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Coupled 3-D full-Stokes modelling of tidewater glaciers

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Abstract

Tidewater glaciers are an important and difficult part of the cryosphere to study owing to their complex nature and often inaccessible and physically challenging environments. The interaction of glacier and fjord processes furthermore presents particular observational challenges. Modelling provides a possible solution to these issues, but, at the glacier scale, the processual complexities require a 3-D full-Stokes approach that is computationally expensive. Additionally, the lack of data for model validation or constraints imposes further obstacles. Despite this, progress on modelling such glaciers with explicit inclusion of all relevant processes is being made. The key remaining challenges are including more realistic representations of calving and coupling 3-D glacier modelling with 3-D fjord circulation modelling to allow inclusion of the effect of cross-fjord circulation. We are confident, however, that these issues can be resolved and will be resolved over the next decade.

Summary

The behaviour of tidewater glaciers represents a key uncertainty in predictions of future cryosphere change and associated sea-level rise. They are responsible for ~50% of total mass loss from the Greenland ice sheet (Mouginot and others, 2019; King and others, 2020), and nearly 100% in Antarctica (Rignot and others, 2019), where surface melting exerts much less influence. However, these glaciers often show very heterogeneous and local responses to environmental forcing due to the complex interplay of particular atmospheric, oceanic and topographic conditions that determines their response (e.g. Seale and others, 2011; Csatho and others, 2014; Catania and others, 2018; Fried and others, 2018).

At the same time, tidewater glaciers are particularly challenging environments in which to gather observations. They are among the world's fastest-flowing glaciers and drain catchments that span thousands of square kilometres. These glaciers also often have ice thicknesses of several hundred metres or more, and they tend to be heavily crevassed. In addition to this, many important processes (submarine melt, plumes, calving) happen at the ice–ocean interface, where the random nature of calving and the front's general instability represent a further barrier to observation or monitoring. As a result, studies have tended to focus on the more accessible, slower and less hazardous land-terminating ice margins, resulting in a relative lack of observational evidence for the marine-terminating glaciers that drain the ice sheet and control its mass balance.

This combination of their central role in ice-sheet dynamics and the sparse observational record means that tidewater glaciers are of particular importance as targets for modelling, in order to both predict sea-level rise from ice sheets and ice caps, and to seek to understand the controlling physical processes that govern their evolution. However, the lack of data (e.g. long-term calving observations, sediment properties, submarine melt rates, ice thickness, subglacial hydrological extent and dynamics) for model validation makes it challenging to assess model performance and to understand which processes and parameters are well-modelled and which are poorly modelled or missing entirely. The complex nature of the tidewater–glacier system, with a slew of interacting glacier and fjord processes, adds a further step in difficulty, as a model that explicitly represents all of these will necessarily be computationally very expensive.

Perhaps not surprisingly therefore, progress in developing 3-D full-Stokes-coupled models of tidewater glaciers has been relatively slow, and focused heavily on using the Elmer/Ice modelling suite (Gagliardini and others, 2013), with computing constraints only beginning to be lifted in the last decade. The first offline-coupled attempts to link ice flow, mass balance, calving, fjord circulation, submarine melt and subglacial hydrology were made by Vallot and others (2018), with much work since then focusing chiefly on improving the representation of calving in glacier models (Todd and others, 2018, 2019) and the notable addition of subglacial hydrology (Cook and others, 2020). Importantly only one method to predict calving (or 'calving law') has been implemented in a 3-D full-Stokes setting (Todd and others, 2018, 2019), a principal-stress version of the crevasse-depth law (Otero and others, 2010). Although other calving laws are established in 2-D planar models or simplified 3-D ones (e.g. Choi and others, 2018), none provide an obvious candidate for 3-D full-Stokes modelling given their requirement for tunable input parameters or lack of a physical basis (Benn and others, 2017a).

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Recently, the first example of a fully coupled 3-D full-Stokes model including glacier flow, meltwater plumes at the calving front, subglacial hydrology and calving has been published (Cook and others, 2021; see Fig. 1). This represents a major computational advance, with all these components of the tidewater–glacier system coupled online for the first time. Yet, the modelling still does not include all necessary processes to arrive at a full representation of a tidewater glacier, with particular issues surrounding the implementation of long-term calving and the modelled submarine melt rates. Further, little work has focused on coupling the glacier–ice-melange system, mainly because its granular nature makes it impossible to model in continuum (e.g. Burton and others, 2018; Amundson and others, 2020; Cassotto and others, 2021). In 3-D full-Stokes glacier modelling, ice-melange has always been represented by a binary backstress parameterisation (e.g. Todd and others, 2018; Cook and others, 2021), despite increasing research showing a close reciprocal relationship between calving and ice-melange (Bevan and others, 2019; Cassotto and others, 2021; Melton and others, 2022). This contrasts with progress on the other individual components of the system, with much modelling work having been undertaken on the fjord and plume circulation alone (e.g. Straneo and Cenedese, 2015; Cowton and others, 2016; Davison and others, 2020), or on ice flow solely (e.g. van Dongen and others, 2020; Crawford and others, 2021; Amundson and others, 2022). Bringing all this smaller-scale work within a fully coupled modelling framework that includes hitherto neglected processes remains an ideal not yet achieved (Table 1).

Future research priorities

Given the progress in numerical modelling of tidewater glaciers over the last decade, future research priorities and directions have emerged and become clearer. In our view, the two most important are more realistic calving representations within models and greater consideration of the warm water that is brought towards the terminus by fjord circulation. Both glacier and fjord models are able to reproduce their respective environments with a reasonably good degree of accuracy, although only when they are considered individually; the difficulties lie at the point where the two systems meet and interact. This has long been recognised with regards to the necessity for high model resolution and full 3-D flow modelling around the grounding line (Pattyn and others, 2012), but this is not the only important feature in this region of the tidewater–glacier system.

Table 1. Summary of how well key processes are included in current tidewater–glacier models along with the main challenge or area for improvement

Process	Inclusion rating	Remaining challenges
Ice flow	Excellent	–
Subglacial hydrology	Good	Improve constraints and sliding law
Meltwater plumes	Fair	Underestimated melt rates
Calving	Fair	Underestimated calving rates
Fjord circulation	Poor	Not yet included explicitly

For calving itself, our view is that calving algorithms that simulate calving based on the stress field of the glacier (e.g. Todd and others, 2018) are the best physically based and computationally reasonable implementation of calving currently available. However, these need to be improved further by considering crevasses as structural weaknesses consisting of damaged ice with a preferred crystal orientation fabric and lower yield strength in the direction of shear, in order to reproduce calving at observed rates. This could be done in several ways. While ice-damage functions already exist in some models (Krug and others, 2014; Mercenier and others, 2019), the technical work to couple one with a full-Stokes 3-D calving algorithm has not yet been undertaken to our knowledge, nor have algorithms that track the deformational history of ice as it advects towards the ocean. It is also far from obvious how damage evolution may be incorporated into current stress-based calving laws. Unless the damage can be modelled as part of the viscous evolution of the ice and stress concentrations accounted for, a stress multiplier would need to be used that would likely end up being a tunable parameter, varying between glaciers, so would be far from ideal. Alternatively, using a Lagrangian approach, crevasse history could be explicitly tracked, something already implemented in 2-D modelling, which has been shown to lead to an increase in modelled calving compared to not including crevasse history (Berg and Bassis, 2022). Another possibility is to use computationally expensive models that explicitly model fracture dynamics to attempt to directly determine new calving laws or, at least, diagnostic stress states for calving (Åström and others, 2013; Benn and Åström, 2018). When these states then appear in continuum-flow

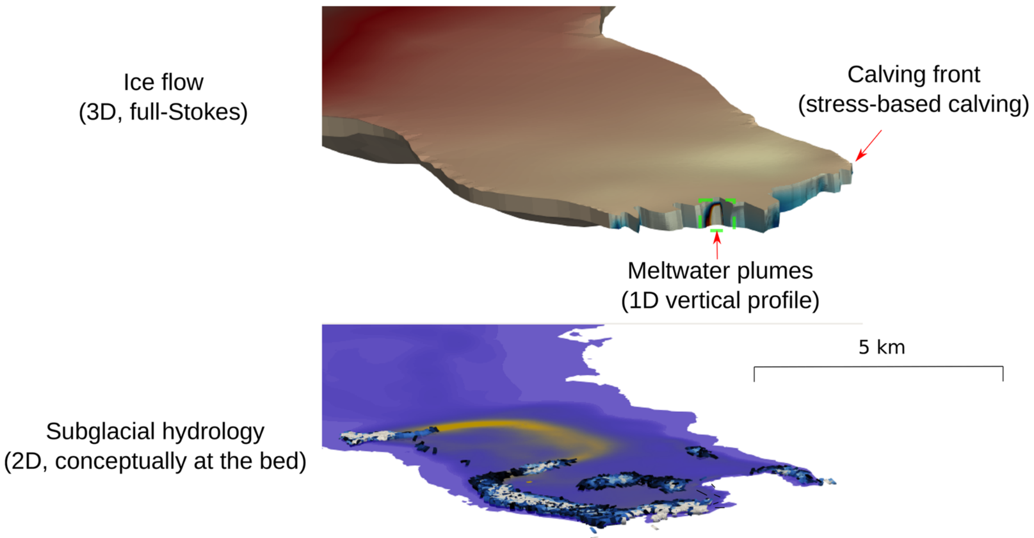

Fig. 1. Major model components in Cook and others (2021). Readers are directed to this paper for a full explanation of the individual components. Top panel (3-D ice-flow mesh) shows glacier surface elevation in m in grey-red, with plume melt rates in $m^3 a^{-1}$ in grey-blue-white on the calving front (low-high in both cases). Bottom panel (2-D subglacial hydrology mesh) shows wintertime channel area in m^2 in black-blue-white colours, and wintertime sheet discharge in $m^3 a^{-1}$ in purple-orange (low-high in both cases).

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models, calving could be assumed to have occurred, but we feel that these states will depend too heavily on the particular geometry of a given glacier to be widely applicable. We therefore consider the crevasse-history route as more promising at this point in time.

We also contend that a lack of inclusion of 3-D fjord circulation may be behind the frequent underestimation of submarine melt rates when derived from models relying on buoyant plume theory (e.g. Jenkins, 2011; Slater and others, 2016; Ezhova and others, 2018; Jackson and others, 2022). We particularly consider that lateral flow, parallel to the calving front, may be a missing element in models that would lead to more accurate melt rates were it to be added. Coupling an ice-flow model to a high-resolution fjord general circulation model would be one way of investigating this, but this would be computationally expensive. If such work were undertaken, it would certainly be best directed towards finding an inexpensive parameterisation that could be widely reproduced in existing 1-D plume models.

Overall, however, we are confident these challenges can be overcome, enabling more accurate predictions of tidewater–glacier behaviour in the forthcoming years. Only then will a fully coupled 3-D full-Stokes model of a tidewater glacier be achievable. We find it difficult to envisage an alternative modelling framework for the detailed simulation of individual tidewater glaciers discussed in this paper, as a full-Stokes approach will always be required at the grounding line at the very least. Discrete-element models (Åström and others, 2013; Benn and others, 2017b; Vallot and others, 2018) are too computationally expensive to be used for large areas or simulations of over a few weeks, and recent machine-learning emulator approaches (Jouvet and others, 2021; Jouvet, 2022) would have to be trained on full-Stokes simulations in the first place (and, given the heterogeneity of tidewater glaciers, might have to be retrained for each individual glacier). We therefore believe that the goal of a fully coupled 3-D full-Stokes model of a tidewater glacier remains a desirable one.

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