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Brief Communication: Newly developing rift in Larsen C Ice Shelf presents significant risk to stability

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Abstract

An established rift in the Larsen C Ice Shelf, formerly constrained by a suture zone containing marine ice, grew rapidly during 2014 and is likely in the near future to generate the largest calving event since the 1980s and result in a new minimum area for the ice shelf. Here we investigate the recent development of the rift, quantify the projected calving event and, using a numerical model, assess its likely impact on ice shelf stability. We find that the ice front is at risk of becoming unstable when the anticipated calving event occurs.

1 Introduction

The Larsen C Ice Shelf is the most northerly of the remaining major Antarctic Peninsula ice shelves and is vulnerable to changes in both to ocean and atmospheric forcing (Holland et al., 2015). It is the largest ice shelf in the region and its loss would lead to a significant drawdown of ice from the Antarctic Peninsula Ice Sheet (APIS). There have been observations of widespread thinning (Shepherd et al., 2003; Pritchard et al., 2012; Holland et al., 2015), melt ponding in the northern inlets (Holland et al., 2011; Luckman et al., 2014), and a speed-up in ice flow (Khazendar et al., 2011), all processes which have been linked to former ice shelf collapses (e.g. van den Broeke, 2005). Previous studies have highlighted the vulnerability of Larsen C Ice Shelf to specific potential changes in its geometry including a retreat from the Bawden Ice Rise (Kulessa et al., 2014; McGrath et al., 2014; Holland et al., 2015) and Gipps Ice Rise (Borstad et al., 2013). Rift tips in that area have been observed to align as they terminate at a confluence of flow units within the shelf. Several studies have provided evidence for marine ice in these *suture zones* (Holland et al., 2009; Jansen et al., 2013; Kulessa et al., 2014; McGrath et al., 2014). The relatively warm, and thus soft, marine ice has been found to act as a weak coupling between flow units with different flow velocities. It has been concluded that this ice inhibits the propagation of rifts because it can accommo-

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date strain in the ice without fracturing further (Holland et al., 2009; Jansen et al., 2013; Kulessa et al., 2014).

In a change from the usual pattern, a northwards-propagating rift from Gipps Ice Rise has recently penetrated through the suture zone and is now more than halfway towards calving off a large section of the ice shelf (Figs. 1 and 2). The rate of propagation of this rift accelerated during 2014. When the next major calving event occurs, the Larsen C Ice Shelf is likely to lose around 10 % of its area to reach a new minimum both in terms of direct observations, and possibly since the last interglacial period (Hodgson et al., 2006).

Here, using satellite imagery and numerical modelling, we document the development of the rift over recent years, predict the area of ice that will be lost, and test the likely impact of this future calving event on ice shelf stability.

2 Methods

2.1 Satellite observations

We use data from NASA MODIS at medium spatial resolution (250 m, red band) from the near-real-time archive (http://lance-modis.eosdis.nasa.gov/cgi-bin/imagery/realtime.cgi) to monitor the general propagation of the rift and to explore its likely future path (Fig. 1). Using Landsat data at high spatial resolution (15 m, panchromatic) from the NASA archive (http://earthexplorer.usgs.gov/), we measure in detail the rift's recent propagation (Fig. 2). Growth of the rift is assessed by digitizing the position of the rift tip in all Landsat images unobscured by cloud between November 2010 and present (January 2015), working within the Polar Stereographic map projection in which the data were provided. Rift length is presented relative to the position in November 2010 prior to the breach of the Joerg Peninsula suture zone. Rift width is measured at the November 2010 rift tip position. These satellite data are subject to variable cloud conditions and solar illumination, the impact of which we minimize by careful control of

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brightness and contrast. Nevertheless, measurements of rift tip position and width are potentially subject to error of up to a few tens of meters.

To investigate a range of possible outcomes from the proposed calving event, we present two scenarios for the rift trajectory based on its current orientation and direction of propagation, and on visual inspection of MODIS data (Fig. 1). Surface features in these data indicate the scale and orientation of existing weaknesses (e.g. basal crevasses) along which the rift might be expected to preferentially propagate (Luckman et al., 2012). In Scenario I the rift approaches the calving front by the shortest route via existing weaknesses, and so would result in a reasonable minimum estimate for the calved area. In Scenario II the rift continues along its current trajectory for a further 80 km before approaching the ice front. The hypothetical turning point in this scenario is chosen to smoothly continue the orientation of the ice front where the rift will meet it (Fig. 1). We present this as a reasonable possibility for which to test the impact of a calving event, rather than a maximum for the projected calved area. The eventual calving may be within the range we test, or may be more extreme still.

2.2 Numerical modelling

To determine the influence of the potential calving event on the future stability of the Larsen C Ice Shelf we use a numerical ice shelf model, previously applied to the Larsen B (Sandhäger et al., 2005) and the Larsen C ice shelves (Jansen et al., 2010, 2013; Kulessa et al., 2014). This finite difference model is based on the continuum mechanical equations of ice shelf flow. Friction at the ice shelf base as well as vertical shear strain due to bending are neglected. Thus horizontal flow velocities are vertically invariant and the flow field is two-dimensional. In the vertical dimension the model domain is divided into 13 levels, scaled by ice thickness, to allow for a realistic vertical temperature profile, influencing the vertically integrated flow parameter.

Simulations are carried out on a 2.5 km grid varying only the position of the ice shelf calving margin between the present ice front position and rift Scenarios I and II. The model we apply is a steady-state mode which assumes that the ice shelf is not in

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transition from one geometry to another. It is important, therefore, to investigate the present stress field at the predicted calving margin as well as the new stress field at the predicted calving margin under the new geometries. These two states represent the stress field immediately after calving, and the stress field towards which the shelf will develop in time through the process of the velocity field adapting to the new geometry (assuming no immediate further calving). The two stress fields may be different, and may indicate increasing or decreasing stability under the new geometries.

3 Results

3.1 Rift evolution and predicted calving

The rift first crossed the Joerg Peninsula suture zone in 2012 and progressed modestly during 2013 into a region which previously appeared to resist transverse fractures (Fig. 2). The rate of rift propagation increased dramatically sometime between January and August 2014, crossing the entire Trail Inlet flow unit (~ 20 km) in just 8 months. We do not have observations within this time period so we cannot say whether the rift propagation during this time period was uniform or was very rapid for only a short part of it. Between August 2014 and late January 2015, the rift increased in length at a steady rate of ~ 2.5 km yr^{-1}. From the start of our measurements the width of the rift at the 2010 rift tip position has increased at a more uniform rate than the length, and is still growing at a rate of ~ 40 m yr^{-1} (Fig. 2).

The area of Larsen C Ice Shelf after the proposed calving event will be 4600 km^2 less than at present for Scenario I, and 6400 km^2 less for Scenario II (Fig. 1). This amounts to potential area losses of 9 and 12 %, respectively.

3.2 Stress field development

To investigate the impact of the two calving scenarios on ice shelf stability, we present fields of the difference between the predicted directions of ice flow and of first principal stress (the *stress-flow angle*; Fig. 3). This diagnostic has previously been used to investigate ice shelf stability on the basis that existing weaknesses (rifts and crevasses) are typically oriented across-flow (Kulessa et al., 2014). Regions of the shelf exhibiting low stress-flow angles are likely to be more affected by small-scale calving because stresses act to open existing weaknesses; conversely, regions with a stress-flow angle approaching 90° are likely to be stable.

The stress-flow angles at the present (early 2015) ice front are generally high (Fig. 3a) and, as a result, calving events are rare and the ice front is stable (Kulessa et al., 2014). If the ice shelf calves under Scenario I, the new ice front will, in the immediate term, still mostly be fringed by ice with a high stress-flow angle (Fig. 3a). However, this safety margin is narrowed by the calving, and the centre of the new ice front will exhibit very low stress-flow angles. Under this modest calving scenario, if the ice shelf is able to adapt to the new geometry (Fig. 3b), a new region of high stress-flow angles develops, but this region remains significantly narrower than at present. Under calving Scenario II, much more of the ice front is immediately left without a buffer of high stress-flow angle ice (Fig. 3a). Even if it were possible to adapt to this new geometry (Fig. 3c), a significant section of the new ice front would retain very low values of stress-flow angle.

4 Discussion

The rift highlighted here has been present since the earliest satellite imagery (Glasser et al., 2009) but has recently propagated beyond its neighbouring structures to the point at which a large calving event is anticipated. Over the past 4 years the rate of development of the rift width has been steady, but the length has grown intermittently with a particular acceleration during 2014 (Fig. 2). We hypothesize that the strain which opens the rift may be relatively constant, but that the fracture response varies with tip position. This may be a result of variations in fracture toughness of the ice which are

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likely to be related the presence of marine ice in suture zones (Holland et al., 2009; Jansen et al., 2013) and the locations of pre-existing weaknesses.

The reduction in area of Larsen C Ice Shelf under Scenarios I and II of 9 and 12 %, respectively will be significant, but will of course not contribute to immediate sea level rise since the floating ice already displaces its own weight of sea water. The predicted ice loss is also not unprecedented: in the late 1980s a calving event removed 14 % of Larsen C Ice Shelf (Cook and Vaughan, 2010). The real significance of this new rift to this ice shelf is two-fold. First, the predicted calving will reduce its area to a new minimum both in terms of direct observations, and probably since the last interglacial period (Hodgson et al., 2006). Second, unlike during the 1980s, but highly comparable to the development of Larsen B Ice Shelf between 1995 and 2002, the resulting geometry may be unstable. According to the stress-flow angle criterion, our calving scenarios lead to a range of unstable outcomes from partial to significant. Under our modest rift propagation Scenario I, immediately following the predicted calving event, the central part of the ice front will be unstable and prone to persistent calving of small ice blocks as the principal strain works to open existing fractures. It is not clear how quickly the velocity of a real ice shelf will be able to adapt to the new boundary conditions, but even if this is rapid, the margin of stabilizing ice becomes very narrow. Under Scenario II, the unstable part of the new ice front is considerably larger and, even if the flow field adapts quickly to the new geometry, parts of the calving margin remain unstable and prone to run-away calving of a similar nature to Larsen B Ice Shelf between 1995 and 2002. Our model demonstrates that the newly developing rift presents a considerable risk to the stability of the Larsen C Ice Shelf.

5 Conclusions

We have investigated a newly developing rift in the south of Larsen C Ice Shelf which has propagated beyond its neighbours in 2013, and grew very rapidly in 2014. It seems inevitable that this rift will lead to a major calving event which will remove between 9 and

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12 % of the ice shelf area and leave the ice front at its most retreated observed position. More significantly, our model shows that the remaining ice may be unstable. The Larsen C Ice Shelf may be following the example of its previous neighbour, Larsen B, which collapsed in 2002 following similar events.

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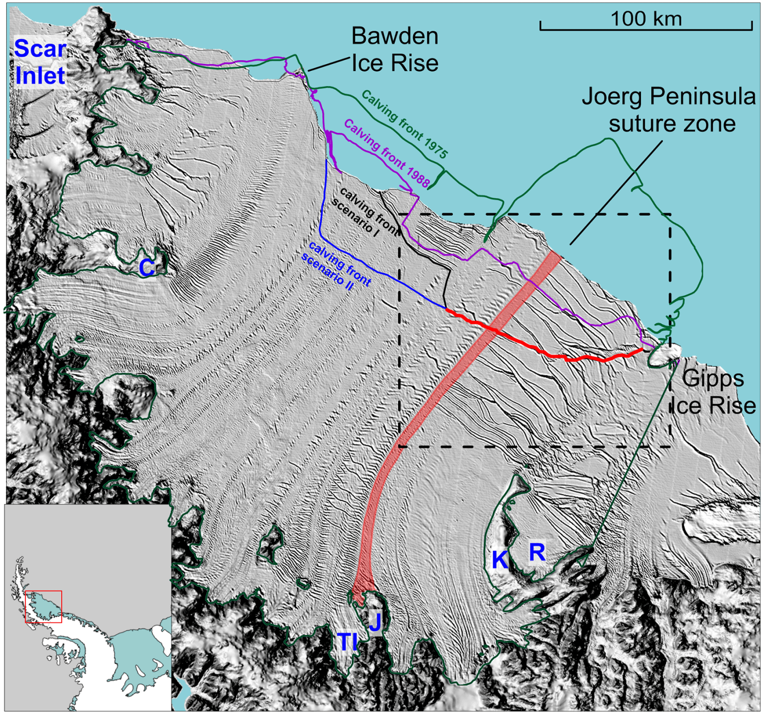

Figure 1. Overview of the Larsen C Ice Shelf in late 2014 showing the contemporary location of the developing rift (red line), and a selection of previous and predicted future calving fronts. Background image is MODIS Aqua, 3 December 2014. Geographic features of interest are marked (R = Revelle Inlet, FI = Francis Island, TO = Tonkin Island, TI = Trail Inlet, SI = Solberg Inlet, K = Kenyon Peninsula) and the dashed box shows the extent of Fig. 2. The highlighted flow line indicates the location of the Joerg Peninsula suture zone.

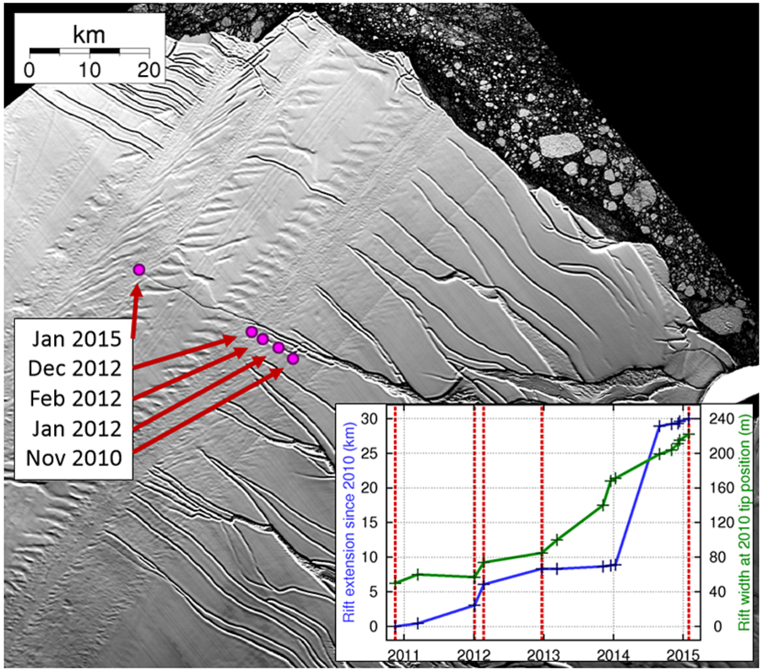

Figure 2. Analysis of rift propagation using Landsat data. Background image, in which the rift is visible, is from 4 December 2014. Inset graph shows the development of rift length with respect to the 2010 tip position, and rift width at the 2010 tip position, measured from 15 Landsat images (crosses). Circles and labels on the map, and dotted red lines on the graph, show the positions of notable stages of rift development.

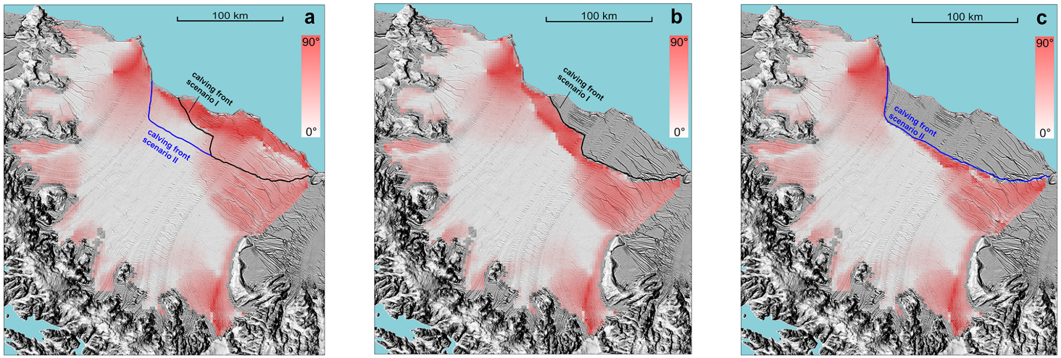

Figure 3. Results from ice shelf flow model: Stress-flow angle fields for the present day ice front geometry **(a)** and for the new geometries under Scenarios I **(b)** and II **(c)**.

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