Connecting Winter Balance and Runoff to Surges of the Bering Glacier, Alaska

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Abstract

Each of the four surges on Bering Glacier in the period 1950 to 2000 occurred after a running total of snow (accumulation or winter balance) on the glacier was above average for five or more years, suggesting a sustained build-up of mass as one requirement for a surge. When sufficient snow has accumulated on the glacier there is evidence that a surge is triggered by an abnormal influx of water as runoff. As high rates of snow accumulation are inversely correlated with high rates of runoff, there appears to be a tendency for the Bering Glacier (and possibly other glaciers) to alternate between surging and non-surging states depending on the timing of snowfall and runoff periods. To examine the connection of accumulation balance and runoff to surges of the Bering Glacier, the mass balance and runoff of the Bering/Bagley Icefield are simulated for the 1950-2000 period with a precipitation-temperature-area-altitude (PTAA) model that integrates the area-altitude distribution of the glacier and daily meteorological observations collected at low-altitude weather stations. It is proposed that the terms winter balance and summer balance be replaced with *accumulation* balance and *ablation* balance.

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 meters altitude and has a total area of 3064 square kilometers. Figure 1 (map of glacier). Within the past 100-200 years, the Bering Glacier began to retreat from its maximum Neoglacial position; however, in the past 100 years this retreat has been interrupted by at least six surges of substantial amplitude and duration (Molnia and Post, 1995). During the 1950-2000 period, surges of the Bering Glacier occurred in 1958-60, 1965-67, 1981 and 1993-95 (Post, personal communication). The 1981 surge was weak and had a short duration; the dynamic 1993-95 surge occurred in two distinct pulses (Molnia and Post, 1993; Fleisher, 1998). Bering Glacier surges are not considered entirely periodic as the time interval between them during this 51-year period varies from 7 to 16 years. It is the intent of this paper to show the link between mass balance, runoff and surges using a computer model that requires only low-altitude meteorological observations. Runoff is defined as the sum of precipitation as rain and ablation, therefore it is not actual runoff, which would include the release of water from storage and measured by a gauge at the terminus.

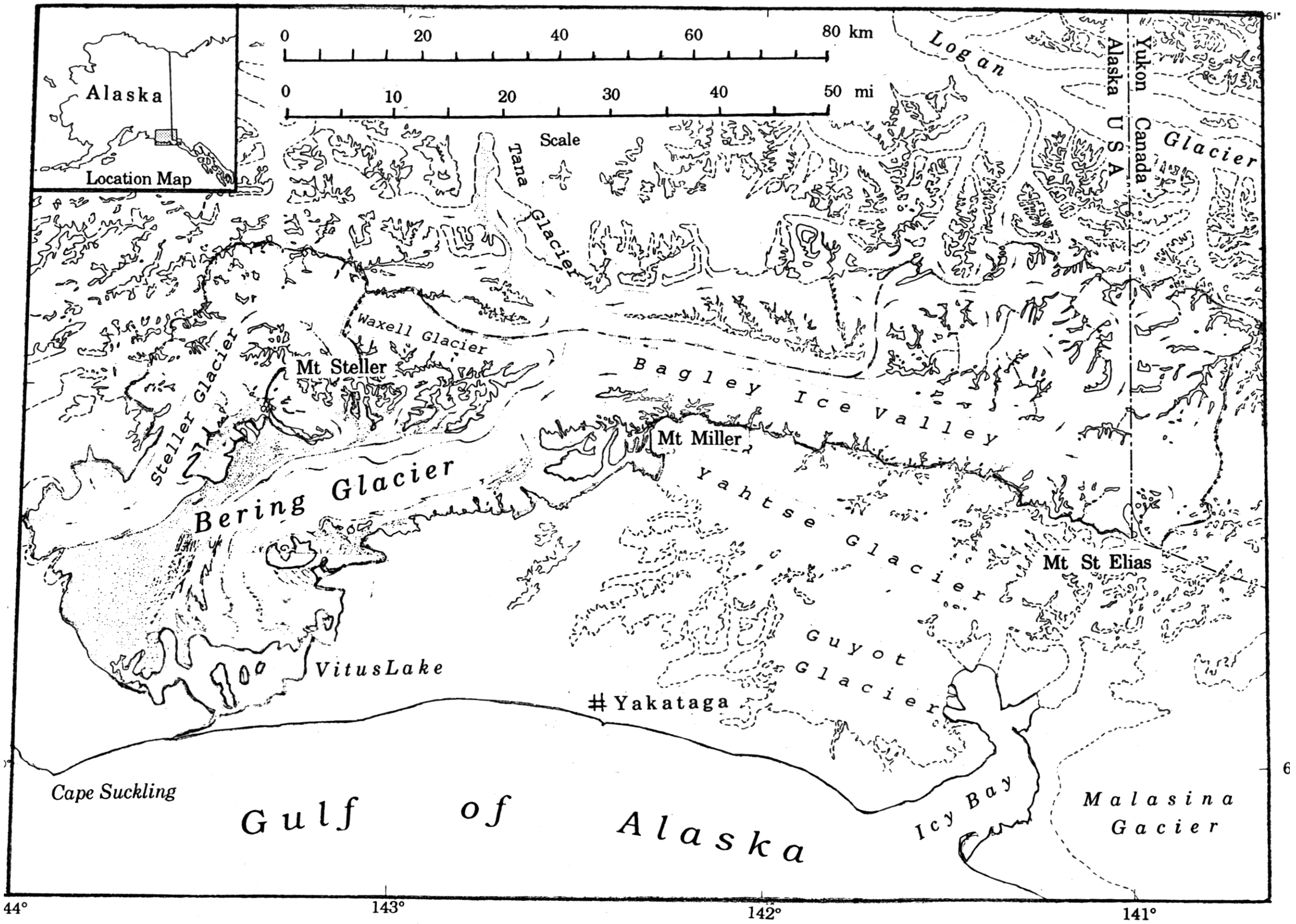

Figure 1. Map of the Bering Glacier, compiled by Austin Post.

Snowfall occurs at the higher altitudes of the Bering Glacier throughout much of the year, including the summer season (approximately May-September), and the ablation of ice occurs at lower altitudes during the winter season (October-April). Therefore, the terms winter balance and summer balance are inappropriate for the Bering and most other glaciers and should be replaced by more suitable terms. A*ccumulation balance* and *ablation balance* have been suggested as replacements (Tangborn and Rana, 2000), and will be used henceforth in this paper.

The PTAA Model

The PTAA (precipitation-temperature-area-altitude) model converts daily observations of precipitation, maximum and minimum temperatures collected at low-altitude weather stations to snowfall and ablation at each area-altitude interval of the glacier. For the Bering Glacier study, the observations are from Yakutat and Cordova weather records for the 1950-2000 period. These long-term weather stations are located 125 km. NW and 200 km. SE of the glacier terminus, and at elevations of 8 and 12 meters, respectively.

The area-altitude distribution of the glacier is a critical part of the model, therefore accurate and up-to-date maps or digital models of the surface area are essential for constructing the AA profile. The Bering Glacier AA profile shown in Figure 2 was calculated from a USGS 15-minute DEM (Muskett and others, 2000), and is made up of 81 intervals defined by 30-meter altitude differences.

FIGURE 2

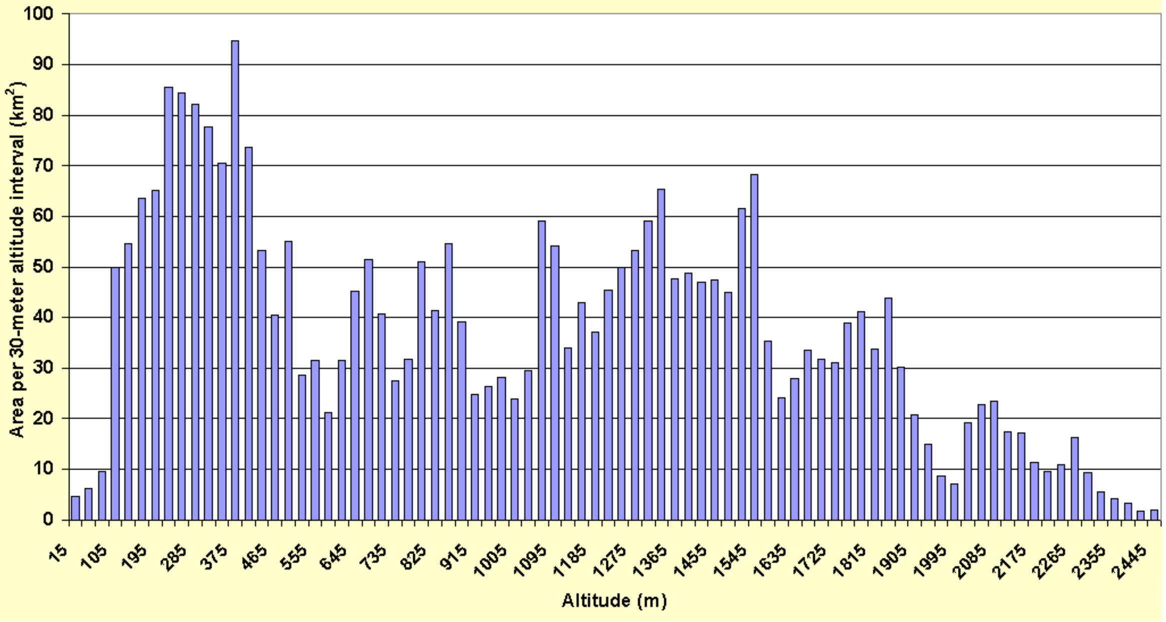

Figure 2. The area-altitude distribution of the Bering Glacier is derived from a USGS 15 minute DEM. There are 81 area intervals, each with a 30-meter altitude difference. The area of the glacier used for this compilation is 3064 km^2, and includes the Waxell and Stellar Glacier tributaries.

Model Description

The computer model, written in Fortran 77, uses 15 coefficients in approximately twenty algorithms to convert, at each AA interval, observed low-altitude daily precipitation to either snow or rain, and observed daily maximum and minimum temperatures at the same stations to the ablation of snow or ice. These determinations are based on the calculated daily temperature at each AA interval's altitude, using the predicted temperature lapse-rate that is also calculated from low-altitude temperature observations. Snowfall (water content) is accumulated continuously at each interval and defined as the *accumulation* balance (Bw). Ablation of snow, and of ice below the snowline is calculated for each interval using a series of algorithms and the mean temperature determined for that interval. Ablation (always a negative value) is accumulated continuously at each interval and defined as the *ablation* balance (-Bs). Accurate simulations of the glacier balance (Bn = B_w + B_s) using only meteorological observations from distant weather stations is possible because the area-altitude distribution is an integral part of the model. Model calibration to obtain optimum values for each of the 15 coefficients is accomplished by multiple regressions of the simulated balance variables, all of which are highly sensitive to the glacier's spatial configuration (the AA profile). A simplex optimization procedure is used to generate optimal coefficient values that produce the minimum average error for all the regressions that are run (approximately 3000 for each iteration of the simplex).

A detailed analysis of the relationship between pairs of simulated balance variables suggests that the model-calibration process has a forcing effect that produces optimum compatibility between two simulated variables. For example, when regressing the zero balance altitude (or transient ELA) against the annual balance for each day of the ablation season for 51 years, there is a propensity for the simplex optimizing procedure to generate values for both variables that fall within compatible, physically-real limits. The model can be considered robust as it uses just fifteen coefficients to calculate over one-half million values (7650 days over 81 altitude intervals), for each set of 20 pairs of balance variables – a total of over 12 million for each iteration of the simplex. Minimizing the mean error while simultaneously regressing all 20 sets of these variables tends to force an internal consistency between all of them. A detailed description of the model and of the calibration procedure can be found in Tangborn (1999).

Model Verification

The main criticism of the PTAA model is that low-altitude meteorological observations cannot represent weather conditions at all altitudes on a glacier that is over 100 km from the weather station. The Bering Glacier lies approximately equal distance from the two weather stations used in this study, Cordova and Yakutat (Figure 3). It is reasoned that if weather observations during the 1950-2000 period at these two stations are significantly correlated, both should have an even higher correlation with an observation site at the glacier terminus. Table 1 shows the relationship of precipitation and temperature observations at Cordova and Yakutat.

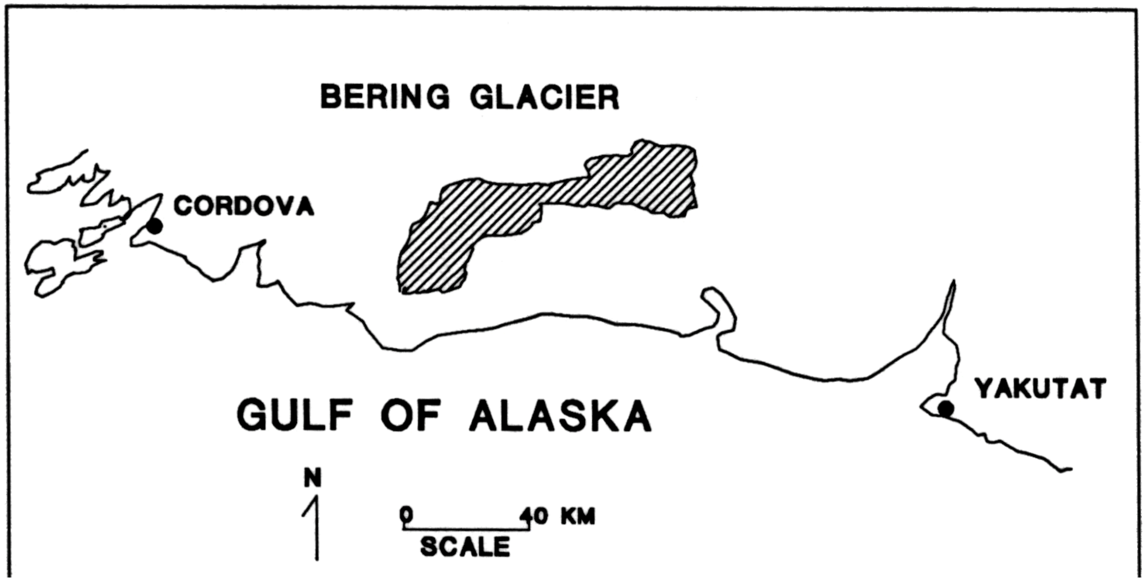

Figure 3. Sketch map showing relative locations of the glacier and the weather stations used in the model.

Table 1. Correlation of Cordova and Yakutat Annual and Daily Meteorological Observations

Variable	Correlation Coefficient	Number in Sample
Annual Precipitation	0.68	51 years
Mean Annual Max Temperature	0.87	51 years
Mean Annual Min Temperature	0.81	51 years
Daily Precipitation		
Feb (max)	0.57	1428 days
Jun (min)	0.37	1530 days
Daily Max Temperature		
Apr (max)	0.82	1428 days
Aug (min)	0.65	1581 days
Daily Min Temperature		
Feb (max)	0.80	1428 days

Jun (min)	0.43	1581 days

The mass balance histories of the Columbia Glacier in Alaska, the South Cascade Glacier in Washington, and the Langtang Glacier in Nepal have been simulated with the PTAA model. The simulated accumulation balance (total snowfall) for the upper Columbia Glacier agrees within a probable error of 0.2 mwe for point accumulation measurements made over a 5-year period that began with a volcanic ash deposit in 1992 (Tangborn, 1997; Tangborn and Post, 1998). The simulated ablation balance below 2000 m agrees within a probable error of 0.15 mwe for ablation measurements made on the Columbia Glacier for one year (Mayo and others, 1978).

The simulated volume change over the 1975-96 period for South Cascade Glacier agrees nearly perfectly (within 0.1 mwe) of the volume change determined by geodetic techniques during this period. However, a linear regression fit between simulated and measured annual balances for the 1959-95 period produced an R^2 of just 0.57 (Tangborn, 1999)

Runoff and ablation results for Langtang Glacier, for which measured balances have not been made, agree within 25-50 percent of measured runoff and ablation at similar altitudes on nearby Lirung and Yala Glaciers (Tangborn and Rana, 2000).

Thus the PTAA model produces mass balances and associated variables that agree reasonably well with independent measurements.

Mass Balance and Runoff Results for the Bering Glacier

Based on the simulated mass balance, the Bering Glacier thinned 54 meters during the 51-year, 1950-2000 period, or a mean annual balance of –0.97 m (we). For the 1972-2000 period, the model-simulated annual balance of the Bering Glacier is approximately –0.94 m (we), which agrees within 0.2 m of mass loss determined independently during this period from topographic maps and surface-change measurements derived from laser-altimeter observations (Muskett and others, 2000). Figure 4 shows the altitude distribution of the winter, summer and annual balance, averaged for the 1950-2000 period. The mean altitude of zero balance (ZBA), where accumulation equals ablation, is at an altitude of 1050 meters on September 30. The ZBA is calculated each day throughout the ablation season; it is more commonly known as the ELA (equilibrium line altitude) at the end of the balance year. The Accumulation Balance is defined as cumulative snowfall, in water equivalent, over the total area of the glacier for one balance year, October 1 to September 30 for the fixed date system. The model-simulated rate of snowfall for the total Bering Glacier, averaged for the period 1950-2000, is approximately 3.9 mm (we) d^{-1}, or 1428 mm (we) y^{-1}. The ablation and accumulation balances for the 1950-2000 period are shown in Figure 5. The annual balance, the sum of accumulation and ablation balances, is becoming increasingly more negative with time: for the 1950-75 period the mean annual balance is -0.83 m(we), and for the 1976-2000 period it is -1.10 m(we), a 32 percent increase.

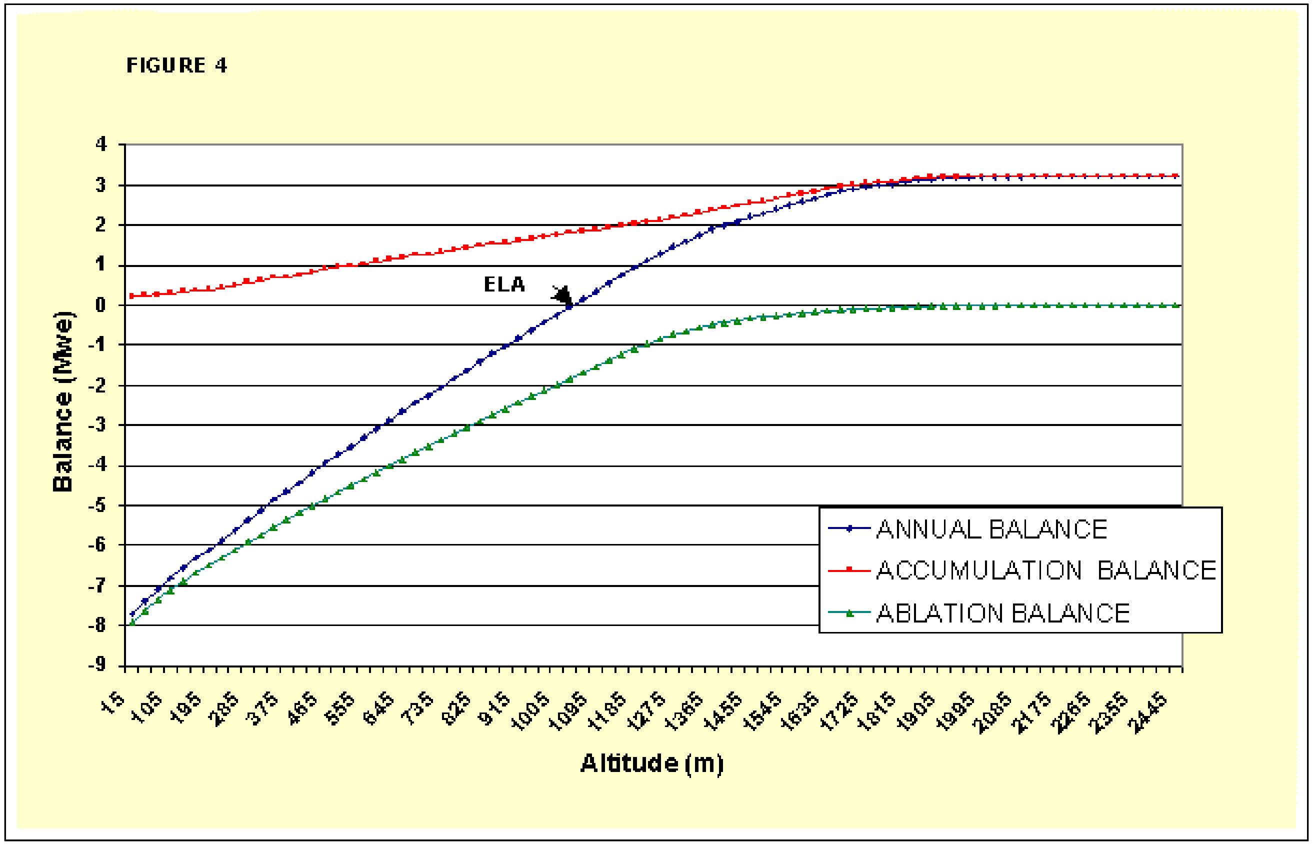

Figure 4. The mean simulated Accumulation, Ablation and Annual Balance for each 30-meter altitude interval. The mean ELA is 1050 m, which is approximately the altitude observed visually.

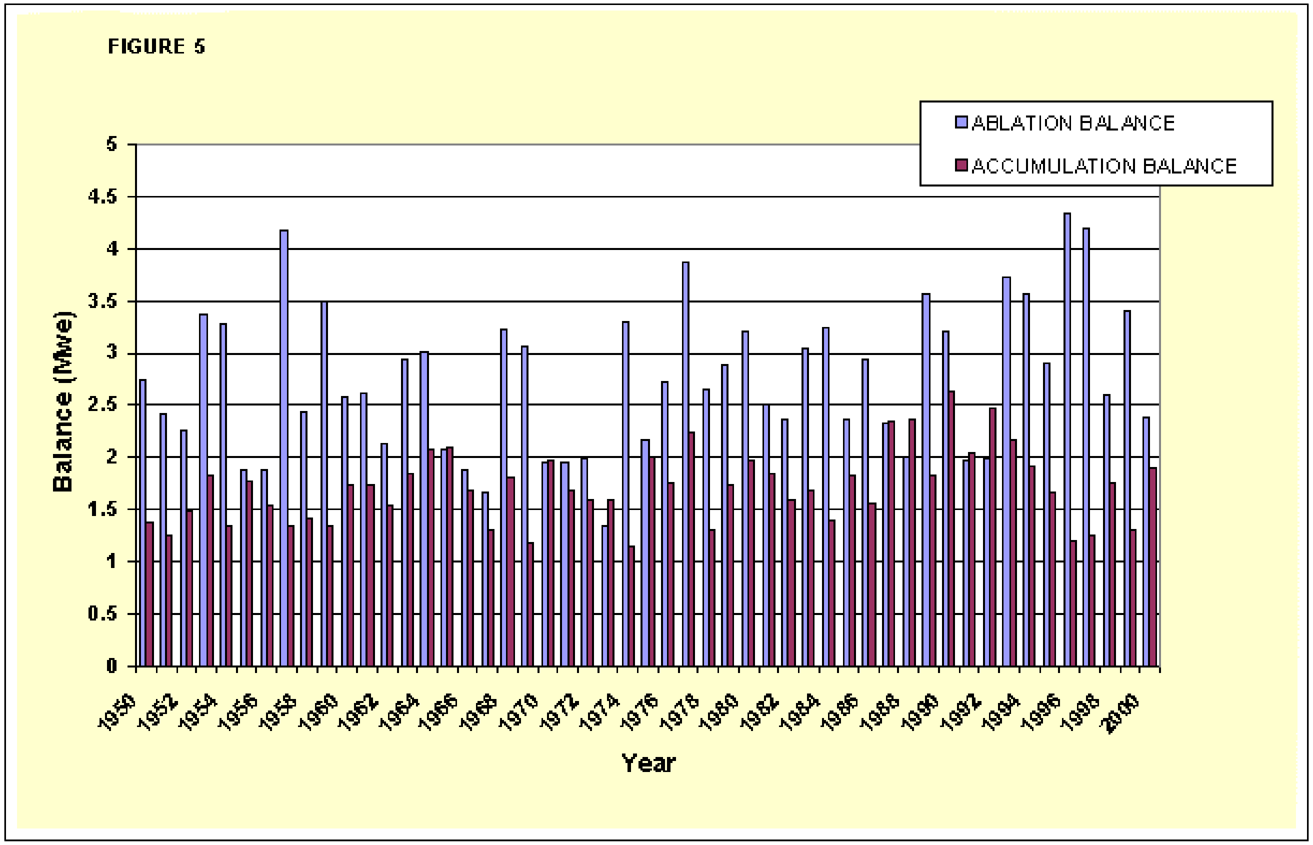

Figure 5. The Ablation and Accumulation Balance for each year of the 1950-2000 period. The ablation balance is plotted as a positive value so that the annual balance (the sum of B_w and B_s) is apparent. Note that periods of above-average accumulation balance roughly correspond to the 1958, 1965, 1981 and 1993 surges.

Runoff from the glacier is derived from two sources: the ablation of snow and ice, and precipitation that occurs as rain. Annual runoff from the Bering Glacier is approximately 3.4 my^{-1} (or an average discharge of 330 m^3s^{-1-}). The large volume of freshwater runoff (12 km^3 y^{-1}), one-third of which is due to increasingly negative annual balances, is believed to have contributed to recent changes in the Alaska Coastal current, which is thought to have adversely affected salmon migration patterns (Tangborn and others, 2000). Surges tend to amplify this effect by transporting large quantities of ice to lower altitudes where it is rapidly melted.

The simulated annual accumulation, ablation, annual balance and runoff for the Bering Glacier are provided in Table 2.

Table 2. Balance and Runoff Results for the 1950-2000 Period

Variable	Average (Mwe)	Explanation
Accumulation Balance (B_w)	1.43	Cumulative snowfall from Oct 1 - Sep 30
Ablation Balance (B_s)	-2.40	Cumulative ablation from Oct 1 – Sep 30
Annual Balance (B_a)	-0.97	$B_w + B_s$
Total Precipitation (P_t)	2.42	Annual snowfall plus rain
Precipitation as rain (P_r)	0.99	Annual liquid precipitation
Annual Runoff (R_a)	3.39	Ablation balance plus rain

Linking Surges to Winter Balance and Runoff

The transport of mass from a higher to lower altitude on a glacier does not proceed at a constant speed. Seasonal and inter-annual fluctuations in ice flow occur for nearly all glaciers (Kamb and others, 1985, Raymond, 1987). The primary controlling mechanism for ice transport is the input of mass to the glacier surface (the accumulation balance or total snowfall), which can vary widely, seasonally and from year to year. For a few glaciers, the transport of ice down glacier does not keep pace with the input of mass to the surface and at periodic intervals extraordinary high flow rates (10 to 10^2 times normal) will result and the glacier is said to surging. Other studies have suggested that the accumulation of snow on the glacier surface, particularly above the ELA, is instrumental in causing a surge (Dyergurov, et al., 1985; Dowdeswell, et al., 1995, Harrison, 2002).

The secondary role of englacial water in promoting and enhancing a surge is well-documented (Bindschadler, 1983). During the Variegated Glacier surge in 1983, floods in the outflow streams correlated with a decrease in ice flow velocity in the surging area indicating a rapid release of stored water that likely had acted as a bed lubricant during the surge (Kamb and others, 1985; Kamb, 1987). The same phenomena were observed for the Bering Glacier at the beginning of the 1993 surge (Fleisher and others., 1998). Prior to that surge, water flow from the glacier was through a well-established tunnel system (the Tsivat Basin Conduit). During the surge, there is strong evidence that water drainage from the glacier switched to linked-cavity discharge (Fleisher and Mueller, 1999).

Some glaciers surge at periodic intervals due to some remarkable instability (Post, 1969). For the Bering Glacier, there is evidence that when the accumulated mass on the glacier surface reaches a critical stage, the exact timing of the surge is controlled by a large influx of water, derived from ablation and/or precipitation as rain, from the surface to the bed where it acts as a bed lubricant that promotes rapid sliding.

The photo in Figure 6 shows the looped moraines that are the result of decades of Bering Glacier surges. The altitude distribution of runoff , R

(z) and the accumulation balance, $B_w(z)$, shown in Figure 7, demonstrates the relationship between these two variables and how they may be linked to surges. Both the climate and the area-altitude distribution of the glacier determine the relative positions of R(z) and $B_w(z)$. The cross-over altitude, Z_{co}, where $R(z) = B_w(z)$, is approximately 1200 meters for the Bering Glacier.

Figure 6. Photo of Bering Glacier, taken by Austin Post on August 25, 1960. The highly folded moraines on the lower glacier are indicative of a surging glacier.

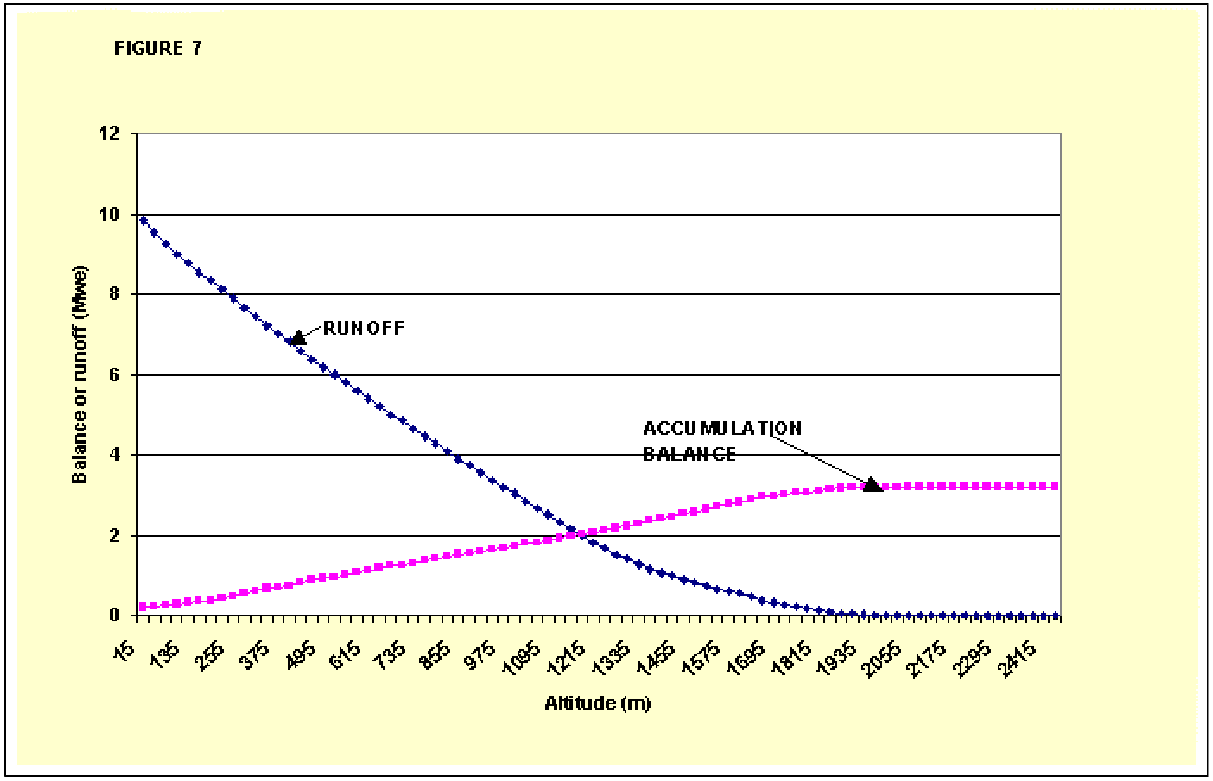

Figure 7. Mean annual runoff and accumulation balance averaged for the 1950-2000 for each 30 m altitude interval. The shape of these distributions is partly determined by the glacier's area-altitude distribution, therefore, the crossing-point altitude, where the accumulation balance equals runoff (about 1200 m for the Bering Glacier) will vary widely between glaciers, depending on the AA distribution. It is suggested that the crossing-point altitude may determine if a glacier is a surging or non-surging type.

It is proposed that the altitude of Z_{co} is critical in determining whether Bering Glacier will surge. If it is at a higher altitude, runoff will supply sufficient water to keep the bed lubricated and allow continuous ice flow so that excessive mass build-up does not occur. If the cross-over is at a lower altitude, runoff will be deficient and the probability of a surge increases. As the result shown in Figure 6 is the only example of R (z) and B_w(z) yet available for any glacier, the range in these altitudes is unknown. A more detailed analysis of the Bering Glacier and a similar study of several other surge-type glaciers is needed to determine whether this theory has merit.

The mechanism for a Bering Glacier surge appears to be a period of 5 to10 years of near normal or above average snowfall (or accumulation balance). The daily, continuous accumulation balance in 1825-day (5 year) running totals is shown in Figure 8 along with the approximate starting date for each of the four surges. A consistent rise in the 1825-day running accumulation total indicates that the long-term average snowfall on the glacier is increasing and the glacier is gaining in mass at a greater than average rate. A decline in the running total means that snowfall during the previous 5-years is less than the long-term average and the glacier mass is decreasing.

Figure 8

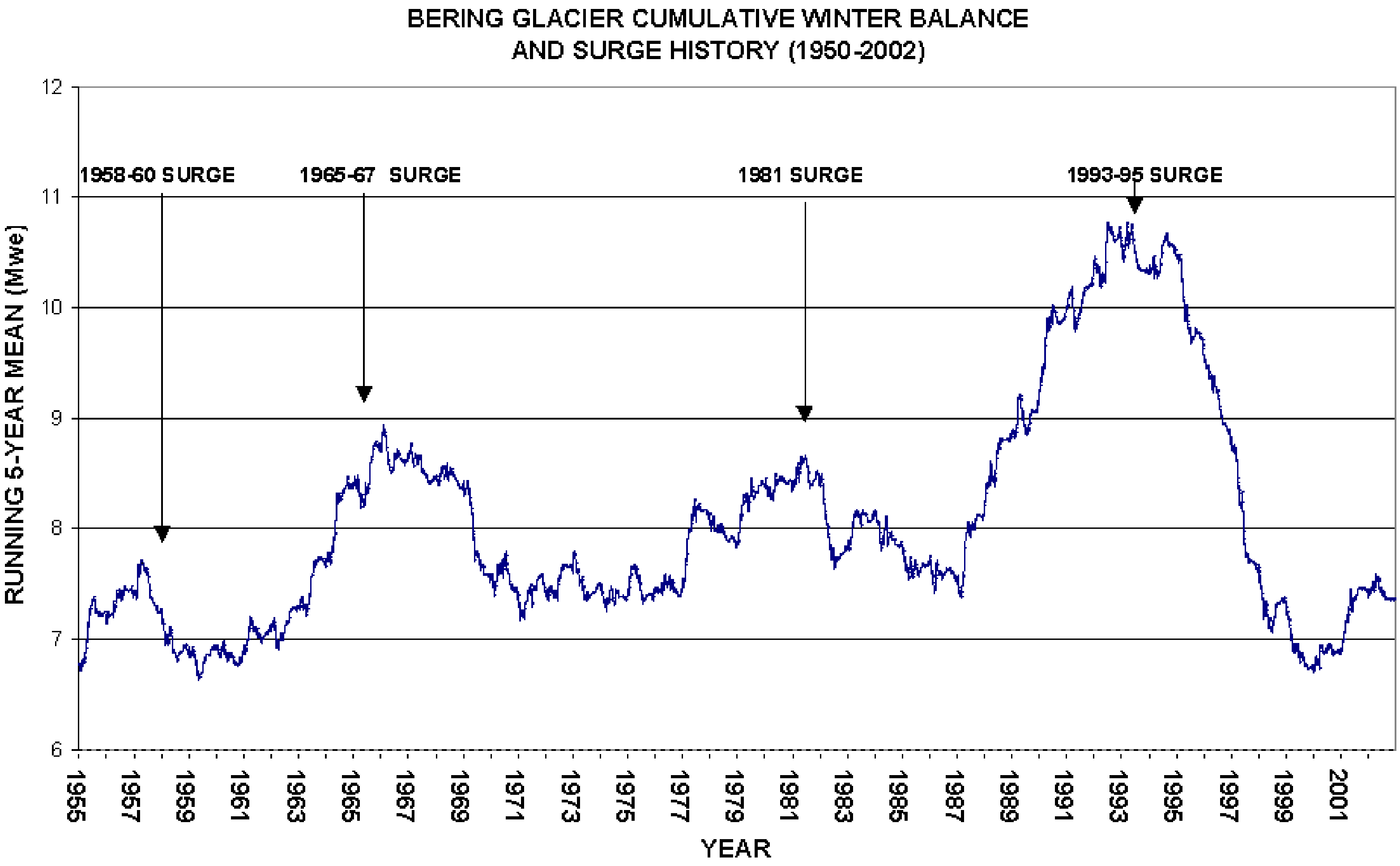

Figure 8. Cumulative daily accumulation balance for the 1950 to September 15, 2002 period, plotted daily with a 1825 day (5 year) running total. The starting years for the four known surges of the Bering Glacier during this period are also shown. The

weak 1981 surge was in response to slightly above normal accumulation balances for approximately 5 years, while the stronger 1993-95 surge followed much above normal accumulation balances for about 8 years.

Except for the 1958-60 surge, there is a good agreement between the onset of a surge and accumulation balance maximums or after the snow load on the glacier has made a relatively rapid gain The large difference between the time of peak accumulation balance and the surge in 1958-60 may be due to its proximity to the first year of the period so that the 5-year running mean is adversely affected).

After the cumulative accumulation balance has been positive for several years, the surge may be triggered by an above normal production of surface runoff. Either a warm storm that generates high rates of precipitation as rain, or a period of high temperatures causing heavy ablation, or a combination of the two, would trigger a surge. The intensity of the surge appears to depend on how long the period of above average accumulation balance occurs before there is triggering influx of water from the surface. The difference between the weak surge in 1981 and the powerful surge in 1993 suggests that the timing of high snowfall rates and high runoff may be a critical factor in surging glaciers.

The 1992-93 surge, which is the most closely studied of the four that occurred during the 1950-2000 period, provides an example of the influence of runoff in promoting a surge. Beginning about 1987, snowfall on the glacier was above average on a majority of days, resulting in a substantial increase in the accumulation balance.

However, the accumulation balance, annual balance and runoff are closely related – the accumulation balance and runoff are inversely correlated. The accumulation balance (B_w) is equal to accumulated precipitation as snow (P_s), and runoff is equal to total ablation, or the ablation balance -(-B_s), plus precipitation as rain (P_r). Total precipitation equals $P_s + P_r$, and the annual balance is $B_w + B_s$. Thus, if precipitation as snow increases, due to a lowering of freezing levels for example, but total precipitation increases or remains the same, both the annual and accumulation balance will tend to increase, but runoff will decrease – this appears to be the case prior to the 1993-95 surge. From 1987 to 1993, snowfall on the glacier was above average, thus precipitation as rain and ablation were below the long-term average. In addition, more snow tends to decrease ablation and runoff by increasing the reflectivity (albedo) of the glacier surface.
Figure 9 shows the mean daily discharge from the Bering Glacier for 1950-2000 and for 1993. Runoff during the May-July season for the period from about 1987 – 1992 was below normal, allowing mass to build to a high level. Abnormally high temperatures during the summer of 1993 (the average daily maximum during May-July was about 2 degrees C greater than normal, the highest on record since at least 1950), contributed to unusually high rates of ice melt. The above-normal runoff simulated from May 15 to June 15, July 1-15, and August 1-15, 1993 was caused by heavy ablation during these periods (simulated ablation during May-August was 200 percent of the 1950-2000 average). Precipitation as rain was just 83 percent of normal for the May-August season in 1993. Thus the summer of 1993 was hot and dry in SE Alaska, making ideal conditions for precipitating a surge when the glacier was loaded with snow.

Forecasting Surges of the Bering Glacier

The results shown in Figures 8 and 9 suggest that surges of the Bering Glacier could be forecast several months before their occurrence. The 5-year running total of the daily accumulation balance indicates that a constant increase over a period several years is a precursor to a surge. Then, when a critical mass has accumulated on the glacier, a surge is triggered by high surface runoff caused by heavy precipitation as rain and/or high-rates of ablation. Both snowfall and runoff can be monitored with the PTAA model, on a daily basis if desired, using daily observations of precipitation and temperature at Cordova and Yakutat. Both stations are now on a real-time network and can be updated as often as necessary. Both Figures 8 and 9 will be revised monthly as new meteorological observations become available.

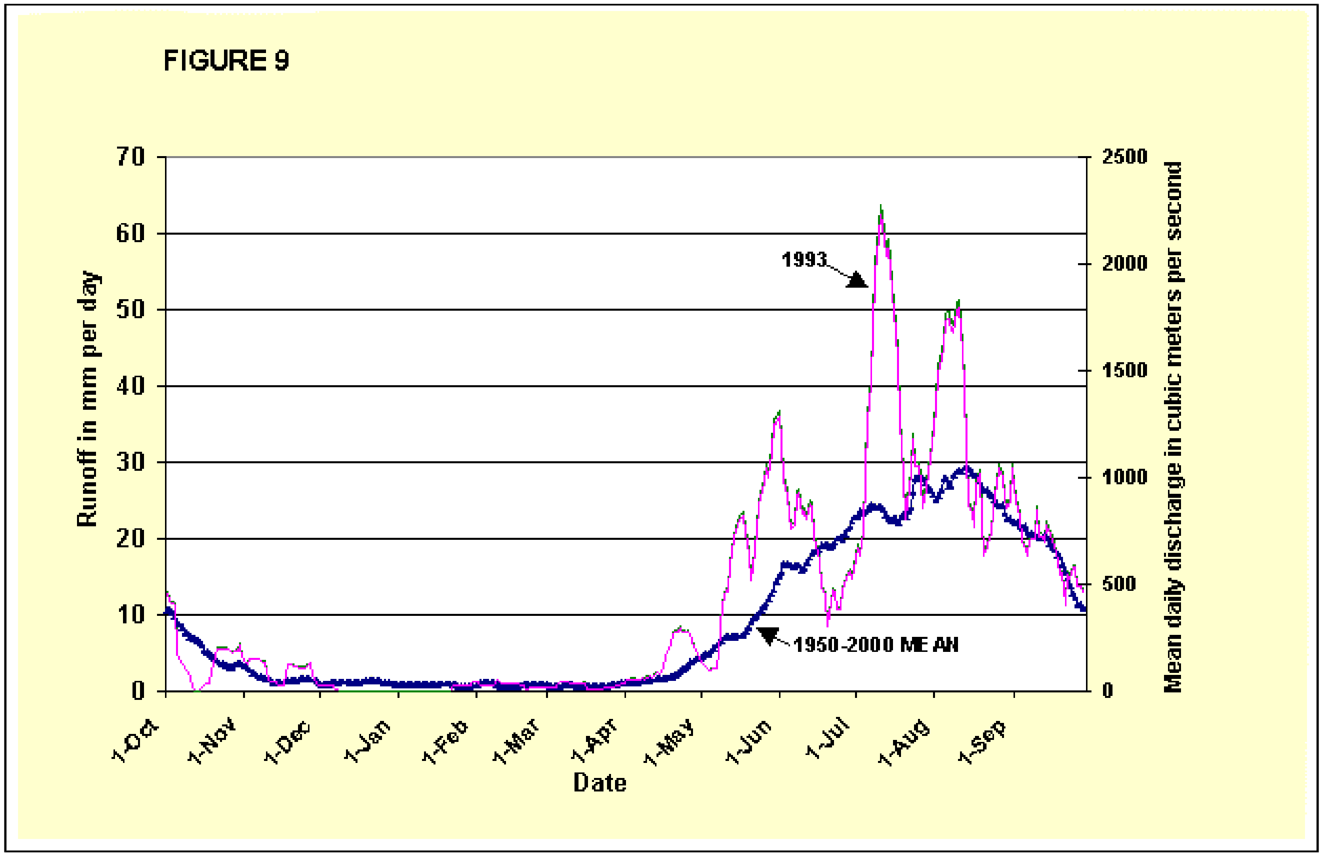

Figure 9. Mean daily runoff (ablation and rain) from the Bering Glacier averaged for the 1950-2000 period (heavy line), and the mean daily runoff in 1993. The 1993-95 surge is believed to have begun in late winter, 1993 (Craig Lingle, personal communication).

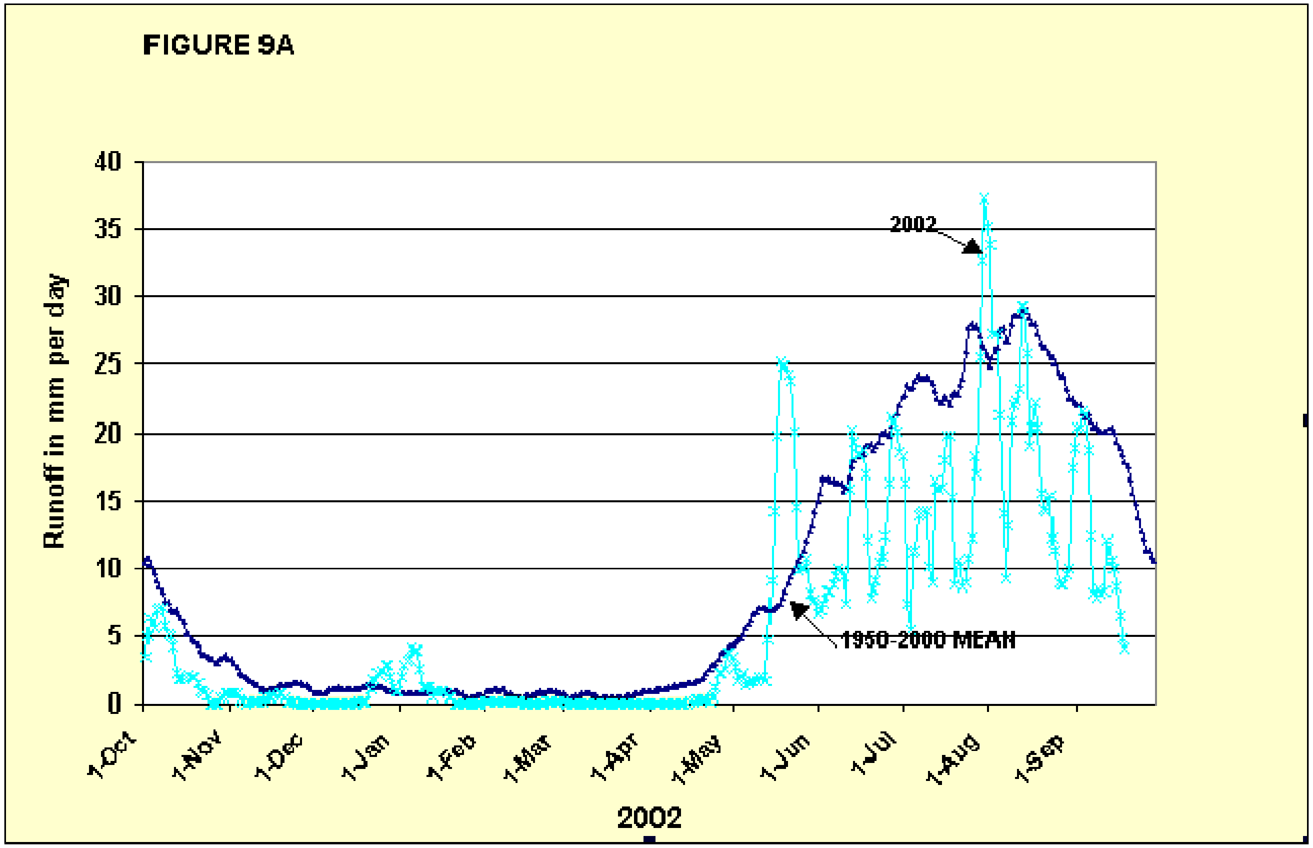

Figure 9A. Mean daily runoff from the Bering Glacier in 2002 and the 1950-2000 mean (heavy line).

Conclusions

1. For the Bering Glacier, a period of 5 or more years of above average snowfall (winter balance) will likely set the stage for a surge.
2. For a surge to occur, once the mass build-up has reached a critical level, an above-normal influx of water (ablation and rain) is needed.
3. The reason some glaciers surge while others do not may be due to the difference in water availability that allows flow of a non-surging glacier to keep pace with the replenishment of snow on the upper reaches of the glacier.
4. Forecasting Bering Glacier surges based on historic and real-time meteorological observations may be possible. Conditions as of September 15, 2002. During the period September 30, 1995 and September 15, 2002 Bering Glacier was not known to have surged. There was a minor increase in accumulation mass that peaked on January 9, 2002 (Figure 8) but is considered too small to cause a surge. In addition, precipitation as rain and ablation, which are thought to initiate surges when sufficient mass has accumulated, was inconsequential during the2001-02 winter. There were several high runoff events during each summer from 1994 through1999, but not in 2000, 2001 and

2002 (Figure 9A). The 1993-95 surge apparently depleted the reservoir of mass on the Bering Glacier so that the occurrence of high runoff during the 1994-1999 period did not initiate a surge.

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