Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf

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[1] Interferometric synthetic-aperture radar data collected by ERS-1/2 and Radarsat-1 satellites show that Antarctic Peninsula glaciers sped up significantly following the collapse of Larsen B ice shelf in 2002. Hektoria, Green and Evans glaciers accelerated eightfold between 2000 and 2003 and decelerated moderately in 2003. Jorum and Crane glaciers accelerated twofold in early 2003 and threefold by the end of 2003. In contrast, Flask and Leppard glaciers, further south, did not accelerate as they are still buttressed by an ice shelf. The mass loss associated with the flow acceleration exceeds 27 km^3 per year, and ice is thinning at rates of tens of meters per year. We attribute this abrupt evolution of the glaciers to the removal of the buttressing ice shelf. The magnitude of the glacier changes illustrates the importance of ice shelves on ice sheet mass balance and contribution to sea level change.   *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 6924 Radio Science: Interferometry; 9310 Information Related to Geographic Region: Antarctica. **Citation:** Rignot, E., G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas (2004), Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, *Geophys. Res. Lett.*, *31*, L18401, doi:10.1029/2004GL020697.

1. Introduction

[2] Earlier theoretical work by *Weertman* [1974], *Hughes* [1977] and *Thomas* [1979] suggested that the removal of buttressing ice shelves could trigger glacier acceleration and ice sheet retreat. These conclusions were disputed by subsequent theoretical studies [*Hindmarsh*, 1993; *Huybrechts and de Wolde*, 1999] and limited observations [*Alley and Whillans*, 1991; *Vaughan*, 1993; *Mayer and Huybrechts*, 1999] which argued that the glacier/ice shelf coupling mechanism was more complex and stable than predicted by earlier theories. This issue has remained controversial due to a lack of direct observations of the effect of ice shelf removal on glacier flow. This situation is now changed with the advent of satellite remote sensing techniques. *Rott et al.* [2002] showed that Drygalski Glacier accelerated threefold after the collapse of Larsen A ice shelf

in 1995. *De Angelis and Skvarca* [2003] found evidence of glacier surge on several glaciers north of Drygalski. These studies suggest that ice shelf removal could indeed contribute to eustatic sea level rise.

[3] Here, we discuss flow changes following the collapse of Larsen B ice shelf in early 2002, in full view of several synthetic-aperture radar satellites. We analyze data collected before and after the collapse until present, and estimate the impact of ice shelf removal on glacier flow and mass balance. The results are used to draw conclusions about the importance of ice shelves on the mass balance of Antarctic glaciers.

2. Data and Methodology

[4] ERS-1/2 radar data collected in 1996 are used interferometrically to map ice velocity using ascending/descending pairs (Table 1) and assuming ice flow parallel to the ice surface. ERS-1/2 differential pairs are used to map glacier grounding lines with a precision of 100 m horizontal, surface topography within a few tens of meters on grounded ice, and changes in ice-shelf flow on floating ice (Figure 1). Mapping of surface topography is controlled by laser altimetry data from a collaborative campaign between Centro Estudio Cientificos (CECS) and NASA onboard a P3 aircraft provided by the Chilean Navy [*Thomas et al.*, 2004; *Rignot et al.*, 2004] (Figure 2). The RAMP elevation model [*Liu et al.*, 1999] is used where interferometry-derived topography is not available.

[5] Ice velocity maps are patchy due to the difficulty of topographic mapping on the steep flanks of the central part of the Peninsula, and temporal decorrelation of the radar signal caused by surface weathering and low signal-to-noise ratio of the snow/ice surface, especially along the western flank of the Peninsula and the central spine. The precision of velocity mapping varies from 10 to 50 m/yr. On ice shelves, ocean tides are removed using tidal predictions and assuming that the ice shelf deforms elastically. Residual errors have no impact on flow changes measured on grounded ice. Radarsat-1 data are analyzed with a speckle tracking technique [*Michel and Rignot*, 1999] to measure ice velocity over 24-day periods, with little contamination from tides on floating ice (Figure 2).

3. Analysis

[6] Comparison of 1996 and 2000 ERS data (Figure 1) reveals a 20-percent acceleration of the ice shelf (100 m/yr), also noted by *Rack* [2001], which decays near the grounding zone to yield no velocity change on the glaciers, with an uncertainty of 30–50 m/yr. In contrast, the same data reveal a threefold acceleration of Drygalski Glacier (or 500 m/yr)

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Table 1. ERS-1/2 and Radarsat-1 Orbit Pairs Used in This Study[a]

Data	Orbit Pairs	Dates
1996 ERS SI	23553/3880, 22456/2783	96/01/16, 95/10/31
1996 ERS DSI	22551/2878, 24054/4381	95/11/07, 96/02/20
2000 ERS DSI	22456/2783, 43498/23825	95/10/31, 99/11/09
2000 RSAT ST	25321–26007	00/09/10–00/10/04
2003a RSAT ST	37326–37669	02/12/29–03/01/22
2003b RSAT ST	41442–41099	03/09/19–03/10/13
2003c RSAT ST	42471–42128	03/12/24–03/11/30

[a]SI = single difference; DSI = double difference; ST = speckle tracking.

flowing into former Larsen A, as shown by *Rott et al.* [2002].

[7] Radarsat-1 data reveal larger changes in glacier velocity after 2002 (Figures 2c–2c). Hektoria, Green and Evans glaciers accelerated eightfold between 2000 and early 2003 (Table 2 and Figure 3a), and decelerated in 2003. Glacier calving fronts are now inland of their 1996 grounding lines. Crane Glacier increased its velocity twofold by early 2003 and threefold by late 2003 (Table 2 and Figure 3b). A similar evolution is detected for Jorum Glacier (Table 2). In contrast, Flask and Leppard Glaciers, which are still buttressed by remnant parts of Larsen B, did not accelerate between 1996 and early 2003 (Table 2 and Figure 3c). In late 2003, however, those glaciers and ice shelf remnants accelerated 15 percent, which could signal an upcoming transition to more rapid flow.

[8] Flow acceleration stretches the ice and thins it. We calculate an average rate of thinning from mass conservation between at outflow gate, G, and an upstream gate, A, where changes in ice discharge are negligible. Gate A is 15 km upstream of the grounding line of Hektoria, Green, Evans, and Crane glaciers (Figures 3a–3b). We assume that the increase in grounding line outflow is proportional to the velocity increase. The resulting glacier thinning rate, dH/dt, is equal to the increase in outflow divided by the glacier area (Table 2). The results indicate thinning rates in the range of tens of meters per year.

[9] The outflow of Crane Glacier calculated from CECS/NASA thickness/elevation data and ERS ice velocity data is approximately in balance with snow accumulation from *Turner et al.* [2002] (Table 3). The same calculation on Drygalski Glacier with ice thickness deduced from ice shelf elevation yields an outflow much larger than snow accumulation, which we attribute to the glacier acceleration. On other glaciers, quality thickness or topography data are lacking, and the 1996 outflow is assumed equal to snow accumulation. Outflow on subsequent years is then deduced from the flow acceleration. The total mass loss calculated for the 6 glaciers exceeds 25 km^3 ice per year, and 27 km^3/yr with Drygalski Glacier (Table 3).

4. Discussion

[10] Regional climate warming is certainly the cause of ice shelf and glacier changes [*Scambos et al.*, 2000; *Vaughan et al.*, 2003]. Warmer air temperatures increase surface melt water production, which may reach the bed and increase basal lubrication near grounding lines [e.g., *Zwally et al.*, 2002]. Similarly, ice shelf thinning and accelerated flow and calving reduce ice shelf buttressing, which allows faster flow. It is not clear a priori which process exerts the

greatest control on ice flow. We note however that most glacier equilibrium lines in the eastern Peninsula are close to grounding lines [*Morris and Vaughan*, 2003], so surface melt should not be a major factor in the glacier acceleration because it is mostly confined to the ice shelves. Furthermore, there has been no marked change in air temperature in the last two years compared to the prior decade that could explain a sudden and widespread glacier acceleration from enhanced surface melting. Indeed, Flask/Leppard glaciers have remained more or less steady although they experience the same climate conditions as Crane, Evans, Green and Hektoria. In contrast, the widespread glacier acceleration coincides with the ice shelf removal, and glaciers still buttressed by an ice shelf did not accelerate. These results are in broad agreement with the theory of ice shelf buttressing. The most likely explanation for the glacier acceleration is a major reduction in ice-shelf buttressing.

[11] The 1996 topography of Hektoria-Green-Evans glaciers suggests the presence of an 'ice plain', or area of slightly grounded ice upstream of the grounding line, with low driving stress, which makes the glaciers prone to rapid retreat [*Thomas et al.*, 2004]. No ice plain is found on Crane Glacier (Figure 3b), which might explain why the flow changes are smaller and slower in time. Flask and Leppard glaciers, in contrast, have remained relatively steady due to the buttressing from remnant parts of Larsen B ice shelf.
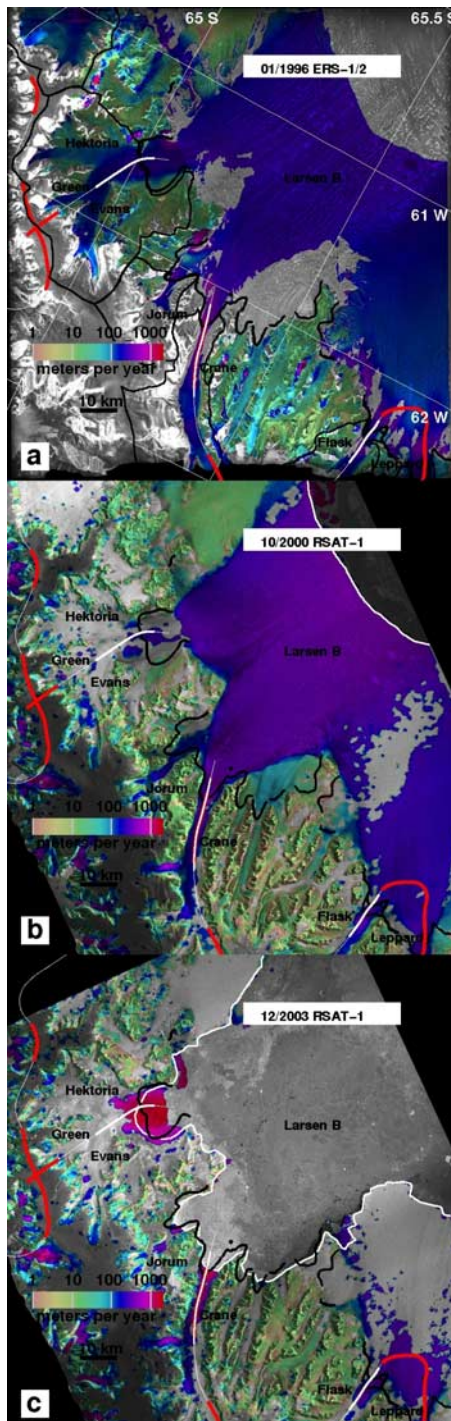
5. Conclusions

[12] Radar interferometry observations of the Antarctic Peninsula suggests that its glaciers accelerated dramatically in response to the collapse of Larsen B ice shelf. Similar results have been obtained by *Scambos and Bohlander* [2003] with Landsat imagery acquired in the months following the collapse of Larsen B. The flow changes are large and affect areas well inland of the glacier grounding lines,
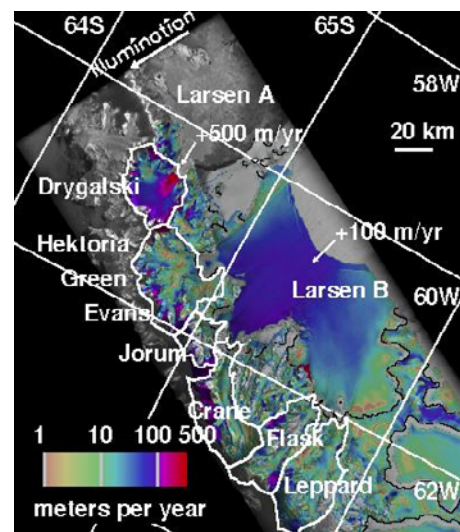
Figure 1. Changes in ice velocity measured in the radar illumination direction of ERS-1/2 between Oct. 1995 and Nov. 1999 over former Larsen A (Drygalski) and B (all other glaciers) ice shelves, Antarctic Peninsula. Drainage basins are thick white lines. Grounding lines are thin black lines.

over time scales measured in months or shorter. The impact of flow changes on glacier mass balance and contribution to sea level is significant. The 8 glaciers discussed here contribute more than 27 km^3/yr mass moss since 2002.

Table 2. Flow Acceleration, dV/V (V is Velocity), at the Grounding Line and Ice Thinning, dH/dt, Averaged Over an Area of, Respectively, 400, 100 and 180 km^2 for Hektoria/Green/Evans, Jorum and Crane Glaciers

Glacier	$dV/V/dH/dt$ (times)/(m/yr)		
	2003a	2003b	2003c
Hektoria/Green/Evans	8.7/52	7.7/45	7.2/42
Jorum	2.3/10	3.1/16	4.2/24
Crane	2.2/17	2.7/24	3.0/28
Flask	1.0/NA	1.1/NA	1.1/NA
Leppard	1.05/NA	2.7/NA	2.8/NA

Further south, glaciers drain larger reservoirs of ice, and the thinning of Larsen C [*Shepherd et al.*, 2003] may trigger an even larger contribution to sea level. These observations are also particularly relevant to the evolution of ice streams and glaciers draining West Antarctica. Although the climate conditions of the Antarctic continent are colder and drier than in the Peninsula, ice shelf thinning could be caused by a warmer ocean instead of warmer air temperatures. As ice shelves thin and eventually break up, the large continental glaciers draining West Antarctica could accelerate and
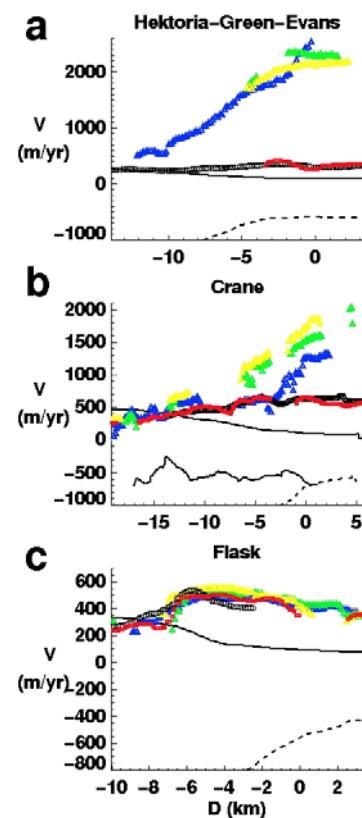

Figure 2. Ice velocity (meters per year, logarithmic scale) of Hektoria, Green, Evans, Jorum, Crane, Flask, and Leppard Glaciers, measured using (a) ERS-1/2 data from Jan. 1996, and Radarsat-1 data from (b) Oct. 2000; and (c) Dec. 2003. CECS/NASA flight lines are thin white. Ice thickness data are thick red. Grounding lines are thick black. Profiles in Figure 3 are thick white segments along CECS/NASA lines. Ice front locations are thin white.

Figure 3. Ice velocity, V, in Jan. 1996 (black square), Oct. 2000 (red square), Dec. 2002 (blue triangle), Oct. 2003 (green triangle), Dec. 2003 (yellow triangle) vs distance, D, from the grounding line along profiles in Figure 2. Surface elevation (meters) from CECS/NASA in (b−c) and InSAR in (a) are thick black lines. Bed elevation (meters) from CECS/NASA are thick black lines in (b). In (a−c), bed elevation deduced from ice shelf elevation assuming ice to be in hydrostatic equilibrium are dotted black lines.

Table 3. Drainage Area, Accumulation, and Outflow of Antarctic Peninsula Glaciers on Different Years[a]

Glacier	Area (km^2)	Accumulation (km^3/yr)	Outflow (km^3/yr)			
			1996	2003a	2003b	2003c
Hektoria/Green/Evans	1482	2.7±0.4	2.7	23.5	20.8	19.4
Jorum	412	0.7±0.1	0.7	1.7	2.3	3.1
Crane	1193	2.5±0.4	2.6	5.6	6.8	7.6
Flask	1020	2.0±0.3	2.0	1.9	2.1	2.1
Leppard	1350	2.4±0.3	2.4	2.5	2.7	2.8
Drygalski	925	1.8±0.3	4.4	NA	NA	NA

[a]Outflow is calculated for Crane and Drygalski Glaciers and assumed equal to the input from snow accumulation for other glaciers.

precipitate the ice sheet into a state of negative mass balance. This is in fact what we believe is happening in the Amundsen Sea sector of West Antarctica [*Rignot et al.*, 2004].

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