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A general theory of glacier surges

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Surging glaciers undergo quasi-periodic velocity cycles, which reflect internal dynamic instabilities rather than external forcing. A wide range of surging behaviours has been observed, and numerous surge mechanisms have been proposed, including switches in the configuration of the subglacial drainage system, transitions from frozen to temperate basal conditions, and interactions between hydrology and till rheology. However, global-scale correlations between surging behaviour, geometric variables and specific climatic conditions point to underlying physical principles underlying all surging behaviour. Here we outline a first general theory of surging based on the glacier enthalpy budget. For an incompressible ice mass, enthalpy relates to the temperature and liquid water content of the ice. Enthalpy is gained at the glacier bed from the geothermal heat flux plus frictional heating due to expenditure of potential energy (PE) through ice flow. Enthalpy losses occur by the dissipation of heat and loss of meltwater from the system. If a glacier is to maintain steady flow, there must be a broad equality between rates of PE expenditure (the mass flux rate) and loss of enthalpy by conductive cooling and runoff. Under certain combinations of climate, geometry and bed geology, glaciers are unable to balance their enthalpy budget, gaining mass and enthalpy progressively during quiescence and losing it dramatically during surge.

We simulate these processes by combining the models developed by Fowler (1987) and Fowler et al. (2001), which show that oscillatory behaviour occurs as a consequence of a multivalued relationship between ice thickness and flux. Surge initiation occurs when frictional heating produces enthalpy faster than it can be lost via heat conduction or meltwater discharge, and water accumulates in an inefficient drainage system; surge termination occurs due to a switch from inefficient to efficient drainage. Imbalanced enthalpy budgets and oscillatory behaviour occur under certain combinations of climate (precipitation, temperature), glacier geometry (thickness, length, slope) and hydraulic conductivity of the bed. Importantly, the model can also reproduce steady slow (low enthalpy) and fast (high enthalpy) regimes, thus potentially encompassing all dynamic behaviour within a single theoretical framework.