

Volume Balance of White Glacier Terminus, Axel Heiberg Island, Nunavut, 1961-2003

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ABSTRACT

Digital elevation models of the White Glacier terminus for 1960 and 2003 are produced in order to calculate terminus retreat and volume change. Below 440 m a.s.l., surface elevation is decreasing at an average rate of -0.35 m a^{-1} , implying a $-14.36 \pm 0.73 \text{ m}$ loss of glacier ice during this 42 balance-year period. Terminus volume is decreasing at a rate of $1.41 \times 10^6 \text{ m}^3 \text{ a}^{-1}$. A loss of 0.78 km^2 in area accounts for 57 % of the volume change, and is in part due to the advance of the neighbouring Thompson Glacier. This study reevaluates hypsometry in order to quantify a geodetic water-equivalent estimate of ablation for White Glacier terminus. Revised hypsometry results in a 24 % reduction in water-equivalent ablation derived from the direct mass balance of White Glacier terminus. Preliminary examination of the error and the level of difficulty suggests that similar geodetic surveys may benefit climatological linkages by expanding the number, size- and spatial-distribution of small glacier mass balance programmes while simultaneously monitoring water-equivalent ablation.

Keywords: Axel Heiberg Island; White Glacier; volume balance; glacier hypsometry; geodetic mass balance

INTRODUCTION

The mass balance of White Glacier has been measured by the direct (stake-based) method (Østrem and Brugman 1991) since 1960. This 42 year record is among the most valuable records for investigating regional climatology in the Canadian Arctic Archipelago. The mass balance normal $+B$, derived from the 1960-2002 record for White Glacier is $-144 \pm 36 \text{ kg m}^{-2} \text{ a}^{-1}$ (Cogley and Jung-Rothenhäusler 2002). The mass balance normal is derived from the annual summation of stake surface changes integrated over glacier area within 100 m elevation bands:

$$\langle B \rangle = \frac{\sum B(t)}{n}, \text{ where} \quad (1)$$

$$B(t) = \int_A b \cdot dx dy / \int_A dx dy \quad (2)$$

where $B(t)$ is the net mass balance ($\text{kg m}^{-2} \text{ a}^{-1}$) for year t , n is the number of balance years in the record, b is the specific annual mass balance at a point on the glacier, and A is the area of the glacier. In practice b is measured only at a small number of stakes, 47 on average over the period of record (Cogley et al. 1996).

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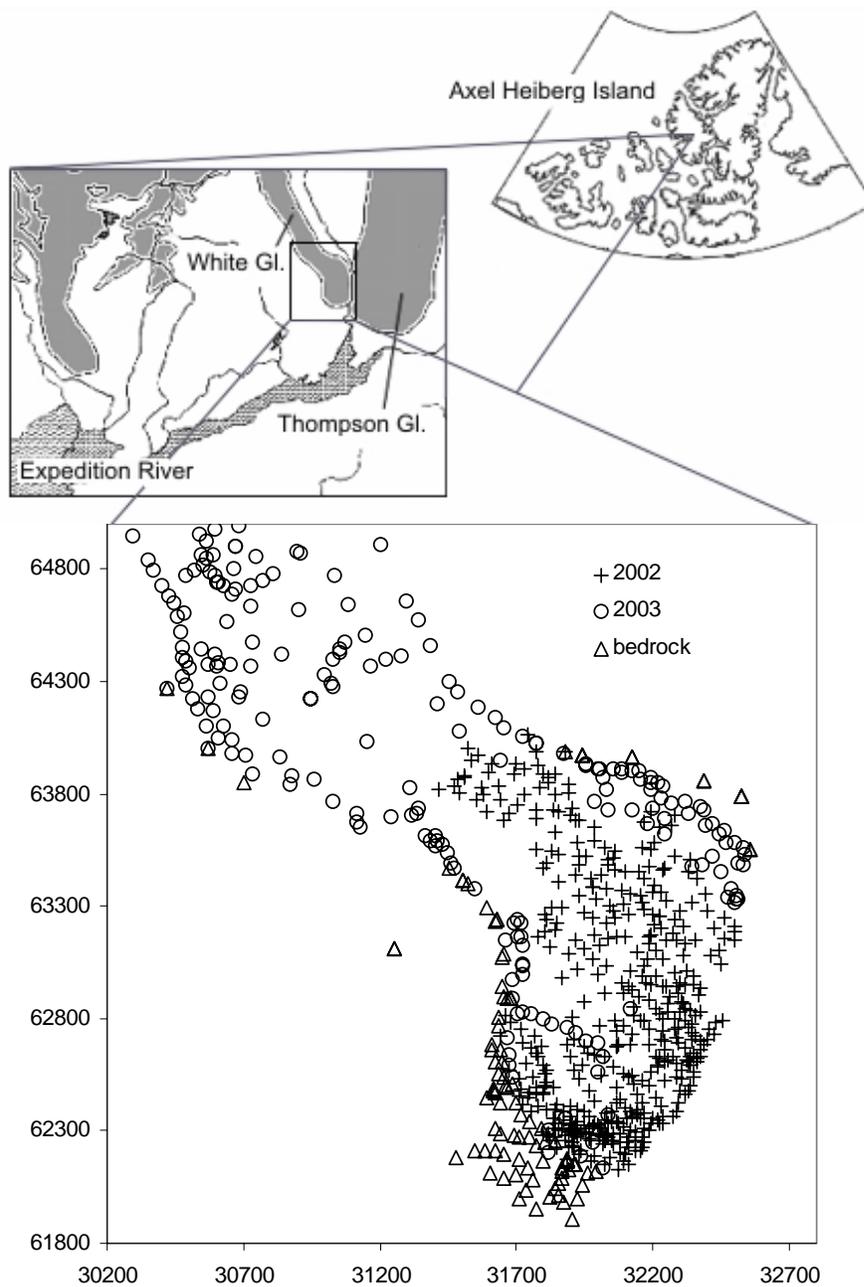


Figure 1. Survey of White Glacier terminus, Axel Heiberg Island, Nunavut during the spring of 2002 and 2003.

The direct method purposely omits surface elevation change so as to isolate climatological controls on glacier mass balance. For example, specific mass balance measurements are integrated over 100 m elevation bands derived from a reference surface surveyed prior to the beginning of the record allowing for estimation of the static sensitivity of White Glacier to climate.

While this procedure benefits the investigation of glacier-climate links it may be inappropriate for estimating the mass balance. Mass balance error from the direct method has been

reported as 16 % (Elsberg et al. 2001) and 15 % (Hopkinson 1997). Elsberg et al. (2001) and Krimmel (1999) show that geodetic mass balance measurements provide dynamic glacier sensitivity by capturing surface change with each subsequent surface measurement, resulting in

$$B = \frac{\int (Z_2 - Z_1) dx dy}{\int dx dy} \rho \quad (3)$$

climatologically and hydrologically valuable information:

where Δ is the density of ice and Z_1, Z_2 are elevations at two survey dates.

In the spring of 2002 and 2003 we undertook surveys of White Glacier terminus below 440 m a.s.l.. The elevation change between these new surveys and the previously established 1960 surface is limited in that it may not be directly compared with the corresponding direct mass balance because the vertical velocity of the surface is unknown. For this reason, the results pertain to a volume balance estimate with two intended purposes: First, the study revises the hypsometry for White Glacier below 440 m a.s.l. Second, error and practical difficulty are reported in order to assess the costs and benefits of the geodetic and direct mass balance methods.

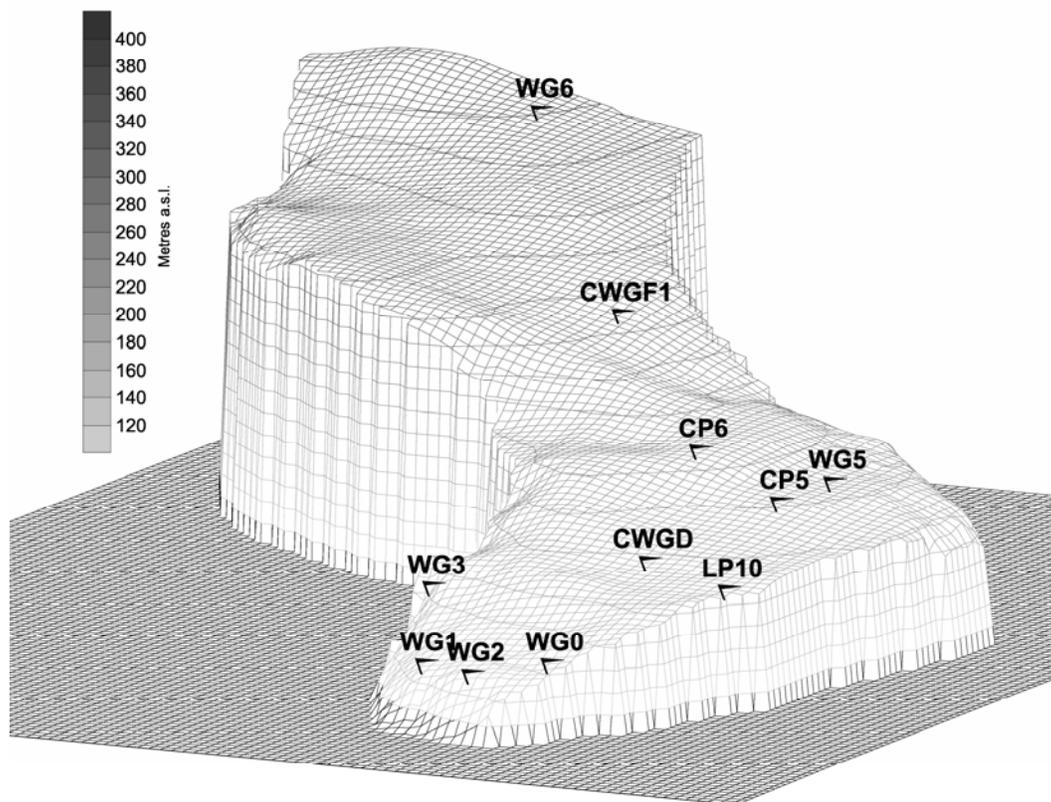


Figure 2. Orthographic representation of White Glacier terminus between 85 m and 440 m a.s.l. derived from 2002 and 2003 surveys. Southeast corner datum: UTM 15-N (32825, 61800).

STUDY AREA

White Glacier (Figure 1) is a valley glacier extending south-east on the south side of Müller Ice Cap, Axel Heiberg Island (79° 26' N, 90° 34' W). White Glacier is approximately 38.7 km² in area and 14.5 km long. Glacier elevation ranges from 75 to 1800 m a.s.l. (Cogley et al. 1996). White Glacier terminus is surrounded by steep valley sides and a well developed terminal moraine (Adams 1966). The east side of White Glacier is contiguous with Thompson Glacier.

Müller (1963) reports a mean annual accumulation of 370 mm for the period 1921-1960 near the highest elevation of Müller Ice Cap, 40 km north of White Glacier. Eureka, the closest climate station, is approximately 100 km away and indicates a 30 year (1971-2000) mean annual precipitation of 75.5 mm and a mean annual temperature of -19.7 °C.

METHODS

Change in surface elevation during the record (1960-2002) is calculated with respect to a reference surface derived from a 1:5 000 scale map of White Glacier terminus based on aerial photography taken on 2 August 1960 (Haumann and Honegger 1962; see also Haumann 1963). Contours at 5 m intervals and detailed representation of surface artefacts are converted into a 16-bit flat binary file and act as a base map for the extraction of a digital elevation model (DEM), interpolated by an algorithm similar to that described by Cogley and Jung-Rothenhäusler (2002). The horizontal and vertical resolutions of the 1960 DEM (reference surface) are 2.5 m and 0.1 m, respectively.

Second and third assessments of the glacier surface were conducted by Total Station survey of more than 450 spot elevations during May 2002 and 213 spot elevations during May 2003 (Figure 1). The Total Station makes distance measurements by sending infrared laser beams toward roving prism-holders and calculating the distance as a function of beam wavelength. The coordinates of the 2002 and 2003 survey elevations were then used to query the corresponding 1960 surface elevations in order to solve for change in surface elevation.

Survey elevations represent the glacier surface at different times of year and therefore require phase-correction (Cogley 2003). To correct the survey elevations, denoted Survey 1, Survey 2 and Survey 3, each set is corrected to the beginning or the end of its balance year depending on whether the survey occurred during winter or summer, respectively. The phase correction is then calculated by assuming a constant maximum seasonal elevation h_A , attained at the end of winter, time t_A , which is assumed to occur on 1 June. Here, h_A is found by dividing a typical mass balance amplitude, b , = 1750 kg m⁻² a⁻¹ by the density of ice Δ = 900 kg m⁻³. A ratio scale calendar is assigned by setting 1 September as the start of a new balance year, so that Survey 1 (performed 2 August, 1960) becomes 1960.92, Survey 2 (performed 1 May, 2002) becomes 2002.66 and Survey 3 (performed 1 May, 2003) becomes 2003.66. The surveys yield corresponding elevations denoted h_1 , h_2 and h_3 :

$$h_1 = \left[\frac{(1-t_1)}{(1-t_A)} \right] h_A \quad (4a)$$

$$h_2 = \left(\frac{t_2}{t_A} \right) h_A \quad (4b)$$

$$h_3 = \left(\frac{t_3}{t_A} \right) h_A \quad (4c)$$

Shifting Survey 1 to the end of its balance year (1961.00) and shifting Survey 2 and Survey 3 to the starts of their balance years (2002.00 and 2003.00), the integer time period of the geodetic

elevation difference ($T_2 - T_1$) is 41 years while ($T_3 - T_1$) is 42 years. The phase-corrected changes in elevation become:

$$\Delta H_{21} = \Delta z - \psi_{21} \quad (5a)$$

$$\Delta H_{31} = \Delta z - \psi_{31} \quad (5b)$$

where Δz is the uncorrected elevation differential and N is the phase correction ($h_2 - h_1$ or $h_3 - h_1$). The phase-corrected mass balance G , in $\text{kg m}^{-2} \text{a}^{-1}$, is expressed as:

$$G = \left(\frac{\overline{\Delta H}}{\Delta T} \right) \cdot \rho \quad (6)$$

Table 1. Phase-correction of the mean surface elevation change for two surveys of White Glacier terminus.

Survey	1961-2002	1961-2003
Δz (m)	-13.64	-12.88
ΔH (m)	-14.74	-13.98
$\Delta H / \Delta T$ (m a^{-1})	-0.36	-0.33
G ($\text{kg m}^{-2} \text{a}^{-1}$)	-323.49	-299.49

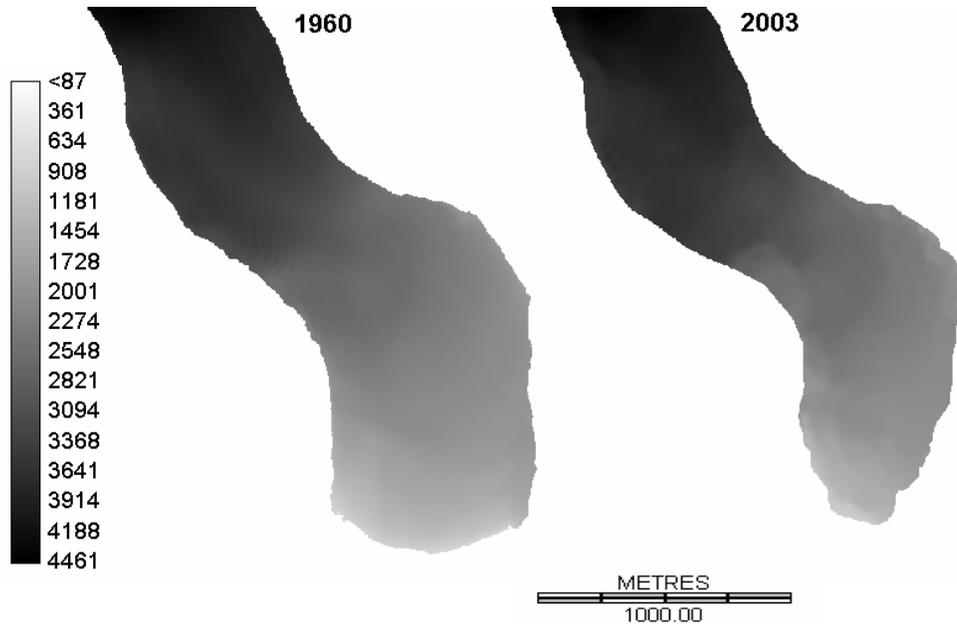


Figure 3. Digital elevation models of White Glacier terminus. Horizontal and vertical resolutions are 2.5 m and 0.1 m, respectively.

RESULTS

The mean phase-corrected elevation changes derived for the (1961-2002) and (1961-2003) periods are -0.36 m a^{-1} and -0.33 m a^{-1} , which combine to give a mean annual elevation change of -0.35 m a^{-1} . The net elevation change is $-14.36 \pm 0.73 \text{ m}$. As illustrated in Figure 1 the 2002 and 2003 surveys cover different areas of the terminus making any detailed attempt to combine the 2002 and 2003 surveys impractical. Addition of the (1961-2002) annual balance normal to 2002 elevations changes Δz by -1.3% . Note that the small (1961-2003) balance normal, relative to the (1961-2002) balance normal, is most likely because the 2002 survey distribution is concentrated at higher elevation and not necessarily because of low melt during the summer of 2002.

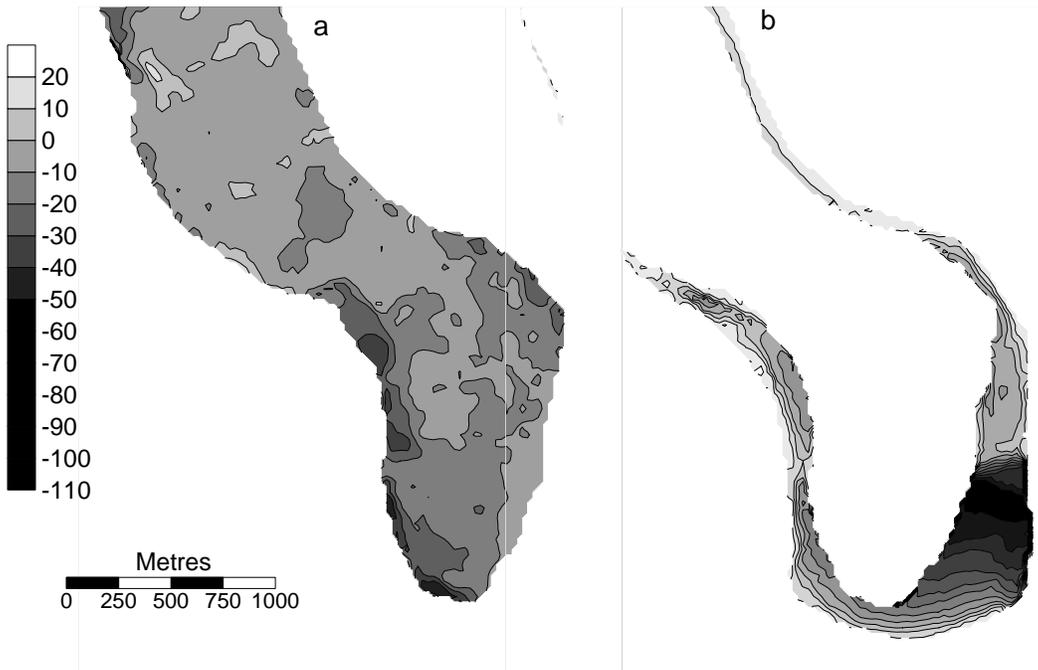


Figure 4. Ten-metre vertical resolution volume balance of White Glacier terminus in the form of (a) surface thinning and (b) retreat (1961-2003). Surface elevation change is negative with the exception of isolated positive anomalies within the gentle upper slope between 350 m and 450 m a.s.l.. In panel b, the eastern part of the area vacated by White Glacier is now occupied by Thompson Glacier.

The set of all 2002 and 2003 elevations is used to interpolate a $2.5 \times 2.5 \text{ m}$ resolution DEM (Figure 3) that is then compared with the 1961 DEM in order to estimate surface volume change below 440 m a.s.l. (Figure 4a) and volume change due to retreat (Figure 4b). The 2003 DEM is derived from the amalgamation of the 2002 and 2003 surveys. The lower limit (bedrock surface) is derived from more than 100 survey elevations covering the area of retreat and both sides of the glacier boundary up to 400 m a.s.l.. Reduction in glacier volume due to retreat is $-3.39 \times 10^7 \text{ m}^3$ while loss of glacier ice due to surface change accounts for $-2.54 \times 10^7 \text{ m}^3$. These measurements indicate that glacier thinning accounts for 43 % of the net negative volume balance of White Glacier terminus. The net change in glacier area below 440 m a.s.l. is -0.78 km^2 . Recall that the area of White Glacier in 1960 is reported as 38.7 km^2 . Table 2 identifies the change in hypsometry for the remaining glacier area between 75 m and 440 m a.s.l.. Figure 5 shows fourth-order polynomial models of the 1961 (heavy line) and 2003 (light line) surface elevation below 440 m a.s.l.. Figure 6 identifies the distribution in area change within 10 m elevation bands

between 1961 and 2003. Figure 7 illustrates terminus hypsometry change in the context of the glacier as a whole.

Table 2. Change in the hypsometry of White Glacier terminus (1961-2003)

Elevation Band Metres a.s.l.	1961 Area (km ²)	2003 Area (km ²)	1961-2003 Area (km ²)
75-99	0.041	0.016	-0.024
100-199	0.794	0.514	-0.279
200-299	1.325	0.918	-0.406
300-399	1.135	1.088	-0.046
400-440	0.132	0.105	-0.027

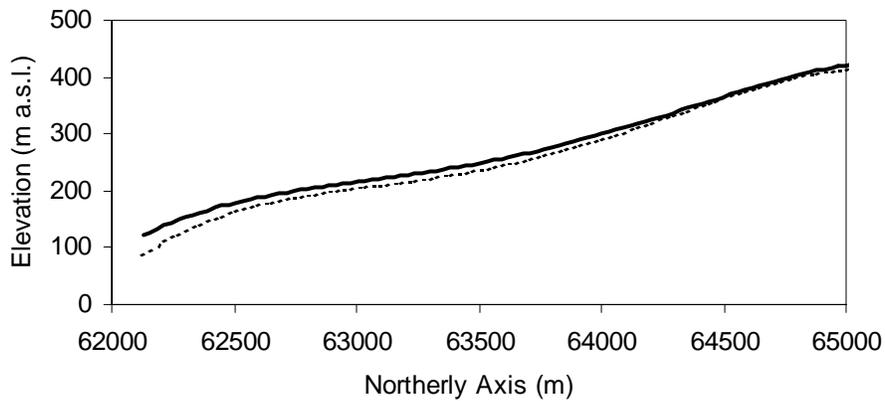


Figure 5. Fourth-order polynomial expressions of the surface of White Glacier terminus during 1960 (heavy line) and 2003 (light line) between 75 m and 440 m a.s.l..

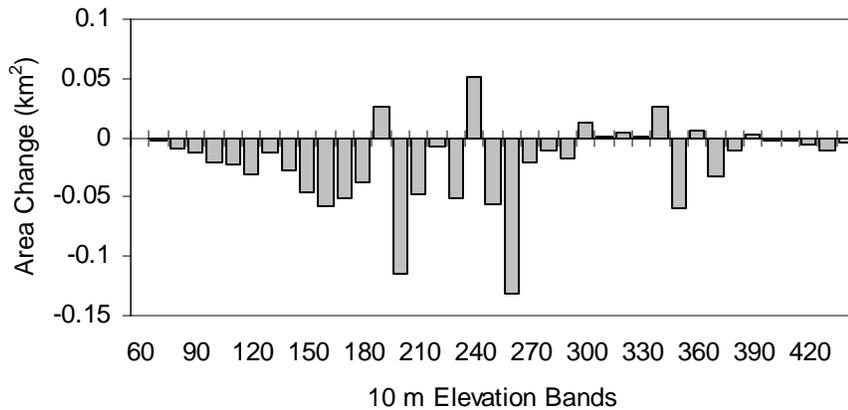


Figure 6. Distribution of hypsometry change for White Glacier terminus between 75 m and 440 m a.s.l..

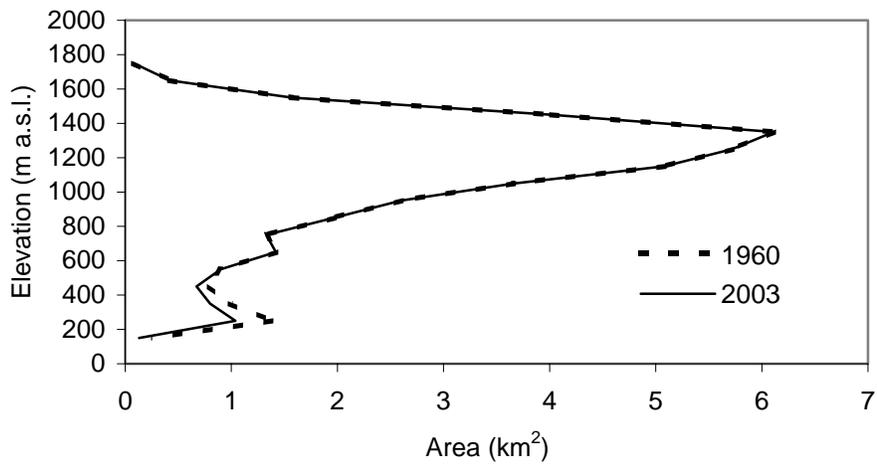


Figure 7. Revised terminus hypsometry for White Glacier.

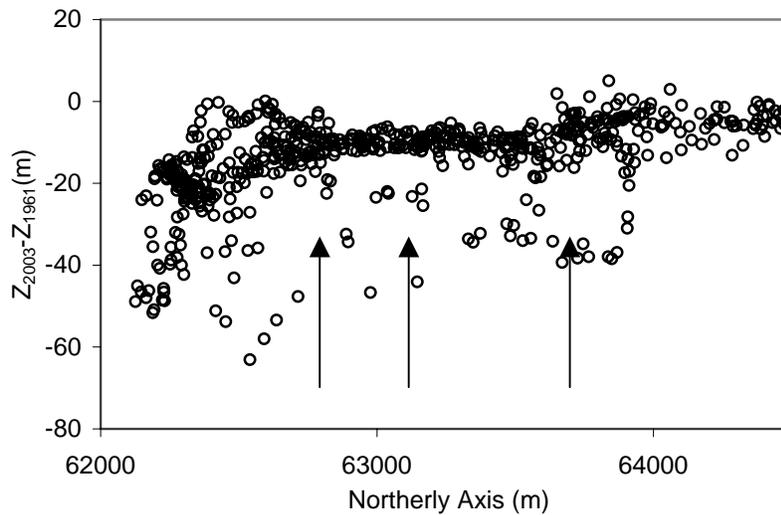


Figure 8. Distribution of spot elevations along the north-south axis surveyed during 2002 and 2003. Arrows indicate intensely crevassed locations that are underrepresented in the volume balance assessment of White Glacier terminus.

DISCUSSION

Measurement Uncertainties

Error in the volume balance of White Glacier terminus is dependent on the quality of the maps used to extract spot elevations and the spatial representativeness of the coordinates. Accuracy in the 1961 DEM is dependent on the accuracy of the initial photogrammetric survey and on the accuracy of the routines used to extract spot elevations from 5 m contours on the 1961 map. Glacial artefacts exist at the spatial scale employed here (2.5m) causing local relief in the

order of metres surrounding survey points. Cogley and Jung-Rothenhäusler (2002) suggest that an error equal to half of the contour interval, or 2.5 m, is appropriate.

It is suggested that there is a potentially significant subjective error in the 2002 and 2003 Total Station surveys. Every effort to survey in a spatially representative manner was undertaken, but two sources of bias do remain: First, the area visible from a survey station includes “blind zones”, where the sighting prism is not visible from the Total Station instrument and no measurement is possible. On a convex surface such as a glacier terminus, these blind zones are more extensive at greater distances from the survey station. For efficiency, the field work must be organized so as to maximize areal coverage from any one survey station, that is, to minimize station moves. This leads to an as yet unquantified bias, increasing with distance from the survey station, away from blind zones and in favour of relatively high measurement points. A second bias arises from the inability to survey intensely crevassed and steep-sloping faces. Crevassed areas of the glacier are not fully represented by the 2002 and 2003 DEMs. This bias is illustrated in Figure 8 by arrows directed at the small number of spot elevations exhibiting highly negative (1961-2003) elevation changes where crevasses are large and impractical for Total Station surveying.

The practical nature of the measurement method also introduces an unknown sampling error due to field mistakes and instrument limitations. Total Station manufacturers commonly indicate instrument error ranging from 1 mm/km to 5 mm/km. However, we are reluctant to report similar error. A brief investigation of 10 survey points, with multiple elevation measurements, ranging in measurement distance from 15 m to 250 m, exhibits a mean error of ± 9 mm. We speculate that much of this error is explained by the handling of prisms. We are currently pursuing a more thorough investigation into instrument error despite early indication that it is an order of magnitude lower than the sampling errors outlined above.

Direct Mass Balance Comparison

The geodetic volume balance estimate is not directly comparable with the direct mass balance estimate below 440 m a.s.l.. The direct mass balance measurement is in reference to the surface of the previous year and, hence, accounts for vertical ice flow. Krimmel (1999) suggests that the geodetic method accounts for processes that may be underestimated by the direct method. The direct method may not fully account for basal melt, internal melt and superimposed ice whereas a more spatially continuous geodetic mass balance circumvents these problems.

Individual elevation-band errors approximate $\pm (200-250) \text{ kg m}^{-2} \text{ a}^{-1}$ for White Glacier (Cogley et al.1996) and are thought to arise from insufficient spatial sampling. The geodetic survey alleviates this error only to be replaced with the considerably larger error derived from the extraction of spot elevations from 5 m contours and, to a lesser extent, sampling bias and instrument error. However, these errors are limited to the measurement frequency which is significantly reduced.

These errors obscure climate signals that might otherwise be shown by long-term mass balance records. It is generally accepted that these errors must decrease by at least an order of magnitude before White Glacier may be used as a practical index of climatic change in the High Arctic. A single glacier-wide geodetic estimate is much more labour-intensive and time consuming than a direct estimate, but likely needs not match the frequency of the direct method, thus reducing systematic error. Time constraint is alleviated by phase correction so that ground survey may take place at the convenience of the researcher. However, early spring tends to be an ideal time in terms of safety and transportation.

Terminus Hypsometry Change:

This study identifies change in hypsometry for White Glacier terminus which may be valuable in monitoring the mass balance. The hypsometry is most different from 200 to 300 m a.s.l. (-0.407 km^2) and 100 to 200 m a.s.l. (-0.279 km^2). White Glacier's advancing neighbour, Thompson Glacier, is thought to have a role in ablation of White Glacier terminus by fracturing the east side, but the extent of this contribution to the volume balance of White Glacier is

unknown. However, retreat of the west side of White Glacier terminus away from White Glacier Hill (Ermine Camp) is substantial suggesting that the volume balance of White Glacier terminus is still controlled by its own physics and local climate, rather than the intrusion of Thompson Glacier.

We suggest two possible explanations for the change in White Glacier hypsometry: First, White Glacier may be responding to the end of the Little Ice Age, seeking a new climatic equilibrium, causing a decrease in the vertical velocity of ice entering White Glacier terminus. Second, White Glacier terminus may be responding to local- and synoptic-scale climatic change. Long-term study of the energy balance and terminus-related phenomena such as downslope katabatic airflow is not available. Alt (1987) identifies synoptic controls of melt on the valley glaciers on Devon Island Ice Cap, however, long-term synoptic climatology for the Axel Heiberg Island region is not available.

Figure 9 compares the mass loss from White Glacier terminus using the 1960 and 2003 glacier hypsometry estimates. The use of the 1960 glacier hypsometry overestimates loss of ice in each elevation band combining for a total 1.22×10^9 kg.

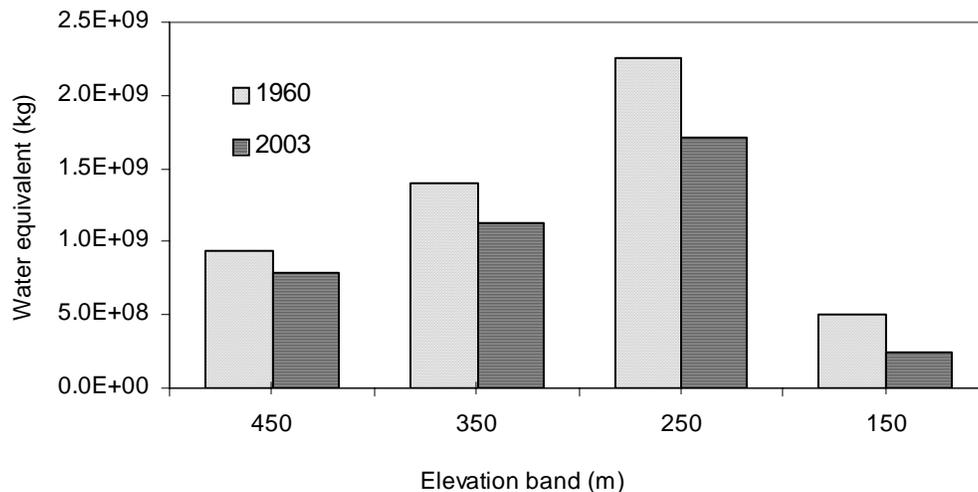


Figure 9. Direct mass balance estimates of ablation from White Glacier terminus between 1961 and 2003 integrated over 1960 and 2003 estimates of glacier hypsometry. Forty-two years later, revised terminus hypsometry helps quantify ablation.

CONCLUSIONS

Uncertainty in the volume balance of White Glacier terminus is most dependent on the quality and contour interval of the reference surface employed. Global positioning systems and laser altimetry show promise in providing adequate reference surfaces in glaciated regions where subsequent glacier-wide geodetic mass balance measurements may be practically performed. Cogley and Adams (1998) suggest that the globally averaged mass balance record for small glaciers is spatially biased toward more negative measurements. The geodetic method may be a realistic approach to broadening the number and distribution of monitored glaciers in remote regions. The method requires intense fieldwork, but relatively low measurement frequency.

The net -5.93×10^7 m³ loss of glacier ice from White Glacier terminus is presumed to be the result of disequilibrium between ice transfer into the terminus and terminus melt. This estimate reinforces the idea that the response of glaciers to previous climatic forcings may be long delayed,

but may have considerable short-term hydrological implications. Figure 9 suggests that the outdated hypsometry exhibits a 24 % overestimate of the loss of mass from White Glacier terminus. In this way future periodic geodetic volume balance measurements of small glaciers could improve upon linkages with climate and hydrology.

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