Relationship between temperature and dry-weather jökulhlaups from South Tahoma Glacier, Mount Rainier, Washington

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Executive Summary

Jökulhlaups, or glacial outburst floods, from South Tahoma Glacier on Mount Rainier pose a threat to park visitors, staff, and infrastructure. Jökulhlaups release without surficial precursors, and transition into debris flows as they surge downslope. Walder and Driedger (1995) calculated the relative frequency, called the conditional probability (P_C), for seven dry-weather jökulhlaups between May-November from 1986 and 1992. Dry-weather jökulhlaups are defined as outburst floods that occur during hot, dry conditions. The P_C is the number of jökulhlaups that occur at a maximum temperature (T_{MAX}) divided by the number of days in the entire distribution that have a T_{MAX} equal to or greater than the given T_{MAX}.

Walder and Driedger (1995) used 1-day average T_{MAX} (T_{MAX-1}) to calculated P_C, which ranged from 0.04 to 0.11 between 17°C and 28°C. I repeated their analyses with a larger data set, using T_{MAX-1} between June-September from 1966-2015, which contained 14 outburst floods. The P_C calculated from the larger data set ranged from 0.008 to 0.023 for the same T_{MAX-1}. This difference in the P_C show there are not enough data to produce robust analyses, and so the P_C should not be used to predict jökulhlaups because it will change as data is added.

Dry-weather outburst floods occur later in the summer compared to peak T_{MAX-1}, so longer intervals of T_{MAX} are required to melt enough water to produce an outburst flood. I calculated 6-week average T_{MAX} (T_{MAX-42}) on the days that jökulhlaups occurred. The peak in T_{MAX-42} aligns with the T_{MAX-42} of the entire distribution. The P_C for T_{MAX-42}, calculated in the same way as T_{MAX-1}, are less than 0.01 for T_{MAX-42} <18.0°C. When T_{MAX-42} is ≥18.0°C, the P_C increases rapidly from 0.01 to 0.10 at 21.1°C.

Table of Contents

List of Tables

List of Figures

Introduction

South Tahoma Glacier is located on Mount Rainier, Washington (Figure 1) and has a history of jökulhlaups. A jökulhlaup, or glacial outburst flood, results from the buildup of meltwater that is trapped and pressurized subglacially. Jökulhlaups have been studied on Mount Rainier since the 1960s (Richardson, 1968; Crandell, 1971; Walder and Driedger, 1994; Walder and Driedger, 1995). Because they occur with no surficial precursors, outburst floods occur unexpectedly and pose a threat to visitors, staff, and infrastructure within Mount Rainier National Park.

Piotrowski (1997), studying the subglacial hydraulics of glacial facies in North-Western Germany, proposed that porewater pressure builds as meltwater production exceeds the transmissivity of the subglacial aquifer. This leads to the formation of subglacial basins, which transition into tunnel networks. The tunnel networks develop in response to meltwater buildup, and provide a pathway for meltwater to evacuate the system. On South Tahoma Glacier, Walder and Driedger (1994, 1995) speculated that tunnel networks form subglacially and have the capacity to store large volumes of water. Meier (1973) presents several explanations for outburst flood release: small flows through a drainage enlarge the passage, producing a flood; ice deformation occurs due to high water pressure, enabling an escape route for the water; weakening of the ice by earthquakes or subglacial melting by volcanic heat creates instability, causing subglacial water release; and overflowing of ice dams around glacier margins produces flooding.

Jökulhlaups that release from South Tahoma Glacier transition into slurries of mud, rock, and trees, known as debris flows. Debris flows surge down the slopes of Mount Rainier and can be highly erosive. On August 12th, 2015, an outburst flood released from South Tahoma Glacier and washed out a section of the West Side Road within Mount Rainier National Park. The damaged portion of the West Side Road is 4km downstream from the terminus of the glacier. In addition to erosion, debris flows have the potential to deposit large amounts of sediment, which can produce avulsions. Avulsions alter river patterns and can threaten old-growth forests and infrastructure that may have otherwise been safe from damage.

Jökulhlaups are triggered by meltwater, and meltwater production is dependent on air temperature. In this report, I use daily maximum temperature to update conditional probabilities of outburst floods calculated by Walder and Driedger (1995). I also show that using longer intervals of time give higher conditional probabilities for jökulhlaups; longer intervals of melting and subsequent meltwater buildup are required to produce an outburst flood than the intervals used in Walder and Driedger's (1995) original study.

Scope

On Mount Rainier, debris flows are produced from three different types of meteorological conditions/glacier interactions: 1) Rain storms destabilize moraines and cause the moraines to collapse, introducing large amounts of sediment into the river (Legg, 2015); 2) Increased precipitation on the glacier itself increases subglacial water, triggering a *wet-weather* jökulhlaup (Driedger and Fountain, 1989; Walder and Driedger, 1995; Legg, 2015); 3) exceptionally, hot, dry conditions produce enough meltwater to trigger a *dry-weather* jökulhlaup (Driedger and Fountain, 1989; Walder and Driedger, 1995). I focus exclusively on *dry-weather* jökulhlaups from South Tahoma Glacier in this report.

The analyses in this report are calculated from daily maximum temperatures (T_{MAX}). T_{MAX} was retrieved from the Paradise SNOTEL station (Site 679), which records T_{MAX} to the nearest °F. The Paradise SNOTEL station recorded 88% of the daily data between 1966 and 2015.

The Paradise SNOTEL station is located 6.5km east-southeast from the terminus of South Tahoma Glacier (Figure 1) and is at 1550 meters in elevation, which is similar to the terminus elevation. Walder and Driedger (1995) found that temperatures recorded from the Paradise SNOTEL station and Longmire weather station, also located on the southern side of Mount Rainier, are well correlated using a linear regression to compare the temperature distributions recorded at each station. They determined the data recorded from both stations are spatially coherent, and the Paradise SNOTEL data may be used as a surrogate for South Tahoma Glacier conditions.

Glacier Conditions

South Tahoma Glacier is a southwest-facing (220°) cirque and valley glacier. Its source is 3200m above sea level, and it terminates at 2100m above sea level. The length of South Tahoma Glacier from source to terminus is 3km, and the glacier's area is 2km^2. The glacier has an ice volume of 9.8x10^{6}m^3 and has the capacity to store 8.7x10^{6}m^3 of water (Beason, 2016).

South Tahoma Glacier retreated considerably during the mid-1880s until about 1960, advanced until 1975, and has continued to retreat and thin since 1975 (Walder and Driedger, 1994; Walder and Driedger, 1995). In the last several decades, South Tahoma Glacier has retreated up steep bedrock steps formed by layers of lava flows from Mount Rainier. The bedrock steps dip at 30° downslope. South Tahoma Glacier's retreat has left large chunks of stagnant ice below the bedrock steps. The ice was cut off from the active glacier as it retreated up each step. These chunks of stagnant ice are likely a source of meltwater (Beason, 2016). Glacier retreat and ice stagnation at the terminus of South Tahoma Glacier will likely continue into the future until the glacier completely disappears or advances again (Beason, 2016).

There have been 39 debris flows recorded from South Tahoma Glacier since 1967, with the two most recent events occurring in August and September of 2015 (Richardson, 1968; Crandell, 1971; Driedger and Fountain, 1989; Walder and Driedger, 1994; Walder and Driedger, 1995; Beason, 2016). Of those events, 25 debris flows have known dates of occurrence (Table 1). Other debris flows do not have a known day, only a month, or in some cases, only the year of occurrence; these events are omitted from this analysis. There are 14 debris flows with exact days of occurrence and 0mm of precipitation within 3 days, <50mm of precipitation within 1 week, and <125mm of precipitation within 4 weeks prior to the event, which I define as the dry period before an outburst (Table 2). These events are classified as *dry-weather* jökulhlaups and are the events considered for this report.

Ten of the 14 dry jökulhlaups were destructive, damaging trails, roads, campgrounds, picnic areas or trees (Richardson, 1968; Crandell, 1971; Beason, 2016). The newly-rebuilt West Side Road has been damaged several times in the past from flooding. Most flood discharges peaked between 500m^3/s and 1000m^3/s, but the minimum and maximum discharges are 30m^3/s and 1700m^3/s. In two events, over a meter of mud and sediment aggraded, causing avulsions (Table 1).

Mount Rainier and South Tahoma Glacier experience large fluctuations in T_{MAX} and precipitation. T_{MAX} recorded from the Paradise SNOTEL can vary 60°C over the course of a year, with extreme winter T_{MAX} at -25°C and summer temperatures reaching 35°C. Typically, monthly average T_{MAX} during January and

February is around 5°C. During the summer, the monthly average T_{MAX} is around 15°C, but can exceed 20°C if a month is exceedingly hot.

Precipitation also varies on the south side of Mount Rainier. From 1966-2015, the Paradise SNOTEL recorded 16m of snow on average per winter. Maximum snowfall has reached 25m or more several times since 1966, and minimum snowfall was recorded in 2015 at 6m. Rain fluctuates as well, with wet summer months receiving 250mm or more, and dry months receiving no rain.

Previous Work

Richardson (1968) identified Mount Rainier as a particularly jökulhlaup-prone mountain based on the frequency of Mount Rainier's floods that were larger than expected. Flood discharges were larger than what was physically possible based upon direct rain or water impounded by a landslide, so Richardson (1968) reasoned that that the main source of these floods was from subglacial storage, which was released when outburst floods were triggered.

Driedger and Fountain (1989) compiled data for outburst floods on Mount Rainier, discussing characteristics of glaciers and floods. They included the Nisqually, South Tahoma, Kautz-Success, Carbon, and Winthrop glaciers. The results of the compilation for the South Tahoma Glacier can be seen in Table 1.

Walder and Driedger (1994) studied the geomorphic changes from debris flows down Tahoma Creek, which drains South Tahoma Glacier. They state that jökulhlaups and debris flows are exceptional at moving sediment, and that there has been 20mm to 40mm of denudation per year in the upper reaches of Tahoma Creek from 1967 to 1991 (originally shown by Osterkamp and Costa, 1986). The sediment that has been transported by debris flows has not yet left the basin, causing downstream aggradation that threatens roads and facilities within Mount Rainier National Park. Walder and Driedger (1994) suggest that the frequency of extreme hydrologic events (outburst floods) is one of the factors that is crucial to geomorphic change in the basin.

Using a logistic regression, Walder and Driedger (1994) calculated the outburst flood probability for 1-day T_{MAX} (T_{MAX-1}) at 31.7°C, which is the highest value of T_{MAX-1} within their period of interest (1986 to 1991). The probability is 0.05. Using 2-, 3-, and 4-day moving averages for T_{MAX}, Walder and Driedger (1994) were only able to increase the probability of a debris flow to 0.06.

Walder and Driedger (1994) also provided an explanation for a potential origin for the volume of jökulhlaups, since floods are greater than what seems possible. The July 26, 1988 outburst flood had a total flood volume of $3\text{x}10^5\text{m}^3$, equivalent to 150mm of subglacial water. They argued that part of the volume of the flood comes from sediments added to the flood as it crosses stagnant ice, stating that if 90 percent of the total derived water volume came from the sediment, the volume of subglacial water only equates to 15mm of storage.

Walder and Driedger (1995) calculated the probability of jökulhlaups using intervals of temperature and precipitation data. The data were collected from the Paradise SNOTEL station, Longmire, and an additional temperature and rain gauge at Glacier Island. The Glacier Island rain gauge was located near the terminus of South Tahoma Glacier, but malfunctioned frequently, producing unreliable results. As mentioned previously, the SNOTEL station was used as a surrogate for conditions at South Tahoma Glacier. By using the Kolmogorov – Smirnov (*KS*) test of goodness of fit (Conover, 1971), Walder and Driedger (1995) assessed how different the distribution of T_{MAX-1} was on days with jökulhlaups compared to the total distribution of T_{MAX}. The *KS* test compares the probability of T_{MAX-1} associated with jökulhlaups to the cumulative distribution function (CDF) of T_{MAX} during May-November from 1986-1992. The result calculates the probability (P_{KS}) that a data set is random; the smaller the P_{KS}, the more unlikely a data set is random. The P_{KS} is 2.80×10^{-4} (Table 3), meaning it is highly unlikely that jökulhlaups occurred randomly with respect to T_{MAX-1}. The P_{KS} for 2-, 3-, and 4-day average T_{MAX} are larger than that of the T_{MAX-1}, suggesting the distributions of those intervals are more likely to be random, compared to the T_{MAX-1}.

Walder and Driedger (1995) then used climatic data to estimate the conditional probability (P_C) of debris flows and jökulhlaups from South Tahoma Glacier using precipitation and daily T_{MAX} across 1-, 2-, 3-, and 4-day averages preceding events. Using T_{MAX} as a surrogate for rate of water input, they hypothesized that temperature, and subsequently rate of water input, drive jökulhlaup occurrences from South Tahoma Glacier. P_C is a ratio: the numerator is the number of jökulhlaups that occur at a T_{MAX} equal to or greater than a given T_{MAX}; the denominator is the number of days that have a T_{MAX} equal to or greater than the given T_{MAX}. The P_C of an outburst flood occurring is the relative frequency of outburst floods that occur above a particular given T_{MAX}.

The P_C values established for each of the four intervals (1-, 2-, 3, and 4-day average T_{MAX}) fit the same approximate trend line. As temperature increases, P_C increases nonlinearly along a concave-up line, with higher values as temperature rises (Figure 2). The P_C is 0.03 at 20°C and rises to just over 0.05 at 25°C. Walder and Driedger (1995) extrapolated the trend line to 30°C and found P_C of 0.13. They believed that at longer averaging intervals, the trend seen in Figure 2 is less obvious, and so they did not pursue evaluating any longer intervals.

Legg (2015) studied the triggering of storm-induced debris flows on Mount Rainer. He identified several temperature thresholds for forecasting debris flows: low debris flow hazard (<0ºC), medium debris flow hazard (0ºC to 4.4ºC), and high debris flow hazard (>4.4ºC). Temperature thresholds were identified over 3-day intervals, and precipitation thresholds were found for 3-day (rain intensity) and 15-day (antecedent conditions) intervals for precipitation and T_{MAX}, based off of prior work for Seattle rain-induced landslides (Chleborad et al., 2006). Legg's results ultimately indicate high hazard storms are occurring during the late summer and early fall. His final technique in studying the triggering of storm-induced debris flows was to create a decision tree to forecast debris flow hazards based on antecedent precipitation and temperature, resulting in low, medium, and high hazard warnings.

Methods

In this study, I used days between June-September, from 1966-2015. Walder and Driedger (1995) included May, October, and November in their analyses, but I exclude these months because there are no occurrences of dry-weather jökulhlaups in any of these months.

I used data from the Paradise SNOTEL station (site 679). Data was converted from ºF to ºC. To find the average T_{MAX} on a given calendar day, I calculated the average T_{MAX} for that day across every year from 1966-2015 (Figure 3). For example, the September 1st average T_{MAX} is the average of the T_{MAX} recorded on September 1st in 1966, 1967, 1968... 2015. Longer intervals of T_{MAX} were found by calculating the average T_{MAX} before the event happened, with the final day always on the day of the outburst flood. For example, if a jökulhlaup occurs on September 1st, the 1-week average T_{MAX} for that event is the average of T_{MAX} on August 26th, August 27th, August 28th… ending September 1st.

The P_C of a jökulhlaup is calculated with the same ratio used by Walder and Driedger (1995), mentioned previously. The P_C for longer intervals of T_{MAX} are calculated the same way as T_{MAX-1}.

Relationship of Jökulhlaups to T_{MAX}

I followed the methods of Walder and Driedger (1995) in calculating the *KS* Test for the days jökulhlaups occurred. It is clear from the probability density function (PDF) of T_{MAX-1} that the days jökulhlaups occurred are different from the entire distribution (Figure 4), but for the purpose of updating the results of Walder and Driedger (1995), I went through the same method. My *KS* test results show that it is highly unlikely that the days that jökulhlaups occurred were random, which is the same result that Walder and Driedger (1995) found (Table 3).

When I calculated P_C using June-September from 1966-2015, I used the same method as Walder and Driedger (1995). The highest P_C value for a jökulhlaup using T_{MAX-1} is 0.023 at 28.3°C. Comparatively, Walder and Driedger calculated P_C nearly four times larger than this value, finding a P_C of 0.11 at 28.3°C. I show a lower 1-day P_C of a jökulhlaup occurring compared to Walder and Driedger (Figure 5).

Walder and Driedger (1995) explicitly say not to use their figures (in this case Figure 2) to *predict* a jökulhlaup. The glacier and its drainage system change with time, which means these results are sensitive to time. Additionally, the outburst flood data set is very small. The method to calculate P_C is not robust, due to the quantity of data. I have proven that the results are fragile and will change with time, and so I also caution against using the P_C to predict when a jökulhlaup will occur. Should these results be recalculated with additional data, they will likely differ from what I found.

Outburst floods typically occur from South Tahoma Glacier during late summer and early fall, which is after the peak T_{MAX-1} (Figure 4). The average annual T_{MAX-1} peak between 1966-2015 occurs around the second week of August. Three jökulhlaups occurred before the T_{MAX-1} peak, ten jökulhlaups occurred after the T_{MAX-1} peak, and one jökulhlaup occurred around the same time as the T_{MAX-1} peak. If T_{MAX-1} were the driving factor for glacier melting, there should be an even distribution of jökulhlaups around the average T_{MAX-1} peak. The late-summer skewing in the jökulhlaup distribution suggests that longer intervals of melting are required to trigger jökulhlaups, rather than the 1- to 4-day averages assessed by Walder and Driedger (1995).

To align the peak of the outburst flood distribution to the peak of the T_{MAX} distribution, I calculated average T_{MAX} intervals by using a running mean across the months of June-September from 1966-2015. I used a trial and error method to determine which interval most evenly distributed the jökulhlaup events around the T_{MAX} peak. 1-week, 2-week, 4-week, 6-week, and 8-week average T_{MAX} intervals were calculated. The 1-, 2-, and 4-week intervals were too short to create even distribution of jökulhlaups around the peak; the 8-week interval was too long to create an even distribution of jökulhlaups around the peak; the 6-week average T_{MAX} (T_{MAX-42}) interval distributed the jökulhlaups most evenly around the T_{MAX-42} peak (Figure 6).

Again, I used the *KS* test to determine how different the T_{MAX-42} for days with outburst floods is from the total distribution (Table 3). Similar to T_{MAX-1}, it is clear from the PDF that the distributions are not the same (Figure 7). However, to keep consistent with the methods of Walder and Driedger (1995), I performed the test. The results show that it is highly unlikely that the T_{MAX-42} on days with outburst floods is random.

The P_C for T_{MAX-42} can be divided into two groups: lower T_{MAX-42} (<18.0°C) and higher T_{MAX-42} (≥18.0°C) (Figure 8). The eight lower T_{MAX-42} values increase from a P_C of 0.004 at 12.8°C to a P_C of 0.008 at 17.8°C. The P_C of a jökulhlaup is quite low at the lower end of T_{MAX-42}. As T_{MAX-42} increases (≥18.0°C), P_C increases rapidly, starting at a P_C of 0.01 at 18.3°C. Once the T_{MAX-42} reaches 21.1°C, as it did before the July 1988 jökulhlaup, P_C reaches 0.10. This trend is reasonable; outburst floods are less probable to occur because lower T_{MAX-42} produce less meltwater than higher T_{MAX-42}.

Recommendations

The 14 outburst floods from South Tahoma Glacier appear to cluster temporally: five floods occur between 1967 and 1971, seven occur between 1987 and 1990, and two occurred in 2015. This report focuses exclusively on T_{MAX-1} and T_{MAX-42} associated with jökulhlaups, which are not long enough to explain the apparent bidecadal clusters. Global weather phenomena, such as the El Niño Southern Oscillation could have an effect on T_{MAX}. El Niño and La Niña, the two phases of the El Niño Southern Oscillation, occur almost yearly, but their intensities vary (Wyrtki, 1975). Examining the relationship between the El Niño Southern Oscillation phases and hot days or days with outburst floods could explain the clustering.

South Tahoma Glacier is complex; physical data needs to be collected and analyzed for relationships between melting intervals, flood volumes, and subglacial storage of the glacier. These data can be collected from a stream gage on Tahoma Creek. Larger jökulhlaup discharges are associated with longer and/or hotter melting intervals. A hydrograph could be used to calculate the flood volume, which would help to understand the subglacial hydraulics and the flood volume would likely be representative of the storage potential of South Tahoma Glacier.

Most of the warmest years on record in the Northwest (Idaho, Oregon, and Washington) have occurred recently (Dalton, Mote, and Snover, 2013). The average temperature in the Northwest has increased 0.8°C since the early 1900s and is expected to increase by nearly 2.0°C by the 2050s, with decadal increases ranging from 0.1°C to 0.6°C from present until 2050 (Mote and Salathé, 2010). These models show mean temperature increase in the Northwest region, so Mount Rainier and South Tahoma Glacier will increase in the same proportion. With increasing mean temperatures, the atypically T_{MAX-42} associated with outburst floods will likely become more common. By creating detailed models for Mount Rainier itself, we could anticipate future T_{MAX} and P_C for the decades prior to 2050.

Future climate models could also help to understand the retreat rate of South Tahoma Glacier. At some point, the glacier could cease to exist. As the glacier retreats, would jökulhlaups in the years of retreat increase, decrease, or stay the same?

Conclusions

Jökulhlaups, or glacial outburst floods, occur without precursors, and have the potential to damage infrastructure and harm people within Mount Rainier National Park. This report re-evaluated the results found by Walder and Driedger (1995) to establish the P_C of jökulhlaups from South Tahoma Glacier. I used a larger data set with 14 jökulhlaups rather than the seven used originally by Walder and Driedger (1995). My results show P_C for T_{MAX-1} is lower than what was originally found; at 28.3°C, the highest T_{MAX-1} on a day with an outburst flood, the P_C is 0.023, compared to Walder and Driedger's (1995) value of 0.11 for the same T_{MAX-1}.

Comparing the results of the P_C analysis to Walder and Driedger's (1995) results, I showed the analyses of this data cannot be robust; by introducing more data, the range of P_C and the shape of the trend has changed. If these analyses are performed again in the future, the results will probably be different from what I have calculated as well. Therefore, P_C should not be used to *predict* jökulhlaups.

Using T_{MAX-42}, I showed that the P_C remains less than 0.008 when T_{MAX-42} is <18.0°C. However, when T_{MAX-42} is ≥18.0°C, the P_C climbs rapidly from 0.01 to 0.10 at 21.1°C. I determined that T_{MAX-42} is more useful for calculating P_C than T_{MAX-1}, because longer intervals of time are needed to produce enough meltwater to generate an outburst flood.

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Table 1: Debris flows recorded from South Tahoma Glacier since 1967. "Dry Weather" type refers jökulhlaups. Legg (2015) complied the data from various sources.

Date	Antecedent Conditions	Type	Estimate of peak discharge (m^3/s)	Effects	Remarks	Information Source
8/29/1967	Exceptionally warm and dry summer. No rain in 2 months	Dry Weather	3 (11 km downstream of glacier	Footbridge 1.9 km below glacier destroyed	Water emerged at ice fall at about 2300 m asl. Occurred at 08.40 h	Driedger & Fountain, 1989; Richardson, 1968, p. 83
8/31/1967	Exceptionally warm and dry summer. No rain in 2 months	Dry Weather	680	Destroyed part of camping ground. Channel eroded in glacier; About 38 * 10^3 m^3 of material eroded	Break-out at 2,300 m a.s.l. Flood had consistency of we concrete, occurred during evening hours. 50% water flow. Flood dissipated 10.4 km below glacier.	Driedger & Fountain, 1989; Richardson, 1968, p. 83
9/15/1967	Exceptionally warm and dry summer. No rain in 2 months	Dry Weather	<680	No damage noted	Moved dlow-valley as far as the camp ground, noted as a small lahar	Driedger & Fountain, 1989; Crandell, 1971, p. 60
8/21/1970	Dryweather, total rainfall <10mm for month	Dry Weather	1000	Wonderland Trail Bridge destroyed	Flood inundated picnic area. Cline's slide show mudline about 2 m high below trail bridge	Driedger & Fountain, 1989; Crandell, 1971; and Cline USGS, Tacoma WA (pers comm)
8/10/1971	Zero rain in month prior to flood	Dry Weather	1000	Damaged trees		Driedger & Fountain, 1989; Mount Rainier National Park Collection
10/26/1986	Dry weather in month proceededed by 58 mm rain on day of flood and day previous	Wet Weather	1000	Trail bridge; parking areas; part of picnic area damaged. Creek re-routed towards west	Debris flow dissipated 6 km down-valley of glaicer. Longmire seismo recorded movement between 1:54 and 2:12 pm.	Driedger & Fountain, 1989; K. Scott, USGS, Vancouver, WA
6/29/1987	18 mm rain during June	Dry Weather	(approximately) 1000	Rocks thrown over trail bridge 20 m above stream bed; Depostied 1+m of mud in picknic area. Levees constructed 3-4m over stream-water level; Destroyed picnic area	Concrete-like mass carried boulders, occurred 14.30 h; flood wave of debris preceeded by rush of wind; sound like aircraft	Driedger & Fountain, 1989; J. Fielding and M. Starkey, park visitors
8/28/1987	Unseasonably dry weather. 8 mm rain during August	Dry Weather	1000	Stream re-routed within existing channel	Occurred 17.00 h	Driedger & Fountain, 1989;
8/31/1987	Unseasonably dry weather. 8 mm rain during August	Dry Weather	1000	1 m aggradation of river bed at picnic area	Occurred during evening hours	Driedger & Fountain, 1989;
9/23/1987	Below normal rainfall, 41 mm rain in September before flood date	Dry Weather	1700	Re-routed stream bed towards west, small percentage flowed over highway; destoyed signs and outhouse	Velocity > 2 m/s through parking lot; occurred 17.30	Driedger & Fountain, 1989;
7/14/1988	Cool and drizzly.	Wet Weather	1300	River km 5.6: overtopped the Westside Road and left bouldery deposits 0.5 to 1 m thick for a distance of 150 m.	Longmire seismo recorded between 1:46 and 2:00 pm. Turbid water followed the debris flow and eroded a trench 1 to 2 m deep near the center of the road. No appreciable rise of water was noted at the highway bridge	Walder and Driedger, 1994

Date	Antecedent Conditions	Type	Estimate of peak discharge (m^3/s)	Effects	Remarks	Information Source
7/26/1988	Warm and dry	Dry Weather	540		Longmire siesmo recorded between 3:48 and 4:01 pm. Peak velocity estimated 5m/s. Disntinct levees deposted.	Walder and Driedger, 1994; observed by GG Parker and CH Swift, USGS
10/16/1988	Cool and very rainy	Wet Weather	600	Westside road seriously damaged.	Longmire seismo recorded between 2:53 and 3:$3 pm. 8m deposit thicknes near river km 7.7. Mudlines showed threere had been a rise in stage of about 5 m at riverkm 6.5. Water level rise at high way bridge of 1 m.	Walder and Driedger, 1994
9/23/1989	Hot and dry weather.	Dry Weather	30-76		Emerald Ridge sesmo recorded this. Flow at km 9.5 2 m depth. No new bouldery deposts, muddy coatings on older deposts. Velocity estimate: 4 m/s	Walder and Driedger, 1994
11/9/1989	Cool and very rainy	Wet Weather	60		Longmire seismo: 5:00 to 6:02 am. Deposition in channel river kms 6 to 9.	Walder and Driedger, 1994
8/4/1990	Hot and dry weather.	Dry Weather	150-180	Forests damaged	Emerald Ridge seismo recorded this. No new bouldery deposits at former picnic area. Vel 2.7 to 3.	Walder and Driedger, 1994
10/3/1990	Cool and heavy rainfall.	Wet Weather	70-500		Emerald Ridge seismo recorded ten debris-flow pulses, durations ranging 10-32 minutes, over a 8.5 hr period. No distinct levees. Several steep snouts of deposits.	Walder and Driedger, 1994
11/5/1991	Cool and very rainy.	Wet Weather	600	Deep gully in westside road above fish FishCreek confluence.	Seismo indicates one hour flow duration; U = 6 m/s; total volume estimate 10^5 m^3	Walder and Driedger, 1994
9/8/1992	Cool and rainy.	Wet Weather	300	Bouldery deposits on the Westside Road.	Sedimentology indicated pulses	Walder and Driedger, 1994
9/20/1992	Cool and rainy.	Wet Weather			Similar size to September 9, 1992 event.	Walder and Driedger, 1994

Date	Antecedent Conditions	Type	Estimate of peak discharge (m^3/s)	Effects	Remarks	Information Source
9/12/2003	No data.	Unknown		Large slope failure at the downstream left moraine; slope failure was estimated to be over 250m in length; likely that the slope failure was the result of failure of an oversteepened, unconsolidated slope that was undercut at the toe by long-term fluvial incision, a pulse of glacier meltwater, or the passage of a debris flow. The slope failure may have reinforced an existing debris flow that initiated at the glacier terminus		Copeland, 2009
9/29/2005		Wet Weather		Traveled Tahoma Creek into Fish Creek and aggraded a large armored culvert known as Texas Crossing (to NPS employees)		Copeland, 2009
11/6/2006	Cool and rainy.	Wet Weather				Copeland, 2009
8/13/2015	Hot and dry weather.	Dry Weather			Several hyper-concentrated flows occurred	Beason, 2016; Author
9/12/2015	Hot, <15mm during week of event. Heavy rain two weeks prior to event.	Dry Weather		Damage to West Side Road, produced aggradation and gullying in channel.	Different source than August outburst.	Beason, 2016; Author

Table 2: The date and cumulative precipitation (in millimeters) for each jökulhlaup used in this report, also showing number of days of rain prior to events.

Date of Jökulhlaup	*Antecedent Precipitation (mm)*				*Number of Days with Precipitation within 28 Days of Jökulhlaup*
	1 Week	*2 Weeks*	*3 Weeks*	*4 Weeks*	
8/29/1967	0	0	0	4	1
8/31/1967	0	0	0	4	1
9/15/1967	46	53	53	53	5
8/21/1970	0	3	6	26	7
8/10/1971	0	0	0	0	0
6/29/1987	1	18	20	36	7
8/28/1987	0	6	36	38	4
8/31/1987	0	0	36	36	4
9/23/1987	0	53	53	55	7
7/26/1988	0	4	9	35	9
9/23/1989	1	1	2	10	5
8/4/1990	1	20	20	25	7
8/13/2015	0	1	12	12	4
9/12/2015	14	94	106	106	9

Table 3: Results of the Kolmogorov – Smirnov test from Walder and Driedger (1995), also with T_{MAX-1} during the months of June-September from 1966-2015.

	Length of Trend	*Number (n) of jökulhlaups in sample*	*K-S Statistic (d_m)*	*Probability that d_m would be exceeded another sample of n points (P_{KS})*
1995	1 Day	7	0.702	2.8×10^{-4}
	2 Days	7	0.600	3.09×10^{-3}
	3 Days	7	0.534	1.09×10^{-2}
	4 Days	6	0.582	9.32×10^{-3}
2016	1 Day	14	0.709	$< 1.00 \times 10^{-4}$
	42 Days	14	0.557	3.41×10^{-4}

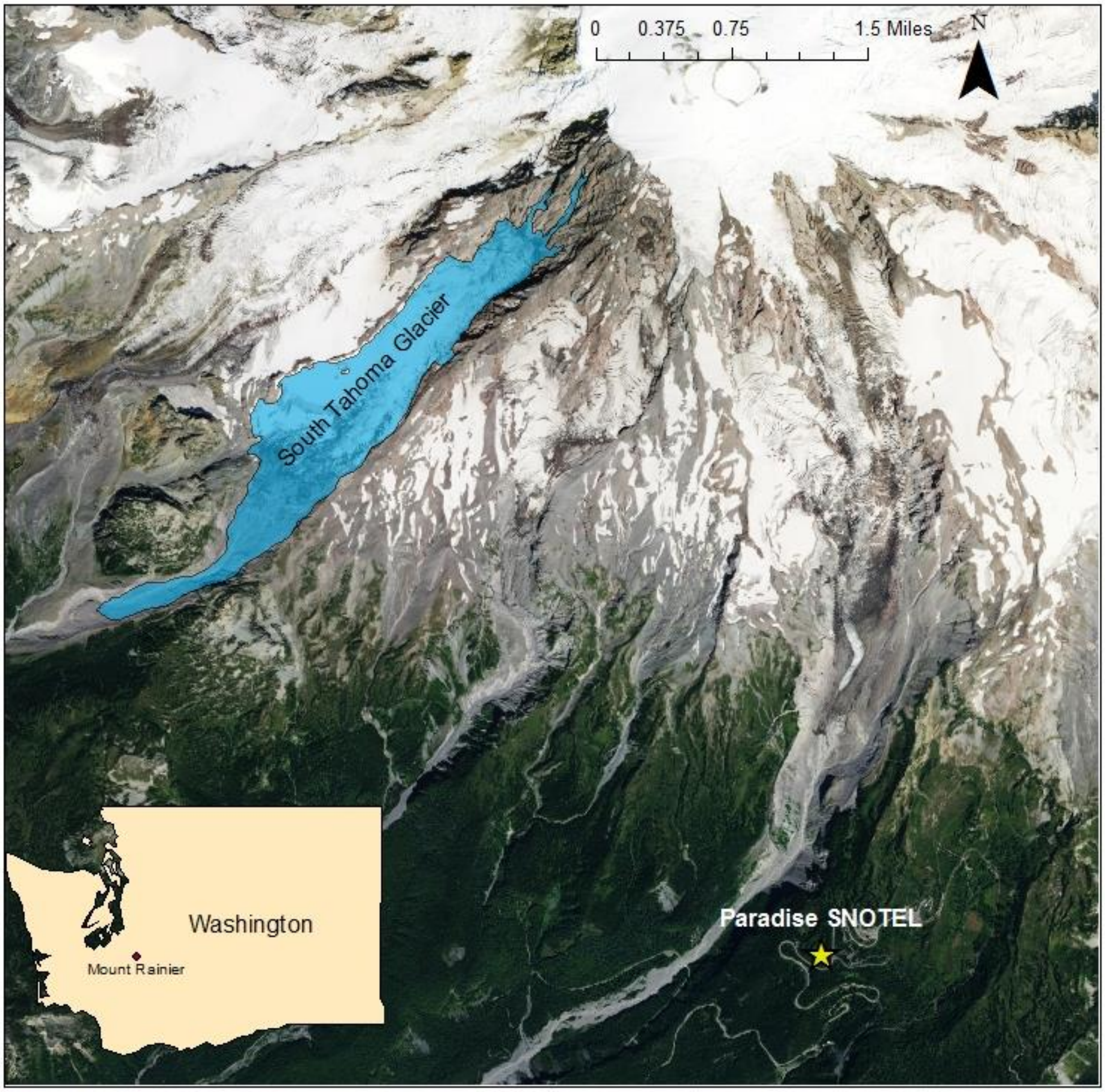

Figure 1: South Tahoma Glacier and the Paradise SNOTEL station are located on the southern side of Mount Rainier, Washington.

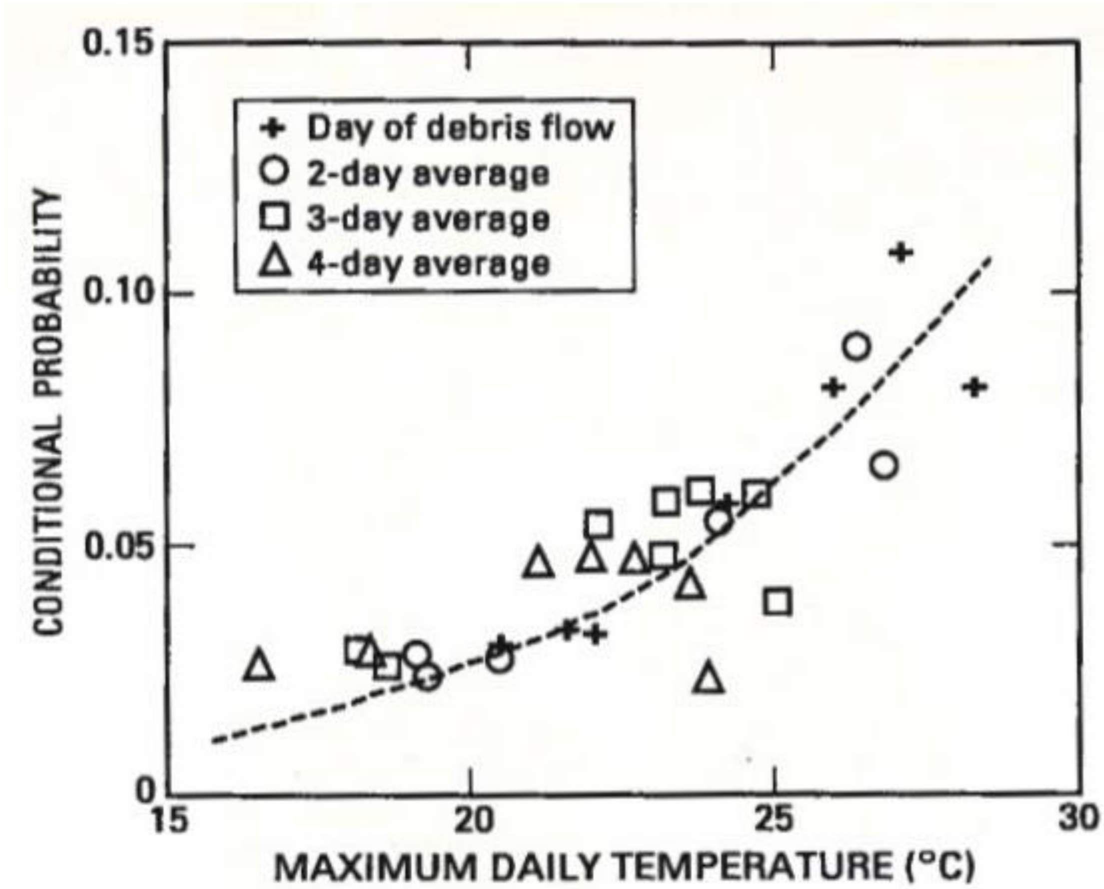

Figure 2: The conditional probability of a debris flow (outburst flood) established by Walder and Driedger (1995) for dry days between May-November from 1986-1992. The dashed line is the approximate fit to the data. When extrapolated, the dashed line shows a conditional probability equal to 0.13 at 30ºC.

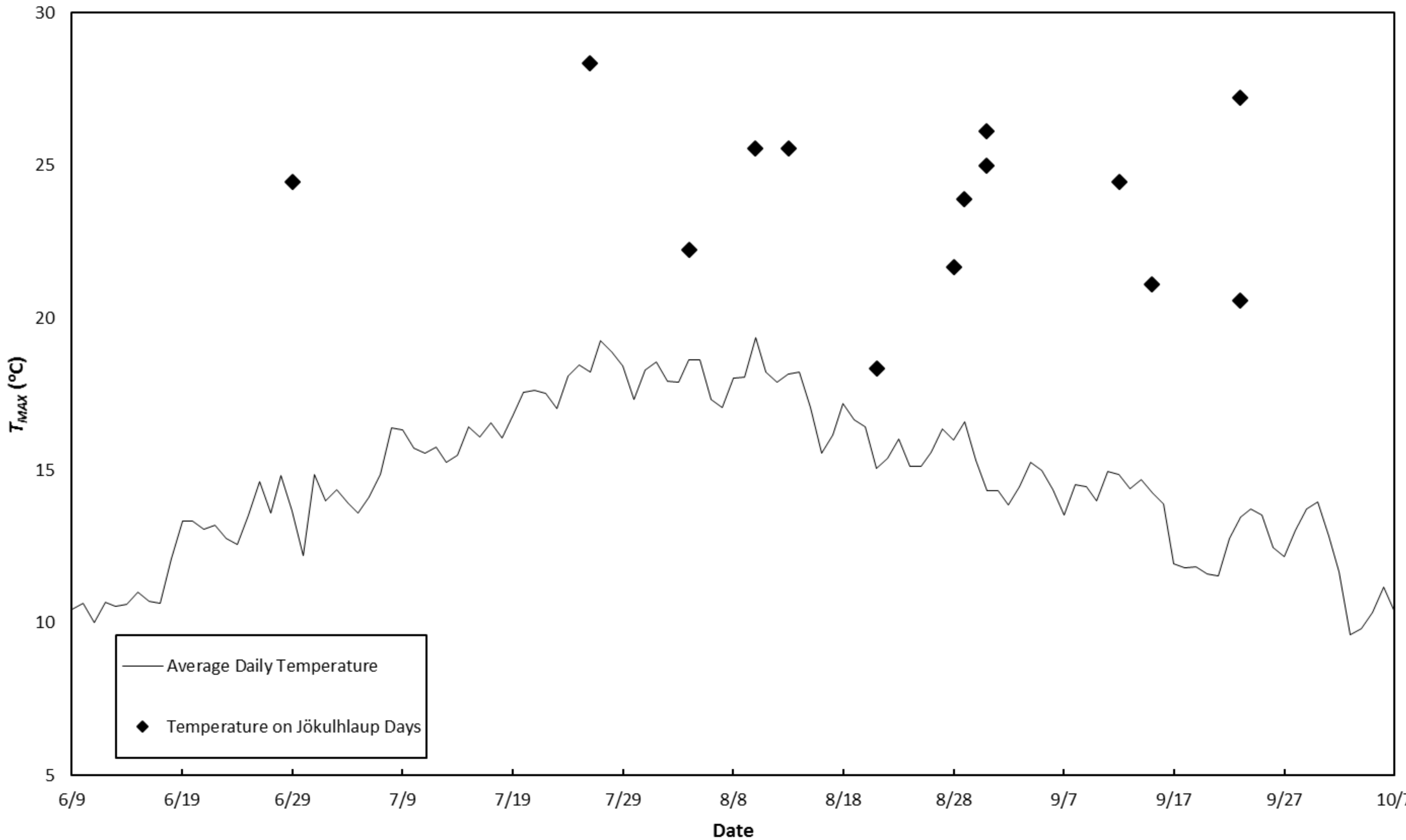

Figure 3: Average daily T_{MAX} during June-September from 1966-2015. The peak average T_{MAX} is around mid-August. T_{MAX-1} on each day a jökulhlaup are shown.

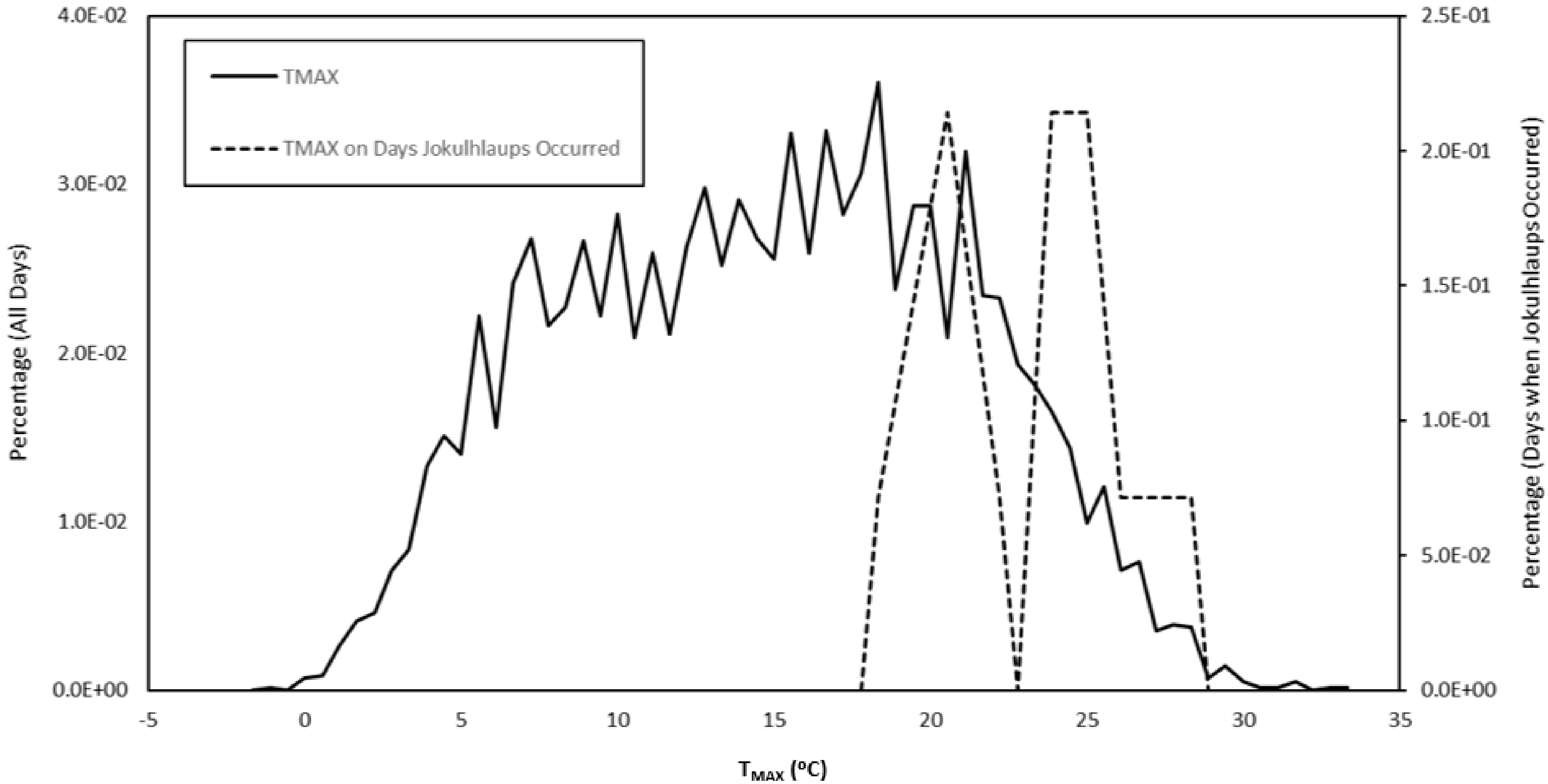

Figure 4: PDFs for T_{MAX-1} for the whole distribution and the T_{MAX-1} on days of jökulhlaups between June-September from 1966-2015. It is clear from the PDFs that the distributions are not the same.

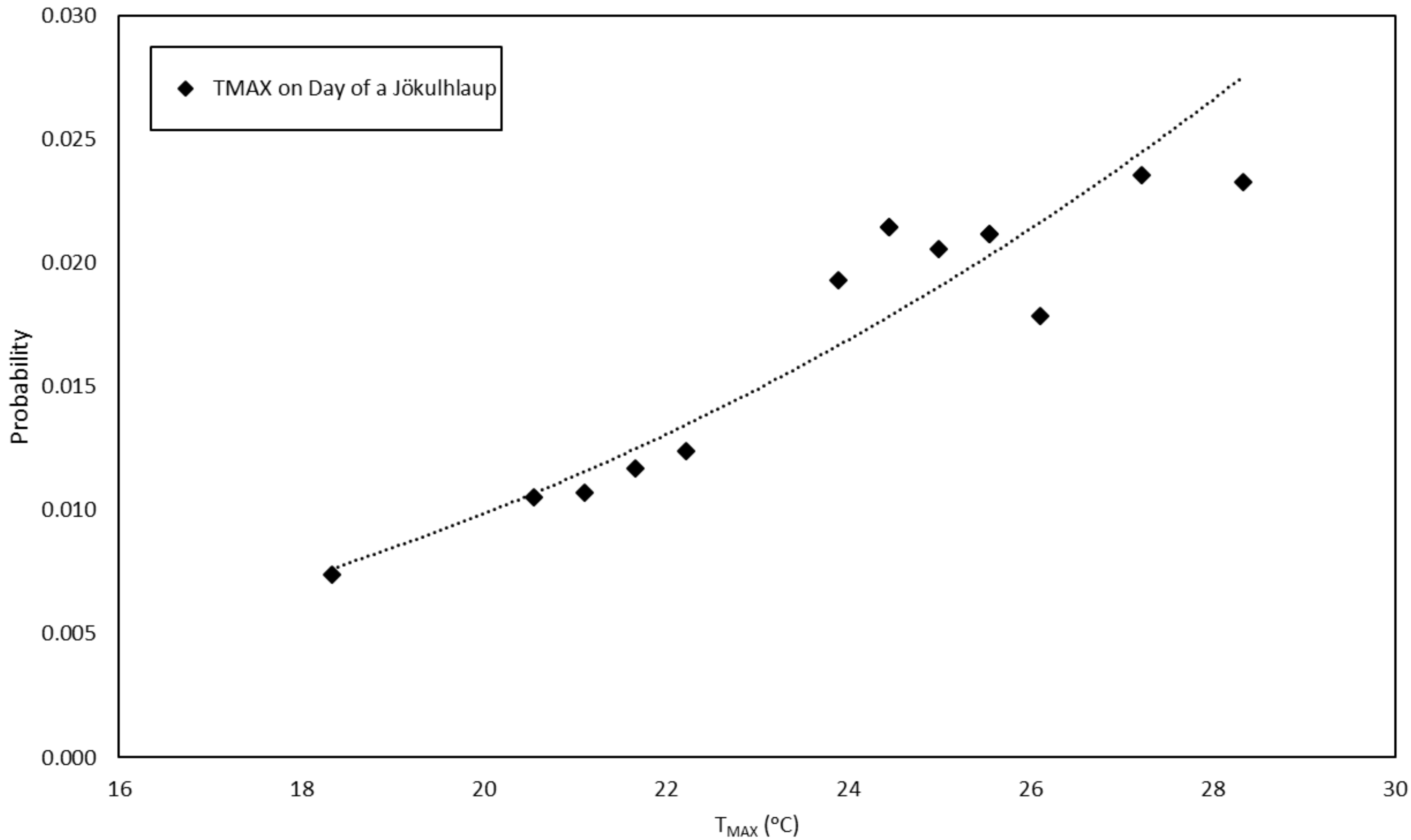

Figure 5: The conditional probability of a jökulhlaup as a function of T_{MAX-1} during June-September from 1966-2015. The dotted line is the best fit.

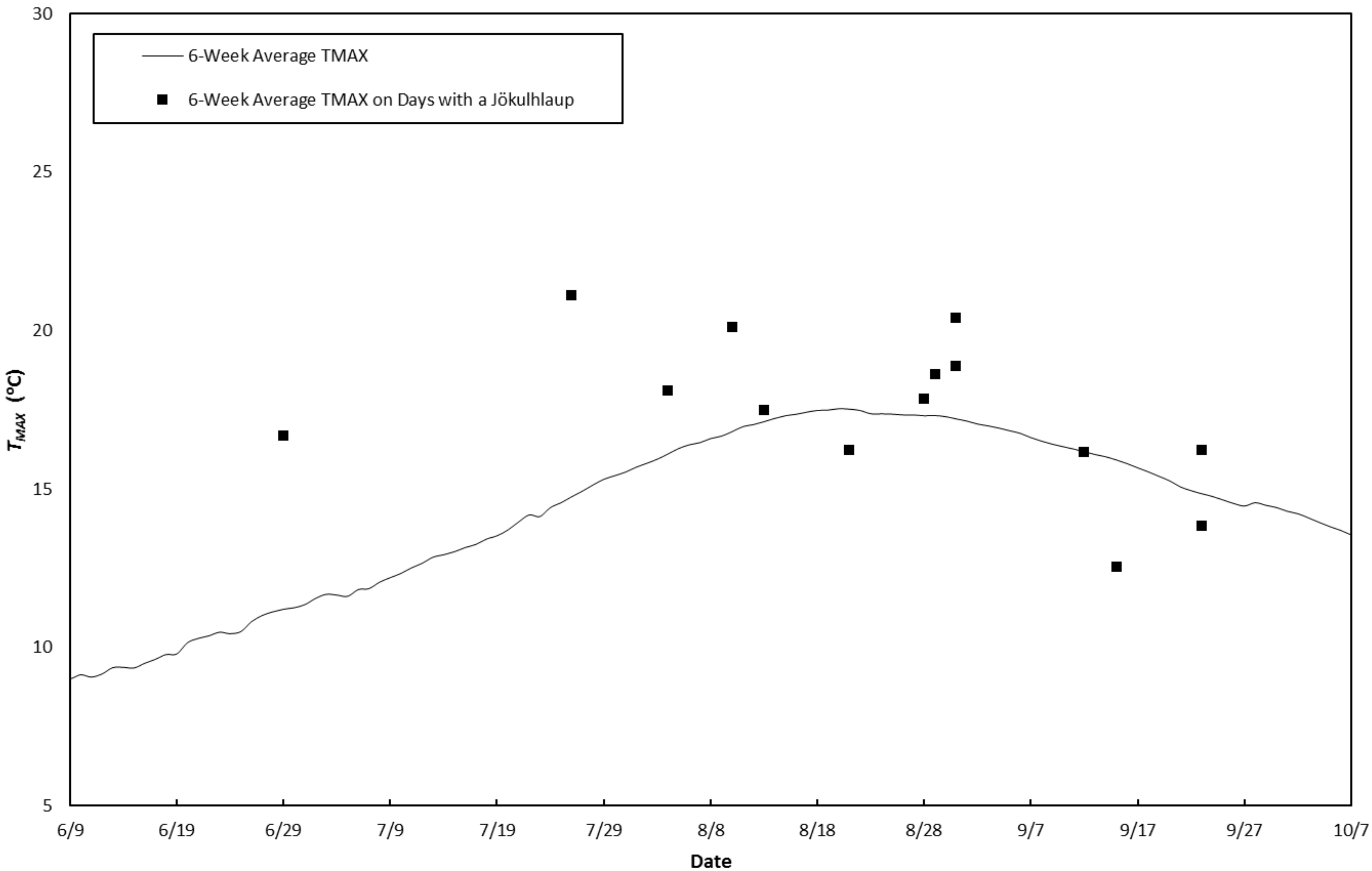

Figure 6: Using a $T_{MAX\text{-}42}$, the annual peak is shifted back to late August, which creates a more even distribution of $T_{MAX\text{-}42}$ around the peak, compared to the $T_{MAX\text{-}1}$.

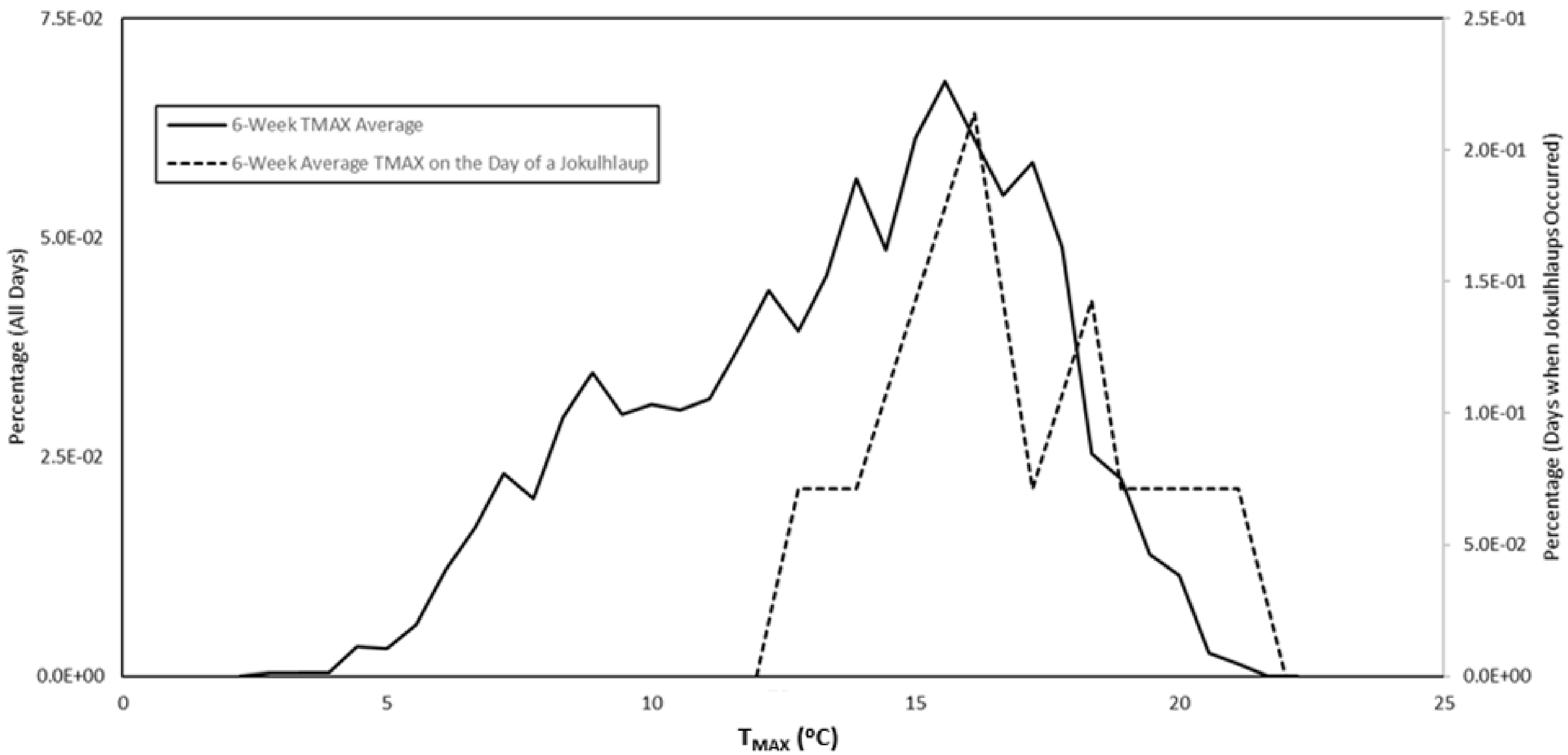

Figure 7: PDFs for T_{MAX-42} for the whole distribution and the T_{MAX-42} on days of jökulhlaups between June-September, from 1966-2015. Similar to the T_{MAX-1} PDFs, the distributions are not the same.

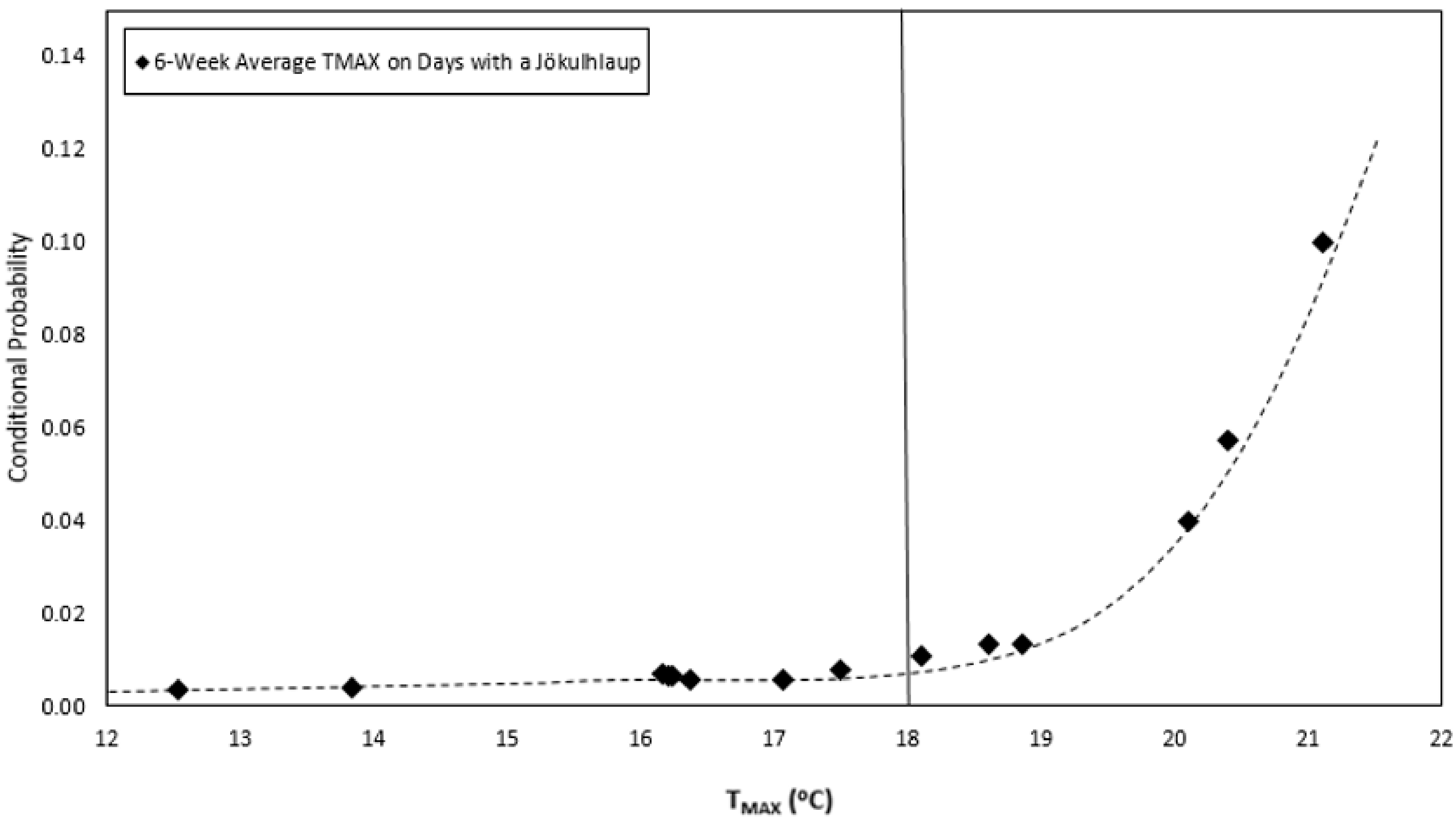

Figure 8: The conditional probability of a jökulhlaup as a function of T_{MAX-42} during June-September from 1966-2015. The T_{MAX-42} (≥18.0ºC) follow a different trend than the lower values (<18.0ºC).