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The evolving instability of the remnant Larsen B Ice Shelf and its tributary glaciers

Ala Khazendar[a,*], Christopher P. Borstad[a,1], Bernd Scheuchl[b], Eric Rignot[b,a], Helene Seroussi[a]

[a] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA
[b] Earth System Science, University of California, Irvine, Croul Hall, Irvine, CA 92697, USA

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ABSTRACT

Following the 2002 disintegration of the northern and central parts of the Larsen B Ice Shelf, the tributary glaciers of the southern surviving part initially appeared relatively unchanged and hence assumed to be buttressed sufficiently by the remnant ice shelf. Here, we modify this perception with observations from IceBridge altimetry and InSAR-inferred ice flow speeds. Our analyses show that the surfaces of Leppard and Flask glaciers directly upstream from their grounding lines lowered by 15 to 20 m in the period 2002–2011. The thinning appears to be dynamic as the flow of both glaciers and the remnant ice shelf accelerated in the same period. Flask Glacier started accelerating even before the 2002 disintegration, increasing its flow speed by ∼55% between 1997 and 2012. Starbuck Glacier meanwhile did not change much. We hypothesize that the different evolutions of the three glaciers are related to their dissimilar bed topographies and degrees of grounding. We apply numerical modeling and data assimilation that show these changes to be accompanied by a reduction in the buttressing afforded by the remnant ice shelf, a weakening of the shear zones between its flow units and an increase in its fracture. The fast flowing northwestern part of the remnant ice shelf exhibits increasing fragmentation, while the stagnant southeastern part seems to be prone to the formation of large rifts, some of which we show have delimited successive calving events. A large rift only 12 km downstream from the grounding line is currently traversing the stagnant part of the ice shelf, defining the likely front of the next large calving event. We propose that the flow acceleration, ice front retreat and enhanced fracture of the remnant Larsen B Ice Shelf presage its approaching demise.

1. Introduction

The disintegration of the northern and central parts of the Larsen B Ice shelf (LBIS) over six weeks in 2002 represented an invaluable large-scale natural experiment. It allowed a direct comparison between the responses of the glaciers terminating where the ice shelf no longer existed, with those glaciers still buttressed by the remnant part of the ice shelf that survived in the southern SCAR Inlet (Fig. 1a). The striking flow acceleration of the glaciers that lost buttressing, similar to the acceleration of the glaciers feeding the Larsen A Ice Shelf after its collapse in 1995, left no doubt about the importance of coupling between ice shelves and their tributaries, and the role of ice shelves in regulating the volume of ice that these glaciers discharge into the ocean (Rott et al., 2002; De Angelis and Skvarca, 2003; Rack and Rott, 2004; Rignot et al., 2004; Scambos et al., 2004). Several subsequent studies unsurprisingly focused on the fast changing tributary glaciers in the Larsen A and northern and central Larsen B embayments (e.g., Hulbe et al., 2008; Shuman et al., 2011; Rott et al., 2011; Berthier et al., 2012). In the meantime, earlier reports after the 2002 collapse emphasized the little change exhibited by the surviving southern LBIS remnant and its main tributary glaciers, Leppard, Flask and Starbuck. These reports detected no change in the surface elevation of Flask Glacier between 2003 and 2004 (Scambos et al., 2004), some acceleration in the flow of Flask between 1996 and 2003, and a 15% speeding up in the flow of Flask and Leppard by the end of 2003 (Rignot et al., 2004). Such early observations led to the suggestion that complete removal of an ice shelf might be necessary to initiate tributary glacier acceleration (Rignot et al., 2004; Scambos et al., 2004). More recent observations, however, are finding indications of change. Thus, surface lowering for both Leppard

* Corresponding author. Tel.: +1 818 393 1581.
E-mail address: ala@jpl.nasa.gov (A. Khazendar).
[1] Present address: Department of Arctic Geophysics, The University Centre in Svalbard, Longyearbyen, Norway.

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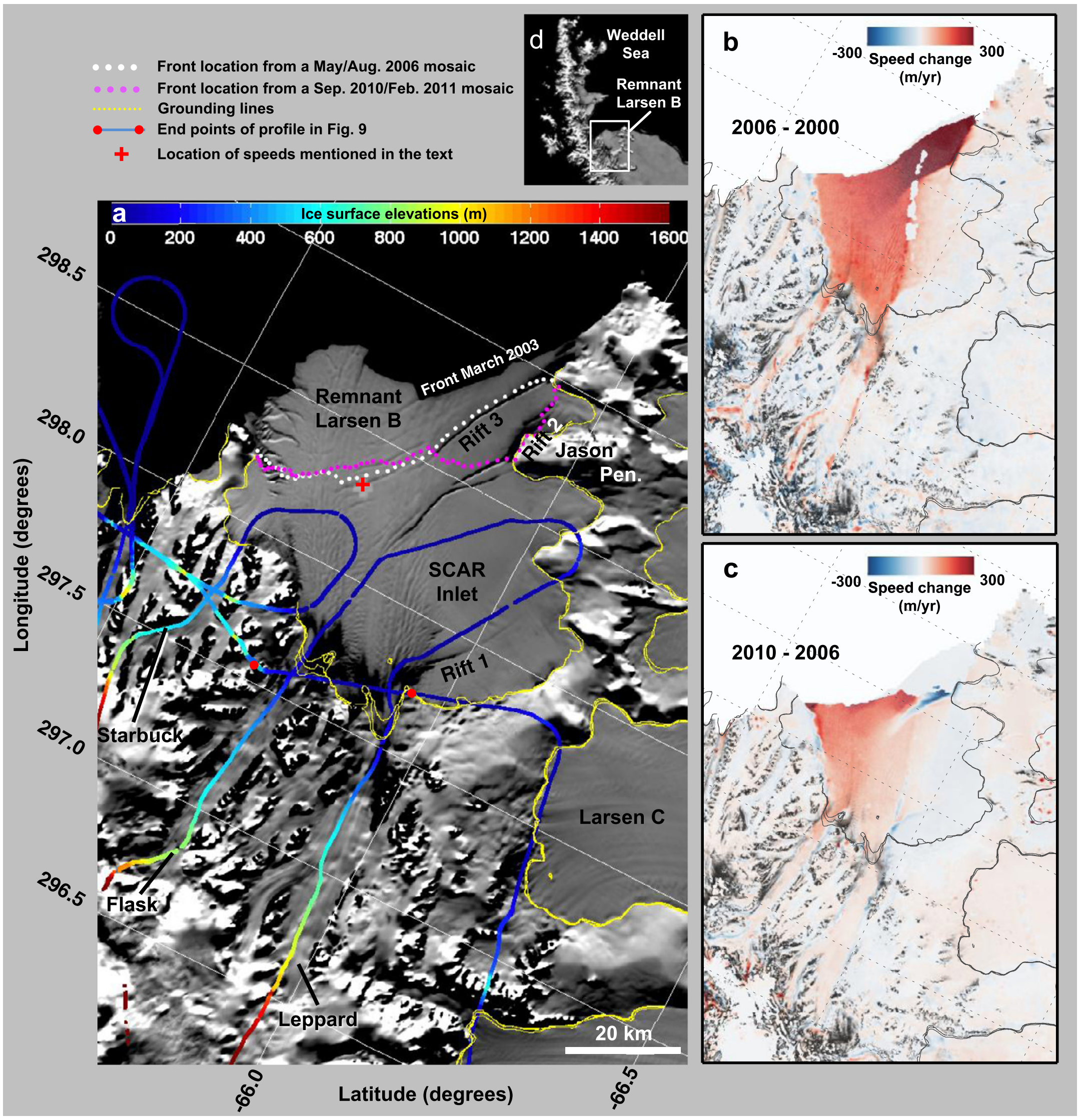

Fig. 1. (a) The study area showing ATM surface elevations (relative to the WGS84 ellipsoid) along the flight path of the 2011 IceBridge campaign, the most recent to overfly this part of the Antarctic Peninsula. Background image is from the 2003–2004 MODIS Mosaic of Antarctica (MOA; Haran et al., 2005). Front location in the MOA image is from March 2003 (Skvarca et al., 2004). (b) Surface ice flow speed change in the study area: speed in year 2000 subtracted from speed in year 2006. (c) Speed in 2006 subtracted from that in 2010. Background in b and c is a composite of RADARSAT-1 images acquired in 2000 as part of the Modified Antarctic Mapping Mission. An ocean mask is applied (Rignot et al., 2013). Panels 1b and 1c cover the same area as panel 1a. They also show the same latitude, longitude and grounding lines. (d) Location of the remnant LBIS in the northern Antarctic Peninsula.

and Flask glaciers was reported for the period 2004–2006, but surface elevation gains or no change were found before and after that period (Shuman et al., 2011), and a negative mass balance for the three main tributary glaciers combined calculated for the period 2001–2010 (Scambos et al., 2014). Also, progress was made in inferring the ice thickness and bed topography of Flask and Starbuck glaciers (Farinotti et al., 2013, 2014).

Here, we focus on the remnant LBIS and its main tributary glaciers, Leppard, Flask and Starbuck. To quantify changes in the surface elevations of the glaciers we analyze ATM laser altimetry from Operation IceBridge and pre-IceBridge campaigns. We find changes in ice flow speeds of these glaciers and the remnant ice shelf from InSAR data. We trace the front positions of the remnant LBIS using SAR mosaics. We finally apply numerical modeling to infer the rheology and backstress fields of the ice shelf to assess the changes in the prevalence of fracture and in buttressing. We present our findings in two parts. In Section 3 we describe the observations of the remnant LBIS and its tributary glaciers, and its modeled rheology and backstress fields. In Section 4 we explore the implications of these results to the question of ice shelf instability, noting that the concurrence of enhanced fracture, front retreat and ice flow acceleration being exhibited by the remnant LBIS is reminiscent of the events preceding the 2002 disintegration (Khazendar et al., 2007).

2. Data and methods

2.1. ATM laser altimetry

We find surface elevation changes from the measurements of the Airborne Topographic Mapper (ATM), which is a laser altimeter that has been flying since 2009 as part of Operation IceBridge but which had flown over Antarctica earlier during the years 2002, 2004 and 2008. Its measurements of surface elevations (Level-2 Icessn Elevation, Slope, and Roughness data) are condensed using the Icessn algorithm that fits a plane to blocks of points selected at regular intervals along track and several across track. The resulting data are presented with an along-track spacing of 50 m. Each