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# Hysteresis and chaos in ice stream behaviour

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Ice streams in West Antarctica have been observed or inferred to speed up, slow down, and even shut down, possibly indicating long time scale cyclic behaviour. Elsewhere, periodic discharges of ice-rafted debris known as Heinrich events are globally important climatic episodes that have previously been ascribed to similar behaviour. For an ice stream underlain with a deformable bed, the binge-purge oscillator of MacAyeal (1992) provides a unifying plausible mechanism: Initially inactive and frozen at the bed, the ice stream thickens due to accumulation, increasing basal melting and weakening the substrate. In time, the bed fails and basally-lubricated sliding begins. Subsequently, fast flow thins the ice until increased thermal conduction leads to basal freezing and termination of streaming flow. At this point, the cycle can begin anew. To reproduce the oscillation, we construct a lumped model that evolves ice thickness and basal conditions, and explore its dependence on naturally variable parameters, such as accumulation rate. Beyond the simple limit cycle above, the model displays rich nonlinear dynamics: for some external forcings, initial conditions dictate whether the ice stream settles into limit cycle oscillation or steady flow. Switches between these modes of flow can occur as forcings vary over time. This leads to the possibility of hysteresis and possibly chaos. On the inferred five to ten-thousand year time scales, the system is sensitive to natural climatic oscillations, such as those associated with solar cycles. We discuss the importance of unresolved physics, and extensions to a spatially extended model.