THE EVOLUTION OF A GLACIER SURGE OBSERVED WITH THE ERS SATELLITES

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ABSTRACT

A time series of ERS-1/2 SAR data from September 1991 to September 1998 was used to monitor the complete surge cycle of Monacobreen in Northwest Svalbard. Significant information for the study of this glacier was provided to glaciologists by the analysis of the backscattering coefficient images (in particular for the position and the crevasses of the front of the glacier), by the use of differential SAR interferometry in descending and ascending mode to retrieve displacement and height maps, and by applying coherence and feature tracking where surge velocities exceed the regime within which interferometric phase could be usefully interpreted. The result for Monacobreen is a complete map of temporal and spatial velocity structure from the beginning of the surge to its end.

1 INTRODUCTION

Studies of the influence of climate change on glacier mass balance often assume a steady flow rate. However, a small number of glaciers around the world are known to exhibit surge-type behaviour which is characterised by long periods (20-200 years) of slow flow punctuated by short periods (1-10 years) of fast flow during which substantial volumes of ice are transferred to lower altitudes causing a temporary acceleration in the overall melt-rate. These surge-type glaciers are geographically clustered and one particularly concentrated cluster is found in the Svalbard archipelago where it has been estimated that between 13% and 90% of the glaciers are of surge-type [1,2]. Glacier surges may provide useful insight into the expected behaviour of ice-streams under the influence of a changing climate. However, the inaccessibility of most surge-type glaciers has made understanding the causes, mechanisms and precise occurrence of surging difficult and there is a need to acquire more information about this type of glaciers. ERS SAR data has provided invaluable tools for remotely studing these relatively rare events.

This study uses ERS SAR interferometry [3,4,5,6] to examine the temporal and spatial development of the surge of Monacobreen in Northern Svalbard in the 1990's. Monacobreen (79° 24'N, 12° 34'E) is a 40 km long, tidewater glacier flowing north from the Isachsenfonna icecap into Liefdefjorden. Most glaciers in the area have been in retreat this century from their maximal extent during the Little Ice Age. Aerial photographs acquired by Norske Polarinstitutt show that the margin of Monacobreen retreated 0.75-1.45 km between 1966 and 1990. Reports from expedition guides, who while visiting this area had identified heavy crevassing, suggested that Monacobreen had begun to surge in the early 1990s. Optical satellite imagery shows an advance of the glacier snout between 1990 and the summer of 1993, thereby helping to confirm these reports. Further evidence of surge-type characteristics in Monacobreen comes from Radio-echo-sounding of the glacier in 1983 [7]. This study identified an internal reflecting horizon which masked the bed return thereby suggesting that at this time the glacier was warm-based over the majority of its accumulation area. Warm-based ice is a pre-requisite for the active phase of glacier surging [8].

2 IMAGE SELECTION

Image selection was given great consideration to maximise the level of coherence. Meteorological data was employed to choose image pairs with minimal precipitation between acquisitions and temperatures below freezing when possible. For this study we used a total of 34 ERS SAR scenes from September 1991 to September 1998. Table 1 shows the dates and baselines for the image pairs selected.

1st image	2nd image	B_{perp}	DEM B_{perp}
4.9.1991	7.9.1991	-184 m	↓
13.10.1991	16.10.1991	-82 m	160 m
16.10.1991	19.10.1991	-242 m	
15.11.1991	18.11.1991	163 m	↑
10.2.1992	13.2.1992	87 m	↓
23.3.1992	26.3.1992	74 m	137 m
26.3.1992	29.3.1992	-63 m	
12.1.1994	15.1.1994	177 m	93 m
15.1.1994	18.1.1994	84 m	
28.3.1994	31.3.1994	141 m	↑
1.6.1995	2.6.1995	-2 m	↓
28.12.1995	29.12.1995	-38 m	-206 m
1.2.1996	2.2.1996	168 m	
30.4.1996	1.5.1996	-35 m	-41 m
3.5.1996	4.5.1996	6 m	
4.9.1998			
26.12.1995	*27.12.1995*	*99 m*	*-33 m*
30.1.1996	*31.1.1996*	*132 m*	
8.10.1997	*9.10.1997*	*-94 m*	↑

Table 1. Image pair parameters for SAR acquisitions (*italic: ascending mode*)

3 RESULTS

3.1 Backscattering coefficient images

In order to map the frontal advance during the surge and analyse displacements of moraines on the glacier, calibrated and geocoded backscattering coefficient images were used. When pairs of SAR scenes acquired in one or three days or triplets of SAR images acquired in six days were available, their amplitudes were averaged in order to reduce the speckle. The position of the front of the glacier is shown in Figure 1 for five of the 16 available sigma-0 images. The margin of Monacobreen advanced significantly from September 1991 to March 1994 and slowly continued its advance until June 1995, for a total progression of around 2 km. From June 1995 to September 1998 the front remained almost stable. Brighter patches on the images indicate a textured or rough surface which shows how the lower parts of the glacier was heavily crevassed during the surge. Further analysis of the backscattering coefficient images is limited by the effect of the snowcover [9].

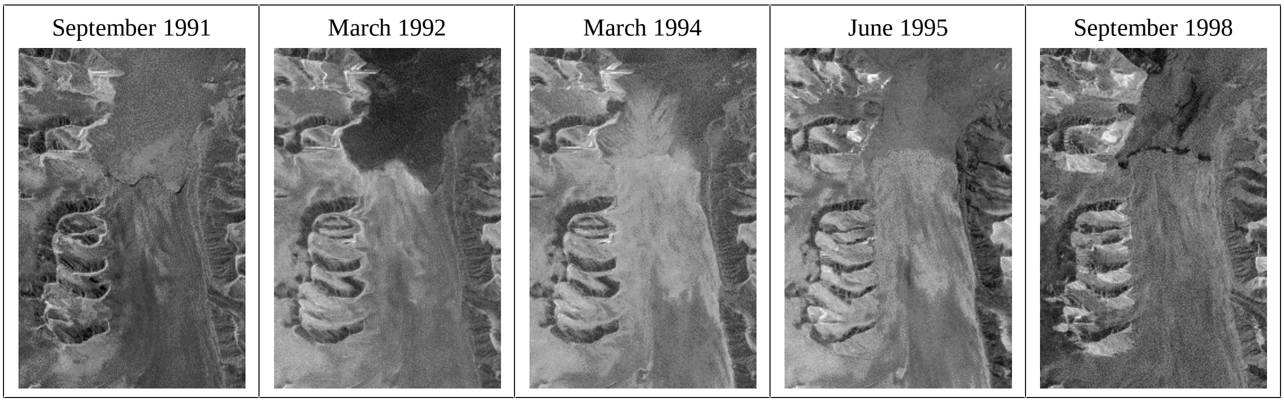

Figure 1. Temporal sequence of geocoded calibrated backscatter images for the front of Monacobreen (12km x 18km).

3.2 Phase noise images

The 34 ERS SAR scenes selected for this study allowed the computation of 18 interferograms. The phase noise of the filtered interferograms (i.e. the fringe visibility) is strongly related to particular displacement fields on the glacier. In the 3-days interferograms acquired before 1994, for instance, the eastern part of the front of Monacobreen was coherent, because of ice flowing from a small outlet glacier. In the following, the surge of Monacobreen stopped the flow of this small glacier. Also in the Tandem pairs the phase noise in the front of Monacobreen was relevant, because of complicated displacement fields. Only in 1997, when the surge terminated, coherence appeared over the whole glacier.

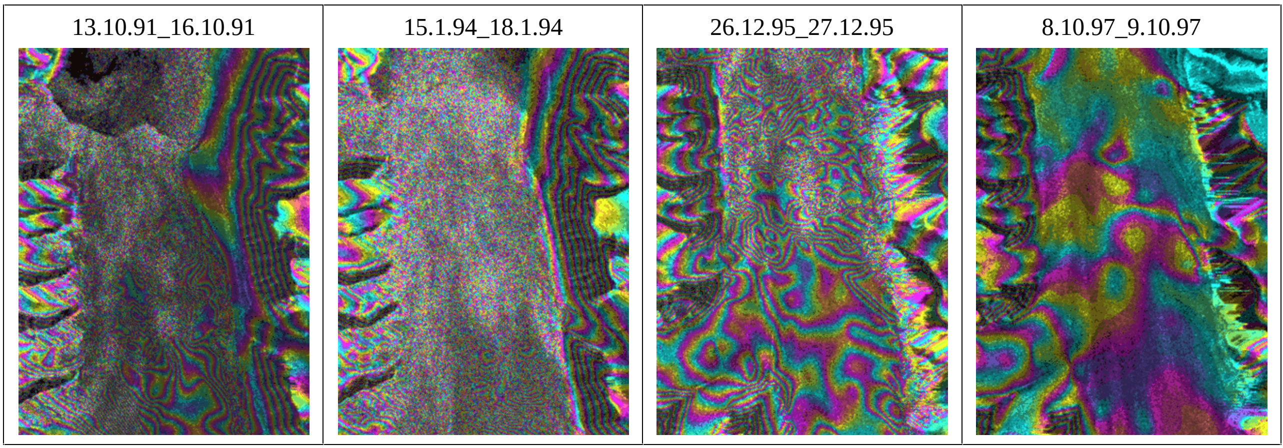

Figure 2. Selected geocoded interferograms over parts of Monacbreen (9km x 12km).

3.3 Height maps

The usual procedure for performing differential interferometry was applied [10,11,12]. The component of the interferometric phase related to the topography was removed from the one related to the displacement by subtraction of two interferograms from which similar displacement can be assumed (i.e. a triplet of SAR scenes acquired with three days time interval or two Tandem pairs acquired a month apart). To help phase unwrapping of the differential interferograms with the topographic-phase only, an external DEM was used. The external DEM was also employed for determination of ground-control points outside of Monacobreen and baseline refinement. Finally, six height maps could be recovered. The DEM's of October 1991 and January 1996 are compared in Figure 3. The height gradient of the upper part of Monacobreen was more pronounced in 1991 than in 1996, meaning that substantial volumes of ice were transferred to lower altitudes.

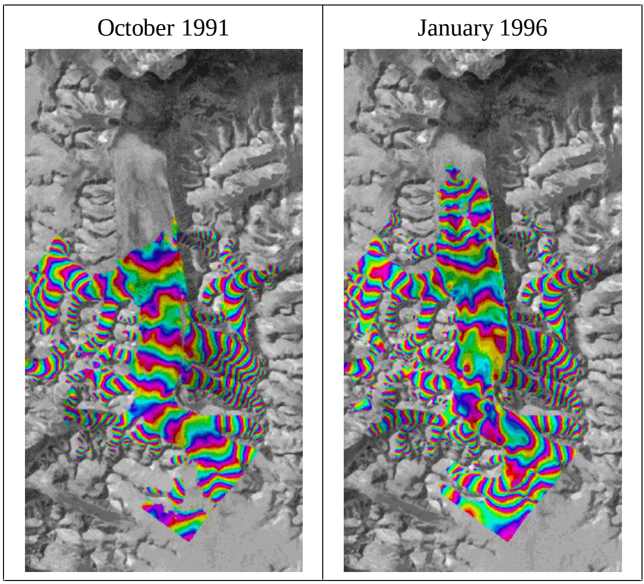

Figure 3. DEM's over Monacobreen (24km x 45km). One colour cycle corresponds to 50 m height difference.

3.4 Displacement maps in look direction

After subtraction of the topography-related phase, maps of the displacement in the line-of-sight direction were obtained. Where full differential data was not available at a particular date, a DEM from the most recent pair was used to correct for topographic effects on phase. In many cases displacement maps from one date were used to as a model of velocity to help unwrap fringes from other dates. In 1994 the velocity was so great that it was possible to reference the lower glacier velocity with the upper only by employing coherence tracking as an independent source of information on ice displacement. A rocky area near the upper part of Monacobreen was used as stable reference. Five of the 12 displacement maps in the line-of-sight direction obtained in this study are shown in Figure 4.

Displacement maps in the line-of-sight direction are the primary source of information of differential SAR interferometry. Even if analysis of the displacement maps in descending mode clearly indicates an increase of the velocity from September 1991 to January 1994 followed by a decrease until January 1996, glaciologists may found the interpretation of these maps difficult in some regions. For instance, in the January 1996 map in ascending mode, the displacement velocity in the upper part of Monacobreen appears to increase, decrease and again increase as a result of the changing flow direction with regard to the look direction.

3.5 3-dimensional displacement maps

In order to obtain a 3-dimensional displacement map, observations from three different look directions are required. ERS SAR data acquired in ascending and descending mode only give two look directions; however, information on the third directions can be overcome by using a DEM and assuming that flowing is parallel to the surface of the glacier [6]. The data of December 1995 – February 1996 were combined with a DEM to obtain a 3-dimensional displacement map. Unfortunately, data in ascending mode are available only for the winter 1995/1996. In order to compute 3-dimensional displacement maps also for the other dates, we assumed that the flow direction did not change. This hypothesis was confirmed by a careful analysis of the displacement direction over Monacobreen that did not show any particular anomaly. However, when look and flow directions were almost perpendicular, the information was masked out. Ten of the eleven 3-dimensional displacement maps are shown in Figure 5.

Profiles of daily displacement were taken down the centre-line of the glacier and are shown in Figure 6. Interpretation of these profiles is not yet complete but preliminary analysis indicates that the surge of Monacobreen occurred in two stages. From September 1991 to January 1994 the velocity increased steadily along the whole length of the glacier from the feeding icecap to the point at which phase coherence was lost (~10 km on the profile). During 1995 and 1996 the lower part of the glacier started to slow down but not the upper part. In 1997 the glacier was approaching normal (compared to 1991) velocities by this stage.

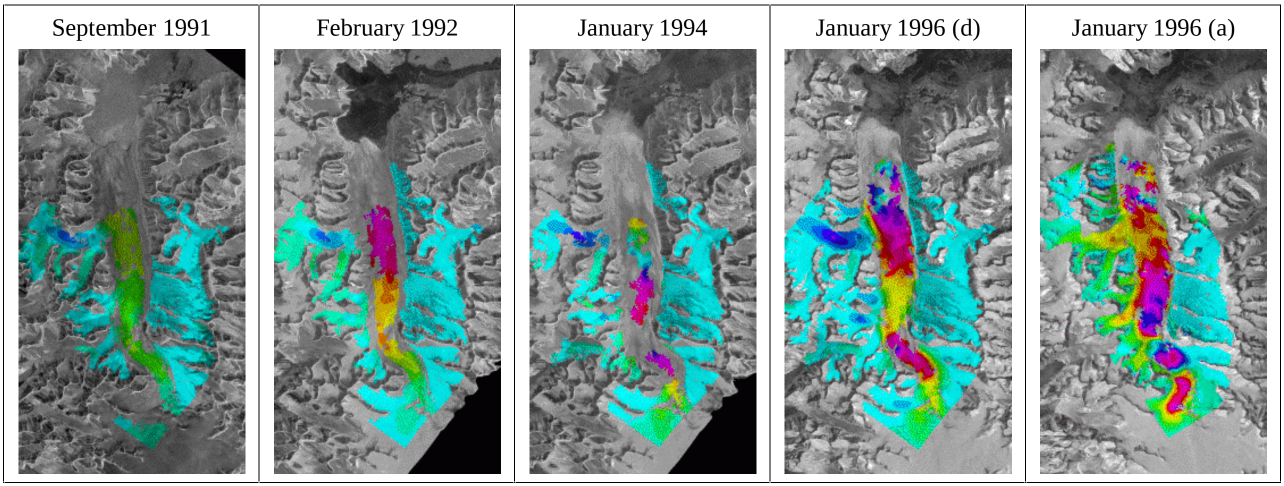

Figure 4. Temporal sequence of geocoded ice displacement maps (24km x 45km). Rate of displacement is measured in the look direction of the radar which is approximately from the SE except in the case of January 1996 (a) which is from the SW. One colour cycle from blue to blue, through green, yellow and red, represents 50 cm displacement per day.

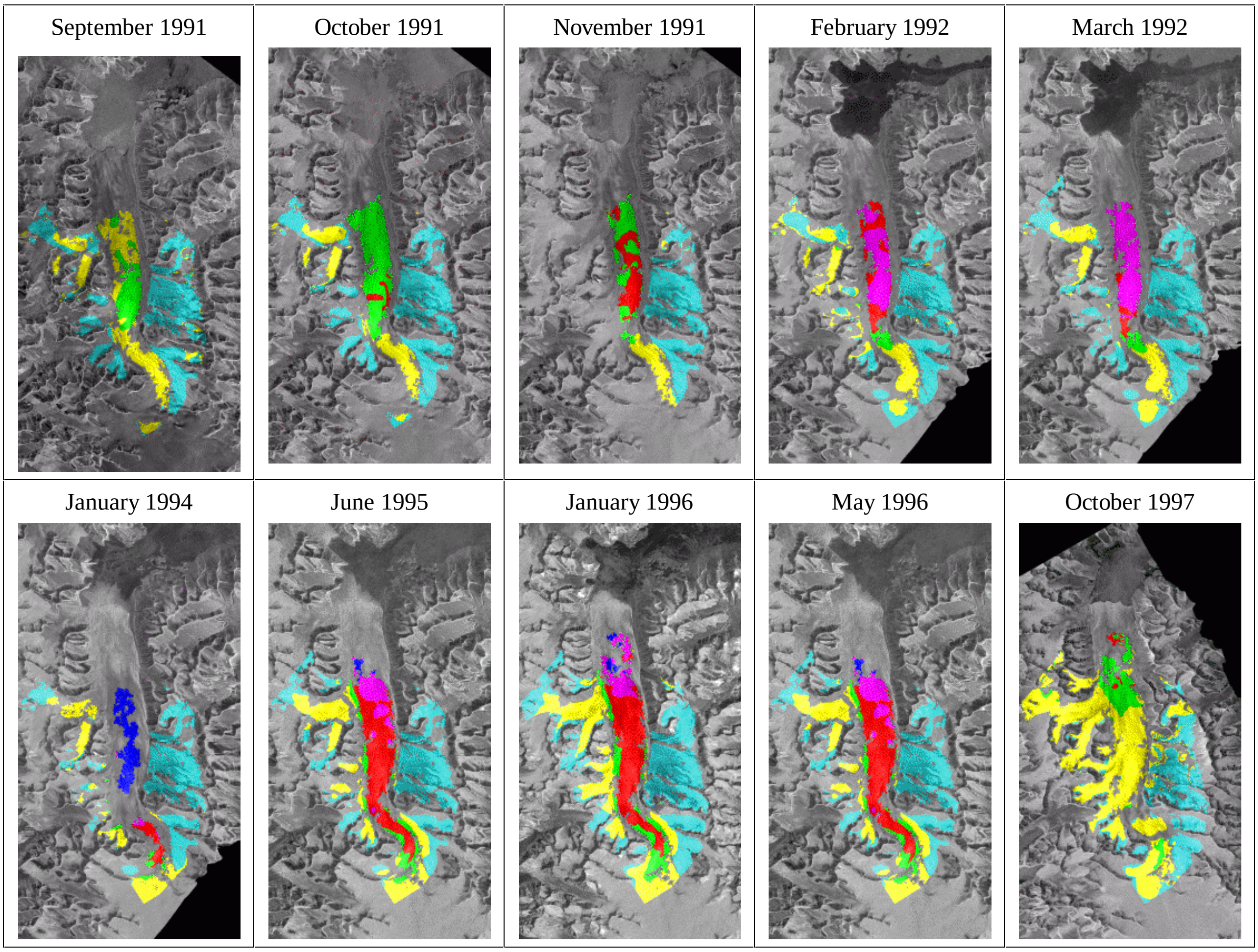

Figure 5. Temporal sequence of geocoded displacement maps (24km x 45km). The magnitude d (in m/day) of the 3-dimensional displacement rate is shown with the following colour scale:

$d < 0.1$	$0.1 < d < 0.4$	$0.4 < d < 0.7$	$0.7 < d < 1.0$	$1.0 < d < 1.3$	$d > 1.3$
cyan	yellow	green	red	violet	blue

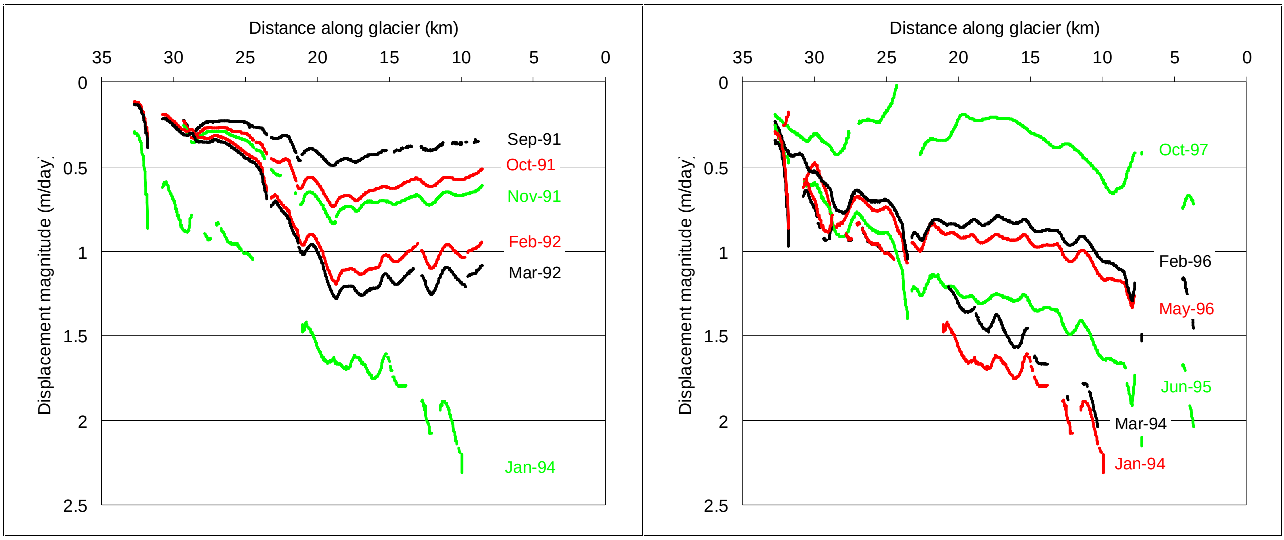

Figure 6. Profiles down centre-line of glacier for each time period, with 0 km being the position of the front of Monacobreen at the end of December 1995.

3.6 Offset tracking

Surge velocities in the front of Monacobreen exceed the regime within which interferometric phase could be usefully interpreted. Therefore we applied an image registration procedure based on the intensity cross-correlation in order to retrieve displacement rates in this area [13,14,15]. The technique could be successfully applied only for large displacement rates. Assuming an estimation error of 0.05 pixel in range and azimuth the displacement error from offset tracking is less than 1.2 m/day for Tandem data and of 0.4 m/day for SAR data of the three-days repeat cycles.

Profiles down centre-line of Monacobreen of the magnitude of the displacement rate from differential SAR interferometry and feature tracking for three data sets are presented in Figure 7. The preliminary analysis of these data indicates a continuous increase of the displacement velocity down to the front of Monacobreen.

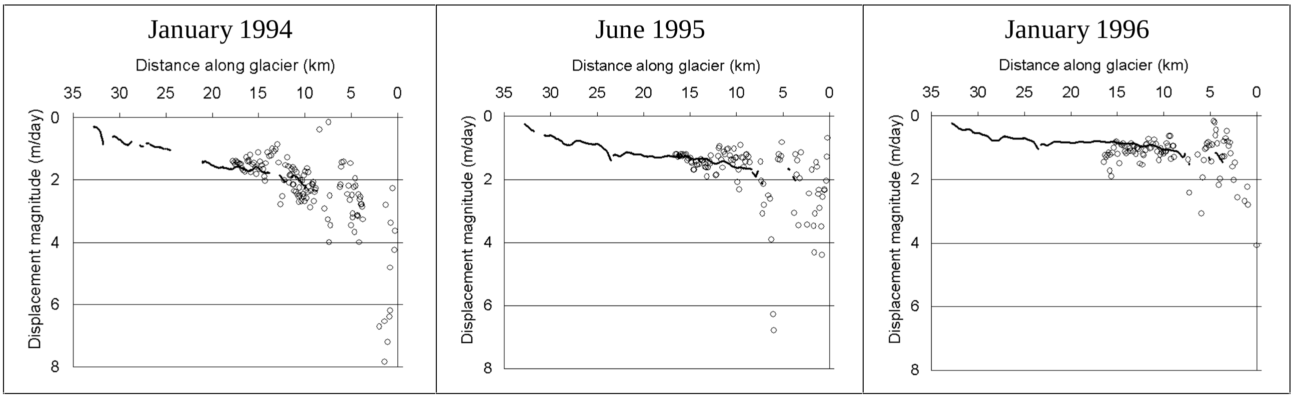

Figure 7. Profiles down centre-line of Monacobreen of the magnitude of the displacement rate. The line represents measurements from differential SAR interferometry, circles are from feature tracking.

4 CONCLUSIONS

The result of the ERS SAR data analysis for Monacobreen is a complete high-resolution map of temporal and spatial ice-velocity structure from the beginning of the surge to its end. Future work will concentrate on the interpretation of the imagery in terms of glacial processes.

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