Increased Export of Grounded Ice after the Collapse of Northern Larsen Ice Shelf, Antarctic Peninsula, Observed by Envisat ASAR

Helmut Rott
University of Innsbruck
Institute for Meteorology and Geophysics
A-6020 Innsbruck, Austria
E-mail: Helmut.Rott@uibk.ac.at

Wolfgang Rack
University of Canterbury
Christchurch, New Zealand
E-mail: wolfgang.rack@canterbury.ac.nz

Thomas Nagler
ENVEO IT GmbH
A-6020 Innsbruck, Austria
E-mail: Thomas.Nagler@enveo.at

***Abstract*— Time series of satellite radar image data of Envisat ASAR were used to study the retreat of ice shelves and glaciers at northern Larsen Ice Shelf, Antarctic Peninsula, up to March 2007. After the disintegration event in March 2002, the small remaining ice shelf section of Larsen B decreased further in area. The retreat of grounded glacier ice continued also. The glacier velocities above previous Larsen B increased further since 2004, but the acceleration has been smaller than in the first two years after the collapse in 2002. Ice export increased rapidly after the glaciers started to calve directly into the ocean. The sea level contribution due to discharge of grounded ice above the disintegrated ice shelf sections amounts to about 6% of the present glacier and ice sheet contribution to sea level rise.**

Keywords: Envisat; ASAR; Antarctica; Larsen Ice Shelf.

I. Introduction

Larsen Ice Shelf on the east coast of the Antarctic Peninsula has been subject to accelerating retreat during the last decades as an effect of significant climate warming in the region, culminating in two spectacular disintegration events in January 1995 for Prince Gustav Channel (PGC) and Larsen A ice shelves, and in 2002 for Larsen B [1] [2] [3]. The ice retreat has been observed by various radar and optical satellite sensors. Of particular importance are the close time series of ERS SAR and Envisat ASAR which enabled to study the collapse events in detail [1] [2].

Of interest in connection with the ice shelf retreat are the physical processes leading to the rapid disintegration events, and the impact of ice shelf retreat on grounded ice. The first evidence on acceleration of outlet glaciers after ice-shelf break-up was based on interferometric (InSAR) analysis of SAR data from the ERS-1/ERS-2 tandem mission [4] which provided repeat pass radar images over one day time spans. The InSAR data from 1995 and 1999 showed significant acceleration for all glaciers above the previous Larsen A and PGC ice shelves after disintegration.

Because of rapid decorrelation of repeat pass radar images due to fast glacier flow and the variable meteorological conditions, InSAR analysis of the outlet glaciers was no more possible after the end of the ERS tandem mission in early 2000. However, image correlation techniques are able to provide information on ice velocities after disintegration of Larsen B [5] [6], though with reduced accuracy and spatial detail compared to InSAR. We use Envisat ASAR to map the further decrease of remnant ice shelf sections, to study the retreat of grounded ice at the outlet glaciers, and to derive frontal ice velocities. These data enable an estimate of the contributions of the glaciers to sea level rise after ice shelf collapse.

II. Further Retreat of Ice Shelf and Glaciers

Fig. 1 shows an ASAR Wide Swath Mode (WSM) image of northern Larsen Ice Shelf from 22 March 2007. For illustrating the retreat, positions of the ice front are shown for some dates in previous years. The ice boundaries were mapped in ERS SAR and ASAR images. The small ice shelf in PGC (in the upper part of Fig. 1) and Larsen A ice shelf had disappeared almost completely by end of January 1995. North of the Seal Nunataks a total of 2500 km2 in ice shelf area disappeared between beginning of 1995 and 2007.

On Larsen B a large calving event happened end of January 1995, followed by gradual retreat until February 2002 when the ice shelf lost about 3000 km2 in area within one month [2]. Fig. 1 points out that the remaining southern section of Larsen B retreated further since that time and shows large rifts, so that complete disintegration can be expected within a few years. The narrow ice shelf section at the Larsen nunataks, that previously separated Larsen A and Larsen B, decreased between March 2002 and 2007 from 900 km2 to 600 km2 in area. This small ice shelf surrounds several volcanic outcrops which, jointly with grounded ice, cover 107 km2 in area [7]. It can be expected that all of these outcrops, now still at least partly surrounded by ice shelf, will become islands surrounded by water within several years.

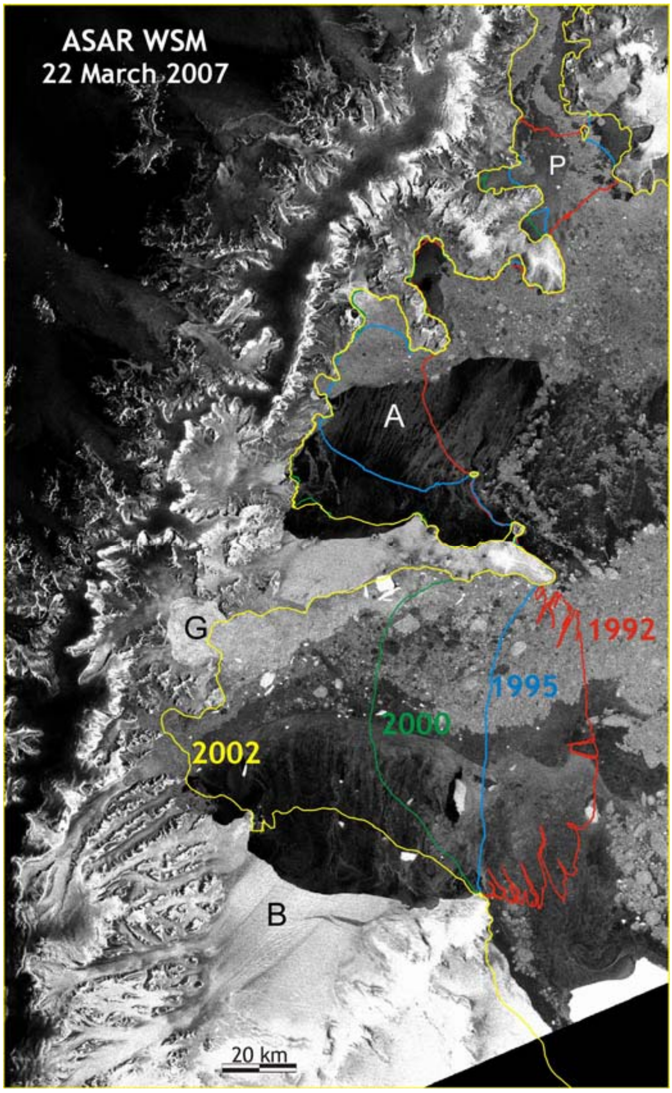

Figure 1. Envisat ASAR Wide Swath image of the northern Larsen Ice Shelf, 22 March 2007. Previous ice shelves: P – Prince Gustav Channel; A – Larsen A. B – remnant of Larsen B. G – bay of Hektoria-Green-Evans glaciers. Red, blue, green, yellow line: Ice edge on 8 Dec. 1992, 30 Jan. 1995, 6 Oct. 2000, 18 March 2002.

TABLE I. Decrease of Larsen B ice shelf area

Date	Area km2	Image source
25 January 1995	11512	ERS SAR
30 January 1995	9192	ERS SAR
4 February 2002	6664	ERS SAR
6 March 2002	3887	Envisat ASAR
13 February 2004	3463	Envisat ASAR
6 March 2002	2633	Envisat ASAR
22 March 2007	1403	Envisat ASAR

Some numbers for the area of Larsen B are listed in Table I. Within 12 years the ice shelf, which as been between 200 m and 350 m thick, has decreased in area by 10,110 km2. The remaining part in March 2007 covers only 12 % of the ice shelf area in January 1995. Even with much colder climatic conditions than present, several hundred years would be needed to rebuild the ice shelf. After the disintegration the outlet glaciers from the Antarctic Peninsula, that previously nourished the ice shelf, retreated many kilometres above the previous grounding line. Altogether about 250 km^2 of grounded ice have been lost by now at the outlet glaciers of former PGC, Larsen-A, and Larsen-B ice shelves**.**

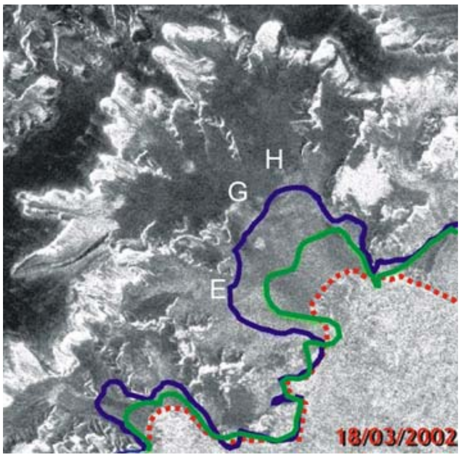

Figure 2. Hektoria-Green-Evans (H, G, E) glaciers in the ASAR image of 18 March 2002. Red – ice front. Green – grounding line. Blue – Ice boundary on 22 March 2007.

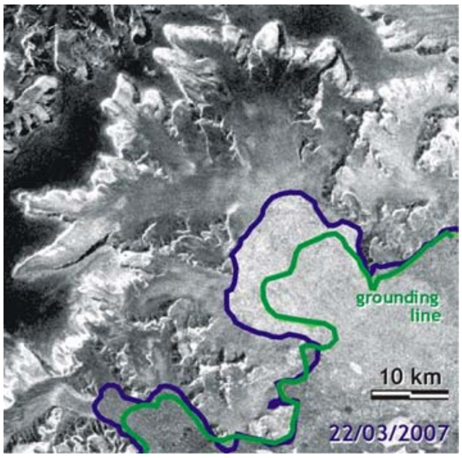

Figure 3. As above, in the ASAR image of22 March 2007.

The largest loss of grounded ice has been observed for Hektoria-Green-Evans glaciers above previous Larsen B ice shelf. The glaciers were a main tributary to Larsen B, covering a grounded area of 1582 km2. Fig. 2 shows a section of an ASAR image of 18 March 2002, immediately after the disintegration of Larsen B ice shelf. At that time there was still some floating ice left in front of the glaciers, which had completely disappeared by March 2003 [2]. The grounding line, separating floating and grounded ice, has been mapped with ERS tandem InSAR data [7] [8]. The ASAR image of 22 March 2007 reveals a total loss of grounded ice of 110 km2, and the ice front retreated up to 8 km from the grounding line.

III. Glacier Acceleration and Ice Export

Whereas disintegration of floating ice shelves does not have any effect on sea level, retreat of glaciers above the grounding line and increased calving flux due to flow acceleration are of relevance. For calculating the calving flux, glacier velocity at the front and glacier thickness need to be known. Only few ice thickness data are available along central flowlines of some of the glaciers [6], so that this is a major uncertainty for estimating the calving flux. The ice flow acceleration of the glaciers north of the Seal nunataks could be measured with ERS InSAR data up to 1999 [4]. For more recent ice velocities we applied image correlation with 5-week repeat pass amplitude images of ASAR.

Fig. 4 shows the velocity profiles of the central flow line of Hektoria and Green glaciers near the calving front. The ERS INSAR analysis in 1995, several years before the ice shelf collapse, shows maximum velocities of 0.9 m/d for Green glacier and 0.8 m/d for Hektoria glacier, slowly decreasing upstreams. In May/June 2004 velocities of 6 m/d were observed at the calving front of Hektoria glacier and 5 m/d of Green glacier decreasing rapidly upstreams. Such flow divergence causes thinning of ice, as observed also by laser altimetry of ICESat [9]. In mid-2006 the glaciers had retreated about 7 km inland of the grounding line. At the 2006 ice front position the ice had accelerated since 2004 by about 20 % on Hektoria glacier and about 30% on Green glacier. This can be attributed to lower resistance at the glacier base due to reduced overburden pressure of the thinning ice. However, the acceleration was much smaller than in the first two years.

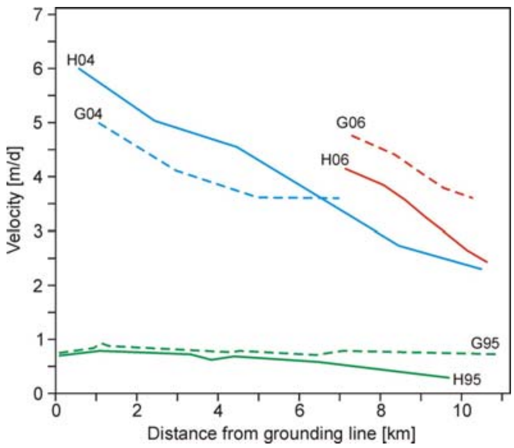

Figure 4. Ice velocity along central flowlines on Hektoria and Green glaciers, from ERS InSAR 1 October - 1 November 1995 (H95, G95), and from ASAR image correlation May -June 2004 (H04, G04) and July - August 2006 (H06 G06).

In spite of grounded ice retreat and increased calving flux, the sea level contribution of the glaciers is not very significant because the ice area above the disintegrated ice shelves is rather small. Before the ice shelf collapse the grounded ice covered 1623 km2 above PGC, 2491 km2 above Larsen A, and 8525 km2 above Larsen B ice shelves [7]. With the BEDMAP ice thickness data, we estimate the total sea level equivalent of this ice at 18 mm.

By now the grounded ice area has decreased by 2%, the main volume of which has been below sea level. Taking into account the percentage of ice above floating, the sea level contribution due to retreat of grounded ice is estimated at 0.03 mm/a in average for the period 2002 to 2007. The same value is estimated for the calving flux of all glaciers after acceleration. This results in a present annual sea level contribution of 0.06 mm/a for all glaciers where the ice shelf had disintegrated.

IV. CONCLUSION

Time series of satellite radar image data, as provided by ERS SAR and Envisat ASAR enable studying in detail the retreat and collapse of the northern sections of Larsen Ice Shelf at the Antarctic Peninsula. In this paper new observational results for the ice shelf and glaciers are presented based on ASAR data up to March 2007. The retreat of grounded ice continued. The glacier velocities above previous Larsen B increased further since 2004, but the acceleration has been much smaller than in the first two years after the collapse in 2002. Ice export increased rapidly after the glaciers started to calve directly into the ocean. The present sea level contribution of grounded ice above the disintegrated ice shelf sections is about 6% of the present glacier and ice sheet contribution to sea level rise [10]. The observations emphasize the vulnerability of ice shelves to climatic warming, and the importance of ice shelves for the stability of glaciers up-streams. The disintegration processes observed at Larsen Ice Shelf are very relevant for estimating the future response to climatic warming of the much larger ice masses of West Antarctica with a sea level equivalent of several metres.

ACKNOWLEDGMENT

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REFERENCES

[1]. H. Rott, P. Skvarca, and T. Nagler, “Rapid Collapse of Northern Larsen Ice Shelf, Antarctica”, *Science*, 271, 788 – 792, 1996.

[2] W. Rack and H. Rott. “Pattern of retreat and disintegration of Larsen B Ice Shelf, Antarctic Peninsula”, *Ann. Glaciol.*, 39, 505-510, 2004.

[3] T.A. Scambos, C. Hulbe, M. Fahnestock, and J. Bohlander. “The link between climate warming and break-up of ice shelves in the Antarctic Peninsula”, *J. Glaciol., 46* (154), 516-53, 2000.

[4] H. Rott, W. Rack., P. Skvarca, and H. de Angelis, “Northern Larsen Ice Shelf, Antarctica: further retreat after collapse”, *Ann. Glaciol*,. 34, 277 – 282, 2002.

[5] C. Riedl, H. Rott, and W. Rack, “Recent variations of Larsen Ice Shelf, Antarctic Peninsula, observed by Envisat”, Proc. of the 2004 Envisat & ERS Symposium”, *ESA SP-572* (CD-ROM), 2005.

[6] E. Rignot et al. “Accelerated discharge for the Antarctic Peninsula following the collapse of Larsen B ice shelf”, *Geophys. Res. Let*,. 31, L18401, 2004.

[7] W. Rack “Dynamic behavior and disintegration of the northern Larsen Ice Shelf, Antarctic Peninsula” *Ph. D. Thesis*, Univ. Innsbruck, Austria.

[8] W. Rack, C.S.M. Doake, H. Rott, A. Siegel, and P. Skvarca. “Interferometric analysis of the deformation pattern of the northern Larsen Ice Shelf, Antarctic Peninsula, compared to field measurements and numerical modeling”, *Ann. Glaciol*,. 31, 205-210, 2000.

[9] T. A. Scambos, J. A. Bohlander, A. Shuman, and P. Skvarca. “Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica”, *Geophys. Res. Let*. 31, L18402, 2004.

[10] G. Kaser, J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura, “Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004”, *Geophys. Res. Let*. 33, L19501, 2006.