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Mass balance, runoff and surges of the Bering Glacier, Alaska

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Abstract

The historical net, ablation and accumulation daily balances and runoff of the Bering Glacier, Alaska are determined for the 1951–2011 period with the PTAA (precipitation-temperature-area-altitude) model, using daily precipitation and temperature observations collected at the Cordova and Yakutat weather stations, together with the area-altitude distribution of the glacier. The mean annual balance for this 61-yr period is −0.6 mwe, the accumulation balance is +1.4 and the ablation balance is −2.0 mwe. Periodic surges of this glacier transport large volumes of ice to lower elevations where the ablation rate is higher, producing more negative balances and increasing runoff. During the 1993–1995 surge the average ablation balance is −3.3 mwe, over a meter greater than the 1951–2011 average. Runoff from the Bering Glacier (derived from simulated ablation and precipitation as rain) is highly correlated with the four glacier surges that have been observed since 1951. Ice volume loss for the 1972–2003 period measured with the PTAA model is 2.3 km^3 we a^{-1} and closely agrees with losses for the same period measured with the geodetic method.

1 Introduction

The Bering Glacier/Bagley Icefield in Alaska, the largest glacier/icefield complex in North America, is 180 kilometers in length, ranges from sea level to 2445 m altitude and has a total area of 4773 square kilometers. Within the past 100–200 yr, the Bering Glacier began to retreat from its maximum Neoglacial position; however, in the past 100 yr this retreat has been interrupted by at least six surges of substantial amplitude and duration (Molnia and Post, 1995). The folds on the lower glacier shown in Fig. 1 are indicative of a surging glacier.

Measuring the daily mass balance and hydrologic parameters of a glacier as large as the Bering would require a small army of researchers and near-infinite resources. The PTAA model was developed to determine the balance for glaciers of any size and location – all that is needed is the hypsometry (area-altitude distribution) of the glacier and historical daily observations of temperature and precipitation collected at a weather station in the region. Nearly every glacier in the Northern Hemisphere meets these criteria.

2 Mass balance results

The PTAA mass balance (precipitation-temperature-area-altitude) model is applied to the glacier's area-altitude distribution shown in Fig. 2, using as input the daily temperature and precipitation observations at Yakutat and Cordova, Alaska, located approximately 125 km. NW and 200 km. SE of the glacier terminus, and at elevations of 8 and 12 m, respectively. The mean annual balance for the Bering Glacier averaged for 61 yr (1951–2011) is −0.6 mwe (Fig. 3). Total thinning averaged over the glacier surface for 61 yr is 39 m of ice or 0.6 m of ice per year (Fig. 4). The mean accumulation balance is +1.4 mwe and the ablation balance is −2.0 mwe (Fig. 5).

Mass balance terminology used in this report deviates slightly from that proposed by the IACS working group of mass balance terminology and methods (Cogley et al., 2011). The main variables that determine mass balance, such as precipitation, temperature, lapse rates and snowfall, are directly dependent on elevation. Glacier balance models are constructed by applying relationships between these variables. For example, precipitation and temperature are both dependent on elevation but for different reasons. Depicting elevation as being dependent on mass balance as is suggested in the IACS report may be misleading. Therefore, in this report, balance and other variables are all shown to be dependent on elevation.

In addition, the terms accumulation balance and ablation balance are preferred over winter balance and summer balance, which are used in the IACS report. For most Alaska glaciers, snow accumulation at higher elevations occurs throughout the year and can be especially heavy in August and September. For many Himalayan range glaciers, snow accumulation is greatest during the monsoon season, from June through September, and at lower elevations ablation often occurs during the winter months.

3 The PTAA mass balance model

The PTAA model relies on the climate history that is embedded in a glacier's area-altitude (AA) distribution. The AA distribution is developed by glacier flow and erosion of the underlying bedrock, both of which are dependent on long-term-mass balances and on the climate. The current mass balance is calculated by combining precipitation and temperature observations at a regional weather station with the glacier's current area-altitude distribution to produce daily and annual balances. Seven different balance variables are found for each day of the period of record and regressed against each other. The average regression error produced by all regressions (several hundred) is used as an optimizing function to determine coefficient values that produce the minimum calibration error. The model has been applied to determine annual balances of South Cascade Glacier and compared with manually measured balances for the 1959–1996 period (Tangborn, 1999). It has also been applied to several glaciers in Alaska to determine annual balances that are compared with manual balances measured by the USGS (Bhatt et al., 2007; Korn, 2010; Zhang et al., 2007a,b).

The PTAA model was developed as an alternative to other methods of measuring glacier mass balances. The only data requirements are daily observations of precipitation, maximum and minimum temperatures at a nearby weather station (or an average of two stations), and the area-altitude distribution of the glacier's surface. For some glaciers the weather stations can be as much as 300 km from the glacier but usually the distance is closer to 100 km or less. The area-altitude distribution (hypsometery) is developed from DEM models or topographic maps. A finely divided area interval produces the most accurate results, e.g. a 10-m interval between areas is preferable to 50 m.

4 Comparison with geodetic balances

The elevation change and volume loss of the Bering Glacier have been estimated by different authors using remote-sensing techniques (Arendt et al., 2002; Beedle et al., 2008; Muskett et al., 2009; Berthier et al., 2010a,b). For the period 1972–2003, using the 1972 USGS map as a reference and a glacier area of 4400 km^2, the geodetic method (ASTER DEM), volume loss for the entire Bering Glacier system equaled $2.6 \pm 0.5\,\mathrm{km}^3\,\mathrm{w.e.}\,\mathrm{a}^{-1}$ (Berthier, 2010a). For the same 31-yr period, using an area of 4773 km^2, the PTAA model cumulative balance change (Fig. 4) is 16.8 mwe or $0.54\,\mathrm{mwe}\,\mathrm{a}^{-1}$ or $2.6\,\mathrm{km}^3\,\mathrm{w.e.}\,\mathrm{a}^{-1}$, approximately equal to the volume loss determined by the geodetic method.

5 Balance versus elevation

The net, accumulation and ablation balances as a function of elevation are shown in Fig. 6a, averaged for the 1951–2011 period, and in Fig. 6b for the 2004 balance year. The widespread forest files in Alaska in 2004 emitted ash and particulates that decreased the albedo of the glacier surface and strongly affected mass balances (Figs. 3 and 5). The contrast between $b(z)$ curves in Fig. 6a, b demonstrate how ablation and the ELA of Bering Glacier were affected by these wildfires and by higher than normal temperatures during the 2004 summer. Ablation at the terminus increased from 5 to 14 mwe and the ELA moved up 550 m, from 1300 m average elevation to 1850 m in 2004. The annual balance in 2004 (–3.1 mwe) is the most negative for the 1951–2011 period of record.

6 Model calibration

The PTAA model is calibrated by calculating the daily balance for each altitude interval and for each day of the 1951–2011 period, using 15 coefficients and a simplex optimizing procedure (Nelder and Mead, 1962). The annual balance is found by integrating daily balances over one year. The coefficients convert observed precipitation and temperature at two low-altitude weather stations (Cordova and Yakutat) to daily snow accumulation and snow and ice ablation. Physical explanations for each coefficient are provided in Tangborn (1999).

The initial 15 coefficient values are random estimates, based on a reasonable range of potential values for each parameter. For example, the coefficient that converts gauge precipitation to basin precipitation is assigned 16 different values that vary from 0.107 to 0.288. The final value after 350 iterations and the calibration is completed is 0.2007. Similar estimates are made for initial values of the other 14 coefficients. The annual balances shown for each iteration in Fig. 7a are based on the coefficient estimates of the 15 coefficients. The first 15 balances vary from approximately −1.0 to +1.0 mwe corresponding to the initial, pre-set coefficient values. As the calibration proceeds, coefficient values are determined automatically by the simplex.

One iteration of the simplex determines for each elevation level the daily and annual balances for the period of record, and calculates the average error that occurs when multiple balance parameters are regressed against each other. The average root-mean-square-error resulting from these regressions is minimized to obtain the optimum coefficients. The size of the error automatically determines the minute adjustment that is made to each coefficient for the next iteration. After approximately 350 iterations, the calibration error reaches a minimum (in this case about 45 %), and the mean annual balance is an optimum value (about −0.6 mwe).

The scatter plot in Fig. 7b shows the mean annual balance versus the corresponding error for each iteration. When the error is a minimum at 45 %, the mean annual balance is −0.60 mwe. For most glaciers the balance-error distribution shows a more distinct balance value (Fig. 8b in the Gulkana Glacier report shows a definite mean annual balance at the minimum calibration error). The immense size of the Bering Glacier may tend to reduce the balance-error distinction and make the determined mean annual balance less definite.

7 Real-time glacier balances

One goal of the PTAAGMB project is to continuously monitor all 200 glaciers in the set and display the current mass balance of each one, in real-time, if up-to-date weather observations are available, or near real-time if weather observations are delayed. The daily balances for the 2011 balance year shown in Fig. 8 demonstrate how real-time mass balances for the Bering Glacier will be displayed in future years.

On 30 September 2011, the net balance is −1.7 mwe, the accumlation balance, 1.0 mwe, and the ablation balance, −2.7 mwe. Analysis of the daily balances of a large number of glaciers simultaneously will be applied to produce an improved understanding of glacier/climate relationships.

Historical and current mass balance results for other glaciers worldwide (including others in Alaska) are shown on http://www.ptaagmb.com.

8 Bering surges, snow accumulation and runoff

Bering Glacier surges are caused by a build-up of mass on the upper glacier from the accumulation of snow that falls nearly every day of the year at higher elevations. When sufficient mass has accumulated, a surge is triggered by an influx of water (runoff) to the glacier bed. These two phenomena (snow accumulation and runoff) tend to be mutually exclusive – high rates of snowfall and runoff usually do not occur simultaneously. Therefore, the timing of snow accumulation and runoff are critical for a surge to occur.

Runoff from the Bering glacier is estimated with the PTAA model by the sum of simulated ablation and precipitation as rain: $r = a + p_r$, where r = runoff, a = ablation, p_t = precipitation as rain, all in units of length averaged over the glacier area. One millimeter of runoff per year averaged over 4773 square kilometers equals an average discharge rate of 51 $m^3 s^{-1}$, thus 2.5 m of runoff per year (approximately the long term average) equals an average discharge rate of 130 000 $m^3 s^{-1}$ (in comparison, the average flow of the Mississippi River at New Orleans is about 15 000 $m^3 s^{-1}$).

Surges of the Bering glacier can produce an ice displacement of as much as 13 km (Post, 1972). Transporting large volumes of ice to a lower and warmer elevation over a short time period (several months) increases the ablation rate and alters the mass balance and runoff of a glacier. Observed surges occurred in 1958–1960, 1966–1967, 1981, 1993–1995 and 2008–2011 (Molnia and Post, 2010). An increase in runoff during these periods would therefore be expected if there is a large transport of ice to lower elevations during a surge.

A plot of Bering Glacier cumulative 5-yr running mean runoff, shown in Fig. 9a, suggests a causal relationship between surges and runoff. Each point represents the cumulative runoff for the previous 5 yr. For example, on 1 October 1981, a total of 14 mwe runoff had occurred over the previous 5 yr, or 2.8 mwe per year. Also shown is the timing of the four observed surges since 1951. Peak runoff occurs near the midpoint of each surge.

A surge usually ends when there a rapid release of stored water (jökulhlaup) that depletes the water supply for bed lubrication. Basal glide from water lubrication for surging glaciers in Iceland is suggested by a general lack of push-moraine formation in front of an advancing terminus (Bjournsson, 1998). It was first thought that the July 1994 observed Bering Glacier jökulhlaup was a surge-ending event because ice velocities decreased following the onset of the jökulhlaup. However, rapid ice movement restarted and the surge continued for throughout 1995 (Molnia and Post, 2010). Runoff during the 1993–1995 surge was greater than for the other three as indicated in Fig. 9a.

Cumulating daily snowfall averaged over the total glacier area in 5-yr running averages demonstrates the variations in glacier mass that have occurred throughout the period of record, 1956–2011 (Fig. 9b). The pattern of the running accumulation balance is similar to the runoff pattern shown in Fig. 9a confirming that surges are initiated by a build-up of mass, then proceed by the introduction of bed-lubricating water.

9 Conclusions

1. Bering Glacier surges transport large volumes of ice to lower elevations where it rapidly melts and increases runoff, which is detected with the PTAA model.
2. The cause of surges is a build-up of mass on the upper glacier coupled with an increase of runoff on the lower glacier, increasing bed lubrication and inducing sliding.
3. Ice volume loss averaged for the 1972–2003 period, determined by both the PTAA model and the geodetic method equals 2.3 km^3, confirming the validity of the PTAA model.

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Fig. 1. Bering Glacier on 23 August 1979. Photo by Austin Post Folds on the lower glacier are indicative of a surging glacier.

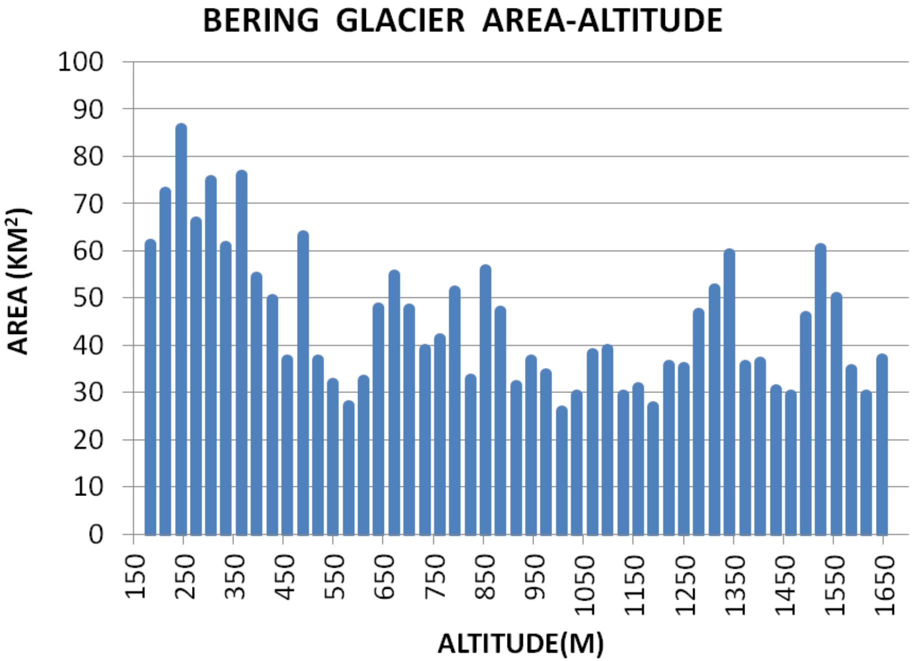

Fig. 2. Area-altitude distribution of the Bering Glacier. The total area of the glacier is 4773 km^2 and there are 49 altitude intervals spaced at 30.6 m, ranging from 150 to 1650 m in elevation. Latitude 60.302° N Longitude −143.20° W.

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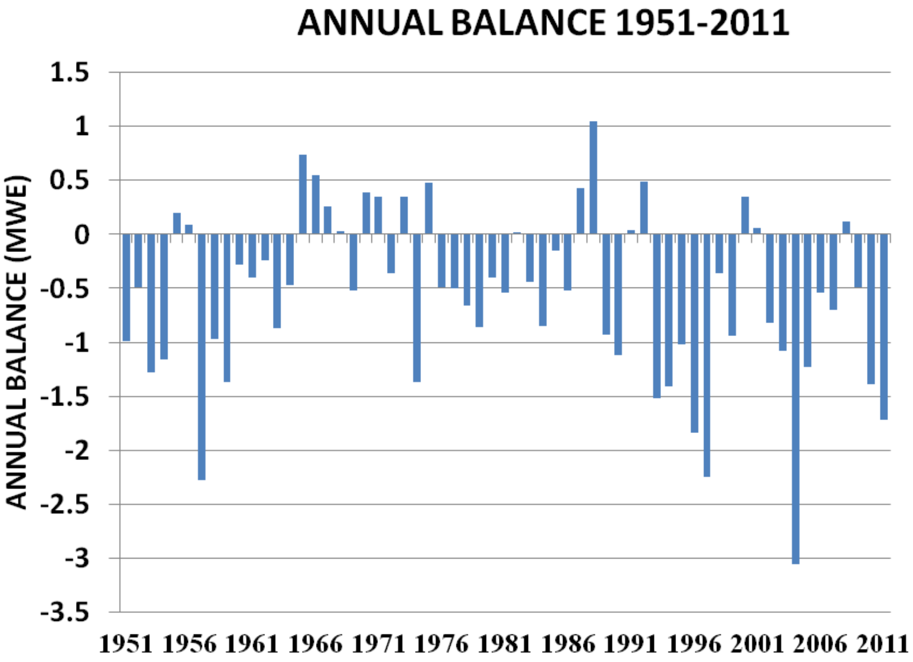

Fig. 3. Annual balance of the Bering Glacier for the 1951–2011 period. The average annual balance is −0.6 mwe. The minimum balance for the period (−3.1 mwe) occurred in 2004.

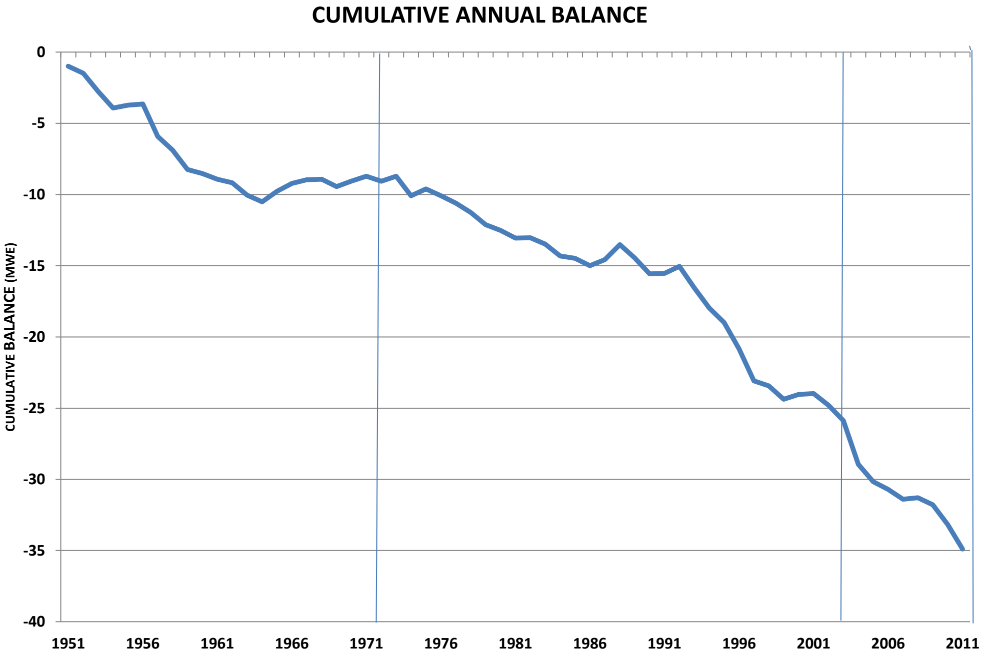

Fig. 4. Cumulative balance of the Bering Glacier. Total thinning during this 61-yr period is 39 m or 0.6 m of ice per year. The vertical lines at 1972 and 2003 delineate the period for which the volume loss determined by the PTAA and geodetic methods are compared.

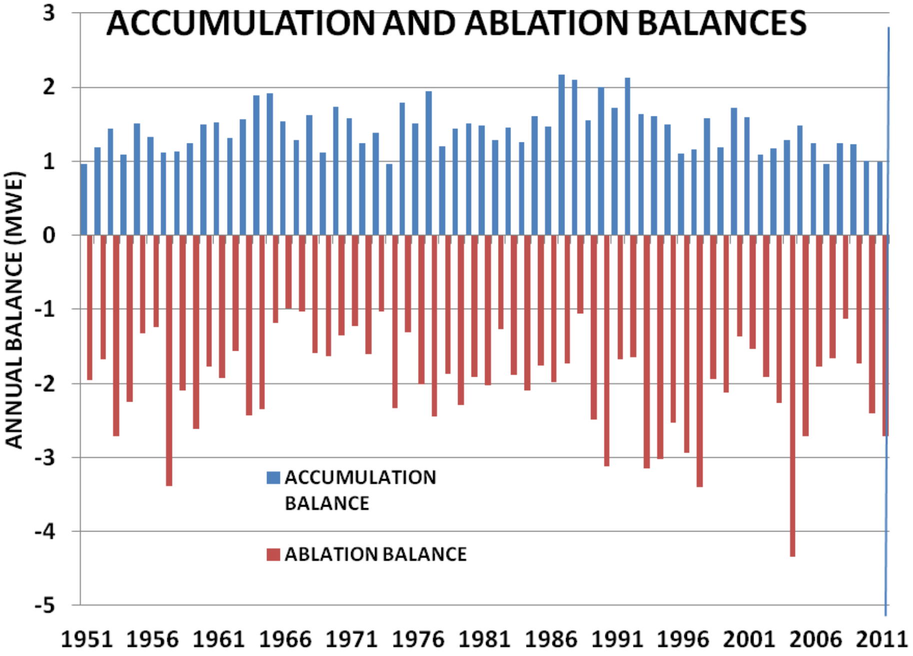

Fig. 5. Accumulation and ablation balances for the 1951–2011 period. The average annual accumulation balance for this period is +1.4 and the average ablation balance is –2.0 (mwe). Maximum ablation (−4.3 mwe) occurred in 2004.

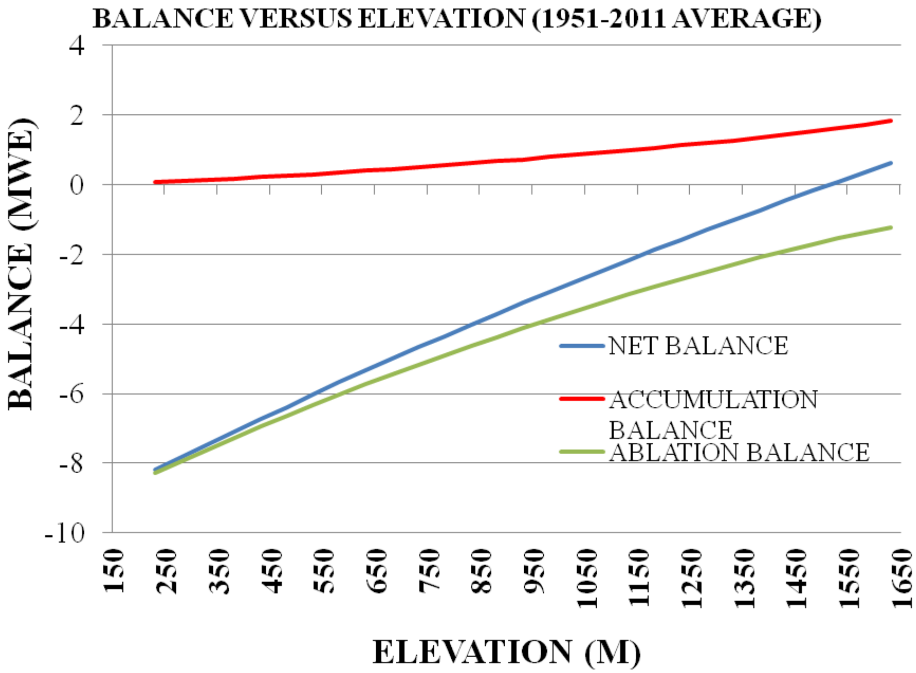

Fig. 6a. Net, accumulation and ablation balances of the Bering Glacier as a function of elevation, averaged for the 1951–2011 period. The ELA (1300 m) is defined as the point at which the net balance crosses the zero balance line.

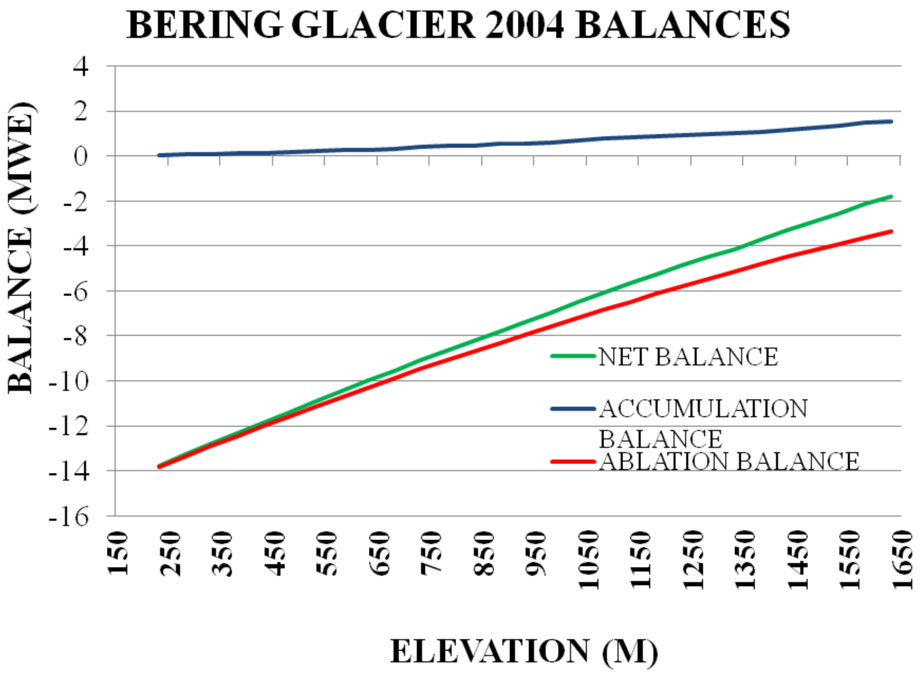

Fig. 6b. Net, accumulation and ablation balances of the Bering Glacier as a function of elevation, averaged for the 2004 period. The ELA is 1850 m, 550 m above average. The balance at the terminus (−14 mwe) is nearly 3 times as negative as on a normal year.

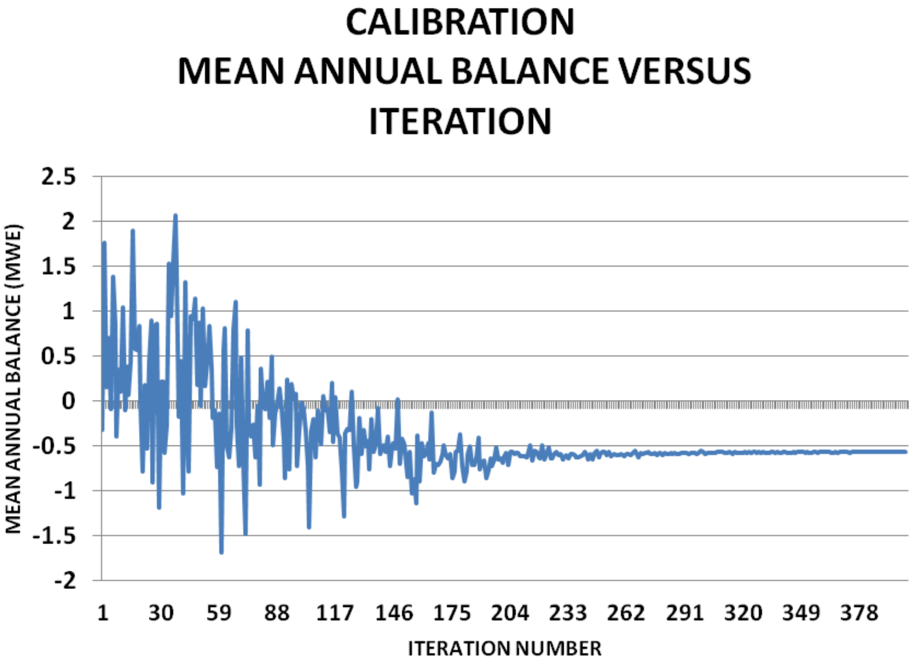

Fig. 7a. Mean annual balance versus iteration number of the optimizing simplex. Balances 1–15 are derived from preset coefficients. Balances 16–350 are calculated automatically from coefficients determined by the simplex optimizing process. When the calibration error reaches a minimum, the average annual balance is −0.6 mwe.

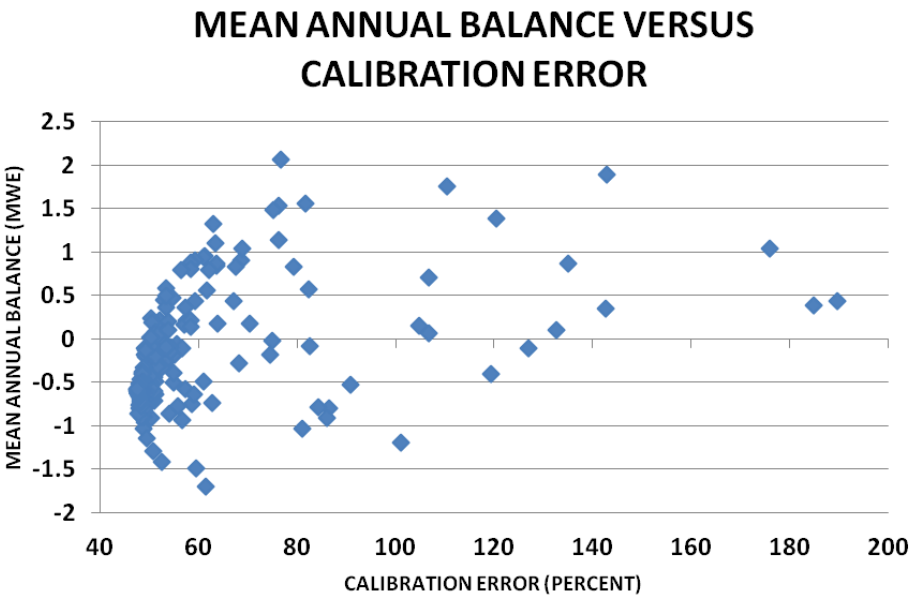

Fig. 7b. Mean annual balance versus calibration error. When the calibration error reached the minimum of about 45 %, the average annual balance is −0.6 mwe. Each point represents the mean annual balance based on 61 yr daily balance determinations.

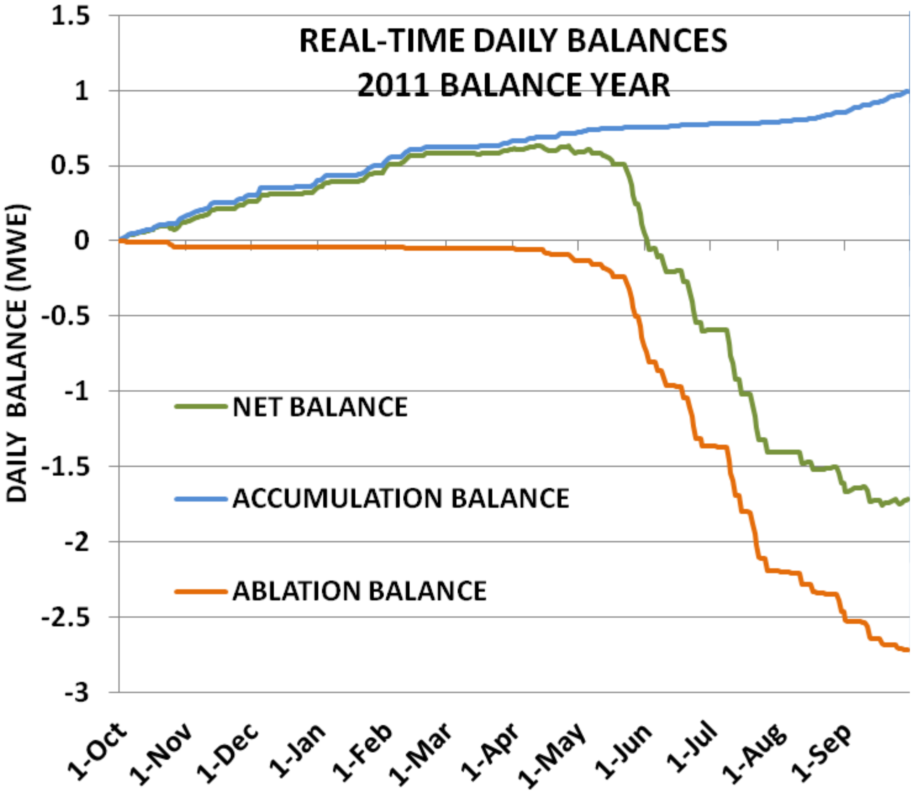

Fig. 8. Daily balances of the Bering Glacier during the 2011 balance year. The final net balance for 2011 on 30 September equals −1.7 mwe, the accumulation balance is 1.0 and the ablation balance is −2.7 mwe. Snow accumulation on the Bering Glacier begins on approximately 1 August each year, thus "winter" balance is a misnomer for this glacier.

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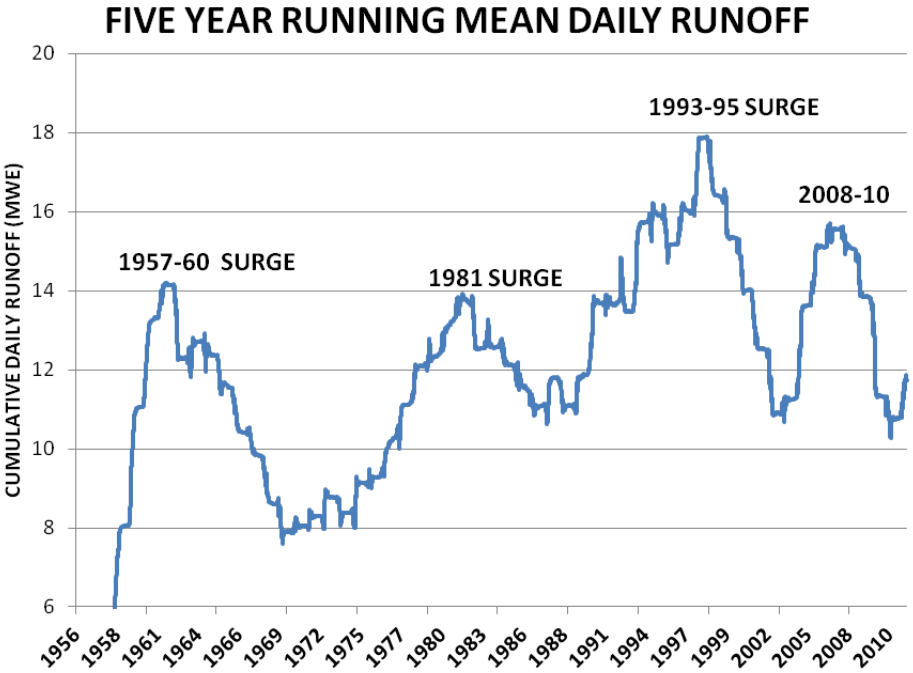

Fig. 9a. Five-year running mean daily runoff (ablation plus precipitation as rain) of the Bering Glacier, and timing of the four observed surges since 1951.

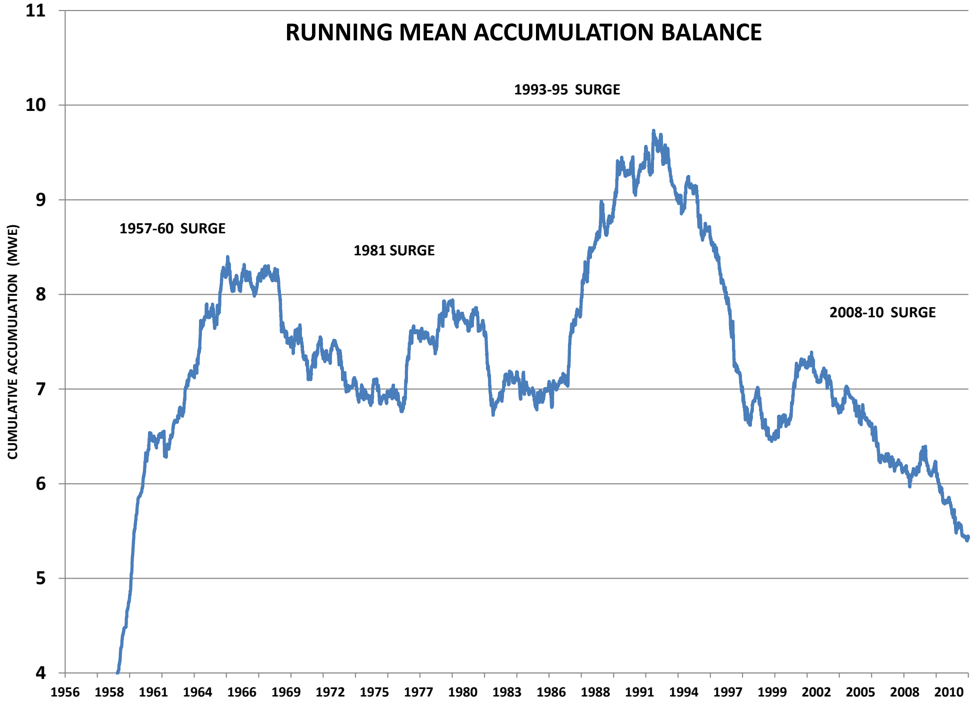

Fig. 9b. The 5-yr running mean of daily snow accumulation on the Bering Glacier, and timing of the four observed surges since 1951.