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Iceberg calving of Thwaites Glacier, West Antarctica: full-Stokes modeling combined with linear elastic fracture mechanics

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Abstract. Thwaites Glacier (TG), West Antarctica, has been losing mass and retreating rapidly in the past few decades. Here, we present a study of its calving dynamics combining a two-dimensional flow-band full-Stokes (FS) model of its viscous flow with linear elastic fracture mechanics (LEFM) theory to model crevasse propagation and ice fracturing. We compare the results with those obtained with the higher-order (HO) and the shallow-shelf approximation (SSA) models coupled with LEFM. We find that FS/LEFM produces surface and bottom crevasses that are consistent with the distribution of depth and width of surface and bottom crevasses observed by NASA's Operation IceBridge radar depth sounder and laser altimeter, whereas HO/LEFM and SSA/LEFM do not generate crevasses that are consistent with observations. We attribute the difference to the non-hydrostatic condition of ice near the grounding line, which facilitates crevasse formation and is accounted for by the FS model but not by the HO or SSA models. We find that calving is enhanced when pre-existing surface crevasses are present, when the ice shelf is shortened or when the ice shelf front is undercut. The role of undercutting depends on the timescale of calving events. It is more prominent for glaciers with rapid calving rates than for glaciers with slow calving rates. Glaciers extending into a shorter ice shelf are more vulnerable to calving than glaciers developing a long ice shelf, especially as the ice front retreats close to the grounding line region, which leads to a positive feedback to calving events. We conclude that the FS/LEFM combination yields substantial improvements in capturing the stress field near the grounding line of a glacier for constraining crevasse formation and iceberg calving.

1 Introduction

Thwaites Glacier (TG) is the second largest and broadest ice stream in the Amundsen Sea Embayment (ASE) sector of West Antarctica (Fig. 1). Recent observations have reported significant thinning and retreat of this glacier (Rignot, 2001; Shepherd et al., 2002; Pritchard et al., 2009; Rignot et al., 2014). The mass balance of Thwaites was $-34 \pm 16\,\mathrm{Gt\,yr^{-1}}$ in 2007 and this value has been decreasing until present to reach $-50\,\mathrm{Gt\,yr^{-1}}$ in 2013 (Rignot, 2008; Shepherd et al., 2012; Mouginot et al., 2014). Its grounding line retreated 14 km from 1992 to 2011 (Rignot et al., 2014). The bed elevation of the vast majority of its drainage basin is well below sea level and decreases inland (Tinto and Bell, 2011; Rignot et al., 2014). Such a bed configuration makes the glacier unstable according to the marine ice sheet instability (MISI) theory (Weertman, 1974; Hughes, 1981; Schoof, 2007). With only a small ice shelf able to buttress it, TG may already be in a state of collapse (Parizek et al., 2013; Joughin et al., 2014). As the glacier retreats farther inland and loses its floating section, its rate of iceberg calving is likely to increase, which would enhance the glacier's contribution to sea level rise (DeConto and Pollard, 2016). It is therefore essential to better understand and simulate the calving dynamics of TG.

Large calving events have been observed on the floating section of TG (Fig. 1b) by satellites (MacGregor et al., 2012). Densely distributed surface and especially bottom crevasses have been revealed by radar depth sounders (Fig. 2). As the buttressing ice shelf calves away and the grounding line retreats, the resistance to flow or buttressing force will decrease, which will favor further retreat and glacier speed up (MacGregor et al., 2012). The calving of icebergs is difficult to model because the processes involved, such as the