

# Monitoring Greenland ice sheet buoyancy-driven calving discharge using glacial earthquakes

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**ABSTRACT.** Since the 2000s, Greenland ice sheet mass loss has been accelerating, followed by increasing numbers of glacial earthquakes (GEs) at near-grounded glaciers. GEs are caused by calving of km-scale icebergs which capsizes against the terminus. Seismic record inversion allows a reconstruction of the history of GE sources which captures capsizing dynamics through iceberg-to-terminus contact. When compared with a catalog of contact forces from an iceberg capsizing model, seismic force history accurately computes calving volumes while the earthquake magnitude fails to uniquely characterize iceberg size, giving errors up to 1 km<sup>3</sup>. Calving determined from GEs recorded at eight glaciers in 1993–2013 accounts for up to 21% of the associated discharge and 6% of the Greenland mass loss. The proportion of discharge attributed to capsizing calving may be underestimated by at least 10% as numerous events could not be identified by standard seismic detections (Olsen and Nettles, 2018). While calving production tends to stabilize in East Greenland, Western glaciers have released more and larger icebergs since 2010 and have become major contributors to Greenland dynamic discharge. Production of GEs and calving behavior are controlled by glacier geometry with bigger icebergs being produced when the terminus advances in deepening water. We illustrate how GEs can help in partitioning and monitoring Greenland mass loss and characterizing capsizing dynamics.

**KEYWORDS:** climate change, glacier calving, glacier discharge, iceberg calving, seismology

## INTRODUCTION AND BACKGROUND

The Greenland ice sheet (GrIS) mass loss and its contribution to sea-level rise has more than quadrupled from 1991–2001 to 2002–11 (Shepherd and others, 2012) due to both increased discharge of ice to the ocean and decreased surface mass balance (Van den Broeke and others, 2009, 2016; Enderlin and others, 2014; Velicogna and others, 2014; Khan and others, 2014). The partitioning of mass loss between dynamic (i.e. changes in ice flow, thinning and calving rates) and surface processes is important because these losses indicate different forcing (Howat and others, 2011). While surface mass balance is driven by atmospheric processes, tidewater glacier dynamics are driven by changes in resistive stress at the terminus (e.g. Nick and others, 2009), likely triggered by changing ocean conditions (Holland and others, 2008; Straneo and others, 2010), and further modulated by glacier geometry (Howat and others, 2005, 2007; Joughin and others, 2008b, 2014; Enderlin and others,

2013; Moon and others, 2014; Felikson and others, 2017; Kehel and others, 2017).

Between one third and one half of the annual GrIS (see Appendix A for definition of acronyms) mass is lost at the termini of tidewater glaciers (Van den Broeke and others, 2009; Enderlin and others, 2014). Iceberg calving and submarine melting are collectively known as dynamic discharge. They are notoriously difficult to quantify separately (Bern and others, 2017b). One goal of this study is to provide independent measurements of the GrIS discharge related to the calving of large rolling icebergs from emitted seismic signals, known as glacial earthquakes (GEs). The characterization of icebergs is important as calving rates are projected to increase during the coming decades and play a significant role in the stability of the entire GrIS (Rignot and Kanagaratnam, 2006; Rignot and others, 2011). Icebergs carry and release freshwater far from the glacier as they drift offshore (Enderlin and others, 2016; Wagner and others, 2017) and can potentially affect the large-scale ocean overturning circulation and ocean temperature (Fichefet and others, 2003; Holland and others, 2008; Wilson and others, 2015; Yang and others, 2016; Stern and others, 2016).

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