

Frequent outburst floods from South Tahoma Glacier, Mount Rainier, U.S.A.: relation to debris flows, meteorological origin and implications for subglacial hydrology

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ABSTRACT. Destructive debris flows occur frequently at glacierized Mount Rainier volcano, Washington, U.S.A. Twenty-three such flows have occurred in the Tahoma Creek valley since 1967. Hydrologic and geomorphic evidence indicate that all or nearly all of these flows began as outburst floods from South Tahoma Glacier. Flood waters are stored subglacially. The volume of stored water discharged during a typical outburst flood would form a layer several centimeters thick over the bed of the entire glacier, although it is more likely that large linked cavities account for most of the storage. Statistical analysis shows that outburst floods usually occur during periods of atypically hot or rainy weather in summer or early autumn, and that the probability of an outburst increases with temperature (a proxy measure of ablation rate) or rainfall rate. We suggest that outburst floods are triggered by rapid water input to the glacier bed, causing water-pressure transients that destabilize the linked-cavity system. The correlation between outburst floods and meteorological factors casts doubt on an earlier hypothesis that melting around geothermal vents triggers outburst floods from South Tahoma Glacier.

INTRODUCTION

Destructive debris flows frequently move along stream valleys on glacierized Mount Rainier, Washington, the highest volcano in the coterminous United States. The smallest, but most frequent, of these debris flows have generally been considered to originate as glacial outburst floods (Richardson, 1968; Crandell, 1971; Driedger and Fountain, 1989; Scott and others, 1992). Transformation from water flood to debris flow generally occurs in channels cut into stagnant ice and glacially derived sediment near glacier termini. In the last few decades, debris flows have been particularly frequent along Tahoma Creek, which drains South Tahoma Glacier (Fig. 1). Twenty-three debris flows moved along Tahoma Creek during the period 1967–92, including 15 in the years 1986–92, and repeatedly damaged a road and visitor facilities in Mount Rainier National Park.

From 1988 to 1992, we served as consultants to the U.S. National Park Service, studying debris flows along Tahoma Creek, their relation to outburst floods, and associated geomorphic change in the Tahoma Creek drainage; assessing hazards presented by debris flows at Tahoma Creek; and examining whether those flows might be predictable. A discussion of geomorphic evolution and of hazards is presented by Walder and Driedger (1994). In the present paper, we first summarize geomorphic and hydrologic data supporting an outburst-flood origin for most or all debris flows. We then present results of

statistical analysis which indicate that debris flows (or outburst floods) are predictable in the sense that they are strongly correlated with measured daily rainfall and maximum air temperature, data that may be considered proxies for the rate of water input to South Tahoma Glacier. Finally, we suggest a plausible hydrological model of the glacier that accounts for the link between weather and outburst floods.

DESCRIPTION OF THE STUDY AREA

South Tahoma Glacier retreated and thinned substantially between the mid-19th century and about 1960 (Sigafos and Hendricks, 1972), resulting in a stagnant tongue of rock-rich ice. The glacier advanced slightly between about 1960 and 1975 (summarized in Driedger (1986)), with advancing ice overriding older, stagnant ice (Fig. 2). Rapid retreat and thinning resumed about 1975, resulting in yet more rock-rich stagnant ice.

During the period 1988–92, outlet streams emerged from the active glacier ice and flowed over the upper stagnant-ice area (Fig. 2) before merging into a single stream. Downstream of that point, Tahoma Creek flows for 2 km at the bottom of a gorge deeply incised into stagnant ice, glacial till and fluvio-glacial deposits. The nature and history of that incision, caused by outburst floods from South Tahoma Glacier, are described in detail in Walder and Driedger (1994). Briefly, incision was initiated by a

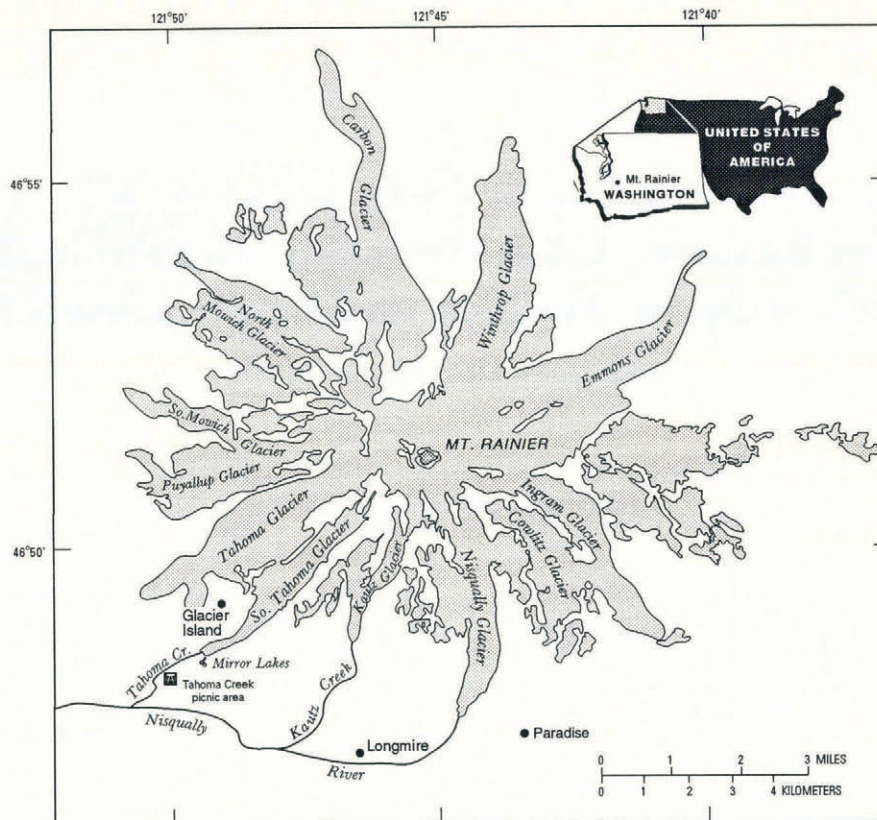


Fig. 1. Index map of Mount Rainier showing location of South Tahoma Glacier and Tahoma Creek. Glaciers are drawn to scale, but streams, cultural features and weather stations (black dots) are shown only schematically. The Tahoma Creek picnic area was destroyed by debris flows in 1986 and 1987. In addition to the Tahoma Creek flows described in this paper, destructive debris flows triggered by outburst floods have also moved along Kautz Creek, Nisqually River and West Fork White River since the middle of the 20th century.

series of outburst floods in 1967 (Fig. 2), and was increased by floods over the next decade. Outburst floods transform to debris flows as they pass through the incised reach. Debris-rich ice that formed the tongue of the active glacier as late as 1976 has itself been deeply incised since the renewal of outburst-flood activity in 1986.

RELATION OF OUTBURST FLOODS TO DEBRIS FLOWS

Most of the evidence for outburst floods from South Tahoma Glacier is circumstantial, owing largely to the glacier’s remoteness from the frequently visited parts of Mount Rainier National Park. A U.S. National Park Service employee observed one outburst flood in 1967 (cited by Crandell (1971, p.58)). There is also good evidence that, on at least a few occasions, flood waters emerged near an icefall and thence flowed over the glacier’s surface, eroding ice along the way (Crandell, 1971; Scott and others, 1992). Most of the evidence for outburst floods, however, has to do with their relation to debris flows. Because of this circumstance, it is necessary briefly to review pertinent data about debris flows at Tahoma Creek.

The debris flow of 26 July 1988 was serendipitously observed by U.S. Geological Survey hydrologist C.H. Swift (written communication, 28 July 1988) in a reach where the flow was neither eroding nor depositing substantially and where it moved within a single, well-

defined channel. For purposes of later discussion, we now summarize his observations. Swift visually estimated flow width, depth and velocity, as well as the relative fractions of water and sediment. A hydrograph based on his estimates is shown in Figure 3. The flow lasted about

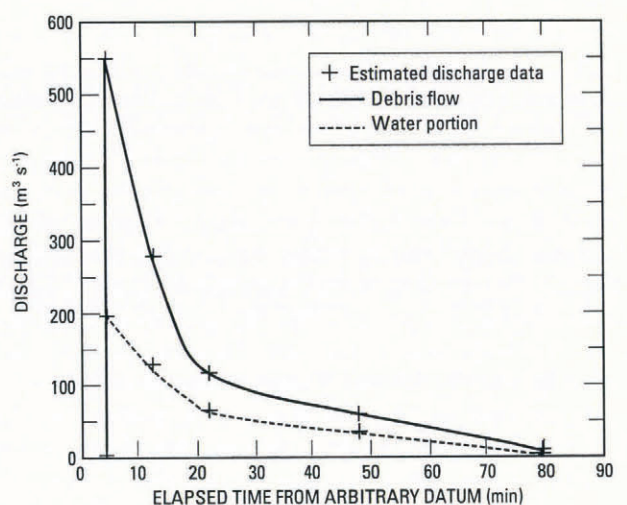


Fig. 3. Hydrograph of the dry-weather debris flow of 26 July 1988 along Tahoma Creek. The estimated water flux within the debris flow is also shown. The abrupt rising limb is typical of a debris-flow hydrograph, although unlike that of a clear-water flood. Flow characteristics were visually estimated by C.H. Swift, U.S. Geological Survey, and are probably accurate to about a factor of 2.



Fig. 2. Oblique aerial photograph (2 October 1984) showing South Tahoma Glacier prior to the outburst-flood phase that began in 1986. Stagnant-ice zones are indicated. Outburst floods in 1967 initiated incision of the reach of Tahoma Creek near center. (Photograph from U.S. Geological Survey archives in Tacoma, Washington.)

80 min. Peak water discharge Q_p was about $190 \text{ m}^3 \text{ s}^{-1}$, and a total water volume of approximately $3 \times 10^5 \text{ m}^3$ passed before discharge returned to normal. Average water discharge during the debris flow was about $55 \text{ m}^3 \text{ s}^{-1}$ —about 15–20 times the base flow. These values are probably accurate to within a factor of 2.

Walder and Driedger (1994) considered whether sources of water other than outburst floods could account for debris flows along Tahoma Creek. Of the 23 debris flows since 1967, 15 (including the one seen by Swift) occurred during periods of sunny, dry weather, and it is plausible that at least these 15 flows began as outburst floods, because their estimated peak water discharge was much greater than typical stream flow in Tahoma Creek. Other potential water sources are (1) stream flow impounded by a slope failure and then released catastrophically; and (2) pore water held within stream-bank sediments that slumped and thence moved downstream as a debris flow. Walder and Driedger (1994) showed that neither of these sources would suffice. There is no geomorphic evidence of damming along Tahoma Creek, nor could a plausibly sized landslide dam impound the volume of water actually discharged in a debris flow of typical size at Tahoma Creek. There is also evidence (with one possible

exception, discussed below) that slumping stream-bank sediments in the deeply incised reach of Tahoma Creek do not mobilize directly into debris flows, even during periods of heavy rainfall. Thus we conclude that dry-weather debris flows along Tahoma Creek originate as outburst floods.

Consider now the wet-weather debris flows. One of these — the debris flow of 16 October 1988 — evidently involved a flowslide of saturated morainal material (Fig. 4). 16 October 1988 was one of the rainiest days on record in the period 1986–92 (U.S. National Oceanic and Atmospheric Administration, 1986–92), so it is conceivable that the flowslide was triggered simply by rainfall, without an outburst flood. However, between 28 September (the date of an earlier aerial photograph than Figure 4) and 28 October 1988, there had been substantial stream incision, bank failure, and stream avulsion upstream of the morainal slump, in a reach where the stream crossed stagnant ice. This observation at least suggests that an outburst flood was involved in the 16 October 1988 debris flow. Subsequently — once during each of the years 1989 through 1991 and twice in 1992 — debris flows moved along Tahoma Creek during rainy periods in late summer or autumn. There is



Fig. 4. Vertical aerial photograph taken on 28 October 1988 showing part of Tahoma Creek drainage. Upstream is toward the top. The circular feature near the center is the scar of a flowslide that transformed into the debris flow of 16 October 1988. The geometry of the scar is inconsistent with an origin of this feature as a rotational slump and strongly suggests that the sediment flowed in a liquified state into the gorge. Note that scars of other slumps along Tahoma Creek are quite different in shape. (Photograph by Washington State Department of Transportation.)

no geomorphic evidence that these latter debris flows began as flowslides.

Wet-weather debris flows of 1989–92 were comparable to the flow observed by Swift (Fig. 3) in their effects and in the extent of their deposits, so we assume, as an admittedly rough estimate, that $Q_p \approx 200 \text{ m}^3 \text{ s}^{-1}$ for each of these flows. For comparison, Richardson (1968), on the basis of flood-frequency relationships suggested by Bodhaine and Thomas (1964), estimated $Q_p \approx 11 \text{ m}^3 \text{ s}^{-1}$ for the mean annual flood of meteorological origin in Tahoma Creek (at a point about 5 km downstream of

Glacier Island); and $Q_p \approx 26 \text{ m}^3 \text{ s}^{-1}$ for a flood with a 2% annual exceedence probability (the so-called 50 year flood). This order-of-magnitude discrepancy, along with the lack of evidence for a flowslide origin for these debris flows, leads us to conclude that the wet-weather debris flows of 1989–92 probably began as outburst floods, although part of the water in these debris flows must comprise pore water in the entrained sediment. In the rest of this paper, we therefore assume that all debris flows at Tahoma Creek, with the possible exception of the 16 October 1988 event, began as outburst floods.

RELATION OF OUTBURST FLOODS TO WEATHER

All outburst floods from South Tahoma Glacier since 1967 have occurred during either summer or early autumn, as noted also by Driedger and Fountain (1989) and Scott and others (1992). We did statistical analysis of meteorological data collected near South Tahoma Glacier to test whether outburst floods have been correlated with atypical weather conditions, and whether meteorological data might be useful predictors of outburst-flood occurrence.

The U.S. National Weather Service maintains two stations near South Tahoma Glacier: one at the Paradise Ranger Station, about 9 km east-southeast of Glacier Island, at an elevation of about 1650 m and near Nisqually Glacier; the other at Longmire, 9.5 km south-east of Glacier Island at an elevation of about 840 m (Fig. 1). Statistical analysis shows that published values (U.S. National Oceanic and Atmospheric Administration, 1986–92) of daily rainfall and maximum daily temperature at these two stations are well correlated. For the period under consideration, we found from linear regression:

$$T_{\max}(\text{Paradise}) = -4.0 + 0.9T_{\max}(\text{Longmire})(r^2 = 0.92) \quad (1)$$

$$R(\text{Paradise}) = 1.4R(\text{Longmire})(r^2 = 0.84) \quad (2)$$

where T_{\max} is the maximum daily Celsius temperature, R is daily precipitation, and r^2 is the coefficient of determination.

During the summer and autumn of 1989 and 1990, we tried to measure temperature and rainfall at an elevation of about 2050 m on Glacier Island, near South Tahoma Glacier (Figs 1 and 2), but data collection was frequently interrupted by equipment failures and we had to abandon the expensive effort to maintain this remote site. For the 1989 data, linear regression gives the result:

$$T_{\max}(\text{Paradise}) = 7.1 + 0.63T_{\max}(\text{Glacier Island})(r^2 = 0.46). \quad (3)$$

We suspect the temperature sensor at Glacier Island might have been inadequately protected from the effects of solar radiation, and that this problem bears on the relatively low r^2 value. The rain gauge malfunctioned, so we did not analyze precipitation data. The 1990 data were too discontinuous for meaningful analysis.

All in all, available data suggest that temperature and precipitation on the south side of Mount Rainier are spatially coherent. In what follows, we will assume that weather data from Paradise may be used as surrogates for conditions near South Tahoma Glacier. We restrict our analysis to weather data for the period 1986–92, because flood dates are not accurately known for earlier years. The analysis uses data for the months May through November, approximately encompassing the typical ablation season for glaciers on Mount Rainier. Actual outburst-flood dates ranged from 29 June to 9 November.

The statistical distributions of rainfall and maximum daily temperature at Paradise are shown in Figures 5 and 6. (Days with measurable snowfall were excluded in

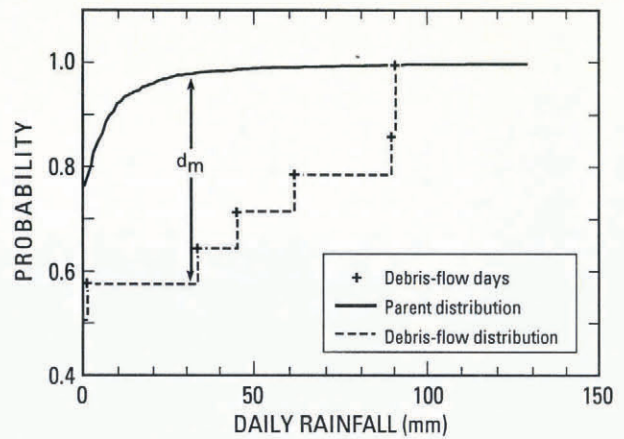


Fig. 5. Cumulative distribution function of values of daily rainfall at the Paradise Ranger Station, for the months May–November in the years 1986–92. Solid curve: all snow-free days. Crosses connected by dashed line: all days with debris flows. The Kolmogorov–Smirnov statistic d_m is indicated.

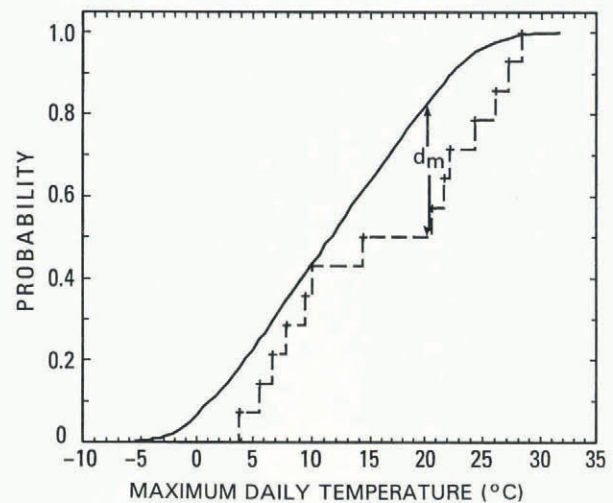


Fig. 6. Cumulative distribution function of values of maximum daily temperature at Paradise Ranger Station, for the months May–November in the years 1986–92. Solid curve: all days. Crosses connected by dashed line: all days with debris flows. The Kolmogorov–Smirnov statistic d_m is indicated.

compiling Figure 6.) The solid curve in each figure is the cumulative distribution function (henceforth CDF); the crosses connected by dashed lines show the distributions for days on which outburst floods from South Tahoma Glacier occurred. We now pose the question: What is the probability that the distributions of meteorological data for days on which outburst floods occurred are drawn at random from the CDFs? We use the Kolmogorov–Smirnov test of goodness of fit (Conover, 1971) to find an answer. The measured test statistic d_m is the largest vertical distance between the CDF and the stepwise sample curve connecting values measured on days of outburst-flood occurrence (Figs 5 and 6). For a given number n of data points in the sample population, one may calculate the probability P that for another sample of n points the largest vertical distance between the curves would exceed

the measured value d_m . P may also be interpreted as the probability that the sample population (in our case, days with outburst floods) is drawn at random from the parent population (all snow-free days from May through November). The Kolmogorov–Smirnov test is preferred to the chi-square test for small sample sizes, as in the present case, because it does not assume a Gaussian distribution of the test statistic (Conover, 1971).

Results are shown in the top halves of Tables 1 and 2 for the cases illustrated by Figures 5 and 6, as well as for

analogous tests using 2, 3, and 4 day moving averages of maximum daily temperature and rainfall. (For moving averages, the last day of the averaging window is always the day of the flood.) We conclude that values of rainfall and maximum daily temperature for days with outburst floods are unlikely to be drawn from the parent population, although this conclusion weakens as we consider progressively longer averaging periods.

We can make stronger statements once we note (Figs 5 and 6) that there are two distinct sub-populations in the

Table 1. Results of Kolmogorov–Smirnov ($K-S$) test for rainfall data from Paradise Ranger Station. Meteorological data used in the analysis are for the months May–November in the years 1986–92. One outburst flood for which the exact date is uncertain was excluded from the analysis. The $K-S$ statistic is defined in the text and illustrated in Figure 5

Type of rainfall data	Number (n) of outbursts in sample	$K-S$ statistic (d_m)	Probability that d_m would be exceeded by another sample of n points	Notes
Daily, all snow-free days	14	0.408	6.36×10^{-3}	
Daily, all snow-free days	13	0.364	2.36×10^{-2}	Excludes 16 October 1988 flow
Daily average, all 2 d snow-free periods	14	0.346	3.38×10^{-2}	
Daily average, all 3 d snow-free periods	14	0.329	4.71×10^{-2}	
Daily average, all 4 d snow-free periods	14	0.260	3.32×10^{-1}	2 sided $K-S$ test applies
Daily, snow-free days with measurable rain	7	0.787	2.08×10^{-5}	
Daily, snow-free days with measurable rain	6	0.763	1.86×10^{-3}	Excludes 16 October 1988 flow
Daily average, 2 d snow-free periods with measurable rain	6	0.737	3.70×10^{-4}	1 flood dropped due to snow in averaging interval
Daily average, 3 d snow-free periods with measurable rain	6	0.715	6.32×10^{-4}	1 flood dropped due to snow in averaging interval
Daily average, 4 d snow-free periods with measurable rain	6	0.532	4.18×10^{-2}	1 flood dropped due to snow in averaging interval; 2 sided $K-S$ test applies

Table 2. Results of Kolmogorov–Smirnov ($K-S$) test for maximum-temperature data from Paradise Ranger Station. Meteorological data used in the analysis are for the months May–November in the years 1986–92. One outburst flood for which the exact date is uncertain was excluded from the analysis. The $K-S$ statistic is defined in the text and illustrated in Figure 6

Type of temperature data	Number (n) of outbursts in sample	$K-S$ statistic (d_m)	Probability that d_m would be exceeded by another sample of n points	Notes
Daily, all days	14	0.317	4.73×10^{-2}	
Daily average, all 2 d periods	14	0.293	1.48×10^{-1}	2 sided $K-S$ test applies
Daily average, all 3 d periods	14	0.279	9.32×10^{-2}	
Daily average, all 4 d periods	14	0.257	2.66×10^{-1}	2 sided $K-S$ test applies
Daily, all dry days	7	0.702	2.80×10^{-4}	
Daily average, all 2 d dry periods	7	0.600	3.09×10^{-3}	
Daily average, all 3 d dry periods	7	0.534	1.09×10^{-2}	
Daily average, all 4 d dry periods	6	0.582	9.32×10^{-3}	One flood dropped due to rain in averaging period

data for days with outburst floods: warm, dry days ($T_{\max} > 20^{\circ}\text{C}$, $R = 0$) and cool rainy days ($T_{\max} < 15^{\circ}\text{C}$, $R > 0$). We therefore examined the statistical distribution of rainfall *excluding dry days*, and that of maximum temperature *excluding rainy days*. Results are presented in the bottom halves of Tables 1 and 2, for tests using daily data and moving averages, as before. Values of P are in some cases less than 0.001.

On the basis of these tests of goodness of fit, we conclude that outburst floods from South Tahoma Glacier are highly correlated with atypical weather, and in particular, with relatively rainy or hot weather. Driedger and Fountain (1989) and Scott and others (1992) reached similar conclusions, but did not support their statements with statistical tests.

The conditional probability P_c of an outburst flood from South Tahoma Glacier, as a function of R and T_{\max} during the years 1986–92, for the two sub-populations noted above, is shown in Figures 7 and 8. The conditional probability is the relative frequency of flood occurrence given a particular value of R or T_{\max} . For example, the probability of an outburst flood on any day with ≥ 40 mm of rain was about 0.22. There are fairly clear relations between P_c and either R or T_{\max} measured on the day of a flood; for progressively longer averaging periods, the trends are not so obvious, owing at least partly to the fact that averaging “compresses” the range of R and T_{\max} . We caution against using Figures 7 and 8 to *predict* outburst-flood probabilities, however, because the glacier, including, presumably, its drainage system, is changing with time, making the statistical problem non-stationary.

If R and T_{\max} measured at Paradise are considered rough surrogates for rate of water input to South Tahoma Glacier, the conditional probabilities shown in Figures 7 and 8 are reasonably consistent with each other. To see this, consider that a plausible value for the ablation rate at South Tahoma Glacier on the hottest summer days (when $T_{\max} \approx 30^{\circ}\text{C}$ at Paradise) is perhaps 40 mm d^{-1} (cf.

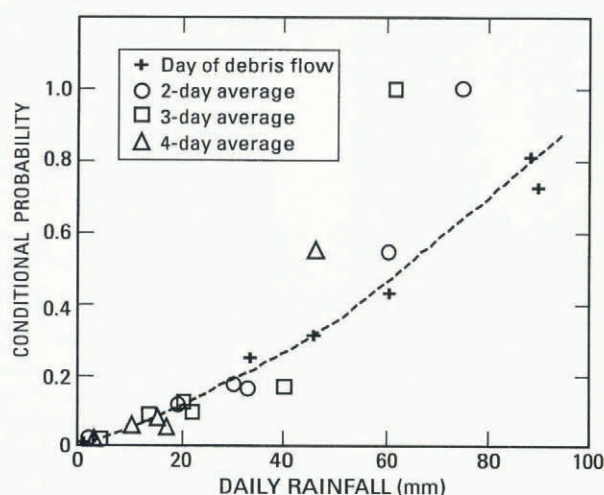


Fig. 7. Conditional probability of an outburst flood from South Tahoma Glacier as a function of daily rainfall at Paradise Ranger Station, for days with measurable rainfall during the months May–November in the years 1986–92. The last day of the averaging period is always the day of the flood. The dashed line is an approximate fit to the data.

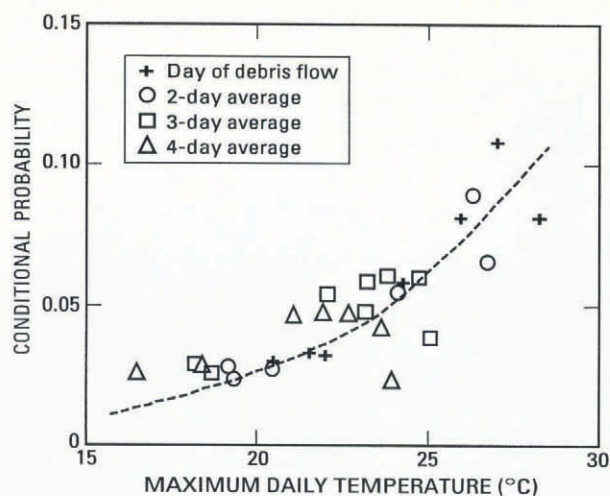


Fig. 8. Conditional probability of an outburst flood from South Tahoma Glacier as a function of maximum daily temperature at Paradise Ranger Station, for dry days during the months May–November in the years 1986–92. The last day of the averaging period is always the day of the flood. The dashed line is an approximate fit to the data.

Fountain, 1992). From Figures 7 and 8, we find (extrapolating from the dashed curves) $P_c \approx 0.13$ for $T_{\max} \approx 30^{\circ}\text{C}$, $P_c \approx 0.22$ for $R = 40$ mm. In light of the surrogate nature of the meteorological data, the two probabilities are reasonably close. We therefore suggest the following physical interpretation, elaborated in the next section: outburst floods from South Tahoma Glacier are meteorologically driven, with the probability of an outburst flood determined primarily by the rate of water input to the glacier.

WATER STORAGE AT THE GLACIER BED AND AN HYPOTHESIS FOR THE ORIGIN OF OUTBURST FLOODS

Outburst floods from South Tahoma Glacier involve release of water stored either englacially or subglacially. For the 26 July 1988 event (Fig. 3), which was probably typical, the total water volume ($3 \times 10^5 \text{ m}^3$), if spread evenly over the glacier bed (area about 2 km^2), would be equivalent to an average thickness of about 150 mm of water. Undoubtedly, part of the water in the debris flow was derived from sediments added to the flood waters as they moved downstream, but even if such added water accounted for 90% of the debris flow's total water content, glacially derived water would still represent average basal storage of 15 mm. The most plausible way to store such a copious amount of water at the bed of South Tahoma Glacier is in basal cavities (Fig. 9). Driedger and Fountain (1989) previously reached the same conclusion by a similar line of reasoning. For comparison, the water volume released from subglacial storage during surge “slow-down” events at Variegated Glacier in 1983 represented average basal storage of about 50–100 mm (Humphrey and others, 1986; Humphrey, 1987).

South Tahoma Glacier rests on very steep slopes

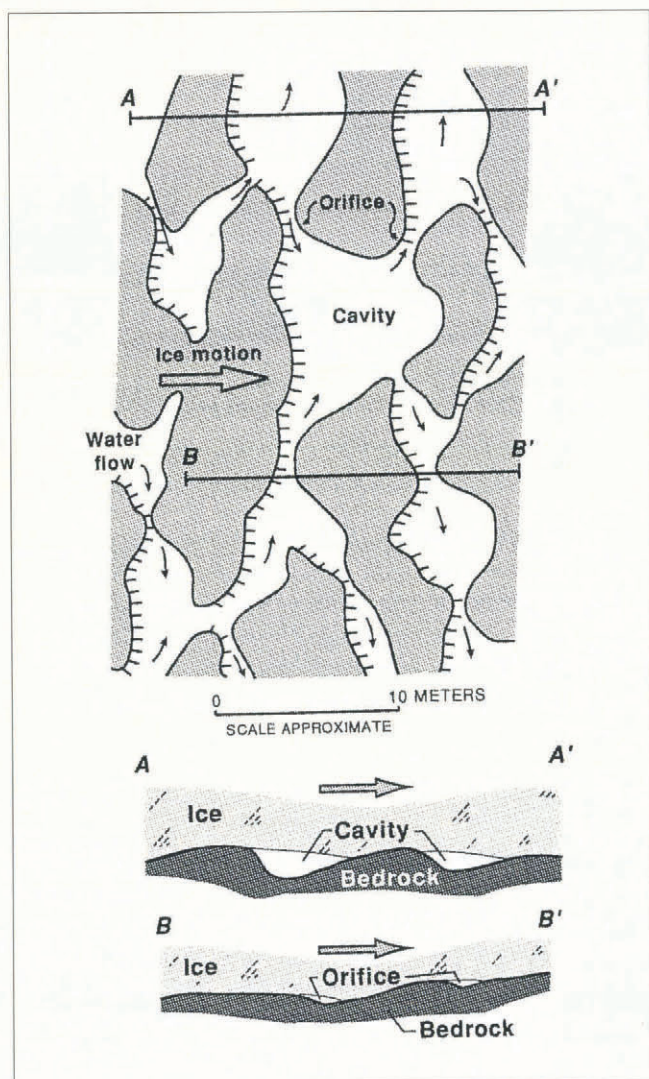


Fig. 9. Schematic drawing of the basal linked-cavity network. Areas of ice/bed contact are shaded, areas of ice/bed separation are blank. Ice separates from the bed along the hachured lines and re-contacts the bed along the plain lines. (After B. Kamb (1987).)

(averaging 20–30°) and probably flows over large ledges eroded from the lavas and volcanoclastic deposits that constitute most of Mount Rainier. Indeed, one such ledge, several tens of meters high and formerly beneath an icefall, has been exhumed as the ice has thinned during the last decade. Supposing a subglacial cavity existed in the lee of such a ledge, with a cross-sectional area along the ice-flow direction of 50 m² — corresponding to a cavity 10 m in height and length, with a triangular cross-section — a total cavity length of 6 km would be required to store 3 × 10⁵ m³ of water. Even if the stored-water volume were an order of magnitude less — corresponding to the case in which most debris-flow water comes from the sediments themselves — a 600 m length of these enormous cavities would be required. Yet it is hard to imagine how the requisite volumes of water could be stored if giant cavities did not exist. If all cavities were decimetric in scale (such as those mapped by Walder and Hallet (1979) and Hallet and Anderson (1982)), hundreds of kilometers of linked cavities would be required to hold the stored volume of water.

Except early in the ablation season, surficial meltwater or rainfall will enter the englacial drainage system rapidly and thence reach the glacier bed. Water at the base of an alpine glacier usually collects in one or more main channels incised into the ice (Shreve, 1972; Röthlisberger, 1972), but at South Tahoma Glacier the route from englacial conduit to trunk channel is likely to involve passage through large linked cavities. Flow along the linked-cavity network (Fig. 9) is regulated by the throttling effect of constrictions, or orifices, where the ice closely approaches the bed (Walder, 1986; Kamb, 1987). Based on these concepts and on results in the previous section, we propose the following hypothesis: outburst floods from South Tahoma Glacier occur when the rate of water input to the subglacial drainage system causes subglacial water pressure to rise rapidly, destabilizing the orifices in the linked-cavity network, in line with Kamb's (1987) analysis. The linked-cavity drainage system then degenerates into a multiple-tunnel system that rapidly drains stored water.

In Kamb's (1987) analysis, orifice stability is controlled by the dimensionless parameter Ξ , defined by

$$\Xi = \frac{2^{1/3}}{\pi^{1/2}} \frac{(\alpha\Lambda/\omega)^{3/2}}{DM} \left(\frac{\eta}{\nu\sigma} \right)^{1/2} h^{7/6} \quad (4)$$

where α is the average hydraulic gradient, approximated as the ice-surface slope; Λ is the length of orifices divided by the length of cavities; ω is the tortuosity of the water-flow path; D is a constant equal to 31 km; M is the Manning roughness of the orifices; η is the effective viscosity of the ice; ν is sliding velocity; σ is effective pressure (ice-overburden pressure minus water pressure); and h is the height of the orifice. For Ξ greater than about 1, orifices will enlarge unstably in response to transient water-pressure increases of any magnitude. For progressively smaller values of Ξ , the orifices are stable against progressively larger water-pressure transients.

To estimate a value of Ξ for the basal-cavity system of South Tahoma Glacier, we adopt the parameter values $\alpha = 0.3$, $\Lambda = 10$, $\omega = 4$, $M = 0.1 \text{ m}^{-1/3} \text{ s}$, $\eta = 0.1 \text{ bar a}$, $\nu = 10 \text{ m a}^{-1}$ and $\sigma = 5 \text{ bar}$. The values for Λ , ω , M and η follow from Kamb, and should be reasonable for the South Tahoma Glacier system. The value of α applies for the active ice and is based on a U.S. Geological Survey topographic map. We have no direct measurements of sliding velocity or effective pressure at the glacier bed. Our choice of ν is intuitive but plausible, based on the fact that South Tahoma Glacier has been thinning and retreating for nearly 2 decades, and our judgment that the glacier is sluggish. (For purposes of comparison, the average sliding speed of the nearby, larger Nisqually Glacier was about 50 m a⁻¹ in 1969, while the glacier was advancing (Hodge, 1974).) The value for σ is approximately equal to the estimated average ice-overburden pressure (based on glacier area-and-volume estimates by Driedger and Kennard (1986)) and thus a rough upper bound on effective pressure. With these parameter values, we find $\Xi = 3.8h^{7/6}$, when h is given in meters. We would then require $h < 0.3 \text{ m}$ for the orifices to have even marginal stability. If meter-scale cavities exist, as we have previously suggested, even the orifices may have decimetric dimensions, and thus be unstable in the event of transient increases in water pressure.

Indirect evidence possibly bearing on the size of orifices comes from a bizarre, macabre source. In December 1946, a U.S. Marine Corps airplane crashed near the head of South Tahoma Glacier, with no survivors. The wreckage was quickly buried under snow and was never recovered. Deposits of the 1986 and 1987 debris flows contained many mangled bits of the aircraft, including propeller blades and pieces of sheet metal up to about 0.5 m on a side (personal communication from K. M. Scott, 1993). A plausible interpretation is that the airplane wreckage had been advected downward to the glacier bed, had melted out and accumulated in cavities, and had finally been flushed out as cavities had drained through R channels during outburst floods. The size of the metal fragments would then set a lower bound on typical orifice dimensions. Other interpretations are possible, of course.

We conclude that Kamb's model of orifice instability yields quantitatively reasonable results for the case in hand. Moreover, in the context of Kamb's model, it is not surprising that the probability of an outburst flood increases as the rate of water delivery to the glacier bed increases (Figs 7 and 8). The greater the rate of water delivery, the larger must be the pressure transients, and thus the greater the likelihood that (for given Ξ) orifices in the cavity network will grow unstably.

The shortest period of time between two outburst floods from South Tahoma Glacier was about 56 h — the interval between the dry-weather floods of 29 and 31 August 1967 (Crandell, 1971, p. 58). The dry-weather floods of 28 and 31 August 1987 were separated by only about 75 h. In the context of the cavity model discussed above, two (at least) interpretations are possible. The linked-cavity system may rapidly reform itself after disruption leading to an outburst flood; alternatively, any individual outburst floods may represent break-down and drainage of just part of the cavity network. We favor the second interpretation, because the volume of water released in the second of each pair of floods could not plausibly have been generated by ablation in the period between floods, even if *all* surface-derived meltwater had been stored subglacially. The second interpretation is also in line with observations elsewhere (e.g. Fountain, 1992), that alpine glaciers may contain several distinct internal drainage basins.

A puzzling aspect of outburst floods at South Tahoma Glacier is their probabilistic nature: few occurrences of hot weather or heavy rain do in fact coincide with outburst floods. One interpretation may be that the glacier's drainage system varies significantly with time. For example, the geometry of orifices in the cavity system might change with time, thereby affecting the value of Ξ . Another interpretation is that we simply have insufficient information about the rate of water input to the drainage system through time, as well as about the geometry of the drainage system itself, to construct a deterministic model of outburst-flood release.

DISCUSSION

Many other investigators have reported cases of glaciers that repeatedly spawn outburst floods, but these have involved drainage of either subaerial ice-dammed lakes

(e.g. Clarke, 1982) or subglacial lakes formed by geothermal activity (Björnsson, 1992). South Tahoma Glacier appears to be different. We are skeptical of Crandell's (1971) conclusion that geothermal activity causes outburst floods from South Tahoma Glacier. Crandell's argument rested on anecdotal evidence, such as observations of supposed steam plumes, gathered from a variety of observers. We believe it would be a remarkable coincidence if the statistical relationship between outburst floods and meteorological variables existed independently of a causal relationship between those variables and outburst floods, even though we understand the pertinent physics inexactly. Furthermore, there is no glacier-surface relief indicative of melting over a geothermal area (cf. Björnsson and Einarsson, 1991).

Other glaciers on Mount Rainier have released outburst floods from subglacial storage, though none with nearly the frequency of South Tahoma Glacier (Driedger and Fountain, 1989). It may be that the bed geometry of South Tahoma Glacier is particularly conducive to the formation of large subglacial cavities. Bed geometry must be related to the structure and erodibility of the bedrock, factors which on a strato-volcano like Mount Rainier are very heterogeneous. We note that the present phase of outburst-flood activity at South Tahoma Glacier coincides with a period of substantial ice retreat and thinning, whereas the previous phase of activity (1967 to the mid-1970s) was during a period of ice advance, with the glacier considerably thicker than at present. This suggests that the propensity for outburst floods is not related simply to ice thickness.

CONCLUSIONS

South Tahoma Glacier, located on Mount Rainier volcano, has released at least 22 outburst floods since 1967, including at least 14 in the years 1986–92. The volume of water released during a typical outburst flood corresponds to a basal water layer several centimeters thick, a physically impossible situation; so water must be stored in large subglacial cavities. Geologic factors such as the volcano's heterogeneous structure promote the existence of large basal cavities.

The likelihood of an outburst flood increases as either the temperature or rainfall rate increases. A reasonable interpretation is that flood probability depends on the rate of water input to the glacier bed. We therefore propose that the physical mechanism of flood release is the breakdown of the linked-cavity network over part of the glacier bed and rapid drainage through a multiple-tunnel system, much as envisaged by Kamb (1987) in his discussion of glacier-surge termination.

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