Polarforschung 67 (1/2), 41 – 51, 1997 (erschienen 2000)

Fluctuations and Ice-Flow Velocity of the Northeast and McClary Glacier on the Antarctic Peninsula Derived from Remote Sensing Data and SAR Interferometry

By Stefan Wunderle[1] and Jürgen Schmidt[2]

Summary: The glaciers of the Marguerite Bay show distinct catchment areas, which differ in size, altitude, slope and aspect. As a result, the response-time of these glaciers to changes of air temperature and precipitation is quite different. This could be shown using remote sensing data like ERS-1 SAR precision imagery and aerial photos in combination with historical topographic maps. Detailed investigation of mass balance requires knowledge of the topography of a glacier, the location of equilibrium line altitude (ELA), the rate of accumulation and ablation as well as the flow velocity. Satellite radar interferometry was used to obtain information on the movement along a selected flow line of the Northeast Glacier located in the Marguerite Bay on the Antarctic Peninsula. Velocity measurement by means of radar interferometry is a demanding task because the interferometric phase difference contains both, information on glacial movement and surface topography. First, the impact of topography on the interferogram has to be eliminated. A digital elevation model (DEM) derived from aerial photographs was used to solve this problem. In a second processing step the part of the phase difference related to glacier velocity could be obtained. We used a pair of single look complex (SLC) SAR images, acquired during the tandem phase of ERS-1/2 on October 15 and 16, 1995, respectively. Surface changes due to melting of snow cover were negligible during this time. In subsequent steps the reference phase of earth ellipsoid (WGS 84) and topography was removed and the remaining motion fringes were converted to flow velocities for a given direction. The direction was determined using flow lines of the Northeast Glacier extracted from aerial photographs and ERS-SAR intensity images. The resulting flow velocities are in good agreement with ground measurements. The technique used to derive flow velocity by means of radar interferometry with one pair of ERS images shows the importance of high quality DEM and precise tie points for further studies of glacial flow on the Antarctic Peninsula.

Zusammenfassung: Die Gletscher der inneren Marguerite Bay weisen unterschiedliche Einzugsgebiete auf und reagieren dadurch auch stark differierend auf Änderungen der Lufttemperatur oder Niederschlagsmenge. Dies konnte gezeigt werden durch die Überlagerung von ERS-1 SAR Aufnahmen bzw. Luftbildern mit historischen topographischen Karten. Die Bestimmung der Massenbilanz erfordert als Eingabeparameter u.a. die Fließgeschwindigkeit eines Gletschers. Für den Northeast Glacier wurde die Geschwindigkeit mittels Radar Interferometrie aus zwei ERS-SAR Single look complex Aufnahmen abgeleitet. Das Interferogram enthält nicht nur Informationen über die Fließbewegung, sondern auch Phasenanteile, die aus der Topographie resultieren und elimiert werden müssen. Dafür wurde ein aus Luftbildern abgeleitetes digitales Höhenmodell (DHM) verwendet. Die Ableitung der Fließgeschwindigkeit des Northeast Gletschers erfolgte entlang von aus Luftbildern und ERS-SAR Aufnahmen extrahierten Fließlinien. Die Ergebnisse werden exemplarisch für eine Fließlinie dargestellt. Die aus der Phaseninformation gewonnene Bewegungskomponente in Range-Richtung wurde auf die Fließlinie projiziert. Die Ergebnisse weisen eine gute Übereinstimmung mit den Geländemessungen auf und zeigen, dass es für weitere Untersuchungen zu Talgletschern der Antarktischen Halbinsel erforderlich ist, ein qualitativ hochwertiges DHM sowie präzise vermessene topographische Passpunkte einzusetzen.

[1] Remote Sensing Group, Department of Geography, University of Bern, Hallerstraße 12, CH-3012 Bern <swun@giub.unibe.ch>

[2] Department of Navigation, University of Stuttgart, Geschwister-Scholl-Str. 24D, D-70174 Stuttgart <juergen.schmidt@nav.uni-stuttgart.de>

Manuscript received 18 June 1999, accepted 24 March 2000

1. INTRODUCTION

Over the last decades significant changes of ice shelf extension were discovered in the vicinity of the Antarctic Peninsula (VAUGHAN & DOAKE 1996, DOAKE & VAUGHAN 1991, SKVARCA 1993). Changes of glacier extension and glacier thickness could also be detected on the South Shetland Islands and the Marguerite Bay area (CORBERA & CALVET 1993, WUNDERLE 1996).

The glaciers on the islands and on the West Coast of the Antarctic Peninsula are in a labile balance or even decaying state. Some authors describe an increase of air temperature during the last three to four decades on the Antarctic Peninsula (KING 1994). In addition an increase in precipitation affects the mass balance of some glaciers, however these findings are not statistically significant. In order to study mass balance and the general state of glaciers knowledge of flow velocity is of particular interest. In contrast to Alpine glaciers which are optimally surveyed by ground based measurement, many other glaciers and ice streams in the world are not well investigated. This is particularly true for glaciers on the Antarctic Peninsula because ground truth campaigns are very expensive and rare. Remote sensing data has the potential to improve our understanding of glacier fluctuations and mass balance studies. The development of satellite based radar remote sensing and SAR interferometry provides unique possibilities to derive snow cover behaviour, mass balance and flow velocity of glaciers and ice streams. This is a tremendous advantage compared to the possibilities of Antarctic science during the last decades. The applicability of SAR interferometry to derive flow dynamics was pointed out for ice streams e.g. of Antarctica (GOLDSTEIN et al. 1993, RIGNOT 1998, FROLICH & DOAKE 1998), Greenland (JOUGHIN et al. 1995, JOUGHIN et al. 1998) and Svalbard (DOWDESWELL et al. 1999). Some studies stressed the need of ground control points or DEMs (FATLAND & LINGLE 1998, ROTT et al. 1998). Satellite based radar interferometry of the Antarctic peninsula using ERS-1 or ERS-2 data should take into account some peculiarities of this region. Firstly, the meteorological conditions change very rapidly linked with changes of snow cover. This impairs the coherence between two consecutive satellite passes significantly and therefore limits drastically the amount of usable ERS image pairs. Secondly, the availability of ERS-data is limited to two or three receiving campaigns per year by the German Antarctic Receiving Station (GARS) located at the Chilean base O'Higgins. For this reason only radar data for the winter season are available to measure the ice flow. In addition, ground control points or a DEM are usually not available. Our investigations are concentrated on glaciers near the Marguerite Bay located at 68 °S and 67 °W on the west-coast of the Antarctic Peninsula because ERS tandem data were available and a base for logistical support was nearby. Several expeditions to the Marguerite Bay gathered a collection of data on snow cover and local climatic conditions (WUNDERLE 1996), together with some tie points and GPS measurements of the ablation zone of the McClary and Northeast Glacier. A late winter campaign at GARS provided us with a coherent pair of radar scenes. The data were received during the ERS-1/2 tandem phase in October 1995.

2. VARIATIONS IN GLACIER EXTENSION OF MCCLARY AND NORTHEAST GLACIERS AT MARGUERITE BAY

The Antarctic Peninsula (Fig. 1) can be divided into two different climatic areas affected by air masses of different origin. The east coast of the peninsula, with the huge Larsen Ice Shelf, is mainly dominated by cold continental air masses from the Antarctic continent, whereas the west coast is influenced by oceanic air. The difference in mean air temperature between east and west coast is approximately 8 k. The transportation of oceanic air masses result from low pressure, predominate at the Bellingshausen Sea and Amundsen Sea. The annual mean air temperature at the Marguerite Bay is -5.3 °C. Yearly accumulation rates vary between 400 and 600 mm. In lower areas of the Northeast and McClary Glacier the snow cover melts down completely during summer time. An additional slight increase of temperature can lead to a change of boundary lines, like the ELA separating areas of ablation and accumulation. In the Marguerite Bay this is particularly true because the air temperature often exceeds the 0 °C line during winter seasons. As a result, the mass balance as well as the flow velocity will change.

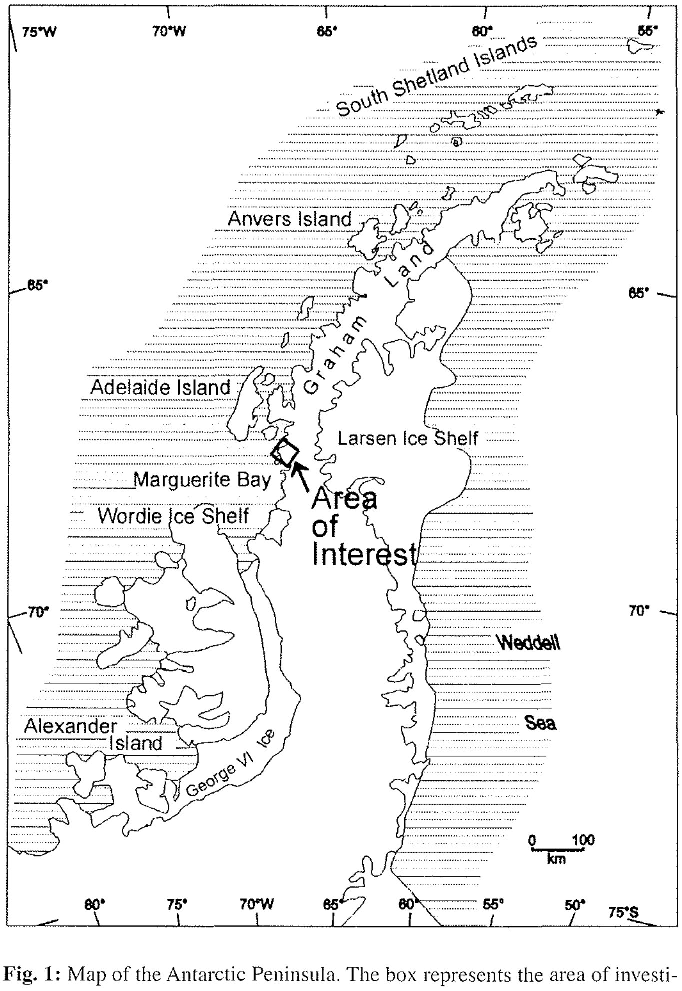

Fig. 1: Map of the Antarctic Peninsula. The box represents the area of investigation covered by ERS SAR images. The McClary and Northeast glaciers are located within the box next to the Marguerite Bay (68 °S, 67 °W).

Abb. 1: Die Antarktische Halbinsel mit dem Untersuchungsgebiet. Die McClary- und Northeast-Gletscher fließen bei 68 °S in die Marguerite Bay. Die beiden Gletscher befinden sich innerhalb des schwarzen Rahmens, der die Abdekkung durch eine ERS-SAR Aufnahme zeigt.

The main focus of this paper concentrates on the flow dynamics of McClary and Northeast glaciers in the center of the Marguerite Bay (Fig. 2). Both glaciers are 15-20 km in length and their orientation is roughly East-West. The accumulation zone of the Northeast Glacier extends approximately 300 m above mean sea level (a.m.s.l.) up to the plateau of the Antarctic Peninsula. The huge outlet glaciers of the Antarctic Peninsula are mainly situated on the east-coast and supply Larsen Ice Shelf. Only a small proportion of the ice has a west-ward flow towards the Marguerite Bay. The valley glacier McClary has no access to the plateau, therefore its catchment area is considerably smaller. The

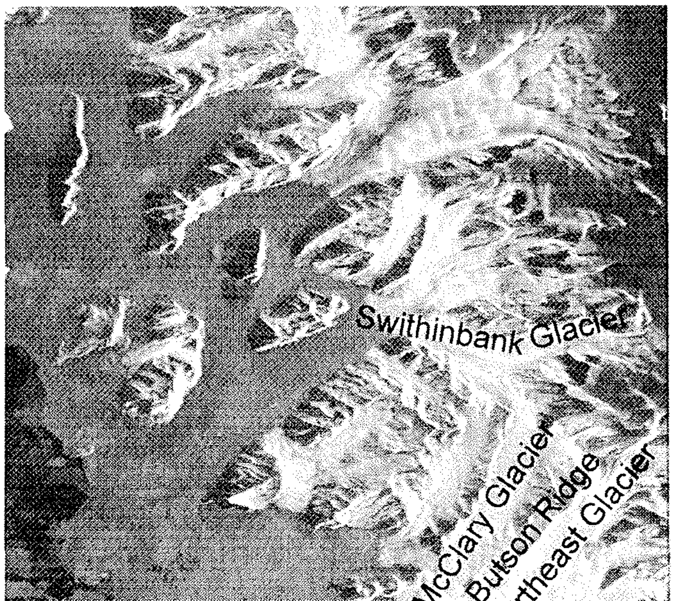

Fig. 2: ERS-1 image of the McClary and Northeast glaciers, which are separated by the Butson Ridge. The Argentine base San Martín is located in front of the ice edge of the McClary and Northeast glaciers. Part of the Marguerite Bay is covered by sea ice visualised in dark greyish colour, whereas the open sea appears in black on the left side.

Abb. 2: ERS-1 Aufnahme der McClary- und Northeast-Gletscher, die durch die Butson Ridge getrennt sind. Die argentinische Station San Martín liegt vor der Eisfront der McClary- und Northeast-Gletscher. Ein Teil der Marguerite Bay ist mit Meereis bedeckt, dargestellt in dunklen Grautönen. Das offene Meer an der linken Seite des Ausschnittes erscheint in schwarzen Farben.

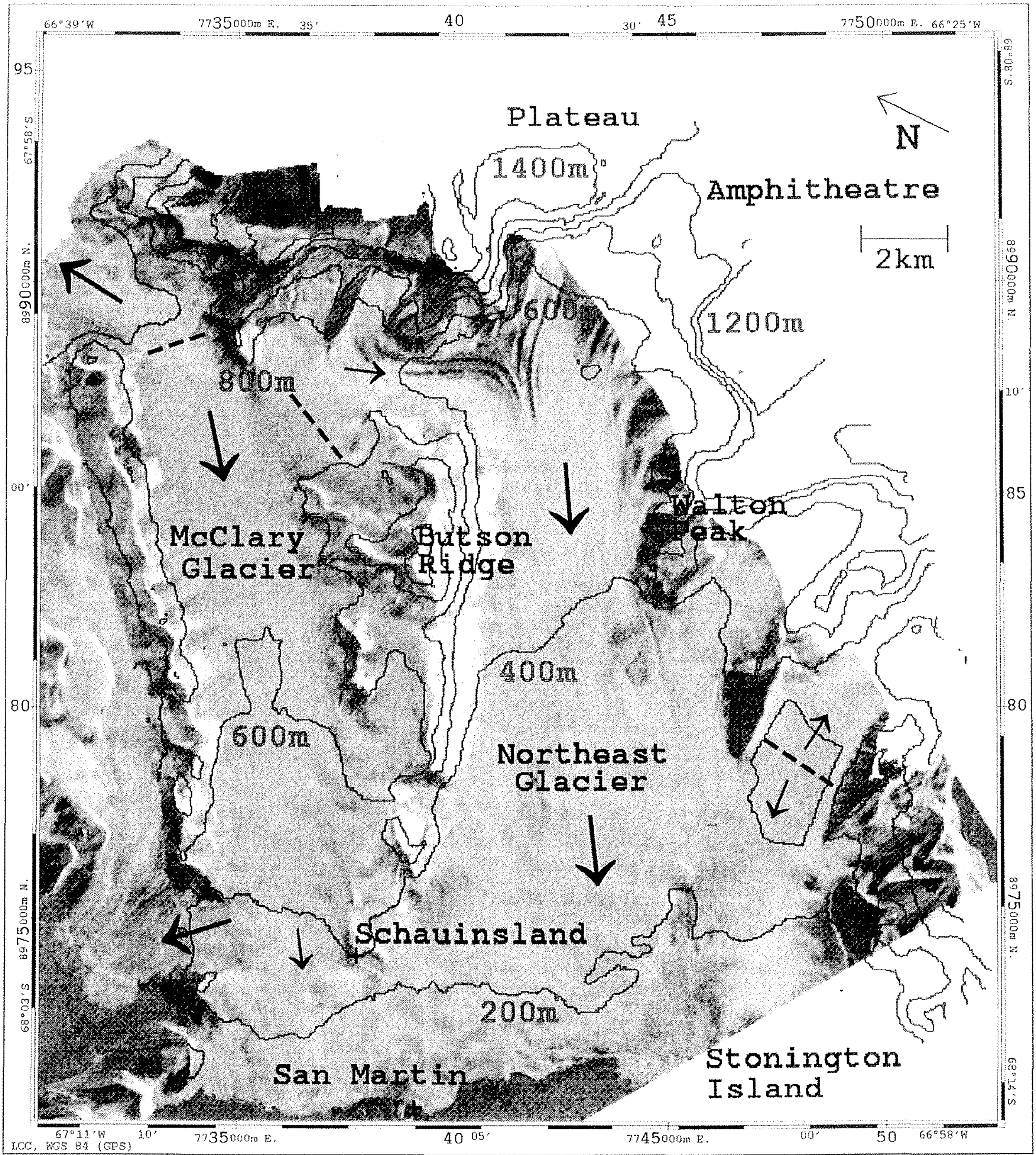

Fig. 3: Geocoded and terrain corrected intensity image of the McClary and Northeast glaciers. Contour lines represent the topography. In front of the ice edge is a small island with the Argentine base San Martín. The local divides on the glacier are marked with a short dashed line. The main flow direction is depicted with arrows. Moraines in the upper part of the Northeast Glacier (black stripes) visualise impressively the flow of the ice masses down from the plateau on the Antarctic Peninsula.

Abb. 3: Die entzerrte und geokodierte Radaraufnahme vom 15. Oktober 1995 zeigt McClary- und Northeast-Gletscher getrennt durch den Butson Ridge. Auf einer kleinen Insel, die der Eiskante vorgelagert ist, wurde die argentinische Station San Martín errichtet. Die Abgrenzung der Einzugsgebiete ist mit einer kurzen Strichlinie dargestellt. Die Pfeile zeigen die Hauptfließrichtungen an. Im oberen Bereich des Northeast Glacier ist die Fließrichtung durch die dunklen Bänder, hervorgerufen durch Moränen, sichtbar.

Butson Ridge with an elevation of 1000 m a.m.s.l separates both glaciers (Fig. 3). Both glaciers, situated near the middle of the Marguerite Bay, differ in their behaviour. As changes in the meteorological conditions are similar, we may presume that the distinct response of the glaciers is due to differences in the catchment areas extensions. In fact, the catchment area of the Northeast Glacier extends to the plateau, whereas the catchment area of the McClary Glacier is restricted to the coastal zone. In addition, the McClary Glacier has different flow directions. A detailed view of the McClary and Northeast glaciers shows the main differences (Fig. 3). It is worthwhile to notice the upper part of McClary, where two divides limit the glacier length to approximately 16 km. Thus, the accumulation zone is restricted to an elevation of 800 m whereas the Plateau of the Antarctic Peninsula with a mean height of 1400 m feeds the Northeast Glacier. Between Schauinsland and Cape Calmette (left corner in Fig. 3) a small ridge beneath the glacier crosses the McClary Glacier and directs the main glacial stream towards north-west. In some decades a decrease in precipitation in the upper part of the glacier will probably cause a thinning of the ice, leading to the result of a separation of the lower part of McClary from the main ice stream. The consequence will be a retreat of the ice front near base San Martín.

During recent years the Northeast Glacier has shown a tendency to retreat while the McClary Glacier advanced significantly since 1936 (Fig. 4). The Argentine base San Martín is located on the Debenham Islands in front of the McClary Glacier, which was partly covered by ice and snow during the last decades. The slight retreat of the Northeast Glacier was one reason to give up the research base Stonington, located on Stonington Island, because the ramp between the island and the Northeast Glacier disappeared (SPLETTSTOESSER 1992). As a result, the station lost direct access to the Northeast Glacier (Fig. 5).

During field campaigns in 1936, 1950 and 1959 British glaciologists determined the position of the ice edge for the first time. In 1936, the ice edge of the McClary Glacier was approximately 200 m behind the position of 1994. The retreat continues until 1950, afterwards an advance could be detected. During the first expedition of scientists of the British Antarctic Survey a small channel separated Barbara Island and the McClary Glacier. Some years later the glacier advanced and covered a part of the small island with ice and snow. The first Argentine base in this region was built on Barbara Island and later on destroyed by the increasing glacier. The reason for the retreat until 1950 and the advance of the McClary Glacier over the years after is not well understood because the available meteorological and glaciological data are sparse. One explanation could be the increase of air temperature over the last decades of 0.067 °C/year determined for the time interval between 1976 and 1994 (WUNDERLE 1996). Unfortunately, we have no clue about the response time of the McClary Glacier.

Investigations by DOAKE & VAUGHAN (1991) show a significant retreat of Wordie Ice Shelf located approximately 120 km south of the McClary and Northeast glaciers between 1966 and 1989. They proposed a close relation between the measured warming trend and the reduction from 2000 km^2 to 700 km^2. In former times two scientific bases of the USA and the UK were built on Stonington Island because the ice ramp between the island and Northeast Glacier gave easy access to the peninsula. Our investigations on glacier fluctuations of the Northeast Glacier are a contribution to the discussion of changes in this region. We used an aerial photo of 1989 superimposed by a topographical map of 1947/48 to visualise the different positions of the ice edge of Northeast Glacier (Fig. 5). The glacier shows a stable behaviour with a small retreat in front of Stonington Island. In contrast to this, McClary Glacier advanced during this time. Further glaciological and climatological investigations have to be done to explain the different behaviour of the McClary and Northeast glaciers. A first contribution is the determination of the glacier velocity allowing to model the response time of these glaciers in the near future.

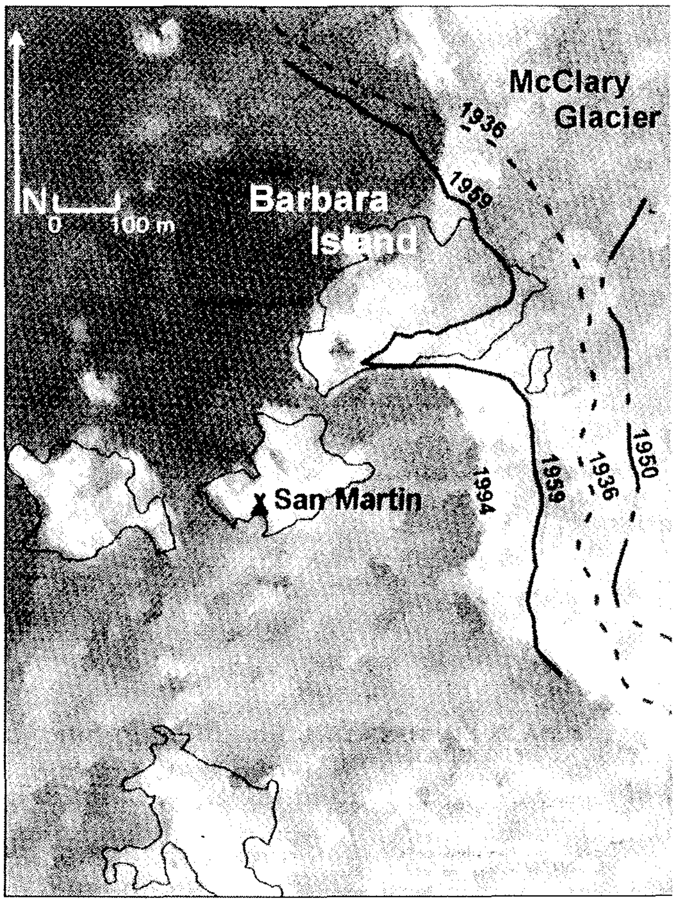

Fig. 4: Historical map with the position of the McClary ice edge in 1936, 1950 and 1959. The map is superimposed by a despeckled ERS-1 SAR image acquired on February, 13 1994. The difference in backscatter between glacier ice (white and greyish color) and the sea (dark greyish colors) shows the position of the ice cliff in 1994.

Abb. 4: Historische Karte mit der Position der Eiskante des McClary-Gletschers von 1936, 1950 und 1959. Die Karte wurde mit einer entspeckelten ERS-1 SAR Aufnahme vom 13 Februar 1994 überlagert. Die unterschiedliche Rückstreuung zwischen Gletscher (weiß und hellgraue Farbtöne) und dem Meer (dunkle Grautöne) zeigt sehr deutlich die Position der Eiskante von 1994.

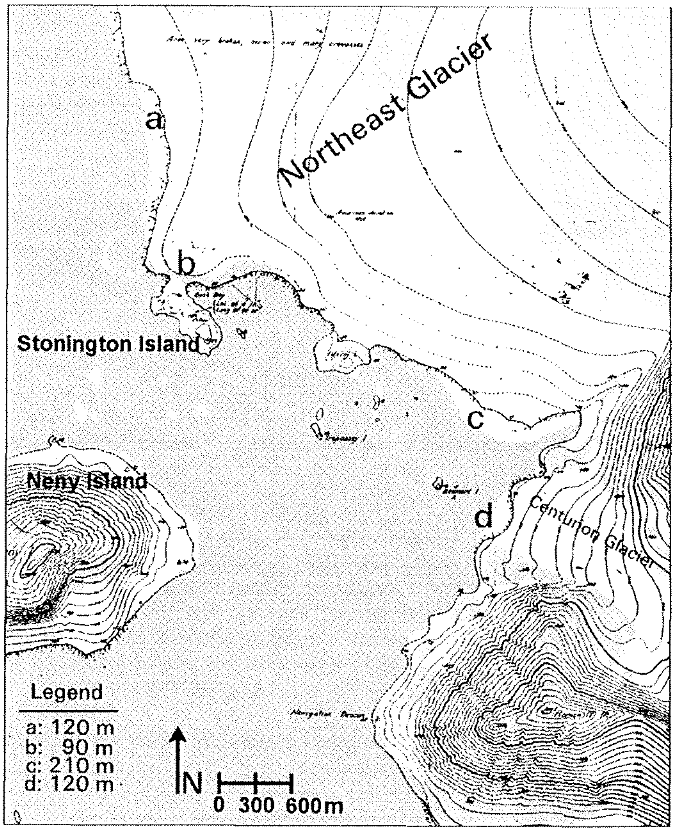

Fig. 5: An aerial photo of 1989 shows the lower part of the Northeast Glacier as well as Neny and Stonington islands. The aerial photo superimposed by a topographic map of 1947/48 visualises the different positions of the ice edge of the Northeast Glacier in 1947 and 1989. The changes along at the front of the Northeast Glacier are small (see legend) and reflect a non-uniform behaviour. A small retreat in front of Stonington Island (b) is in contrast to the advance of positions a and c as well as position d on the Centurion Glacier.

Abb. 5: Ein Luftbild aus dem Jahre 1989 stellt den unteren Teil des Northeast-Gletschers sowie die Neny- und Stonington-Inseln dar. Das Luftbild wurde mit einer topographischen Karte aus dem Jahre 1947/48 überlagert und zeigt die unterschiedlichen Positionen der Eiskante. Nur kleine Veränderungen mit einem uneinheitlichen Verhalten bilden sich ab. Im Gegensatz zu dem geringen Rückzug vor der Stonington-Insel (b) zeigt sich an den Stellen a und c ein geringer Vorstoß.

3. FLOW DYNAMICS OF THE NORTHEAST AND MCCLARY GLACIERS

A precondition to compute interferograms is a high coherence between two ERS data sets. The coherent image gives a first impression whether the ERS data pair is useful for further processing. Areas with low coherence caused by temporal de-correlation appear in dark greyish colours whereas parts with high coherence are shown in white and bright greyish colours. In addition, the coherent image shows features of the glacier flow behaviour (Fig. 6). A black zone marks the border between the Swithinbank and McClary glaciers. It indicates the shear zone between both glaciers caused by different flow velocities. The Swithinbank Glacier, directly linked to the plateau of the Antarctic Peninsula has a relatively high flow velocity comparable with that of the McClary Glacier. Crevasses on the McClary Glacier appear as dark areas because they significantly changed their structure in 24 hours.

Some slight moraines are mapped in the upper part of the Northeast Glacier, which visualise the confluence zone of the main ice stream and a small glacier. Near the ice edge of the Northeast Glacier a disturbed zone appears in a black square.

3.1 *Prerequisites to determine the flow velocity*

The flow velocity of glaciers and ice streams can be determined by expensive ground truth campaigns using GPS measurements or by means of radar interferometry. At a first glance the later offers a simple method to derive topography and flow velocity of remote areas using only satellite based radar imagery (JOUGHIN et al. 1996, KWOK & FAHNESTOCK 1996). Unfortunately, the technique of interferometry requires some additional data, if only one repeat pass is available (e.g. ascending or descending). The geometry of an interferometric SAR system is basically given by the first sensor position, a baseline vector separating the two sensors positions, a range vector pointing from sensor 1 to the earth's surface and the range difference. The relation between measured and unwrapped phase difference ϕ_{unwrap} and geometrical range difference Δ is

$$\Delta = (\lambda/4\pi)\phi_{unwrap}$$

where λ is the radar wavelength. The factor 4π is valid for repeat-pass interferometry. Topography and displacement of a glacier surface influence the range difference. The interferometric phase consists therefore of two related terms,

$$\phi_{unwrap} = \phi_{topography} + \phi_{displacement}.$$

The topographic part has to be removed in order to extract the displacement term, which is an expression of the flow velocity of the glacier surface. A digital elevation model as well as the geometry of the interferometric system are necessary to calculate a synthetic interferogram which simulates the topographic phase term. We used a digital elevation model created from aerial photos to model the phase values of topography. The DEM of the McClary and Northeast glaciers has a spatial resolution of 20 m with an accuracy of approximately 10 m (Fig. 8). The accuracy of the baseline significantly affects the results because the phase difference is a function of baseline, distance of sensor-surface and surface elevation. Unfortunately the ERS-1 orbits are not sufficiently precise to determine the baseline with the needed accuracy. Additional tie points have to be used to model the baseline (JOUGHIN et al. 1998). During the field survey four corner reflectors and some stakes were installed along a transect in the confluence zone of the McClary and Northeast glaciers. The positions of the corner-reflectors and the stakes as well as the tie points on the Debenham Islands were measured by GPS and theodolite in summer 1993/94 and 1994/95. The deduced flow vectors described in chapter 3.3 are a good aid to verify the satellite based flow velocity.

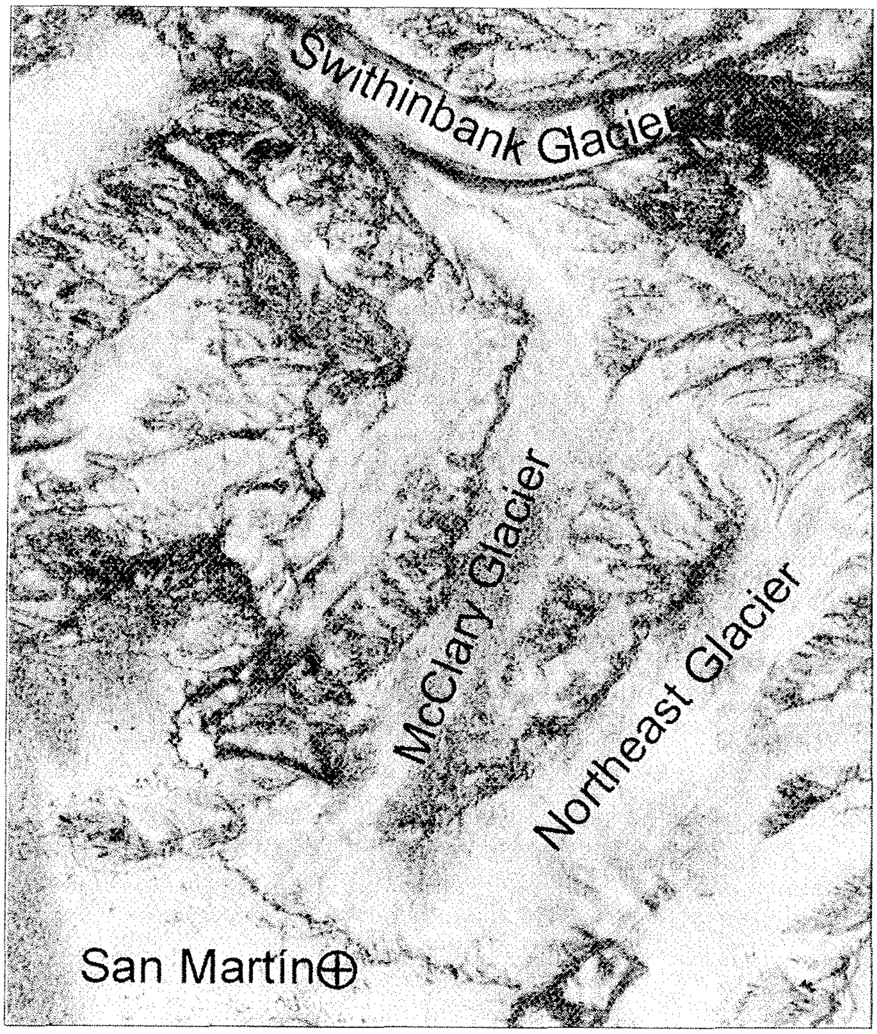

Fig. 6: Detailed view of the Marguerite Bay with the Swithinbank, McClary and Northeast glaciers. The coherent image was calculated from ERS-1 and ERS-2 data of October 15 and 16, 1995. Areas with high coherence appear in greyish colours, whereas the dark areas represent low values of coherence. A dark zone divides the Swithinbank and McClary glaciers.

Abb. 6: Das Kohärenzbild zeigt einen Ausschnitt der Marguerite Bay mit den Gletschern Swithinbank, McClary und Northeast. Am Rande der Gletscherkante ist die Lage der argentinischen Station San Martín eingezeichnet. Das Kohärenzbild wurde aus den ERS-1- und ERS-2-Aufnahmen vom 15 und 16. Oktober 1995 berechnet. Gebiete mit hellen Grauwerten zeigen eine hohe Kohärenz zwischen den Aufnahmen, im Gegensatz zu den dunkleren Zonen, die auf geringe Kohärenzwerte hinweisen. Die Scherzone zwischen Swithinbank-Gletscher und McClary-Gletscher wird eindrücklich durch eine schwarze Linie markiert.

3.2 *Derivation of glacier flow velocity*

In order to keep temporal de-correlation at a minimum we used two subsequent ERS-1/2 images of the tandem phase with only 24 hours difference (Tab. 1). A distance (baseline) of 113 m separates the antenna positions between both images. The first processing step was a careful co-registration at sub-pixel accuracy using the phase information of the complex data sets. In subsequent steps, we calculated the coherence and the phase difference between both images. The coherent image (Fig. 6) was used to check the quality of the tandem pair for further processing.

Sensor	ERS-1	ERS-2
Orbit	22227	02554
Track	195	195
Frame	5013	5013
Date	19951015	19951016
Time	12:55	12:55

Tab. 1: SAR-Images used to derive the flow velocity.

Tab. 1: Verwendete SAR-Aufnahmen zur Ableitung der Gletscherfließgeschwindigkeit.

Clear fringes can be seen on the interferogram (Fig. 7) in the area of the McClary and Northeast glaciers. Based on the WGS 84 the effect of the Earth's curvature has already been eliminated. Now, the remaining phase difference only reflects topographical effects, glacier movement and an error term. Impressive are the fringes on the sea ice in front of the Swithinbank Glacier (see Figs. 2 and 6 for orientation) as well as in front of the Northeast Glacier. Unfortunately the border of the ERS-frame does not completely show the fringes at the second location. Nevertheless it shows the predominantly ice transport of both glaciers into this part of the Marguerite Bay. In contrast to these findings only one fringe appears in front of the McClary Glacier, which depicts the relatively slight transport of ice masses into the Marguerite Bay.

The influence of the local topography on the phase difference has to be removed to obtain the phase information caused only by glacier movement. One high resolution DEM was available (Fig. 8) computed from aerial photos of 1986 by means of photogrammetric techniques. In comparison with observations and measurements during the ground campaigns the DEM exhibits some small errors in the upper part of the Northeast Glacier. Nevertheless it is a valuable aid to remove the topographic part

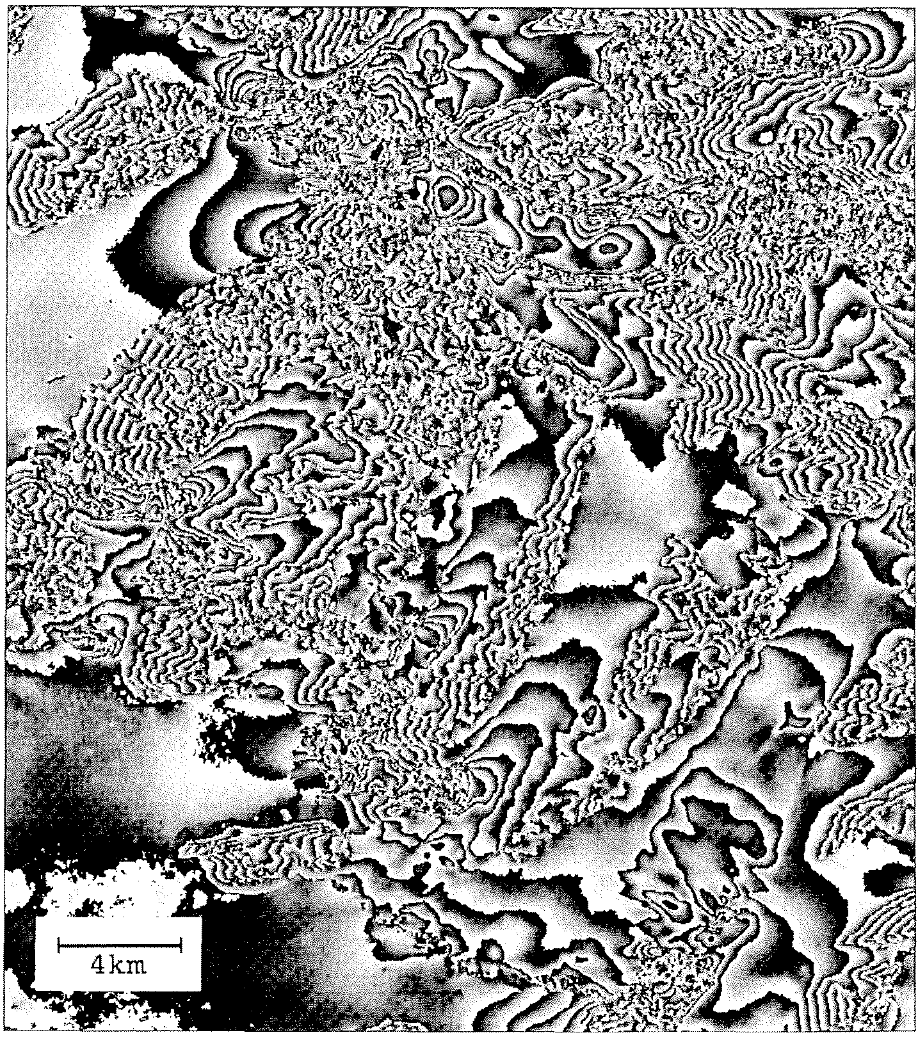

Fig. 7: Shown is the phase difference from SAR images acquired on October 15 (ERS-1) and October 16 (ERS-2), 1995 in slant range geometry. Clear fringes can be seen on the McClary and Northeast glaciers reflecting glacier movement and local topography.

Abb. 7: Dargestellt ist die Phasendifferenz der beiden ERS-Aufnahmen vom 15. und 16. Oktober 1995. Die eindeutigen Phasenmuster auf McClary- und Northeast-Gletscher bilden die lokale Topographie und das Bewegungsfeld ab.

of the phase. Computation of a synthetic interferogram requires the same orbit information as known for the ERS-1/2 images used as well as an improvement of the baseline (MOHR et al. 1998).

We selected some additional GCP´s at the coast and on the unique nunataks to georeference the DEM, which are clearly visible on the ERS imagery and topographic maps. The DEM was converted to Lambert Conformal Conic (LCC) Projection using the Earth ellipsoid WGS 84. The fringes of the simulated interferogram visualise the elevation of the area of investigation (Fig. 9).

Both interferograms were transformed into the same projection to subtract the phase values of the local topography from the phase difference of the ERS data sets. The major part of topography was removed (Fig. 10). Now, the data set presented in Figure 10 is a starting point for the calculation of the flow velocity along estimated flow lines.

The flow lines were extracted from aerial photographs and ERS-SAR intensity images. They give the horizontal direction of the ice movement. One flow line was selected exemplary here (see Fig. 10). The corresponding hight profile starts almost at 600 m elevation with a slight slope (Fig. 11). The small peak at a distance of 1300 m is an error of approximately 13 m in the DEM. This error will propagate in the estimation of glacier velocity. The further progression of the profile shows an uniform decrease with a small depression of 40 m at a distance of 11000 m.

As pointed out before only one repetition pass of ERS data was used and consequently we reduced the number of variables with the assumption of no vertical movement. In general, this assumption does not completely reflect the glacial flow, because a slight movement in the vertical direction is always existent (PATERSON 1994). The derived flow direction of the Northeast Glacier was a pre-condition to deduce the glacier velocity by means of interferometry (CUMMING & VALERA 1997) because only the phase information in range could be used. The resolution in azimuth is too coarse relative to size and expected movement of the small test site to apply correlation techniques. A phase shift of 360° represents 2.8 cm displacement in the line-of-sight direction of a surface point in 24 hours. Re-projecting this displacement component to the flow direction defined by the local tangent of a flow line yields to the amount of surface

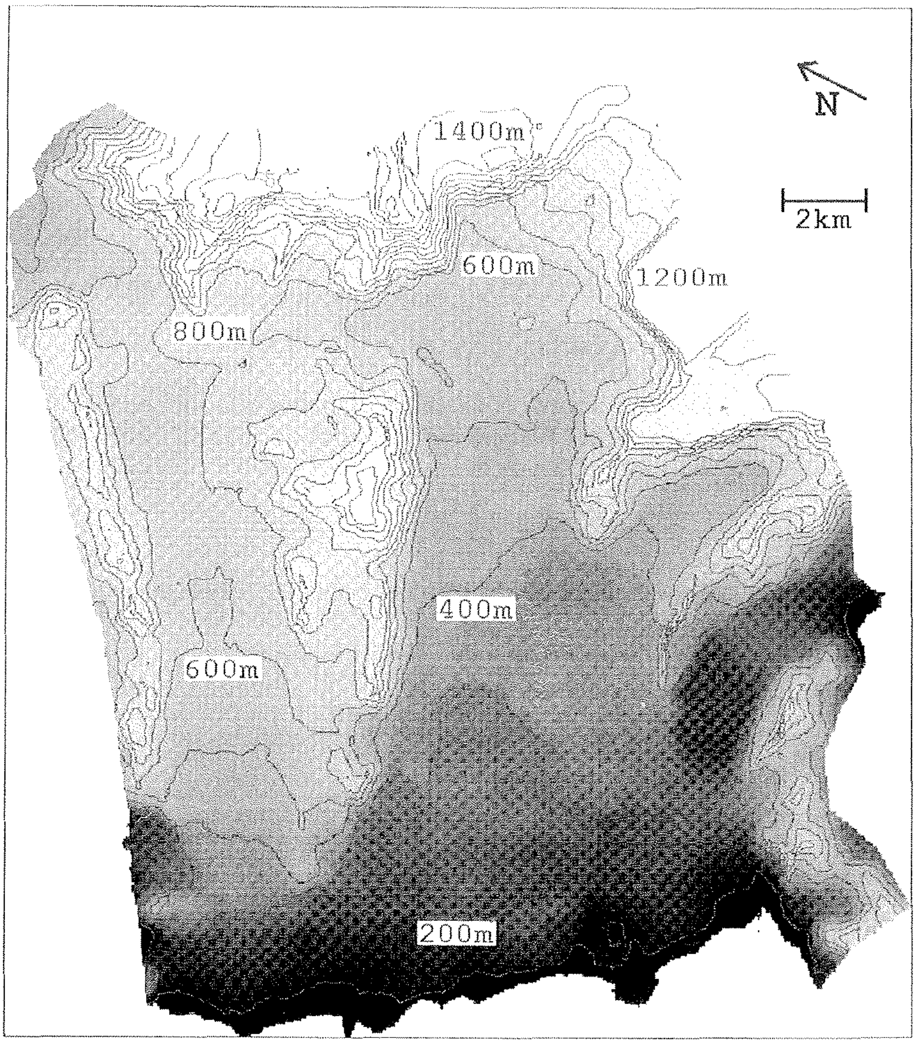

Fig. 8: Digital elevation model (DEM) derived form aerial photos of 1986 with a spatial resolution of 20 m and an accuracy in height of 10 m. The contour interval is 100 m. (Map co-ordinate system: see Fig. 3)

Abb. 8: Das digitale Höhenmodell wurde aus Luftbildern des Jahres 1986 mit einer räumlichen Auflösung von 20 m und einer Höhengenauigkeit von 10 m abgeleitet. Die Äquidistanz der Isohypsen ist 100 m.

velocity (Fig. 12). Ground truth data points on McClary Glacier were used to solve for the unknown reference constant.

The glacier starts with a velocity of approximately 115 m/year near the Amphitheatre and decelerates to 50 m/year at 2500 m. At this location the glacier widens out. The ice input from two small glaciers is less than expected because the glacier velocity slows down. Further downstream the glacier accelerates to a velocity of approximately 128 m/year caused by a narrowing of the glacier bed (6000 m). The second minimum of the flow velocity occurs at a distance of 9500 m because the glacier widens out. At the lower parts of the Northeast Glacier the input of the small glaciers accelerates and the velocity is approximately 110 m/year. The third minima was localized at 15000 m. The flow velocity is approximately 10 m/year caused by the divergence of the ice.

3.3 *Comparison with ground truth*

During the austral summer 1993/94 we marked some positions on the McClary and Northeast glaciers with ablation stakes. Insitu theodolite measurements and a Global Positioning System (GPS) survey determined the positions in 1993/94 and 1994/95. Flow-vectors visualise the measurements and represent velocity and direction of glacial movement at the points A13, A15 and A17 (Fig. 13). Vector A17 is almost parallel to the exemplary flow-line of the Northeast Glacier. The estimated flow velocity of A17 is 70 m/year, of A15 30 m/year and of A13 20 m/year, respectively.

The decrease in velocity from the middle of the Northeast Glacier to the McClary Glacier supports the findings of the slight ice transport to Marguerite Bay near the base San Martín (Fig. 7). Beneath A17 the glacier velocity derived by means of interferometry is 51 m/year. Ground truth inaccuracies are caused by errors in the theodolite measurements due to only a few reference points. In addition, the ground measurements represent a mean of one year in contrast to the ERS-1/2 remote sensing data, which were acquired within 24 hours. Considering that, the field measurements show an acceptable agreement with the results derived from interferometry.

4. DISCUSSION

Particularly in maritime Antarctic regions the limits of interferometry become obvious. Highly dynamic atmospheric con-

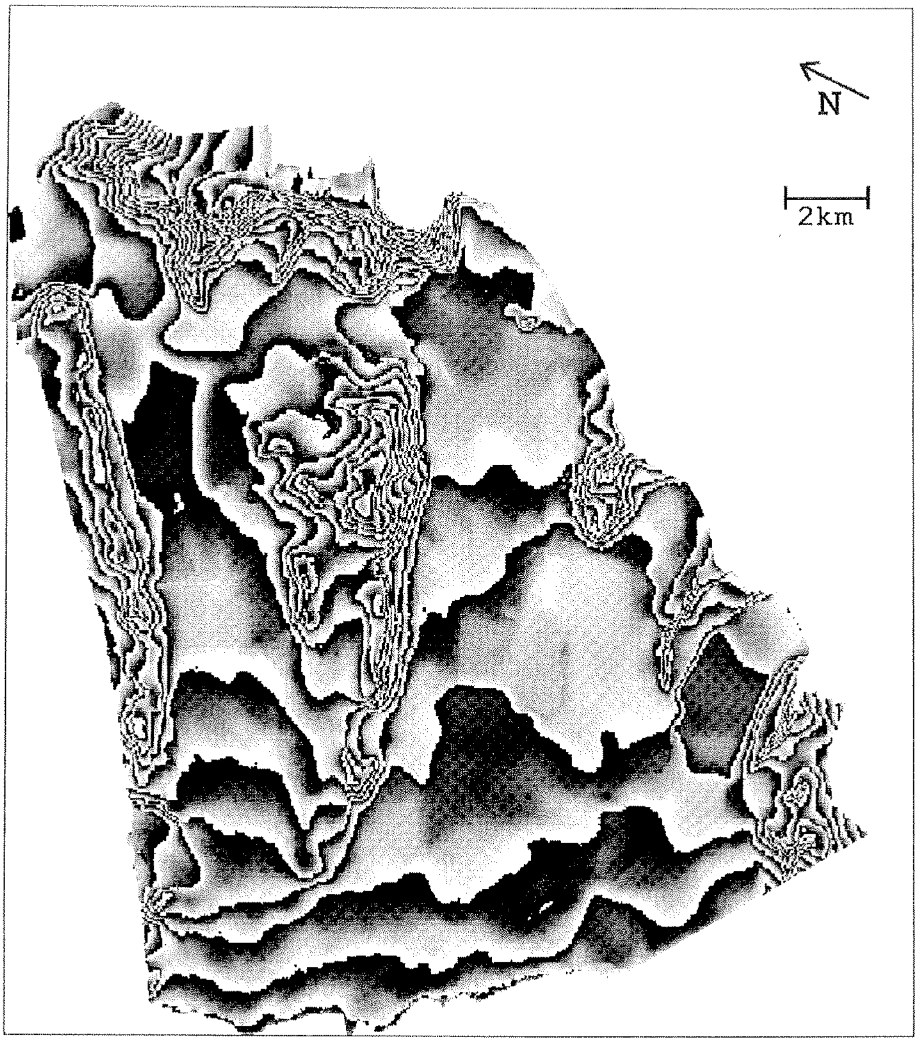

Fig. 9: Synthetic interferogram in ground range geometry calculated for the aerial photography DEM. Areas not covered by the SLC data or the DEM were masked. (Map co-ordinate system: see Fig. 3).

Abb. 9: Die Abbildung zeigt das synthetische Interferogram in Ground Range, dass von dem digitalen Höhenmodell abgeleitet wurde. Gebiete, die nicht von der SLC-Szene oder vom Höhenmodell abgedeckt wurden, sind ausmaskiert.

ditions lead to snow cover fluctuations, which in turn result in large-scale de-correlation between two or more SLC images. Not only does a slight deviation of the snow cover's liquid water content cause significant changes in the intensity of the reflected radar signal, it also shifts the dominating backscatter levels within the snow cover itself. However, to determine velocity fields eliminating topographic information from the interferogram is essential. This requires the integration of DEMs created with traditional methods. Further processing was done on a subsection of the Marguerite Bay in order to investigate the general applicability of the method to the exploration of radar data. Especially in the case of slow moving glaciers the remaining phase error will result in inaccurate flow vectors. Relative to the topographic term the phase information resulting from the glacier's velocity is small. Existing DEMs should be improved for maritime Antarctica, particularly for areas of the Antarctic Peninsula, in order to be able to determine the flow dynamics of selected glaciers on a large scale (WUNDERLE & SCHMIDT 1997). The derivation of glacier flow velocities on small glaciers by means of single-pairs interferometry requires a high precision DEM. This is necessary especially in the case of large baselines or slow ice movement because of the dominant influence of topography on the phase information. Atmospheric arefacts can't be identified. The availability of such a DEM allows the calculation of the flow velocity in areas where no ground measurements exist. This new information could be helpful for mass balance studies in the context of global climate change for the Antarctic Peninsula.

5. ACKNOWLEDGEMENT

The work was supported by the German Secretary of Science and Research (BMBF) within the program "Dynamic Processes in Antarctic Geosystems" and by the ESA project "Monitoring of Dynamic Processes in Antarctic Geosystems". The authors would like to thank the Instituto Antartico Argentino (IAA) and the German Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI) for their support in respect to logistics and field equipment. We are grateful to Dr. D. Vaughan of BAS who made the historical maps of the McClary and Northeast Glacier available to us. The authors wish to thank Dr. J. Sievers (BKG) who made the DEM available to us. Special thanks go to the reviewers for their helpful comments and to S. Vogt as well as M. Schultze for proof-reading.

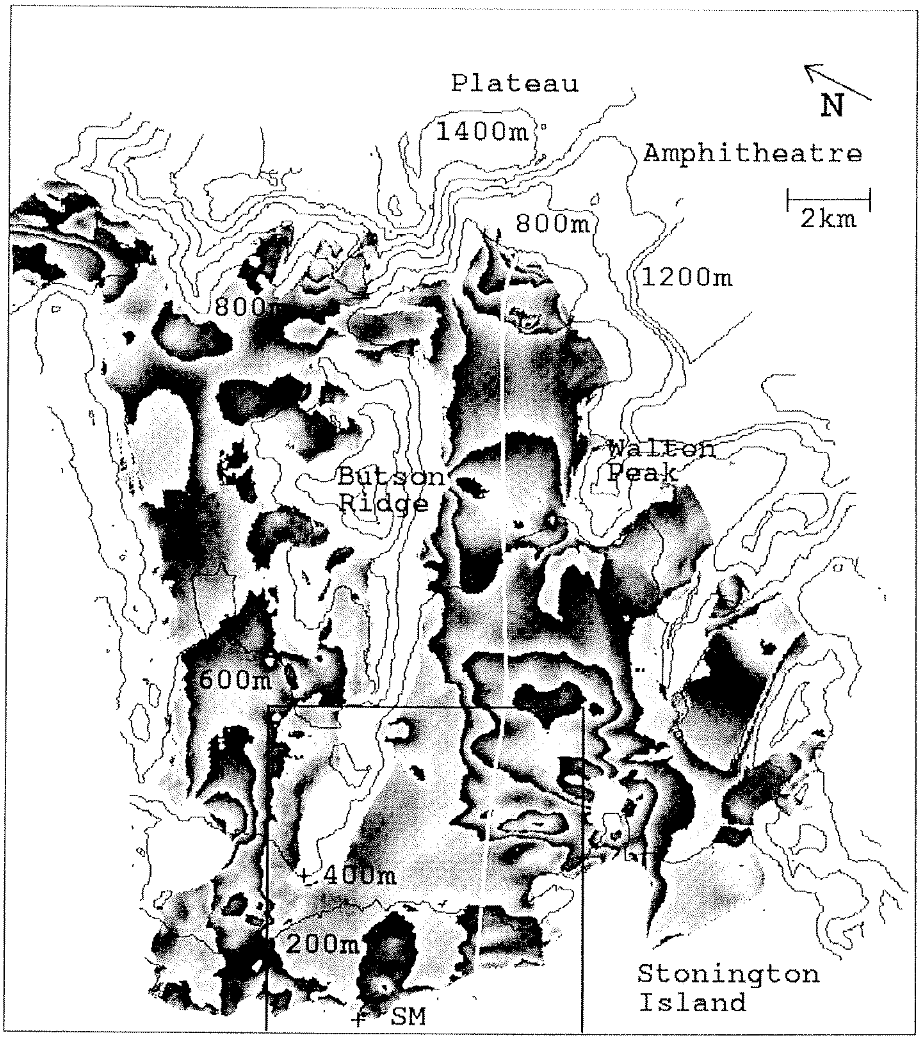

Fig. 10: The difference between real and synthetic interferogram representing fringes caused by the displacement within the acquisition interval of 24 hours. The selected exemplary flow line of the Northeast Glacier is marked in white. The black box depicts a subset visualised in figure 13 comparing the velocity with ground truth data.

Abb. 10: Die Phasendifferenz zwischen dem realen Interferogram, berechnet aus den ERS-Daten, und dem simulierten Interferogram, das basierend auf dem Höhenmodell berechnet wurde. Die dargestellten Phasenwerte sind ein Maß für die Gletscherbewegung innerhalb von 24 Stunden. Eine ausgewählte Fließlinie des Northeast Glacier ist in weiß dargestellt. Ein Vergleich mit Bodenmessungen wurde in dem schwarz umrahmten Ausschnitt durchgeführt und in Abb. 13 dargestellt.

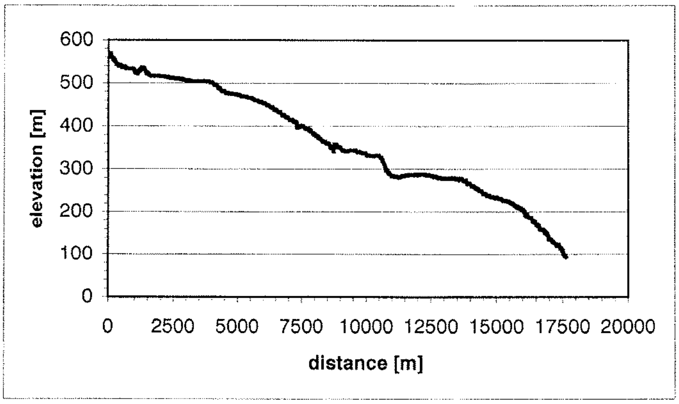

Fig. 11: Elevation profile of the flow line with a continuos descent from the Amphitheatre to the ice cliff. The flow line crosses a small depression at approximately 11.000 m.

Abb. 11: Das Höhenprofil der Fließlinie zeigt einen kontinuierlichen Abfall vom Amphitheatre bis zur Eiskante. Die Fließlinie kreuzt bei ca 11.000 m eine kleine Senke.

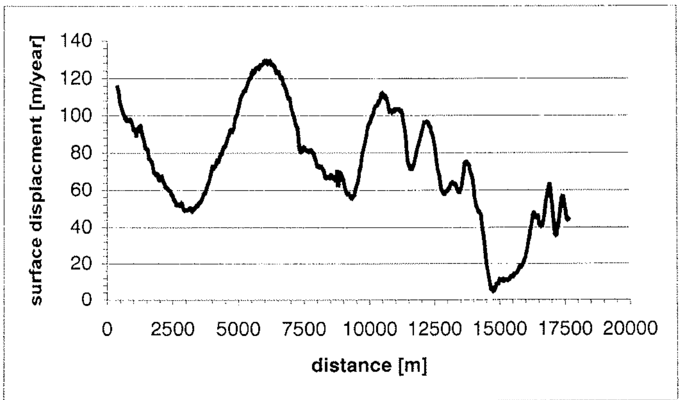

Fig. 12: Glacier velocities at the exemplary flow line of the Northeast Glacier. The diagram of the surface flow velocity reflects the complex topography of this area.

Abb. 12: Fließgeschwindigkeit des Northeast-Gletschers entlang der beispielhaften Fließlinie. Der Verlauf der Geschwindigkeitskurve spiegelt die komplexe Topographie wieder.

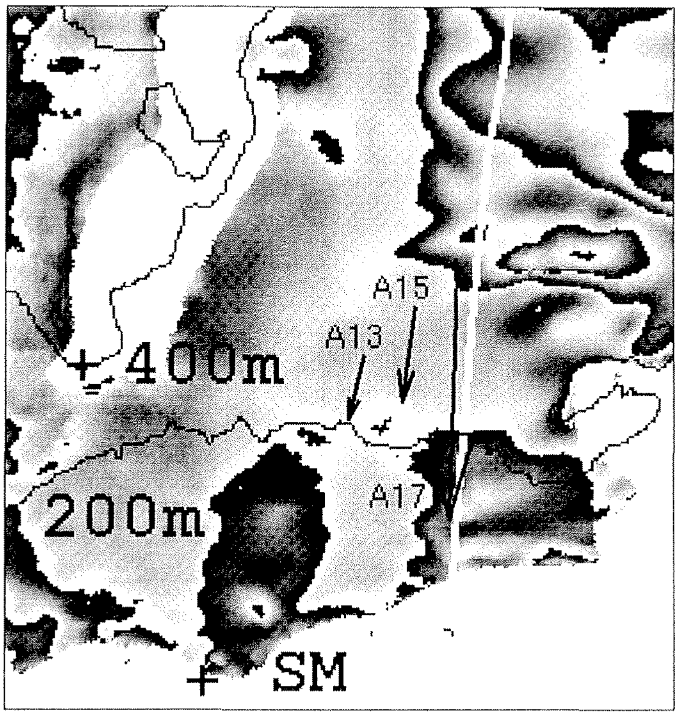

Fig. 13: Flow vectors determined by ground measurements for the Northeast Glacier (A13, A15, and A17). Measurements were done during field surveys 1993/94 and 1994/95. The selected flow line is visualised as a white line in the neighbourhood of A17. The lower cross marks the base San Martín.

Abb. 13: Fließvektoren (A13, A15 und A17), die mittels Messungen aus den Jahren 1993/94 und 1994/95 berechnet wurden. Die ausgewählte Fließlinie ist als weiße Kurve dargestellt und befindet sich neben A17. Das untere Kreuz zeigt die Position der Basis San Martín.

References

Corbera, J. & Calvet, J. (1993): Use of SPOT panchromatic imagery to evaluate glacier fluctuation in Livingstone Island.- SELPER 9: 31-35.

Cumming, I. & Valero, J.-L. (1997): Glacier Flow Measurements with ERS Tandem Mission Data.- Proc. of the Fringe 96 Workshop on ERS SAR Interferometry, Zürich, 30 Sept. - 2 Oct. 1996, (ESA SP-406): 353-362.

Doake, C.S.M. & Vaughan, D.G. (1991): Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming.- Nature 350: 328-330.

Dowdeswell, J.A., Unwin, B., Nuttall, A.M. & Wingham, D.J. (1999): Velocity structure, flow instability and mass flux on large Arctic ice cap from satellite radar interferometry.- Earth Planet. Sci. Letters 167/3-4: 131-140.

Eldhuset, K., Aanvik, F., Asknes, K., Amlien, J., Andersen, P.H., Isaksson, E., Wahl, T. & D. J.Weydahl, D.J. (1997): First results from ERS tandem INSAR processing on Svalbard.- Proc. of the Fringe 96 Workshop on ERS SAR Interferometry, Zürich, 30 Sept. - 2 Oct. 1996 (ESA SP-406): 337-344.

Fatland, D.R. & Lingle, C.S. (1998): Analysis of the 1993-95 Bering Glacier (Alaska) surge using differential SAR interferometry.- J. Glaciol., 44/148: 532-546.

Frolich, R.M. & Doake, C.S.M. (1998): Synthetic aperture radar interferometry over Rutford ice stream and Carlson Inlet, Antarctica.- J. Glaciol. 44/146: 77-92.

Goldstein, R.M., Engelhardt, H., Kamb, B. & Frolich, R.M. (1993): Satellite radar interferometry for monitoring ice sheet motion: Application to an Antarctic ice stream.- Science 262: 1525-1534.

Joughin, I., Winebrenner, D.P. & Fahnestock, M.A. (1995): Observations of ice-sheet motion in Greenland using satellite radar interferometry.- Geophys. Res. Letters 22/5: 571-574.

Joughin, I., Kwok, R. & Fahnestock, M. (1996): Measurement of ice-sheet topography using satellite-radar interferometry.- J. Glaciol. 42/140: 10-22.

Joughin, I., Kwok, R. & Fahnestock, M.A. (1998): Interferometric estimation of three-dimensional ice-flow using ascending and descending passes.- IEEE Transactions on Geosci. Remote Sensing 36: 25-37.

King, J.C. (1994): Recent climate variability in the vicinity of the Antarctic Peninsula.- Intern. J. Climatol. 14: 357-369.

Kwok, R. & Fahnestock, M.A. (1996): Ice sheet motion and topography from radar interferometry.- IEEE Trans. Geosci. Remote Sensing GRS-34: 189-200.

Mohr, J.J., Reeh, N. & Madsen, S.N. (1998) Three-dimensional glacial flow and surface elevation measured with radar interferometry.- Nature 391: 273-276.

Paterson, W.S.B. (1994): The physics of glaciers.- Pergamon, Oxford, ed.2, 480 pp.

Rignot, E.J. (1998): Fast recession of a West Antarctic glacier.- Science 281: 549-551.

Rott, H., Stuefer M., Siegel, A., Skvarca, P. & Eckstaller, A. (1998): Mass fluxes and dynamics of Moreno Glacier, Southern Patagonia Icefield.- Geophys. Res. Letters 25/9: 1407-1410.

Skvarca, P. (1993): Fast recession of the northern Larsen Ice Shelf monitored by space images.- Annals Glaciol. 17: 317-321.

Splettstoesser, J. (1992): Antarctic global warming.- Nature 355:503.

Vaughan D.G. & Doake, C.S.M. (1996): Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula.- Nature 379: 328-330.

Wunderle, S. (1996): Die Schneedeckendynamik der Antarktischen Halbinsel und ihre Erfassung mit aktiven und passiven Fernerkundungsverfahren.- Freiburger Geographische Hefte, 48, University of Freiburg, 172 pp.

Wunderle, S. & Schmidt, J. (1997): Comparison of Interferograms using different DTM's - A case study of the Antarctic Peninsula.- In S. WUNDERLE (ed.), EARSeL-Proceedings, workshop on remote sensing of land ice and snow. April, 17-18, 1997: 131-135.