A physics based iceberg calving model coupled with a global ice-sheet flow model for accurate assessment of sea level rise **November 24, 2015**

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Abstract

Mass loss from the Antarctic Ice Sheet occurs primarily through its ice shelves, which are floating platforms of ice that extend into the ocean and surround the Antarctic ice sheet. Because of the cold atmospheric temperatures, most of this mass loss comes from the combination of the detachment of icebergs (calving) and the gradual erosion of ice by submarine melting. One challenge in predicting future ice sheet mass loss, however, is that many of the processes associated with ice shelf demise remain poorly understood. Although progress has been made in our understanding and modeling of submarine melting, a quantitative understanding of iceberg calving from ice shelves remains elusive. This is partly because calving requires that we understand and simulate the three-dimensional initiation and propagation of fractures within the ice over timescales that range from seconds to decades (or longer) [1, 2]. Iceberg calving rates provide boundary conditions to global ice sheet models and thus are extremely important. However, current models are too simplistic and do not demonstrate an ability to mimic observations of ice shelf fracture and calving. Future atmospheric warming may lead to increased melt ponding, "hydrofracture" (as occurred on the Larsen A/B ice shelves), and calving of Antarctic ice shelves (see, e.g., [4]). This process is critical to include in large-scale, predictive models of the Antarctic ice sheet [6, 5]; without accurate models of ice shelf fracture and calving, a critical link between atmospheric forcing and ice shelf decay will be absent in coupled ice sheet and climate models, biasing projections of ice sheet evolution and sea-level rise.

To this end, we propose a physically-motivated ice fracture and calving model (solid mechanics based) coupled with an ice sheet dynamics model (fluid mechanics based), to be incorporated as part of a larger global Earth System Model. The overarching goal is to provide more realistic predictions (including uncertainty ranges) of ice sheet evolution for estimating sea-level rise due to climate warming.

Background/Research to Date

In our previous work, a thermo-viscoelastic model for ice together with a creep damage model was proposed to model ice rheology and ice calving. The model was calibrated using laboratory data of uniaxial creep tests and is currently implemented in the finite element program FEAP [3, 7, 8]. Damage mechanics provides a promising approach to model ice calving and alleviate some of the limitations of traditional fracture mechanics. For example it (1) can model crack initiation and propagation (2) does not require adaptive re-meshing or mesh moving procedures to track fractures and (3) can easily be incorporated with viscoelastic constitutive laws to model the time dependent behavior of ice. In this approach, the usual continuum equations are augmented with an additional internal state variable D representing material deterioration or damage, ranging from $D = 0$ (ice is completely intact) to $D = 1$ (ice is entirely fractured). The evolution of the damage variable D accounts for the progressive accumulation and coalescence of micro-cracks (and also micro-voids) within the ice as it deforms under low loading rates.

In a recent work, the approach described above has also been extended to account for the simultaneous propagation of water filled surface and basal crevasses using a unique poro-

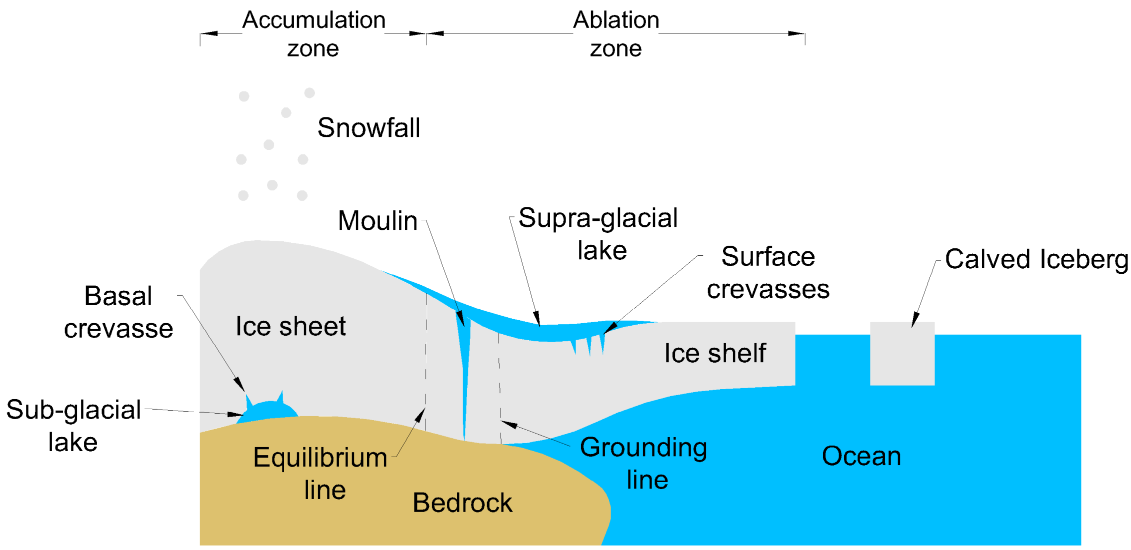

Figure 1: A global ice sheet model coupled to a damage mechanics model at the boundaries

mechanics approach [9] which is important for accurate modeling of the calving physics.

Proposed Direction of work

Coupling a global ice sheet flow model with a calving model at its boundaries is illustrated in Figure 1. This will require significant research to address several open questions related to: (1) the coupling approach: a fully concurrent approach (fluid and solid parts are solved concurrently) versus a staggered approach (fluid and solid parts are solved sequentially) versus an information passing approach (parametric studies are carried out on the solid part to obtain reduced order models or “calving laws” in a functional form, and are then applied to the fluid as boundary conditions); (2) uncertainty quantification across the fluid-solid model and propagation with time; (3) appropriate time stepping methods and solvers for the fluid-solid models, considering a range of time scales and large-scale problems; (4) further improvements to the ice fracture and calving modeling capabilities developed by the PIs (e.g., considering melting and erosion of the ice).

Connections to Math, Comp Sci & and Climate Science

The proposed work leverages past and ongoing DOE-funded efforts (e.g., ISICLES, PISCEES, LDRD, some of which have supported the relevant work discussed herein) in developing next-generation ice sheet models and coupling of those models to DOE-supported Earth System Models. Software and tools developed previously through the DOE BER/ASCR SciDAC initiative as well as the Trilinos solver software will be leveraged in order to solve these large-scale coupled systems on DOE’s high-performance computing platforms. Successful completion of the project will build upon the PIs expertise and collaboration in the disciplines of glaciology, applied mathematics, and computational science.

Potential Impact on the field

Most existing ice sheet models (including DOE's) simulate ice flow dynamics on a large scale, e.g. over all of Greenland and Antarctica, but are currently biased by their inability to simulate fracture or iceberg calving in a physically motivated or verifiable way. Fracture and calving rates, which have a tremendous impact on ice shelf evolution and stability, are also tightly coupled to atmospheric and ocean processes. An advanced capability at including ice sheet models as components of Earth System Models puts DOE in a unique position to take advantage of the proposed improvements to fracture and calving models, in order to provide more realistic predictions and uncertainty ranges on estimates of future sea-level rise due to climate warming.

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