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Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013

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Abstract

We use repeat-pass SAR data to produce detailed maps of surface motion covering the glaciers draining into the former Larsen B ice shelf, Antarctic Peninsula, for different epochs between 1995 and 2013. We combine the velocity maps with estimates of ice thickness to analyze fluctuations of ice discharge. The collapse of the central and northern sections of the ice shelf in 2002 led to a near-immediate acceleration of tributary glaciers as well as of the remnant ice shelf in Scar Inlet. Velocities of the glaciers discharging directly into the ocean remain to date well above the velocities of the pre-collapse period. The response of individual glaciers differs and velocities show significant temporal fluctuations, implying major variations in ice discharge and mass balance as well. Due to reduced velocity and ice thickness the ice discharge of Crane Glacier decreased from 5.02 Gt a^{-1} in 2007 to 1.72 Gt a^{-1} in 2013, whereas Hektorja and Green glaciers continue to show large temporal fluctuations in response to successive stages of frontal retreat. The velocity on Scar Inlet ice shelf increased two- to three fold since 1995, with the largest increase in the first years after the break-up of the main section of Larsen B. Flask and Leppard glaciers, the largest tributaries to Scar Inlet ice shelf, accelerated. In 2013 their discharge was 38 %, respectively 45 %, higher than in 1995.

1 Introduction

Atmospheric warming and changes in ocean conditions during the past decades led to wide-spread retreat of ice shelves around the Antarctic Peninsula (API) (Cook and Vaughan, 2010). Progressive retreat culminated in the final disintegration of the Larsen A ice shelf in January 1995 and of the northern and central sections of the Larsen B ice shelf in March 2002 (Rott et al., 1996; Rack and Rott, 2004; Glasser and Scambos, 2008). The glaciers flowing from the Antarctic Peninsula plateau, previously feeding the ice shelves, became tidewater calving glaciers and accelerated, resulting in increased

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ice discharge (Rott et al., 2002; De Angelis and Skvarca, 2003; Rignot et al., 2004; Scambos et al., 2004). The response of these glaciers to ice-shelf disintegration is of particular interest not only for quantifying the contributions of API outlet glaciers to sea level rise, but also for studying processes of ice shelf retreat and interactions with grounded ice masses.

Investigations on retreat and acceleration of glaciers in the Larsen ice shelf region so far focused mainly on the Larsen B embayment. Rignot et al. (2004) and Scambos et al. (2004) reported on acceleration of main glaciers draining into the Larsen B embayment, based on analysis of satellite images. Rott et al. (2011) derived velocities of nine Larsen B glaciers in pre-collapse state and in 2008 and 2009 from high-resolution radar images, and estimated calving fluxes and mass balance. Estimates of the mass balance of Larsen B glaciers in recent years have been derived from changes in surface topography. Shuman et al. (2011) and Scambos et al. (2011) tracked elevation changes over the period 2001 to 2009 using optical stereo imagery and laser altimetry of ICE-Sat and of the airborne ATM sensor. Shuman et al. (2011) reported a combined mass loss of -8.4 Gt a^{-1} for these glaciers for the period 2001 to 2006, excluding ice lost by frontal retreat. Berthier et al. (2012) explained that the mass loss of former Larsen B tributary glaciers was going on unabated over the period 2002 to 2011, reporting a mass loss rate of -9.04 Gt a^{-1} for the period 2006 to 2010/11. Scambos et al. (2014) used satellite laser altimetry and satellite stereo-imagery to map ice elevation change and infer mass changes for 33 glacier basins of the northern API over the time span 2001–2010. They report a mass balance of -7.9 Gt a^{-1} for the tributaries to the Larsen B embayment and -1.4 Gt a^{-1} for the tributaries to the remnant ice shelf in Scar Inlet.

These reports provided estimates of mass depletion for the Larsen B tributaries integrated over multi-year periods. Here we present new analysis of satellite data showing the spatial and temporal variability in velocities over the whole Larsen B area dating back to 1995. We have included new satellite data not used in any previous studies so far, and have also reprocessed satellite radar images to generate fully consistent and comparable data sets on surface velocities. Our work includes both recent acquisi-

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tions by high resolution radar sensors as well as archived data, some of which have not been exploited until now. Velocity data and estimates of ice thickness are used to derive ice discharge at different epochs, showing significant temporal variability as well. The data sets provide a comprehensive basis for studying the dynamic response of the ice masses to the disintegration of Larsen B, including the glaciers that are draining now directly into the ocean as well as the remnant ice shelf in Scar Inlet and its tributary glaciers.

2 Data and methods

We derived maps of ice flow velocities from repeat-pass Synthetic Aperture Radar (SAR) data of the satellite missions ERS-1, ERS-2, Envisat, TerraSAR-X (TSX), and ALOS, applying either offset tracking or SAR interferometry (InSAR). The source data were obtained from the archives at the European Space Agency (ESA) and the German Aerospace Center (DLR). We retrieved two-dimensional surface displacement in radar geometry which we projected onto the surface, defined the ASTER based Antarctic Peninsula DEM (API-DEM) of Cook et al. (2012), in order to produce maps of surface velocities. The resulting maps of the surface velocity vector are provided in Antarctic polar stereographic projection resampled to a 50 m grid.

The spatial resolution of the SAR images along the flight track and in radar line-of sight (LOS) ranges from 1.2 m × 3.3 m for TSX and 5.6 m × 9.6 m for the Advanced Synthetic Aperture Radar (ASAR) of Envisat. The time span of the repeat pass image pairs ranges from one day for ERS-1/ERS-2 tandem images to 46 days for ALOS Phased Array L-band SAR (PALSAR) images. Because of temporal decorrelation of the phase of the backscatter signal the interferometric (InSAR) method could only be applied for ERS-1/ERS-2 tandem images, available for the years 1995 to 1999. InSAR provides the surface displacement in LOS. We combined ascending and descending image pairs to derive 2-D velocity fields for the period late 1995 to early 1996, based on two different LOS directions from crossing orbits. Being well before the collapse of

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the Larsen B ice shelf, this period is of particular importance as reference for studying the impact of ice shelf disintegration on tributary glaciers. For 1999 ERS SAR data were available only from single view direction. Assuming unaltered flow direction since 1995/96, we derived velocity maps in November 1999, using the argument from the velocity maps of crossing orbits.

For retrieving maps of ice motion from the TSX SAR, Envisat ASAR and ALOS PAL-SAR we apply the offset tracking technique which is based on cross-correlation of templates in SAR amplitude images. Offset tracking delivers along track and LOS velocity components from a single image pair. It is less sensitive to displacement than InSAR, but this drawback is (at least partly) compensated by the longer time span between the repeat pass images (Rott, 2009). We used templates of 64×64 and 96×96 pixels size and applied sampling steps of 10 pixels for generating velocity maps. TSX images are our main data sources for velocity maps between 2007 and 2013, complemented by occasionally available ALOS PALSAR data. Envisat ASAR data are the basis of velocity maps for 2003 to 2006 on large glaciers and on the Scar Inlet ice shelf.

The uncertainty of retrieved velocities differs between the sensors. The ERS InSAR motion maps are based on InSAR pairs of good coherence, with typical accuracy of 0.1 fringe (phase cycle of 2π), corresponding to 4 mm in LOS and 10 mm projected onto the surface. For one day repeat pass this corresponds to $\pm 0.01 \text{ m d}^{-1}$ uncertainty in surface velocity. For offset tracking the accuracy depends on the pixel size, the time interval, and the quality of features in order to obtain good correlation peaks. We excluded areas of low correlation, so that the uncertainty for retrieval of displacement is on the order of 0.2 to 0.3 pixels. The resulting uncertainties in the magnitude of surface motion are $\pm 0.05 \text{ m d}^{-1}$ for TSX SAR, $\pm 0.08 \text{ m d}^{-1}$ for ALOS PALSAR and $\pm 0.15 \text{ m d}^{-1}$ for Envisat ASAR.

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The mass flux across a gate Y near the calving front or grounding line is computed according to:

$$F_Y = \rho_i \int_0^Y [u_m(y) \sin \theta H(y)] dy \quad (1)$$

Where ρ_i is the density of ice, u_m is the vertically averaged horizontal velocity, θ is the angle between the velocity vector and the gate, and H is the ice thickness. We use a column-average ice density of 900 kg m^{-3} to convert ice volume into mass. The surface velocity, u_s , is obtained from satellite data. For calving glaciers full sliding is assumed. For glaciers discharging into the ice shelf we assume $u_m = 0.95 u_s$. This is based on an estimate for ice deformation in the lower section of main outlet glaciers applying the laminar flow approximation (Paterson, 1994).

Ice thickness at the flux gates is obtained from various sources. For Flask and Starbuck glaciers radar sounding data are available (Farinotti et al., 2013, 2014). For Crane Glacier the cross section of the calving gate is deduced from bathymetric data (Zgur et al., 2007; Rott et al., 2011). For Leppard Glacier ice thickness data of Huss and Farinotti (2014) are used. For calving fluxes of Crane, Hektoría and Green glaciers the ice thickness in the centre of the flux gate is estimated from surface height above sea level assuming flotation. The central sections of the glacier fronts have been floating at least since 2007. The surface elevation near the calving front is obtained from laser ranging data of ICESat and Airborne Thematic Mapper (ATM) (Shuman et al., 2011; Krabill and Thomas, 2013, 2014) and in 2011 and 2013 also from digital elevation data of TanDEM-X (Krieger et al., 2013). For uncertainty estimates of mass fluxes through the gates we assume $\pm 10\%$ error of the cross section area for Starbuck, Flask and Crane glaciers, and $\pm 20\%$ for Hektoría, Green and Leppard glaciers. For velocity across the gate we assume $\pm 5\%$ uncertainty.

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3 Evolution of glacier velocities

3.1 Velocities and frontal retreat of glaciers draining into Larsen B embayment

The location of the glacier basins is shown in Fig. 1, and the areas of the basins for the region upstream of the 1995 grounding line and of the 2012 glacier fronts are specified in Table 1. The basin outlines inland were provided by A. Cook based on the ASTER derived Antarctic Peninsula DEM (API-DEM) (Cook et al., 2012). The positions of the grounding lines in 1995 are from the ERS InSAR analysis of Rack (2000). The update of glacier fronts and areas in 2012 is based on a Landsat image of 12 January 2012. Before 2002 all glaciers between the Seal Nunataks and Jason Peninsula drained into Larsen B ice shelf. Since its collapse, in March 2002, they drain into a wide bay and in the remnant part of the ice shelf in Scar Inlet. The area of the Larsen B tributary glaciers decreased by 270 km² since 1995. The 2012 area refers to the ice front rather than the grounding line, so that the total loss in grounded ice extent is slightly higher because frontal sections of some glaciers are floating.

The largest glaciers north of Scar Inlet, where the ice shelf disappeared in 2002, are Hektoria-Green-Evans (HGE) and Crane glaciers. Before the ice shelf breakup the frontal zone of HGE glaciers was formed by the confluence of the three glaciers, stretching across a wide bay. Following the ice shelf collapse these frontal regions of HGE retreated quickly (Rack and Rott, 2004; Scambos et al., 2004), suggesting that they were lightly grounded and sensitive to changes in ice-shelf buttressing. The ice shelf collapse resulted in the progressive breakup of larger and larger areas of grounded ice concomitant with acceleration of ice flow and dynamic thinning, amounting to a total retreat of 174 km² by January 2012. On Crane Glacier the loss of grounded ice has been smaller (35 km²) because the terminus is confined in a narrow fjord. Jorum Glacier lost 24 km² in grounded ice, and Punchbowl Glacier 12 km². The frontal positions of Mapple and Pequod glaciers have been stationary, while Melville Glacier lost 4.1 km² in area. The frontal velocity of these three glaciers increased between 1999 and 2008 by a factor of 1.8, 2.0 and 2.8 respectively, but the mass turnover is

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rather modest so that these glaciers have been less affected by the ice shelf breakup (Rott et al., 2011).

An overview map of surface velocities for the Larsen B region is shown in Fig. 2a for the year 1995 based on ERS InSAR data, and in Fig. 2b as composite of several velocity maps from TSX and ALOS PALSAR offset tracking analysis of the years 2008 to 2012. As the figures show, a major flow acceleration is observed for HGE, Jorum, Punchbowl, and Crane glaciers. Flask and Leppard glaciers in Scar Inlet also accelerated, but at a lower rate. In order to investigate the temporal evolution of velocities we extracted profiles along the central flow line of the main glaciers: Hektoría, Green, Jorum and Crane, now terminating with calving fronts (Fig. 3), and Flask and Leppard which are still confined by the remnant part of Larsen B ice shelf. The location of the profiles is charted in Fig. 1.

The velocity of Hektoría and Green glaciers is presently still much higher than in 1995, but has been subject to strong variations since 2002 associated with glacier thinning and frontal retreat. The velocity profiles (Fig. 3) show periods of acceleration followed by gradual deceleration. Superimposed on this general trend there is a smaller annual variation in velocities with higher velocities in summer. These annual variations in flow may possibly be related to changes in sea ice cover and associated buttressing. In 2008 Hektoría and Green glaciers still had a common terminal section, but the lower terminus was already heavily fractured (Fig. 4). In 2009 a major section along the front broke away leading to another rise in velocities. In November 2009 the frontal velocity of Hektoría and Green glaciers was about twice the velocity at the same point in October 2008. The high velocities persisted until March 2012, after which significant slow-down and an interim advance of the floating tongues was observed in 2013.

Ice flow and calving fluxes of Crane and Jorum glaciers have been investigated by Rott et al. (2011) based on ERS InSAR data of 1995 and 1999 and TerraSAR-X data of several dates between October 2008 and November 2009. During 2008/09 the velocity was comparatively stable on both glaciers (Rott et al., 2011). Our analysis of the extended TSX data set shows a strong deceleration since 2007. The velocity in the cen-

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tre of the flux gate 1 km upstream of the 2008 glacier front decreased from 6.8 m d^{-1} in June 2007 to 5.2 m d^{-1} in November 2008 and October 2009, and to 2.9 m d^{-1} in November 2013. Between 2003 and 2007 the strong acceleration of Crane Glacier caused dynamic thinning and subsidence on the order of 150 m on the lower terminus (Scambos et al., 2011). In spite of continued thinning, although with reduced rate, the position of the glacier front has been rather stable since 2006. The shape of the glacier bedrock in form of a deep canyon, inferred from bathymetric data, indicates that the central part of the lower terminus has been ungrounded since several years (Rott et al., 2011). This suggests that lateral drag plays a key role in maintaining the frontal position since 2006. Also the velocity of the Jorum Glacier terminus is still higher than before ice shelf collapse. As on Crane Glacier, the velocity decreased since 2007, but at smaller percentage.

3.2 Velocities of SCAR Inlet ice shelf and tributary glaciers

The area of the ice shelf in Scar Inlet decreased from 3463 km^2 on 18 March 2002 (Rack and Rott, 2004) to 1870 km^2 in January 2012. The velocities on the ice shelf section which is nourished by Flask and Leppard glaciers increased two- to three-fold since 1995/99. This section is separated by distinct shear zones from the ice shelf sections along Jason Peninsula and the section downstream of Starbuck and Stubb glaciers (Fig. 5). Major rifts are apparent on the ice shelf in the ASAR image of 28 January 2004, indicating that the disintegration of the central and northern sections of Larsen B ice shelf affected the stability of the remnant ice shelf section in Scar Inlet rather soon. In June 2004 the velocities along the central flowlines downstream of Flask and Leppard glaciers had already doubled compared to the pre-collapse values (Fig. 6), another indication that the Larsen B disintegration event had a rather immediate impact on the stress field of Scar Inlet ice shelf. In the profiles of 1995 and 1999, based on one-day InSAR repeat pass data, we exclude the tidal deformation zone because of ambiguity between horizontal motion and vertical displacement.

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In spite of still being backed up by an ice shelf, both Flask and Leppard glaciers accelerated since 1995/99 (Fig. 6). Between 1995 and 1999 there are no apparent differences in velocity. On Flask Glacier the mean velocity in 2009 to 2013 at the flux gate, 6 km above the grounding line, is 38 % higher than the velocity in 1995/99. On Leppard Glacier the velocity at the flux gate, 4 km above the grounding line, increased by 45 %. The signal of acceleration between the two periods extends more than 30 km up-glacier, with velocity change decreasing with distance from the grounding zone. The acceleration of the glaciers is in line with substantial acceleration of Scar Inlet ice shelf since 2002. The main speed-up happened before 2009. Between September 2009 and July 2013 the velocities have been rather stable. The smaller Rachel, Starbuck and Stubb glaciers do not show any significant change in velocities since 1995.

4 Temporal variations of ice discharge

Estimates of ice discharge of Crane, Jorum, Hektorja, and Green glaciers in different years are presented in Table 2. The estimated discharge of Hektorja and Green glaciers for 1995 amounts to 1.19 Gta^{-1} using the same gate near the 2008 front as Rott et al. (2011) (Fig. 4). By February/March 2004, two years after the collapse, the maximum velocity at this gate was 5.1 m d^{-1} (1862 ma^{-1}), five times higher than in 1995. A transect on Hektorja Glacier, acquired by NASA ATM in 2004 (Krabill and Thomas, 2013), allows for an estimate of an ice thickness of 406 m under the assumption of flotation, resulting in a flux of 4.74 Gta^{-1} . The estimate for 2008 by Rott et al. (2011) amounts to 2.88 Gta^{-1} . At that time the two glaciers still formed a single calving front. The maximum velocity at the front was 4.23 m d^{-1} (1545 ma^{-1}) and the maximum ice thickness of the (floating) calving gate, inferred from an ICESat profile, is estimated at 268 m. Because of retreat of the terminus by 4 km between 2008 and 2011, the gates, used here for 2010 and 2013 fluxes, are shifted inland (Fig. 4). A transect of surface elevation on Hektorja Glacier was measured in 2011 by ATM during the IceBridge campaign. The freeboard at the gate is 55 m, resulting in a maximum

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ice thickness of 450 m assuming freely floating ice. The corresponding numbers for the calving fluxes, with November 2010 velocities, are 1.67 Gt a^{-1} for Hektor Glacier and 1.99 Gt a^{-1} for Green Glacier, adding up to 3.66 Gt a^{-1} which is 27 % higher than the flux in 2008. By July 2013 the combined flux decreased to 3.05 Gt a^{-1} . This illustrates the impact of velocity variations on calving fluxes, resulting in major fluctuations of glacier net mass balance within a few years.

For computing the ice flux for Crane Glacier, the same flux gate about 1 km inland of the front location in 2008 and 2009 is used as by Rott et al. (2011) (Fig. 4). Because of slow down of ice flow (Fig. 3) and reduction in ice thickness, the calving flux of Crane Glacier decreased significantly during recent years. For June 2007 the flux across the gate is estimated at 5.02 Gt a^{-1} , 4.4 times higher than the pre collapse calving flux of 1.15 Gt a^{-1} . Until November 2013 it decreases to 1.72 Gt a^{-1} , one third of the 2007 flux.

In 1995 the combined mass flux of Jorum Glacier across the 2008 calving gates of the two glacier branches amounted to 0.35 Gt a^{-1} (Rott et al., 2011). In 2008 elevation data from an ICESat transect close to the gates were used to estimate the maximum ice thickness. For estimating the ice thickness in 2012 we use surface elevation data of the TanDEM-X satellite mission, which show surface lowering by a few metres since 2008. The estimated calving flux for the two branches of Jorum Glacier decreased from 0.61 Gt a^{-1} in 2008 to 0.45 Gt a^{-1} in 2013.

For Starbuck, Flask and Leppard glaciers data on ice thickness are available from ice sounding measurements and ice flow modelling (Farinotti et al., 2013, 2014; Huss and Farinotti, 2014). On Starbuck Glacier the TSX ice motion data of 2009 and 2011 do not reveal any significant difference vs. 1995 (Fig. 7). Therefore the discharge has likely not changed significantly either. The flux through the cross section near the grounding line, with maximum velocity of 0.34 m d^{-1} (124 m a^{-1}), yields a flux of 0.67 Gt a^{-1} (Table 3). The ice on Flask and Leppard glaciers is thicker and velocities are higher. For Flask Glacier the mass flux is derived for a gate along a transverse profile 4 km above the grounding line (Fig. 7). This corresponds to the position of radio echo sounding profile 1, acquired by the BAS Polarimetric Airborne Survey Instrument in November 2011

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(Farinotti et al., 2013). In the centre of the profile the ice thickness is 690 m. In 1995 and 1999 the velocities in the centre are 1.31 m d^{-1} (478 m a^{-1}), respectively 1.36 m d^{-1} (496 m a^{-1}), resulting in an ice discharge of 0.78 Gta^{-1} . Velocities in 2009 to 2013 range from 1.76 m d^{-1} (642 m a^{-1}) to 1.93 m d^{-1} (704 m a^{-1}), and ice discharge ranges from 1.08 to 1.23 Gta^{-1} , without a clear temporal trend. The discharge increased between 38 and 57 % compared to 1995 and 1999. On Leppard Glacier the centre line velocity at the gate near the grounding line has increased from 1.00 m d^{-1} (365 m a^{-1}) in 1995 to 1.44 m d^{-1} (526 m a^{-1}) in 2009 and 1.48 m d^{-1} (541 m a^{-1}) in 2013. The flux increased from 1.22 Gta^{-1} in 1995 to 1.74 Gta^{-1} in 2011 and 1.78 Gta^{-1} in 2013, an increase of 43 and 46 %, respectively. As for Flask Glacier, there is no significant difference between 2009 and 2013.

The flow acceleration and increased ice discharge results in dynamic thinning which is confirmed by ICESat laser altimeter measurements. For analysis of elevation change we selected dates with closely spaced ICESat repeat tracks: track 129 of 1 June 2004 and 27 November 2008 shifted by 31 m on Leppard Glacier and 28 m on Flask Glacier; track 390 of 18 June 2004 and 19 March 2008 shifted by 71 m on Leppard Glacier. We corrected for the shift by taking into account the surface slope derived from the API-DEM. For track No. 129, crossing Flask Glacier 0.5 km downstream and Leppard Glacier 5 km upstream of the Flux gate, we obtain a mean annual rate of surface elevation change of -1.93 m a^{-1} on Leppard Glacier and of -2.22 m a^{-1} on Flask Glacier. For track No. 390 we obtain for a profile across Leppard Glacier 13 km upstream of the flux gate a mean annual rate of elevation change of -1.71 m a^{-1} .

5 Discussion

In line with previous studies our data shows a drastic increase in flow velocities of major tributaries following the collapse of Larsen B ice shelf in early 2002. Reduced backstress and frontal retreat caused the signal of flow acceleration that moved up-

glacier. Beyond that, our analysis of new velocity data shows that some of the glaciers slowed down significantly during recent years.

Scambos et al. (2004) present data of ice motion in 2001, 2002, and 2003 along selected points of the central flow-lines of the glaciers Crane, Jorum, Hektor, and Green, derived by feature tracking in Landsat images. They report for a point near the Hektor Glacier front a velocity increase from 1 m d^{-1} in 2001 to 5 m d^{-1} in early 2003. Rignot et al. (2004) derived velocities up to 6 m d^{-1} in 2003 near the front of Hektor Glacier from Radarsat images which agrees with our analysis of ASAR data of December 2003. Scambos et al. (2011) derived velocities for six dates between April 2002 and December 2009 for a point 6 km upstream of the Crane Glacier front, showing a maximum velocity of 5.3 m d^{-1} in January 2006, similar to the value of 5.5 m d^{-1} we derived for this point from TSX data of June 2007.

Subsequently, our analysis shows significant deceleration for Crane Glacier since mid-2007, yet over this time period the position of the ice front has remained comparatively stable. This suggests that the ratio of driving stress vs. lateral shear due to traction at the valley walls decreased, in accordance with decreasing surface slope on the lower glacier terminus. From June 2007 to November 2013 the calving flux of Crane Glacier decreased from 5.02 to 1.72 Gt a^{-1} . Under the assumption that the pre-collapse flux corresponds to the balance flux (Rott et al., 2011), the resulting rate of mass loss decreased from 3.87 to 0.58 Gt a^{-1} . Based on differencing of DEMs from optical stereo imagery in combination with ICESat data, Scambos et al. (2014) report a mean loss rate of 2.24 Gt a^{-1} for the period March 2003 to November 2008. This is 42 % lower than our estimate for June 2007 and 35 % higher than our estimate for 2008/09. These large temporal variations emphasize the importance of using common epochs when comparing glacier contributions to sea level rise obtained by different methods.

Whereas on Crane Glacier a period of major flow acceleration during the first five years after ice shelf disintegration was followed by gradual decrease in velocity, the flow behaviour of Hektor and Green glaciers has been more variable. Periods with increased flow velocities and frontal retreat alternated with periods of comparatively

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stable front positions or short-term advance. ASTER and ICESat data show substantial elevation losses on lower Green Glacier amounting to about 100 m during the time span November 2001 to late 2008 (Shuman et al., 2011). Scambos et al. (2014) report a mean loss rate of 3.84 Gt a^{-1} for the period March 2003 to November 2008 out of which 0.53 Gt a^{-1} are attributed to loss of ice mass above floating for the retreating glacier area. Our estimate of the calving flux across the 2008/09 gate, located about 4 km inland of the 2004 ice front, yields 4.74 Gt a^{-1} for March 2004 and 2.88 Gt a^{-1} for 2008/09. With the estimated balance flux of 1.19 Gt a^{-1} (Rott et al., 2011), the resulting net balance for the glacier area above the 2008/09 gate amounts to -3.56 Gt a^{-1} based on velocities of March 2004. For 2008 the estimated net balance is -1.69 Gt a^{-1} . The loss rate increased in 2010/11, and decreased in 2013, with the discharge in Table 3 referring to gates shifted inland because of frontal retreat.

The different patterns of frontal retreat and flow behaviour depend on glacier geometry, glacier size, topography of the glacier bed, and mass turnover. Hektoria, Green and Evans glaciers, forming a joined terminus in a wide bay in 2002, have been particularly vulnerable to stress perturbation after ice shelf collapse as evident from the frontal retreat. Successive phases of transition from weakly grounded to floating ice due to flow acceleration and thinning, associated with major calving events, have been maintaining high rates of mass depletion for HGE glaciers to date. Crane and Jorum glaciers, terminating in deep and narrow fjords, have been subject to acceleration and major mass depletion during the first five years after ice shelf collapse, but slowed down afterwards. Similar behaviour after retreat in narrow fjords is observed for Sjögren–Boydell glaciers in Prince-Gustav-Channel and for Dinsmoor–Bombardier–Edgeworth glaciers in the Larsen A embayment (Rott et al., 2014). The ratio of longitudinal stress to lateral shear stress is critical for glacier motion in narrow valleys (Hulbe et al., 2008). Decreasing ice thickness and surface slope affect driving stresses causing deceleration in flow. However, considering the ongoing thinning of the terminus and the resulting decrease of lateral shear stress, it can be concluded that Crane and Jorum glaciers will still be subject to major retreat before reaching a new equilibrium state further inland.

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The two main glaciers draining into Scar Inlet ice shelf, Flask and Leppard glaciers, have also been affected by flow acceleration in recent years. GPS measurements at stakes on Larsen B located 50 km downstream of these glaciers showed flow acceleration on the order of 10 % between 1994 and 1999 (Rack, 2000). This indicates that also the southern sections of Larsen B ice shelf had weakened mechanically previous to the disintegration event in 2002, as reported for the northern and central sections (Rack et al., 2000; Rack and Rott, 2004). Our analysis of substantial flow acceleration and development of rifts, evident in satellite data of 2004, imply that the break-up had a near immediate impact on the stress field of Scar Inlet ice shelf. Fricker and Padman (2012) report for two crossover points on Scar Inlet ice shelf relatively constant elevation change of $\sim -0.19 \text{ m a}^{-1}$ during 1992 to 2008. Our analysis on the temporal evolution of ice shelf flow points out that changes in the rheology and stress field might not have been continuous during this period. Main speed-up on Scar Inlet ice shelf occurred during the first two years after the disintegration of the northern and central sections of Larsen B, whereas changes later on were more gradual. According to the spatial pattern of acceleration, with main speed-up in the outflow region downstream of Flask and Leppard glaciers, increased weakening has to be expected for the ice in the shear zones vs. slowly moving ice, and also for the ice immediately downstream of the grounding zone. Numerical models of Larsen B ice shelf in pre-collapse state show a band of weak ice along the shear zone that separates the outflow of Leppard Glacier from the slowly moving ice along Jason Peninsula (Rack et al., 2000; Vieli et al., 2006). The differential acceleration of flow and the formation of additional rifts, which are evident in ASAR images and TSX images over the years 2004 to 2014, indicate that ice in this zone has further weakened since 2002.

Whereas the ice at the flux gates of Leppard and Flask glaciers accelerated from 1995 to 2009 by 44 and 38 %, respectively, the velocity of Starbuck Glacier has been stable. This can on one hand be attributed to the bedrock topography, on the other hand to the rather modest mass turnover. The lower terminus of Starbuck Glacier is firmly grounded, with a broad sub-glacial ridge in the area of the grounding zone (Farinotti

et al., 2014). Under the assumption of mass balance equilibrium, supported by the observed steady ice motion since 1995, a specific surface mass balance $b_n = 230 \text{ kg m}^{-2}$ is inferred from the ice flux across the grounding line

The stable velocity in 1995 and 1999 suggests that Flask Glacier has been close to equilibrium state in those years. Thus, assuming equilibrium condition, the 1995 mass flux of 0.78 Gt a^{-1} across the flux gate results in $b_n = 779 \text{ kg m}^{-2}$, 3.4 times higher than on Starbuck Glacier. The large difference in b_n can be explained by the strong west-east decrease of accumulation (Turner et al., 2002). Flask Glacier flows down from the main ice divide of the peninsula, whereas the upper boundary of Starbuck Glacier is located 25 km to the east of the divide with the trough of the Crane Glacier tongue in between.

Flask and Leppard glaciers have responded to the changing stress conditions on the ice shelf in front by acceleration. The bedrock of Flask and Leppard glaciers ascends towards the grounding zone from depressions several kilometres upstream (Farinotti et al., 2013; Huss and Farinotti, 2014). The elevation of the glacier surface above the bedrock suggests that the glaciers are still firmly grounded above the transects which we use for retrieving the mass fluxes. Consequently, changes in the force balance of the grounding zone probably played a main role for initializing flow acceleration.

Scambos et al. (2014) report rates of mass change of $+0.12 \text{ Gt a}^{-1}$ for Flask Glacier and -1.31 Gt a^{-1} for Leppard Glacier, based on differencing of optical stereo DEMs from November 2001 to November 2006 and ICESat data from 2003 to 2008. Our analysis over recent years does not show a contrasting behaviour for the two glaciers. Under assumption that the 1995 fluxes correspond to the balance fluxes, we obtain for different dates between 2009 to 2013 mass change rates of -0.30 to -0.44 Gt a^{-1} for Flask Glacier and -0.52 to -0.55 Gt a^{-1} for Leppard Glacier.

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The collapse of the main section of Larsen B ice shelf in March 2002 triggered a near immediate response of its tributary glaciers with increased velocities for most glaciers maintained until the present. Acceleration of ice flow is also observed on the remnant part of the ice shelf in Scar Inlet as well as on its major tributaries. Later on the behaviour of the glaciers varies, and velocities show significant fluctuations over time. Whereas, after an initial speed up, the velocity of both Crane and Jorum glaciers decreased significantly since mid-2007, the Hektoria and Green glaciers continue to show widespread fluctuations in velocity and periods of major frontal retreat intermitted by more stable positions or short term frontal advance. This different response can partly be explained by glacier geometry and the geographic setting. Crane and Jorum retreated into deep and narrow fjords while Hektoria and Green glaciers still calve into a wide bay. Ice discharge, being primarily a function of ice velocity and thickness, shows a similar fluctuating pattern over time as velocities, emphasizing the importance of using common epochs for reconciling glacier mass balance estimates by different methods (Shepherd et al., 2012).

Because of the combined effect of reduced velocity and ice thickness, the ice discharge of Crane and Jorum glaciers decreased by 66 % between 2007 and 2013. Both glaciers are expected to retreat further inland before reaching a new equilibrium in spite of slow-down, concluding from ongoing thinning and the increase of floating ice area. Hektoria and Green glaciers maintain variable and high rates of mass depletion in recent years, as the calving front alternates between floating and weakly grounded phases. Increase of flow velocity on Scar Inlet ice shelf and its larger tributaries started soon after the 2002 Larsen B collapse event, but changes have been discontinuous with most of the increase in the first years followed by reduced acceleration rates. On the smaller tributaries changes have been more modest or absent. The ice flow on the ice shelf increased two- to three fold since 1995/99 and the velocity at the flux gates near the hinge line of Flask and Leppard Glaciers, its largest tributaries, increased

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until 2009 by 36 and 44 %, respectively. The fast flowing sections nourished by Flask and Leppard glaciers are separated from the stagnant sections of the ice shelf by distinct shear zones. The enhanced development and widening of rifts and the sustained high velocities are clear signs of ongoing gradual breakup that if continued will lead to a complete disintegration of Scar Inlet in the near future.

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Table 1. Area of glacier basins (in km²) shown in Fig. 1 above the October 1995 grounding line and updated for glacier fronts on 12 January 2012, and change of glacier area 1995 to 2012. NC – no significant change of front position or grounding line. The areas of glacier basins include rock outcrops and mountain slopes.

Nr.	Glacier	Area [km ²] Oct 1995	Area [km ²] Jan 2012	ΔArea 1995–2012
1	Hektoria Glacier Headland	118.13	100.64	–17.49
2	HGE	1588.97	1415.05	–173.92
3	Evans Glacier Headland	124.38	119.49	–4.89
4	Punchbowl	129.56	117.82	–11.74
5	Jorum	484.09	460.36	–23.73
6	Crane	1354.29	1319.74	–34.55
7	Mapple	154.97	155.43	+0.46
8	Melville	295.26	291.18	–4.08
9	Pequod	151.06	150.64	–0.42
10	Rachel	51.27	51.27	NC
11	Starbuck	300.69	300.69	NC
12	Stubb	109.92	109.92	NC
13	Flask	1144.84	1144.84	NC
14	Leppard	1877.08	1877.08	NC
Sum		7884.51	7614.15	–270.36

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Table 2. Drainage area above the flux gate, velocities at the centre of the flux gate (V_c), discharge across the flux gates, and difference of discharge vs. 1995; for glaciers draining into Larsen B embayment.

Glacier	Gate	Area (km ²)	Date	V_c (ma ⁻¹)	Discharge (Gta ⁻¹)	Δ 1995–Date 2 (Gta ⁻¹)	
Crane	C1	1235	1995/99*	548	1.149 ± 0.128		
			Jun 2007	2464	5.018 ± 0.561	–3.869	
			2008/09*	1882	2.919 ± 0.326	–1.770	
			Apr 2010	1650	2.437 ± 0.272	–1.288	
			Jan 2011	1329	2.209 ± 0.247	–1.060	
			Aug 2012	1292	2.145 ± 0.240	–0.996	
			Nov 2013	1059	1.724 ± 0.193	–0.575	
Jorum	J1	382	1995/99*	475	0.346 ± 0.071		
			2008/09*	865	0.534 ± 0.110	–0.188	
				Apr 2012	759	0.388 ± 0.080	–0.042
	J2	52	1995/99*	68	0.042 ± 0.009		
			2008/09*	146	0.082 ± 0.017	–0.040	
Apr 2012			153	0.064 ± 0.013	–0.022		
Hektoria–Green	H1 and G1	1188	1995/99*	387	1.186 ± 0.246		
			Mar 2004	1862	4.741 ± 0.978	–3.555	
			2008/09*	1545	2.878 ± 0.593	–1.692	
Hektoria	H2	341	Nov 2010	822	1.670 ± 0.344		
			Jul 2013	741	1.490 ± 0.307		
Green	G2	618	Nov 2010	1278	1.993 ± 0.411		
			Jul 2013	1095	1.560 ± 0.313		

* From Rott et al. (2011).

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**Table 3.** Drainage area above the flux gate, velocities at the centre of the flux gate (V_c), discharge across the flux gates, and difference of discharge vs. 1995; for glaciers draining into Scar Inlet ice shelf.

Glacier	Area km ²	Date	V_c (ma ⁻¹)	Discharge (Gta ⁻¹)	Δ 1995–Date 2 (Gta ⁻¹)
Starbuck	296	Oct 1995	124	0.067 ± 0.007	
		Sep 2009	125	0.069 ± 0.008	
		Jan 2011	124	0.068 ± 0.008	
Flask	1003	Oct 1995	478	0.781 ± 0.087	
		Nov 1999	496	0.781 ± 0.087	
		Sep 2009	661	1.111 ± 0.124	−0.330
		Jan 2011	704	1.226 ± 0.137	−0.445
		Feb 2012	690	1.154 ± 0.129	−0.373
		Jul 2013	613	1.076 ± 0.120	−0.295
Leppard	1822	Oct 1995	365	1.223 ± 0.252	
		Oct 2009	526	1.739 ± 0.358	−0.516
		Jul 2013	541	1.777 ± 0.366	−0.554

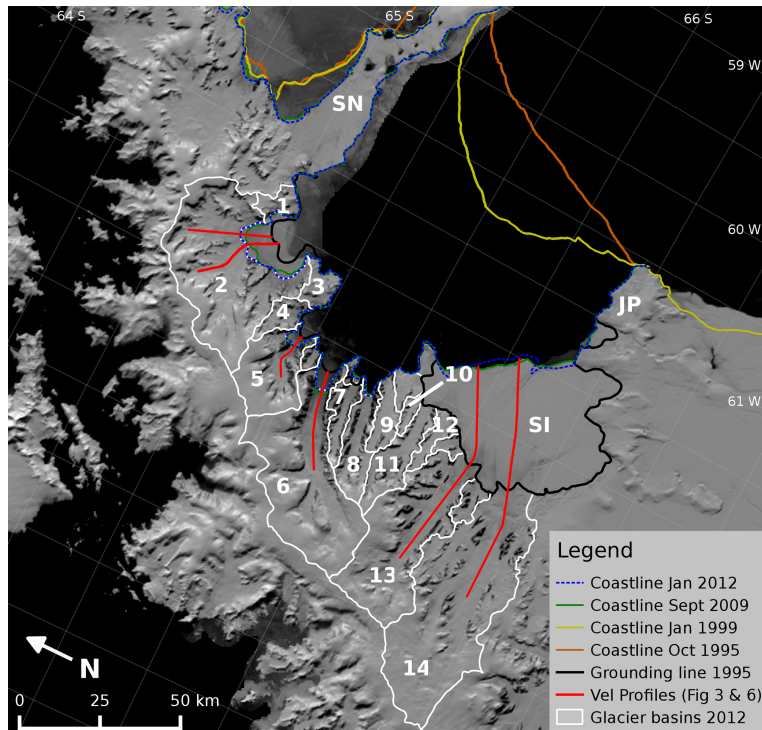


Figure 1. Overview map of glacier basins in the Larsen B region. Background: 2009 MODIS mosaic (Haran et al., 2014). Names and size of basins in Table 1. Glacier boundaries inland are based on the ASTER GDEM (courtesy A. Cook). Coastlines and grounding line derived from ERS-1 and Landsat images. SN – Seal Nunataks, SI – Scar Inlet, JP – Jason Peninsula. Red lines show location of velocity profiles in Figs. 3 and 6.

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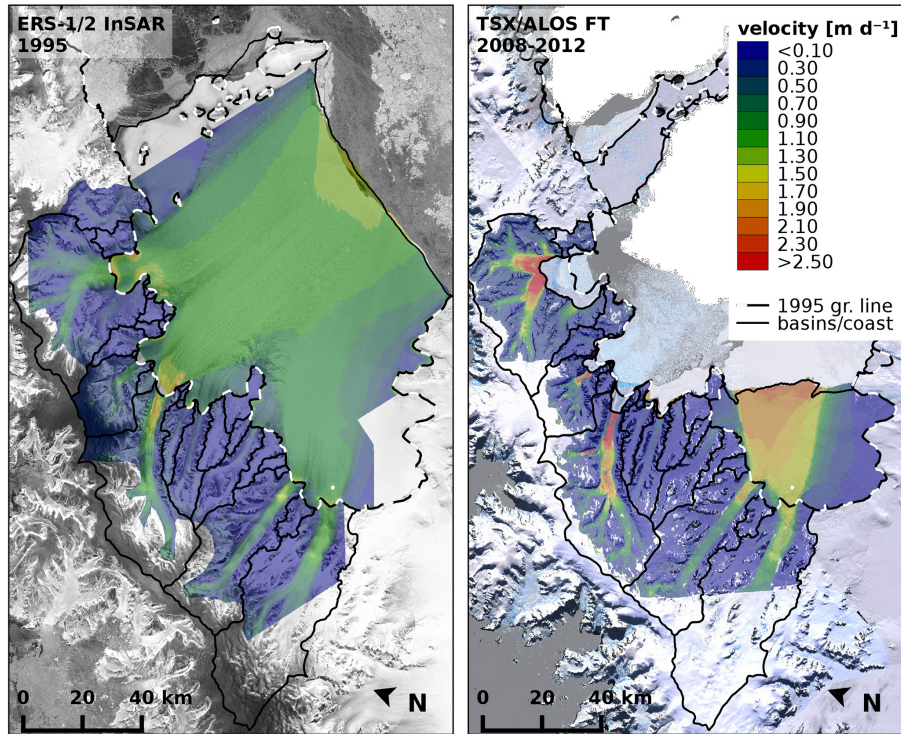


Figure 2. Maps of glacier surface velocity in the Larsen B region. Left: based on ERS InSAR data of October/November 1995 (background RAMP mosaic; Jezek et al., 2013). Right: based on TSX and PALSAR offset tracking 2008–2012 (background LIMA mosaic; Bindschadler et al., 2008). The dashed line shows the position of the 1995 grounding line, front positions are from October 1995 (left) and January 2012 (right).

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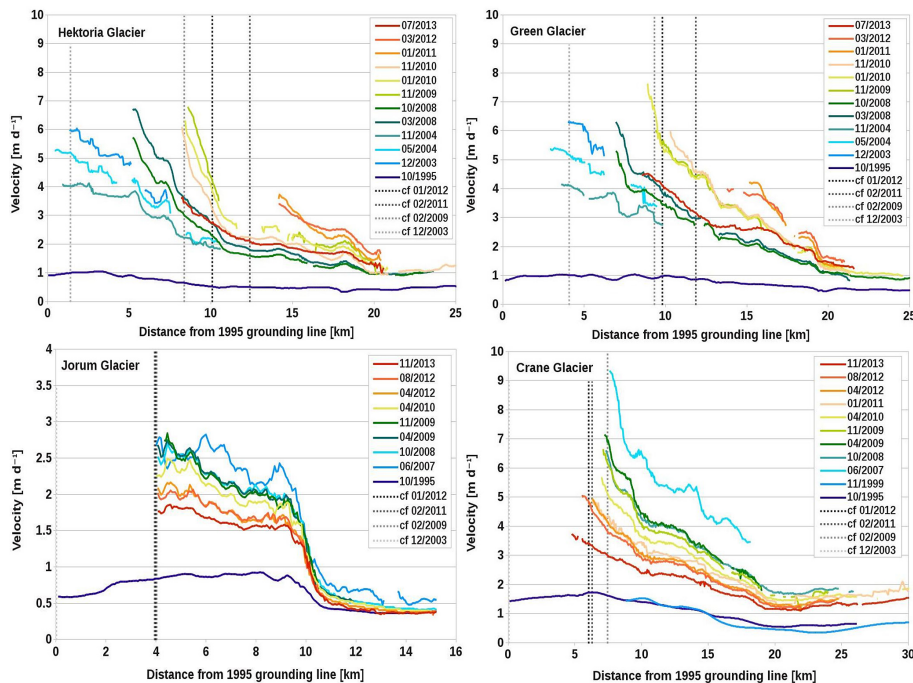


Figure 3. Surface velocities along the central flow line of Hektoria, Green, Jorum and Crane glaciers and their frontal positions at different dates (month/year). Vertical lines show positions of calving front (cf).

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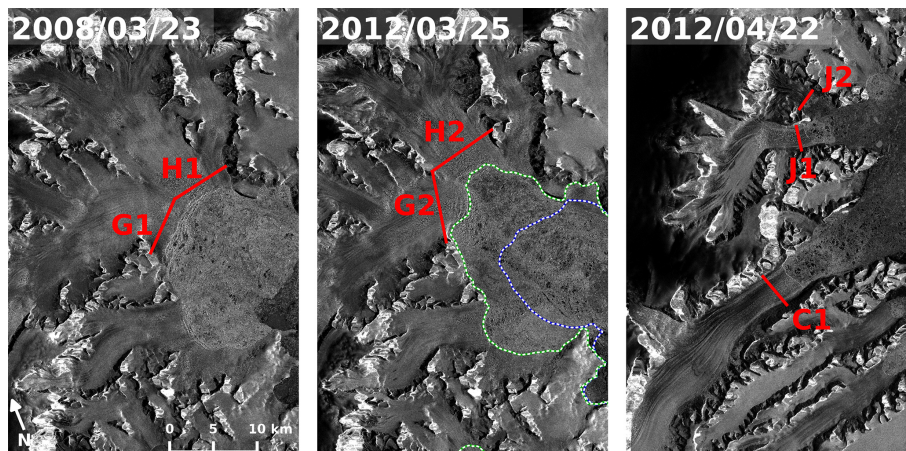


Figure 4. Section of TerraSAR-X amplitude images. HGE glaciers on 23 March 2008 and 25 March 2012, with flux gates on Hektor (H) and Green (G) glaciers and location of the glacier front on 24 December 2004 (dotted blue line) and 25 March 2012 (dotted green line). TSX image of Crane (C) and Jorum (J) glaciers on 22 April 2012 with flux gates.

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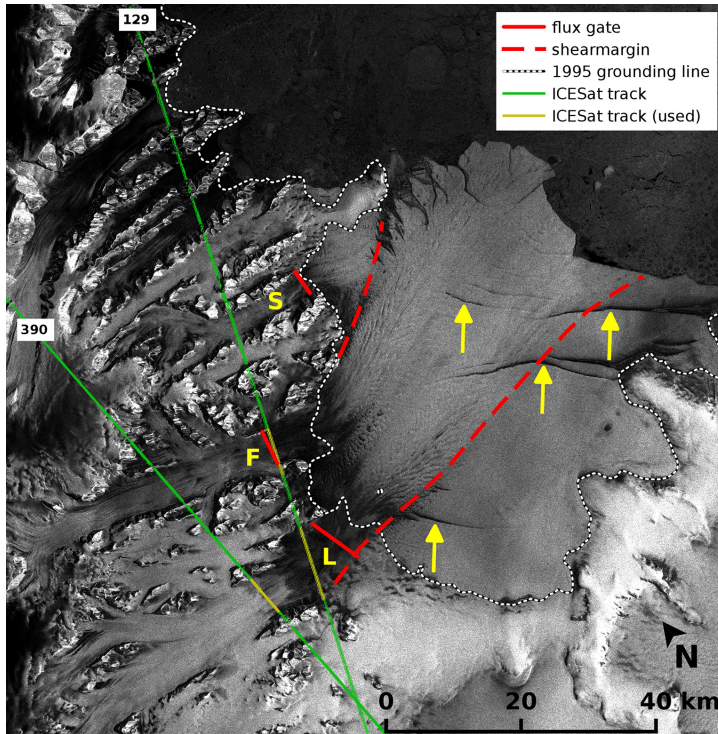


Figure 5. Envisat ASAR image of Scar Inlet ice shelf and tributary glaciers, 28 January 2004. Red lines show the flux gates for Flask (F), Leppard (L) and Starbuck (S) glaciers. The broken red lines delimit the outflow downstream of Flask and Leppard glaciers. The yellow sections of the ICESat tracks are used for deriving surface elevation change on Leppard and Flask glaciers. The arrows point to major rifts.

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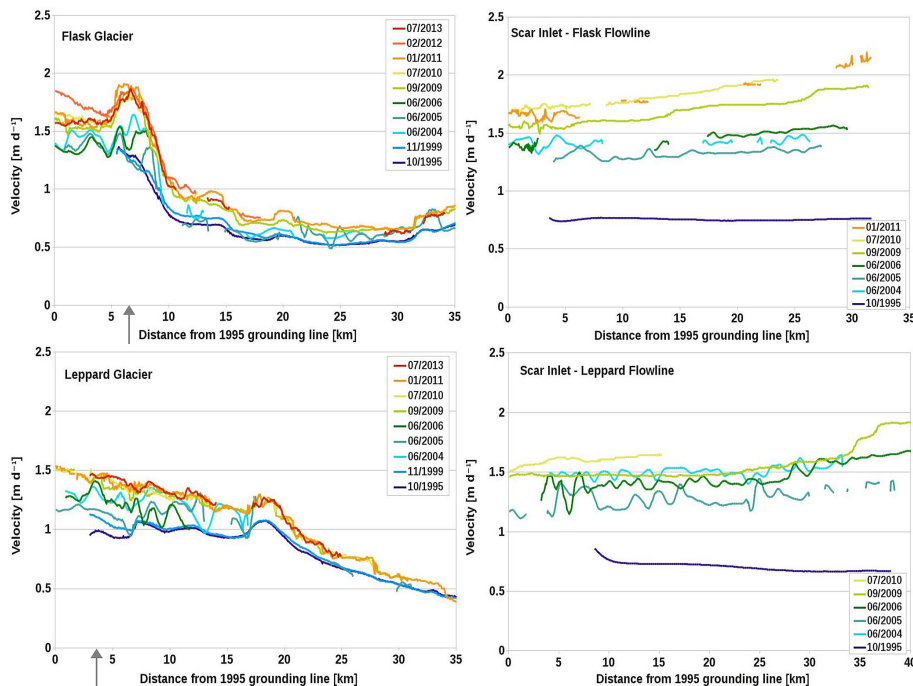


Figure 6. Surface velocities along the central flowline of Flask (top left) and Leppard (bottom left) glaciers and downstream of these glaciers on Scar Inlet ice shelf (right, top and bottom). The arrow shows the location of the flux gate. Position of flowline profiles in Fig. 1 and of flux gates in Fig. 5.

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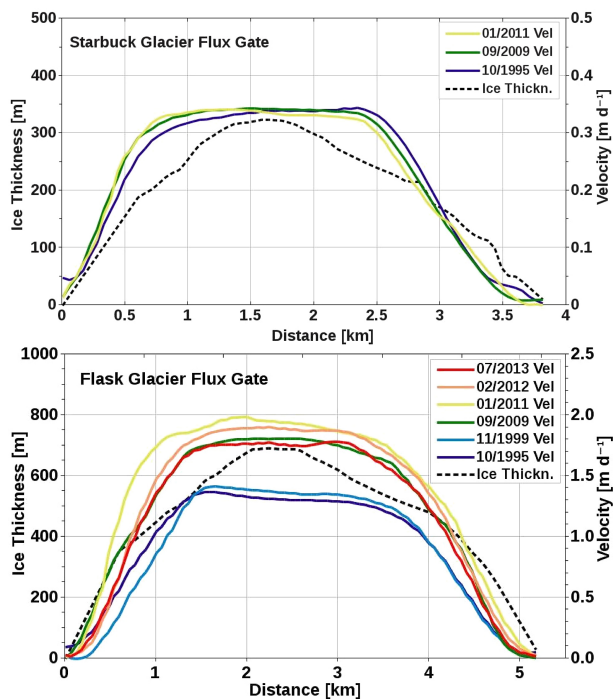


Figure 7. Ice thickness and surface velocity across the flux gate of Starbuck Glacier (top) and Flask Glacier (bottom). Ice thickness from Farinotti et al. (2013, 2014).

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