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Glacier surges initiated in the ablation zone of Hagen Brae, Greenland: observations and theory

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Enthalpy balance theory predicts that dynamic oscillations (surge cycles) occur when glaciers cannot achieve stable steady states with regard to their mass and basal enthalpy (heat and water) budgets. That is, if the enthalpy produced by geothermal and frictional heat cannot be removed by conduction or water flux from the bed, sliding-heating feedbacks will lead to surging behaviour. To date, model simulations have focused on 'classic' surges, in which snow accumulation causes ice thickening in a reservoir zone during quiescence, and transition to surge occurs in response to a locally-driven sliding-heating feedbacks. However, many surges are initiated in glacier ablation zones, where surface mass balance is negative. Here, we show that such surges can be explained if the local mass and enthalpy budget is supplemented by non-local sources. Ice thickening during quiescence can occur if ice flux from upglacier exceeds losses by surface melt, and transition to surge occurs if accumulation of water from both local and non-local sources triggers the sliding-heating feedback. We illustrate these processes using data from Hagen Bræ, a major marine terminating glacier in North Greenland. The dataset, which covers the past 35 years at high temporal resolution, shows elevation changes, ice velocities and basal enthalpy budgets over recent surge cycles that are consistent with theory. The average surge cycle lasts 20-30 years while the duration of the active phase is approximately a decade based on the recent cycle. The theory has potentially wide applicability to surges in a range of climatic and topographic contexts.