Analysis of glaciological transition zones based on field observations and numerical modelling

Key words: transition zones, basal conditions, hydrology, ice sheets, temperate glaciers, polythermal glaciers, forward modelling, inverse modelling, field observations, radio-echo sounding, GPR, radar layers.

Background and interest of the proposed research

We are proposing a study of a central theme in glaciology – the way flow changes in transition zones. Flow transitions are examples of unusual, vertical boundary “layers” widely found in glaciology. These are columns of ice, which overlie basal transition zones where the flow is anomalous. They are characteristic of particular areas of the ice sheets, though, at a different scale, they also occur in temperate and polythermal glaciers. In this way, the proposal addresses both polar regions. It combines forward modelling, inverse modelling and uses a wide range of satellite and field observations (radar, DGPS, borehole data, mass balance and velocity measurements, hydrological observations, meteorological data, …).

Ice sheet dynamics are particularly affected by areas in the glacier where there are flow transitions, which are believed to be fundamental in controlling the stability of ice sheets. Examples of these are the ice-stream onset, where fast flow begins; the ice-stream margin, which defines the flanks of the fast-flowing ice-stream, separating it from slow moving domes; and the grounding line which separates grounded and floating ice. The influence of the grounding line on the overall stability of ice sheets has been a hotly contested topic for thirty years. Ice divides can also be considered as transition zones. The divide is not a transition zone induced by changes in the basal boundary conditions, but has many of the features of the transition zone owing to large horizontal changes in the viscosity distribution, as a consequence of the non-linear rheology of ice.

Since ice sheet models represent areas with length scales of thousands of kilometres, these transition zones are poorly resolved and at the moment there is poor understanding of these zones. It is known that the mechanical approximations used in large-scale ice sheet models do not adequately describe the behaviour of transition zones. Improvements in our understanding of these zones will improve the predictive power of ice sheet models with benefits for our understanding of sea-level rise.

Ice sheet vertical boundary layers are complicated compared with other fluid boundary layers on account of (a) the dependence of the viscosity on the stress and the temperature; and (b) the unusual mixed boundary conditions at the base, where the velocity parallel to the bed depends upon the stress, temperature and generally water pressure at the ice-bed interface. The abrupt change in the basal conditions induces very large gradients in the stress and velocity fields, which lead to non-physical singularities in the stress fields. However, experience shows that away from these singular zones, the flow is represented accurately. Certain analytical solutions exist for linear rheologies and there is some numerical information about the nature of the singularity for non-linear rheologies and various basal boundary conditions. In principle the singularity could be ameliorated by introducing extra physical processes into the model, but at the present level of understanding this is more ad hoc than simply representing the singularity.
Typically the flow upstream and downstream of these transition zones tends (asymptotes) towards the simpler flow regimes used in ice sheet models – for example the approximations used to characterise sheets, streams and shelves. Theory gives estimates for the length scale of these changes and any changes in the mean properties of the flow regime due to the presence of the transition zones. These are strictly estimates, and conclusions about the large-scale dynamics of ice sheets depend upon these estimates being right. The proposed research will investigate the transition zones quantitatively, test the accuracy of the estimates referred to above and use this information to constrain the dynamics of large ice masses.

An important further effect on basal dynamics is the hydrology of the sub-glacial water system. This is important quantitatively, but, for ice sheets, it does not, at the local scale, affect the presence or absence of a sharp transition, and it will be a secondary priority.

For temperate and polythermal glaciers, however, the hydrology of the sub-glacial (and englacial) water system will focus our attention. In particular, the following transitions will be considered:

- For temperate glaciers, the transition between basal zones with different hydrological regimes: the ice-bed interface below the accumulation area, characterised by a distributed system (e.g., a series of linked-cavities), and the ice-bed interface below the ablation area, characterised by a channel/conduit system. The former is mainly fed by snowmelt and water has a slow transit, while the latter is fed by both icemelt and the distributed system, and the water has a rapid transit.
  Both tidewater glaciers and glaciers presently ending on land will be considered.
- For polythermal glaciers, the transition between the warm-based zone under the accumulation area and the ice frozen to the bed near the snout, both zones showing also different hydrological regime, generally less well understood than that of temperate glaciers. A significant proportion of icemelt near the snout is believed to drain directly off the surface or may be englacially routed without contact with the bed. However, melt may also be routed to the warm-based bed, being unclear whether or not water from the warm-based area can flow through the cold-based region near the snout. Some drainage may occur through englacial channels above the bed, but it is believed that most of this flow originates directly from surface melting. There may also be a restricted drainage system through the cold ice along the bed or within unfrozen/permeable subglacial till or sediment.
  For polythermal glaciers, another clear transition is that between cold and temperate layers, though this is different from all previously considered, as it is mainly horizontal and determined by the thermal structure. Limited attention has been paid to the role of this transition in the ice flow, and it is worth to consider it. The temporal changes of this interface will also be considered.
  Concerning polythermal glaciers, both surging and non-surging glaciers will be considered, as well as tidewater glaciers and glaciers presently ending on land.

What we propose

We propose modelling idealised and real examples of these transition zones in order to understand the flow, mechanics and thermodynamics of these areas. We will model ice as a non-linear thermoviscous fluid. This implies modelling of the mechanical and thermal balances. We will model fixed, free slip and sliding boundaries at the base of the conditions, and model sharp transition between them. Much of the modelling will be plane flow
modelling (2D) on accounts of its computational tractability, but certain cases will be investigated in three dimensions.

Inverse modelling will play an important role, and will closely link data gathering and modelling. Mathematical models of basal transition zones can be embedded in inverse formalisms to deduce unknown flow parameters using data gathered in fieldwork. Typically one would want to know flow rates, accumulation rates and use internal layers to deduce the flow paths. In polythermal glaciers, radar layers can give information about the water content of ice. Boreholes can provide information about temperatures.

These local studies can in particular give information about the mechanical properties of ice, sediment (if present) and the sliding viscosity. Current models of transition zones predict very high stresses at transitions in the basal boundary condition, where present laboratory measurements would predict fracture. Inverse modelling would give information about the stress distributions in these sensitive areas, and in particular about whether ignoring fracture is compromising our models of transition zones.

Investigations such as those by Conway et al. about Roosevelt Island (West Antarctica) indicate a very promising avenue of inverse modelling in divide areas, where the non-linear rheology of ice causes vertical velocity anomalies (the Raymond effect). These can be used to date the formation of the ice divide (up to a maximum limit) and to invert for the rheology of ice. A further systematic study of ice divides like this could date glaciological events. This requires radar profiling along divides, and would be particularly appropriate in the rises and domes flanking the two current great ice sheets, as well as in smaller ice caps in the high arctic, where recent flow changes could be detected.

The synergy of the teams involved in this proposal provides the necessary expertise on the investigation of the thermo-mechanical regime of ice sheets, polythermal and temperate glaciers, both from the point of view of modelling and of field procedures. Many polythermal glaciers on Spitsbergen and temperate glaciers on the South Shetland Islands (Antarctica) have been studied, mainly with the support of Polish, Russian and Spanish Arctic/Antarctic stations. Many modelling experiments concerning ice sheets and glaciers at other locations have also been performed by team members. Further field work in Arctic and Antarctic areas will be required to accomplish the proposed investigations, for which the support of other parties will be of paramount importance and is expected in the spirit of the IPY, as is expected the adhesion of any researchers to this open proposal.

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