A General Theory of Glacier Surges (Ref IAP2-18-81)

University of St Andrews, School of Geography and Sustainable Development
In partnership with Durham University

Overview

Surge-type glaciers switch between slow and fast modes of flow over periods of several years to decades, with surge-phase velocities typically 2-3 orders of magnitude higher than those in the slow (quiescent) phase. During a surge, the ice-front can advance several kilometres and lead to hazards such as flooding, rapid iceberg discharge, and crevasse formation on glacier travel routes. Some types of surges may become more frequent as a result of climate change. Improved understanding of surges is thus of high scientific and practical importance.

Only 1% of glaciers worldwide are of surge type, but particularly high concentrations occur in well-defined geographical regions, including Alaska, Iceland and Svalbard.

Global analysis reveals that these surge clusters are associated with a narrow range of climatic conditions relative to the whole global glacier population (Fig. 1; Sevestre and Benn, 2015). Additionally, within every cluster, surge-type glaciers have greater mean areas and lengths than non-surgeing glaciers (e.g. Grant et al., 2009). These patterns can be explained in terms of coupled mass and energy flows within glacier systems. The key concept is that ice flow dissipates potential energy, which is mostly converted into internal energy or enthalpy (temperature and liquid water content of the ice). Ice flow rates depend sensitively on ice temperature and water storage at the bed, so for a glacier to maintain steady flow there must be a broad equality between enthalpy gains associated with the mass flux and enthalpy losses via conductive cooling and runoff. If enthalpy gains exceed enthalpy losses, the system is unstable and a surge will occur. Numerical model experiments (Benn et al. 2018) show that certain combinations of climate conditions, bed characteristics and geometry allow glaciers to balance their mass and enthalpy budgets. For other combinations, however, steady state flow cannot occur, and glaciers undergo repeated cycles in which mass and enthalpy build up during quiescence and are discharge rapidly during surge. Enthalpy cycle theory has the potential to explain the dynamics of all surge and non-surgeing glaciers within a single framework.

This PhD project aims to:

- develop enthalpy cycle theory;
- test key predictions using local and regional-scale data; and
- apply the principles of enthalpy cycle theory to predict the impact of climate change on glacier dynamics.

Fig. 1: ERA-40 climatic means associated with surge-type glaciers (purple) and non-surgeing glaciers (grey).
Methodology

The project aims will be addressed using four complementary approaches: 1) remote sensing analysis of velocity and elevation changes for a sample of surge-type glaciers; 2) regional data analysis to better define climatic and geometric boundary conditions conducive to surging; 3) field study of a Svalbard glacier undergoing transition from quiescence to surging; 4) experiments with the glacier model ELMER/Ice to predict glacier response to changes in climatic boundary conditions.

1. Remote Sensing

A range of archive and newly acquired satellite imagery (ASTER, Landsat 8, SENTINEL-1, ICESat-2) will be used to quantify velocity and elevation changes for a sample of surging glaciers. The primary geographical target will be Svalbard, where typically ~5 surges are in progress at any given time, although data from other surge clusters (e.g. Alaska-Yukon) may also be included in the analysis. In combination with climatic and bed elevation data (Fürst et al. 2018), velocity and elevation changes will be used to quantify mass and enthalpy budgets for key stages in the evolution of each surge. Analysis of glacier velocity data will be conducted in collaboration with Prof. Adrian Luckman, Swansea University.

2. Regional data analysis

The global data analysis by Sevestre and Benn (2015) used ERA-I data to parameterize glacier climatic environments. ERA-I cells are 0.75° x 0.75° in area (approximately 83km x 28km at 70° latitude) and the climatic data are applicable for the mean ground-surface elevation of the cell. These climatic data are therefore not truly representative of conditions on the glaciers, particularly in regions with high relative relief. In the present project, this problem will be overcome by conducting detailed regional analyses of surge clusters and adjacent regions (e.g. Svalbard plus mainland Norway) using high-resolution gridded climatic data products and glacier mass balance data. These analyses will allow the climatic and geometric envelopes associated with surging to be defined with high precision. In turn, this will allow definition of the external boundary conditions associated with cyclic mass and enthalpy fluctuations.

3. Field studies

Some types of key data, such as thermal regime and drainage system characteristics, cannot be obtained from remote sensing but must be collected in the field. Fieldwork will be conducted on Kongsvegen, Svalbard, where routine monitoring by the Norwegian Polar Institute has shown that the glacier is now in the earliest stages of a surge (Fig. 2).

Fig. 2: Kongsvegen last surged in 1948, since which time it has been thickening and steepening through the build-up of snow in its accumulation area. Its confluence with the perennially fast-flowing Kronebreen is marked by the prominent medial moraine. Image: TopoSvalbard.

Kongsvegen is the subject of a NERC-funded Urgency Grant REBUS (Resolving Enthalpy Budget to Understand Surging; PI: Benn) in collaboration with the Norwegian KINGSURGE project. Fieldwork will consist of time-lapse photography; mapping of surface, englacial and proglacial drainage systems; and ground-penetrating radar surveys of the glacier's thermal structure (cf. Sevestre et al., 2015).

4. Modelling

The current implementation of enthalpy cycle theory adopts the 1-D 'lumped' approach of Fowler et al. (2001). This is appropriate for exploring the relationships between surging behaviour and statistical mean climates and geometries, but its lack of horizontal spatial dimensions make it inappropriate for detailed study of particular cases. For a small sample of surge-type and non-surging glaciers selected from the remote sensing data set, ELMER/Ice will be used to simulate mass and enthalpy evolution under a range of climatic boundary conditions. ELMER/Ice solves for full stress, velocity, and enthalpy fields in 3-D and incorporates routines for evolving subglacial hydrology, so it is ideally suited for this purpose. Guidance in initializing and running ELMER/Ice simulations will be provided in-house in St Andrews by Post Doctoral Researcher Joe Todd, and additional training will be given during a 3-day workshop at the IT-Center for Science, Helsinki by core developers of ELMER/Ice.

Taken together, the remote sensing, regional data analysis, field and modelling components of the project will allow systematic development and testing of enthalpy cycle theory. The modelling work will
furthermore test the hypothesis that certain types of surges may increase in frequency, severity, or geographical extent as the result of climate change.

**Timeline**

Year 1: Literature review, experimental design, training in remote sensing data analysis and ELMER/Ice, Svalbard fieldwork, analysis of remote sensing and regional statistical data.

Year 2: Analysis of field, remote sensing and regional statistical data, diagnostic simulations with ELMER/Ice.

Year 3/3.5: Data analysis and synthesis, prognostic simulations with ELMER/Ice, writing up thesis.

**Training & Skills**

The candidate will be trained in analysis of satellite imagery and Elmer/Ice in-house at the Universities of St Andrews and Durham, and at the IT-Center for Science in Helsinki. Arctic field safety training will be provided in Svalbard by the Norwegian Polar Institute.

**References & Further Reading**


**Further Information**

For further information, please contact Prof. Doug Benn
School of Geography and Sustainable Development
University of St Andrews
North Street
St Andrews
KY16 9AL
+44 (0)1334 463853
dib2@st-andrews.ac.uk