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Rain-induced speed up events of a temperate surging glacier, AK, inferred from GPS measurements

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Abstract. Temperate surge-type glaciers undergo periodic order-of-magnitude increases in flow speeds generally attributed to drainage system evolution, making them ideal sites to explore how the kinematic response of glaciers to rain events varies with subglacial drainage system efficiency. Here, we compare ten GPS-derived glacier surface speed records with modeled rainfall to assess short-term evolutions of the drainage system at the end of a surge (2020-2021) and during quiescent flow (2022-2024) at Sít' Kusá, Alaska. Speed anomalies were identified using a short-term to long-term average ratio approach and all speed anomalies that followed large rain events were characterized by their duration, magnitude, and immediacy. During the surge, 9 of 16 large rain events (56%) caused speed anomalies, peaking at 7.5 m/d (116% increase) and lasting 66.5 hours on average. During quiescence, rain-induced speed-ups were less frequent (17 of 37 rain events (46%)), smaller (~1.5 m/d), shorter (~33 hours), but greater in percent increase (251%). Although the differences in speed characteristics generally indicate that the drainage system is more efficient during quiescence, speed-ups throughout the surge cycle suggest there is a persistently inefficient component of the drainage system. We find that particularly large and prolonged rain events can cause temporary slow-downs during the surge, but that speeds return to pre-event levels in less than two weeks as the drainage system reverts to its inefficient state. Our work supports recent analyses of glacier instabilities suggesting there isn't a binary switch in drainage system configuration during surges. More broadly, our findings expand our understanding of glacier kinematic responses to rainfall, demonstrating that rain events can modulate speeds of both fast- and slow-flowing glaciers.

1 Introduction

Understanding extreme variability in flow at surge-type glaciers is useful for predicting when and where glacier flow instabilities may arise in the future. A broad spectrum of flow instabilities have been observed across the world, ranging from Alaskan mountain glaciers to Antarctic Ice Streams, and it is possible that surge-like instabilities will change in extent and frequency as a result of climate change (Bennett, 2003; Frappé and Clarke, 2007; Copland et al., 2003; Herreid and Truffer, 2016). Better understanding these rapid speed fluctuations during surge cycles can provide valuable insights into the relationships between glacier speeds, subglacial water storage, and drainage efficiency which are insights that may be used to refine model projections of future glacier mass loss.

Summary of Comments on egusphere-2026-6232.pdf

Page: 1

Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:06:52

When? During surges or anytime? What part of this is meant to be unique to surge-type glaciers?

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:08:04

lag time? Onset relative to precip?

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:24:36

The intro is fine, but could be better by preferentially focusing on topics more specific to this paper. A more thorough review of glacier responses to rain seems appropriate (rather than just a couple of examples) to set the stage and generate some hypotheses. A second area that warrants more thorough coverage would be speed variations on surge-type glaciers (outside of the surge cycle). Mini surges come to mind as a starting point.

Number: 4 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:12:24

I'm surprised not to see the recent review paper on surges by Lovell et al not cited in a general context like this (or in this paper).

Lovell, H., Benn, D. I., Jiskoot, H., Stokes, C. R., Flowers, G. E., Guillet, G., Mannerfelt, E. S., Falaschi, D., K..b, A., King, O., Benediktsson, I. O., Bhambri, R., Lv, M., Muhammad, S., and Luckman, A.: Glacier surging and surge-related hazards in a changing climate, Nature Reviews Earth and Environment, https://doi.org/10.1038/s43017-025-00757-9, 2026.

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A glacier surge is an order-of-magnitude increase in speed that is generally attributed to a rapid increase in basal sliding caused by changes in subglacial hydrology or thermal state (Benn et al., 2019). Surge-type glaciers periodically cycle between relatively short periods of surging flow and longer-term periods of slow flow, called quiescence. For glaciers that have a bed at the pressure melting temperature, surges initiate when sufficient basal water builds up to reduce effective pressure and increase sliding speeds. A surge will persist so long as the subglacial drainage system sustains high levels of basal water pressure (Kamb, 1987; Kamb et al., 1985). A surge terminates and the quiescent phase begins when the drainage system adapts its morphology to a more efficient system (Benn et al., 2019; Kamb, 1987; Eisen et al., 2005).

Central to both surge initiation and termination is the structure and efficiency of the subglacial hydrologic system, which regulates how subglacial water content can influence basal motion (Eisen et al., 2005; Kamb, 1987; Benn et al., 2019; Flowers, 2010). A subglacial drainage system is considered inefficient when it consists of isolated cavities and efficient when the drainage system consists of linked channels (Benn et al., 2019). A glacier underlain by a relatively inefficient system is generally considered to be sensitive to pulses of water because water inputs cause cavities to expand, reducing friction between the glacier and its bed, increasing sliding (Flowers, 2010). If an efficient system is present, glacier speeds should be largely insensitive to gradual increases in water inputs because channel size can expand to accommodate the increased inputs (Flowers, 2010). However, increased water inputs can still overwhelm channelized systems and produce a kinematic response if the input changes rapidly due to moulin drainage or large melt or rain events, for example (Bartholomaus et al., 2008; Nanni et al., 2023; Mair et al., 2002).

While surge-type glaciers highlight an example of how drainage system evolution can impact glacier speeds on year-to-decadal scales (Liu et al., 2024; Benn et al., 2019), drainage system evolution can occur on daily time scales as well. Sub-daily observations of glacier speeds have shown that changes in basal water pressure or water inputs to the subglacial system are sufficient to force daily evolutions of a drainage system (Horgan et al., 2015; Iken and Truffer, 1997; Vieli et al., 2004). For example, periods of high rain-rate have been shown to correspond with 24-hour increases in speeds and with periods of bed separation (Horgan et al., 2015). In some cases, changes in water inputs to the bed are enough to periodically overwhelm even efficient systems resulting in short-lived speed-up events (Bartholomaus et al., 2008).

Here, we analyze Global Positioning System (GPS) records of glacier speed with respect to rain events across the surge and quiescent phase of a temperate surging glacier, Sít' Kusá (Turner Glacier), in southeast Alaska. We analyzed time series of glacier surface speeds and rainfall to understand how the drainage system responds to short lived pulses of water to the glacial system. By leveraging speed records from approximately the same location but over periods with dramatic differences in speed due to the surge, we are able to infer the effects of the subglacial drainage system on kinematic sensitivity to pulses of water.

2 Methods

2.1 Study Site

The study site of this research is Sít' Kusá, a surge-type glacier located in the St. Elias range of Southeast Alaska. In the context of this research, Sít' Kusá is divided into 4 main zones; the upper-northern tributary, the icefall, and the reservoir and receiving

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:14:29

This seems like a narrow view of the cause of temperate surges that could be read as relying only on the accumulation of subglacial water rather than, more fundamentally, on the estbalishment of an ice reservoir.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:17:30

This also seems to overgeneralize. Inefficient drainage is not necessarily comprised only of isolated (I read as disconnected) cavities. Inefficient drainage involves connected and unconnected elements that aren't channels; they could be cavities, but they could also be canals or take other forms. This description is Kamb's theory, but I think a more general description (or just more careful wording) would be helpful.

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:32:44

This is a fairly insubstantial description of the study site. What about some basic details like elevation range and ELA? Wouldn't it also make sense to sketch out the glacier surge history?

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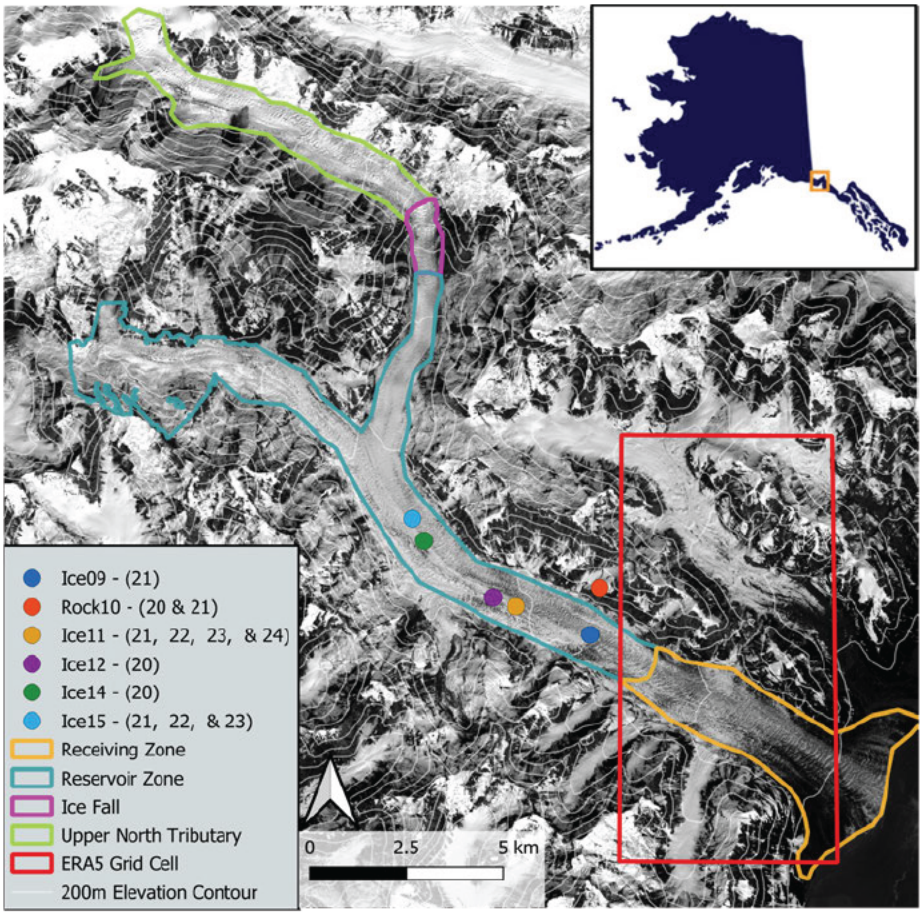


Figure 1. Map of Sít' Kusá showing the location of all GPS stations, ERA5 grid cell, and glacier zones. Stations labeled 'Ice' were deployed on the glacier surface while 'Rock' stations were deployed off ice. The two digit code following 'Ice' or 'Rock' corresponds to km up glacier at time of deployment. The numbers after the station label indicate the years (YY) of data coverage (e.g., 21 = 2021, 22 = 2022).

zones (Fig. 1). The glacier's surface elevation drops ~500 m throughout the icefall located 20.5 - 22.5 km from the terminus, effectively dividing the glacier's ablation zone from its upper northern tributary. The reservoir zone stretches from the base of the icefall to the dynamic balance line located 7-8 km from the terminus of the glacier (Nolan et al., 2021). The receiving zone is located down-flow from the reservoir zone, extending from the dynamic balance line to the terminus.

2.2 GPS Processing

For this study, we used 12 Global Positioning System (GPS) records – 10 on ice stations from the reservoir zone and 2 off-ice stations deployed along Sít' Kusá's rock walls (Fig. 1). The GPS naming convention is as follows: on- and off-ice stations were listed as "Ice" and "Rock", respectively, followed by a number that indicates the distance from the terminus, in km, where the GPS unit was installed, and end with a number after a dash that indicates the date of installation in YYMM format. All GPS

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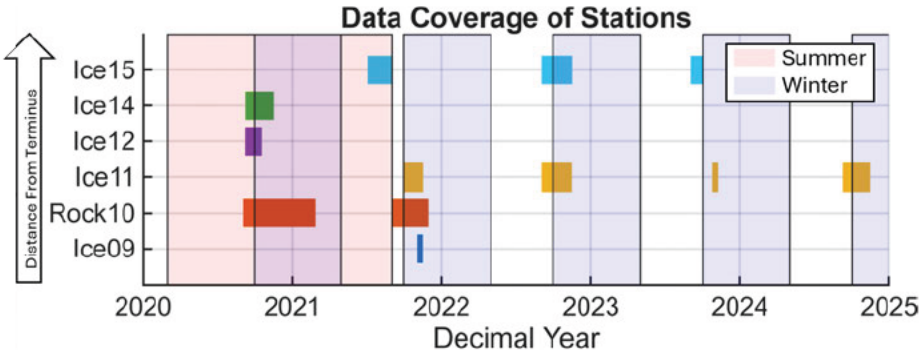


Figure 2. Temporal coverage of GPS stations. The colors of the horizontal bars denote different station locations. Blue transparent rectangles mark winter months (October to May) and the 1d rectangle represents the surge from March 2020 to September 2021.

units used in this study were NetR9 GPS systems (true GPS) from the EarthScope Consortium that were programmed to record signals every 15 seconds. GPS stations were deployed from 2020 through 2024 but the duration of the records was limited to late summer through early fall (Fig. 2) due to power supply and instrument difficulties in the meters-deep snowpack typical for the glacier. The fragmented record created by the 10 on ice GPS stations captured the middle of Sít' Kusá's 2020-21 surge, the surge termination in the late summer of 2021, and 2t' Kusá's subsequent quiescent phase (Fig. 2).

To convert the GPS records into measurements of glacier surface speeds, all GPS records were fed through the same processing pipeline that consisted of the following steps: 3ost-processing, smoothing, time-domain filtering, and detrending. The GPS data were post-processed through Canadian Precise Point Processing (CPPP) for the Yukon's GPS Epoch (2002.0). The processed positions were then converted into Universal Transverse Mercator (UTM) and shifted from Coordinated Universal Time to Alaska Standard Time.

UTM positions were then smoothed and converted into records of eastward and northward velocities using a rolling centered moving-window linear fit. Here a moving window polynomial fit was applied to the Northing and Easting positions 4 calculate the speed in each direction as the first-degree coefficient (i.e., change in position over time). A window size of one day reduced signal noise, created continuous records for the majority of GPS stations, but retained daily and longer-period variations in speed. Based on the 15 second recording interval of the system, we expected 5760 positions to be included in each window. However, more often than not, the expected number of samples within the window were not present and a minimum threshold of 90% of the expected samples was required to move forward. This threshold of 90% was similar to thresholds used by previous on-ice GPS analyses (Ahlstrøm et al., 2013).

5ock10 suffered from repeated power outages and their records were insufficient for direct use in kinematic post-processing but proved useful as a benchmark for signal filtering. Rock10 was post-processed and smoothed as described above so that periodic signals in the velocity records caused by atmospheric effects could be identified. Rock10 was deployed off ice, meaning it was stationary for the entirety of its record and each component of the velocity vector (i.e., speed in the Northing and Easting directions) should have been zero over its recording period. A frequency analysis of Rock10's velocity components revealed

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:36:32

Change legend if caption is correct.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:35:53

The whole quiescent phase until the next surge or the first N years?

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:39:39

Details coming later in manuscript? These steps could mean a lot of things.

Number: 4 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:42:34

meaning the coefficient of the polynomial that represents the linear term?

Number: 5 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:48:15

What was the installation method on the ice versus on the rock? Wondering about stability. Can you use Rock to quantify at least some of the uncertainty (not just frequency content of stationary receiver)?

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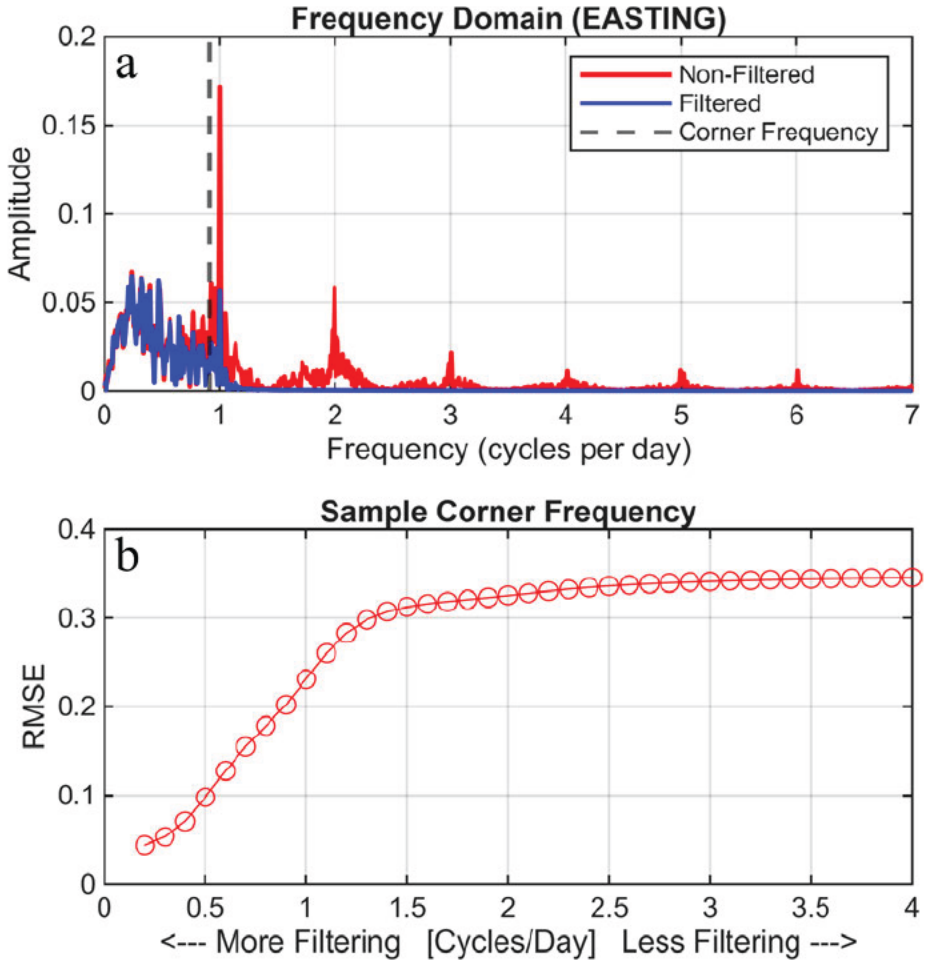


Figure 3. (a) Power spectra for the frequency domain of Rock10's Easting velocity vector before filtering (red) and after filtering (blue) using the chosen corner frequency. The dashed vertical line highlights the abrupt change in signal attenuation at frequencies higher than the chosen corner frequency (0.9 cycles/day). (b) Root mean squared difference between Rock10 filtered at the corresponding corner frequency on the x-axis relative to its true velocity record (i.e., 0 m/day).

that Rock10's velocity variation operated on regular cycles (Fig. 3a) that peaked at 1, 2, 3, and 4 cycles/day (24, 12, 8, and 6 hour intervals). These frequencies have previously been attributed to variations in Earth's Ionosphere and atmospheric tides (den Ouden et al., 2010).

To minimize these periodic atmospheric effects on our interpretation, we filtered the velocities in the time-domain using a low-pass fourth-order Butterworth filter. A Butterworth filter was selected because it can effectively attenuate high-frequency periodic noise (Du et al., 2000; Fang et al., 2020; Vergnano et al., 2025). For a low pass Butterworth filter, a corner frequency must be determined, marking the point where frequencies below the corner frequency are largely preserved, while frequencies above it are progressively attenuated. We tested corner frequencies between 1 and 4 cycles per day (increments of 1) for

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:53:05
Units on amplitude and RMSE?

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 07:54:30
increments of 0.1?

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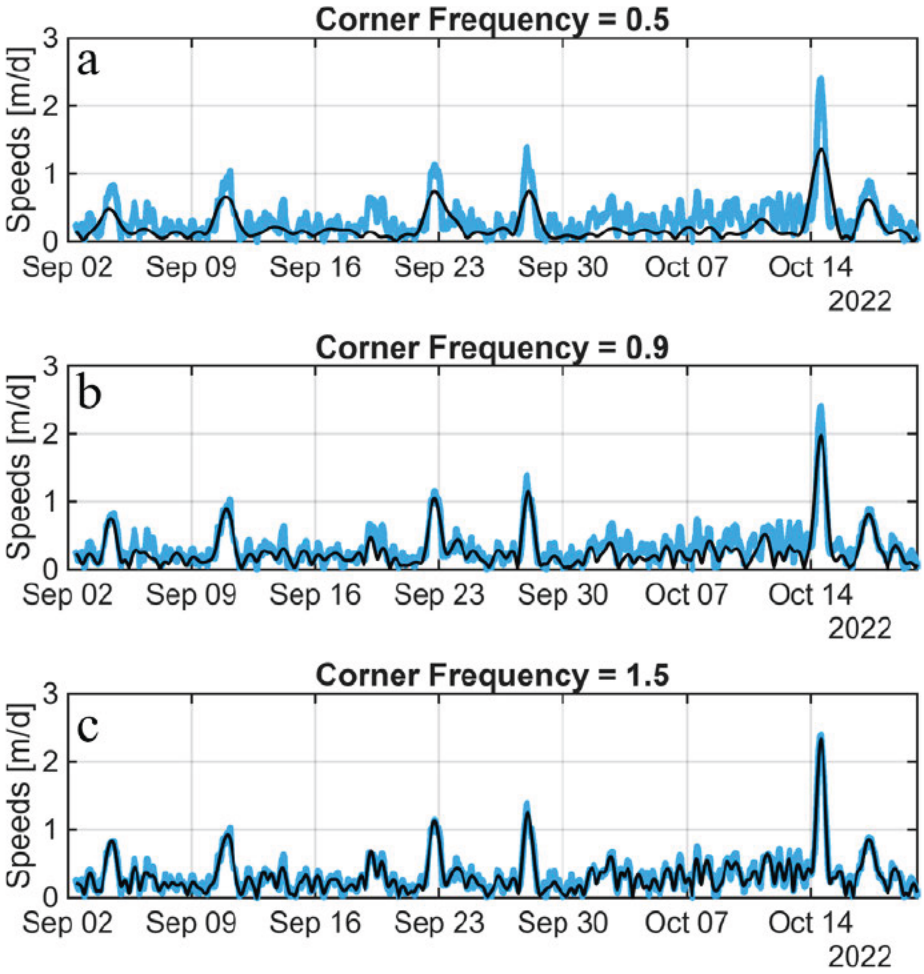


Figure 4. Ice15-2208 speeds filtered by a corner frequency of 0.5 (a), 0.9 (b), and 1.5 (c). For each plot, the unfiltered speeds are in light blue and filtered speeds are in black.

Rock10 by computing the root mean squared difference relative to an idealized 0 m/day velocity vector baseline (Fig. 3b). A corner frequency of 0.9 cycles/day was used because it provided the best trade-off between removing atmospheric signals (Fig. 3) while retaining natural on ice variation at frequencies lower than once per day (Fig. 4). Unfortunately, potential daily oscillations in speed caused by surface melt were also removed by our filter. However, since we were concerned with rain-driven speed anomalies, attenuation of the natural diurnal signal was not problematic for our interpretation. Throughout testing and final application, this filter was applied separately to the Northing and Easting velocity components, then along-flow speeds were calculated as the magnitude of the velocity vectors.

To isolate short-term rain-driven changes in speed from longer-term variations in speed associated with the glacier surge (Fig. 5a), the last step in our GPS processing pipeline involved detrending of the speed time series. Detrending was also necessary to properly compare the magnitude of speed up events from the surge and quiescence. In the context of this study, detrending

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:03:59

Give units on corner frequencies somewhere.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:12:37

I'm struggling to understand the argument here, given the ROCK data in Figure 3. If ROCK should be stationary, but has significant amplitude not only at 1,2, etc cycles per day, but also at < 1 cycle per day (see amplitude in Fig 3a at 0.2-0.4 cycles per day), why would a filter that passes those low frequencies be acceptable?

I understand that there is an interest in preserving SOME signal in the GNSS records on useful timescales, so one cannot filter everything out. However the arguments in relation to the ROCK station should be clarified.

The credibility of this approach could be demonstrated by plotting the same figures for ROCK and ICE, i.e., show the amplitude spectrum of an ice station with the rock station. And assess a minimum uncetainty on velocity as the fictitious velocity of ROCK. These uncertainties should be shown or at least reported in Fig 4.

Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:03:10

Is it possible that the distance to base stations with the PPP processing is too large?

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:13:22

and uncertainty propagated?

Number: 4 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:19:17

Is there a reason not to do this in the above step by using a bandpass filter? Maybe because the minimum rather than central trend was used? But why not remove the central trend so as to isolate anomalies without assuming they should be positive? I can imagine rain events could lead to speed up or slow down depending on the context.

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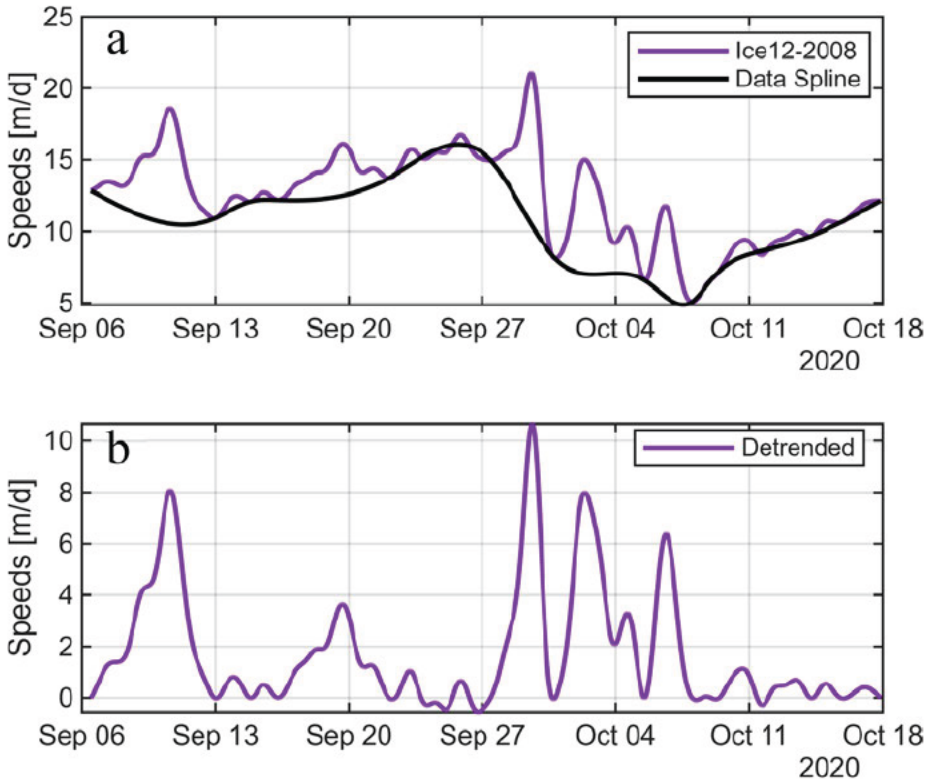


Figure 5. (a) Speed record of Ice12-2008 before detrending (purple) and the spline fit to the 6-day minima in order to capture background trends in speed (black). (b) Ice12-2008 after detrending (purple).

was the removal of approximately weekly or longer-period variations in speed. These variations in speed, hereafter referred to as background speeds, were modeled using a smoothing spline fit to speed minima within a 6-day moving window during the surge and 1 the average of a given GPS record during quiescence. The spline was subtracted from the surge speed time series, as demonstrated for the 'Ice12-2008' time series in Fig. 5b. A larger window (10 or 12 days) tended to over generalize the data and did not sufficiently capture the background patterns, while a shorter window (2 or 4 days) tended to follow the speeds too closely and individual speed-up events were removed.

2.3 Modeled Rain ~~Data~~ 2

To make inferences about variations in kinematic sensitivity to water pulses due to drainage system evolution, we analyzed our speed records alongside rain estimates. Rain estimates were sourced from the 3 25° x 0.25° ERA5 grid cell covering Sít' Kusá's terminus. ERA5 reanalysis rain data was downscaled to the surface using ArcticDEM elevations from the Polar Geospatial Center and down sampled to 100x100m. We used the 4 recipitation downscaling component of the energy balance 5 n model (EBFM) (van Pelt et al., 2012) to statistically downscale the ERA5 precipitation to the glacier surface. Modeled

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:22:21

Why not same window as surge interval? Not sure what this means. The average value of speed over the entire GPS record during quiescence?

Number: 2 Author: anonymous Subject: Inserted Text Date: 2026-11-08, 08:25:40

Estimates

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:24:43

Why use only this grid cell rather than others also that cover the glacier? If only one gridcell is chosen, why not choose the one that overlaps most of the GNSS stations?

Number: 4 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:26:19

Please briefly state what this entails, e.g., statistical vs physically based downscaling, etc. Also important to note whether this includes discrimination of rain vs snow within the downscaling.

Number: 5 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:41:34

Is this model equally applicable over ice? It would be good to reassure the reader who is not familiar with this particular model.

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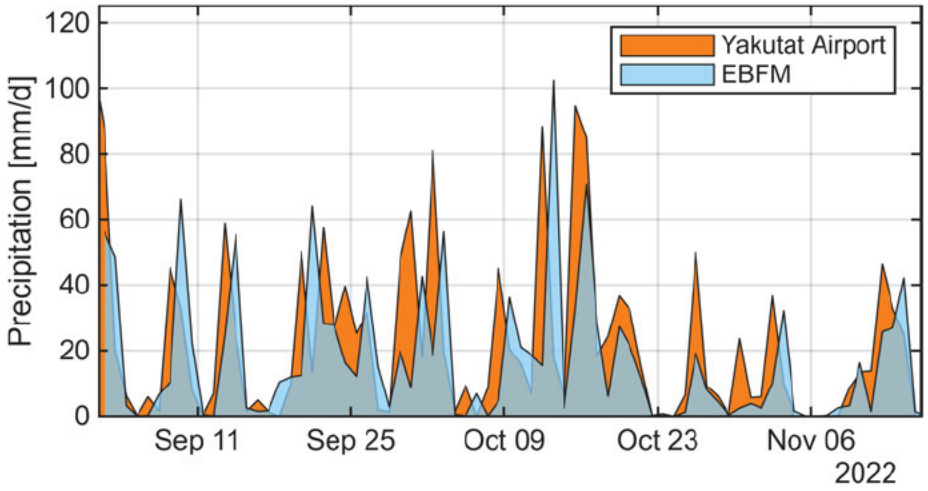


Figure 6. Time series of modeled rain (blue) and measured precipitation at the Yakutat Airport (orange) in millimeters per day [mm/d] for September 01 - November 15, 2022. The elevation-scaled ERA5 rain data area is slightly transparent so that the Yakutat data can be visualized behind it. This example reflects typical patterns in both datasets.

precipitation was downscaled based on the elevation difference between the DEM and ERA reference elevation:

$$P(z) = P_{\mathrm{ERA}}(1 + \gamma(\Delta z/100)) \quad (1)$$

where P(z) is corrected precipitation, P_{ERA} is the base precipitation data from ERA5, γ is the fractional increase in precipitation per 100m of elevation (0.1), and Δz is the elevation difference between the DEM and the ERA5 reference elevation. Additional weather parameters were explored using outputs from the EBFM for which the methods and discussion of this can be found in the Supplement.

Due to Sít' Kusá's remote location, we had limited access to observational rain data to validate our modeled rain, but we did compare our model outputs to daily precipitation records at the nearby Yakutat airport, 55 km south of the glacier terminus. Precipitation was reported daily at the airport weather station, with no clear distinction between liquid and solid precipitation. We did not expect that the precipitation records would match exactly given the distance to the glacier and topographic effects on weather, so we only performed a visual comparison to determine whether the model outputs were reasonable. We see similar magnitudes of precipitation events across both datasets and a consistent lag time was observed between the two, where the Yakutat dataset tended to lead the model outputs (Fig. 6). Based on the assumption that weather patterns would travel inland from the coast, a lag was to be expected between the two locations.

2.4 Analysis

Rain occurs throughout a large portion of the year at nearby Yakutat, but our analysis of impacts of rain events on glacier speed is limited to July 1 and November 15 due to data limitations. Early September typically reflects the timing of GPS deployment or servicing (Fig. 2), with July 1 representing the earliest deployment date across sites, while November 15 marks the onset of

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:29:25

For Yakutat using the same methods or for the field site? Important to know if differences illustrate shortcomings of ERA5/downscaling only or also include spatial mismatch. The apparent lag in many of the peaks is concerning if a similar lag would be present between real and estimated rainfall at the study site.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:27:19

Is this precip lapse rate locally tuned, taken from van Pelt et al, other?

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:37:11

It would still be easy to report some basic statistics to compare the two series shown (total precip, max rate).

Number: 4 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:30:58

I think it would make more sense to test the downscaling approach on Yakutat rather than compare the glacier downscaled precip to Yakutat.

Number: 5 Author: anonymous Subject: Inserted Text Date: 2026-11-08, 08:39:07

f

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increased GPS uncertainty, which we attribute to burial by snow. The mid-November cut-off also coincides with the cessation of EBFM's meltwater equivalent or MWE (further specifics of the EBFM's MWE can be found in the Supplement) output across the 5-year study period, indicating that either all precipitation fell as snow or that any rainfall was refrozen within the glacier around this date.

The GPS derived surface speed record produced by this study showed clear speed anomalies, as seen in Fig. 5 & 7. To identify speed anomalies, we used a short term-long term average filter on the detrended speeds because it can effectively identify anomalies in GPS signals (Ohta et al., 2012; Allen and Ziv, 2011). For a given detrended speed record, 1 moving window mean of 0.75 days was applied to create a short-term average (STA) time series and a moving window mean of 90 days was applied to create a long-term average (LTA) time series. The ratio of the two time series was then taken, STA / LTA, to create a ratio time series of speed. 2 he window sizes of 0.75 days for the STA and 90 days LTA were chosen because their ratio most effectively isolated speed anomalies. To identify speed anomalies using this ratio time series, Matlab's findpeaks function was applied to the ratio time series with a manually-tuned threshold ratio value > 1.9 and a requirement that peaks had to be at least 2 days apart. Manual inspection of the identified peaks revealed that some were less than 0.65 m/d which were too close to the background speed variation during quiescence. Due to this, we were not confident in their identification as peaks and implemented a minimum threshold to the speed time series of 0.65 m/d which removed 3 of the 43 identified peaks from the STA/LTA approach. Further manual inspection revealed 4 additional peaks (10%) that were 3 lse positives: 1 from Ice12-2008 and 3 from Ice14-2008 (Fig. 7a). There was 1 peak (3%) missed by the STA/LTA approach and was added to Ice11-2208 (Fig. 7b), resulting in 37 speed anomalies throughout the GPS record. Although the manual identification of speed anomalies contains some levels of subjectivity, manual verification was needed given the limited effectiveness of our speed anomaly assessment method in the speed time series (Fig. 7).

Speed anomalies were analyzed alongside weather time series to evaluate differences in glacier sensitivity to rain under presumed contrasting drainage conditions during the surge and quiescence. Large rain events were identified using a thresholding approach. Matlab's findpeaks function was used with a manually-tuned threshold >2 mm/h for the peak rate of rain and an event separation period of at least 1 day. Although the threshold of 2 mm/h was chosen somewhat subjectively, the average peak in rain rates for the identified events was 3.5 mm/h, which was approximately the 95th percentile of all rain events. A less strict threshold of 1.5 mm/h was explored that captured all large and moderate rain events; however, ~~softening~~ 4 s threshold generally only added rain events to the dataset that did not cause a speed-up. For example, if the moderate threshold was implemented, 17 more rain events would have been added to the data set while only 2 those correspond to a speed-up.

Starting at the peak in rain rates, the start and end of a given rain event was determined using a thresholding approach moving outwards from the peak: the start and end of each rain event were identified using a threshold of 0.67 mm/h. This threshold was chosen because rain rates between rain events were generally zero, but very low rain rates could persist for hours before or after a sharp change in rain rate. Altering this threshold (ranges from 0.16 to 0.67 mm/h were explored) did not affect the lag times between rain onset to either the point of acceleration or the peak in speed.

To assess variations in the 5 nematic response to rain events over time, de-trended speed profiles were extracted immediately prior to, during, and immediately following each rain event. To start, the speed time series was extracted from a period from

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:07:18

Are these phase preserving filters? I had assumed so, but Figure 7b makes me question this given the apparent phase lag between speed and STA/LTA timeseries.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:49:25

Out of what other values tested? Either dcelete "most" or clarify.

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:51:09

Why false positives? Do you just mean not big enough to have confidence?

Number: 4 Author: anonymous Subject: Inserted Text Date: 2026-11-08, 08:53:02

lowering?

Number: 5 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:53:47

Why kinematic instead of dynamic?

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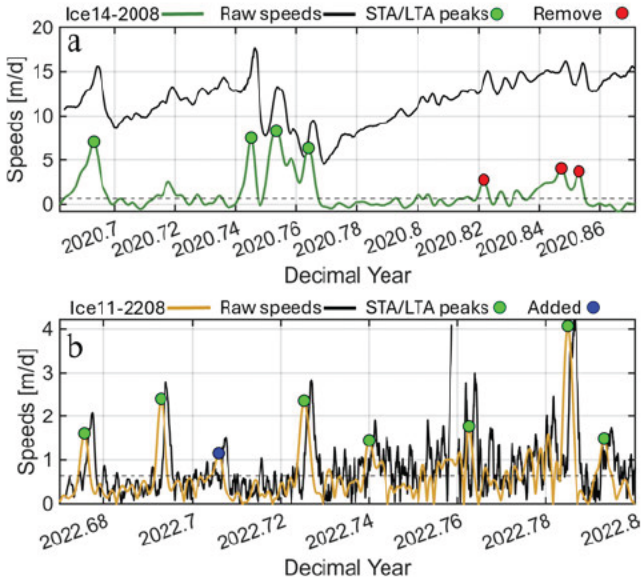


Figure 7. (a) Ice14-2008 speeds used in the analysis (green line), raw speeds (non-detrended and non-filtered speeds (black line)), speed anomalies identified by the STA/LTA approach that passed the manual inspection (green circles), and manually removed peaks (red circles). (2) The same as for (a) but for Ice11-2208, with a tan line showing the speed time series used in the analysis and manually added peaks shown as blue circles. The dashed horizontal line in both plots marks the minimum speed threshold of 0.65 [m/d] that served as additional filtering after peaks were automatically identified by the STA/LTA approach. The x-axis on both plots is the decimal year and both plots span early September to mid November.

4 hours prior to the start of a rain event to the next peak in rain rate. Speeds 4 hours prior to the start of the rain event were included to capture the background speeds prior to the onset of a possible speed-up event. If, however, the time between the start of a rain event to the next peak in rain rate exceeded 6 days, then the end of the profile was truncated to 6 days from the start of a rain event. A 6-day window was selected based on the average lag time between the STA/LTA speed-up events and the preceding rain events as described above and was found to be sufficient to capture the entire evolution of each speed anomaly (described below). After partitioning the speed record by rain events, we found that two rain events in quick succession would confound our interpretation of speed change in relation to the rain events. When two events compounded into one large speed anomaly that consistently increased between the peaks in rain, we classified it as a compound rain event and the start of the first rain event and end of the second rain event were assigned as the start and end of the compound event, respectively.

For each rain event, through comparison with the STA/LTA speed-up event record, we classified this period as a high or low sensitivity event. High sensitivity events were periods when one of the STA/LTA speed anomalies occurred within a 6-day window of a rain event. If no speed-up event was identified, this period was classified as a low sensitivity event. Lastly, the speed time series were averaged into 4-hour blocks for ease of plotting and visualization. Since all of our GPS records span the

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 08:46:09

Bigger please. Way too hard to see panel b at this scale.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:09:35

Why are peaks in raw data out of phase with STA/LTA peaks? I'm missing something here because this seems problematic for the analysis. These two timeseries also make me question the value of the STA/LTA timeseries. What is it contributing that the speeds are not? It appears to be discontinuous and noisy.

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:03:36

Here it would be very useful to have the uncertainty assessment from ROCK so there could be a meaningful separation of signal and noise.

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glacier's reservoir zone, we interpreted our high and low sensitivity events to be periods when the reservoir zone was in a state of high or low kinematic sensitivity to rain events.

The speed and rain time series for the high and low sensitivity periods were interrogated further to assess rain accumulation differences over the typical speed-up period between the rain events with and without associated speed-ups. For each rain event, we calculated the cumulative rain over a duration that spanned from the start of each rain event to the end of each rain event's corresponding speed profile. To align the 3-hour sampling rate of the rain time series with the 4-hour averaging blocks of the speed profiles, the rain time series were linearly interpolated to a 4-hour sampling interval.

The speed time series of the high and low sensitivity events, averaged into 4-hour blocks, were also used to calculate the additional glacier displacement that results from the speed-up events. To do this, the average speed for every speed time series category (surge high and low sensitivity and quiescent high and low sensitivity) were calculated for each 4-hour block. This created a characteristic speed profile for each of the four categories defined above from which the total displacement could be calculated. To determine how much additional displacement occurred as a result of the speed-up events from the surge and quiescent phase, the total displacement from the low sensitivity category was subtracted from the total displacement from the high sensitivity category. The values for additional displacement were used in conjunction with the total displacement from each GPS record to determine the percent displacement due to speed-up events.

3 Results

3.1 Speed Variability

The average speed, number of observed speed anomalies, duration of the analyzed record, the number of speed anomalies per week, and the average speed of the peak of a speed anomaly are listed for each GPS record in Table 1. Speeds during the surge are more than an order of magnitude greater than speeds during quiescence. Sít' Kusá's 2020-2021 surge terminated in the late summer of 2021 meaning stations Ice09-2110 and Ice11-2108 captured the beginning of the quiescent phase. Although these records are relatively short, these records had the lowest average speeds for all our GPS records. Ice11-2308 had the second shortest record, only lasting two weeks but had the highest average speeds during quiescence. The highest average number of speed anomalies per week was from Ice15-2308 with 1.1 anomalies per week while the lowest observed was for Ice15-2106 spanning surge termination with 0.2 anomalies per week.

Across the GPS record there are two GPS station pairs that had substantial temporal overlap between their two records: Ice12-2008 and Ice14-2008 during the surge, and Ice11-2208 and Ice15-2208 during quiescence (Fig. 8). Although the speed magnitudes and variations over time differ between the two observation periods, as described below, the down-glacier station is faster on average compared to the up-glacier station during both observation periods (Fig. 8).

The speed time series for Ice12-2008 and Ice14-2008 follow similar background trends. Both records show a period of gradual acceleration of ~6 m/d over a 2-week period from Sept. 13-28. This is followed by a dramatic step down in speeds at both stations, punctuated by 3 speed-up events, where background speeds drop by ~10 m/d over 9 days, from Sept. 29th to Oct. 7th. After this, a second period of gradual acceleration at approximately the same rate as before begins between both stations.

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Table 1. Duration of each record, the average speed, the total number of speed anomalies, the number of anomalies per week, and the average speed of a GPS record's anomaly (based on detrended speeds) for each GPS record. All values were rounded to one decimal place.

Station name	Surge phase	Length of record [days]	Mean speed [m/d]	Anomaly count	Anomalies per week	Average speed peak [m/d]
Ice09-2110	Quiescent	12.5	0.2	1	0.6	0.9
Ice11-2108	Quiescent	40	0.2	2	0.3	0.7
Ice11-2208	Quiescent	72.2	0.6	8	0.8	2
Ice11-2308	Quiescent	14	1.4	1	0.5	4.3
Ice11-2408	Quiescent	67.4	0.3	5	0.5	1.5
Ice12-2008	Surge	41.4	12.4	4	0.7	8.3
Ice14-2008	Surge	69.5	11.8	4	0.4	7.3
Ice15-2106	Surge	62	3.5	2	0.2	6.7
Ice15-2208	Quiescent	73.5	0.2	6	0.6	1.1
Ice15-2308	Quiescent	26.2	0.5	4	1.1	1.2

Unlike Ice12-2008 and Ice14-2008, Ice11-2208 and Ice15-2208 are much noisier, with the record lower on the glacier having more variable speeds, and Ice11-2208 and Ice15-2208 appear to have no similarities in their background trends.

Further differences arise when comparing the two station pairs' speed anomalies. The speed anomalies of Ice12-2008 and Ice14-2008 have similar magnitudes, with averages of 8.1 m/d and 7.2 m/d, respectively. In contrast, the speed anomalies of Ice15-2208 are generally half the magnitude of Ice11-2208's speed anomalies, with averages of 2.0 and 1.1 m/d, respectively. In addition to differences in speed anomaly magnitude the speed anomalies of Ice12-2008 and Ice14-2008 were generally longer in duration compared to the speed anomalies of Ice11-2208 and Ice15-2208. Speed anomalies lasted an average of 74 and 54 hours for Ice12-2008 and Ice14-2008, respectively, compared to ~43 hours for both Ice11-2208 and Ice15-2208.

3.2 Characterization of Speed-up Events

Based on manual inspection of the rain records relative to the STA/LTA-picked speed-up events, we infer that Sít' Kusá's short-term speed-up events are driven by rain events. Fig. 9 shows an example of speed-up events for Ice11-2208 (dashed gray lines) and its corresponding rain record. For Ice11-2208, as for all other GPS records, the STA/LTA-identified speed-up events are generally preceded by a rain event but there are no clear relationships between the characteristics of the speed-ups (i.e., max speed, duration of speed up event, lag time between max rate of rain and max speed, percent increase in speed, and lag time between max MWE and max speed) or the weather preceding or during the speed-up events. Correlation coefficients for the speed-up event characteristics relative to max rate of rain, duration of rain event, volume of rain, max temperature, max MWE, time between speed up events, and prior speed trend are shown in Fig. S3, in the Supplement, but are not discussed further due to the relatively weak relationships identified between the variables.

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:21:27

This seems like a good hypothesis, but wouldn't it also make sense to evaluate temperature (and perhaps wind) data to rule out melt as a driver of some of the anomalies?

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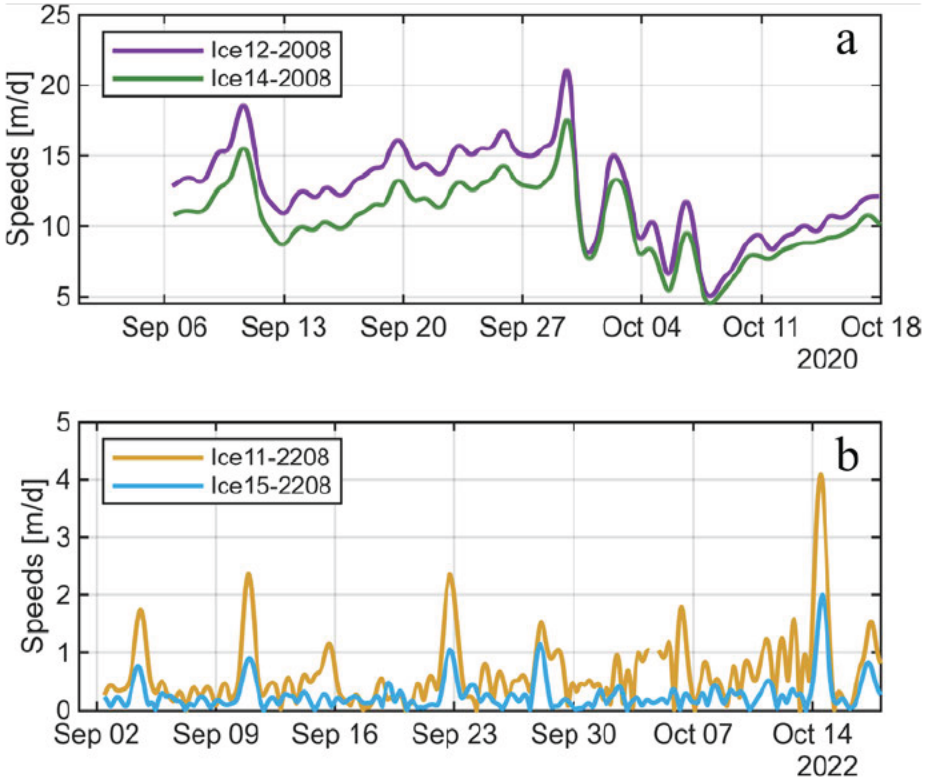


Figure 8. 1) Speed records of Ice12-2008 (purple) and Ice14-2008 (green). (b) Speed records of Ice11-2208 (tan) and Ice15-2208(light blue).

3.3 Evolving Kinematic Sensitivity to Rain

Across the entirety of the GPS record, 53 large rain events were identified. The average duration of these large rain events was 30.5 hours and the average peak rate of rain was 3.5 mm/h with a standard deviation of 1.6 mm/h. Based on our classification method, there was a speed anomaly following 49% (26 events) of the rain events. 2cross the GPS records from the surge, there were 16 rain events in total and 56% of them (9 events) were followed by speed anomalies. During the quiescent phase there were 37 rain events in total and 46% of them (17 events) were followed by speed anomalies.

During the surge (Fig. 10a), for the high sensitivity events, speeds begin to increase approximately 12 hours on average after the start of the rain event, peaking at ~6 m/d faster than the pre-event speeds. After this, the speeds of high sensitivity events begin to drop and appear to reach a stable state ~3 days after the start of a rain event (~1 day after the peak in speeds). For the low sensitivity events, speeds fluctuated around 1 m/d until around 2.5 days after the start of a rain event. Interestingly, in the case of both high and low sensitivity events, 3peeds dropped to a minimum, lower than speeds prior to the onset of rain, ~3 days after the start of the rain event.

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:19:35

Would help to briefly restate the processing applied to these. The top looks low-pass filtered but not detrended. The bottom looks filtered (but seems to have higher frequency content than the top) and detrended.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:30:22

I wonder if some rain events might be associate with negative speed anomalies (or whether negative anomalies would follow positive ones) if the detrending were done with central rather than minimm values.

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:31:16

This is what I have been wondering.

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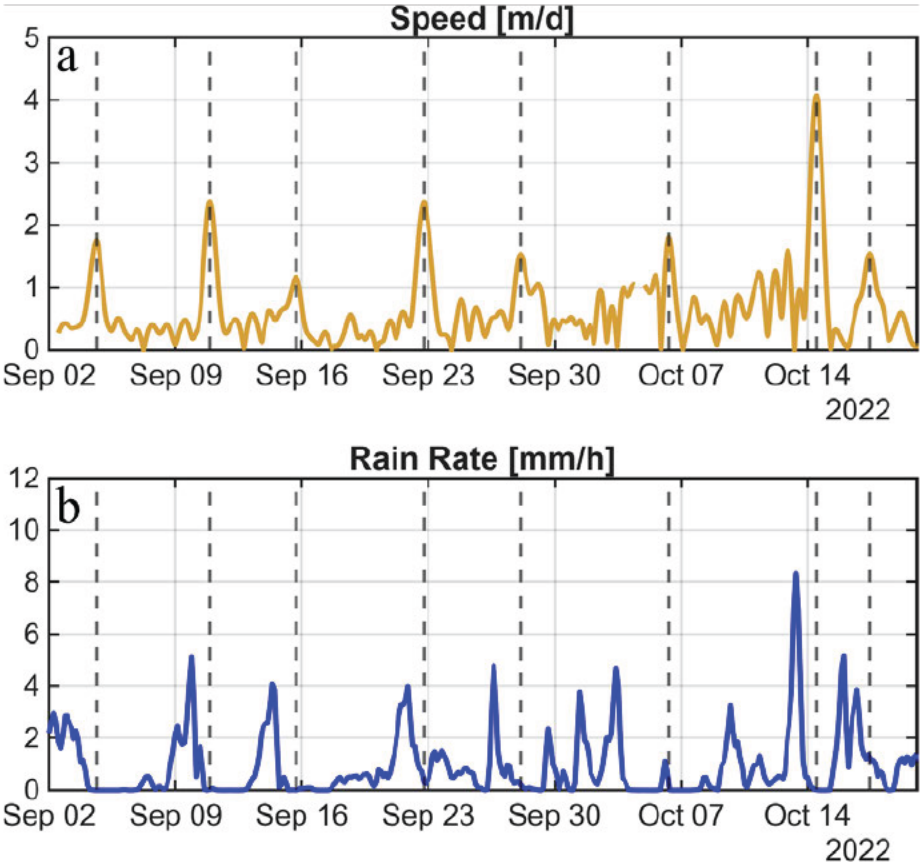


Figure 9. (a) Time series of speed of Ice11-2208 in tan and (b) rain rate in blue. Vertical dashed lines mark the timing of peak speeds during speed-up events.

During quiescence, similar patterns in speed are observed (Fig. 10b). Prior to a rain event, background speeds remain fairly stable and do not begin to increase until ~32 hours after the start of a rain event for the high sensitivity events. High sensitivity events then reach a peak speed anomaly of ~0.5 m/d relative to the pre-rain speed at ~48 hours after the start of a rain event (Fig. 10b). In contrast, low sensitivity events remain stable for the entirety of the 6-day window used in the analysis (Fig. 10b).

An interesting point of comparison between the surge and quiescent speed profiles is the general response time to large rain events. Although both high sensitivity surge and quiescent events generally reach a peak in speeds ~36-48 hours after the start of a rain event, surge speed profiles begin to increase far quicker than quiescent speed profiles (Fig. 10). In the case of high sensitivity surge events, speeds become elevated shortly after the rain event begins. This contrasts to high sensitivity quiescent events, where speeds only begin to increase ~24 hours after the start of a rain event.

The difference in the onset of speed-up events (i.e. the point when the speeds of a high sensitivity speed profile begin to increase relative to the background) during the surge relative to quiescence is not easily explained by similarities or differences in a threshold of rainwater accumulation across the surge cycle. During the surge, there is not an appreciable difference in the

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:23:16

A cross-correlation analysis on standardized timeseries should work well here. It could even be done for segments of the timeseries individually to evaluate whether the lag between precip events and speed up changes.

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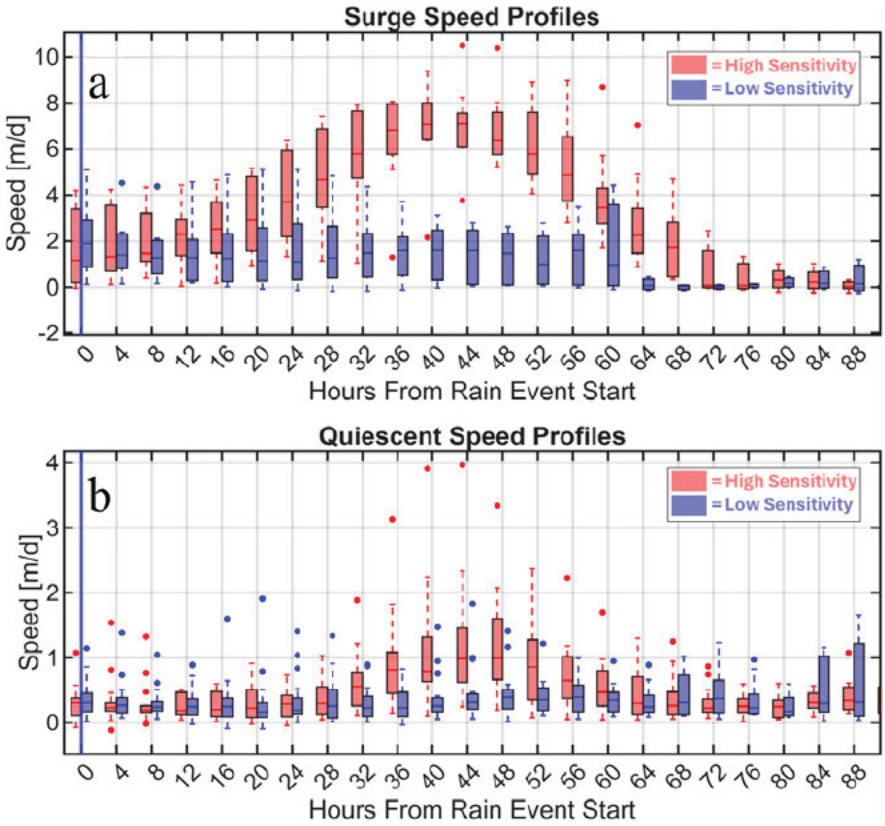


Figure 10. (a) Surge speed profiles and (b) quiescent speed profiles, averaged into 4-hour windows relative to the onset of rain events. Red box plots represent high sensitivity events; blue box plots represent low sensitivity events. Vertical blue lines indicate the start of rain events. The x-axis is in hours relative to the start of a rain event. While all speed profiles spanned to 6 days from rain start, plots (a) and (b) were truncated for ease of visualization.

amount of accumulated rain at the onset of the speed-up event for high and low sensitivity events. During the surge, for high sensitivity events, typical speed-up onset occurs at 20 mm of accumulation compared to 22 mm for low sensitivity events (Fig. 11a). During quiescence however, there is a slight difference between the rain accumulation values for high and low sensitivity events at the typical onset of the speed-up event. During quiescence, for high sensitivity events, typical speed-up onset occurs at 60 mm of accumulation compared to 45 mm for low sensitivity events (Fig. 11b). The difference between rain accumulation at the onset of speed-up events for surge and quiescence is consistent with the presence of a less efficient subglacial drainage system during the surge, which would need a smaller pulse of water to become overwhelmed.

In average, each speed-up event contributed 8.6 m of additional horizontal displacement during the surge compared to 0.7 m during quiescence. Although each speed-up event from surge accounts for far more displacement when compared to quiescence, speed-up events from quiescence contribute more to total station displacement (Table 2). On average during quiescence, speed-up events accounted for 57% of glacier displacement compared to only 6% glacier displacement during the surge. The

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:36:05
This is interesting.

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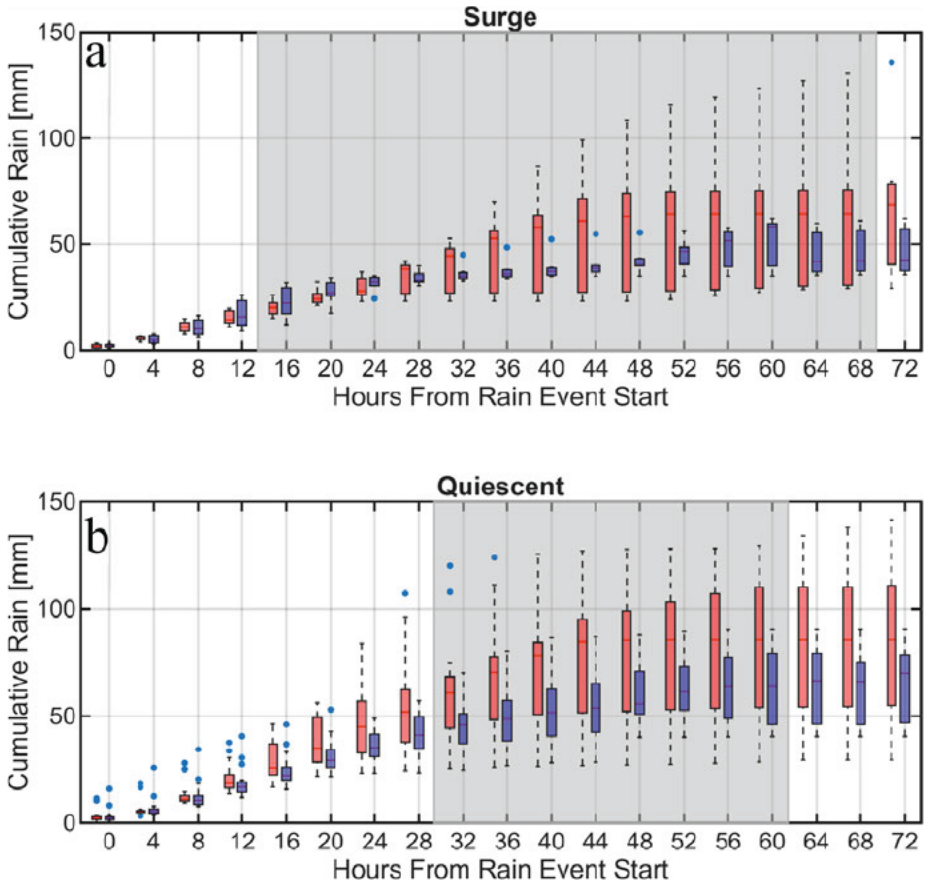


Figure 11. Cumulative rain profiles for (a) the surge and (b) quiescence. As with Fig. 11, times are relative to the onset of rain events. Red box plots represent high sensitivity events; blue box plots represent low sensitivity events. The transparent grey rectangle on both plots represents the approximate time period when high sensitivity events have elevated speeds. While all extracted accumulation profiles spanned to 6 days from rain start, plots (a) and (b) were truncated for ease of visualization

difference in the relative contributions of speed-up events to total displacement are due differences in the percent change in speed, not the duration of the speed-ups: speed-up events during quiescence account for 15% of the total recording period compared to 17% during the surge's recording period.

4 Discussion

Our observations of speed variability in relation to rain events during the surge and subsequent quiescent period of Sít' Kusá broaden our understanding of how a temperate surging glacier's drainage system evolves across surge cycles. A key finding of our study was that across both the surge and quiescent phase, speed-up events coincide with rain events. This suggests that short lived pulses of water to the glacial system drive short term glacier accelerations (Horgan et al., 2015; Bartholomaus et al.,

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:40:38

This implies to me across multiple surges. Do you mean evolves from surging to quiescence?

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Table 2. The length of record in days, the total distance traveled in meters, the cumulative distance traveled from speed-ups in meters, the percentage of total displacement as a result of speed-up events, and the percentage of time accounted for by the speed-up events for each GPS record. All values were rounded to one decimal place.

Station name	Surge phase	Length of record [days]	Total distance traveled [m]	Speed-up cumulative distance [m]	% of displacement from speed-ups	Cumulative percentage of time from speed-ups
Ice09-2110	Quiescent	12.5	0.9	0.7	0.8	0.1
Ice11-2108	Quiescent	40	2.2	1.4	0.6	0.1
Ice11-2208	Quiescent	72.2	19.7	5.5	0.3	0.1
Ice11-2308	Quiescent	14	0.9	0.7	0.7	0.1
Ice11-2408	Quiescent	67.4	5.3	3.4	0.6	0.1
Ice12-2008	Surge	41.4	503.5	34.5	0.1	0.3
Ice14-2008	Surge	69.4	794.3	34.5	0.1	0.2
Ice15-2106	Surge	62.1	207	17.2	0.1	0.1
Ice15-2208	Quiescent	73.5	8.5	4.1	0.5	0.1
Ice15-2308	Quiescent	26.2	5.4	2.7	0.5	0.4

2008; Vieli et al., 2004; Mejia, 2016) throughout the surge cycle. We interpret rain events followed by a peak in speed (high sensitivity events) as indicative of a lower efficiency subglacial drainage system and those without a speed-up (low sensitivity events) as indicative of a predominantly efficient subglacial drainage system. Based on this, we suggest that during the surge, the glacier's drainage system is, on average, less efficient when compared to quiescence; rain-induced speed-ups are more frequent and more immediate, longer-lasting, and greater in magnitude during the surge. Nevertheless, signs of both efficient and inefficient subglacial drainage systems were observed across both phases.

There are a number of sources of uncertainty in both our speed time series and our rain estimates, as described below, but we are confident in our broad-scale interpretations. Sít' Kusá is an extremely difficult site to instrument due to its deep snowpack, steep mountain slopes, and extensive crevassing, resulting in limited temporal GPS coverage. Our records are limited to mostly late-summer and fall and the spatial coverage is limited to the glacier reservoir zone, so the scope of our investigation of subglacial drainage is restricted. However, despite their short coverage, they provide novel opportunities to assess the difference in surging and non-surging flow speeds at spatially-distributed locations on a surging glacier.

Snow burial prevented us from maintaining a Rock base station over the entire recording period, inhibiting our ability to perform precise kinematic post-processing. Despite this, we are confident in our analysis of speed variability at Sít' Kusá because were able to remove obvious atmospheric signals through time-domain filtering as demonstrated with our limited base station record (Fig. 3a) and we focused on speed anomalies with a lower frequency than the primary atmospheric signals (den Ouden et al., 2010).

The comparison with the Yakutat Airport weather station (Fig. 6) indicates that the difference in observed and modeled daily rain varies in sign and magnitude between rain events, potentially obscuring real relationships between speed-up and

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:41:36

Even during the surge? This statement seems too sweeping.

Number: 2 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:43:53

The general relationship between the drainage system and speed is known, so it would be more interesting at the beginning of the discussion to focus on what new has been learned. Why is it that the glacier would NOT be sensitive to rain events while surging? That subtlety has more value (I think) than the general statements in this paragraph.

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:45:20

Not sure that Fig 6 establishes this since the downscaling for the glacier is compared with obs from Yakutat.

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rain event characteristics. Systematic biases in the timing of modeled rain relative to observed events, along with the relatively coarse temporal resolution (4 hrs) used to bin speeds, may contribute to the lag between rain onset and the resulting speed-ups. However, biases in model timing or speed binning should result in a uniform time lag that cannot explain the differences in the timing of speed-ups during the surge and quiescence.

Advection was one potential source of uncertainty in our speed time series that we were able to confidently eliminate through comparisons with remotely sensed velocities, an assessment further described in the Supplement (section 1.1). Advection of GPS through regions with different geometries and boundary conditions could have caused changes in speed during the time series that were independent of variations in environmental forcing. Results from this analysis aligned with other interpretations of the GPS data suggesting that advection into different flow regimes played no substantial role on the GPS speed time series. Results from this section and interpretations of these results are further discussed in the Supplement (Section 2.2).

Despite sources of uncertainty we remain confident in our analysis and interpretations. During quiescence, although speeds are slow, approximately half of the large rain events are accompanied by a speed-up, approximately 24 hours after the onset of rain (Fig. 10b). This suggests that the reservoir zone is underlain by an efficient subglacial hydrologic system that can become episodically overwhelmed by rain. Since the reservoir zone falls within the ablation zone of the glacier and our observations are from the end of the melt season, temporary water retention in a snow or firn layer cannot explain the lagged speed-up events. The glacier is highly crevassed, and no surface water impoundment is evident, suggesting that surface water can rapidly enter the englacial system (Terleth et al., 2024; Liu et al., 2024). Instead, we attribute this lag to a retention of water within the englacial system or within the underlying till. As rain events persist, water in the subglacial system gradually accumulates, lowering friction at the bed and eventually triggering a speed-up. Englacial and subglacial storage have been previously called upon to explain winter acceleration of Sít' Kusá and other Alaskan glaciers (Lingle and Fatland, 2003; Zhan, 2019; Liu et al., 2024). Differences in the relative abundance of distributed cavities and channels throughout the reservoir zone during the surge and quiescence would potentially be associated with a higher threshold of water accumulation needed to trigger a speed-up during quiescence as supported by the higher median rain accumulation before the onset of rain-induced speed-ups during quiescence. Such storage could also explain why some rain events do not cause speed-ups and why there are speed-ups not associated with rain events: englacially- or subglacially-stored water does not necessarily require a rain event in order to be released.

Sít' Kusá's kinematic sensitivity to large rain events during the surge is greater than during quiescence, but the subglacial drainage system is not fundamentally different during the surge than during quiescence. We interpret the gradual ~2 week-long speed-up in the paired surge records (Fig. 8a) as an indicator that water at the bed is gradually accumulating, reducing effective pressure and promoting faster sliding (Sugiyama and Gudmundsson, 2004). This gradual speed-up ended with three large rain events within ~10 days (Fig. 8a), each resulting in a short term speedup followed by an "extra slowdown". Such events have also been observed at the non-surging Yahtse and Columbia glaciers in coastal Alaska and at Hansbreen Glacier in Svalbard (Mejia, 2016; Vieli et al., 2004; Meier et al., 1994). Each of the three speed-ups were similar to other rain-induced speed-ups during the surge (Fig. 10a), which were more immediate, longer-lasting, and greater in magnitude than those observed during quiescence. However, the subsequent slow-downs following the events suggest that the subglacial drainage system can

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reorganize into a more efficient state even during the surge. Similar slow-downs have been observed at non-surging mountain glaciers in response to pulses of water inputs and have been attributed to improved drainage efficiency,which increases the effective pressure at the bed and decreases sliding speeds (Horgan et al., 2015; Mejia, 2016). Furthermore, the termination of Variegated Glacier's 1995 surge coincided with a large rain event and the discharge of turbid water at the glacier terminus, supporting our inference that rain can drive dramatic reorganization of subglacial drainage systems during a surge (Eisen et al., 2005).

1 raditionally, surges of temperate glaciers have been viewed as oddities, characterized by long periods of slow flow, typically associated with efficient subglacial drainage, punctuated by shorter episodes of rapid motion attributed to enhanced basal sliding driven by water accumulation at the bed (Kamb et al., 1985; Terleth et al., 2024; Harrison and Post, 2003; Thøgersen et al., 2024). Our observations of rain-induced speed-ups suggest that components of an inefficient and efficient drainage system can persist throughout the surge and quiescence phase. There is reduced kinematic sensitivity relative to the surge which could indicate that the subglacial drainage system is more efficient during quiescence, however there is also evidence for water drainage during the surge and also unexpected signs of water impoundment during quiescence. These conclusions are in line with previous research on Sít' Kusá (Liu et al., 2024; Terleth et al., 2024) and support the notion that surges are a part of a spectrum of kinematic instabilities driven by a progressively changing subglacial drainage system rather than a binary switching of drainage states (Terleth et al., 2023; Herreid and Truffer, 2016). Although our observations of varying levels of subglacial drainage efficiency during the surge are short lived, longer disruptions of the drainage system as a result of seasonal increases in water inputs to the bed can have broad implications for surge evolution (Liu et al., 2024). Additionally, as rain on glaciers becomes more common (on Climate Change, 2019; Llactayo et al., 2024), it is possible that rain will drive changes in the frequency of surges (Terleth et al., 2023) and the duration of surges as well.

Although the duration of rain events and their resulting speed-ups may be short lived, their effects can compound over time. On average, during quiescence, rain events accounted for 51% of glacier displacement and 2 ~~non-trivial~~ 6% of glacier displacement during the surge. Although it is possible that the kinematic sensitivity to rain is different for non-surging glaciers, GPS observations from Tasman Glacier, New Zealand, indicate that large non-surging mountain glaciers are also sensitive to rain events (Horgan et al., 2015). At Tasman Glacier, rain events can drive 10% or more of annual glacier displacement (Horgan et al., 2015). This combined with the fact that 3 in on ice flow is expected to increase in frequency as a result of climate change could have implications for future glacier mass loss (Llactayo et al., 2024; on Climate Change, 2019). To fully account for how glacier flow will change as the climate warms, it is important to understand ~~how~~ 4 xes of water flow into and out of the glacier system and how these fluxes influence glacier flow. Failing to do so over the full range of time scales that glacier speeds can vary limits our prediction of flow instability and glacier mass loss.

5 Conclusions

Detailed glacier surface speeds and rain estimates from Sít' Kusá, Alaska, reveal that across both the surge and quiescent phase, rain events drive short-term speed-ups. During the surge, 56% of rain events triggered a speed-up compared to 46%

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Number: 1 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:54:17

Really? Temperate surging glaciers are not uncommon, so this statement surprises me. I don't think even Kamb meant to imply that surge-type glaciers have persistently efficient drainage during quiescence. That would eliminate seasonal speedups that are experienced by surge-type and non-surge-type glaciers alike.

Suggest more nuanced language about what this study shows without oversimplifying the existing understanding of surge-type temperate glaciers.

Number: 2 Author: anonymous Subject: Cross-Out Date: 2026-11-08, 09:55:39

Number: 3 Author: anonymous Subject: Comment on Text Date: 2026-11-08, 09:56:29

rain on snow? rain on glaciers?

Number: 4 Author: anonymous Subject: Inserted Text Date: 2026-11-08, 09:56:53

the

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during quiescence. In addition, during the surge rain-induced speed-ups were more immediate (12 hrs between rain onset and glacier acceleration compared to 32 hrs), longer-lasting (66.5 hrs in duration compared to 33 hrs), and greater in magnitude (7.5 m/d peak in speed compared to 1.5 m/d) compared to quiescence. Altogether, the higher kinematic sensitivity of the glacier to rain events during the surge supports the notion that surging glaciers are underlain by less efficient subglacial drainage systems during a surge than during their quiescent phases. However, nearly half of the rain events did not result in speed-ups during either the surge or quiescence, indicating that there is not a binary switch from an inefficient system during a surge to an efficient system during quiescence. These observations of kinematic insensitivity to rain, combined with observations of speed-ups not caused by obvious rain events, also suggests that there are other factors that influence the velocity response, for example, water may be retained englacially or within till for some period of time after it falls as rain on the glacier surface. Although these observations are limited to primarily one season (~August-November), this study marks the first systematic investigation of short-term changes in kinematics at a surge-type glacier during a surge and the following quiescent period. This work supports our evolving understanding of surges as part of a spectrum of kinematic instabilities driven by a progressively changing subglacial drainage system.

Code availability. The code used in this study is publicly available on GitHub at Parker149/gps-derived-surface-speed-surging-glacier-analysis and has been archived on Zenodo at https://doi.org/10.5281/zenodo.22235895

Data availability. The datasets used in this study are available from Zenodo at https://doi.org/10.5281/zenodo.21761717

Author contributions. PW and EE designed the study with contributions from all co-authors. PW developed a majority of the code and carried out analysis under the supervision of EE. EE developed code to preform detrending of speed data. PW extracted data for rainfall estimates under the supervision of YT. JL provided remotely sensed speed data used in this study's advection analysis. PW prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. TEXT

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