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OPEN FILE 8031

A Glacier Condition and Thresholding Rubric for use in Assessing Protected Area / Ecosystem Functioning

M.N. Demuth and M. Ednie

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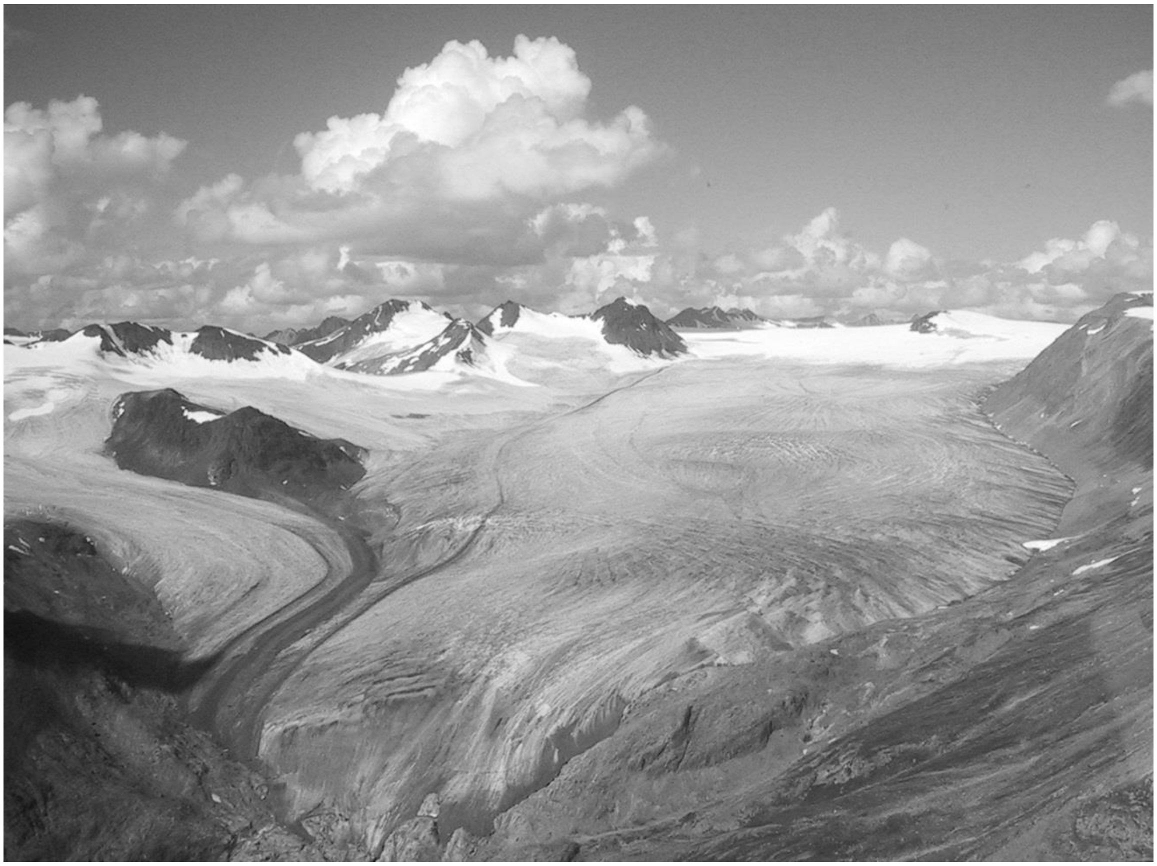
Summary

Glaciers are found in many of Canada's Arctic and alpine regions. Short and long-term changes in their mass play a significant role in regional and global sea-level change; and modulate mountain runoff that impacts natural and human system functioning. Many of Canada's glaciers lay within protected areas such as National Parks and Reserves and Provincial Parks. Employing its Reference Glacier-Climate Observing System (Appendix A) the Geological Survey of Canada issues data reports and research on the state of Canada's glaciers. This forms part of Canada’s international commitments towards the goals of the United Nations Framework Convention on Climate Change. In parallel, Canada’s National Parks are required, under the Canada National Parks Act and the United Nations Heritage Convention, to report on the "State of the Park" ecosystem integrity and therein detail the "condition" of various Park bio-physical elements. The conditions and related thresholds inform a framework for Park and ecosystem functioning management. While regional climate and glaciers cannot be "managed", understanding the effects of their fluctuations on downstream bio-physical elements permits the development of management strategies for those elements. Geological Survey of Canada Open File 8031: i) reviews the methods by which glacier mass balance and related metrics can be measured; including the theoretical and practical basis for placing contemporary glacier mass balance measurements in a longer term context; and ii) proposes a rubric and methodology by which a glacier condition may be determined on an annual basis for a single site or multiple sites within a region. The rubric is based on a commonly reported mass balance metric, the *Accumulation Area Ratio* (***AAR***) – the ratio of a glacier’s accumulation area to its total area.



The Brintnell Glacier, Nahanni National Park Reserve, NT. Margaret J. Demuth photograph (2006-July-30).

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INTRODUCTION

Parks Canada’s Rocky Mountain National Parks and Northern Bioregion Parks and Reserves are nationally significant examples of Canada's natural and cultural heritage. The study of their glaciers, icefields and ice caps, and the ultimate transfer of knowledge through Parks Canada and other inter alia, foster public understanding, appreciation and enjoyment in ways that ensure their ecological and commemorative integrity for present and future generations. Glacier-hydro-ecological study and outreach in these realms fosters the conservation of highly valued natural and cultural resources, as well as enhancing visitor experience and education provided to Canadians and international visitors who come to enjoy, experience, learn and connect with their lands and natural resources.

Glaciers and the terrain associated with their fluctuations have the inherent property of providing information on both internal glacier-climate variability and external factors that drive disequilibrium beyond known or estimated natural variability. The climate in Canada is changing and these changes are one of the numerous threats to the ecological integrity of the lands contained within the system of protected areas.

Glaciers hold intrinsic landscape values and have public safety, visitor experience and ecological significance. For example, 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.

Glaciers provide controls on the magnitude and duration of river flow during critical seasonal turnovers in the climate and energy exchanges occurring in the high country. These cool and turbulent waters also exert a significant regulation of water quality for highly adapted biota, as well as a exerting a significant influence on stream morphometry and related habitat.

Measures of glacier fluctuations include cumulative changes in length and area and the forcing function provided by the seasonal, inter-annual glacier and icefield-scale “mass balance”, which is in-turn driven by climate and weather. In an ecosystem based approach, these same measures and metrics, by themselves and in association with other ecological indicators, contribute to State of the Park assessments, related contributions to the PCA ICE (Information Centre on Ecosystems) meta-data/data inventory and mandated periodic reporting under the Canada National Parks Act.

Central to this information is an assessment of *Ecological Integrity* (EI). EI, as a state, implies that native park elements remain intact, whether they are abiotic or biotic; that their ability to adapt to stressors is retained within natural limits exhibited by ecosystem processes. Assessment of EI is complex and must incorporate the regional evolutionary and historic context that has shaped the system. Because glaciers and icefields and related ecosystems are constantly changing, conservation strategies need to be informed so that key bio-physical processes can be characterized (through their natural trajectory and rates of change) and any disequilibrium identified and brought into analysis of detected trends or regime shifts.

Key to the methods employed in studying glacier fluctuations is ascribing characteristic rates of change. As already stated, understanding rates and trends are critical to understanding the system; and both are the basis for EI assessment. These assessments must be conducted and ultimately understood at the landscape scale. While baseline, reference work may take place at the single glacier/icefield scale, we know that the impacts of climate change will manifest at any scale, whether it is the contraction of glaciers generally and long-term declines in late summer water flow, or the water temperature of a particular river reach being impacted by the contraction and fragmentation of glacier cover.

While glaciers in the long term may contract significantly or disappear out right (Marshall et al, 2013; Clarke et al. 2015; UNEP/WGMS, 2010), the key to assessing the wholeness of the ecological integrity of the region is to understand what might harm diversity and other properties of downstream systems native to the region. In 100 years hence, a “part” (glaciers) of the “whole” may be entirely absent and so it is the goal of this work to assist in assessing the state of the Park EI and how it is changing. An individual Park may not be able to alter ongoing changes in regional climate, but an understanding of the most immediate impacts of climate change on the Park may be important for the management of other ecological issues that the Park is able to manage.

Geological Survey of Canada (GSC) Open File 8031 provides:

1. a condensed background on the nature and measurement of glacier fluctuations (mass balance and related metrics such as the Equilibrium Line Altitude and Accumulation Area Ratio) at the single site and landscape scale. In particular, the

background includes details on a methodology with which to contextualize recently acquired but short and sparsely distributed glacier mass balance time series'.

2. a review on the hydro-ecological significance of glaciers – as a variable low pass filter between the process of meteorological inputs and streamflow generation; and as source of high-frequency disturbance.

3. a proposed 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. The rubric is centred on a glacier mass balance metric - the *Accumulation Area Ratio* ($\boldsymbol{AAR}$) and its deviation from the *equilibrium value*, $\boldsymbol{AAR_0}$. A rate-of- change threshold decision structure and workflow is presented, and illustrated using synthetic data.

Included are reference and supplementary appendices:

APPENDIX A: GEOLOGICAL SURVEY OF CANADA'S REFERENCE GLACIER-CLIMATE OBSERVING SYSTEM IN THE CORDILLERA.

APPENDIX B: GLACIER MASS BALANCE METHODS – GEODETIC

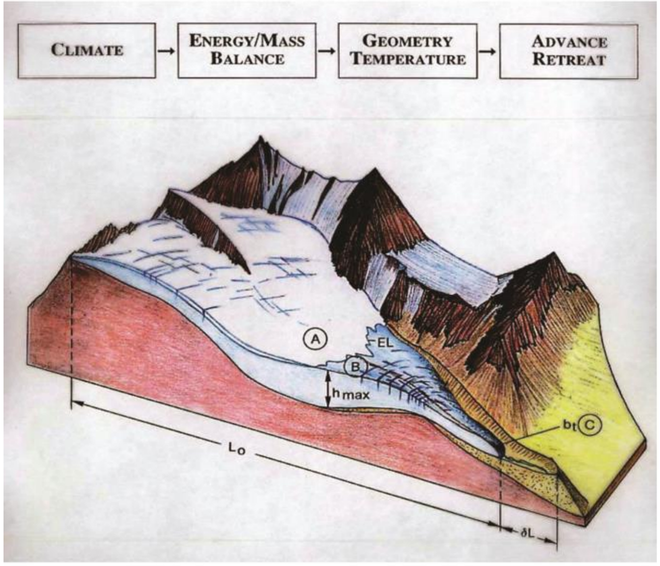
APPENDIX C: GLACIER MASS BALANCE METHODS – MASS-FLUX DIVERGENCE

APPENDIX D: APPLICATION GUIDELINES FOR IMPLEMENTING AN ***AAR***-BASED GLACIER CONDITION RUBRIC

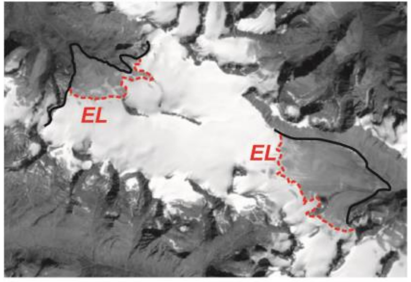
APPENDIX E: TOWARDS UNDERSTANDING AND GENERATING HIGH-QUALITY DERIVED QUANTITIES

1. 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).



Landsat 5: 1984-August-03



Landsat 8: 2014-August-15

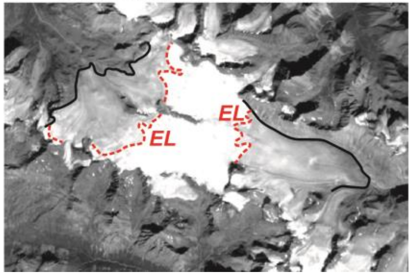


*FIGURE 1 A TYPICAL ALPINE GLACIER FEATURES NET ACCUMULATION AND NET ABLATION ZONES DIFFERENTIATED BY AN EQUILIBRIUM LINE (**EL**). ABOVE THE EL LAY THE SNOW AND FIRN FACIES OF THE ACCUMULATION AREA Ⓐ; BELOW IT THE ICE FACIES OF THE ABLATION AREA Ⓑ. LATE-SUMMER LANDSAT IMAGES OF THE BRINTNELL-BOLOGNA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

Other relevant metrics include the Equilibrium Line Altitude (***ELA***) which, for temperate glaciers, generally corresponds to the maximum elevation attained by the seasonal snowline (see Demuth and Pietroniro, 1999 and the references therein) and the ratio of the *Accumulation Area* to the total area of the glacier, or the *Accumulation Area Ratio,* ***AAR***.

An important construct is that at the ***EL*** of the glacier, the net *mass balance* is zero; above it there is net mass gain; below it a net mass loss. Ice mass generated through the accumulation and densification of snow and firn above the ***EL*** will flow from the upper reaches of the glacier to its lower reaches where warmer conditions promote its ablation. Moreover, the apparent "retreat" of a glacier terminus (calving not withstanding) is due to “melt back” exceeding the down valley flux of ice. In general, a glacier will, under weather and climate forcing that places it in mass balance disequilibrium, constantly attempt to re-attain equilibrium by adjusting its area and thickness distribution through dynamic flow.

1.1 MASS BALANCE

The mass balance of a glacier is an accounting of how much mass is added and taken away by the processes of accumulation and ablation. Accumulation can result from precipitation, condensation, drift snow or avalanching; while ablation results from melt, sublimation, or avalanching (commonly ice calving from the glacier margins). In regions where the mass balance is primarily driven by climatic factors such as air temperature, precipitation, solar radiation and cloud cover, the measurement of mass balance provides a high-confidence, integrated indicator of the climate.

There are several methods and conventions for estimating the mass balance of a glacier (refer to Cogley et al., 2011). An important distinction is to understand the method by which the estimate is based. Three dominant methods are employed: i) traditional, *glaciological*, *direct*; ii) geodetic*, cartographic*, *topographic*; and iii) mass flux divergence.

The tradition method is described herein – primarily because it results in the practitioner being able to determine the surface mass balance and the metrics used in the proposed glacier condition rubric. For completeness, the other methods are instead described in Appendix B and C.

<u>The traditional, “glaciological”, or “direct” method</u> is most commonly applied over simple mountain and outlet valley glaciers and amounts to an estimate of the “surface mass balance”, ignoring processes where by mass is exchanged internally and at the glacier base. The method generates both seasonal and annual balance (b) estimates at points after:

$$\boldsymbol{b_a = b_w + b_s} \qquad \textit{(EQN. 1)}$$

where subscripts *a, w, s* refer to the annual[1], winter and summer balances respectively.

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[1] The *annual* mass balance is the mass balance of the glacier over a mass-balance year regardless of whether the fixed-date or the floating-date system is used. See Cogley et al. (2011; page 62-63) for

Point values are then integrated to generate the specific balance values over the whole glacier:

$$\boldsymbol{B = \frac{1}{S}\int_S b\, ds} \qquad \textit{(EQN. 2)}$$

This is equivalent to the cross product of the balance-altitude relationship, $\boldsymbol{b(z)}$*,* with the area-altitude relationship, $\boldsymbol{s(z)}$, all divided by the total glacier area, $\boldsymbol{S}$; and can be calculated using continuous numerical methods or in a discrete, step-wise tabular fashion.

Variations in the approach result from whether the distribution of mass balance is simple (f.ex., largely dominated by elevation) or more complex due to topographic complexities that may justify integration over multiple dimensions. Where calving or contact of the glacier margins with water are involved, the considerations and resulting formulation become more complex (refer to Cogley et al., 2011; page 7).

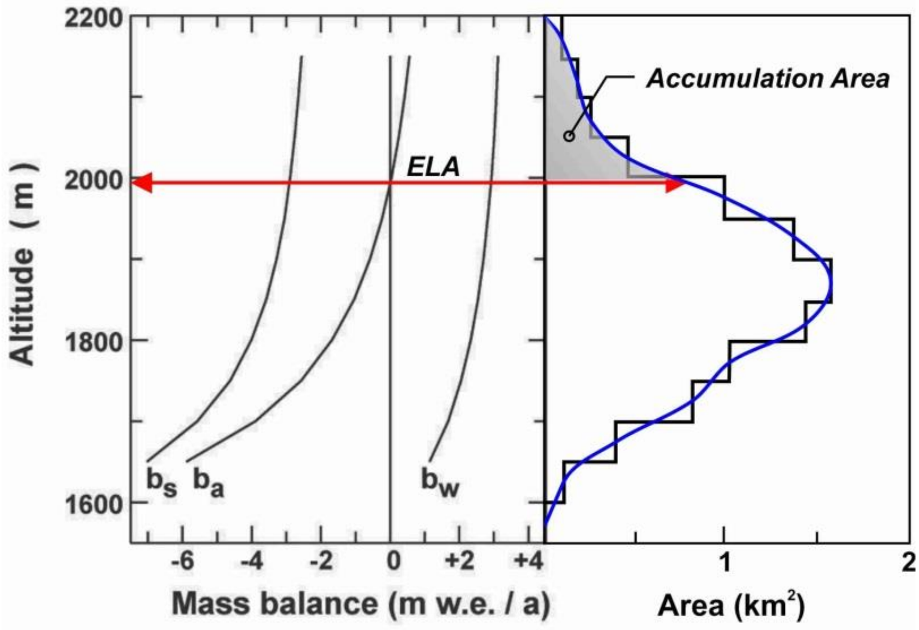

FIGURE 2 EXAMPLE OF MASS BALANCE-ALTITUDE (WINTER, SUMMER AND ANNUAL) AND AREA-ALTITUDE RELATIONSHIPS FOR AN ALPINE GLACIER IN NORTHWESTERN AMERICA. THE ONE-DIMENSION DETERMINATION OF THE EQUILIBRIUM LINE ALTITUDE (ELA) AND THE ACCUMULATION AREA IS ILLUSTRATED.

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further information on the ambiguity with the term “net” mass balance in relation to the stratigraphic system.

1.2 REPORTING MASS BALANCE

Mass balance changes have been documented for many decades in numerous regions of the world (mostly using the traditional method); and the annual mass balance data are usually presented as inter-annual series' and cumulative series' (*Figure*s 3, 4); the later imposing a low-pass filter effect on the data but also enabling a robust recognition of trends and accelerations.

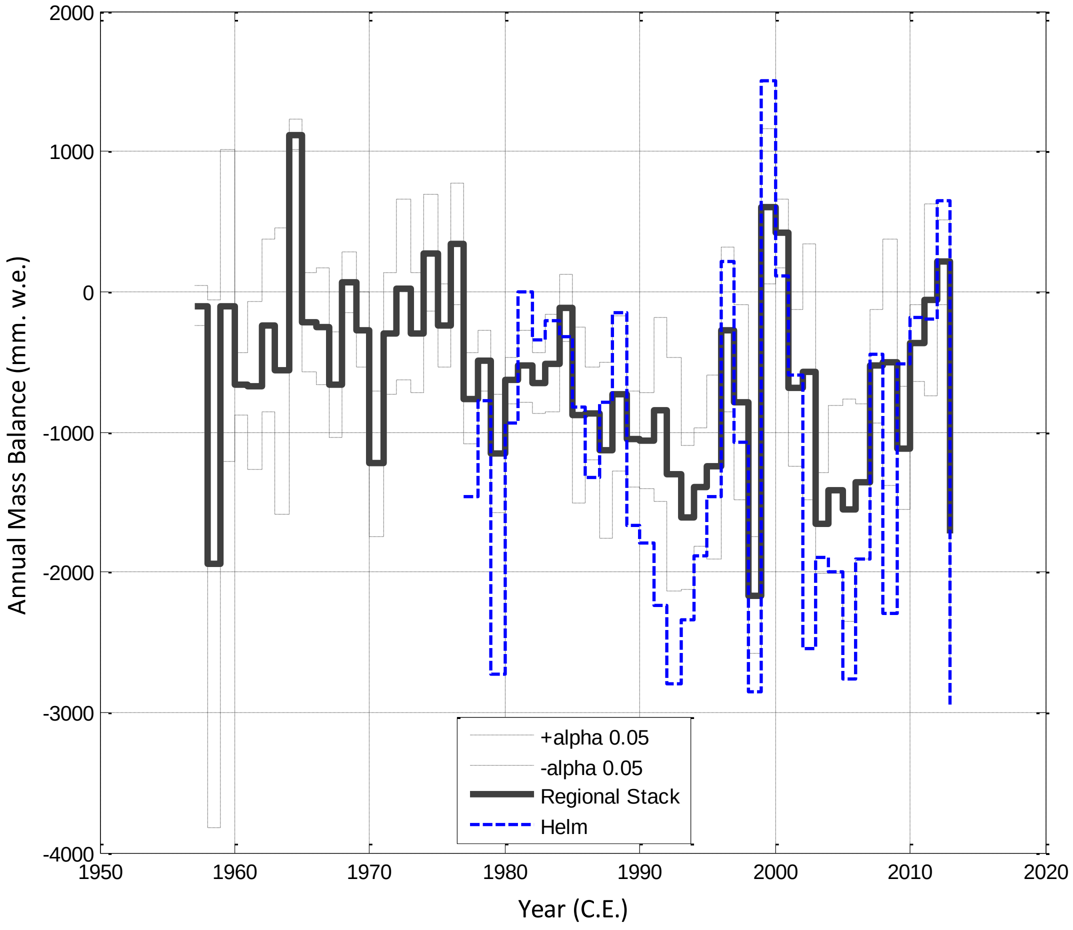

FIGURE 3 THE ANNUAL MASS BALANCE TIME SERIES PLOT FOR HELM GLACIER, PACIFIC RANGES, SOUTHERN COAST MOUNTAINS, GARIBALDI PROVINCIAL PARK. REFERENCE IS MADE TO THE REGIONAL STACK FOR GLACIERS REPRESENTING THE PACIFIC NORTHWEST AMERICA.

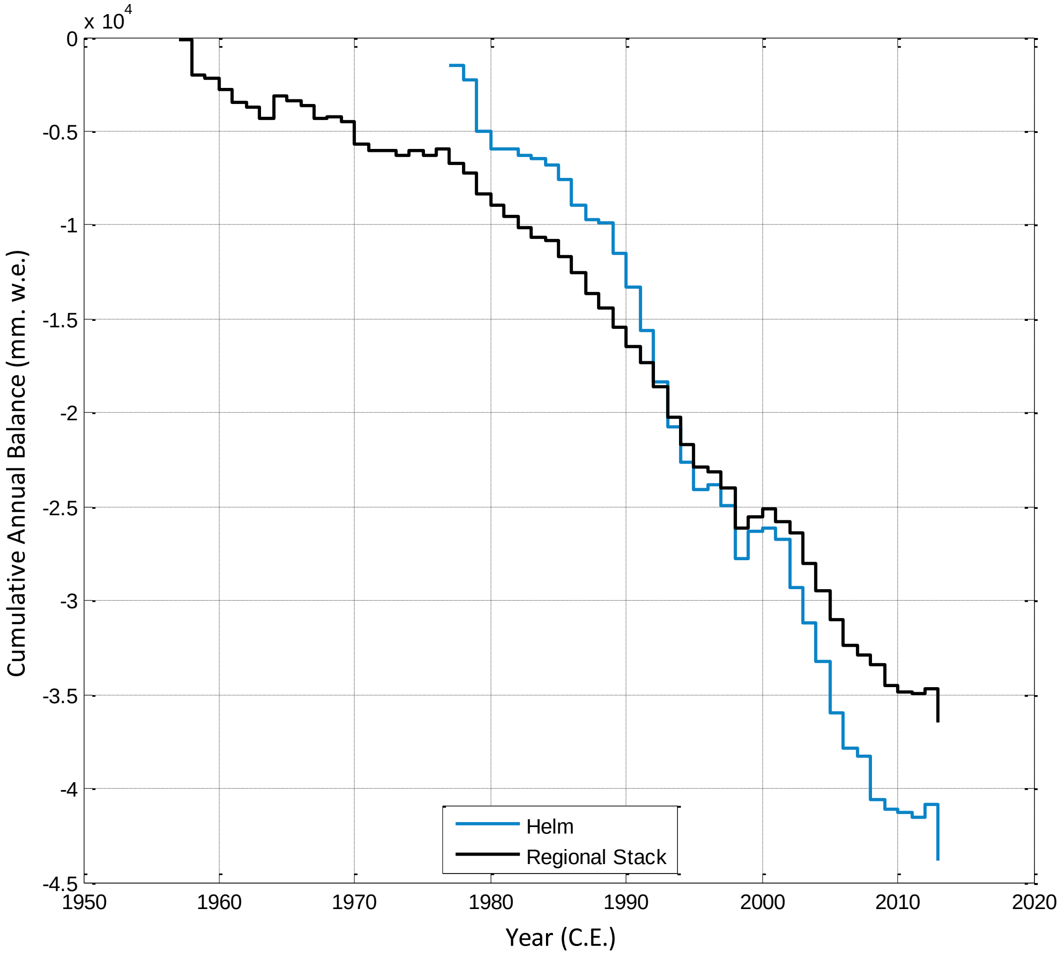

FIGURE 4 THE CUMULATIVE ANNUAL MASS BALANCE FOR FOR HELM GLACIER, PACIFIC RANGES, SOUTHERN COAST MOUNTAINS, GARIBALDI PROVINCIAL PARK. REFERENCE IS MADE TO THE REGIONAL STACK FOR GLACIERS REPRESENTING THE PACIFIC NORTHWEST AMERICA.

In addition to illustrating annual mass balance as serial or cumulative time series', additional mass balance metrics are tabulated and presented as in *Figure* 5. The metrics include the mass balance gradient with elevation (represents the regional component of the mass balance-climate signal), and the relationship between the annual mass balance and the $\boldsymbol{ELA}$ and $\boldsymbol{AAR}$. From the later, the equilibrium values $\boldsymbol{ELA_0}$ and $\boldsymbol{AAR_0}$ can be determined.

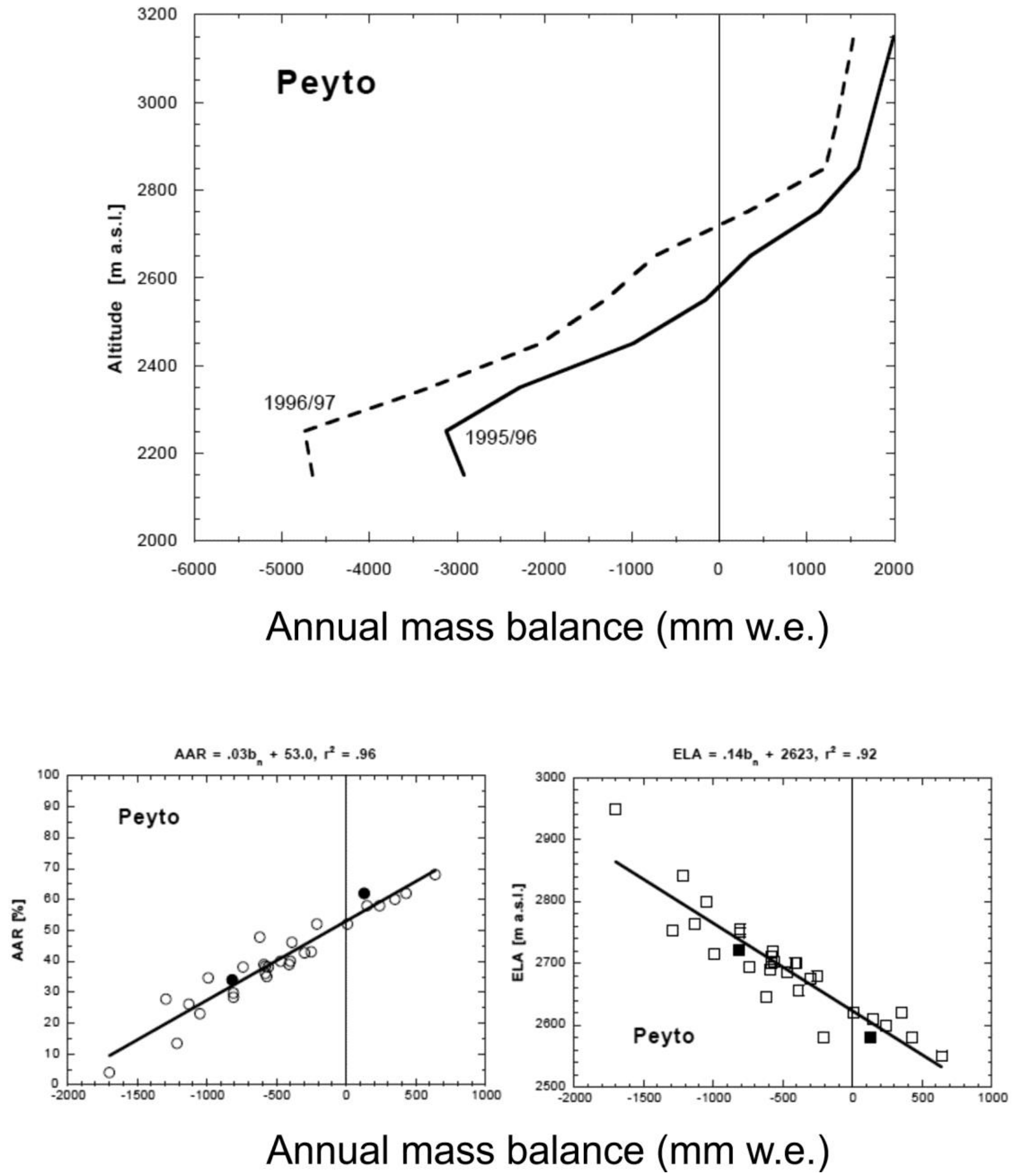

FIGURE 5 MASS BALANCE METRICS FOR PEYTO GLACIER, 1996 AND 1997, AS REPORTED TO THE WORLD GLACIER MONITORING SERVICE THROUGH THE BIENNIAL GLACIER MASS BALANCE BULLETIN AND PUBLISHED BY UNEP (SEE IAHS(ICSI)/UNEP/UNESCO, 1999).

A critical matter related to the interpretation of mass balance changes manifest at the single glacier or landscape scale is whether the aforementioned process of ice flow and dynamic readjustment is present or not. A dynamically active glacier in mass balance disequilibrium is constantly driving towards re-attaining equilibrium by adjusting its area and thickness distribution through dynamic flow. Such glaciers have been referred to as "glacier evacuators" (Lliboutry, 1965). Conversely, glaciers that change their mass by a simple increase or decrease in their thickness without any significant flow or mass flux divergence from one region of the glacier to another are termed "glacier reservoirs" (Lliboutry, 1965).

Where this becomes pertinent is in the application of equation 2. In the matter of monitoring a changing climate -the driver- we wish to assess a "reference" or "climatic" surface mass balance. To do this we hold the glacier hypsometry constant and thereby isolate the driver effect of a changing surface climate from the effects of a responding glacier area-elevation distribution. Conversely, we continually incorporate the changing glacier hypsometry when tracking the glacier as a water resource or contribution to sea-level change. In this instance the application of equation 2 results in a "true" or "hydrological" mass balance. Elsberg et al. (2001) discuss homogenizing mass balance time series derived from these two applications of equation 2.

One practical consequence of this is that glaciers which are "topographically preserved" by having retreated into terrain niches that protect the glacier from solar radiation, and may also be nourished by reliable drift snow, may have transitioned from being a glacier evacuator to a glacier reservoir. As such, other measures of glacier condition (site or landscape scale) such as those based on area or length change are rendered less useful.

1.3 REPORTING LANDSCAPE SCALE CHANGE

Mass balance measurements are generally labour intensive and can be technically and fiscally demanding. Efforts are usually directed towards the analysis of one or more intensely studied reference glacier(s) (f.ex. Demuth and Keller, 2006); and then regional and temporal context is provided by incorporating geo-botanical and/or remote sensing perspectives (f.ex., Demuth et al., 2008; 2014; Wood et al., 2011). While remote sensing is utilized in the geodetic and mass flux divergence methods (Appendix B and C), and enjoys broad use at the synoptic scale over the Canadian High Arctic (f.ex, van Wychen *et al*., 2013 using satellite SAR) and at selected individual sites in the Cordillera (f.ex, Hopkinson and Demuth, 2006 using aircraft lidar; see also Demuth, 2013), the use of remote sensing to extract simple mass balance metrics over wide regions has long been possible.

Gratton *et al*., (1990), Demuth and Pietroniro (1999) and Sidjak and Wheate (1999) report on remote sensing efforts over glaciers in the Canadian Rocky Mountains and

Interior Ranges – namely the extraction of relevant surface facies features using satellite-borne radar and optical sensors. These techniques permit the delineation of the $\boldsymbol{ELA}$ and $\boldsymbol{AAR}$. The regional mapping of $\boldsymbol{ELA}$ and $\boldsymbol{AAR}$ has been shown to be possible and applied in many glaciered regions of the world (see f.ex., GLIMS, 2014).

Demuth and Pietroniro (1999) point out that mapping the $\boldsymbol{ELA}$ from a particular surface facies configuration may be relatively straightforward, but ascribing a bin of elevation data to it is dependent on there being an image-representative DEM. When mapping the $\boldsymbol{AAR}$, however, an image representative DEM is not required. That said, the image utilized to extract the $\boldsymbol{AAR}$ must permit the practitioner to map the current extent of the glacier margin; and identifying the glacier margin may be complicated by debris cover and spectral ambiguities created by shadowing or cloud cover.

In section 3 we will return to the concept of the using the $\boldsymbol{AAR}$ to describe a glacier condition (single site or regional), in particular as it pertains to the glacier as an element of hydro-ecological functioning.

It is important first to provide the mass balance practitioner a method with which to place relatively short annual mass balance time series into a meaningful context suitable for assessments of a single glacier or numerous glaciers across a region of interest.

1.4 DEVELOPING CENTENARY MASS BALANCE PERSPECTIVES

Recent efforts towards attending glacier-climate observing site biases (size and regional site density (Spence et al., 2009; Demuth, 2010) have resulted in the development of new but still short annual mass balance time series'. Many of these initiatives evolved through the collaboration between NRCan/GSC Glaciology, Parks Canada Agency ecosystem integrity monitoring co-ordinators in the Mountain National Parks and Northern Bioregion field units, and in some cases involving academia. It is important, when reporting these relatively short-term results, to place them in a longer temporal context and better define natural ranges of variation.

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.

1.4.1 *f*-PARAMETER THEORY

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 described in terms of a *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:

$$\boldsymbol{f(t)} = \langle \Delta \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{t}) \rangle \,/\, \langle \Delta \boldsymbol{h}(\boldsymbol{l_0}, \boldsymbol{t}) \rangle \qquad \textit{(EQN. 3)}$$

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 6*). 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:

$$\Delta \boldsymbol{V}(\boldsymbol{t}) = \boldsymbol{f}(\boldsymbol{t}) \Delta \boldsymbol{h}(\boldsymbol{l_0}, \boldsymbol{t}) \boldsymbol{l_0} \boldsymbol{w} \qquad \textit{(EQN. 4)}$$

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 $\boldsymbol{f}$ values (*Figure 7)*). 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.

From *Figure* 7, $\boldsymbol{f}$ appears to be insensitive to glacier length, while thickness change varies in proportion to length change; corresponding to a greater proportion of the thickness/volume change occurring between the respective termini positions.

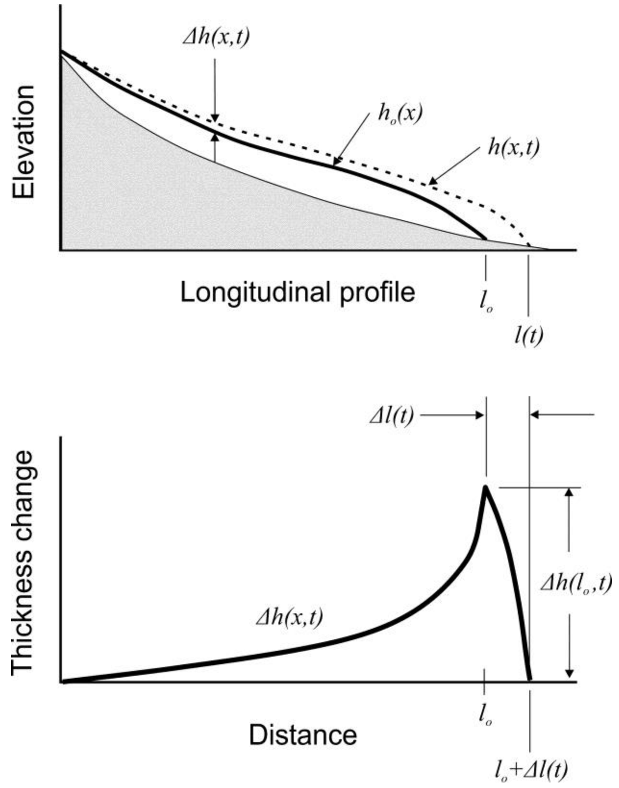

FIGURE 6 DEFINITION OF QUANTITIES IN EQUATIONS 4 AND 5. ADAPTED FROM SCHWITTER AND RAYMOND, 1993.

Additional profile change parameterizations are: $\boldsymbol{r1} = \boldsymbol{\Delta l/l}$ and $\boldsymbol{r2} = \boldsymbol{\Delta h(l^*)\ /\ \Delta h(l)}$; where $\boldsymbol{l^*}$ is the distance from the head of the glacier to the highest available data describing the thickness change. $\boldsymbol{r1}$ describes the non-dimensional magnitude of the retreat. $\boldsymbol{r2}$ is an important consideration when evaluating data from sites where the elevation changes for upper reaches of the glacier are more difficult to determine because of the absence of defining morphological data (i.e., lateral moraines are absent). This challenge is clearly not an issue when examining change directly using digital terrain models.

1.4.2 NON-STEADY STATE ISSUES AND OTHER CAUTIONS

In anticipation of implementing a simplified notion of the $\boldsymbol{f}$-parameter approach, there are several cautions that should receive some attention. Primary is that both the climate and a particular glacier are always changing and never in steady state – implying

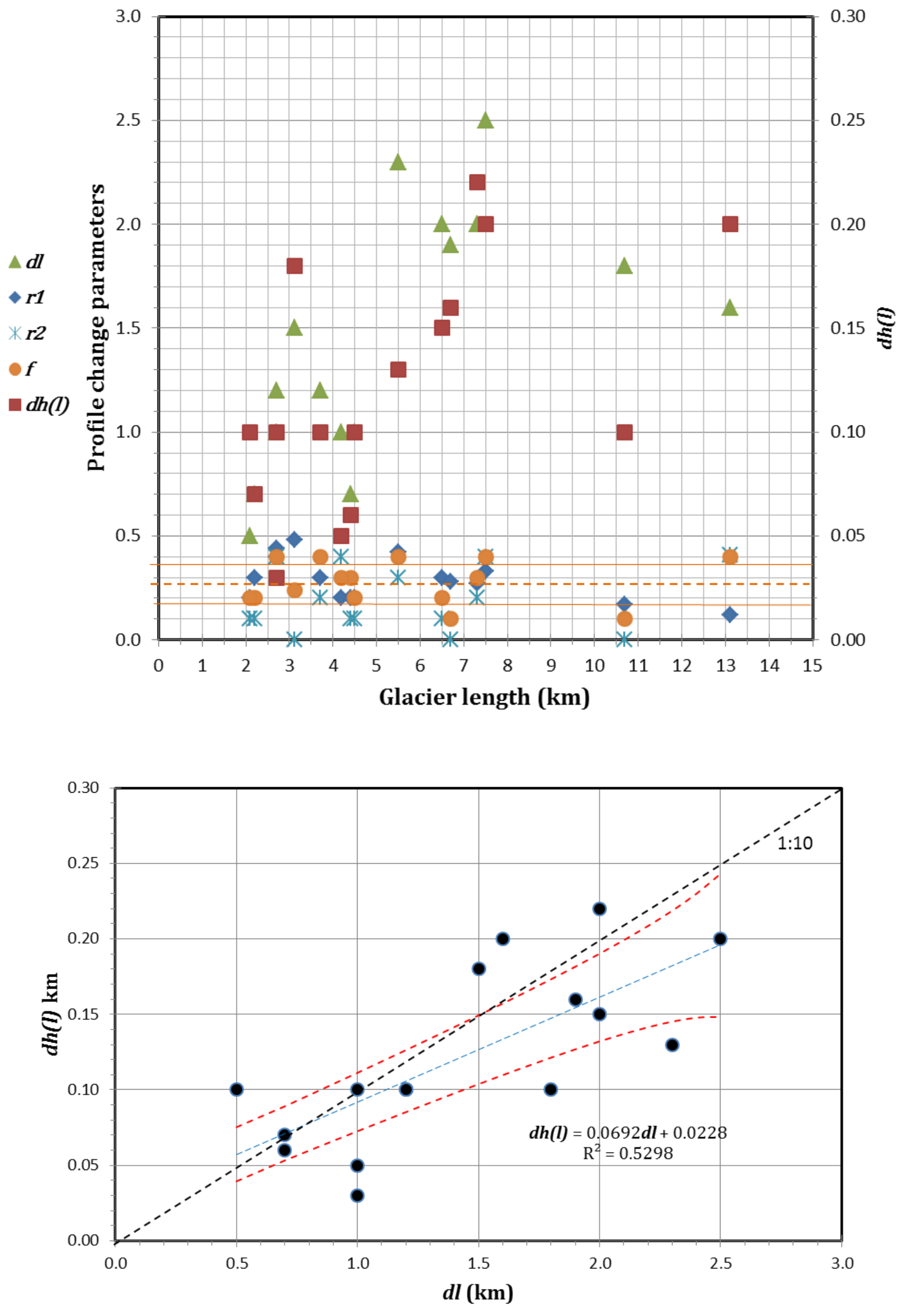

FIGURE 7 TOP PANEL: GRAPHICAL SUMMARY OF PROFILE CHANGE PARAMETERS FROM THE DATA OF SCHWITTER AND RAYMOND (1993; PAGE 586). THE MEAN VALUE FOR f IS 0.28; STANDARD DEVIATION 0.102. BOTTOM PANEL: RELATIONSHIP BETWEEN THICKNESS CHANGE AND LENGTH CHANGE (ALPHA = 0.05).

that there will be complexities in the manner that thickness changes occur in time and space for the glacier under examination.

If we constrain ourselves to examining 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 (see f.ex, Raper and Braithwaite, 2009). Never-the-less, S-R caution that for the largest glaciers in their dataset, documented changes may have occurred over periods <u>shorter</u> than their response times.

When applying this *morphological – post-Neoglacial retreat* method, other considerations include:

- the method takes advantage of the matter that contemporary lengths are shorter than those exhibited in the *Neoglacial* period;

- many glaciers may not have well-defined, nor independent accumulation areas (refer to parameter $\boldsymbol{r2}$);

- some glaciers with easily recognizable and measurable morphological features may have contemporary termini in close proximity to or even beyond the highest mapping evidence of trim lines or lateral moraines, and therefore, may not be useable (see S-R, page 584);

- the relationship between the morphological features and the former ice surface may be affected by the transverse tilt of the cross-section profiles;

- morphological features are time-variant and may not represent a former surface stage at a definite period of time;

- dating errors of the *Neoglacial* maximum stage and therefore values of $\boldsymbol{\Delta t}$;

- the elevation of moraine crests may have suffered significant deflation (f.ex., erosion by wind or water; melt out if ice cored) since their expression.

Lastly, in anticipation of using digital topographic mapping products from historical and contemporary efforts, there is the distinct advantage that the surface elevation of the glacier can be retrieved directly and unambiguously referenced to a specific date. A necessary caution is that the geodetic referencing of the mapping products must be co-registered to obtain valid profile change data (Goulden *et al.*, 2012, 2013). If a digital map also renders the trim line and/or lateral moraine features with adequate fidelity, then this too is an advantage, notwithstanding the cautions surrounding dating and deflation.

1.4.3 f-PARAMETER IMPLEMENTATION

Given the aforementioned cautions and the great variety of processes that contribute to the value of $\boldsymbol{f}$ (see full discussion in S-R), it is encouraging that $\boldsymbol{f}$ exhibits a small range (*Figure 7*). Indeed, modern observing methods and resulting available digital terrain models will allow the generation of additional data with which to apply the parameterization; and to also evaluate whether there are important regional variations in $\boldsymbol{f}$.

Recalling that $\boldsymbol{f}$ reflects the distribution of thickness change over the glacier length, we write, as an approximation to equation 4, the mean, centenary-scale, mass balance as:

$$\Delta\langle \boldsymbol{B} \rangle \approx \boldsymbol{f}\ \Delta \boldsymbol{h}(\boldsymbol{l})\ /\ \Delta \boldsymbol{t} \qquad \textit{EQN. 5}$$

where $\Delta\boldsymbol{h}(\boldsymbol{l})$ 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 8*); 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* 8, the field measurements required to determine $\Delta\boldsymbol{h}(\boldsymbol{l})$ in equation 5 are simple, though acquiring them may be both difficult and hazardous. Adequate planning and making reference to available mapping, photography and satellite imagery are paramount. Alternatively, if high-resolution digital terrain information is available, field measurements may not be necessary.

While absolute values of terminus and lateral moraine/trimline elevations would be desirable for plotting on related geomatics media, relative vertical differences between the terminus and the height of the across-valley lateral features are adequate. In fact, using a precision aneroid barometer/altimeter to measure relative height differences may be preferable to, for example, using autonomous GPS measurements whose vertical accuracy is limited, particularly in situations where the GPS antenna sky view may be severely impaired.

As discussed in section 1.4.2, site selection should consider glaciers that have well-defined and independent accumulation areas. Critical is that the glacier's contemporary terminus is below the highest evidence of trim lines or lateral moraines.

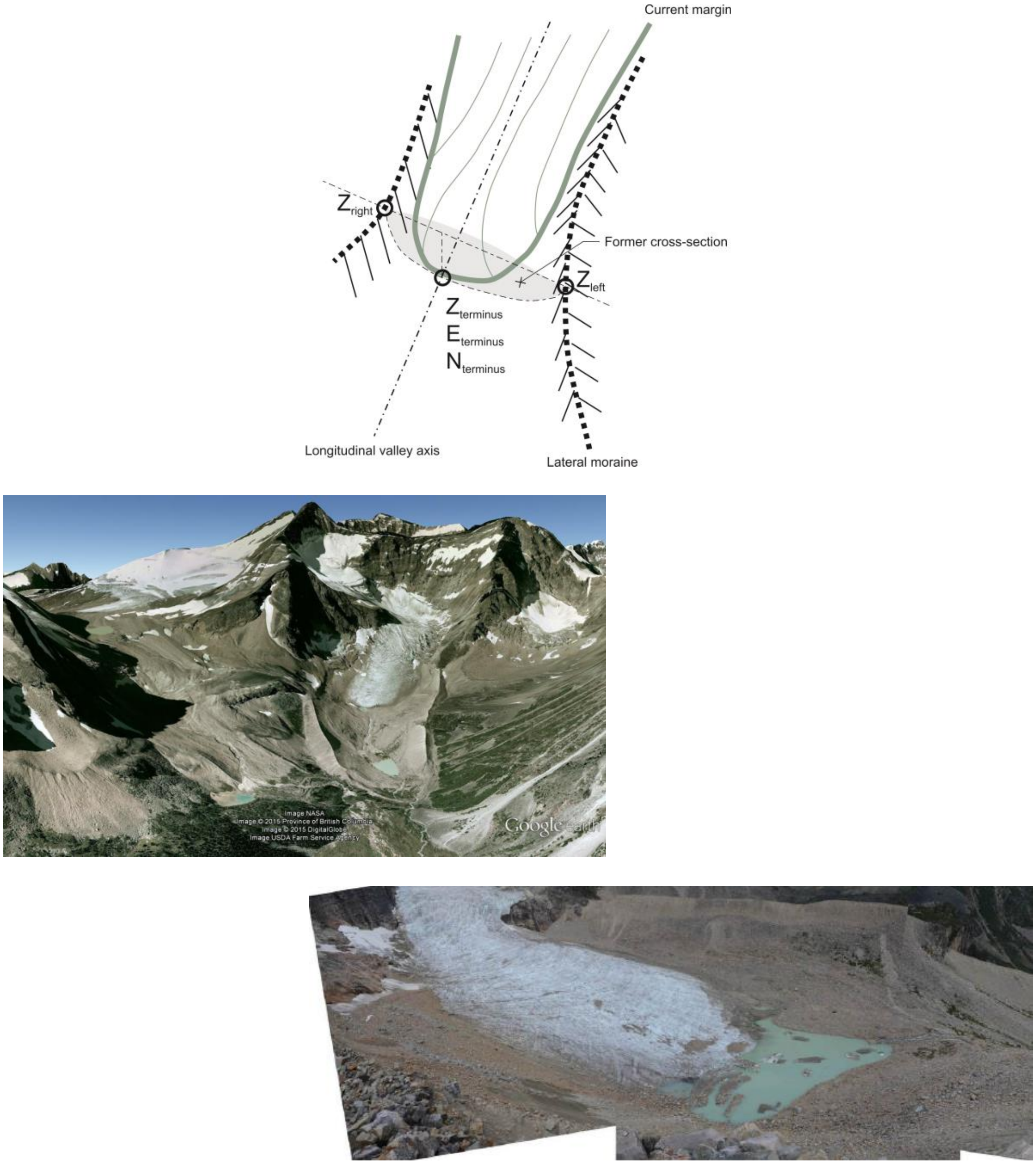

FIGURE 8 THICKNESS CHANGE MEASUREMENT SCHEMATIC AT THE CONTEMPORARY TERMINUS. EXAMPLE SHOWN IS THE PARAPET GLACIER IN JASPER NATIONAL PARK. PHOTO IS TAKEN FROM THE RIGHT-HAND LITTLE ICE AGE MORAINE CREST; ΔH ≈ C. 90 METRES (PHOTO CREDIT: GREG HORNE, JASPER NATIONAL PARK, AUGUST 23, 2013).

As an example, *Figure* 9 illustrates the annual mass balance time series for Peyto Glacier, Banff National Park, AB, 1966-2015. The application of equation 5 enables a first-order estimate that places this already long record in a valuable centenary context – that is, since the morphological expression of the Cavell Advance maximum (Luckman and Osborne, 1979; Luckman, 2006) during the Liitle Ice Age, c. 1850 C.E.:

$\Delta \boldsymbol{h}(\boldsymbol{l})$ = - 223 m (from a 2006 laser DEM),

$\Delta \boldsymbol{t}$ = 156 a (i.e., c. 1850-2006),

With $\boldsymbol{f}$ = 0.28, the derived average mass balance, 1850-2006, is:

$<\boldsymbol{B_a}>_{\boldsymbol{LIA}}^{\boldsymbol{max}} \approx$ - 0.4 m w.e. a^{-1}

This value is illustrated in relation to the inter-annual surface mass balance series, the series as a 10-year moving average and the overall series average (*Figure* 9).

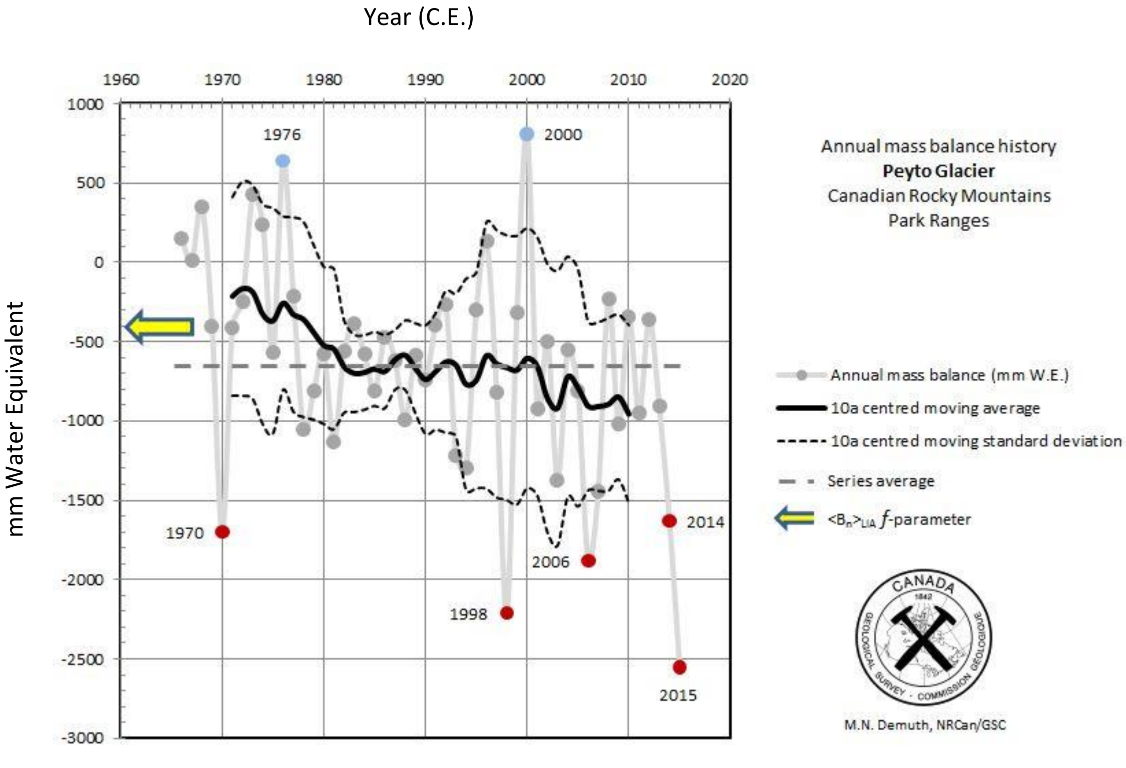

FIGURE 9 ANNUAL MASS BALANCE TIME SERIES FOR PEYTO GLACIER, ILLUSTRATING THE f-PARAMETER DETERMINED AVERAGE POST NEO-GLACIAL MASS BALANCE (SINCE C. 1850 C.E.).

2. GLACIER FLUCTUATIONS IN RELATION TO HYDRO-ECOLOGICAL FUNCTIONING

The presence of glaciers provides for terrestrial ecological qualities that are beneficial to some species. Mammals, for example, may travel over glaciers and high-level travel routes to access preferable habitat. An additional example is katabatic wind flow, enhanced by the presence of snow and ice, acting to diminish insect harassment.

Another important bio-physical system strongly connected to the presence of glaciers is the ecological functioning of streams and rivers that are glacier fed. *Cold stream ecology* is not a new sub-discipline of study in either hydrological or ecological realms (see Ward, 1994; and reviews by Demuth, 1997, and Petts *et al*., 2006). The number of studies where detailed assessments of glacier fluctuations are paired with downstream hydro-ecological observations, however, is more limited. They include the seminal work of Petts, Milner and Gurnell in the European Alps and Alaska (Petts *et al*., 2006).

Most of these studies concern the nature of swift water along the longitudinal zonation below the glacier portal, and defined primarily by variations in water temperature: *metakryal* $T_w \leq 2$°C; *hypokryal* $2 < T_w < 4$°C; and *glacio-rhithral* $4 < T_w < 10$°C (see Ward, 1994). Environmental harshness in relation to upstream/downstream differences in zoobenthic populations and diversity are also influenced by specific habitat characteristics - for example where lake outlets and non-glacial tributaries may attenuate the effects of severe inlet hydraulic and temperature conditions. Seasonal influences and habitat age are additional determining factors; as of course are the local and regional climatological and geomorphological settings.

For the purposes and scope of this GSC Open File, there is an emphasis on the effect of glacier fluctuations on aquatic systems. Further, we presuppose a *hydrology effects ecology* paradigm. As such, a brief review of the hydrological significance of glaciers is warranted.

2.1 GLACIERS AS STORAGE-DISTURBANCE

Glaciers act as *storage* (*Figure 10*; see also Jansson et al., 2003) whereby water in the form of firn and glacier ice is *stockpiled* during cool-wet climate episodes (positive mass budgets with an eventual tendency to expand the glaciers' boundaries); and *depleted* during warm, dry episodes (negative mass budgets with an eventual tendency to contract the glaciers' boundaries); and so, occurs in relation to their formation and decline. At the annual/seasonal scale, glaciers extend the seasonal peak river discharge by providing surface water when other sources are absent (rain) or in seasonal decline (snow). The major implication over climatic time-scales is global sea-level change; whereas for hydrology, the presence of glaciers modulates runoff.

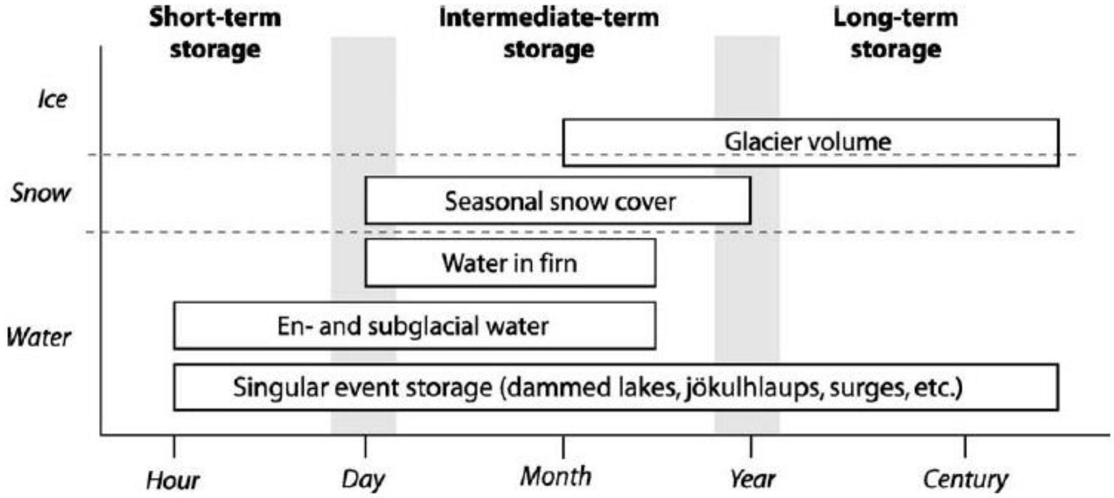

FIGURE 10 THE CONCEPT OF GLACIER STORAGE OVER VARYING TIMESCALES AND PHYSICAL MEDIA (JANSSON ET AL., 2003).

Glaciers may act as a source of disturbance, providing transient and extreme conditions such as those manifested from rain-on-glacier events. This, however, depends very much on the surface facies configuration of the glacier (*Figure 11*). If firn pack exists, snowmelt volumes entering the system from the glacier will be lagged. If firn pack is absent, snowmelt will not be lagged while the glacier surface remains relatively impermeable. As the permeability and hydraulic conductivity of the supra and englacial systems increases, meltwater from snow, ice and firn sources are lagged (i.e., sheet flow is lagged as the surface becomes rougher at both the micro-topography and inter-granular scales); and a portion of sheet flow is re-routed englacially and subglacially. With time, the englacial plumbing system becomes more fully developed and its lag contribution decreases.

Another defining and hydrologically relevant feature is streamflow *diurnality*. The degree that the seasonal snowline rises will expose more or less glacier ice (and possibly firn). This imparts a distinct but variable diurnal signal according to the amount of low albedo glacier ice and firn that become exposed to short-wave radiation. For temperate regions generally, this albedo effect overcomes the influence of declining solar azimuth, and so, even in August (northern hemisphere), specific runoff from exposed ice and firn facies is relatively high.

The evolution of the daily hydrograph in temperate latitudes where glaciers exert their influence is as follows (northern hemisphere):

- a gradual increase in mean monthly discharge from June to August;
- until mid-July the curve is smooth, with minimal diurnal variability reflecting the lag effect induced by snowpack and firnpack storage; the conduits within the glacier ice are only partially developed;
- from mid-July until late August, the amplitude of the diurnal oscillation increases with increasing net radiation inputs, as increasing exposure of relatively low albedo glacier ice outweighs the effect of decreasing solar radiation receipts;
- during this later period, the maximum diurnal discharge moves forward (i.e., earlier) from late afternoon on account of the decreasing snow storage lag and the maturation of the englacial drainage network.

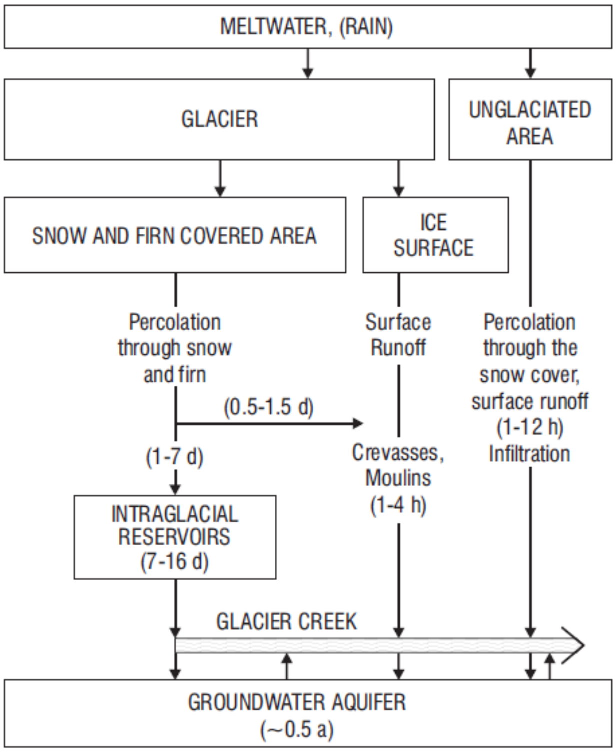

FIGURE 11 THE ESCHER-VETTER CONCEPTUAL MODEL OF HEADWATER ROUTING TO THE GLACIER STREAM, AFTER OERTER ET AL. (1981) AND REVIEWED IN MORRIS (2006).

2.2 KEY CONCEPT REVIEW

Glaciers:

- serve as robust indicators of climate variability and change;
- act as low-pass hydrological "filters", useful to and relied upon by numerous natural and human systems. The filter effect operates at many time scales as the melt process and glacier drainage features evolve seasonally;
- are a source of water when other sources are in seasonal decline or absent;
- are a source of disturbance, within the general pattern of: i) sequential high primary productivity; ii) high disturbance; iii) post-disturbance recovery; iv) secondary productivity fostered by sustained stable conditions;
- are source of disturbance stemming from sediment flushing from the glacier or sediment intrusions from collapsing banks or slope erosion - possibly induced by glacier debutressing as glaciers retreat or the region thaws.

The next section of this Open File considers the development of a "glacier condition" rubric that includes a thresholding measure tied to the aquatic resource qualities exerted by the presence and physical disposition of headwater glaciers. In considering this, one has to broaden the consideration from the current "new normal" - that for the most part, glaciers, in virtually all regions of the World, have contracted over the last one and one-half centuries (see f.ex., Zemp *et al*., 2015).

3. GLACIER CONDITION PROTOCOLS AND REPORTING

Under the influence of a particular surface energy balance regime, the presence of glaciers and their surface facies configuration (i.e. the distribution of ice, firn and snow over the glacier) will modulate the nature of run-off generation and water quality. Characteristics include the seasonality of initiation and cessation of glacier derived streamflow, streamflow magnitude over multiple scales, turbulence, and water temperature, dissolved oxygen and sediment load.

From section 1.2, the Accumulation Area Ratio ($\boldsymbol{ARR}$) is closely coupled to the mass balance of the glacier, with the later an integrated outcome of weather and climate forcing (precipitation, air temperature, solar radiation and cloud cover). The $\boldsymbol{AAR}$ is the ratio of the accumulation area to the total area of the glacier. In essence, it describes the facies configuration of the glacier as a proportion of the area that is being adequately nourished, in an annual sense, and thereby contributing to the production of glacier ice. A particular glacier will exhibit an *equilibrium* $\boldsymbol{AAR}$ or $\boldsymbol{AAR_0}$, and the related $\boldsymbol{ELA_0}$ - in other words, the $\boldsymbol{AAR}$, and thereby its facies configuration, when it is in mass balance equilibrium.

In a cumulative sense, deviations from equilibrium $\boldsymbol{AAR}$ will eventually result in *committed area loss* (Mernild et al., 2013) or, as the case may be, a committed area gain. In the former case, the committed area loss ($\boldsymbol{CAL}$) under a constant climate can be written as:

$$\boldsymbol{CAL = \frac{1-AAR}{AAR_0}} \qquad \textit{EQN. 6}$$

The “constant climate” could be prescribed as the average of, say, the last decade and the associated average $\boldsymbol{AAR}$ for that decade; with equation 6 describing the committed area loss that would occur if the climate were to remain unchanged from that prescribed average condition – in other words, in this case, without any further warming (Zemp et al., 2015).

While the $\boldsymbol{CAL}$ may give an intuitive and long-term regional sense of the water flux potential under a state of mass balance disequilibrium, the inter-annual variation of the $\boldsymbol{AAR}$ lends itself to quantifying the state or “condition” of a glacier in terms of it providing hydrological storage and generating runoff.

3.1 AAR-BASED GLACIER CONDITION INDICATOR

In a general sense, glaciers cannot be managed, but their presence and configuration (f.ex., size and surface facies configuration) affect, in the context of this discussion, hydro-ecological functioning. Fish habitat, on the other hand, can be managed through knowledge of upstream streamflow generation processes and trends in combination with efforts to, for example, augment minimum streamflows for habitats influenced by sediment deposition (f.ex., Wood, 1997).

While the mass balance of a glacier is a useful measure of its condition from a glacio-climate point of view, even the simple designation of the mass balance being in equilibrium, positive or negative cannot reconcile, for example, the notion that a glacier exhibiting a positive mass balance (to a point) will still be providing meltwater and thereby some positive hydro-ecological value. Conversely, a glacier exhibiting negative mass balance (also to a point) will still be generating storage. Essentially, the measure of mass balance alone may be difficult to interpret in terms of a resource conservation goal and related policy messages.

The ***AAR*** is one of the metrics used by a glaciologist to characterize and understand glacier mass balance, but in a more general system sense can describe the glacier's propensity to generate storage and provide disturbance. For example, from section 1.1, the proportion of accumulation area relative to total glacier area suggests how much of the glacier is generating firn and ice through the accumulation and densification of seasonal snow. Conversely, the amount of ablation area governs meltwater generation, and runoff lag through the variable exposure of glacier ice and the presence of varying firnpack (Moore and Demuth, 2001).

Figure 12 describes the *balanced budget* ***AAR*** or $\boldsymbol{AAR_0}$ for the Earth's temperate alpine glaciers. As an example of the data contributing to a global $\boldsymbol{AAR_0}$, *Figure* 12 also presents the relationship between the annual mass balance and the ***AAR*** for a long-studied glacier in the Canadian Rocky Mountains - Peyto Glacier. Specifically, it illustrates Peyto Glacier's ***AAR*** for a balanced mass budget (i.e, $\boldsymbol{AAR_0}$ = 52.5 %).

If adequate data is available to describe the ***Bn-AAR*** relationship (f.ex., *Figure* 5, lower left panel), the $\boldsymbol{AAR_0}$ value can be readily determined. This value may then also be useful for assessing the condition of the glaciers in the surrounding region, providing the site is representative in terms of setting, configuration and typology.

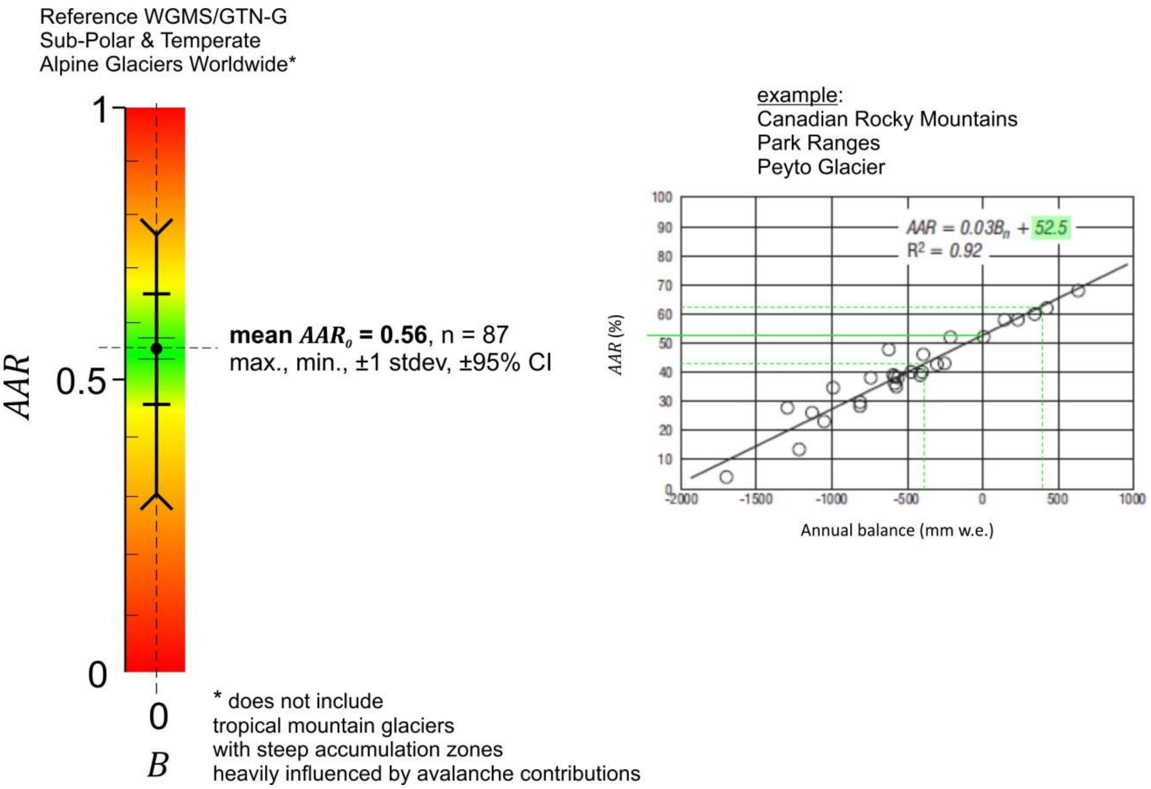

FIGURE 12 THE GLOBAL MEAN AAR_0 FOR THE MEASURED SUB-POLAR AND TEMPERATE ALPINE GLACIERS (n= 87). ALONGSIDE IS AN EXAMPLE DATA SET ILLUSTRATING THE B_a-AAR RELATIONSHIP FOR PEYTO GLACIER AND CONTRIBUTING TO THE GLOBAL VALUE AND ITS VARIANCE. DATA IS FROM WORLD GLACIER MONITORING SERVICE AND DEMUTH AND KELLER, 2006.

The AAR is easily interpretable, scale invariant (i.e., a ratio), and relatively easy to measure (for example, from remote sensing; see section 1.3). It is also inherent that the AAR-based glacier condition indicator is applicable to the general situation where one is unable to ascribe a site specific AAR_0, and therefore employs knowledge of the regional AAR_0 (if available) or the global AAR_0; or for the situation where the mass balance observing program is mature enough to ascribe an AAR_0 value.

3.2 GLACIER CONDITION THRESHOLDING AND IMPLEMENTATION

Parks Canada’s ecosystem integrity indicator approach uses a three-level system to describe the “condition” of a valued ecosystem element (Parks Canada, 2011; Technical Appendix 5) - good (green), fair (yellow) and poor (red). Arriving at “scores” and deciding on thresholds for delineating a condition for individual indicators, or a composite of measures towards an indicator, involve various strategies – both quantitative and qualitative. Challenges arise when attempting to describe the overall status and trend of a biophysical element when its constituent measures and metrics are complex and, in fact, when the interactions between elements are not well studied or understood.

By reviewing the glacier hydrology, geomorphology and glacier river ecology literature (f.ex., Moore et al. 2009; Gurnell and Fenn, 1987; Petts et al., 2006), several basic riverine and landscape qualities have been incorporated into a conceptualization of a hydro-ecologically relevant glacier condition measure. Importantly, they are contemplated from a bimodal view of the glacier's state.

Figure 13 illustrates a proposed glacier condition/thresholding rubric that utilizes the deviation from an equilibrium $\boldsymbol{AAR}$ configuration. Also mapped out in a qualitative and pseudo-quantitative manner are glaciological and landscape characteristics and their hydro-ecological manifestations. They include trends in the proportion of ice and firnpack, and general glacier cover extent (amount and fragmentation); and basic geomorphological attributes such as side valley slope stability and foreland river encroachment. Hydro-ecological manifestations are linked to streamflow seasonality (timing and volume) and its higher frequency constituents. Sediment loading and water temperature are additional and complimentary attributes (see f.ex., Petts et al., 2006). The later may in fact be part of parallel condition reporting.

While the $\boldsymbol{AAR}$ mass balance metric is a continuous property between the limits of $\boldsymbol{AAR}$ = 0 or 1, it is proposed that the need for "thresholding" incorporate the $\boldsymbol{AAR}$ sample variance. This could be accomplished more or less simply by noting the occurrence of a standard deviation from the mean, or by evaluating shifts in the mean using a *t-test* or *Mann-Kendall test*, for example.

As a starting point, it is proposed that the initial threshold from an equilibrium configuration is crossed when the value of $\boldsymbol{AAR}$ deviates from $\boldsymbol{AAR_0}$ by a single standard deviation (in either direction). This is the good-to-fair threshold. Further, it is proposed that persistence and rate-of-change in the deviation be incorporated as a subsequent threshold - fair-to-poor.

To reiterate the bimodal considerations of the proposed rubric we consider - a glacier that exhibits an $\boldsymbol{AAR}$ value approaching 1 (or 100%) will exert a negative influence on streamflow characteristics that concern the highly adapted biota in glacier affected streams - even though we might, from a glacio-climate point of view, determine that a period of extreme positive annual mass balance is a desirable "condition" for a glacier in today’s new “normal” of negative mass balance disequilibrium and accelerating glacier contraction.

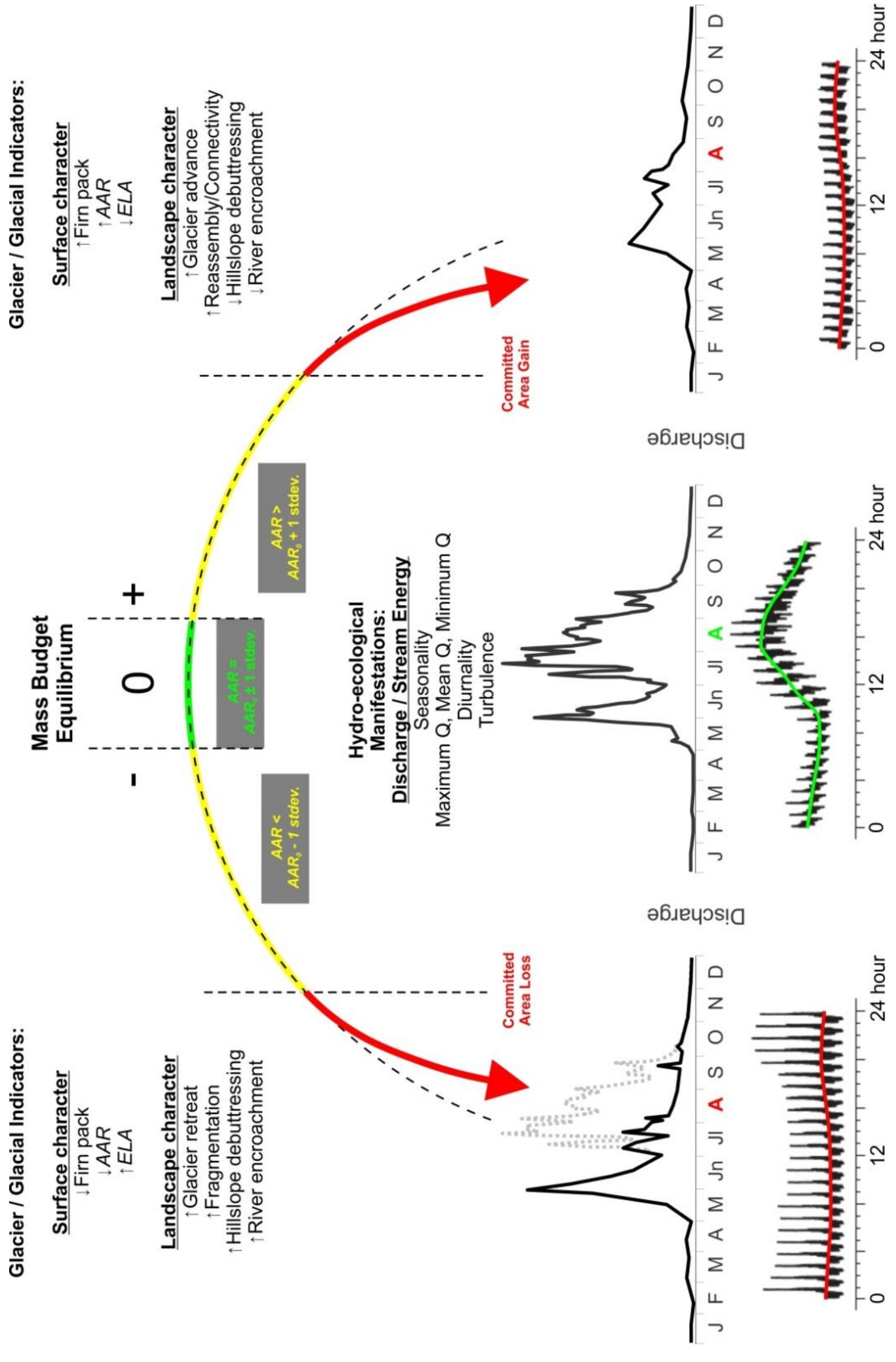

FIGURE 13 A GLACIER CONDITION AND THRESHOLDING RUBRIC IN RELATION TO GLACIOLOGICAL, LANDSCAPE AND HYDRO-ECOLOGICAL QUALITIES FOR EQUILIBRIUM AND DISEQUILIBRIUM GLACIER CONFIGURATIONS.

Figure 14 illustrates a decision framework for assessing glacier condition based on whether the glacier $\boldsymbol{AAR}$ deviates from its equilibrium value and whether that deviation is persistent or accelerating. To implement this, a deviation quantity $\boldsymbol{\Delta R_0}$ is defined as the difference between the current $\boldsymbol{AAR}$ and the equilibrium value.

$$\boldsymbol{\Delta R_0 = AAR - AAR_0}$$

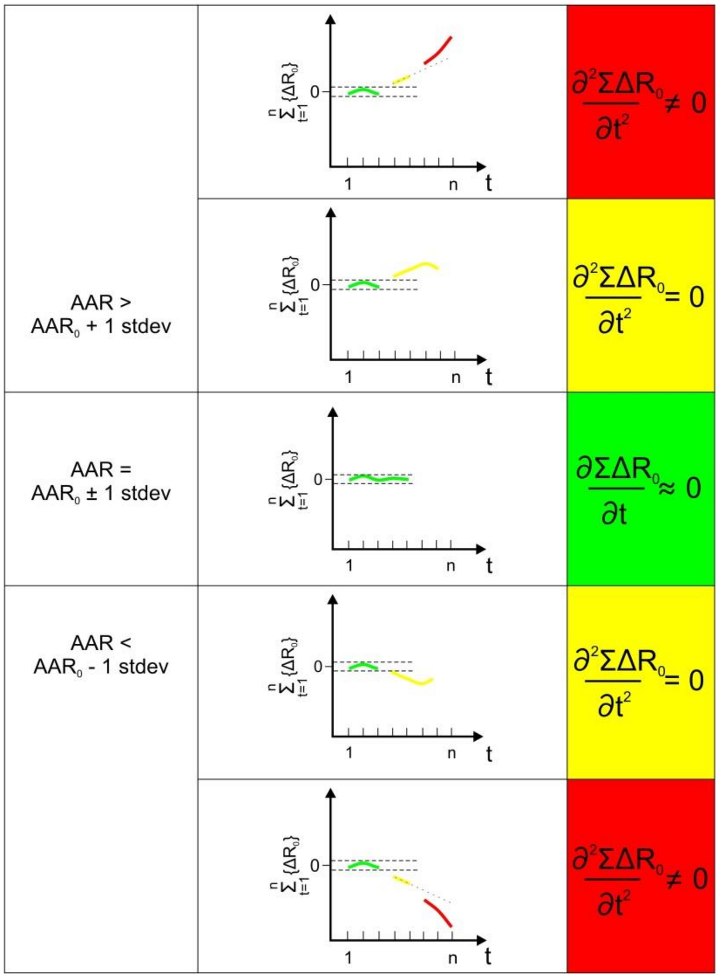

FIGURE 14 A MAGNITUDE AND RATE-OF-CHANGE DECISION FRAMEWORK FOR ASSESSING AN AAR-BASED GLACIER CONDITION. COLOURS GREEN, YELLOW AND RED ARE IN ACCORDANCE WITH PARKS CANADA'S GOOD, FAIR AND POOR CONDITIONS RESPECTIVELY.

Figure 15 illustrates the implementation of the decision framework of *Figure* 14 using a workflow schematic. A synthetic $\boldsymbol{AAR}$ dataset is used to provide examples of determining a glacier condition as guided by the magnitude of its deviation ($\boldsymbol{\Delta R_0}$,), persistence and acceleration, irrespective of direction. The workflow is self-explanatory. Notably, an $\boldsymbol{AAR}$ of 0 or 1 is assigned a *poor* condition.

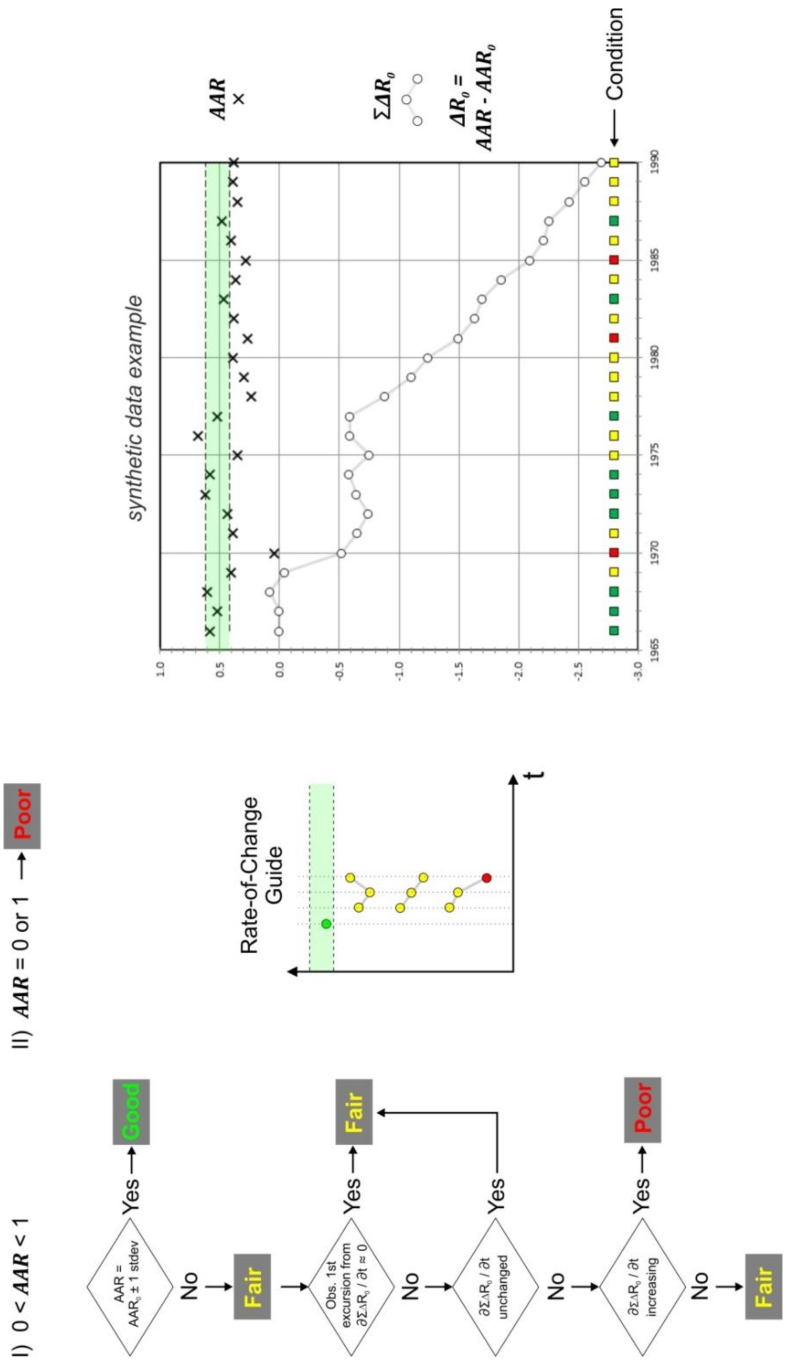

FIGURE 15 WORKFLOW FOR AN AAR-BASED GLACIER CONDITION DECISION FRAMEWORK. ITS IMPLEMENTATION CONSIDERS AAR LIMITS APPROACHING THE END POINTS OF 0 AND 1. SYNTHETIC DATA IS USED TO ILLUSTRATE HOW THE SERIAL PROGRESSION OF AAR MANIFESTS IN TERMS OF PERSISTANCE AND ACCELERATION.

Appendix D presents a step-by-step application guideline for the implementation of an $\boldsymbol{AAR}$-based glacier condition rubric.

CONCLUSIONS AND RECOMMENDATIONS

This Open File report has proposed a 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. The rubric is centred on a glacier mass balance metric - the *Accumulation Area Ratio,* $\boldsymbol{AAR}$ - and its deviation from an equilibrium value $\boldsymbol{AAR_0}$. A rate-of-change threshold decision structure and workflow implementation is presented, and illustrated using synthetic data.

The aforementioned work is first founded by: i) an overview of the nature and measurement of glacier fluctuations (mass balance and related metrics) - in particular, presenting a methodology ($\boldsymbol{f}$-parameter) with which to contextualize recently acquired but short and sparsely distributed annual mass balance time series’; and ii) a review of the hydro-ecological significance of glaciers – as low-pass filters between meteorological/climate forcing and the generation of hydrological storage and streamflow; and as source of high-frequency disturbance.

It is recommended that further work be conducted whereby mutually relevant ecosystem functioning indicators are continuously evaluated from an individual and whole system perspective where glaciers are concerned; and that this be done with adequate two-way feedback between specialists as Parks Canada considers the role of glacier monitoring and assessment in their need to evaluate and manage ecosystem integrity. For example, as some glaciers become “preserved” by retreating into topographical niches, or disappear completely, new ecosystem resilience or vulnerably issues may emerge.

Glacier fluctuation is a complex phenomenon in terms of its external drivers, internal processes and feedbacks, and outward impacts. It will be important that uniform nomenclature is used in both technical and outreach interactions. Strategies on measurement and the assessment of derived quantities is provided in Appendix E.

As detailed by Petts et al. (2006) considerable opportunity exists to understand downstream ecosystem functioning and health by conducting interdisciplinary monitoring science and research science. Our protected areas are ideal venues for such study given the availability of mutually beneficial logistical and intellectual resources. Given that systematic glacier observation can provide a measure of internal system variability versus that due to global climate change, continuing to incorporate the information is critical for improving our understanding of what are and are not natural system limits.

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

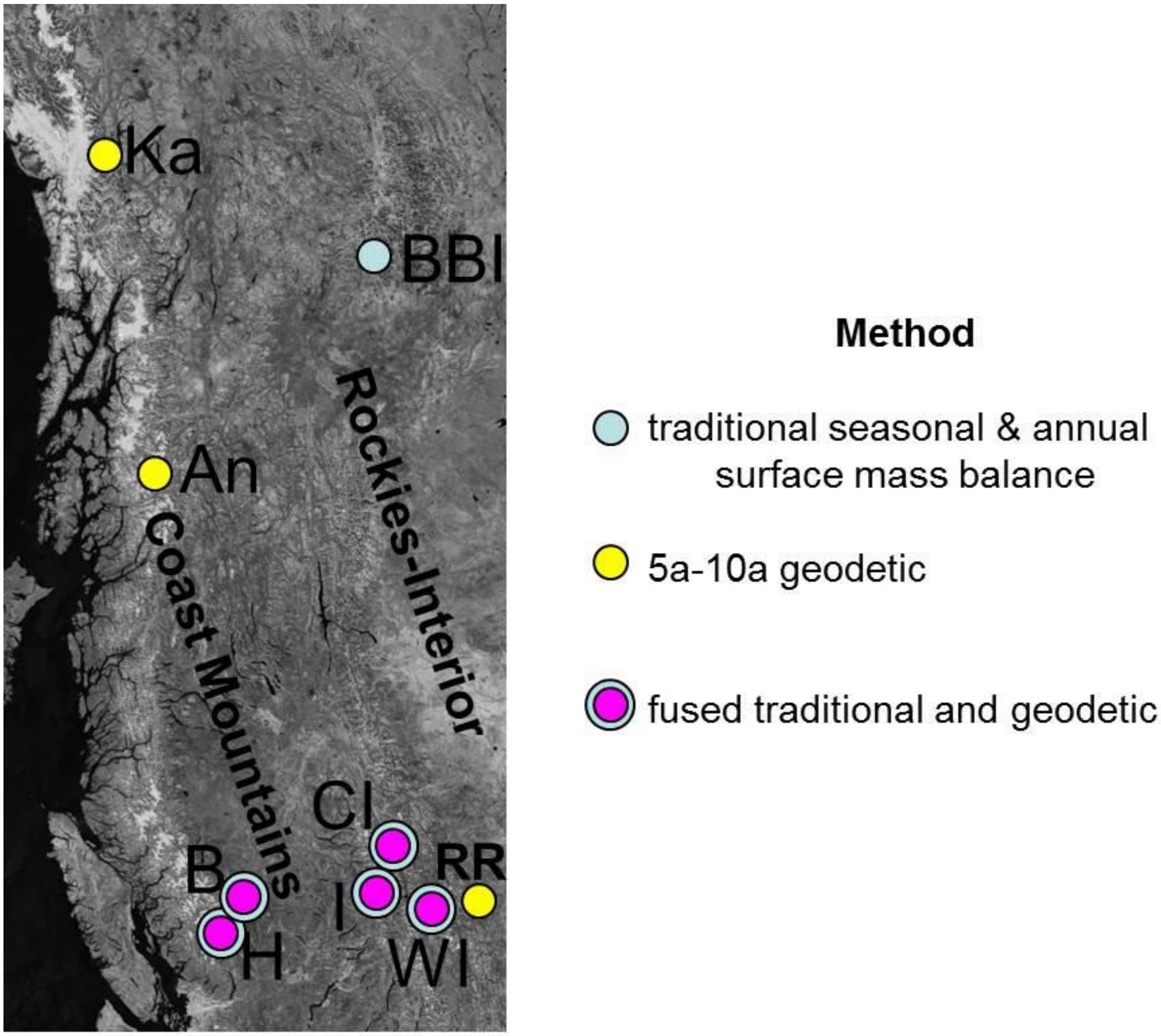

FIGURE A 1 REFERENCE MASS BALANCE OBSERVING SITES FOR THE CORDILLERA: WI = WAPTA ICEFIELD (PEYTO AND YOHO); RR = RAM RIVER; CI = COLUMBIA ICEFIELD (ATHABASCA AND SASKATCHEWAN); I = ILLECILLEWAET; BBI = BRINTNELL-BOLOGNA ICEFIELD (BOLOGNA); KA = KASKAWULSH; AN = ANDREI; B = PLACE; H = HELM.

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 the authors.

APPENDIX B: GLACIER MASS BALANCE METHODS – GEODETIC

The geodetic, "cartographic" or "topographic" method involves the multi-temporal mapping of glacier surface elevations; these data usually provided in the form of digital elevation models (DEM). DEMs may be derived from historical mapping products, or determined from terrestrial optical theodolite or GPS positioning surveys, photogrammetry or laser scanning. Conversion of elevation change to mass balance requires information on density variation in space and time. This method has become increasingly popular because of its relative simplicity, though knowledge of the DEM's vertical and horizontal reference systems is critical for accurate multi-temporal analysis (Goulden et al., 2012 and 2013).

Mass balances are increasingly being reported from measurements derived using the geodetic method. As introduced earlier, the geodetic method utilizes two digital elevation models to derive a volume change – which is in-turn translated into a mass change by applying a simple density adjustment for the ablation and accumulation areas present over the course of the time interval considered. Moreover, if laser scanners are employed and there is a capacity to record laser return waveforms, it is possible to discriminate between snow, firn and ice facies and so map the accumulation area and the ablation area in addition to obtaining a DEM (f.ex., Hopkinson and Demuth, 2006).

While geodetic and direct derivations of mass balance are complimentary, great care must be taken when attempting to combine them or deduce a process or systematic error when comparing them. For example, the density adjustment used may be too simplistic and result in cumulative errors since the ablation area may constitute both ice and old firn – particularly when the trajectory of the equilibrium line altitude (dividing the accumulation and ablation regions) is progressively upward. The geodetic method is also subject to the effects of dynamic readjustment from a previous climate forcing episode; and while it represents the "true" or hydrological mass balance (density adjustment error notwithstanding) over the time interval used, it may be out-of-phase with the reaction/volume adjustment of the glacier.

Fischer (2011) provides a valuable analysis for understanding and reconciling the difference borne out by the two methods; methods whose results are often presented together. Importantly, trends in the difference between the results of using the direct and geodetic methods can vary from glacier to glacier and can differ for specific glaciers under varying types of climate forcing (Fischer, 2011).

APPENDIX C: GLACIER MASS BALANCE METHODS – MASS-FLUX DIVERGENCE

The flux-divergence method applies the principal of mass continuity, where the thickness (***h***) change at a point of the glacier is caused by a variation in the surface, internal and basal balances and the flux of ice into and away from that point.

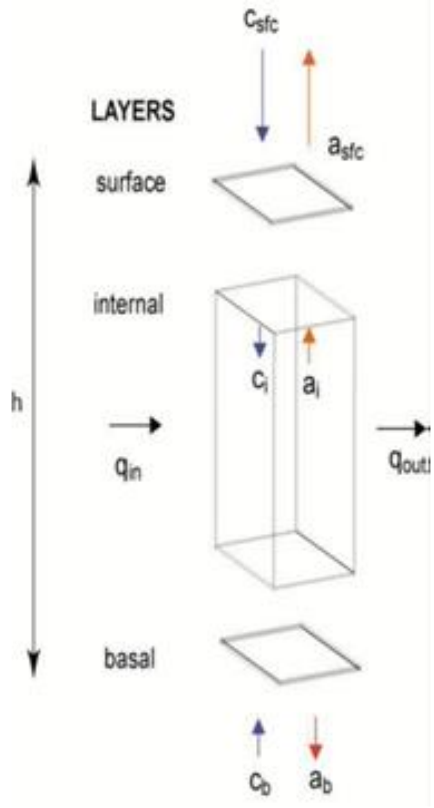

FIGURE C 1 A CONTROL VOLUME REPRESENTATION OF THE PRINCIPLE OF MASS CONTINUITY

The generalized mass continuity equation is:

$$\dot{\boldsymbol{h}} = \dot{\boldsymbol{b}} - \boldsymbol{\nabla} \cdot \vec{\boldsymbol{q}} \qquad \textit{(EQN. B-1)}$$

$\dot{\boldsymbol{h}}$ is the rate of glacier thickness change and $\dot{\boldsymbol{b}}$ is the rate of mass gain or loss for the glacier surface, interior and bed. The last term is the divergence of the horizontal flux vector $\vec{\boldsymbol{q}}$ which is the integral through the glacier thickness of the vertical profile of the horizontal mass flux vector $\boldsymbol{\rho}\vec{\boldsymbol{u}}$, where ρ is the density and $\vec{\boldsymbol{u}}$ is the velocity vector.

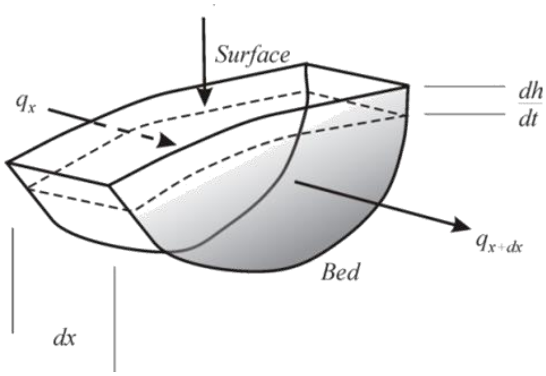

FIGURE C 2 THE CONCEPT OF MASS CONTINUITY REPRESENTED FOR AN INFINTESSIMAL GLACIER ELEMENT ALONG THE LONGITUDINAL GLACIER AXIS.

The technique is particularly applicable to large icefields and ice caps and their outlet glaciers where, instead of measuring the direct or surface balance over large complicated regions, it may be more viable to assess the quantity of mass flowing through a flux gate (commonly the long-term equilibrium line); and so determine whether the amount of mass flux leaving the flux gate is being replaced from up-glacier. Also required are data on ice thickness/thickness change and accumulation rates above the flux gate.

The technique requires an estimate of $\vec{q}$ in equation B-1. This is normally derived from the average of the surface velocity at the flux-gate cross-section. While one can measure the surface ice motion using multi-temporal trigonometric or GPS position measurements at reference points distributed over the glacier surface, it is more common to now employ satellite remote sensing and detect motion using radar interferometry (see f.ex., van Wychen et al., 2013) or optical feature tracking. The latter is often confounded by cloud cover. The former requires specialized expertise and can be confounded by changes in radar image coherence due to new snow on the surface, melting or surface roughness changes.

Figure B-3 illustrates surface ice velocities over the Columbia Icefield derived from satellite radar interferometry. The “speckle-tracking” method was employed (f.ex., Gray et al., 2001; Short and Gray, 2004) using repeat Radasat2 images (ultrafine beam mode (U25); 2015-03-05 and 2015-03-29) to track surface motion. Geocoding was enabled using data from the Canadian Digital Elevation Model Mosaic (CDEM; NRCan, 2012).

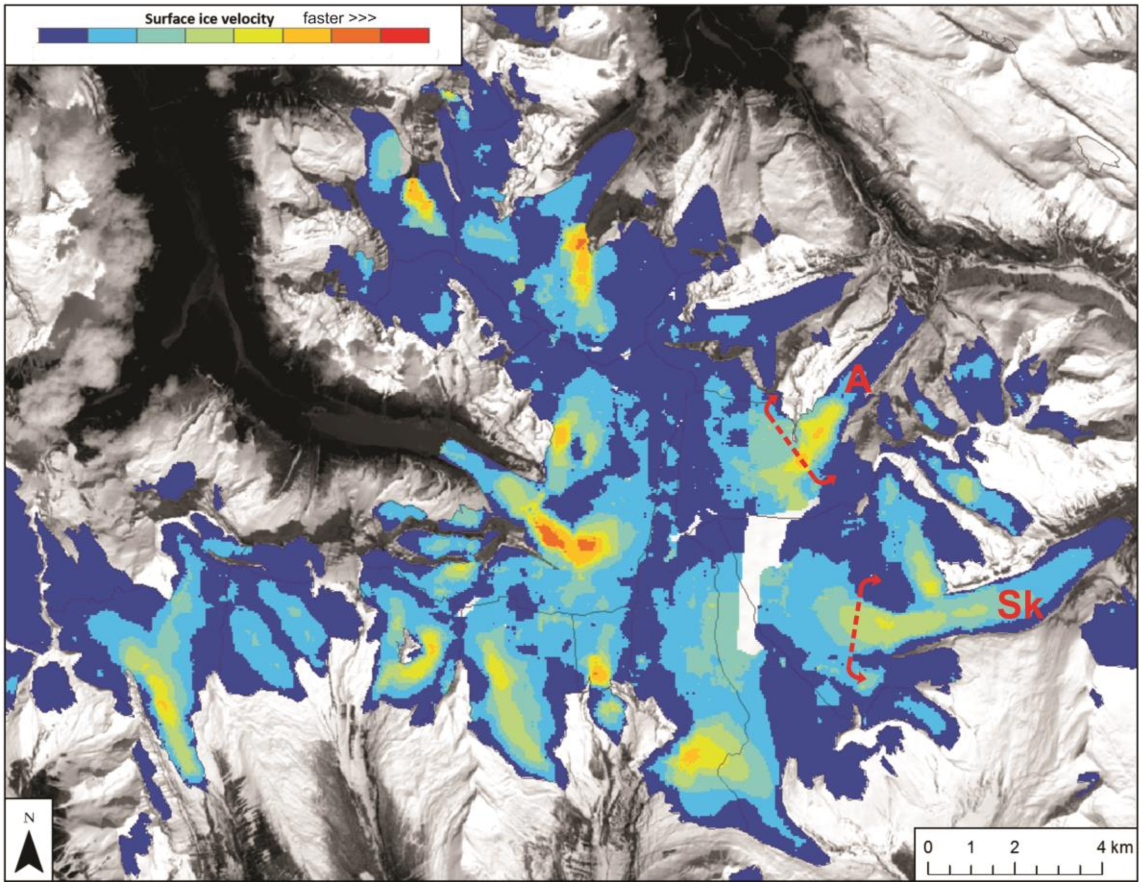

FIGURE C 3 SURFACE FLOW VELOCITIES OVER THE COLUMBIA ICEFIELD DETERMINED FROM SPECKLE TRACKING INTERFEROMETRY USING RADARSAT2 DATA. THE ATHABASCA (A) AND SASKATCHEWAN (SK) GLACIER FLUX GATES ARE NOTED. WARMER COLOURS CORRESPOND TO HIGHER VELOCITIES. INTERFEREOMETRIC PROCESSING WAS PERFORMED BY W. VAN WYCHEN UNDER CONTRACT TO M. SHARP, UNIVERSITY OF ALBERTA. RADARSAT2 DATA IS COURTESY OF PARKS CANADA.

The authors are currently using the surface velocity data to estimate the mass flux divergence values for the Athabasca Glacier and Saskatchewan Glacier flowsheds. It should be noted that the mass flux divergence method is only informative when inputs (surface balance) are averaged over a time scale representative of the current climatic period (i.e., decadal scale); and so, inter-annual variability is filtered out in the measured values of flux.

This information will be reported periodically alongside annual mass balances determined using the traditional method as part of a glacier monitoring and assessment collaboration between the Geological Survey of Canada, Jasper National Park and Banff National Park (Demuth et al., 2012a, 2012b; Persad et al., 2013).

APPENDIX D: APPLICATION GUIDELINES FOR IMPLEMENTING AN AAR-BASED GLACIER CONDITION RUBRIC

1. *AAR* delineation using the Traditional Method for a single reference observing glacier:

a) Refer to *Figure* 2, $\boldsymbol{b_a(z)}$

b) Determine the altitude z where $\boldsymbol{b_a} = 0$

This is the Equilibrium Line Altitude, ***ELA***

c) Refer to *Figure* 2, ***s(z)***

d) Determine the area above the ***ELA***

This is the Accumulation Area, ***AA***

e) Compute ***AAR*** = ***AA*** / ***S*** ; where ***S*** is the total glacier area

f) Relate ***AAR*** to the site, regional or global $\boldsymbol{AAR_0}$ (f.ex. *Figure* 12)

g) Refer to *Figure* 14 and 15 to determine the AAR-derived glacier condition

2. *AAR* delineation using remote sensing for a single or multiple glacier(s) - in isolation from or in conjunction with the Geodetic Method:

Option i) multiple sources of ortho-rectified and geo-referenced satellite imagery obtained from optical sensors such as Landsat8 and SAR sensors such as Radasat2 may be used to classify glaciological zones and facies, and enable the delineation of the annual ***EL*** and thereby the ***AA*** (see Sidjak and Wheate, 1999; Demuth and Pietroniro, 1996; GLIMS, 2014).

Option ii) laser scanners used for generating DEMs (used in the Geodetic Method and to generate ***s(z)***) may also facilitate the recording of laser return waveforms and thereby allow the classification of snow, firn and ice facies and the delineation of the annual ***EL*** and ***AA*** (see Hopkinson and Demuth, 2006; Demuth 2013).

Option iii) conducting field transects (employing dGPS or laser-based trigonometric survey techniques) along visible signs of the annual ***EL*** can be used to plot the ***EL*** and ***AA*** on available ortho-rectifed and geo-referenced maps and imagery. This can provide validation for the results from Option i) or ii), and can be compared to the result derived from the traditional method (steps 1a to 1e).

APPENDIX E: TOWARDS UNDERSTANDING AND GENERATING HIGH-QUALITY DERIVED QUANTITIES

1. Plan

Modernize your approach to leverage national and international experts in measurement network design, technology, training, data processing and condition assessment.

2. Understand the science

Be informed by a clear understanding of the science and physics principles behind glacier fluctuations.

3. Systematically analyze your data and manage the variance

Understand the sources of variance by adaptively managing the monitoring plan. Mitigate for non-stationarity to provide timely, evidence-based (applicability, measurement error and deviations) results.

4. Qualify derived glacier condition results

To provide evidence of reliability use ICE to maintain and disclose all comprehensive records and condition decision levels and some estimate of the quality of that decision.

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LITERATURE CITED

Clarke, G.K.C., A.H. Jarosch, F.S. Anslow, V. Radic and B. Menounos, 2015. Projected deglaciation of western Canada in the twenty-first century. *Nature Geoscience Letters,* 2015-April-6. DOI: 10.1038/NGEO2407.

Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp, 2011. Glossary of Glacier Mass Balance and Related Terms. Working Group on Mass-balance Terminology and Methods of the International Association of Cryospheric Sciences (IACS). IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

Comeau, L.E.L., A. Pietroniro and M.N. Demuth, 2009. Glacier contribution to the North and South Saskatchewan Rivers. *Hydrological Processes* **23**: 2640-2653.

Demuth, M.N., 1997. Effects of short-term and historical glacier variations on cold stream hydro-ecology: A synthesis and case study. *National Hydrology Research Institute Contribution Series* CS-96003, 15p.

Demuth, M.N., 2010. Glacier-Climate Observing in Canada – The State and Evolution of Canada's Glaciers. In - WGMS 2010: Summary Report on the WGMS General Assembly of the National Correspondents 2010. Zemp, M., Gärtner-Roer, I., Nussbaumer, S.U., Paul, F., Hoelzle, M. and Haeberli, W. (Eds). World Glacier Monitoring Service, Zurich, Switzerland.

Demuth, M.N., 2013. Lidar in Glaciology. In - Encyclopedia of Snow, Ice and Glaciers. V.P. Singh, P. Singh and U.K. Haritashya editors. p.713-722. Springer-Verlag Encyclopedia of Earth Sciences Series. ISBN: 978-90-481-2641-5, ISBN: 978-90-481-2642-2 (eBook).

Demuth, M.N., A. Chichagov, S. Samsonov, C. Armenakis, G. Mitchell and C. Hopkinson, 2012a. The form and flow of the Columbia Icefield Canada – towards understanding its mass balance using traditional and geodetic approaches supported by optical, laser and radar remote sensing. Abstract Proceedings, Canadian Remote Sensing Symposium, University of Ottawa, June 2012.

Demuth, M.N., D. Haggarty and P. Wilson, 2014. The glaciers of Nahanni National Park Reserve. Chapter 16 in – <u>Global Land Ice Measurements from Space</u>. J.S. Kargel, G.L. Leonard, M.P. Bishop, A. Kääb and B. Raup (Eds). Springer Praxis Books – Geophysical

Sciences. ISSN 1615-9748, ISBN 978-3-540-79817-0, ISBN 978-3-540-79818-7 (eBook), DOI 10.1007/978-3-540-79818-7.

Demuth, M.N. and R. Keller, 2006. An assessment of the mass balance of Peyto Glacier (1966-1995) and its relation to recent and past century climatic variability. In - Peyto Glacier: One Century of Science, M.N. Demuth, D.S. Munro, and G.J. Young (Eds). *NHRI Science Report Series* **8**, Environment Canada, National Hydrology Research Institute, Saskatoon, Saskatchewan, p.83-132.

Demuth, M.N., S. Marshall, G.K.C. Clarke, C. Hopkinson, A. Chichagov, J. Pomeroy, R. Wheate and J. Hirose, 2012b. The Columbia Icefield – Water for Life 2010-2015. An intersection of cryosphere, climate and water with natural resource and environmental sectors. Poster presentation to the Geological Survey of Canada Earth Science Management Council – available from the authors.

Demuth, M.N., D.S. Munro and G.J. Young (Editors), 2006. Peyto Glacier: One Century of Science. National Hydrology Research Institute Science Report #8, 278pp. Cat No. En 36-513/8E; ISSN: 0843-9052; ISBN: 0-660-17683-1.

Demuth, M.N. and A.Pietroniro, 1999. Inferring glacier mass balance using RADARSAT: Results from Peyto Glacier, Canada. *Geografiska Annaler* **81A**(4): 521 540.

Demuth, M.N., V. Pinard, A. Pietroniro, B.H. Luckman, C. Hopkinson, P. Dornes, and L. Comeau, 2008. Recent and past-century variations in the glacier resources of the Canadian Rocky Mountains–Nelson River system. *Terra Glacialis*, Special Issue: Mountain Glaciers and Climate Changes of the Last Century, L. Bonardi (Ed). p.27–52.

Elsberg, D.H., W.D. Harrison, K.A. Echelmeyer and R.M. Krimmel, 2001. Quantifying the effects of climate and surface change on glacier mass balance. Journal of Glaciology **47**(159): 649–658. DOI: 10.3189/172756501781831783.

Fischer A., 2011. Comparison of direct and geodetic mass balances on a multi-annual time scale. *The Cryosphere* **5**: 107-124.

GLIMS, 2014. Global Land Ice Measurements from Space. J.S. Kargel, G.L. Leonard, M.P. Bishop, A. Kääb and B. Raup (Eds). Springer Praxis Books – Geophysical Sciences. ISSN 1615-9748, ISBN 978-3-540-79817-0, ISBN 978-3-540-79818-7 (eBook), DOI 10.1007/978-3-540-79818-7.

Goulden, T., C. Hopkinson and M.N. Demuth, 2013. Sensitivity of alpine glacial change detection and mass balance to datum and sampling inconsistencies. *The Cryosphere Discuss*. **7**(1): 55-101, DOI:10.5194/tcd-7-55-2013.

Goulden, T., C. Hopkinson and M.N. Demuth, 2012. Sensitivity of glacial change detection on Bridge River Glacier to horizontal datum transformations. Remote Sensing and Hydrology 2010 – Jackson Hole, USA. *International Association for the Hydrological Sciences*/IUGG Redbook Publication **352**: 280-283.

Gratton, D. J., P.J. Howarth and D.J. Marceau, 1990. Combining DEM parameters with Landsat MSS and TM imagery in a GIS for mountain glacier characterization. *IEEE Transactions on Geoscience and Remote Sensing* **28**: 766-769.

Gray, A.L., N.H. Short, K.E. Mattar and K.C. Jezek, 2001. Velocities and ice flux of the Filchner Ice Shelf and its tributaries determined from speckle tracking interferometry. *Canadian Journal of Remote Sensing* **27**(3): 193-206.

Gurnell, A.M. and C.R. Fenn, 1987. Proglacial channel processes. In - Glacio-fluvial Sediment Transfer: An Alpine Perspective, A.M. Gurnell and M.J. Clark (Eds.). pp.423-472. Wiley, Chichester.

Hopkinson, C. and M.N. Demuth, 2006. Using airborne lidar to assess the influence of glacier downwasting on water resources in the Canadian Rocky Mountains. *Canadian Journal of Remote Sensing* **32**(2): 212-222.

IAHS(ICSI)/UNEP/UNESCO, 1999. Glacier Mass Balance Bulletin No. 5 (1996-1997). World Glacier Monitoring Service, W. Haeberli, M. Hoelzle, R. Frauenfleder (Eds). 96 pp.

Jansson, P., R. Hock and T. Schneider, 2003. The concept of glacier storage: a review. *Journal of Hydrology* **282**: 116-129.

Lliboutry, L., 1965. 12-17. Glaciers réservoirs et glaciers évacuateurs. In – Traité de Glaciologie – Tome II Glaciers Variations du Climate sols Gelés – Chapitre 12 - Généralités sur les Glaciers. Masson et C^{ie}, Éditeurs, Paris, France.

Luckman, B.H. and G.D. Osborn, 1979. Holocene glacier fluctuations in the middle Canadian Rocky Mountains. *Quaternary Research* **11**: 52-77.

Luckman, B.H., 2006. The Neoglacial History of Peyto Glacier. In - Peyto Glacier: One Century of Science, M.N. Demuth, D.S. Munro, and G.J. Young (Eds). *NHRI Science*

Report Series **8**, Environment Canada, National Hydrology Research Institute, Saskatoon, Saskatchewan, p.25-57.

Marshall, S.J., E.C. White, M.N. Demuth, T. Bolch, R. Wheate, B. Menounos, M.J. Beedle and J.M. Shea, 2013. Glacier water resources on the eastern Slopes of the Canadian Rocky Mountains. *Canadian Water Resources Journal* **36**(2): 109-134. DOI:10.4296/cwrj3602823

Mernild, S.H., W.H. Lipscomb, D.B. Bahr, V. Radić, and M. Zemp, 2013. Global glacier changes: a revised assessment of committed mass losses and sampling uncertainties. *The Cryosphere* **7**(5): 1565–1577. DOI:10.5194/tc-7-1565-2013.

Moore, R.D. and M.N. Demuth, 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. *Hydrological Processes* **15**: 3473-3486.

Moore, R.D., S.W. Fleming, B. Menounos, R. Wheate, A. Fountain, K. Stahl, K. Holm and M. Jakob, 2009. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes* **23**(1): 42-61.

Morris, E.M., 2006. Techniques for predicting runoff from glacierized areas. In - Peyto Glacier: One Century of Science, M.N. Demuth, D.S. Munro, and G.J. Young (Eds). *NHRI Science Report Series* **8**, Environment Canada, National Hydrology Research Institute, Saskatoon, Saskatchewan, p.203-225.

Natural Resources Canada, 2012. Canadian Digital Elevation Model Mosaic (CDEM). Accessed: http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/C40ACFBA-C722-4BE1-862E-146B80BE738E.html

Oerter, H., D. Baker, H. Moser and O. Reinwarth, 1981. Glacial hydrological investigations at the Vernagtferner glacier as a basis for a discharge model. *Nordic Hydrology* **12**(4-5): 335-348.

Ommanney, C.S.L., 2002. Glaciers of the Canadian Rockies. In - Satellite Image Atlas of Glaciers of the World. Glaciers of North America - Canada. U.S. Geological Survey Professional Paper 1386-J-1, J199-289.

Parks Canada, 2011. Consolidated Guidelines for Ecological Integrity Monitoring in Canada’s National Parks. Parks Canada Agency, Gatineau, Quebec, 155 pp.

Parks Canada, 2009. Nahanni National Park Reserve of Canada Nah'a Dehe State of the Park Report 2009: Fort Simpson, NT (Cat. No. R64-368/2009E), Parks Canada Agency, Gatineau, Quebec, 67 pp.

Persad, R.A., C. Armenakis, A. Chichagov, M.N. Demuth and C. Hopkinson, 2013. Matters concerning the detection of geospatial changes using temporal earth observations over the Columbia Icefield, Canada. Abstract Proceedings, Canadian Institute of Geomatics Annual Conference joint with 4th International Conference on Earth Observation for Global Changes - June 5 to 7, 2013. Ryerson University. Session TS EOGC1: Remote Sensing and GIS for Snow and Ice.

Petts, G.E., A.M. Gurnell, and A.M. Milner, 2006. Ecohydrology: New opportunities for research on glacier fed rivers. In - Peyto Glacier: One Century of Science, M.N. Demuth, D.S. Munro, and G.J. Young (Eds). *NHRI Science Report Series* **8**, Environment Canada, National Hydrology Research Institute, Saskatoon, Saskatchewan, p.255–275.

Raper, S.C.B. and R.J. Braithwaite, 2009. Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry. *The Cryosphere* **3:** 183–194.

Schwitter, M.P. and C.F. Raymond, 1993. Changes in the longitudinal profiles of glaciers during advance and retreat. *Journal of Glaciology* **39**(133): 582-590.

Short, N.H. and A.L. Gray, 2004. Potential for RADARSAT-2 interferometry: glacier monitoring using speckle tracking. *Canadian Journal of Remote Sensing* **30**(3): 504-509.

Sidjak, R. W. and R.D. Wheate, 1999. Glacier mapping of the Illecillewaet Icefield, British Columbia, Canada, using Landsat TM and digital elevation data. *International Journal of Remote Sensing* **20**, 273-284.

Spence, C., S. Hamilton, P. Whitfield, M.N. Demuth, D. Harvey, D. Hutchinson, B. Davison, T.B.M.J. Ouarda, J.G. Deveau, H. Goertz, J.W. Pomeroy and P. Marsh, 2009. Invited Commentary: A Framework for Integrated Research and Monitoring (FIRM), *Canadian Water Resources Journ*al **34**: 1-6.

UNEP/WGMS, 2010. Global Glacier Changes – Facts and *Figure*s. United Nations Environment Programme. Available at http://www.grid.unep.ch/glacier/

van Wychen, W., D. O. Burgess, L. Gray, L. Copland, M. Sharp, J. A. Dowdeswell, and T. J. Benham, 2013. Glacier velocities and calving Flux from the Queen Elizabeth Islands, Nunavut Canada. Geophysical Research Letters **41**: 484-490. DOI:10.1002/2013 GL058558 Cont. # 20130293.

Ward, J.V., 1994. Ecology of alpine streams. *Freshwater Biology* **32**: 277-294.

Wood, J.A.,1997. Augmenting minimum streamflows in sediment deposition reaches. Chapter 14 in – Fish Habitat Rehabilitation Procedures, Watershed Restoration Technical Circular No. 9. P.A. Slaney and D. Zaldokas (Eds). ISBN 0-7726-3320-7.

Wood, L.J., D.J. Smith and M.N. Demuth, 2011. Extending the Place Glacier mass balance record to AD 1585, using tree-rings and wood density. *Quaternary Research* **76**(3): 305-313.

Zemp. M., H. Frey, I. Gaärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, W. Haeberli, F. Denzinger, A.P. Ahlstrøm, B. Anderson, S. Bajracharya, C. Baroni, L.N. Braun, B.E. Cáceres, G. Casassa, G. Cobos, H. Delgado Granados, M.N. Demuth, L. Espizua, A. Fischer, K. Fujita, B. Gadek, A. Ghazanfar, J.O. Hagen, P. Holmlund, N.Karimi, M. Pelto, P. Pitte, V.V. Popovnin, C.A. Portocarrero, R. Prinz, C.V. Sangewar, I. Severskiy, O. Sirgurdsson, A. Soruco, and C. Vincent, 2015. Historically unprecedented global glacier changes in the early 21st century. *Journal of Glaciology* **61**(228): 745-762, DOI: 10.3189/2015JoG15J017.

From Parker Ridge, AB, the eastern margins of the Columbia Icefield drape the landscape below Mount Castleguard (right). Michael N. Demuth photograph (2013-April-29).