icefield is currently approximately 205 km^2. A portion of the Columbia Icefield lays within the northwestern reaches of Banff National Park (BNP). The Icefield's configuration over the *Continental Divide* (demarcating the border between the provinces of Alberta and British Columbia) gives it the distinction of being the hydrological apex of Canada's mountain west.

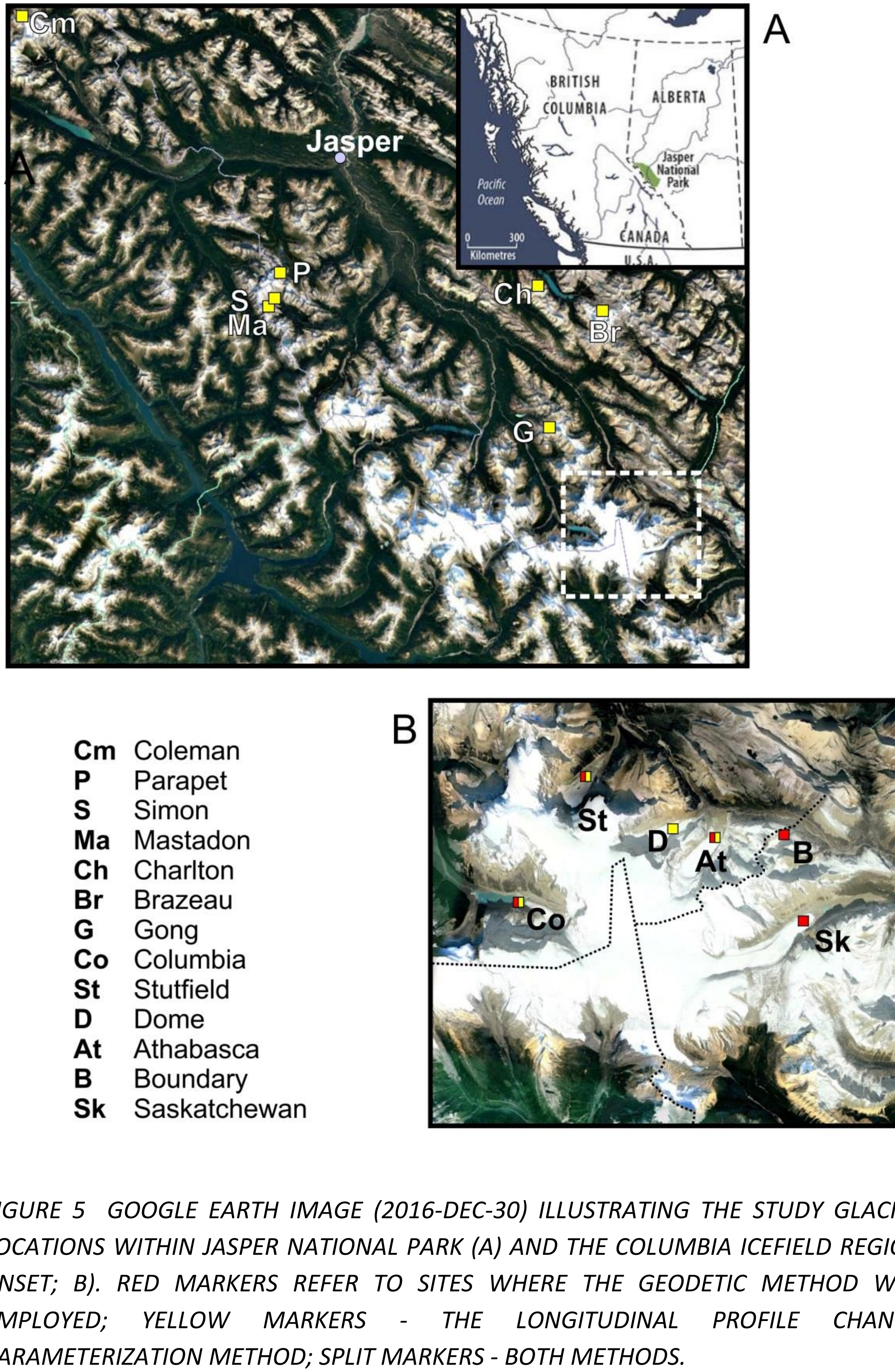


FIGURE 5 GOOGLE EARTH IMAGE (2016-DEC-30) ILLUSTRATING THE STUDY GLACIER LOCATIONS WITHIN JASPER NATIONAL PARK (A) AND THE COLUMBIA ICEFIELD REGION (INSET; B). RED MARKERS REFER TO SITES WHERE THE GEODETIC METHOD WAS EMPLOYED; YELLOW MARKERS - THE LONGITUDINAL PROFILE CHANGE PARAMETERIZATION METHOD; SPLIT MARKERS - BOTH METHODS.

Seven major outlet glaciers drain the Columbia Icefield through flow into surrounding valley systems, while there are also broad terminal margins that extend across broad benches of bedrock. In addition, extensive high-elevation sérac margins partition mass to several smaller reconstituted glaciers laying beneath them.

The mean annual air temperature (MAAT) at nearby Sunwapta Pass (2,035 m a.s.l.) is c. -3°C, with the Icefield plateau region MAAT estimated then to be c. -8°C. Snow accumulation rates over the upper reaches of the Icefield are robust; reaching c. 3 m w.e. a^{-1}, though wind-scoured regions of the Icefield's numerous summits exhibit annual accumulations one order of magnitude less than this. Mass balances over the terminal regions of the Icefield's outlet glaciers currently range from -4 to -6 m w.e. a^{-1} (f.ex., for the Athabasca and Saskatchewan Glaciers; see Ednie et al., 2017). Additional details on the Columbia Icefield can be found in an excellent treatment of its changing glaciers by Tennant and Menounos (2013).

2.1 Study Sites – Columbia Icefield – Geodetic Method

Figure 5 illustrates the location of the glaciers in the Columbia Icefield region where the geodetic method was applied over the period 1964 – 2009. They include the Columbia, Stutfield and Athabasca Glaciers (JNP), and the Boundary and Saskatchewan Glaciers (BNP). The earth observation data sources and digital elevation models (DEM) used by Tennant and Menounos (2013) were exploited; notably, from which Tennant and Menounos generated cumulative geodetic mass changes for the following intervals: 1964-70, 1970-74, 1974-79, 1979-86, 1986-93, 1993-2000 and 2000-09. Except for the Boundary Glacier, a small detached glacier lying to the east of the main Icefield, all of the geodetic study glaciers are nourished from the main Icefield.

2.2 Study Sites – Longitudinal Profile Change Parameterization

Figure 5 illustrates the location of the glaciers in Jasper National Park used to parameterize their longitudinal profile changes from c. 1841 to 2013/14. Location and survey details are to be found in Horne (2017). These sites were accessed during parallel ecological integrity surveys and resource conservation work by JNP. They represent a wide cross section of glacier locations throughout the central and southern reaches of the Park, and generally simple glacier planform configurations (f. ex., single accumulation basins). In each case, Little Ice Age lateral moraines were in evidence above and orthogonal to the longitudinal valley cross section at the contemporary terminus position. This enabled confident documentation of the absolute and relative $\boldsymbol{\Delta h(l_o)}$ illustrated in *Figure* 4 and used in *equation* 7.

3. Data Reduction and Results

3.1 Geodetic Mass Changes – Columbia Icefield Region, 1964-2009

This study exploited previously published values of the cumulative geodetic mass change for several glaciers in the Columbia Icefield region (Tennant and Menounos, 2013: Figure 8[2]). A record of cumulative mass change represents a low-pass filtered version of the originating serial data set. For this study, the low-pass filtered data was de-convolved to reveal 1964-70, 1970-74, 1974-79, 1979-86, 1986-93, 1993-2000 and 2000-09 interval mass change variability over the time period 1964-2009.

Table 1 and *Figure* 6 illustrate the average annual mass changes for the Columbia, Stutfield, Athabasca, Boundary and Saskatchewan Glaciers. Uncertainty in the geodetically-derived values is c. 0.1 m w.e. a^{-1}. *Figure* 6 also illustrates the surface mass balance for the Athabasca and Saskatchewan Glaciers, 2015 and 2016, as reported by Ednie et al. (2017).

TABLE 1 AVERAGE ANNUAL MASS CHANGES (m w.e. a^{-1}) 1964-2009 FOR SELECTED GLACIERS IN THE COLUMBIA ICEFIELD REGION.

Glacier	1964-70	1970-74	1974-79	1979-86	1986-93	93-2000	2000-09
Columbia	-0.40	-0.06	-0.13	-0.26	-0.42	-0.46	-0.59
Stutfield	-0.40	-0.06	0.14	-0.38	-0.28	-0.58	0.11
Athabasca	-0.40	0.09	-0.01	-0.24	-0.46	-0.64	0.05
Boundary	0.58	-0.29	0.02	-0.32	0.31	0.16	-0.67
Saskatchewan	-0.80	-0.20	-0.20	-0.50	-0.79	-0.79	-0.34
mean	-0.28	-0.10	-0.04	-0.34	-0.33	-0.46	-0.29
std. deviation	0.51	0.15	0.13	0.10	0.40	0.37	0.36

During the 1964-2009 time period, mass change is becoming increasingly negative, and shows signs of increasing temporal and intra-region variability after the late-1980s.

[2] In their original interval geodetic mass change estimation, Tennant and Menounos (2013) used a zonally variable conversion factor in *equation* 4.

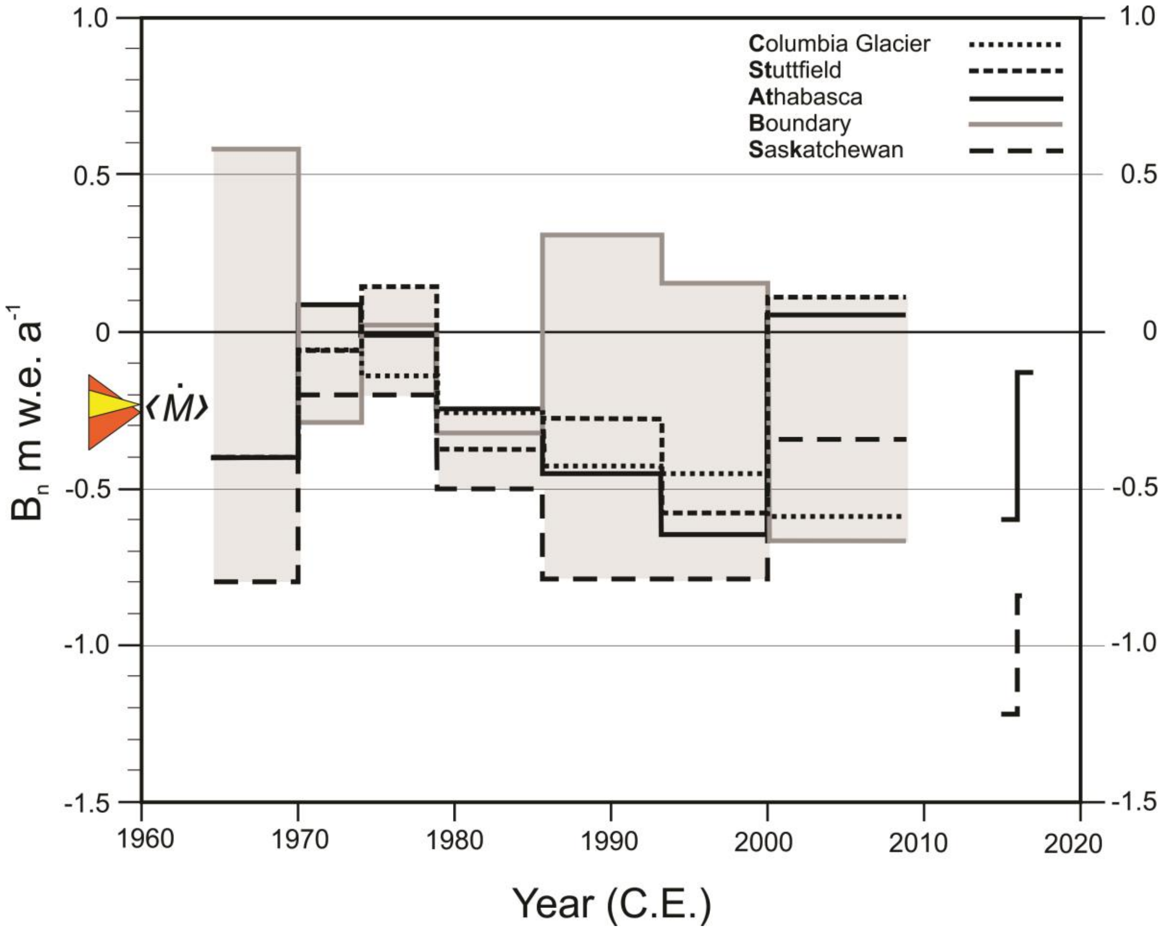


FIGURE 6 THE GENERAL MASS FLUCTUATION OF SELECTED GLACIERS IN THE COLUMBIA ICEFIELD REGION SINCE THE MID-1960S. THE AVERAGE ANNUAL MASS CHANGE SINCE C. 1841 FOR GLACIERS IN THE SAME REGION, INCLUDING A BROADER SAMPLE OF GLACIERS ELSEWHERE IN JASPER NATIONAL PARK, IS SHOWN USING THE COLOURED TRIANGLES TO INDICATE MEAN VALUES AND STANDARD DEVIATIONS (LENGTH OF THE TRIANGLE'S VERTICAL SIDE). DETAILS IN THE TEXT AND TABLE 2.

3.2 MASS CHANGE FROM LONGITUDINAL PROFILE PARAMETERIZATION – JASPER NATIONAL PARK, SINCE C.1841

Table 2 summarizes the measurements detailed in Horne (2017) and tabulates (far right column) the average annual mass change estimated for the surveyed glaciers since c. 1841. The baseline time period used in *equation* 7 corresponds to the time interval between the $\boldsymbol{\Delta h(l_0)}$ surveys (2013 and 2014) and the year of the maximum expression of the Little Ice Age (LIA_x) Cavell Advance in the region (c. 1841; see Luckman and Osborne (1979) and Luckman (2017) for details).

TABLE 2 SITE LOCATIONS, INPUT DATA AND ESTIMATES OF THE POST LITTLE ICE AGE (AFTER c. 1841) AVERAGE ANNUAL MASS CHANGE DERIVED FROM PARAMETERIZED LONGITUDINAL PROFILE CHANGE (SEE FIGURE 6).

	Terminus co-ordinates[3] UTM zone 11U, NAD 83			Altimeter[4] $\Delta h(l_0)$ ±1 m	Baseline Δt a	Post 1841 $\langle \dot{M} \rangle$ m w.e. / a
Glacier site	Easting m	Northing m	Elevation m a.s.l.			
Brazeau	477926	5825146	2277	135	172	**-0.22**
Parapet	413706	5835411	1991	100	172	**-0.16**
Mastadon	411295	5829979	2036	170	172	**-0.28**
Simon	411968	5831332	2160	120	172	**-0.20**
Coleman	363134	5893945	2035	170	172	**-0.28**
Dome	482330	5785044	1989	178	172	**-0.29**
Gong	466958	5802675	2302	120	173	**-0.19**
Columbia	472447	5780321	1559	373	173	**-0.60**
Stutfield	476530	5788705	1713	148	173	**-0.24**
Charlton	464549	5831184	2113	128	173	**-0.21**
Athabasca	483872	5784022	1986	143	173	**-0.23**
mean (excluding Columbia and Athabasca Glaciers)						**-0.23**
mean (all listed glaciers)						**-0.26**

The composite $\boldsymbol{f}$-parameter-derived average annual mass change since c. 1841 is plotted in *Figure* 6. The small, yellow and larger, orange triangles indicate the means (see *Table* 2) and the length of the vertical sides, the standard deviation.

The differentiation in the triangles is: yellow excludes the values for both the Columbia and Athabasca Glaciers; orange includes the values. Notably, the Columbia Glacier has terminated in its pro-glacial lake through much of its post Little Ice Age history. This would enhance ablation rates at the terminus compared to if it terminated on land only. Further, over the time period since the LIA_x the Athabasca Glacier has undergone drastic

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[3] Terminus co-ordinates determined using autonomous GPS with WAAS enabled.

[4] Given sky view complications, the altimeter-derived values of Δh were considered more reliable than those derived using the GPS.

changes in its configuration – from a highly dendritic glacier system, nourished by ice flux from not only the Columbia Icefield plateau but also from side and hanging valley contributions. The long-term evolution of both of these settings may preclude the validity of the ***f***-parameter approach.

The annually averaged centenary mass changes are reasonably uniform across the region - a reasonable result given the long time period over which the parameterization is conducted. Notably, the centenary value is three or more times less negative than more contemporary annual mass change values indicating increasing and possibly accelerating glacier mass imbalance.

4. Discussion

4.1 Temporal Context

Figure 6 illustrates the long-term fluctuation of the annual mass change for glaciers in the Columbia Icefield region for varying time periods during the interval 1964-2009. Also plotted are the 2014-15 and 2015-16 annual balances for the Athabasca and Saskatchewan Glaciers reported by Ednie et al. (2017).

The temporal pattern revealed in *Figure* 6 has features of the well documented shift after 1976 to more negative glacier mass balances due to lower end-of winter snow water equivalence over southwestern Canada and the Pacific northwest generally (f.ex., Moore and McKendry, 1996), and lower winter glacier mass balances specifically (f.ex., McCab and Fountain, 1995; Demuth and Keller, 2006; Demuth et al., 2008).

The 1976 shift (and others documented before it: see *Figure* 7 – 1947, 1922) have been associated with the so-called “Pacific Decadal Oscillation” (PDO) and its “warm” and “cold” phases. Whitfield et al. (2010) summarize and update the nature and role of the PDO on hydro-climatic phenomenon associated with a modulation of the Pacific North American (PNA) circulation pattern governing, in part, the advection of moisture-bearing storm tracks into the region. In particular they comment that the view of Pacific variability is more complicated than the conventional notion that the PDO represents a simple binary cold or warm configuration. Key to understanding this nuance is how the PDO interacts with extra-tropical El Niño Southern Oscillation (ENSO) influences, and the character of PDO-ENSO in-phase or PDO-ENSO out-of-phase regimes as discussed by Fisher et al. (2008).

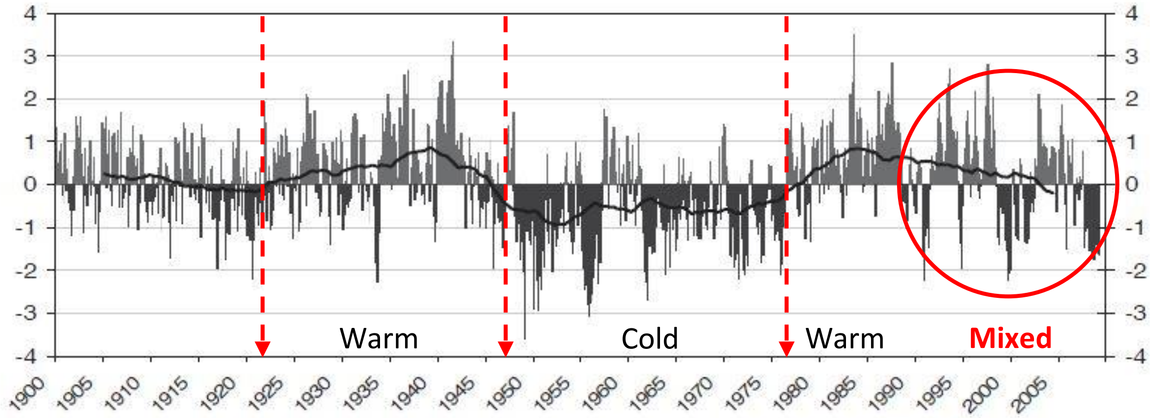

FIGURE 7 MONTHLY VARIABILITY OF THE PACIFIC DECADAL OSCILLATION INDEX FROM JANUARY 1900 TO MAY 2009, AND ITS 20th & 21st CENTURY PHASES. ADAPTED FROM WHITFIELD ET AL., (2010); DATA FROM http://jisao.washington.edu/data_sets/

Conspicuously, in the late 1980s, a different kind of regime appears to have been manifested – dropping out of the warm regime that had been in-place since 1976 into a more variable or "mixed" regime of warm-cold episodes (*Figure* 7). A persistent period of higher variability has indeed been documented to have taken hold after 1990 (see f.ex., Demuth et al., 2008: Figure 8; Zemp et al. 2015: Figure 5 – refer to "WNA"; Demuth and Ednie, 2016: Figure 9 – Peyto Glacier) where near record mass losses of glaciers occurred in 1998 followed by two years of mass gains – one of which (2000) was a record mass gain.

The notion of higher variability is also evident in the measured record mass losses experienced in 2014-15 by most glaciers in southwestern Canada and the Pacific northwest (Brian Menounos et al., 2015: personal communication; Demuth and Ednie, 2016: Figure 9), followed by much more modest losses in 2015-16. Notably, Ednie et al. (2017) report this is reflected in the recent short in-situ mass balance records documented for the Athabasca and Saskatchewan Glaciers.

4.2 IMPLICATIONS

As it concerns the general, long-term glacier diminution observed since the close of the Little Ice Age period, the results provide context for the changes of glacier cover forecasted to take place by the close of the 21st century (see f.ex., Clarke et al., 2015). In particular, Clarke et al. summarize that "by 2100, the volume of glacier ice in western Canada will shrink by 70 ± 10% relative to 2005", and "According to our simulations, few glaciers will remain in the Interior and Rockies regions". Given that we have already witnessed or inferred similar volumetric changes for certain well-documented glaciers over a significantly longer period of time (f.ex., Demuth and Keller, 2006; Demuth et al, 2008: page 46), fosters a general notion that the region's glaciers are in a state of extreme negative imbalance fuelled further by the positive feedback effect of increasingly lower to non-existent accumulation areas and thereby lower albedos affecting surface energy balance.

When examining increasing variability, the new normal governing nearly all mountain glaciers around the world is that they are in in a severe state of negative imbalance (Zemp et al., 2015). As such, any reported annual mass gains are viewed as being a generally *positive* situation. Demuth and Ednie (2016) propose a bimodal rubric with which to ascribe a "glacier condition" in relation to the bio-physical qualities exerted by the presence of glaciers in various disequilibrium and equilibrium configurations – underscoring, in particular, that a glacier exhibiting mass loss does not always exert a negative influence, while one that exhibits mass gains does not always exert positive influences. Never-the-less, the results of glacier mass fluctuation assessments such as those reported herein are nearly always discussed by non-specialists in terms of the archetypal *less glacier mass = warmer climate*. While this is true at the scale of climate cycles, Ice Ages and the glacial and interglacial periods within them, a more variable state of glacier nourishment, wastage and melt under the influences of a more variable climate system – a finger print of human-induced climate change (f.ex., IPCC, 2013) – within the response times of typical mountain glaciers (order 1-100 a), will have implications on documenting and understanding hydro-climatic influences on related ecosystem functioning and health.

It should also be noted that, under increasing fiscal pressures, many monitoring-based scientific efforts are being asked to reduce their measurement networks both spatially and even temporally. Under climatic conditions that manifest increasing variability and non-stationarity at multiple scales, it is prudent to do quite the opposite by building sustainable observing partnerships and increasing observing system density and measurement frequency. Such efforts can be made more effective, in part, by developing novel approaches to observing and interpretation such as those presented herein.

Conclusions

Geological Survey of Canada Open File 8229 has presented an analysis of recently documented glacier volume and longitudinal profile changes to illustrate the decadal-to-centenary variability of mass change for selected glaciers in Jasper National Park including those in the Columbia Icefield region. Over the last several decades, the study glaciers have experienced negative annual mass changes at a rate equal to or greater than thrice that of their long-term annualized centenary value (since c. 1841). The results also reflect large-scale regional glacier mass balance variability observed since the mid-20th century – namely, the general pattern of glacier mass loss since the mid-20th century appears to be influenced, in part, by shifts in the regime of the Pacific North American circulation pattern. Further, it is noted that for the study glaciers and for glaciers in southwestern Canada, the northwest Pacific and globally, mass change values over the last several decades and into early 21st century are exhibiting higher variability including several instances of record mass gains.

This is an important result because glacier fluctuations and climate change are nearly always discussed by non-specialists in terms of the archetypal *less glacier mass = warmer climate*. A more variable state of glacier nourishment, wastage and melt under the influences of a more variable climate system – a finger print of human-induced climate change – will have implications on how their role on hydro-ecological functioning is documented, understood and managed.

Appendix A: Geological Survey of Canada's Reference Glacier-Climate Observing System in the Cordillera.

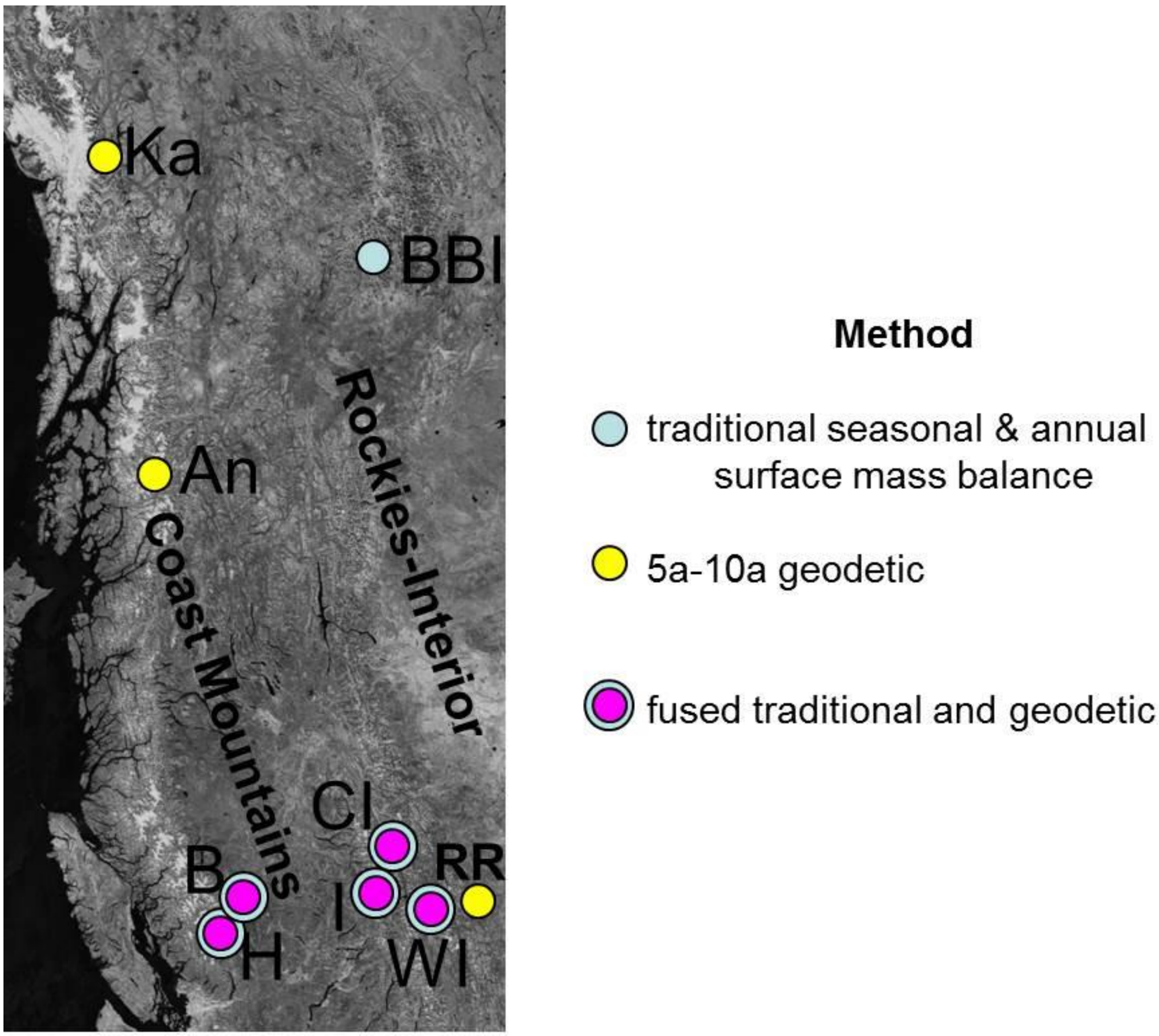

Figure A 1 Reference mass balance observing sites for the Cordillera: WI = Wapta Icefield (Peyto and Yoho); RR = Ram River; CI = Columbia Icefield (Athabasca and Saskatchewan); I = Illecillewaet; BBI = Brintnell-Bologna Icefield (Bologna); Ka = Kaskawulsh; An = Andrei; B = Place; H = Helm.

Mountain National Parks:

Wapta Icefield is located in ***Banff*** (Peyto Glacier) and ***Yoho*** (Yoho Glacier) *National Parks*.

Columbia Icefield is located in ***Jasper*** (Athabasca Glacier) and ***Banff*** (Saskatchewan Glacier) *National Parks*.

Illecillewaet Glacier is located in ***Glacier and Mount Revelstoke National Park***.

Northern Bioregion Parks and Reserves:

Kaskawulsh Glacier is located in ***Kluane National Park Reserve***.

Brintnell-Bologna Icefield (Bologna Glacier) is located in ***Nahanni National Park Reserve***.

British Columbia Provincial Parks:

Helm Glacier is located in ***Garibaldi Provincial Park***

Metadata for each glacier/icefield site, including details on observing and research partnerships, measurement infrastructure and First Nations territorial references, are available from: mark.ednie@canada.ca

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Mike Demuth (left) and Steve Bertollo (right) on the Saskatchewan Glacier near mass balance stake Sk20 after descending from the Columbia Icefield plateau and Mount Snow Dome during annual winter mass balance measurements. Eric Courtin photograph, 2015-May-06.

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