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Simulating Seasonal Evolution of Subglacial Hydrology at a Surging Glacier in the Karakoram

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Simulating Seasonal Evolution of Subglacial Hydrology at a Surging Glacier in the Karakoram

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ABSTRACT.

Glacier motion, retreat, and glacier hazards such as surges and glacial lake outburst floods (GLOFs) are likely underpinned by subglacial hydrology. Recent advances in subglacial hydrological modeling allow us to shed light on subglacial processes that lead to changes in ice mass balance and GLOFs in High Mountain Asia (HMA). We present the first application of the SHAKTI subglacial hydrology model on an alpine glacier. Shishper Glacier, our study site, is a surge-type glacier in northern Pakistan that exhibits concurrent GLOFs which endanger local communities and infrastructure. The subglacial hydrological system undergoes transitions between inefficient to efficient drainage and back during spring and fall, supporting previous observations of spring and fall speedups of glaciers in the region. We also conclude that subglacial hydrology, while important in sliding dynamics, cannot provide a standalone explanation for surging, implicating a need for coupled hydrological and ice dynamics modeling of surge conditions. This work demonstrates the potential

of using ice sheet models for alpine glaciology and provides a new nucleus for modeling of glacial hazards in alpine environments.

INTRODUCTION

The High Mountain Asia (HMA) region, known as the "Third Pole," contains the largest concentration of ice outside of the polar ice sheets. The glaciers of HMA feed major water systems which provide water and sanitation for over a billion people (Scott and others, 2019). In particular, the Karakoram is the most heavily glaciated mountain range in Asia (RGI Consortium, 2017) and is a critical water source for large parts of Pakistan and parts of northern India (Scott and others, 2019). However, climate change has led to increasingly negative mass balance, putting the area's future at risk (Zhang and others, 2023a; Shean and others, 2020; Rounce and others, 2020; Bolch and others, 2011). Glacial lake outburst floods (GLOFs) in the region have also caused significant loss of human lives and infrastructure damage in recent decades (Shrestha and others, 2023), and the risk of exposure to local communities and infrastructure due to growing proglacial lakes may potentially increase (Zhang and others, 2023b, 2024; Zheng and others, 2021; Harrison and others, 2018). GLOFs in the Karakoram region occur through breaches of moraine or ice dams, which are associated with rapid (re)-organization of subglacial waters and channels (Nye, 1976; Gudmundsson and others, 1995; Bigelow and others, 2020; Kingslake and Ng, 2013; Flowers and others, 2004). Proglacial and proximal lakes, which are often hydraulically connected with the subglacial drainage network, also exert an important boundary condition on the subglacial water network (Bigelow and others, 2020; Anderson and others, 2005; Armstrong and Anderson, 2020)).

The Karakoram region is also home to a high concentration of surge-type glaciers (Sevestre and Benn, 2015; Copland and others, 2009, 2011). Surges are a phenomenon characterized by cyclical, order-of-magnitude accelerations of glaciers that can be sustained for months to years (Eisen and others, 2001; Jay-Allemand and others, 2011; Round and others, 2017; Bhambri and others, 2020; Björnsson, 1998). They occur in geographical clusters that fall in "climatic envelopes" that may provide favorable temperatures and accumulation rates for surge motion (Sevestre and Benn, 2015; Jiskoot and others, 2000). Surges are also associated with till deformation (Minchew and Meyer, 2020; Minchew and others, 2016). Buildups of basal water pressure are thought to play a role in the initiation and sustenance of surge motion (e.g., Kamb (1987); Flowers and others (2011); Björnsson (1998); Jay-Allemand and others (2011)). However, the causes of surge behavior remain unclear as not all surging glaciers seem to directly attributable to changes in mass-balance state or thermal regime (e.g., Liu and others (2024); Murray and others (2000)).

Subglacial hydrology controls ice velocity through changes in effective pressure, defined as the difference between the overburden pressure and the hydraulic head at the bed (Nienow and others, 2005). Seasonal variations in subglacial hydrology modulate ice sheet and glacier velocities in Iceland and Greenland (Hart and others, 2022; Sommers and others, 2024; Schoof, 2010; Zwally and others, 2002; Iken and others, 1983). Numerous studies have shown that the velocity of glaciers increases during melt seasons (e.g., Nanni and others (2023); Zwally and others (2002); Hart and others (2022); Bhambri and others (2020)). In alpine glaciers of HMA, observed regional speedups have been proposed to occur due to changes in subglacial drainage efficiency. In particular, these glaciers can also exhibit a pattern of speedups in both the spring and fall (Beaud and others, 2022; Nanni and others, 2023). It is inferred that these seasonal speedups occur due to variations in meltwater production and subsequent lubrication at the ice-bed interface.

While surges and outburst flooding have for the most part been investigated as separate phenomena, multiple studies in the Karakoram have observed GLOFs to occur concurrently with transitions in surge motion, suggesting that subglacial hydrology may play a non-straightforward role in the synchronous timing of these events (Beaud and others, 2021; Bhambri and others, 2020; Bazai and others, 2022a; Round and others, 2017; Bazai and others, 2022b; Steiner and others, 2018). Understanding the role that subglacial hydrology plays in the severity and timing of these hazards could improve early warning systems for water availability and outburst flooding. While several in-situ observational studies have been conducted and are in progress (e.g., Gilbert and others (2020); Miles and others (2021, 2019); Pritchard and others (2020)) there are very few direct observations of subglacial hydrology in HMA. Therefore, in this study, we lay the groundwork for investigating the role of subglacial hydrology in ice dynamics and outburst flooding through modeling.

We focus on Shishper Glacier (36.40°N 74.61°E) in the eastern Karakoram range in Pakistan (Fig. 1). The glacier has also been referred to in literature as Shisper and Shishpare. Located in the Hunza Valley in Gilgit-Baltistan, Pakistan, Shishper is part of a surge and lake drainage system with another glacier to its west, called Muchuwar (also previously spelled as Muchuhar or Mochowar). The two glaciers were connected prior to 1950, when the two separated (Muhammad and others, 2021). Shishper's main trunk is approximately 7 km long and is fed by several tributary glaciers at the northeast (upper-elevation) side. In total, the glacier is about 15 km in length.

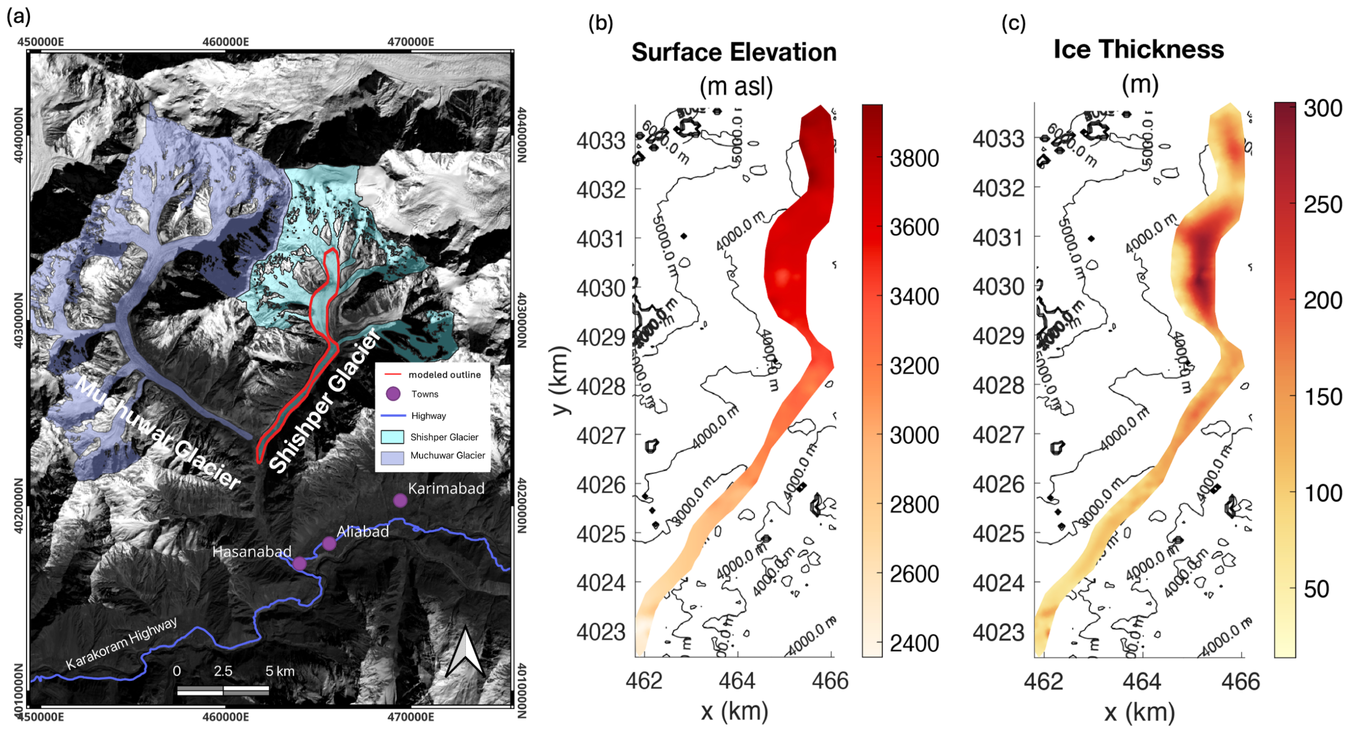

Fig. 1. (a) Outlines of adjacent valley glaciers Shishper and Muchuwar (Randolph Glacier Inventory Version 6.0) overlaid on Landsat 8 OLI NIR imagery from December 2016. Our modeled domain is outlined in red. (b) Surface elevation from TanDEM-X 90m DEM. (c) Ice thickness from Millan and others (2022)'s global dataset.

Both Shishper and Muchuwar have surged cyclically for as long as observations have been recorded, since the early 1900s (Beaud and others, 2021). Shishper underwent major surges in 1973, 2000-2011 and most recently between 2017-2019 (Bhambri and others, 2020). During this time, the terminus advanced approximately 1.5 km (Bhambri and others, 2020). In 2019, the surge and resulting lake drainage resulted in the closing of two power plants, the evacuation and considerable damage of some houses in the downstream village, lasting damage to agricultural land, and finally the destruction of the main road bridge crossing the stream, affecting transport along the main transport axis in the region. In mid-November 2018, the advancement of Shishper blocked meltwater flow from Muchuwar Glacier, which created an ice-dammed proximal lake (Beaud and others, 2022). This lake tends to fill up in November-December and in May to a depth of 30-80m, with an estimated volume of 30 million m^3. When the lake drains, the outburst flood drains through the terminus of Shishper and down into the valley below. The maximum river flow observed at the downstream village of Hassanabad is 150-200 m^3 s^{-1}, compared to a base flow of about 20 m^3 s^{-1} (Muhammad and others, 2021). After the lake is filled in the winter, drainage occurs more gradually, as opposed to the spring filling which results in a more dramatic drainage of the lake.

In this study, we simulate the seasonal dynamics of the subglacial drainage system of Shishper Glacier.

We use a state-of-the-art subglacial hydrology model, forced with realistic meltwater inputs, to gain insight into the evolution of the water flow and pressure distribution beneath the glacier. The following sections describe the modeling methods and assumptions, meltwater forcing data, simulation results, a discussion of implications for understanding surge initiation and cessation, and limitations of the approach.

MODEL SETUP AND ASSUMPTIONS

To simulate the subglacial hydrological system of Shishper Glacier, we employ the SHAKTI (Subglacial Hydrology and Kinetic, Transient Interactions) model (Sommers and others, 2018), which is implemented in the Ice-sheet and Sea-level System Model (ISSM) (Larour and others, 2012). SHAKTI is capable of modeling a variety of network systems between the end-member cases of efficient and inefficient drainage systems. It does this by allowing the hydraulic transmissivity to vary spatially and temporally (Sommers and others, 2018). In addition, it accounts for varying laminar, turbulent, and intermediate flow regimes (Sommers and others, 2018).

The model domain is traced from the Randolph Glacier Inventory, Version 6.0 (RGI Consortium, 2017). The tributary branches of Shishper Glacier, located above 3500 m asl, likely experience less liquid precipitation and decreased melting compared to the lower section of the main trunk and therefore may not contribute as much to the subglacial hydrological system. Our aim is to examine the evolution in the hydrology in the main trunk, rather than evaluating the exact quantity of subglacial water in the system; for these reasons, we reserve including hydrological contributions from the tributary glaciers for future work. The modeled hydrological domain overlaid on the RGI 6.0 outline is shown in Fig. 1. The outline is from 2016, before the 2017-2019 surge event. We focus on modeling the subglacial hydrology and do not change the glacier outline or ice thickness.

To obtain a geometry for the glacier, we use the TanDEM-X global DEM (German Aerospace Center, 2018) along with a global glacier thickness dataset (Millan and others, 2022). Glacier thickness is subtracted from surface elevation to obtain a bed topography, and all spatial data are projected to WGS 84/UTM Zone 42N. We manually trace the model domain to the RGI outline using in-built functionality in ISSM. The DEM and bed topography data are interpolated onto a 2-dimensional unstructured triangular mesh with 40 m resolution. This mesh size and geometry were determined after conducting a winter equilibration for 600 days at varying mesh sizes (shown in Appendix A). We conclude from these tests that the location of channel formations is insensitive to mesh size. The 40 m resolution provides enough detail and stability while saving on computational costs. The mesh provides the basis for the P1 triangular Lagrange finite element solver used by SHAKTI. To ensure model stability and robustness, we test 20 slightly varying domain shapes and conduct a winter equilibration, wherein all subglacial water is generated by basal melt (see section "Establishing Winter Base State") for 1000 days on each. The final geometry used for the transient simulations is chosen based on the criteria that mean gap height, basal flux, and effective pressure equilibrate after 1000 days. Finally, the velocity boundary condition is set to 0 throughout all of the transient simulations, allowing us to isolate the evolution of subglacial hydrology without frictional heating feedbacks from basal sliding.

All simulations in this work are carried out with ISSM Version 4.23 using a MATLAB interface on MacOS.

Surface Melt Timeseries

To estimate timing and magnitude of seasonal meltwater inputs to the bed, we used the European Centre for Medium-Range Weather Forecasts (ECMWF)'s Reanalysis v5 (ERA5) (Muñoz-Sabater and others, 2021) as inputs to Litt and others (2019)'s temperature-indexed ice melt model to obtain spatio-temporally varying estimates for surface melt across the domain (Fig. 2). These ERA5 weather data are based on an array of field stations and weather models (Setchell, 2020), and directly provide estimates for snow cover, air temperature, and total liquid precipitation across the five years (Muñoz-Sabater and others, 2021). Ice melt across the mesh is calculated using the temperature index (TI) melt parametrization from Litt and others (2019) (Fig. 2). We calculate daily melt over ice when the glacier surface is bare (using a temperature index of 6.5 mm $^{\circ}C^{-1}$ day^{-1}, computed from values from Litt and others (2019) and melt from snow for pixels that are snow covered (using an index of 4.1 mm $^{\circ}C^{-1}$ day^{-1}, following Braithwaite (2008)). While melt or surface runoff from rainfall from outside the model domain may also reach the model domain and eventually the glacier bed, we do not consider these inputs here. The TI model is shown to be more accurate for glaciers below 3500 m above sea level (a.s.l) (Litt and others, 2019), which is where most of Shishper's tongue is located (Fig. 1). The melt and liquid precipitation data was downscaled from its native 9 km to the model resolution (50 m) using a Kriging interpolation (Kusch and Davy, 2022). While some in-situ climate data is available in the region, no station was operational in the vicinity of the glacier; using in-situ data from an off-glacier station far away from the glacier would introduce its own set of uncertainties. Due to the relatively high temporal (1 day) and spatial (1 deg^2) resolutions, relying on

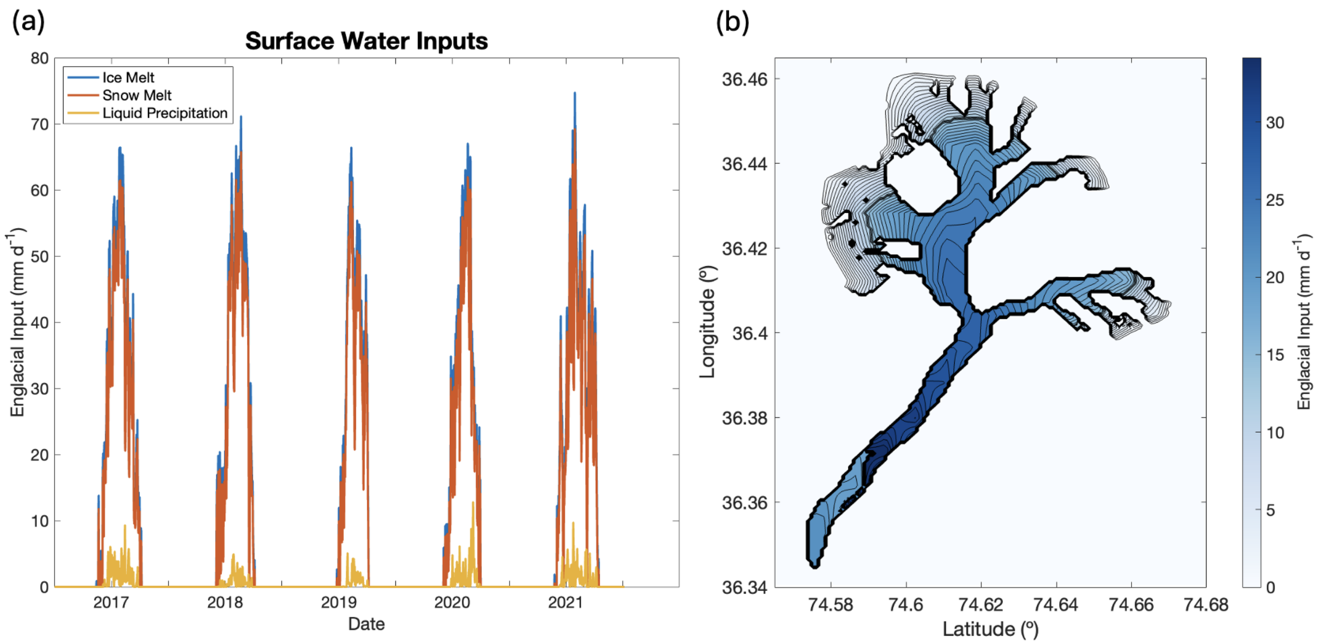

Fig. 2. (a) Englacial inputs to the transient subglacial hydrology model, averaged over the glacier, as calculated by ERA-5 Land and the temperature-indexed ablation model. (b) Average englacial input during the 2017 melt season (May through September).

ERA5 data is considered sufficient here.

The strong hydraulic coupling between surface and basal meltwater environments (Miles and others, 2017; Zwally and others, 2002; Iken and Bindschadler, 1986; Shepherd and others, 2009; Gulley and Benn, 2007) has given us justification to make the assumption that all meltwater inputs to the bed (i.e., surface melt, rainwater, aquifer contributions) are instantaneous. In reality, englacial water storage can delay the delivery of surface water to the base (Miles and others, 2017; Gulley and Benn, 2007); however, we neglect it in these simulations due to a lack of constrained knowledge about delay timing and storage magnitude.

TRANSIENT GLACIER HYDROLOGY SIMULATIONS

Establishing Winter Base State

Before transient simulations can be run, the base winter state of the hydrological system must be established. To do this, we prescribe some initial input parameters (Table 1) and allow the system to equilibrate. During the winter, we assume that there is no surface or englacial melt, with geothermal flux and melt opening/turbulent dissipation as the only hydrological inputs to the bed. Note that we have prescribed sliding velocity to be zero, so there is no frictional heating or cavity opening from sliding over bumps.

Table 1. Constants and parameter values used in this study

Symbol	Value	Units	Description
A	9.3×10^{-25}	$\mathrm{Pa^{-3}\ s^{-1}}$	Flow law parameter
G	0.07	$\mathrm{W\ m^{-2}}$	Geothermal flux
g	9.81	$\mathrm{m\ s^{-2}}$	Gravitational acceleration
H	Varying	m	Ice thickness
L	3.34×10^{5}	$\mathrm{J\ kg^{-1}}$	Latent heat of fusion of water
n	3	Dimensionless	Flow law exponent
z_b	Varying	m	Bed elevation with respect to sea level
ν	1.787×10^{-6}	$\mathrm{m^2\ s^{-1}}$	Kinematic viscosity of water
ω	0.001	Dimensionless	Parameter controlling nonlinear laminar/turbulent transition
ρ_i	917	$\mathrm{kg\ m^{-3}}$	Bulk density of ice
ρ_w	1000	$\mathrm{kg\ m^{-3}}$	Bulk density of water

Because we exclude all contributions from tributary glaciers, a Neumann boundary condition of zero flux is applied to all edges of the domain. A coarse time step of 1 day is sufficient for obtaining the final equilibrated state.

Once all output parameters reach equilibrium, after approximately 600 days, there is clear formation of a channel down the main trunk of the glacier (Fig. 3a). It is important to note that the channel has formed in the absence of any surface water melt, indicating its potential to persist through the winter months just given a small amount of geothermal heat flux and pressure melting. This perennial channel then forms the basis for the subglacial system during the melt season.

The subglacial drainage network reaches a second stable equilibrium following a year of transient seasonal melt forcing. Beginning from the base winter state (Fig. 3a), we run a transient simulation of 1 year (January 1 - December 31). Following this year, the model reaches a new stable winter state (Fig. 3b). The second stable state is largely similar to the first, but shows more efficient, concentrated drainage at a few isolated areas including the terminus and up-glacier at 4028 km N. Running additional melt seasons yields no additional changes in winter drainage patterns, indicating that this is a new equilibrium. The presence of this second equilibrium indicates that the cyclical melt season is necessary to maintain a perennial channel down the main trunk that returns to a similar configuration each winter.

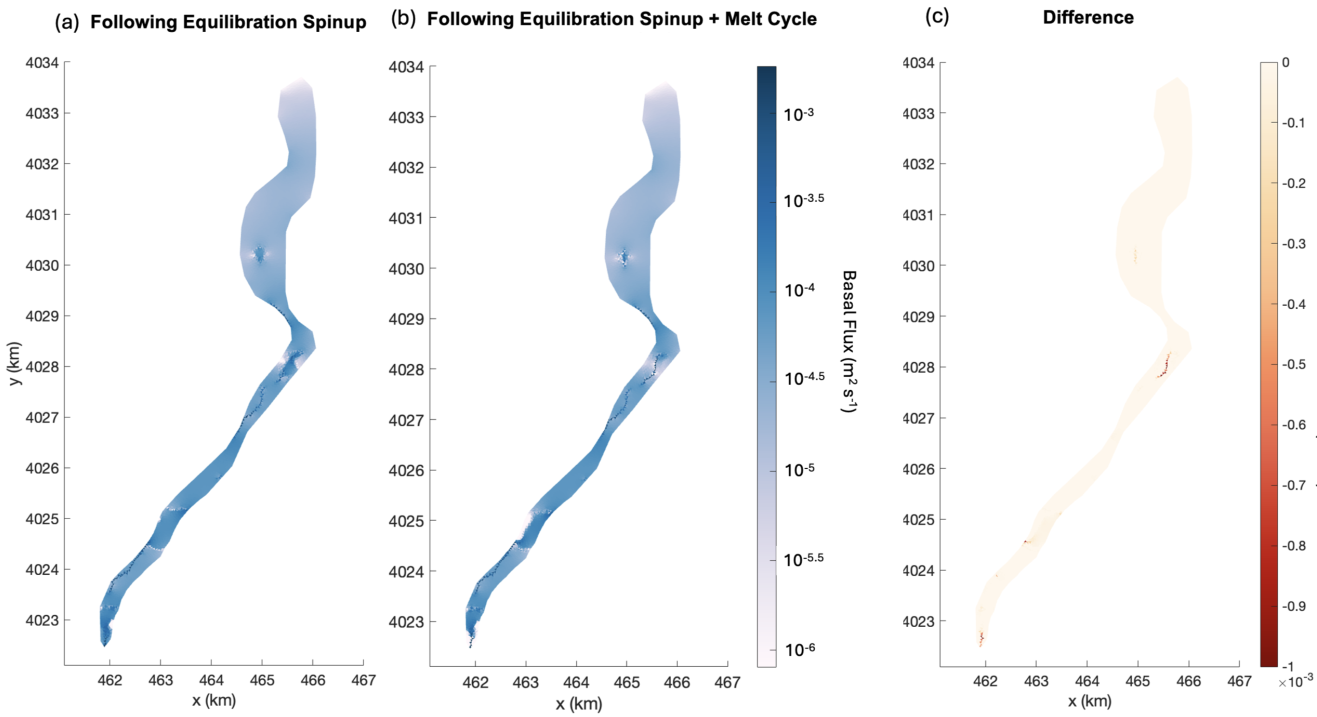

Fig. 3. Basal flux across the modeled domain following (a) a "winter state" equilibration spinup with no melt inputs to the system (b) a transient simulation through a full calendar year including a summer melt season and return back to frozen winter conditions. (c) The difference between the two equilibrated states.

Seasonal Evolution of Subglacial Hydrology

To understand how Shishper's subglacial drainage network responds to seasonal changes in meltwater flux, we run transient simulations across a period of five years, 2017-2021. The transient input for these simulations is the temporally and spatially varying sum of ice melt, snow melt, and liquid precipitation (Fig. 2). Melt inputs from tributary glaciers are excluded from the simulations.

Fig. 4 illustrates changes in the configuration of the drainage system throughout 2017, which is representative of the pattern observed across all five years. We see a mostly closed system in winter (Fig. 4b) which transitions to a highly efficient, channelized system at the peak of the melt season (Fig. 4c). At the peak of the melt season, the drainage system extends to the northernmost part of the domain, splitting into arborescent patterns characteristic of channelized drainage (Röthlisberger, 1972). By October 5, these channels then disappear, with the upper part of the system having completely shut down. Finally, the system returns to the winter state by late October (Fig. 4d and e).

The lower channel which traverses the mid- to lower trunk clearly persists through every simulated winter in 2017-2021, and can be seen in both images of the "closed" state (Fig. 4a, d, and e). We know

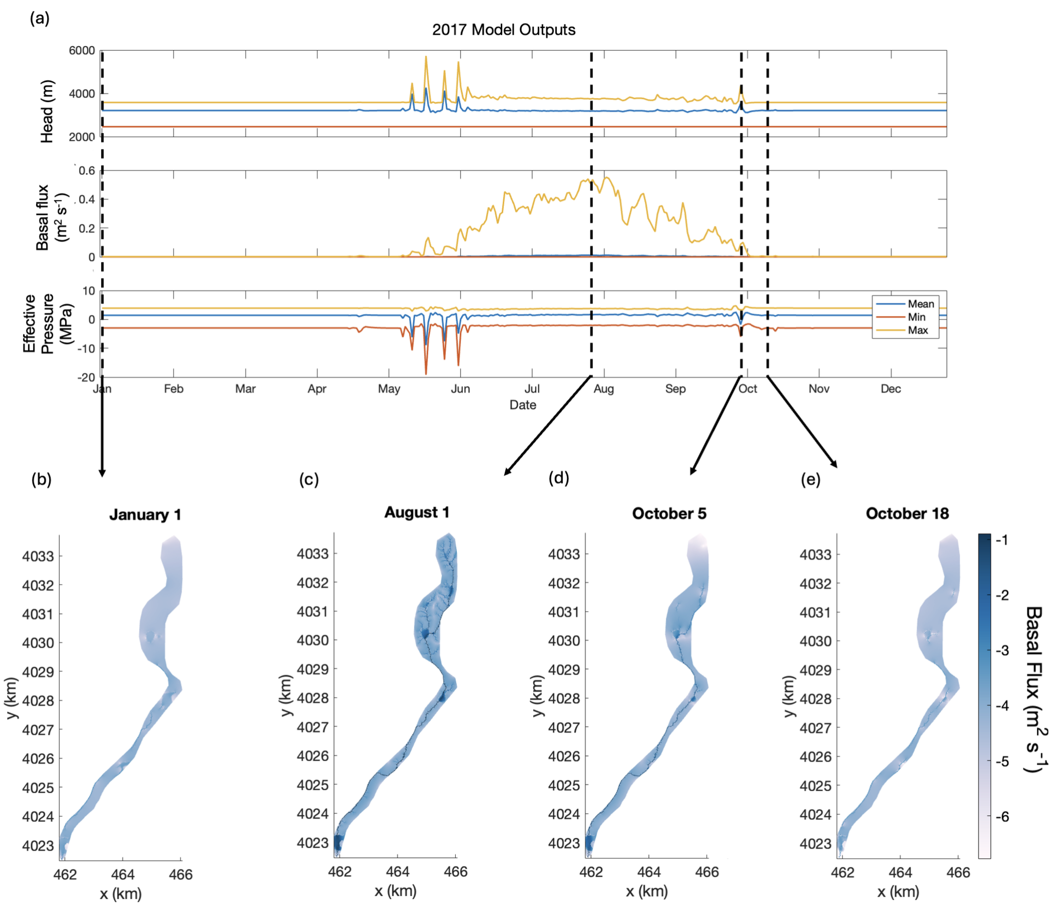

Fig. 4. (a) Model outputs for 2017 including hydraulic head, basal flux, and effective pressure. (b) Log_{10} basal flux across the glacier at four times during the year: January 1 (winter), August 1 (peak melt), October 5 (drawdown of drainage network at the end of the melt season), and October 18 (return to winter conditions).

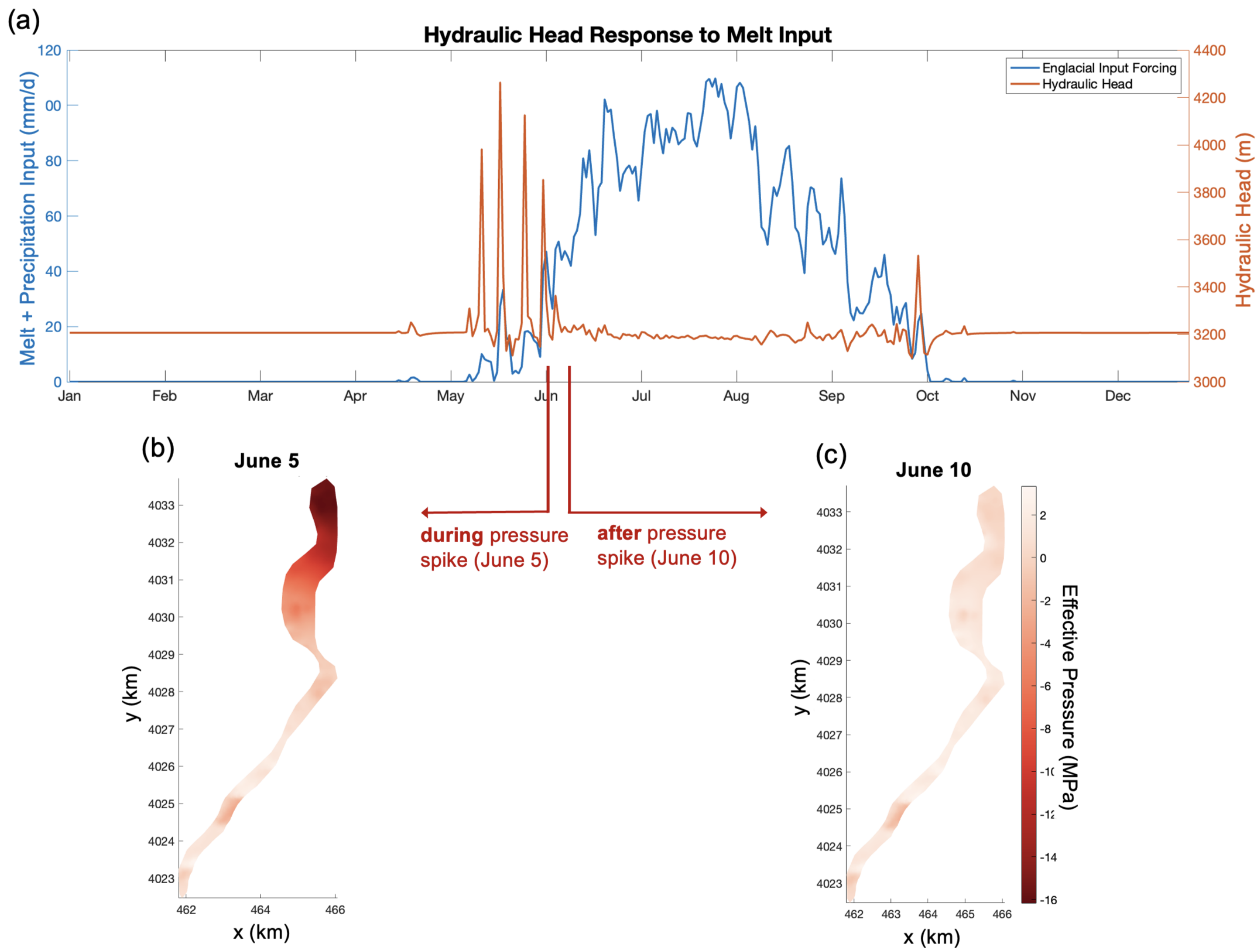

Fig. 5. Top: (a) Melt input (blue) overlaid with the model output hydraulic head (red) during 2017. Bottom: pressures across the mesh during (b) and after (c) the spike in hydraulic head in early June.

that this channel appears during the winter equilibration, during which time the only water at the ice-bed interface comes from pressure-induced melting and geothermal heat flux. Because Shishper is a temperate glacier, parts of the basal interface are usually able to be maintained at the pressure melting point for most of the year (Hubbard and Nienow, 1997). Therefore, there is always a consistent stream of water, although small, that keeps the main channel open. Bhambri and others (2020) show that surface melt elevations move from 6400 m in peak summer to 3500 m at the end of winter (no surface melt is observed in December, January, or February) meaning that the bottom part of the glacier will always receive more melt, and is more likely to contain channels, than the top.

Fig. 5 takes a closer look at the rapid decreases in effective pressure at the beginning of the melt season (May-July). Coming from distributed winter drainage, the rise in hydraulic head due to the system's

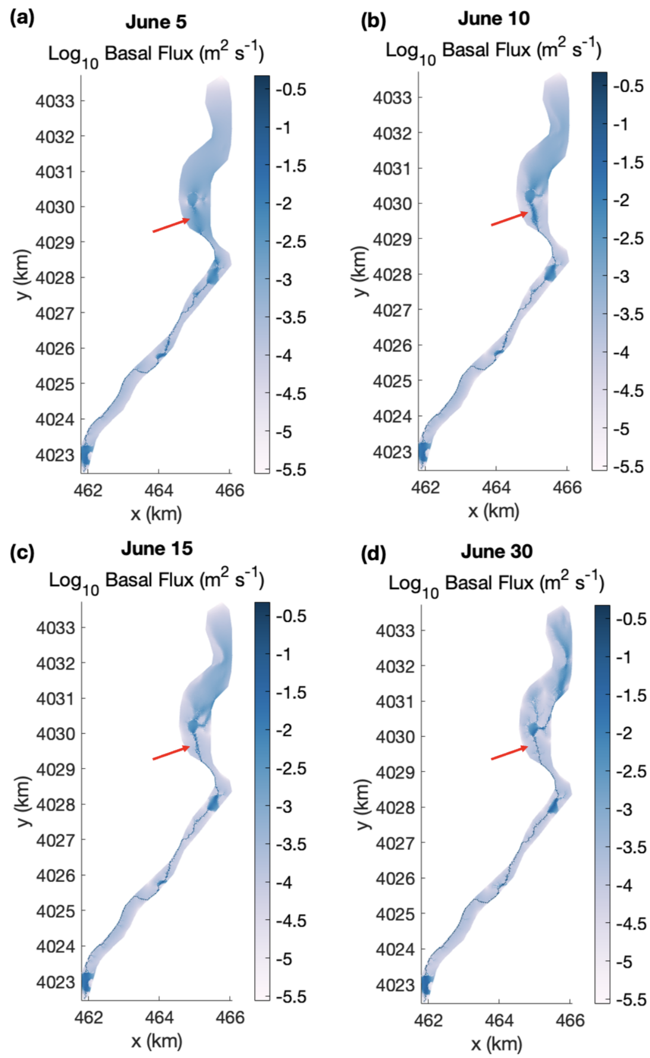

Fig. 6. Basal fluxes surrounding an early-season spike (depicted in Fig. 5) show a transition at the upper trunk from distributed, sheetlike flow to efficient, channelized flow.

inability to transport growing fluxes, and the rapid fall in head back to the equilibrium value shows that the system resolves this pressure by becoming more efficient. The buildup of hydraulic head can be observed in Fig. 5b (June 5), where a large area of negative N can be seen at the northern part of the domain. On June 10, this area of uplift at the northern part of the glacier has lessened, and by June 30 the entire section has almost completely returned to the original state of effective pressure, around 2 MPa across the mesh. Fig. 6 depicts the channel system that is established during and after these events, showing that an area of distributed, heavy flow around 4029 and 4030 km N quickly coalesces to a narrow and efficient channel in response to higher water pressures.

So long as high fluxes continue, melt opening exceeds creep closure, keeping channels open during the majority of the melt season. The drainage system is able to quickly shuttle large fluxes through, allowing it to return to a low-pressure state. Although velocities are not directly simulated here, it is likely that sliding velocities decrease due to a return to higher effective pressures in the summer. Beaud and others (2022)'s velocity dataset at Shishper Glacier from 2013-2019 shows that the glacier does indeed slow down significantly during summer months. In addition, increases in surface displacement further up the trunk of Shishper were observed by Bhambri and others (2020) during the early melt season (May to June) between 2013-2016, indicating that there is decreased effective pressures at the northern part of the domain during this time. This agrees with our model results: near the terminus, the system remains perennially channelized, while the upper part sees an inefficient, distributed system during the early melt season.

As the system closes and the capacity of the drainage system falls, it re-gains its sensitivity to temporary increases in melt, as is seen in the early and late summer spikes in hydraulic head (Fig. 5; Hart and others (2022)). This contraction happens as basal flux falls, allowing melt opening to fall and creep closure to dominate. The spikes are smaller than the ones at the beginning of the melt season because the system has not had much time to close yet, so it is still more efficient than it would be at the beginning of spring.

Overall, these findings corroborate the established understanding that there is a transition from a distributed to channelized drainage system and back during the course of the year (Fig. 4) (Schoof, 2010; Werder and others, 2013; Flowers, 2015; Hubbard and Nienow, 1997). As long as high meltwater fluxes persist, melt opening exceeds creep closure, maintaining open channels throughout most of the melt season (Schoof, 2010; Werder and others, 2013; Flowers, 2015). As the system closes and the drainage capacity decreases toward the end of the melt season, it regains sensitivity to temporary melt increases, which is evident in early and late summer hydraulic head spikes (Fig. 5) (Bartholomew and others, 2012).

SHISHPER SURGE PHASES BETWEEN 2017 AND 2019

Hydrological Insights into Surge Dynamics

Comparing the modeled effective pressures with observed surge phases reveals that incipient surge motion in November 2017 and subsequent slow acceleration through the winter 2017-2018 lack a clear hydrological trigger, indicating a non-hydrological mechanism (Kamb, 1987; Björnsson, 1998). However, significant hydraulic head spikes correspond with rapid acceleration in June 2018, suggesting that elevated water pressures may have escalated already-occurring ice motion (Kamb, 1987; Björnsson, 1998).

Fig. 7 overlays effective pressure simulated by SHAKTI on top of satellite-derived velocity observations

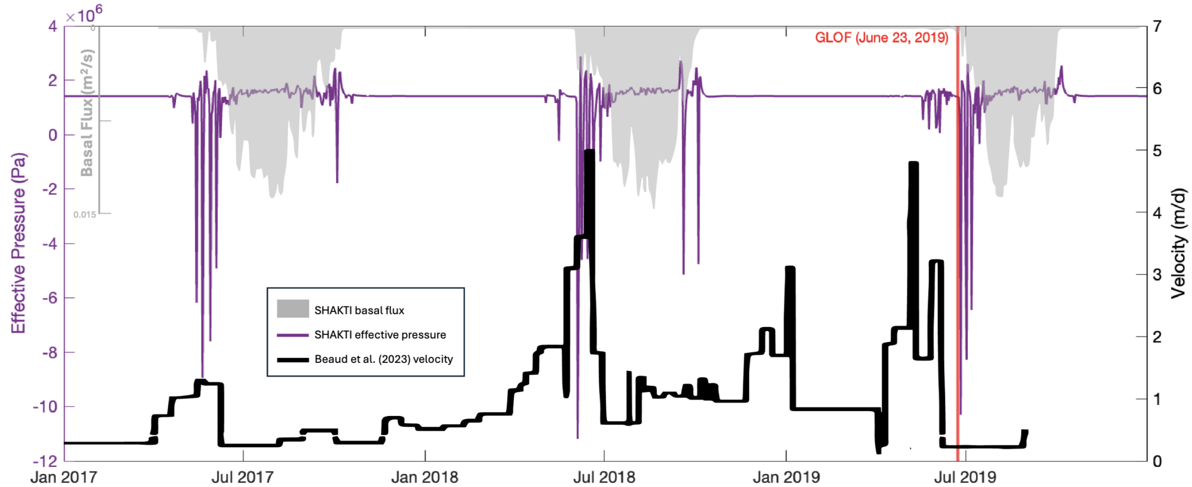

Fig. 7. Surge velocities from the dataset of Beaud and others (2022) overlaid on model outputs of head (m), basal flux (m^2/s) and effective pressure (Pa). The bright red line indicates a GLOF that occurred on June 22-23, 2019.

from Beaud and others (2022). Observations show a pre-surge acceleration begins in November 2017, but the model outputs indicate increase in subglacial lubrication during this acceleration (Kamb, 1987; Björnsson, 1998). At the beginning of June 2018, Bhambri and others (2020) describe a rapid but brief acceleration, which corresponds to the peak of about 5.5 m d^{-1} described by Beaud and others (2022) at the same time, coinciding with a series of modeled "spikes" in hydraulic head at the beginning of the 2018 melt season. As the drainage system enters its efficient summer state, the surge then enters a very slow "semi-quiescent" period during which velocity is only slightly higher than normal summer velocities, lasting until September 2018 (Beaud and others, 2022). The glacier then accelerates again, reaching speeds of of approximately 2 m d^{-1} by November 2018 and 3.5 m d^{-1} in January 2019. Another surge peak occurs from late April to early May 2019 (Bhambri and others, 2020). A small GLOF of the proximal lake, which damaged the Karakoram Highway, follows from June 22-23, 2019 (Bhambri and others, 2020; Beaud and others, 2022).

Our simulated spring and fall dips in effective pressure correspond with Beaud and others (2022)'s observations of spring and fall speedups at Shishper Glacier even during quiescent (non-surging) periods. The model results show larger and longer-duration effective pressure drops in spring compared to fall, aligning with observations of larger spring speedups. These findings support the hypotheses of observational studies suggesting that seasonal hydrology evolution is largely driving seasonal glacier motion trends in HMA (e.g., Nanni and others (2023); Sam and others (2018)).

Subglacial Hydrology's Contribution to Surge Motion

The slow acceleration to surge velocities beginning in November 2017 and continuing until January 2018 (Bhambri and others, 2020; Beaud and others, 2022) lacks a clear modeled hydrological trigger, indicating a non-hydrological mechanism that is not accounted for by our model (Björnsson, 1998; Jiskoot and others, 2000). We suggest that some unknown factors(s) may first condition the glacier for surging, causing slow acceleration - for example, a build-up of potential energy (i.e., through mass or enthalpy accumulation) (Benn and others, 2019), dynamical thinning (i.e., as in Minchew and Meyer (2020)), or combination of factors (Terleth and others, 2024) could put the system at an elevated state of surge "risk". Then, a hydrological trigger could enhance ice velocities to sustain or set off additional surge motion. In our results, spikes in hydraulic head corresponded to rapid acceleration in June 2018, suggesting that elevated water pressures escalated the ice motion that was already occurring.

Role of Hydrology in Surge Termination

Subglacial hydrology may also or instead play a strong role in *halting* surge motion. Both surge peaks ended when the system transitioned to a low pressure state (Fig. 7): the first in July 2018 after the channelization of the early melt season and the second following a lake drainage in June 2019. The abrupt transition from unstable, high water pressures to low (sub-flotation) pressures could play a significant role in the termination of motion. Benn and others (2019) also found that in systems where surface water is closely coupled to bed lubrication, surge motion terminates due to rapid discharge of water during the switch from distributed to channelized drainage. Our findings, combined with those of Benn and others (2019), support the idea that subglacial hydrology plays a stronger role in surge termination than initiation, although it is important to note that the first channelization in spring 2018 did not completely stop surge motion, as the channelization in 2019 did.

Why the surge terminated in 2019 (when the proximal lake drained through Shishper's terminus) but not 2018, is unclear. The concurrent occurrence of surge termination and proximal lake drainages in the Karakoram Range is well-established (e.g., Steiner and others (2018), Round and others (2017)). However, the causal link between proximal lake drainage and surge termination requires further investigation.

Limitations and Future Directions

To further disentangle the drivers of surge motion, we need to consider and model additional processes such as frictional feedbacks due to sliding at the ice-bed interface, till deformation, dynamic advances and retreat of the terminus, and changes in ice thickness at the reservoir and receiving zone of the glacier. Two-way coupling of SHAKTI with ice dynamics in ISSM has been implemented and applied recently to Helheim Glacier, Greenland (Sommers and others, 2024), which could provide further insights into these complex interactions. Future studies should focus on integrating these processes into the model to better understand the interplay between subglacial hydrology, ice dynamics, proximal lake floods, and surge behavior.

SUMMARY AND CONCLUSIONS

Our study demonstrates that subglacial hydrology plays a crucial role in modulating glacier dynamics, particularly in surge-type glaciers like Shishper. The simulations show that at least one year's melt cycle is required to bring the drainage system to a long-term equilibrium in which the subglacial drainage system returns to the same configuration every winter. This winter configuration features a single channel in the lower trunk of the glacier which remains year-round and serves as the basis for an arborescent, channelized drainage system that grows far up the glacier as the melt season peaks.

Our simulations also demonstrate SHAKTI's ability to represent the transition from an inefficient to efficient drainage pattern as melt flux rises and vice versa. These transitions are marked by large spikes in hydraulic head and corresponding dips in effective pressure, which support numerous previous observations of spring and fall speedups at Shishper and other mountain glaciers and strengthen existing hypotheses that seasonal glacier motion in High Mountain Asia is largely driven by changes in subglacial hydrology.

While subglacial hydrology may play a role in terminating surges or escalating an existing surge, it cannot provide a standalone explanation for surge motion. The lack of a clear hydrological trigger for incipient surge motion and for the second surge peak highlights the complexity of surge dynamics and the need for further investigation into the interactions between subglacial hydrology, ice dynamics, and other potential triggering mechanisms (Sevestre and Benn, 2015; Benn and others, 2019).

This is the first time the SHAKTI model has been applied to a realistic mountain glacier. While our simulations here involve several simplifying assumptions, the successful reproduction of transitions between distributed and channelized drainage over the course of several years provides a solid framework for future work to refine the model. These future studies should focus on analyzing the complex coupling between subglacial hydrology and glacier motion (Hoffman and Price, 2014; Sommers and others, 2024). Additionally, investigating the causal link between proximal lake drainage and surge termination may provide valuable insights into the role of subglacial hydrology in modulating surge behavior (Björnsson, 1998; Jiskoot and others, 2000).

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APPENDIX A: MESH RESOLUTION TESTS

We conducted a simple test of the finite element mesh resolution to ensure that the development of basal channels was not dependent on an arbitrary choice of mesh element size. We ran winter equilibrations with triangular mesh sizes of 10m, 20m, 40m, 50m, 100m, 200m, and 250m. Each was run with 6-hour timesteps for 300 days and were initialized with the same initial conditions. In Fig. 8 we show gap heights at the end of each of these winter equilibrations.

Areas of high gap height show the location of channels and subglacial lakes. The location of these channels is largely invariant with mesh resolution, suggesting that channel locations exhibit a higher dependence on topography than on mesh resolution.

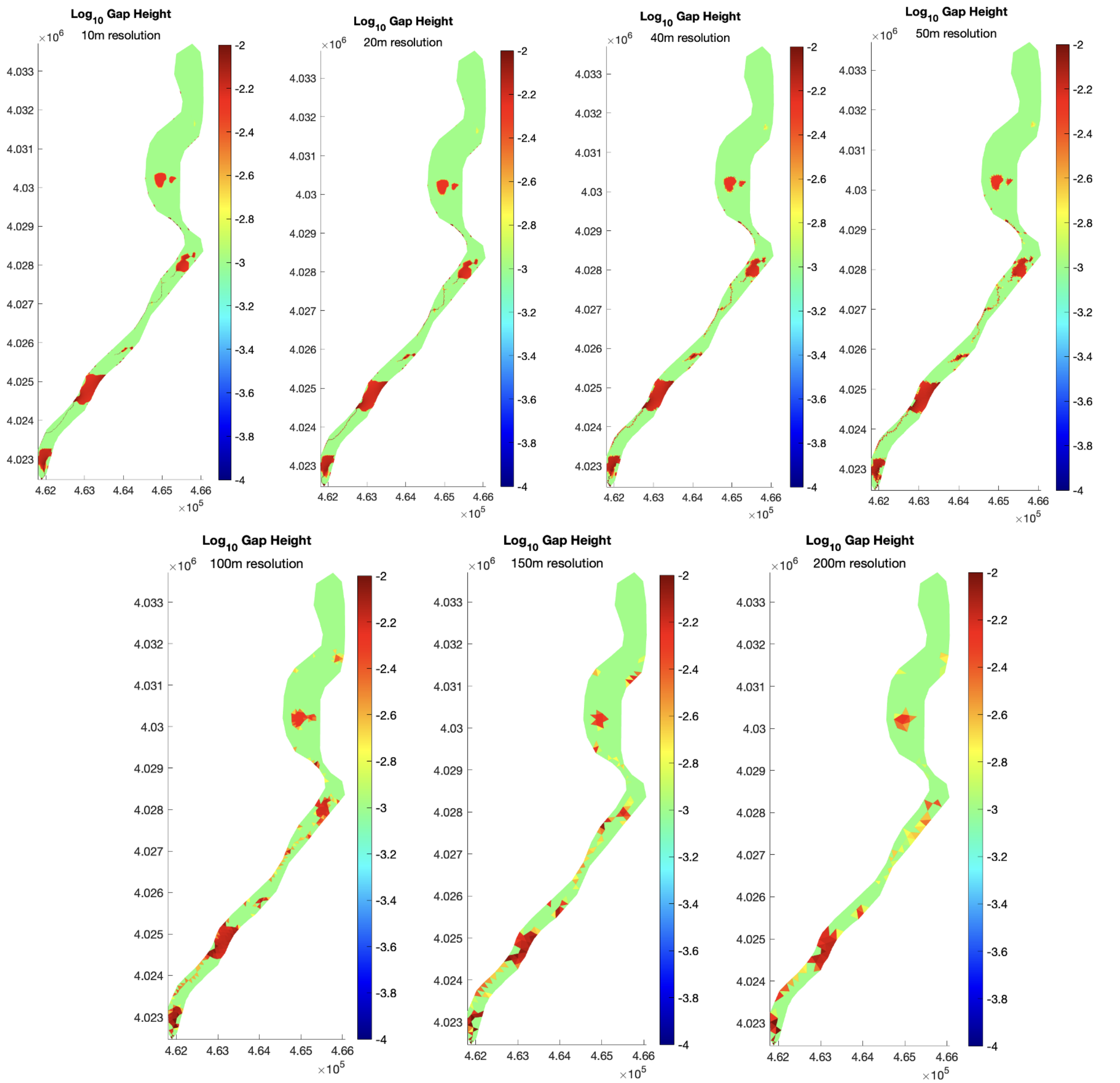

Fig. 8. Gap height (m) across the domain, shown for mesh resolutions of 10 m, 20 m, 40 m, 50 m, 100 m, 150 m, and 200 m.