Glacier Modeling in Support of Field Observations of Mass Balance at South Cascade Glacier, Washington, USA

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Introduction

The mass balance of a glacier is the most holistic metric of its health. It reflects the communication of climate to glacier, and is an indispensable parameter for predicting the evolution of glaciers on the landscape. As one of the most important quantities in glaciological science, glacier mass balance is the subject of much measurement and modeling activity worldwide.

Glaciers are extremely difficult and inconvenient places to collect data and critical mass balance phenomena, such as annual glacier mass extremes, are rarely directly observed, but instead must be partly estimated. The goal of this work is to describe the U.S. Geological Survey (USGS) mass balance monitoring program at South Cascade Glacier, Washington, (fig. 1) and to present recently developed methods for systematically estimating critical mass balance phenomena.

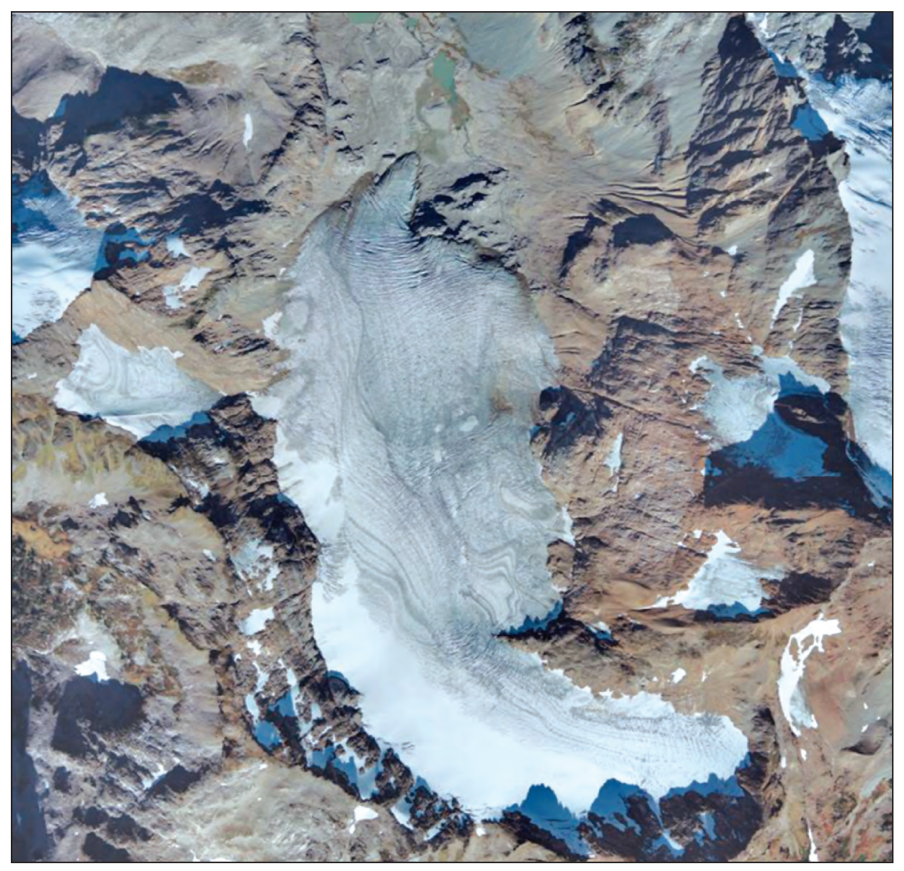

Figure 1. South Cascade Glacier, Washington, September 28, 2006.

Measured Mass Balance

Glacier mass balance computed by the method of in situ glaciological measurements is the "gold standard" of glacier mass balance and has been a foundation of the USGS Ice and Climate Project in Washington and the Alaska-based Glaciology Project for more than five decades. During that time, the USGS has contributed substantially to the establishment of standards for mass balance measurement and reporting (fig. 2).

The high-quality, long-term mass balance records published by USGS since 1958, such as those for South Cascade Glacier, Washington (fig. 3), have borne considerable fruit for the understanding of glacier/climate interactions (Bitz and Battisti, 1999) and of glacier-wastage contribution to sea-level rise (Dyurgerov and Meier, 2000).

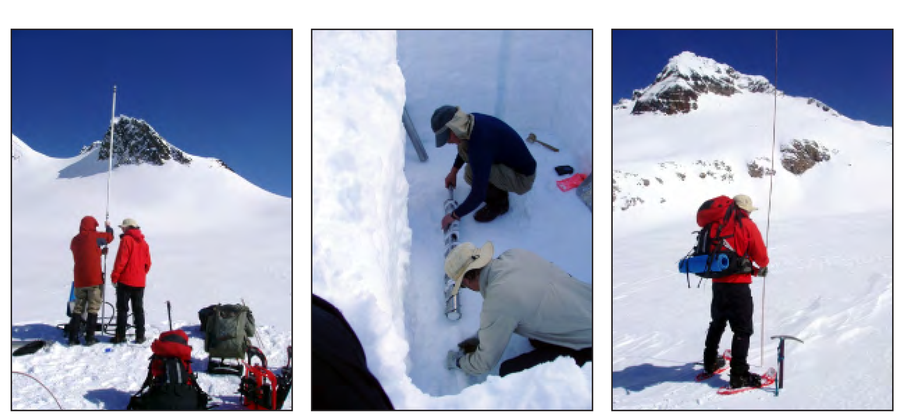

Figure 2. Examples of basic glaciological data collection for mass balance (from left to right: setting an ablation stake, taking a core sample to measure snow density, and probing for depth of the late-winter snow pack).

Mass Balance and Air Temperature Modeling

Critical glacier mass balance phenomena, including the net, winter, and summer balances, are rarely observed directly because of the difficulty and cost of conducting day-to-day continuous measurements. Instead, mass balance practitioners typically make mass balance measurements on intermittent schedules timed to approximately coincide with the ends of the winter and summer glaciological seasons and they interpolate or extrapolate between the intermittent measurements to estimate the times and magnitudes of the critical phenomena. Probably, the most systematic and defensible scheme for making these approximations is a meteorologically based mass balance model.

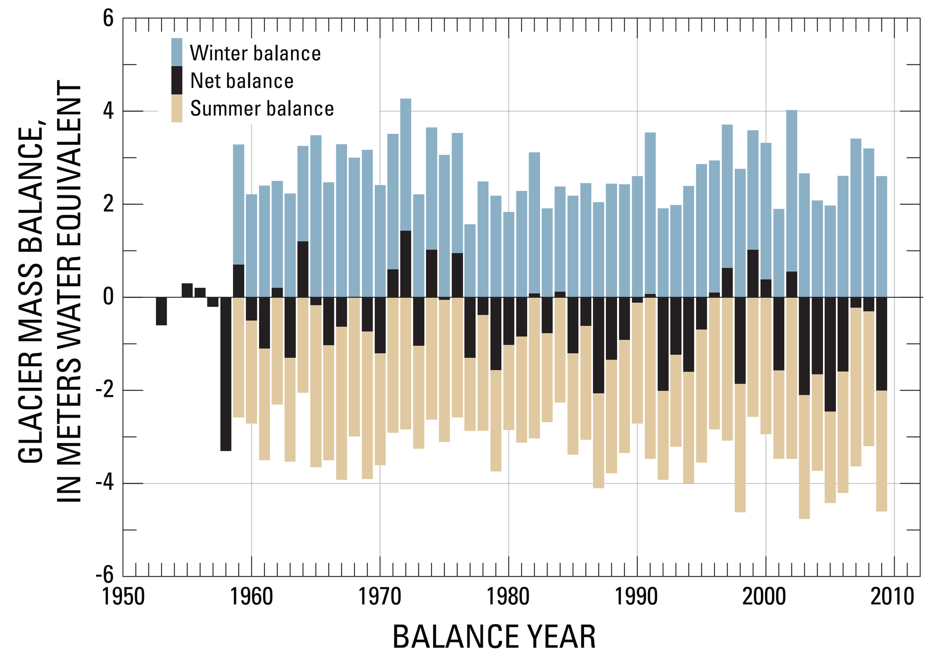

Figure 3. Winter, summer, and net balances of South Cascade Glacier, Washington, 1953 and 1955–2009. Mass balances for 2008 and 2009 are preliminary. The glacier net balance is the glacier-average thickness change, expressed as meters water equivalent, during a glacier balance year. A glacier balance year is the time between one annual glacier mass minimum and the next. The balance year is divided into winter and summer seasons. The winter and summer balances, the mass balances for respective seasons, sum to the net balance.

We have developed a site-specific daily mass balance model to use in close conjunction with local glaciological and meteorological data (Bidlake and others, 2010). The model computes daily precipitation as the product of precipitation at a reference site and an empirical precipitation factor. Precipitation is tallied as snow accumulation if "free-atmosphere" temperature (temperature of the air mass away from the cooling influence of the glacier and that is governed largely by adiabatic processes) is equal to or less than 2 degrees Celsius (°C). Ablation of snow or ice by melting is computed as the product of air-temperature positive degree days (PDD) than a base temperature times the degree-day factor (DDF) for the glacier site(s) of interest (melt = PDD*DDF; Hock, 2003). The DDF for ice melt is larger than that for snow and firn melt; the model selects the appropriate DDF based on which material is exposed.

Figure 4. Self-adjusting sensor stand and its anchor stake.

Air temperature near the surface of a melting glacier, is controlled partly by adiabatic processes (for example the lapse rate) and partly by energy exchange with the cool glacier surface. For this work, "near-surface" was a standard height of 2 m that was maintained over the ablating glacier surface by a self-adjusting sensor stand (fig. 4). To supply glacier-site air-temperature data for melt modeling, we developed a simple empirical model for estimating near-surface air temperature at selected sites from air temperature at a nearby reference site. First, we computed an overall average lapse rate as described in figure 5. Second, we analyzed departures of measured air temperature from those predicted from an off-glacier reference site and the computed lapse rate (fig. 6). We then statistically fit two-parameter empirical equations to the departures to account for the "glacier cooling effect" (Braithwaite, 2008). The data and the equations indicated that the glacier cooling effect increased with increasing ambient temperature and was much stronger at some sites than at others. These results were similar to those reported by Shea and others (2008).

We implemented the mass-balance model for six altitudinally distributed sites on South Cascade Glacier, balance years 2006 and 2007 (fig. 7). Precipitation data from a site about 20 km distant were used to compute accumulation and measured or modeled near-surface air temperature at each site was used to compute melt. We calibrated the mass balance model's accumulation and degree-day factors against intermittently measured mass balances during 2006 and 2007.

Initial calibration attempts revealed statistical interdependence between modeled accumulation and melt. Because accumulation and ablation are essentially opposing processes, overestimation (or underestimation) of accumulation by the model could be compensated by underestimation (or overestimation) of melt. Therefore, it was necessary to constrain the ranges of allowable variation for the DDF's, which we did on the basis of independently observed DDF's from South Cascade Glacier (fig. 8). The analysis also revealed that accounting for glacier cooling effect increased DDF's substantially, which points to the strongly empirical nature of temperature-index melt modeling and to the importance of using DDF's to estimate melt only for conditions similar to those under which they were derived.

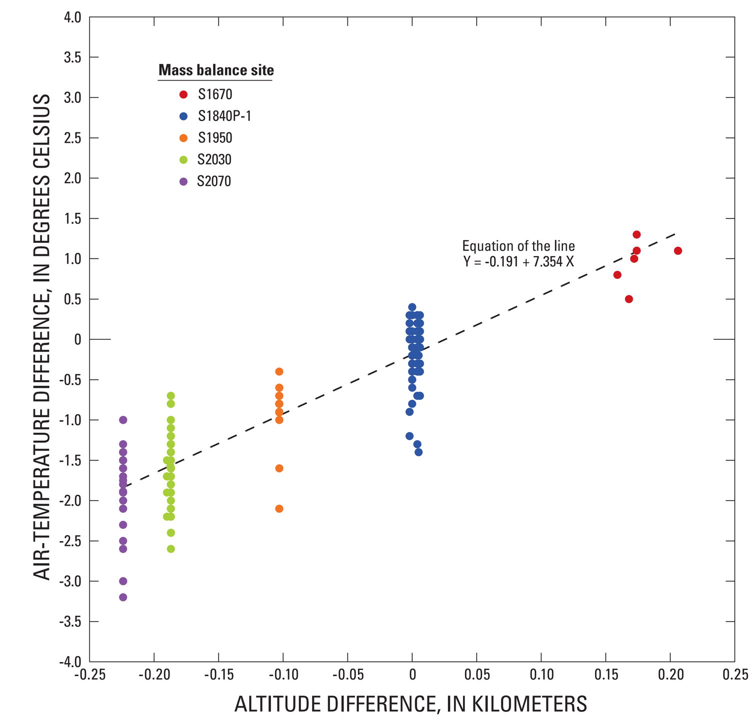

Figure 5. Air-temperature and altitude differences between selected glacier sites and an off-glacier site, restricted to days when air-to-glacier energy exchange was presumed to be negligible (average site-measured air temperature was within 1°C of the presumed glacier surface temperature, 0°C), South Cascade Glacier, Washington, during April–October, 2003 to 2007.

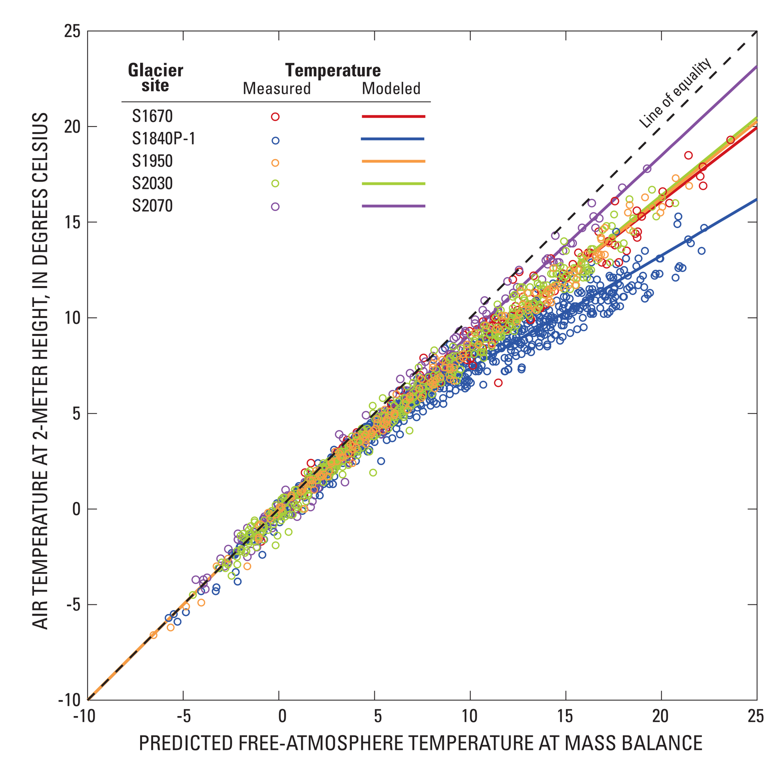

Figure 6. Measured and modeled daily average air temperature at 2-meters height at selected sites on South Cascade Glacier, Washington, as they varied with free atmosphere temperature predicted from temperature at a reference site using a constant temperature lapse rate (7.35 degrees Celsius per kilometer), during parts of April to October, 2003 to 2007.

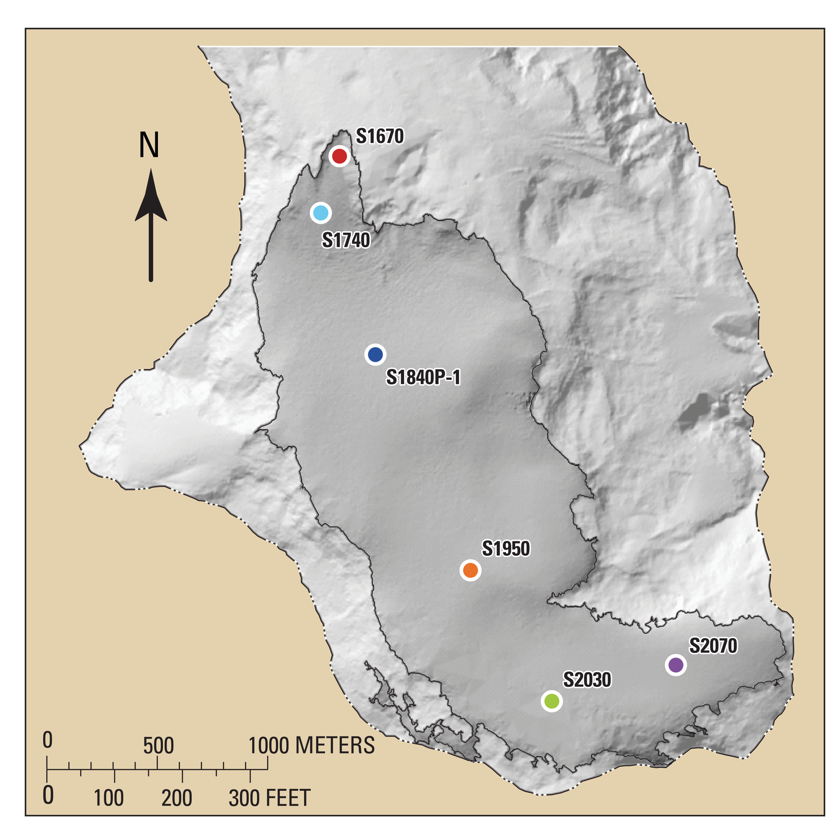

Figure 7. Shaded-relief map showing part of South Cascade Lake basin, Washington, and six mass balance sites on South Cascade Glacier, Washington, September 2006 and showing. Mass balance sites (colored dots) ranged from 1,670 m to 2,070 meters altitude.

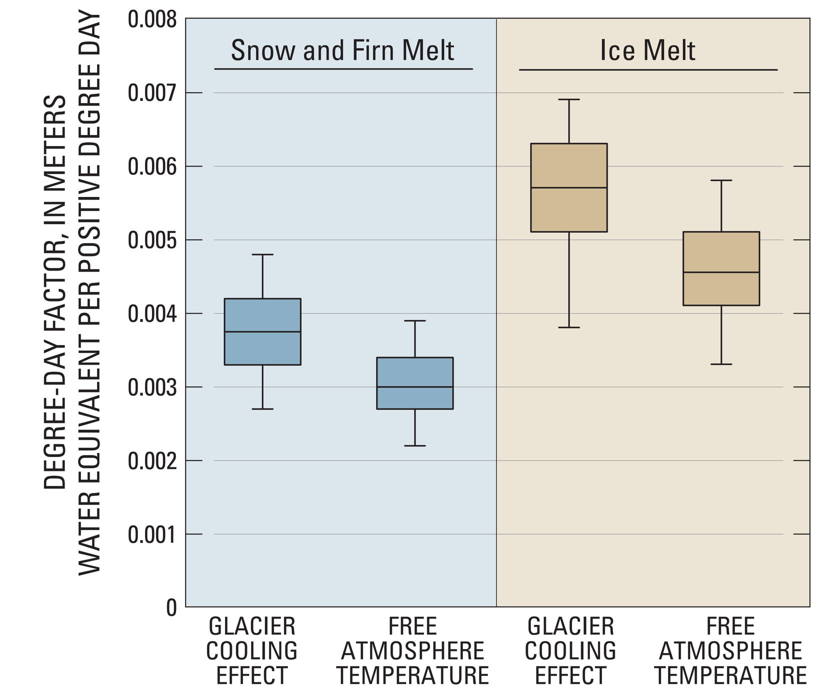

Figure 8. Degree-day factors computed from air-temperature and ablation data, South Cascade Glacier, Washington, 2003 to 2007.

Constraining the DDF's reduced but did not eliminate the potential for compensating accumulation and melt errors during calibration to the 2006–07 observations. We suspect this interdependence and the resulting lack of unique model solutions is inherent to the type of mass-balance model that we used. Thus, model factors used to portray the mass-balance time series (fig. 9) were manually selected primarily to minimize model errors near the end of winter and summer. Daily mass balance over the entire glacier was computed using the glacier DEM and by scaling simulated mass balances with altitude between sites (fig. 10). Operationally, we used a DEM with 100-m spacing to reduce computation requirements; however, figure 10 is based on a DEM with 4-m spacing for clarity. The glacier mass balance on any given day was the DEM-average mass balance. The time series of daily glacier mass balance then could be queried for the glacier seasonal and net balances shown below.

BALANCE YEAR:	2006	2007
WINTER BALANCE	2.61	3.41
SUMMER BALANCE	-4.20	-3.63
NET BALANCE	-1.59	-0.22

Balances are expressed in meters water equivalent.

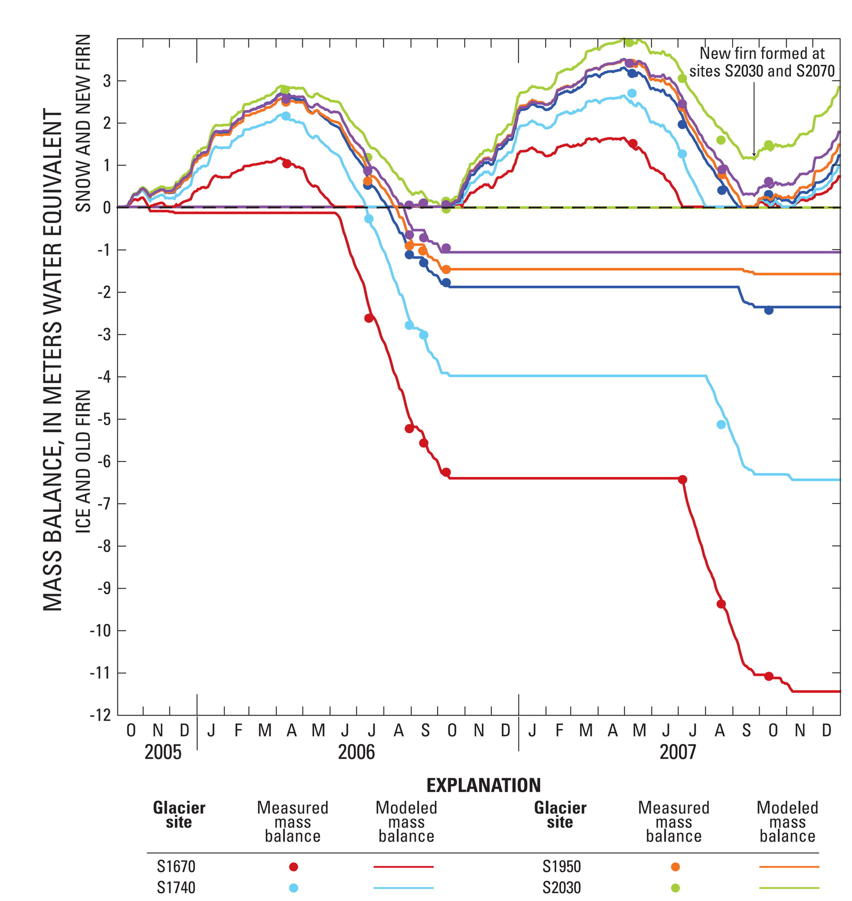

Figure 9. Simulated and measured mass balance at six sites on South Cascade Glacier, balance years 2006 and 2007. Line and symbol colors correspond to sites shown in figure 7.

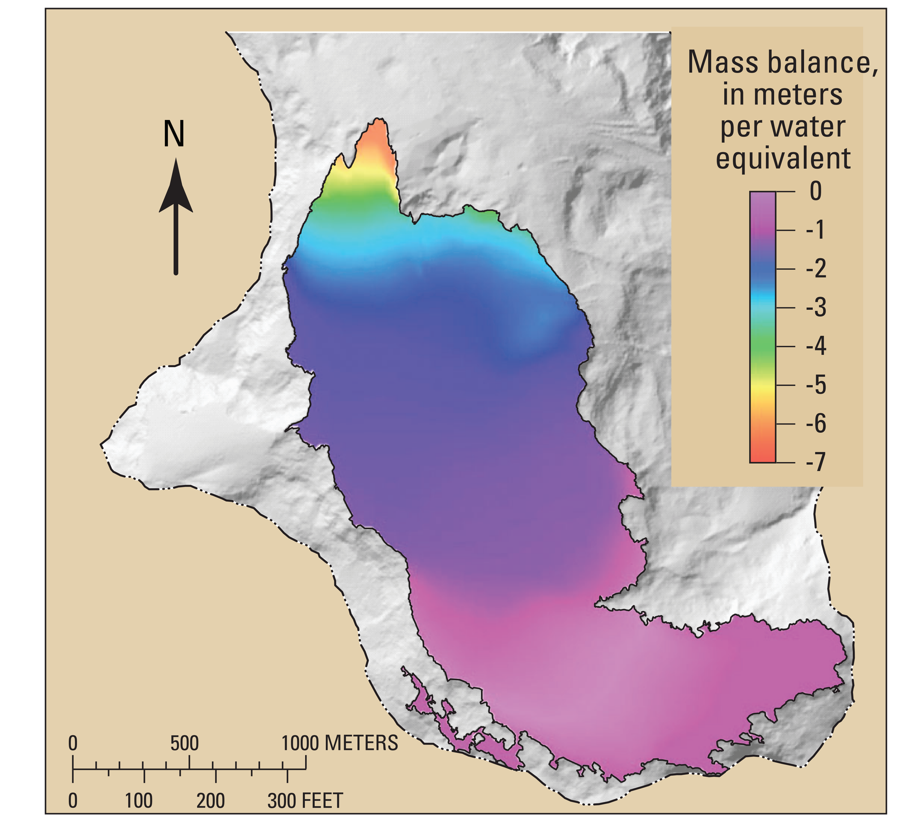

Figure 10. Mass balance on South Cascade Glacier, Washington, in meters water equivalent, at the end of balance year 2006 (October 14, 2006). The glacier net balance is the mass balance averaged over the entire glacier on that date.

Conclusions

The glacier cooling effect varied substantially among glacier sites and systematically with ambient air temperature.

Mass-balance modeling on the basis of precipitation and temperature provided a systematic and practical means for identifying and estimating critical mass balance phenomena from intermittent mass balance measurements.

South Cascade Glacier continued to lose mass during 2006 and 2007.

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