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Enthalpy balance theory unifies diverse glacier surge behaviour

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Abstract

It is commonly asserted that there are two distinct classes of glacier surges: slow, long-duration 'Svalbard-type' surges, triggered by a transition from cold- to warm-based conditions (thermal switching), and fast, shorter-duration 'Alaska-type' surges triggered by a reorganisation of the basal drainage system (hydraulic switching). This classification, however, reflects neither the diversity of surges in Svalbard and Alaska (and other regions), nor the fundamental dynamic processes underlying all surges. We argue that enthalpy balance theory offers a framework for understanding the spectrum of glacier surging behaviours while emphasising their essential dynamic unity. In this paper, we summarise enthalpy balance theory, illustrate its potential to explain so-called 'Svalbard-type' and 'Alaska-type' surges using a single set of principles, and show examples of a much wider range of glacier surge behaviour than previously observed. We then identify some future directions for research, including strategies for testing predictions of the theory against field and remote sensing data, and priorities for numerical model development.

1. Introduction

Surge-type glaciers exhibit quasi-periodic velocity cycles on multi-annual timescales, in which velocities during the surge phase may be two or three orders of magnitude greater than during the quiescent phase (Meier and Post, 1969; Truffer and others, 2021). A wide variety of mechanisms have been proposed to account for surging behaviour, but in recent years there has been a tendency to adopt a binary classification of 'Svalbard-type' and 'Alaska-type' surges (e.g. Barrand and Murray, 2006; Pitte and others, 2016; Falaschi and others, 2018; Gao and others, 2022). 'Svalbard-type' surges are typically characterised as multi-annual in duration with relatively low peak velocities, associated with a switch from cold- to warm-based conditions at the base of polythermal glaciers (thermal switching), whereas 'Alaska-type' surges are characterised as shorter-lived with higher peak velocities, and associated with a reorganisation of the basal drainage system (hydraulic switching). This classification was proposed when very few glacier surges had been studied in detail, and the range of variation was just beginning to coming into focus (Murray and others, 2003; Barrand and Murray, 2006). Because of increased availability of satellite data and theoretical advances, it is now clear that a binary classification reflects neither the great diversity exhibited by surge-type glaciers (in Svalbard, Alaska and elsewhere), nor the underlying physical principles underlying all glacier dynamics.

Enthalpy balance theory (Sevestre and Benn, 2015; Benn and others, 2019*a*) offers a framework for understanding the spectrum of glacier surging behaviours while emphasising their essential dynamic unity. In this paper, we summarise enthalpy balance theory, illustrate its potential to explain so-called 'Svalbard-type' and 'Alaska-type' surges using a single set of principles, and show examples of a much wider range of glacier surge behaviour than previously observed. We then identify some future directions for research, including strategies for testing predictions of the theory against field and remote sensing data, and priorities for numerical model development.

2. Mass and enthalpy balance

To address the question of why some glaciers surge, it is useful to consider which conditions must be satisfied for glaciers to maintain a stable steady state under constant climatic conditions (i.e. for glaciers *not* to surge). First, mass must be transferred through the glacier at rates that balance patterns of accumulation and ablation at the surface. Second, inputs of thermal energy and/or water must balance losses, such that the temperature and water content of the glacier (collectively, internal energy or enthalpy) neither increases nor decreases. Both conditions are here assumed to apply on timescales of one year or more, annual fluctuations being neglected. These conditions are not independent, because glacier mass and enthalpy budgets are tightly coupled. For example, enthalpy at the bed controls rates of ice flow (via ice temperature and basal water storage) whereas ice flow converts potential energy into enthalpy via frictional heating.

The ways that coupled mass and enthalpy budgets influence glacier dynamics can be illustrated using a simple lumped model (Benn and others, 2019*a*), a generalisation of the models developed by Andrew Fowler (e.g. Fowler, 1987; Fowler and others, 2001). The core of the model is a pair of ordinary differential equations, representing changes in glacier thickness (H) and basal enthalpy (E), respectively, in a glacier accumulation area of unit width and length l:

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \dot{a} - \dot{m} - \frac{Q_\mathrm{i}}{l} \tag{1}$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \tau u + G - q_\mathrm{i} - \frac{\rho L Q_\mathrm{w}}{l} + \rho L \beta \dot{m} \tag{2}$$

In (1), $\dot{a}$ is the prescribed accumulation rate, $\dot{m}$ is the net ablation rate (i.e. meltwater that is not refrozen or otherwise stored in firn) and Q_i is the ice flux leaving the accumulation area. H, $\dot{a}$ and $\dot{m}$ are average values for the accumulation area. In (2) τu is the frictional heating from sliding (τ is the basal shear stress and u the sliding speed), G is the geothermal heat flux, q_i is the conductive cooling flux, Q_w is the discharge rate of basal water, β is the proportion of surface melt that reaches the bed, ρ is the density and L is the latent heat of fusion. In this formulation, no ice or water is advected from up-glacier, although terms can be added to represent these additional fluxes. The enthalpy variable is scaled such that positive values represent varying water content at a warm bed, and negative values represent the ‘cold content’ of ice below the melting point. Basal drainage is represented as a two-component system, with an inefficient (‘distributed’) component that dominates when water storage is low and an efficient (‘conduit’) component that dominates when storage is high. These components are encoded by the dependence of Q_w on E.

Solutions to these coupled equations can exhibit either stable steady states or oscillations. The processes underlying these contrasting behaviours can be illustrated using phase portraits of the system (Fig. 1). Changes in H reflect the competition between accumulation and ice discharge, and changes in E reflect the balance between enthalpy sources (geothermal heat flux, frictional heating, water influx from the surface) and enthalpy sinks (conduction, meltwater drainage) (Figs 1a and b). Stable steady states occur when the system converges on the condition $\mathrm{d}H/\mathrm{d}t = \mathrm{d}E/\mathrm{d}t = 0$ (Figs 1c and d) whereas oscillatory states (surge cycles) occur when this condition is unstable to small perturbations and the system undergoes cyclic variations in mass and enthalpy (Figs 1e–h). In essence, the distinction between steady and oscillatory states arises from the relationship between frictional heating and drainage efficiency. If the basal drainage system of the glacier is able to evacuate all of the water delivered from the surface or produced by frictional heating (proportional to the ice flux), the glacier can exist in a stable steady state. If the drainage system cannot achieve this, water accumulates at the bed and increases the sliding speed, and feedbacks between frictional heating and sliding trigger a surge. Increased ice discharge draws down H, and increasing water storage causes the efficient component of the drainage system to kick in, draining the bed and terminating the surge. The cycle repeats, and the glacier undergoes out-of-phase oscillations of mass and enthalpy.

The processes that initiate and sustain the surge phase are the same for both temperate and polythermal glaciers, the only difference being that in the polythermal case (Figs 1e and f) the bed dips into a cold state during quiescence. In this case, low ice fluxes lead to ice thickening, reducing conductive heat losses and warming the bed. Once the melting point is reached, friction-velocity feedbacks initiate the surge, in the same way as in the temperate case (Figs 1g and h).

In the model, oscillatory behaviour depends on combinations of accumulation, air temperature, glacier length and slope, and hydraulic conductivity of the bed, explaining the tendency of surges to cluster in particular climatic environments and on particular substrates, and for surges to preferentially affect longer, low-gradient glaciers (Jiskoot and others, 1998; Sevestre and Benn, 2015; Benn and others, 2019*a*).

3. Surges in Svalbard and Alaska

Surges in Svalbard do not conform to a single ‘type’. Some surges persist for several years with low peak velocities (e.g. Bakaninbreen: Murray and others, 1998, 2003) whereas others are much shorter in duration with peak velocities of several metres per day (e.g. Paulabreen: Kristensen and Benn, 2012). Surges affect both tidewater and land-terminating glaciers, and may propagate up- or downglacier or both (e.g. Sevestre and others, 2018).

Some of the diversity of recent Svalbard surges is illustrated in Figure 2, which shows velocity time series derived from Sentinel-1 image pairs (cf. Luckman and others, 2015). Surge duration varies from ∼2 years (Tunabreen) to >6 years (Negribreen) while others (e.g. Basin 3 on Austfonna, not illustrated) started before 2016 and are still ongoing. In some cases, the surges appear to be the culmination of slow dynamic changes that had been in progress for many years, but in one case, Tunabreen, surge onset coincided with an extreme rain event in October 2016. This glacier had been notable for its regular ∼40-year surge cycle, the last being in 2004–05 (Flink and others, 2015). External forcing may therefore have short-circuited Tunabreen’s surge cycle by rapidly increasing its basal enthalpy to the point where a surge was triggered.

In all cases shown in Figure 2, surge velocities are modulated by annual velocity fluctuations which are variable in form and magnitude. Three basic patterns can be recognised: (1) summer speed-up followed by asymptotic slowdown in winter and spring (Kvalbreen); (2) brief early summer speed-up followed by extra-slowdown and winter recovery (Monacobreen, Vestre Osbornebreen); and (3) early summer speed-up followed by brief slowdown (Negribreen). These annual patterns are similar to those identified on Greenland tidewater glaciers by Moon and others (2014), and indicate variable drainage system response to seasonal meltwater inputs.

It is interesting to compare these patterns with records from glaciers that experience fast flow on an annual basis. Stonebreen experienced a fourfold increase in speed every summer from 2016 to 2019, followed by an asymptotic decline similar to that during the surge of Kvalbreen. In winter 2019–20 the glacier failed to slowdown to typical winter levels, providing a higher baseline for the speed-up in 2020 which peaked at almost double formerly typical values. The period 2021–22 appears to mark a return to the previous pattern. The cause of the 2019–20 winter anomaly is unknown. Kronebreen is a perennially fast-flowing tidewater glacier with annual early summer speed-ups and late summer extra-slowdowns. The glacier has experienced a general increase in speed, probably due to a combination of hydrological factors and changing force balance at the retreating terminus (Schellenberger and others, 2015; Vallot and others, 2017). The records from Stonebreen and Kronebreen are instructive because they show that surge-type glaciers may share features with those that may be classed as nonsurge type, supporting the idea that there may not be a clear-cut distinction between the two. Indeed, the case of the ‘premature’ surge of Tunabreen shows that it may not be desirable, or even possible, to adopt a rigid distinction between externally forced speed-ups and internally forced surges.

In Svalbard, small glaciers (< ∼100 m thick) are cold-based and are rapidly losing mass in the current warming climate (Schuler and others, 2020). None have been observed to surge in recent decades, and under present (and projected future) climatic conditions may be regarded as ‘senescent’ rather than

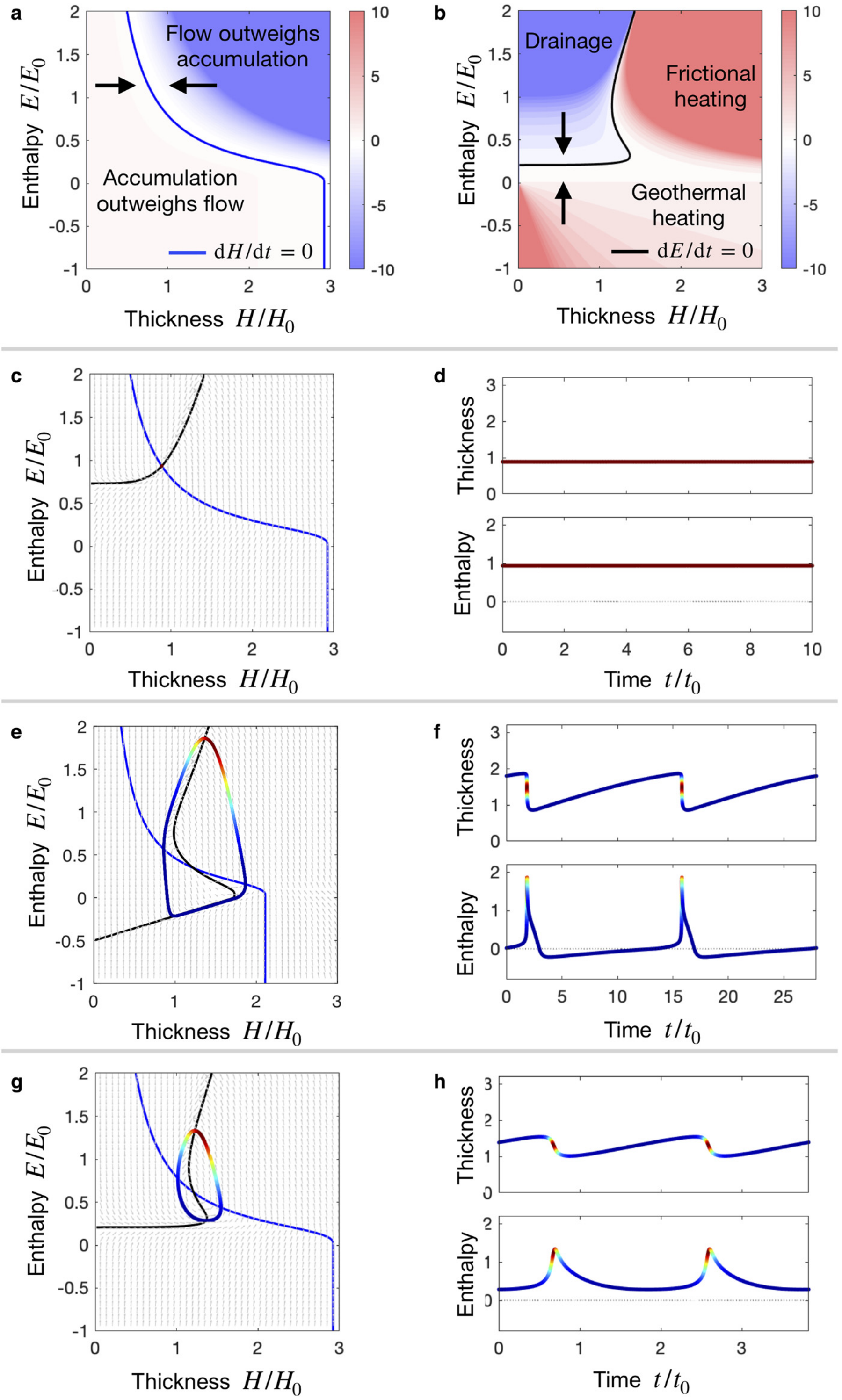

Figure 1. a, b: Plots of standardised ice thickness H/H$_0$ and basal enthalpy E/E$_0$, showing regions of increase (red) and decrease (blue) in thickness (a) and enthalpy (b). The blue and black lines represent the nullclines of thickness and enthalpy, respectively, where rates of change are zero. The shape of the nullclines depends on values of the input variables in Eqns (1) and (2). c, d: Case where the cross-over point of the thickness and enthalpy nullclines is an attractor, representing a stable steady state. Annual variations that might arise from variable surface-to-bed drainage are not included in the simulation. e, f: Case where the enthalpy nullcline has sigmoidal form and the thickness nullcline crosses in the middle branch. The cross-over is unstable to small perturbations, and the system cycles anticlockwise around steady state with alternating periods of fast (red) and slow (blue) flow. Note negative basal enthalpy during the slow part of the cycle, indicating cold basal conditions. g, h: Similar to the previous case, but the bed remains temperate throughout the cycle.

quiescent. Larger glaciers (i.e. all of those affected by recent surges) are mainly warm-based except near their margins, indicating that thermal switching is not a key process in surge initiation (Sevestre and others, 2015). The evolution of Morsnevbreen during its most recent surge cycle has been examined in detail by Benn and others (2019*b*), who showed that the bed of the upper glacier underwent a slow increase in enthalpy during late quiescence, followed by an accelerating friction-velocity feedback that initiated the surge. The glacier accelerated further when crevassing permitted surface-to-bed drainage, but the most dramatic acceleration occurred after loss of the glacier's frozen frontal zone, which had hitherto acted as a source of resistance. This shows that the presence of frozen margins may strongly influence the evolution of surges, a factor that is not represented in the simple lumped model outlined above. Removal of restraining cold-ice barriers may explain aspects of the 'explosive' surges of glaciers such as Nathorstbreen and Negribreen (cf. Nuth and others, 2019; Haga and others, 2020).

As is the case in Svalbard, surges in Alaska are very diverse. Herreid and Truffer (2016) quantified early suggestions that glacier speed-up events in the Alaska Range form a continuous spectrum, from short-lived 'pulses' to multi-year surges. It is well-known that the Alaska-Yukon surge cluster contains both temperate and polythermal glaciers (Frappé and Clarke, 2007), and there appears to be considerable overlap in the character of surges in Alaska and Svalbard.

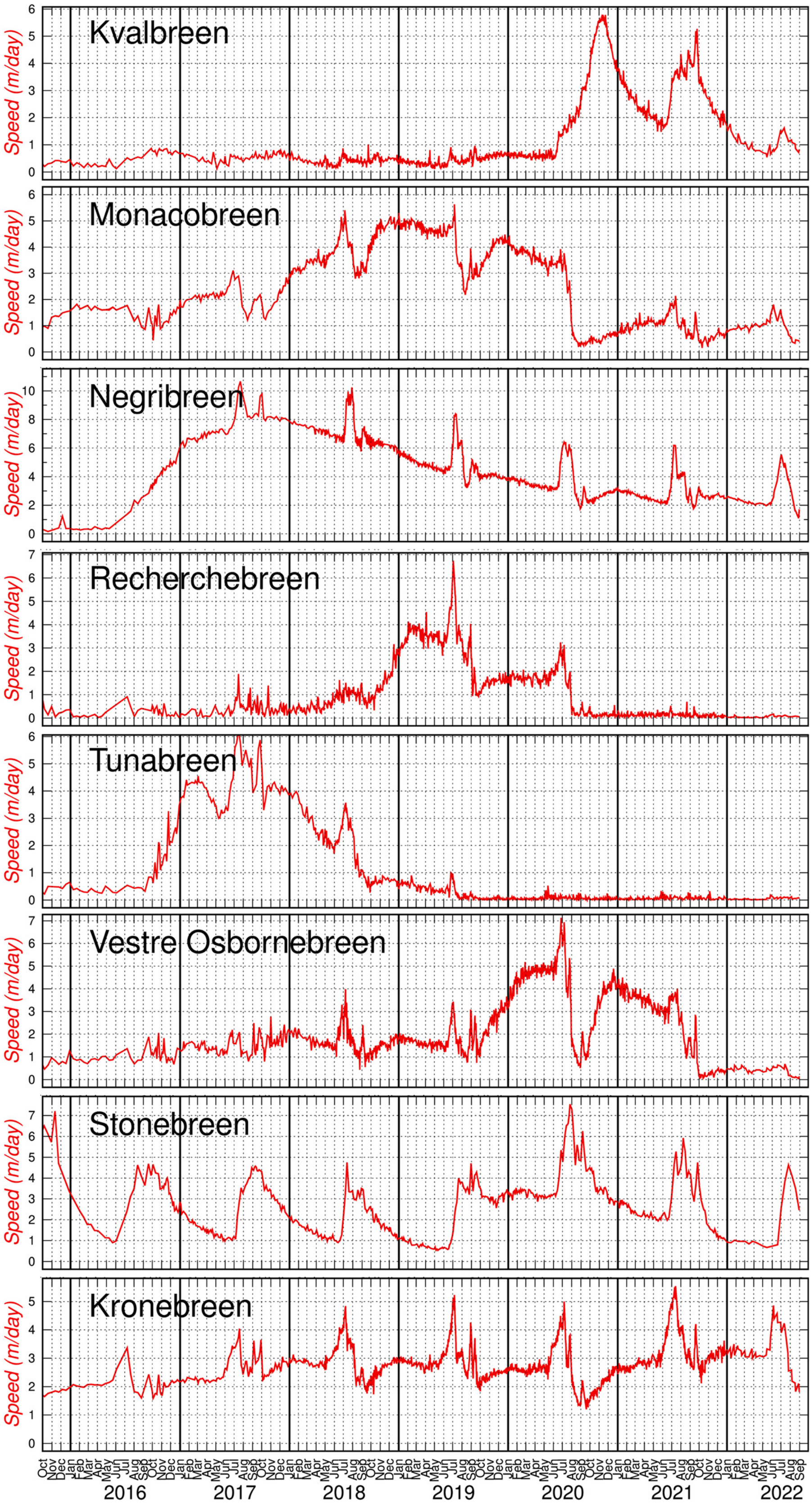

Figure 2. Velocity time series for selected Svalbard glaciers, showing diverse seasonal and multi-annual fluctuations.

The association between Alaskan glacier surges and the 'hydraulic switch' mechanism originates in the peerless study of the 1982–83 surge of Variegated Glacier, summarised by Kamb and others (1985) and reported in numerous papers cited therein. That study convincingly demonstrated that the surge event was associated with a high-storage, pressurised, distributed drainage system and that surge termination coincided with the rapid release of water from the bed following development of an efficient conduit system. The conditions required for a switch from distributed 'linked cavity' system to efficient conduits was the subject of a detailed analysis by Kamb (1987). However, the processes that might trigger the opposite switch (conduits to a high-storage distributed system) are not well understood, although some possibilities have been sketched out (e.g. Eisen and others, 2005).

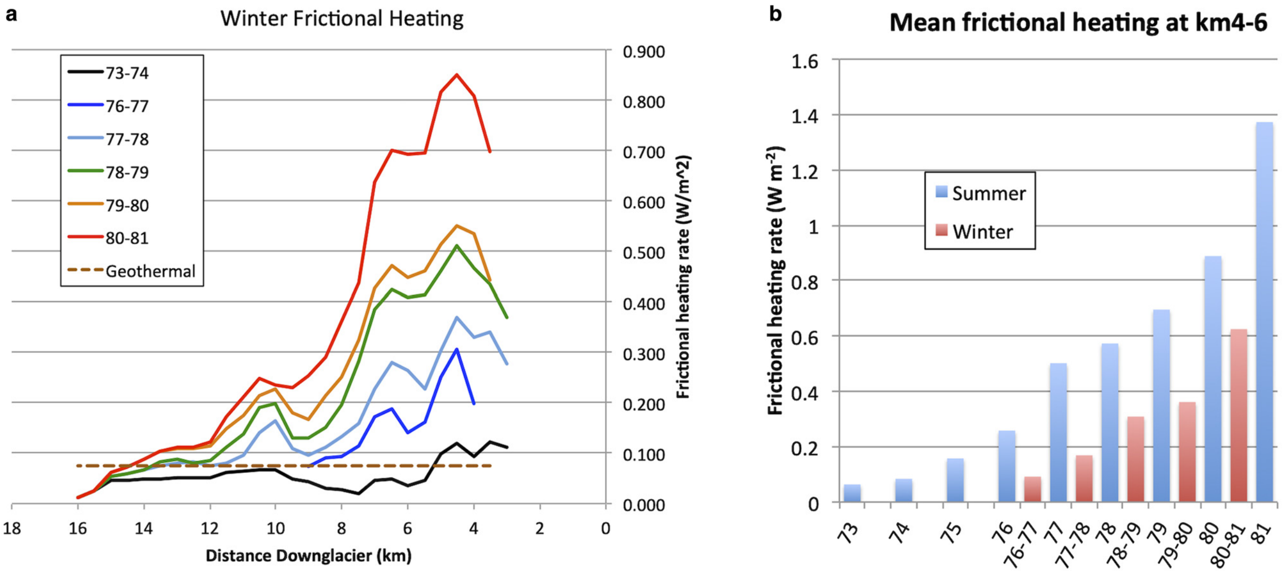

Figure 3. a: Patterns of frictional heating beneath Variegated Glacier during the last 8 years of quiescence prior to the 1982–83 surge. b: Time-series of summer and winter frictional heating below the upper glacier (mean for km 4–6). Data calculated from velocity and shear stress data presented by Raymond and Harrison (1988).

In addition, the ‘hydraulic switch’ mechanism applies specifically to cavities over a hard bed, whereas in all cases where the bed type is known (including Variegated Glacier) surge-type glaciers overlie beds of soft sediment (Harrison and Post, 2003; Minchew and Meyer, 2020). It is fair to say that the ‘hydraulic switch’ model is incomplete and, at least in its present form, inapplicable to the actual conditions beneath surge-type glaciers.

The enthalpy balance framework circumvents this difficulty by offering the possibility that surge onset does not occur in response to a switch from a conduit system to a high-storage distributed system. Rather, a switch from a conduit system to a *low-storage* distributed system occurs when the bed is drained at surge termination, and a high-storage distributed system develops gradually during quiescence in response to feedbacks between frictional heating and sliding. The plausibility of this idea is illustrated in Figure 3, which shows changes in frictional heating below the upper part of Variegated Glacier during its quiescent phase (1973–1981), based on sliding velocity and basal shear stress data in Raymond and Harrison (1988).

Below the upper part of Variegated Glacier, frictional heating rose quasi-exponentially during the second half of the 18-year quiescent period. By late quiescence, frictional heating rates exceeded 0.6 W m^{-2} in winter and were double that in summer, an order of magnitude greater than typical geothermal heating and equivalent to basal melt rates of ~0.1 m yr^{-1}. Melt from frictional heating is therefore likely to have been a significant component of the basal water budget of Variegated Glacier during late quiescence, at least during the winter months, consistent with predictions of the enthalpy balance model. It is notable that seasonal velocity fluctuations are superimposed on the overall velocity increase between 1973 and 1981, similar to the patterns observed in Svalbard. The existence of summer velocity peaks and slowdowns implies that surface meltwater reached the glacier bed during the melt season, and was subsequently evacuated relatively quickly without interrupting the overall year-on-year increase in velocity. One possibility is that the basal drainage system of the glacier was spatially heterogeneous, with both surface-fed and basally-fed components. Although the amount of meltwater reaching the bed from the surface likely exceeded that produced by basal melting, if significant regions of the bed remained isolated from surface-fed conduits, friction-velocity feedbacks could operate without interruption resulting in an overall increase in water storage through time. This is of course a speculative hypothesis, which highlights the importance of rigorously investigating the character and evolution of basal drainage systems rather than simply assuming the operation of a ‘hydraulic switch’.

In summary, we argue that surges of both polythermal and temperate glaciers occur due to essentially the same mechanism: the inability of drainage systems to keep up with basal enthalpy production, leading to feedbacks between frictional heating and sliding. This may reflect a discontinuity in drainage system efficiency, between ‘slow’ systems (e.g. linked cavities, canals and porewater flow) and ‘fast’ conduit systems. Surging glaciers therefore may inhabit the zone where basal enthalpy production is too great to be evacuated by ‘slow’ systems, but too small to sustain a ‘fast’ one.

4. Non-surging glaciers

For stable steady states to occur, enthalpy production and meltwater evacuation must broadly match on annual timescales. These conditions can occur either in cold, arid environments where enthalpy production is very low, or in warm, humid regions where summer temperatures and surface-to-bed meltwater fluxes are sufficient to maintain efficient drainage systems, at least on a seasonal basis (Sevestre and Benn, 2015; Benn, 2021). Non-surging glaciers exhibit annual cycles of mass and enthalpy in response to seasonal fluctuations in accumulation and surface melt (e.g. Kronebreen, Fig. 2). The precise form of these cycles is variable, depending on the timescales over which drainage systems adjust to changes in water flux, but for many glaciers adjustment appears to occur rapidly.

There is perhaps a widespread idea among glaciologists that surge-type glaciers are anomalies that deviate from typical behaviour, reflected in the terminology of ‘normal’ vs ‘surge-type’ glaciers (e.g. Clarke, 1991; Jiskoot and others, 1998) and the oft-cited statistic that only 1% of the world’s glaciers are surge-type. However, for certain glacier populations in some climatic environments, surging is normal. Seen from this perspective, it is the existence of stable steady states that require special conditions, in which glaciers are able make the adjustments required to balance their mass and enthalpy budgets on timescales of one year. It so happens that these conditions are met in the areas with the longest traditions of glaciological research, the European Alps and Scandinavia.

5. Future directions

Enthalpy balance theory makes several testable predictions regarding the sequence of processes that plays out during quiescence, surge onset, peak and termination and the relationships between glaciers and their climatic, topographic and geologic environment (Benn and others, 2019*a*). The availability of lengthening records of glacier dynamics from remote sensing, particularly in combination with surface elevation changes, provide opportunities to test these predictions at the glacier scale (e.g. Benn and others, 2019*b*), and the population scale (Guillet and others, 2022). Current inventories of surge-type glaciers are very variable in quality, and there is a need to increase global coverage using consistent quantitative criteria (cf. Guillet and others, 2022; Guo and others, 2022). Regional and global inventories will allow many important issues to be addressed, including better definition of the climatic envelopes of surge clusters, the geometric characteristics of surge-type glaciers and the types of substrate on which they are found. Importantly, rich remote sensing data mean that new glacier inventories need not be static, but can encompass the spatial and temporal structure of glacier dynamics at the regional scale. Our understanding of the spectrum of glacier types, and the role they play in the flux of mass and energy through the earth system, is still in its infancy and there remains much to explore and learn.

The simplicity of the 1-D model we have employed to develop enthalpy balance theory has both advantages and disadvantages. It allows rapid analysis of complex parameter space and the identification of core processes and their interactions. Conversely, those processes are represented in highly simplistic form and the model omits spatial phenomena likely to be key in the initiation and evolution of surges. Perhaps the most pressing problem is incorporating a more realistic treatment of friction laws and hydrology, the tightly coupled processes at the core of glacier dynamics (e.g. Zoet and Iverson, 2020; Zoet and others, 2022). Recent analyses of frictional instabilities on hard and soft beds (e.g. Thøgersen and others, 2019; Minchew and Meyer, 2020) highlight important processes that may operate during surge initiation and propagation, and have opened up exciting new avenues. At present, these analyses do not include frictional heating – argued here to be of fundamental importance – and doing so remains an important, if formidable goal for future research. The prospect of integrating these detailed models of frictional instabilities with enthalpy balance theory has been discussed in a perceptive paper by Terleth and others (2021).

Experiments with two- and three dimensional models are required to explore the role of spatial processes in surge initiation and propagation, including variable enthalpy sources and sinks along glacier flowlines and the role of frictional instabilities. Developing complete models of surging glaciers will involve solving and integrating several problems at the frontier of glaciological research, including glacier-bed friction, basal motion, hydrology and thermodynamics. While that prospect may lie some distance ahead, much can be learned using the tools already at hand.

Finally, we recommend that researchers abandon the false dichotomy of ‘Svalbard-type’ and ‘Alaska-type’ glaciers, and embrace the wide diversity of glacier behaviours (both within and between regions) and consider their underlying dynamic unity.

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