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Localised thickening and grounding of an Antarctic ice shelf from tidal triggering and sizing of cryoseismicity

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ABSTRACT

We observe remarkably periodic patterns of seismicity rates and magnitudes at the Fimbul Ice Shelf, East Antarctica, correlating with the cycles of the ocean tide. Our analysis covers 19 years of continuous seismic recordings from Antarctic broadband stations. Seismicity commences abruptly during austral summer 2011 at a location near the ocean front in a shallow water region. Dozens of highly repetitive events occur in semi-diurnal cycles, with magnitudes and rates fluctuating steadily with the tide. In contrast to the common unpredictability of earthquake magnitudes, the event magnitudes show deterministic trends within single cycles and strong correlations with spring tides and tide height. The events occur quasi-periodically and the highly constrained event sources migrate landwards during rising tide. We show that a simple, mechanical model can explain most of the observations. Our model assumes stick-slip motion on a patch of grounded ice shelf, which is forced by the variations of the ocean-tide height and ice flow. The well fitted observations give new insights into the general process of frictional triggering of earthquakes, while providing independent evidence of variations in ice shelf thickness and grounding.

1. Introduction

In recent years, repetitive tide-modulated seismicity has been discovered at glaciers and ice shelves in Antarctica (e.g., Barruol et al., 2013; Hammer et al., 2015; Lombardi et al., 2016; Winberry et al., 2014; Zoet et al., 2012) and Greenland (Podolskiy et al., 2016). Typically observed near the grounding zone, it shows a wide variety of temporal patterns and correlations with the components of the ocean tide, which can be used as diagnostic tools to assess the driving mechanisms of this type of cryogenic seismicity and potential links to glacial dynamics. Main interpretations involve stick-slip motion at the ice/bedrock interface (e.g., Barruol et al., 2013; Lombardi et al., 2016; Winberry et al., 2014; Zoet et al., 2012) and brittle deformation of the ice shelf due to tidal flexure (Barruol et al., 2013; Hammer et al., 2015; Lombardi et al., 2016), all recognising the importance of stress and strain rate variations to the triggering of cryoseismic activity (e.g., Bindschadler et al., 2003; Hammer et al., 2015; Podolskiy et al., 2016; Winberry et al., 2014). However, relevant studies often have short observation intervals, due to the need for dedicated field deployments (e.g., Lombardi et al., 2016; Podolskiy et al., 2016), the longest ranging ones reporting one or more non-consecutive intervals of about a year (Barruol et al., 2013; Hammer et al., 2015; Winberry et al., 2014).

The study focuses on the Fimbul Ice Shelf (FIS), in Dronning Maud Land (DML), East Antarctica. The main contributor to the ice shelf is the outlet of the Jutulstraumen glacier, whose ice tongue, the Trolltunga, partly extends past the continental shelf break into the Weddell Sea (Fig. 1a). The differential flow between the fast-flowing central part of the outlet glacier and the much slower lateral parts of the shelf (e.g., Rignot et al., 2011) creates zones of shear deformation, characterised by abundant crevasses and rifts (Humbert and Steinhage, 2011). Although the central basin

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Abbreviations: CC, Cross-correlation; CFS, Coulomb Failure Stress; DML, Dronning Maud Land; FIS, Fimbul Ice Shelf; HMM, Hidden Markov Model; SNR, Signal-to-noise ratio; STA, Short-term average.

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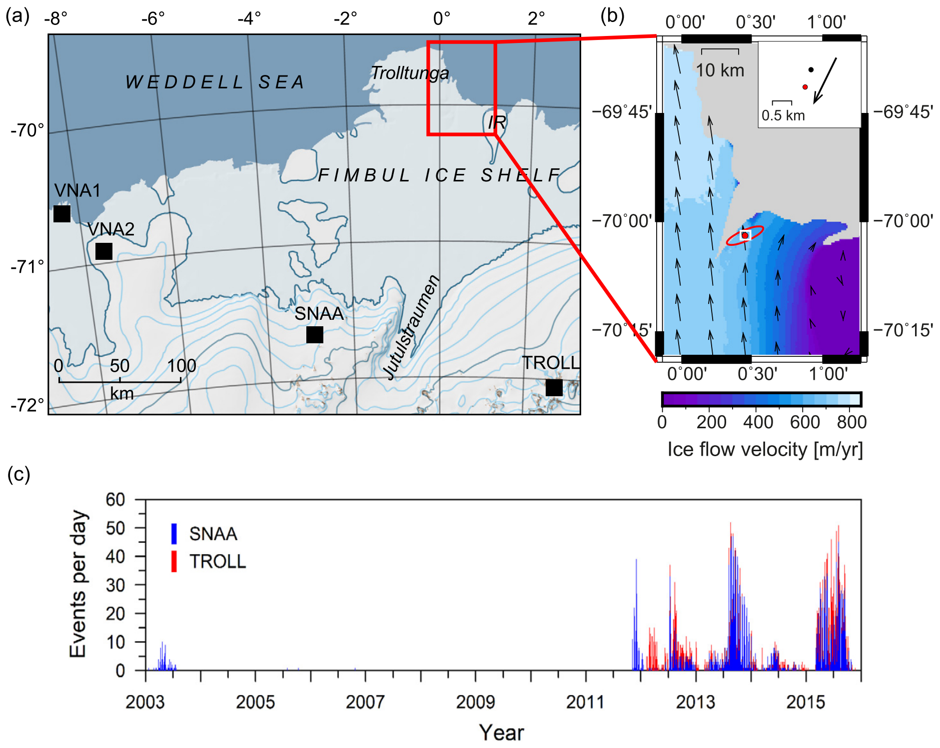

Fig. 1. Geographic and temporal aspects of observed cryoseismicity. (a) Map of western DML. Grounded ice is in white, floating ice shelf in light blue, ocean in blue and bedrock outcrops in brown. Thin contour lines are topography in 200 m increments. The locations of permanent seismic stations in the region are noted with black squares. IR marks the Kupol Moskovskij ice rise. The red rectangle encloses the source region of the cryoseismic activity shown in panel (b). (b) The cryoseismicity source region. The red circle notes the absolute location result for the source of the large cryoseismic event that occurred on 9 September 2013. The overall uncertainty of this estimate is expressed by the 95% confidence-level error ellipse, shown in red. The colour scale describes ice flow velocity in m/yr and the vectors show direction of flow (Mouginot et al., 2012; Rignot et al., 2011, 2017), scaled to a maximum of 850 m/yr. The white rectangle encloses the area in the inlet, that shows the absolute location epicentre in red and the relative location estimate in black, the arrow noting the direction of epicentre migration. (c) Number of cryoseismic events per day from 2003 to end 2015 (no detections between 1997 and 2003), based on the results of the CC-detector at SNAA (blue) and TROLL (red).

of the FIS cavity has a deep seabed (e.g., Nøst, 2004), near the calving front, the ice shelf becomes locally grounded on shallow bathymetric features that either divert ice flow (ice rises) or allow it to continue over them (ice rumples) (Matsuoka et al., 2015; Van Oostveen et al., 2017).

We present seismic records of an almost two decade long continuous monitoring of a specific source region at the FIS, showing emergent activity and trends over several years with strikingly similar and regular seismic events near the ocean front, in an area of outcrops of bedrock. A key question is whether the distinct seismicity pattern can be explained with established, physics-based models of earthquake triggering, and whether environmental drivers can be identified and quantified. We employ a simple mechanical model based on tidally modulated shear and normal stress and demonstrate that this activity is likely related to stick-slip motion of the thickened ice shelf, which is newly grounded on a shallow bathymetric feature.

2. Data and methods

2.1. Data

We use waveform data from the permanent, international seismic network in DML (Fig. 1a). Continuous data are used from the broadband, three-component stations SNAA and TROLL, situated at the South African research station SANAE IV and the Norwegian station Troll, respectively. Employed SNAA records span the time-period March 1997 to end 2015, and TROLL data February 2012 to end 2015. In addition, we use selected records from the Watzmann seismic array, deployed around station VNA2, both belonging to the seismic network of the German research station Neumayer III.

Ocean tide heights for the study region, sampled at each full minute, are estimated from the high-resolution regional inverse tide model CATS2008a_opt (Padman et al., 2002, 2008) for the ocean around Antarctica, including the areas under the floating ice shelves. GPS measurements (Kohler and Langley, 2016) obtained in November 2010 at a location near the study region (∼30 km to the SSE) are used to assess the accuracy of the predicted tidal phase.

2.2. Compilation of cryoseismic event catalogue

2.2.1. Detection by waveform cross-correlation

The observed cryoseismic events have so similar waveforms that they can be identified by visual inspection (Fig. 2). Therefore, we compile our event catalogue using the array-based waveform cross-correlation (CC) detector of Gibbons and Ringdal (2006). Small magnitude events are detected through the enhancement of signal-to-noise ratio (SNR), by stacking the correlation traces for all individual channels of a seismic array or a single, three-component station. Master template events (Table S1 in Supplementary Material), selected to have sufficiently high SNR and to sample adequately intervals of high activity, as well as to cover the entire duration of the study, run through the continuous waveform records of TROLL and SNAA in search of similar events, based on a user defined SNR threshold. The master templates employ the entire body-wave wavetrain, with a length of 50 s for TROLL and 45 s for SNAA, bandpass filtered in the frequency range of maximum SNR (2–6 Hz). Detection thresholds (SNR, CC-coefficient) are defined through visual inspection of a large sample of results, ac-