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# Monitoring Multi-Year Snow Cover Dynamics on the Antarctic Peninsula Using SAR Imagery

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**Summary:** The capability of mapping different radar glacier zones on a regional scale using multi-temporal SAR-mosaics derived from ERS-1/2 quicklook imagery is demonstrated. The 1992 and 1997 winter mosaics and the 1998 summer mosaic facilitate a discrimination of the major radar glacier zones on the Antarctic Peninsula: (1) the dry snow radar zone, (2) the frozen percolation radar zone, (3) the wet snow radar zone and (4) the bare ice radar zone. The boundaries between these zones have been identified as indicators of climatic variability providing information on different time scales: (1) the dynamic wet snow line approximately coincides with the position of the actual 0 °C isotherm, (2) the transient snowline at the end of the ablation season documents the spatial extension of the ablation zone and (3) the dry snow line is a sensitive indicator for singular extreme melt events. Furthermore, SAR-data might be used to establish the timing of melt onset over glaciers and thus enables to determine the duration of the annual ablation period. Comparison of the 1997 winter mosaic with the mosaic from the 1998 ablation season reveals the seasonal large-scale patterns of snow cover dynamics along the Antarctic Peninsula. Although the quicklook - mosaics lack a radiometric and geometric correction, they provide a cost- and time-efficient tool for monitoring and investigating the large-scale patterns of snow cover properties, identifying unusual radar signatures features, and discriminating areas of special interest. This is demonstrated with three regional case studies from Adelaide Island, the inner Marguerite Bay and the South Shetland Islands.

**Zusammenfassung:** Die vorliegende Arbeit zeigt die Möglichkeiten der großmaßstäbigen Kartierung verschiedener Radar-Gletscherzonen unter Nutzung von aus ERS-1/2-Quicklooks erzeugten, multi-temporalen SAR-Mosaiken auf. Die Mosaike der Winter 1992 und 1997 sowie des Sommers 1998 ermöglichen die Ausscheidung der dominierenden Radar-Gletscherzonen im Bereich der Antarktischen Halbinsel: (1) die Trockenschnee-Radarzone (dry snow radar zone), (2) die gefrorene Perkolationsschnee-Radarzone (frozen percolation radar zone) (3) die Nassschnee-Radarzone (wet snow radar zone) und (4) Gletschereis-Radarzone (bare ice radar zone). Die Grenzlinien dieser Zonen dienen als sensitive Indikatoren klimatischer Variationen, wobei sie jeweils Informationen unterschiedlicher Zeitskalen darbieten: (1) die dynamische Nassschneelinie stimmt annähernd mit der Position der aktuellen 0 °C-Isotherme überein, (2) die Position der Schneelinie am Ende der Ablationsperiode dokumentiert die räumliche Ausdehnung der Ablationszone und (3) die Trockenschneelinie dient als Indikator für außerordentlich starke, singuläre Schmelzereignisse. Darüber hinaus lässt sich mit SAR-Daten der Zeitpunkt des Beginns der Schneeschmelze auf Gletschern zu bestimmen. Dadurch ist die Erfassung der Dauer der gesamten jährlichen Ablationsperiode möglich. Ein Vergleich des Winter-Mosaiks 1997 und dem der darauf folgenden Ablationsperiode 1998 verdeutlicht die großräumigen, jahreszeitlichen Muster der Schneedeckendynamik im Bereich der Antarktischen Halbinsel. Obwohl die Quicklook-Mosaike keine radiometrischen und geometrischen Korrekturen aufweisen, stellen sie ein kostengünstiges und zeiteffektives Hilfsmittel zur Erforschung und Überwachung der großräumigen Verteilung der Schneedeckeneigenschaften dar und dienen der Identifikation ungewöhnlicher Radarsignaturen sowie der Ausweisung spezieller Interessengebiete. Die genannten Einsatzmöglichkeiten werden anhand von drei regionalen Fallstudien aus Adelaide Island, der zentralen Marguerite Bay und den South Shetland Islands demonstriert.

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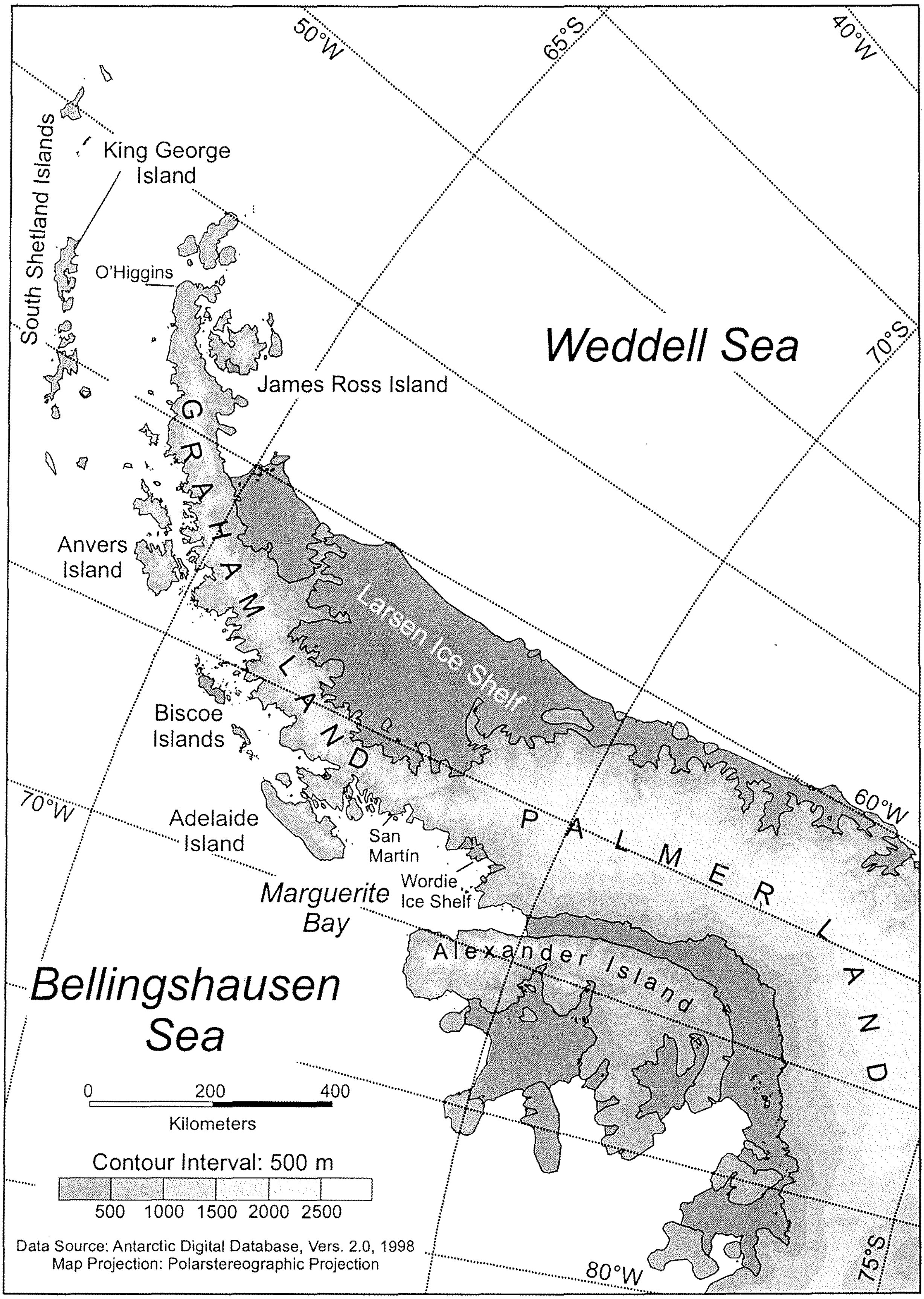
## 1. INTRODUCTION

The Antarctic Peninsula (Fig. 1) is a transition zone where climatic conditions vary between a temperate north and a polar-influenced south and between a polar-maritime west coast and a continental east coast. Due to these particular climatic settings, the Antarctic Peninsula represents an area of highest sensitivity to changes of the climatic system. Long-term surface air temperature records from the Antarctic Peninsula revealed a recent warming trend of 0.02-0.04 K/year in the last decades for both, the western and the eastern side of the peninsula (KING & HARANGOZO 1998, SKVARCA et al. 1998, HARANGOZO et al. 1997, STARK 1994, KING 1994). An additional year-round increase in the number of precipitation events and a higher amount of rainfall during the summer season, as stated by TURNER et al. (1997) for the northern part of the western Antarctic Peninsula, will result in changing accumulation and ablation patterns of the snow cover. The retreat of the glaciers and the rapid disintegration of Wordie and northern Larsen ice shelves (VAUGHAN & DOAKE 1996, ROTT et al. 1998) are additional indicators of the changing environmental conditions in this area. These observations are in good agreement with the predictions of numerical global circulation models (GCM), which suggest, in case of a warming trend for high southern latitudes, a decrease in the extent of sea ice and more precipitation events in the Antarctic coastal zone (BUDD & SIMMONDS 1991). However, the GCMs still do not simulate the observed significant warming in the Antarctic Peninsula region (O'FARRELL & CONNOLLEY 1998). Year-round measurements of the meteorological parameters are restricted to a few manned research stations or automated weather stations (AWS) in the coastal zone of the peninsula. Therefore, it is highly desirable to develop methods for a regional climate monitoring on a year-round basis.

The availability of weather- and season-independent data from orbital synthetic aperture radar (SAR) satellites since 1991 not only enables the unhindered monitoring of changes of the coastlines of the ice shelves and the extension of the seasonal sea ice cover, but also facilitates the large-scale, year-round observation of the dynamic, climate-sensitive properties of the snow cover (e.g. PARTINGTON 1998, SMITH et al. 1997, WUNDERLE 1996a, JEZEK et al. 1993).

In this study, we present an analysis of SAR-mosaics that were derived from quicklook images in order to monitor the general snow cover dynamics on the entire northern Antarctic Peninsula.




Cartography: M. Braun

**Fig. 1:** The Antarctic Peninsula with place names mentioned in the text.

**Abb.1:** Die Antarktische Halbinsel mit den im Text erwähnten Ortsbezeichnungen.

The interpretation is based on ground truth information gathered during several field campaigns between 1991 and 1998 to different regions of the Antarctic Peninsula and on auxiliary meteorological records. The mosaics are used to define areas of special interest for detailed investigations. The suitability of SAR-data for climatological and glaciological investigations is demonstrated with three regional case studies. The results obtained allow us to draw conclusions on the variability of the regional climate and may serve as an input into climatological and glaciological models.

## 2. RADAR REMOTE SENSING OF SNOW COVER DYNAMICS

Starting with the launch of the European Remote Sensing Satellite (ERS-1) in 1991 (followed by ERS-2 in 1995) and the installation of the German Antarctic Receiving Station (GARS) at the Chilean base O'Higgins at the northern tip of the Antarctic Peninsula, an archive of SAR-images covering the whole Antarctic Peninsula has been created. Furthermore, the Canadian RADARSAT, launched in 1996, offers the possibility to close the data-gaps between the acquisition campaigns at GARS due to its built-in data-storage facilities. Both satellites operate in the C-band (5.3 GHz, 5.6 cm), although they have different polarization characteristics (ERS: VV; RADARSAT: HH). The capability of multi-temporal ERS-1/2 SAR-data for mapping snow cover properties and the discrimination of glacier snow zones has been demonstrated by different authors (e.g. RAU & SAURER 1998, PARTINGTON 1998, SMITH et al. 1997, WUNDERLE 1996a, WUNDERLE & SAURER 1995, SHI & DOZIER 1993, FAHNESTOCK et al. 1993, BINDSCHADLER & VORNBERGER 1992).

Due to the sensitivity of SAR-data to the presence of liquid water within a snowpack, it offers the possibility to differentiate the actual wet and dry snow zones on glaciers. The backscattered radar signal not only results from surface scattering, but also from volume scattering of the snowpack. Therefore, SAR-data provide information from subsurface layers and consequently facilitate a further classification of glacier snow zones. While surface scattering mainly depends on surface roughness and the local incidence angle, the part of the backscatter resulting from volume scattering is influenced by the physical properties of the snowpack (e.g. liquid water content, density, crystal size and stratification). These variables are directly determined by precipitation, radiation, temperature, humidity, and wind speed. Consequently, the backscatter coefficient obtained from the snowpack is directly linked to the meteorological conditions prior to and during the image acquisition.

As a result, different snow zones (Fig. 2) are identifiable in the SAR-images and can be classified by their backscatter characteristics and their elevational positions with respect to each other. However, the spatial and temporal evolution as well as the delimitation of these snow zones identifiable in SAR-images do not necessarily coincide with the characteristics of the glaciological snow zones on a glacier (BENSON 1962, PATERSON 1994). These classical glacier facies or glacier snow zones are

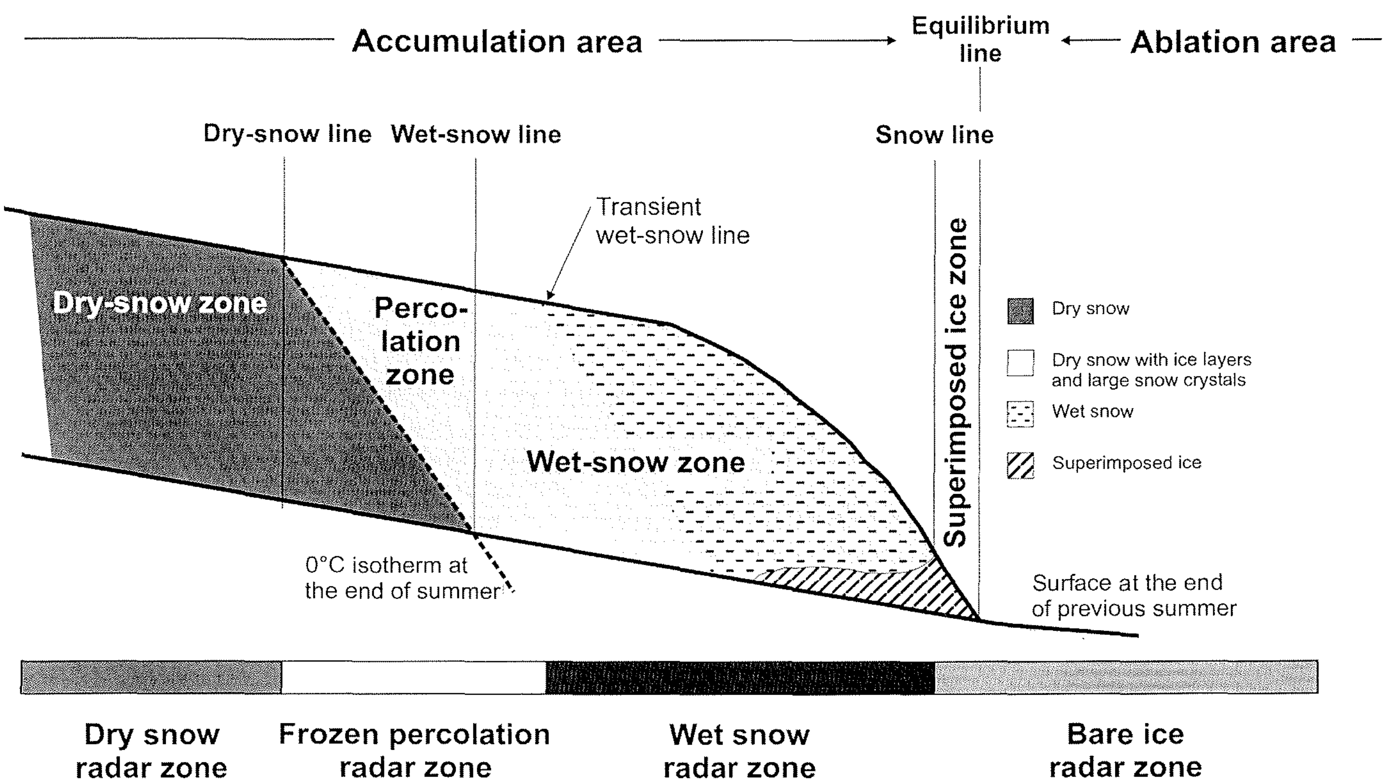



**Fig. 2:** Glacier snow zones and the corresponding radar glacier zones (after PATERSON 1994).

**Abb. 2:** Die Schneezonen eines Gletschers mit den entsprechenden Radar-Schneezonen (nach PATERSON 1994).

based upon properties integrated over time periods of years (BENSON 1962). In contrast, snow zones observable in SAR-images are dynamic on a time scale of days to weeks and show remarkable inter-annual variations. As such, they should be referred to as radar glacier zones (FORSTER et al. 1996, SMITH et al. 1997).

A classification scheme of radar glacier snow zones has been provided by SMITH et al. (1997) from the Stikine Icefields, Canada. However, this terminology leads to ambiguities, as the proposed dry radar glacier zone (SMITH et al. 1997) is assigned to a winterly frozen snowpack, which evidently is subject to periodical melting during the ablation season. Therefore, we refer in this paper to an altered classification scheme, which includes dry snow, frozen percolation, wet snow and bare ice radar zones as the major radar glacier zones. Hereby, the dry snow radar zone is restricted only to the highest areas, in which the temperatures never rise above the melting point. Due to the high penetration depth and dominating volume scattering, the dry snow radar zone is characterized by low backscatter values. Frequent or occasional melt-freeze-cycles lead to the formation of numerous ice layers and large grain sizes in the snowpack of the frozen percolation radar zone. Both, ice layers and large snow grains act as strong scatterers of the radar beam resulting in high backscatter values in this zone. During the ablation season, melting increases the liquid water content in the snowpack of the lower parts of the glaciers. As liquid water absorbs a large percentage of the radar beam, the wet snow radar zone can be identified by very low backscatter values. In the subsequently developing snow-free bare ice radar zone, surface scattering causes a relatively strong backscatter signal in comparison to the wet snow radar zone. The characteristics of each snow zone in relation to their backscatter behaviour are reviewed in detail by PARTINGTON (1998).

## 3. DATA PROCESSING

The ERS-1/2 SAR-images, that were used for the generation of the mosaics of the Antarctic Peninsula, were recorded at the GARS during the 1992 and 1997 winter campaigns and during the 1998 summer campaign. To provide a complete spatial coverage of the northern peninsula and to reduce the required storage space, the mosaics were produced with the help of digital quicklook images. The pixel spacing of 100 x 200 $m^2$ provides sufficient spatial resolution for a visual interpretation. The images are neither radiometrically nor geometrically corrected. The 1992 mosaic was assembled from 52 quicklooks, that were recorded in July 1992. The 1997 and 1998 mosaics consist of quicklook stripes, which were generated on-site at the GARS for quality control purposes during the image acquisition in June/July 1997 and January/February 1998, respectively. The generation of the mosaic products included co-registration to the coastline of the peninsula (Antarctic Digital Database, Version 2.0, 1998) and subsequent mosaicking.

The high resolution images, which were used for the detailed analysis, were recorded by the European Space Agency (ESA, ERS-1/2) at the GARS and the Alaska SAR Facility (ASF, RADARSAT). All images were radiometrically calibrated by the providers. For each scene, normalized backscatter coefficients ($\sigma^{o}$) were calculated. A 5x5 median filter was applied to reduce image speckle. Finally, the images were co-registered to each other.

## 4. RADAR GLACIER ZONES OF THE NORTHERN ANTARCTIC PENINSULA

The mosaics cover Graham Land, i.e. the northern part of the Antarctic Peninsula, which stretches from 61° to 70° southern latitude, and the adjacent islands, which include the South Shetland Islands in the North and parts of Alexander Island in the Southwest. The western and eastern side of the Antarctic Peninsula are characterized by a sharp climatic contrast. The Bellingshausen Sea to the west of the Antarctic Peninsula is usually ice-free during summer. In contrast, the Larsen Ice Shelf and an almost perennially ice-covered Weddell Sea skirt the eastern side of the peninsula. Graham Land is almost completely glaciated with only coastal areas and some nunataks remaining ice-free. Focussing on the snow cover, the Antarctic Peninsula shows the entire sequence of glacier snow zones, as described by PATERSON (1994).

### 4.1 *The winter situation*

The narrow spine of the Antarctic Peninsula, characterized by a plateau that stretches from the Northeast to the Southwest, appears black in the images (Figs. 3 and 4). The plateau is located above an altitude of 1500 m a.s.l. and varies in lateral extent. The dark radar zone is identical with the dry snow glacier zone. It is restricted only to the highest parts of the central plateau, where the temperatures never rise above 0 °C. On the Antarctic Peninsula, this zone roughly coincides with areas, where the mean annual temperature is below –11 °C (PEEL 1992). Assuming a temperature lapse rate of -0.82 K/100 m for the western side of the Antarctic Peninsula (MORRIS & VAUGHAN 1992), it was calculated, that this zone should be limited to altitudes above 1000 m a.s.l. on the South Shetland Islands and to altitudes above 800 m a.s.l. at 65 °S and 700 m a.s.l. at 68 °S on the western side of the peninsula, respectively. In fact, near the Argentine base San Martín (68 °S, 67 °W), occasional melt events could be proven by own observations (1998) up to an altitude of 1250 m a.s.l. This is in good agreement with the minimum altitude of 1260 m a.s.l. for the lower boundary line, i.e. the dry snow line, which was calculated from meteorological records from San Martín (1976-94). On the eastern side of the Antarctic Peninsula at 68 °S, the dry snow line was calculated to be approximately at 700 m a.s.l. (WUNDERLE 1996 b). The comparison of both methods indicates, that the annual mean temperature lapse rate given by MORRIS & VAUGHAN (1992) is not applicable and should be replaced by a summer season temperature lapse rate of -0.55 K/100 m as measured during the field campaign 1998.

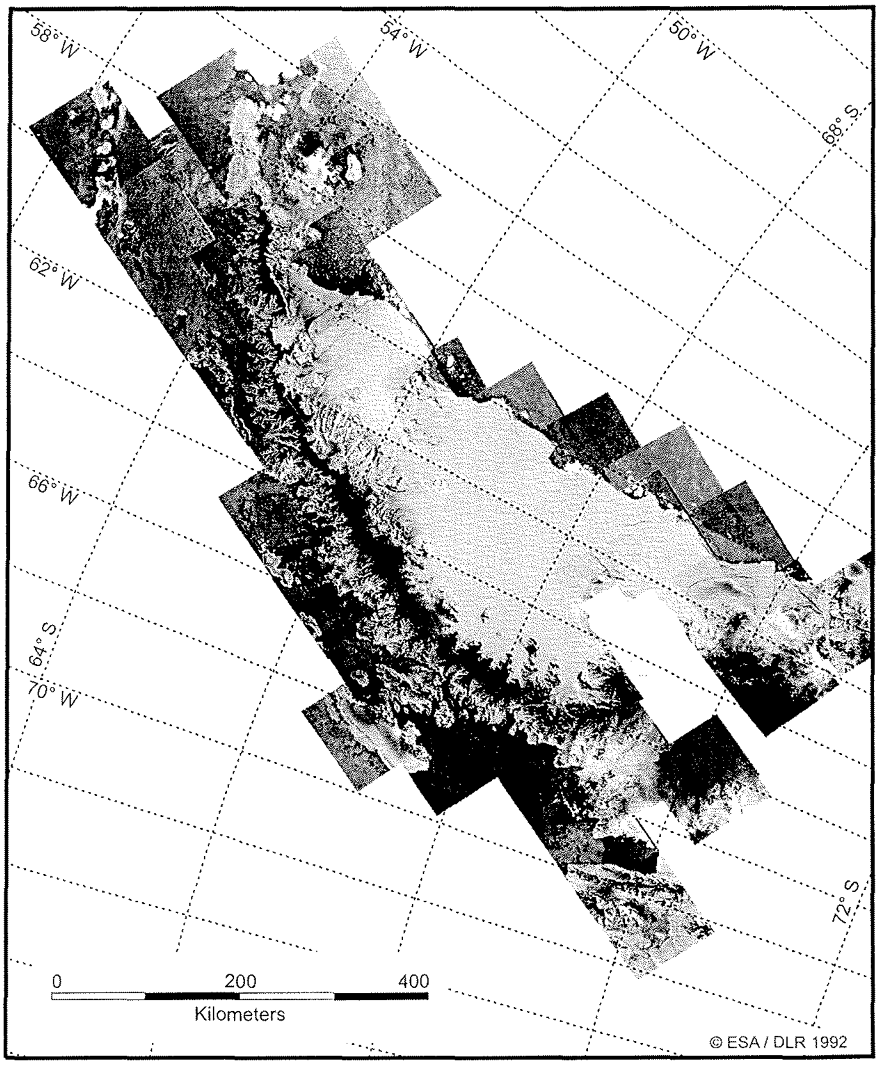



**Fig. 3:** ERS-1 quicklook-mosaic of the Antarctic Peninsula (June 1992).

**Abb. 3:** ERS-1 Quicklook-Mosaik der Antarktischen Halbinsel (Juni 1992).

The lack of melting events in this area leads to a snowpack that is characterized by small grain sizes and the absence of ice layers. Snow undergoes compaction under its own weight, further metamorphism is driven by the effects of wind and of temperature gradients within the snowpack. The backscattered radar signal is determined by high penetration depth and volume scattering within the snowpack. Variations in the backscatter values are largely attributed to variations in grain sizes. In calibrated SAR-images, the $\sigma°$-values generally range from -14 to -20 dB. Backscatter values from the dry snow radar zone are characterized by an extraordinary low variability both in space and time (PARTINGTON 1998). This is caused by the year round absence of melt events.

In the 1992 and 1997 winter mosaics (Fig. 3 and 4), the radar-dark dry snow zone borders on a zone of bright colour that stretches down to the coast. The extended surface of the Larsen Ice Shelf and its tributaries dominates the east coast. The western side of the Antarctic Peninsula is characterized by numerous outlet and piedmont glaciers, which drain the glaciated plateau in a westerly direction towards the ocean. These glacial systems are located in altitudes below the dry snow line. Superficial melting occurs regularly or occasionally during the ablation season. The high energy input into the snowpack enables wet snow metamorphism, which, in turn, enhances snow crystal growth and snowpack densification. Percolating and subsequently refreezing meltwater forms ice layers and ice pipes. Therefore, a well defined stratification of the snowpack is characteristic for this snow zone. In SAR-images, this zone can be identified by its brightness, which is caused by the strong backscatter of the microwave on large snow grains and horizontal ice layers. Due to these characteristics, this zone should be refered to as frozen percolation radar zone. Typical calibrated backscatter values range between -2 and -6 dB. The frequency of melt events, the mean grain size, and the number of ice layers decrease with increasing altitude. Consequently, the upper boundary is rather a transition zone than a marked boundary line. Depending on the slope inclination, the zone in which backscatter intensities gradually decrease may span several kilometres in a horizontal direction. Hereby, the upper limit of this frozen percolation radar zone coincides with the dry snow line as defined by PATERSON (1994), whereas the lower boundary fluctuates on a daily or weekly basis depending on the current location of the melt front.

When comparing the 1992 with the 1997 winter mosaic, it is striking that the ice shelves to the east of the Antarctic Peninsula eroded to a high degree. The ice shelf connection between

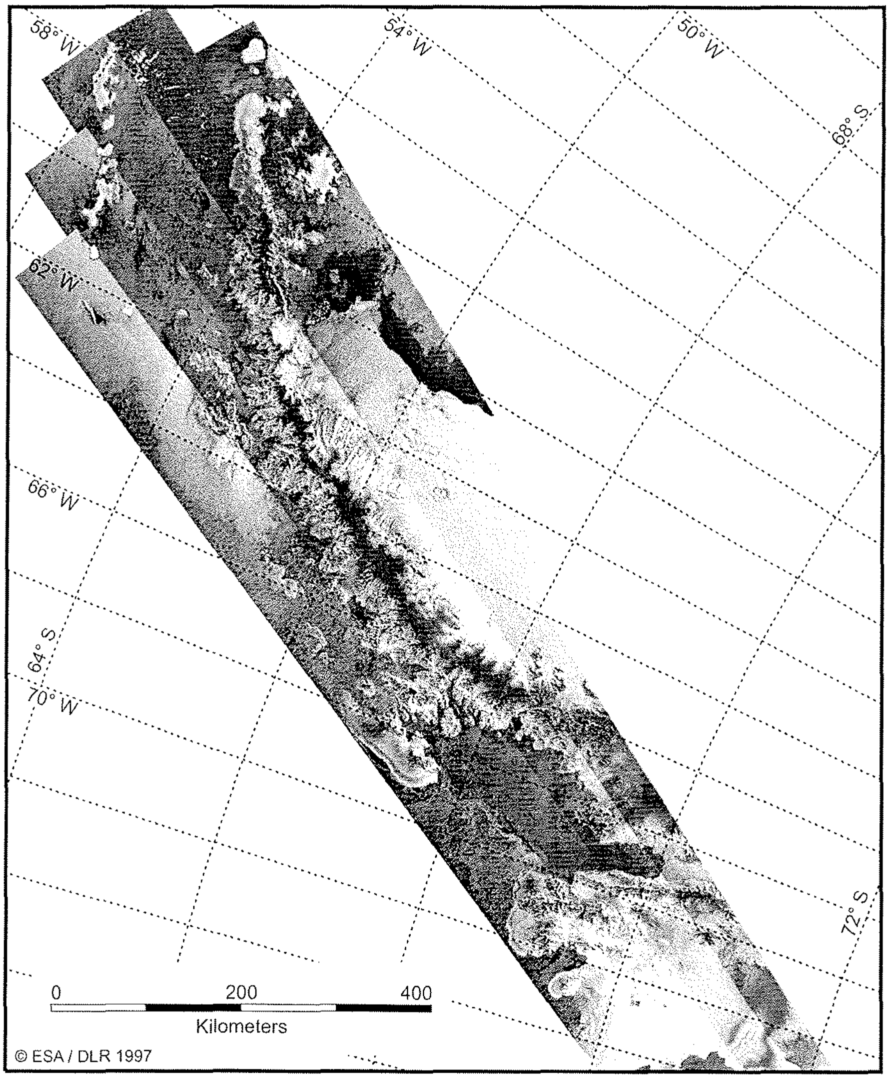



**Fig. 4**: ERS-2 quicklook-mosaic of the Antarctic Peninsula (July 1997).

**Abb. 4:** ERS-2 Quicklook-Mosaik der Antarktischen Halbinsel (Juli 1997).

the mainland and James Ross Island decayed in 1993 and the northern parts of Larsen Ice Shelf disintegrated in 1995 and 1997, respectively (VAUGHAN & DOAKE 1996, ROTT et al. 1998). Furthermore, a variable margin of alternating bright and dark radar signatures is recognizable in the coastal areas of some piedmont glaciers and smaller island ice caps on the western side of the Antarctic Peninsula.

4.2 *The summer situation*

The 1998 summer mosaic (Fig. 5) shows a completely different pattern of radar zones. As described above, the temporally invariant dry snow zone remains in the same location all year round. It is surrounded by a narrow bright margin of the frozen percolation radar zone. However, the glacier surfaces near sea level including the entire Larsen Ice Shelf can be identified by their dark appearance. Regarding their horizontal and vertical extension, the backscatter pattern on the western slopes of the Antarctic Peninsula differs from that on the eastern slopes.

The presence of liquid water within the snow matrix during the ablation season produces a drastic change in the observed backscatter pattern. Liquid water almost completely absorbes the radar beam. Therefore, the penetration depth of the microwave is reduced to the uppermost layer, i.e. several centimetres. Consequently, a melting snow cover of this wet snow radar zone appears dark in a SAR-image. As the backscattered signal is only determined by the uppermost layer of the wet snowpack, it is important to note, that the brightness pattern identified as the wet snow radar zone does not correspond with the wet snow zone as given by PATERSON (1994). His glaciological definition described the wet snow zone as the area, in which all snow that has been accumulated since the end of the previous summer reaches temperatures of 0 °C at least once a year (PATERSON 1994).

This wet snow radar zone should be regarded as an extremely dynamic zone, as it fluctuates with the advances and retreats of the melt limit during the summer. The actual location of the upper transition zone, i.e. the wet snow line, depends on the current and previous meteorological conditions and approximately coincides with the 0 °C isotherm. The snow cover is subject to wet snow metamorphism, which enhances recrystallization and thus results in large grain sizes and further densification. The high energy input during summer also

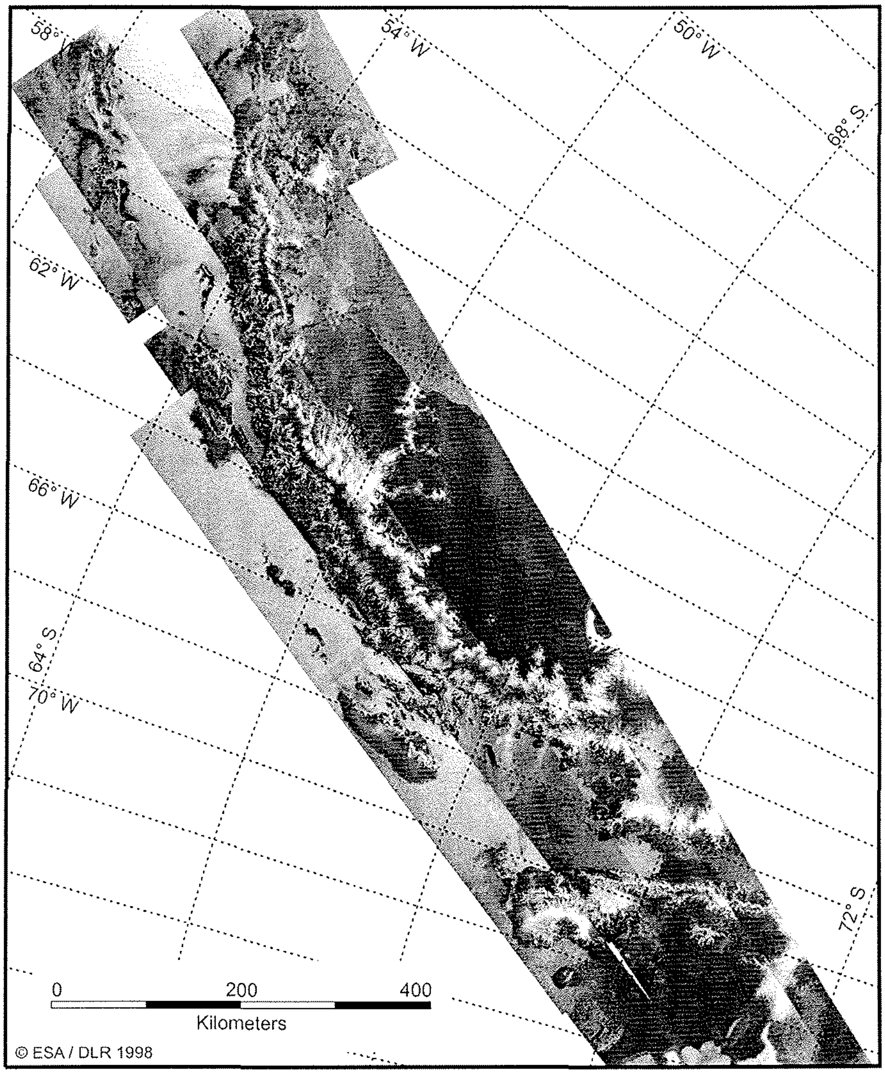



**Fig. 5:** ERS-2 quicklook-mosaic of the Antarctic Peninsula (January 1998).

**Abb. 5:** ERS-2 Quicklook-Mosaik der Antarktischen Halbinsel (Januar 1998).

produces high amounts of melt water. Particularly at lower elevations, slush accumulates at the snow-ice-interface and occasionally reaches the snow surface in supraglacial depressions. There, slush-lagoons and meltwater-lakes develop. These can be identified as dark patches in a SAR-image (BINDSCHADLER & VORNBERGER 1992) and probably cause the observable patchiness on the Larsen Ice Shelf.

During winter, the refrozen snowpack of the former wet snow radar zone shows the backscatter characteristics of a frozen percolation radar zone due to the pronounced stratification and the large grain sizes (Figs. 3, 4).

The location of the wet snow line on the 1998 summer mosaic reflects the asymmetric pattern of surface temperatures on both sides of the peninsula. On the eastern side, the wet snow radar zone is limited to altitudes below approximately 250 m a.s.l., whereas on the western side, the wet snow line even exceeds the 500 m contour line. The bright areas of the frozen percolation zone between the wet and the dry snow radar zone were not affected by melting during the acquisition period of the images. However, it is evident, that these areas are subject to occasional melt events and consequently intensified metamorphism and snowpack stratification.

4.3 *Capabilities and limitations of the mosaics*

With the image mosaics presented in this work, it is possible to monitor the spatial and temporal evolution of the major radar glacier zones of the entire Antarctic Peninsula. However, the quicklook mosaics are mainly restricted to visual interpretation, as they are neither radiometrically nor geometrically corrected. Additionally, they do not represent a snapshot of the snow cover properties. Instead, the images and image stripes, used to compose each mosaic, were acquired over a period of several weeks. However, a single image stripe spans about 100 km in range direction and several hundreds of kilometres in azimuth direction. These image stripes are therefore particularly suitable to investigate the meridional differences of snow cover properties. Furthermore, due to the rapid and economic generation of the mosaics, they have strong potential for large-scale monitoring purposes.

In spite of the limitations mentioned above, the large-scale patterns of snow cover properties can be investigated, unusual features identified, and areas of special interest discriminated. These areas might be selected for future detailed studies, as is demonstrated in the following section using examples from Adelaide Island, the inner Marguerite Bay and the South Shetland Islands.

## 5. CASE STUDIES

### 5.1 *Snowline detection on Adelaide Island*

Both winter mosaics from 1992 (Fig. 3) and 1997 (Fig. 4) show a characteristic sequence of alternating light and dark grey colours on the piedmont glacier of the west coast of Adelaide Island. The same feature can be identified on the piedmont glaciers of northern Alexander Island and on the smaller island ice caps of the Biscoe Islands to the north of Adelaide Island. An analysis of meteorological records from the Argentine research base San Martín (Fig. 6) confirmed, that no liquid water was present in the snowpack during image acquisition. A time series of quicklooks and calibrated high resolution images (Fig. 7) was generated to investigate the temporal evolution of this backscatter signature. The absence of this phenomenon in the images from 1991 and 1996 indicate a reversible process, which finds its expression in a changing backscatter signature pattern. The area of alternating colours is restricted to the lowermost 200 m a.s.l. and thus agrees well with the zone in which local glaciers get snow-free at the end of the ablation season, as it was reported e.g. for Anvers Island (CASASSA 1989) and the inner Marguerite Bay (FOX & COOPER 1998, own observations 1994/95 and 1997/98). To explain the observed backscatter pattern, a sequence of idealized snow profiles was proposed based on own field observations. Using a scattering model (SCHNEIDER et al. 1997), the $\sigma^{\circ}$-values of these snow profiles were simulated and subsequently compared to the measured values of the calibrated SAR-images.

The dark central zone was interpreted as the area of bare glacier ice, which occurs at the end of the melt season. Newly fallen, dry snow might cover the glacier ice, but is transparent for the radar signal. Therefore, the backscatter mainly originates from the underlying glacier ice with typical $\sigma^{\circ}$-values ranging from -10 to -15 dB. This is in good agreement with the measured values from the analyzed SAR-images. The well defined upper boundary line of this bare ice radar zone, where the backscatter intensity increases abruptly, correlates with the transient snowline at the end of the previous summer season (MARSHALL et al. 1995). At the end of the ablation period, the transient snowline may be regarded as an approximation of the equilibrium line altitude (ELA), which is directly related to glacier mass balance. Above, the snow cover consists of a highly metamorphosed and stratified snowpack, which causes high backscatter values of -2 to -6 dB, although it is probably relatively shallow. Within the lowermost parts of the ice piedmont, a bright margin fringes the dark bare ice zone. This signature is attributed to multiple-path scattering caused by crevasses and a chaotic surface roughness, which characterize the coastal area of the glaciers (Fig. 8).

In colder years, the ELA is located near or below the sea level. In this case, the dark bare ice zone is absent and cannot be detected in SAR-images. This is the consequence of a metamorphosed and stratified snowpack that persistently covers the glacial ice, resulting in high backscatter intensities. In the radar satellite images, these snowpack properties resemble the characteristics of a frozen percolation radar zone. The measured and modelled $\sigma^{\circ}$-values agree very well and confirm the previously assumed sequence of snow profiles.

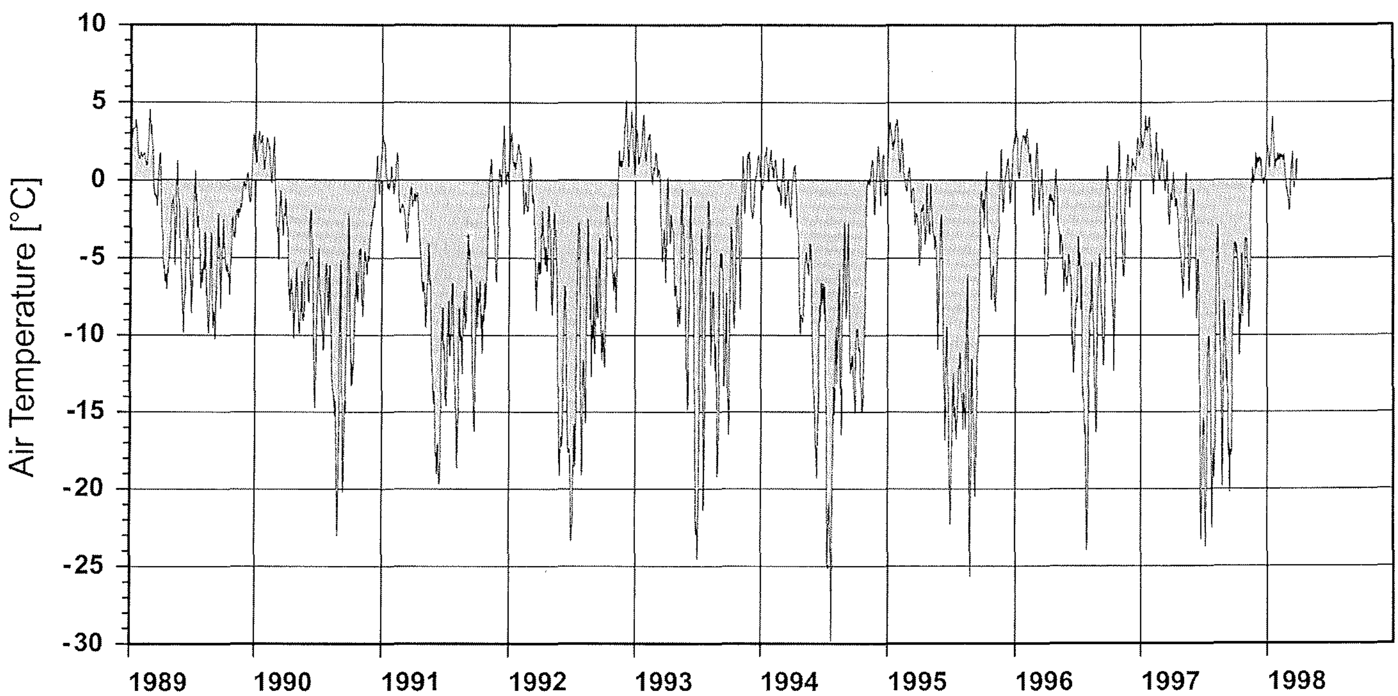



**Fig. 6:** Daily mean air temperature 1989-1997 [°C] from base San Martín, Marguerite Bay (7 day running mean) [Data: San Martín].

**Abb. 6:** Tagesmittelwerte der Lufttemperatur 1989-97 [°C] von San Martín, Marguerite Bay (7-tägiges gleitendes Mittel) [Daten: San Martín].

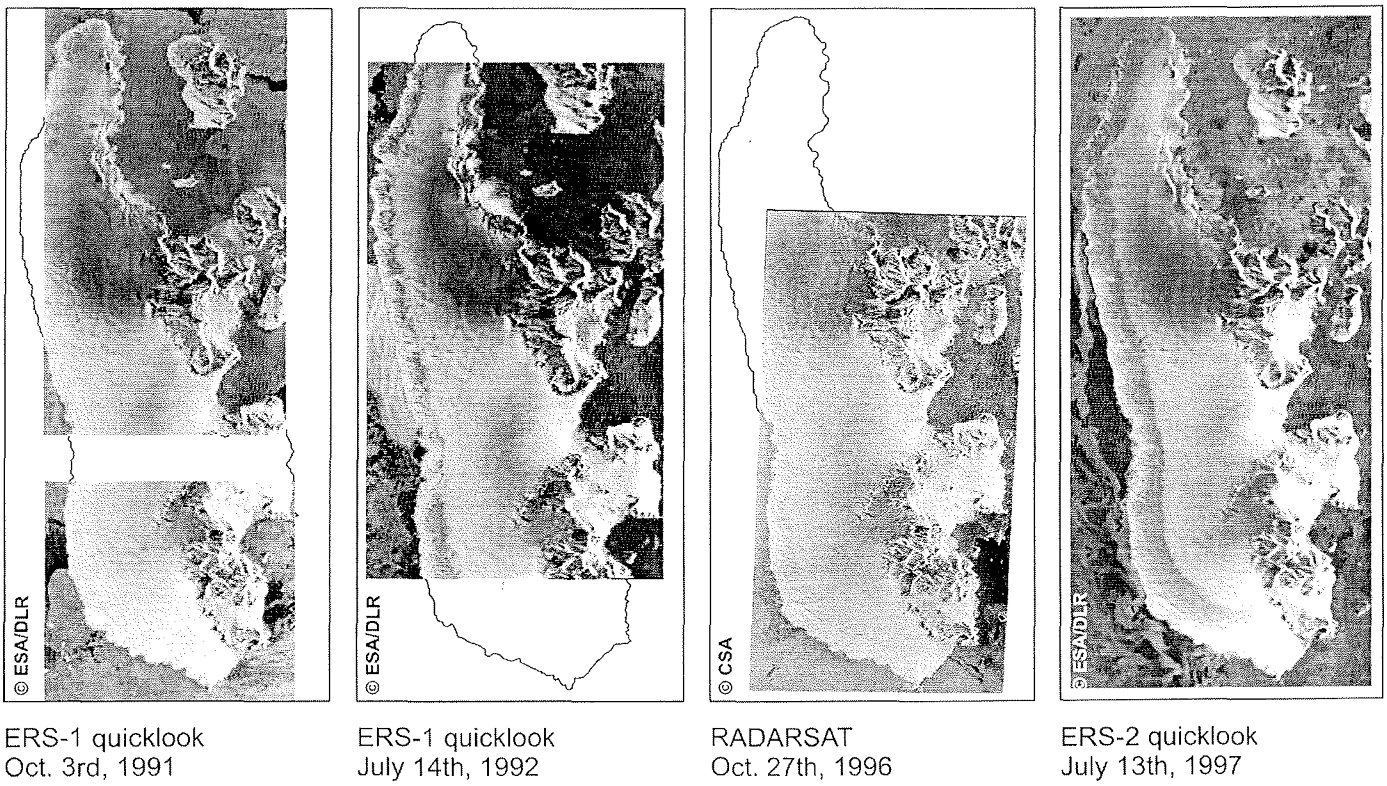
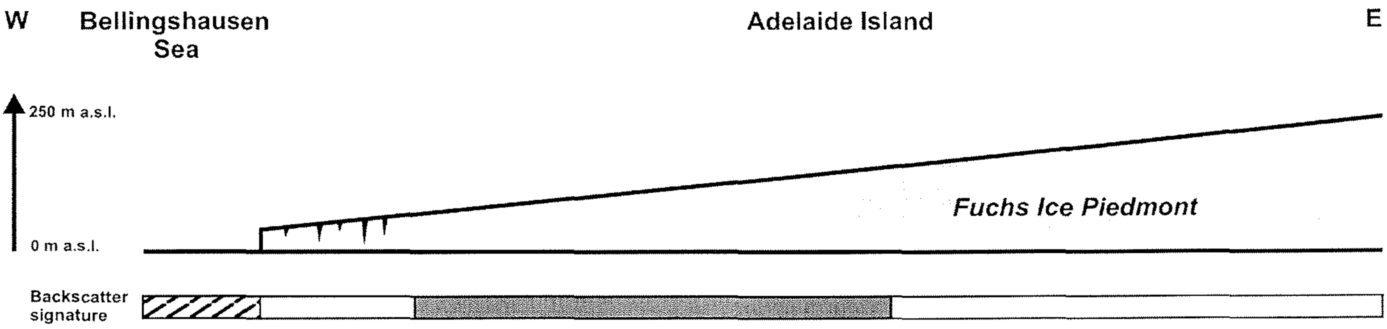



**Fig. 7:** Time series of Adelaide Island derived from ERS-1/2 quicklooks and calibrated RADARSAT high resolution images.

**Abb. 7:** Zeitreihe von Adelaide Island aus ERS-1/2 Quicklooks und einer kalibrierten, hochaufgelösten RADARSAT-Szene.




| | Ocean | Marginal zone | Bare glacier ice at the end of the ablation season | Frozen percolation radar zone |
|---|---|---|---|---|
| **Snow pack properties** | Partly covered by sea ice | Chaotic surface and crevasses | Bare glacier ice covered by a frozen snow cover, which accumulated since the end of the ablation period and which is characterized by small grain sizes and the absence of ice layers | Multi-year, stratified snow pack, characterized by large grain sizes (1 - 3 mm) and ice layers due to summerly wet snow metamorphism and percolation, covered by frozen fresh snow (small grain sizes, no ice layers). Snow depth increases with altitude. |
| **Backscatter mechanisms** | | High radar back-scatter due to multipath scattering | Predominantly volume scattering of the glacier ice; the overlying frozen snowpack appears transparent for the radar signal | High backscatter values due to surface scattering of the ice layers and volume scattering of the large snow grains; the overlying frozen snowpack appears transparent for the radar signal |
| **Typical backscatter values** | Variable | -2 - -6 dB | -10 - -16 dB | -1 - -6 dB |

**Fig. 8:** Sequence of radar glacier zones in the coastal part of the Adelaide Island ice piedmont (Fuchs Ice Piedmont) and corresponding snowpack properties.

**Abb. 8:** Abfolge von Radar-Gletscherzonen in den küstennahen Gebieten des Fuchs Ice Piedmonts, Adelaide Island, mit korrespondierenden Schneedeckeneigenschaften.

*5.2 $\sigma°$-profile of the Antarctic Peninsula at 68° South*

Wunderle (1996b) showed a good agreement between dry snow lines derived from meteorological records and ERS-1 data (August 08, 1993) near the Argentine research base San Martín in the inner Marguerite Bay. To detect position changes of the dry snow line, the RADARSAT scene from May 10, 1997 (Fig. 9) was selected for further analysis. This scene has a similar observation geometry as the August 1993 scene and is also characterized by similar meteorological conditions.

The profile follows the 68 °S latitudinal parallel and spans from the Marguerite Bay at the western side of the Antarctic Peninsula to the Larsen Ice Shelf on the eastern side of the Antarctic Peninsula. At the time of image acquisition, the inner Marguerite Bay is still ice-free and only covered by single ice floes. Backscatter values of the open sea range from -10 to -15 dB. An abrupt increase from -12 to almost 0 dB marks the ice-cliff of Northeast Glacier. Due to cold temperatures prevailing in April and May 1997, the frozen percolation zone stretches down to the ice-cliff. It is characterized by $\sigma°$-values between -2 and -4 dB. A minimum of about -8.5 dB marks a zone of lateral moraines in the upper glacier area. The steep ascent to the plateau faces the sensor. Therefore, it shows maximum backscatter intensities. The dark area, which borders to the east, corresponds to the dry radar snow zone. It typically shows low backscatter values that range from -17 to -22 dB. It is located above an altitude of 1300 m a.s.l. on the western side of the Antarctic Peninsula, but reaches down to approximately 700 m on the eastern side. Due to precipitous slopes, the dry snow line on the west side of the plateau appears as a marked boundary line. In contrast, a broad transition zone of several kilometres is found to the east. The lack of ice layers and predominantly small grain sizes with diameters smaller than 1 mm result in a low backscattering of the radar signal. Brighter areas within the dry snow zone are caused by topographic effects, where slopes are facing the sensor. The snow cover of the glacier leading down to the Larsen Ice Shelf, appears as a bright area and thus indicates that strong scatterers, e.g. relatively large snow grains and ice layers, become more prevalent in the snowpack. Although the

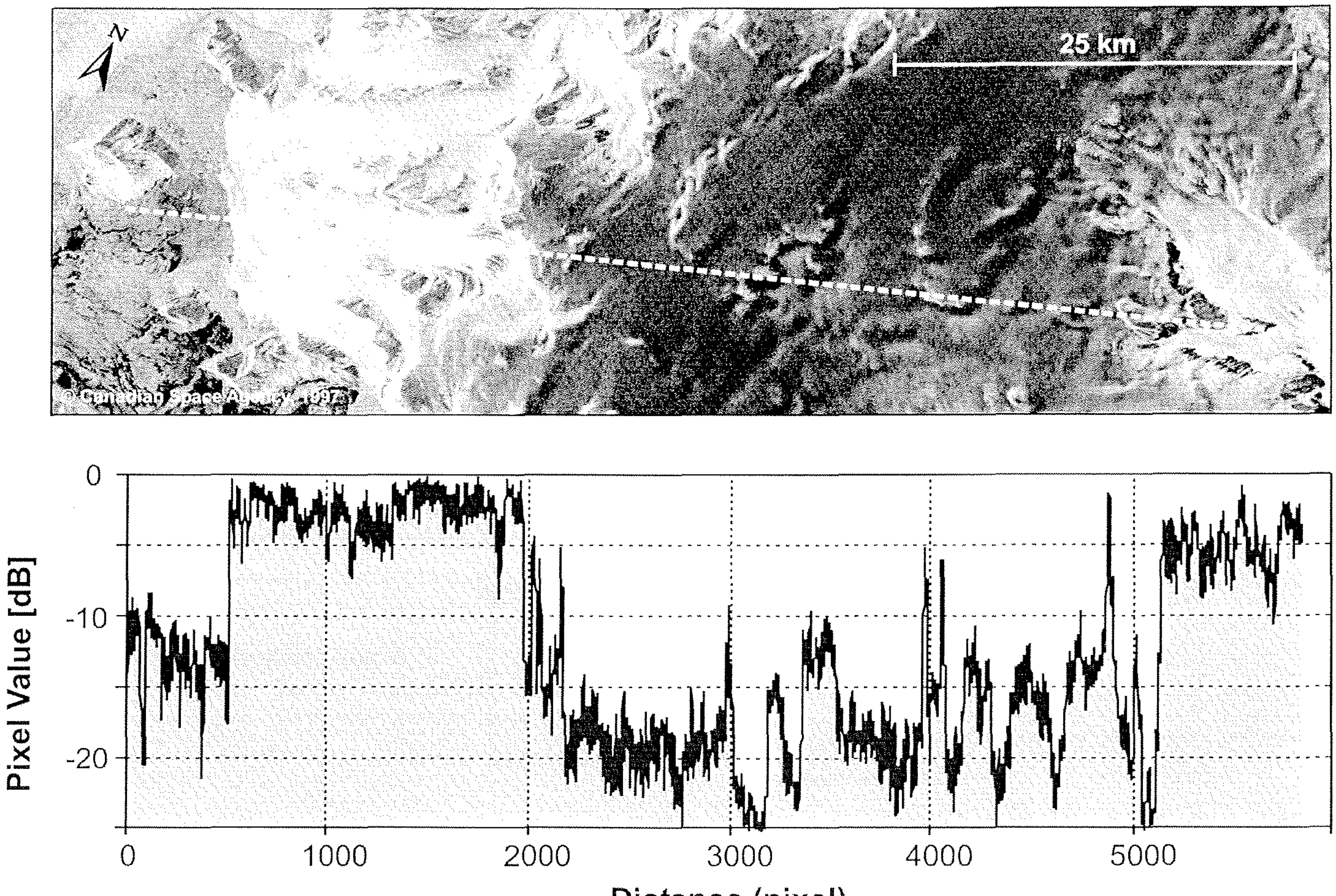



**Fig. 9:** $\sigma°$-profile at 68 °S (RADARSAT; May 10, 1997). The profile follows the 68 °S latitudinal parallel and spans from the Marguerite Bay on the western side to the Larsen Ice Shelf on the eastern side of the Antarctic Peninsula. The bright frozen percolation radar zone of Northeast Glacier is characterized by $\sigma°$-values between -2 and -5 dB, the dry snow radar zone of the plateau area by values below -10 dB.

**Abb. 9:** $\sigma°$-Profil auf 68 °S (RADARSAT, 10. Mai 1997). Die Profillinie folgt dem 68 °S-Breitenkreis und erstreckt sich von der Marguerite Bay auf der Westseite der Antarktischen Halbinsel zum östlich gelegenen Larsen Ice Shelf. Die hell erscheinende, gefrorene Perkolationsschnee-Radarzone (frozen percolation radar zone) ist durch hohe $\sigma°$-Werte zwischen -2 und -5 dB gekennzeichnet, die Trockenschnee-Radarzone (dry snow radar zone) der Plateau-Region weist Werte niedriger -10 dB auf.

backscatter values on the glaciers draining towards the Larsen Ice Shelf are lower than the ones on Northeast Glacier, it is assumed that they represent a frozen percolation zone. The difference between backscatter intensities on the western and eastern side of the peninsula might be caused by the different exposition of the glacier surfaces relative to the sensor.

The location of the dry snow line in the 1997 image agrees very well with the one derived from the 1993 ERS-1 image. This indicates, that the climatic variations did not significantly impact the snow cover in higher altitudes during the observation period. As any melt event, which would lead to the formation of ice layers and larger grain sizes in the transition zone, could be detected by a persistent shift of the dry snow line towards higher altitudes, this boundary line acts as a sensitive indicator for singular melt events. It might be hypothesized, that the last shift of this indicator line occurred during 1989, which was the warmest year in Antarctic meteorological records (MORRISON 1990).

5.3 *Advection of warm air masses on the South Shetland Islands*

The variability of snow properties due to short-term weather effects ranging on time-scales from days to weeks does not show up on the mosaics, but can be clearly demonstrated with two high resolution ERS-2 images from October 19 and November 4, 1996 (Fig. 10). Although mid-winter thawing events occur frequently on the maritime South Shetland Islands (RACHLEWICS 1997, WUNDERLE et al. 1998), the sequence of October and November 1996 images documents a snowmelt event which was caused by an extraordinary intensive high temperature event. Due to the availability of meteorological data (Fig. 11), it was possible to determine the timing of melt onset and to document the duration of the advection of warm maritime air masses.

In the October image an entirely frozen and stratified snowpack covers Nelson Island and King George Island (South Shetland Islands), which can be identified as a frozen percolation radar zone. Advection of warm air masses starting on October 27

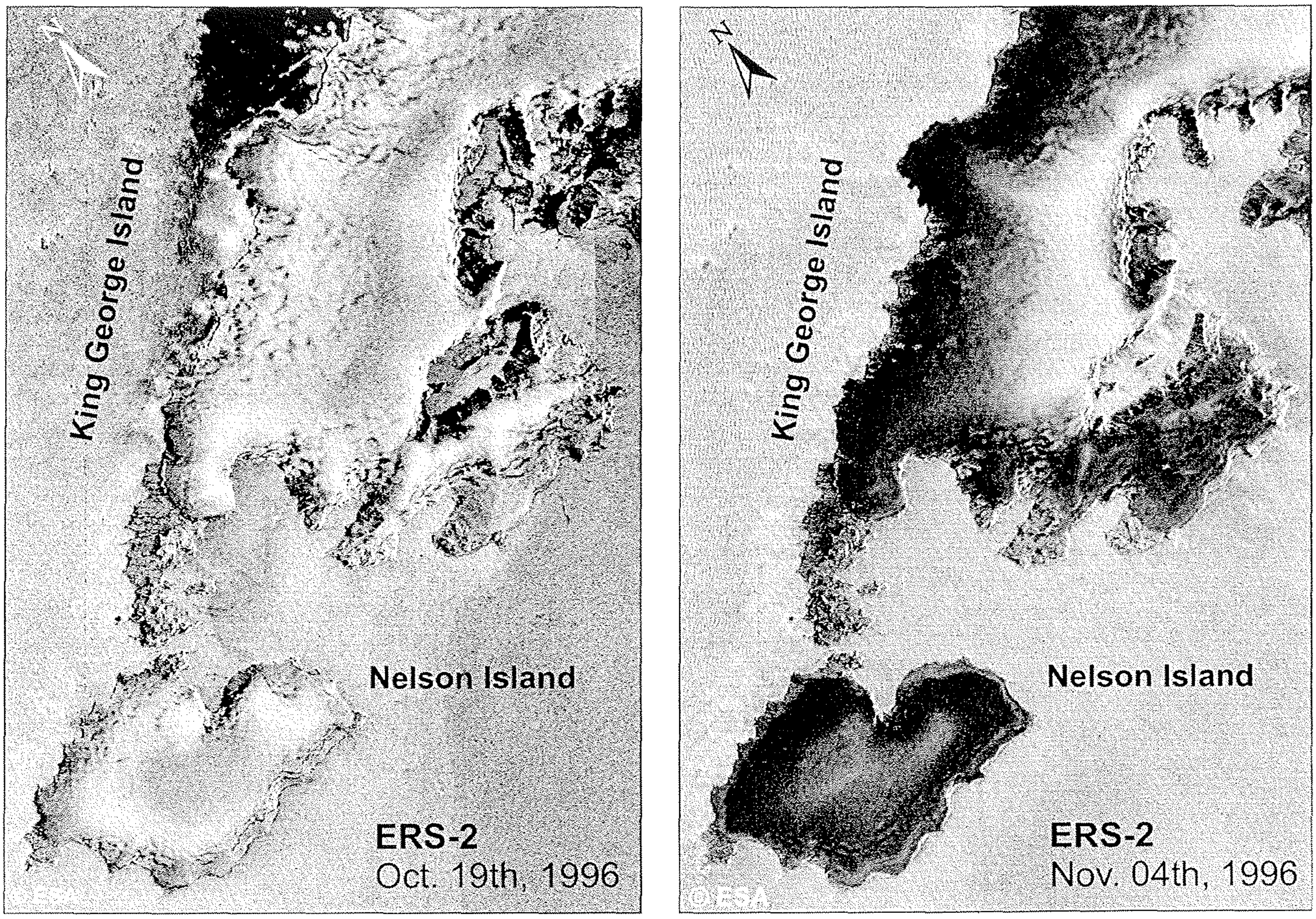



**Fig. 10:** Onset of snowmelt on King George and Nelson islands (South Shetland Islands). On October 19, 1996, both islands are covered by an entirely frozen snowpack (frozen percolation radar zone). Due to advection of warm maritime air masses, superficial wetting of the snow results in low σ°-values up to elevations of 300 m (November 04, 1996). Above, the frozen percolation radar zone remained persistent.

**Abb. 10:** Beginn der Schneeschmelze auf King George und Nelson Island (South Shetland Islands). Am 19. Oktober 1996 sind beide Inseln durch eine vollständig durchgefrorene Schneedecke geprägt (frozen percolation radar zone). Aufgrund der Advektion maritimer, warmer Luftmassen setzt die oberflächliche Durchfeuchtung der Schneedecke ein, in deren Folge niedrige σ°-Werte in den tieferen Lagen bis 300 m NN resultieren (04. November 1996). Darüber bleibt die gefrorene Perkolationsschnee-Radarzone erhalten.

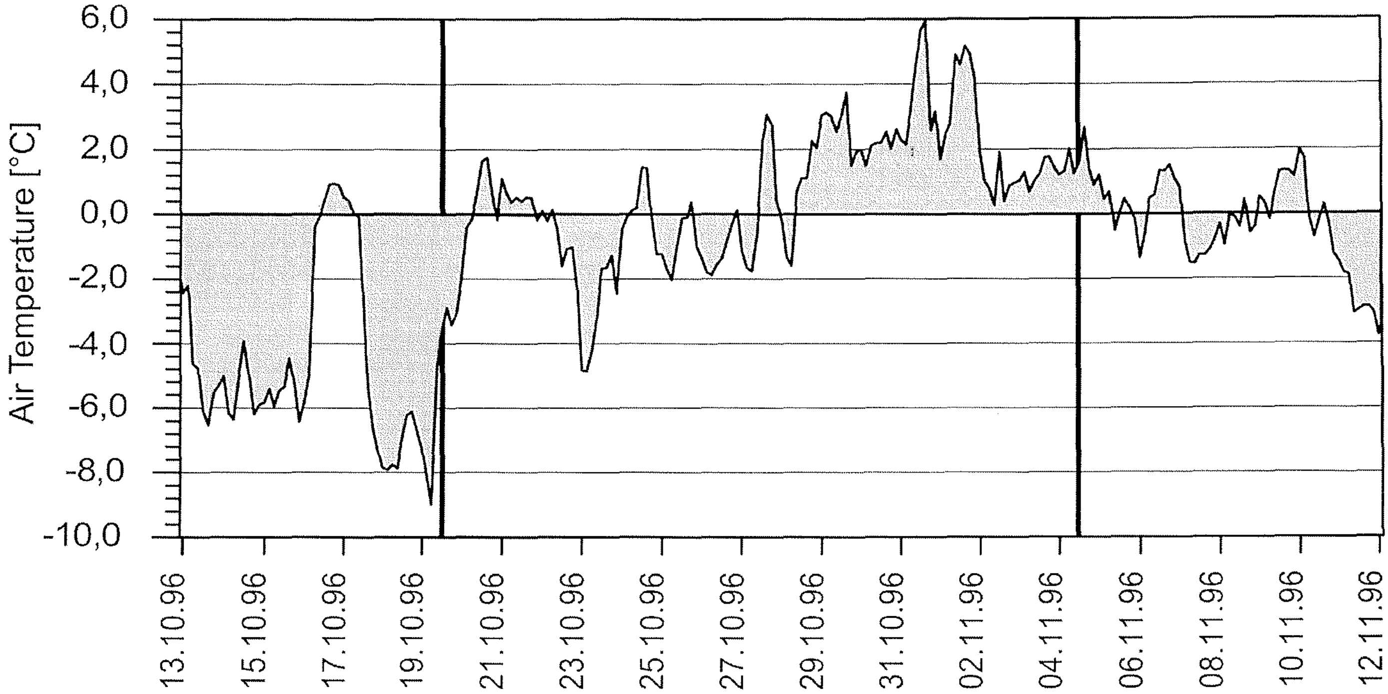



**Fig. 11:** Air temperature [°C] from October 13 to November 11 1996 recorded at the Brazilian base Comandante Ferraz (King George Island). The vertical solid lines indicate the acquisition of the ERS-2 images [Data: Instituto Nacional de Pesquisas Espaciais].

**Abb. 11:** Lufttemperaturen [°C] vom 13.10.-11.11. 1996 an der brasilianischen Station Comandante Ferraz (King George Island). Die Vertikallinien markieren die ERS-2-Bildüberflüge [Daten: Instituto Nacional de Pesquisas Espaciais].

caused a progressive wetting of the snow surface. On November 4, the snow cover of the lowermost areas was almost completely wet, but superficial snowmelt did not reach elevations above 300 m a.s.l. Above, the frozen percolation radar zone remained persistent as a consequence of the relatively low energy input into the snowpack in higher elevations. Within this radar zone, the major ice divides can be directly identified on King George and on Nelson Island. Intermediate elevations were covered by a transition zone characterized by increasing backscatter intensities due to decreasing liquid water contents in the snowpack. The upper boundary line of the wet snow radar zone approximately coincides with the 0 °C isotherm (SMITH et al. 1997).

The advection of warm maritime air masses also significantly reduced the snow cover extent in periglacial areas (WINKLER et al. 1998), which can be clearly distinguished from the adjacent glaciers in the SAR-images.

## 6. DISCUSSION

Although the spatial resolution of the quicklook images, that were used to generate the mosaics, is low, it could be shown that their quality allows the interpretation of large-scale snow cover patterns. Furthermore, quicklook images facilitate the cost- and time-efficient generation of mosaics. Alternatively, images with a higher resolution could be used, but the compilation of a single mosaic would require more than 50 high resolution SAR-images. Additionally, quicklook images effectively supplement existing SAR-data archives, which can therefore be used more effectively for time series analysis. Although the SAR-mosaics lack geometric and radiometric calibration and although the image acquisition for a single mosaic covers a period of several weeks, they provide an effective tool for the identification of potential future research sites. Examples from Adelaide Island, the inner Marguerite Bay and the South Shetland Islands exhibit the limitations of the mosaics. Conversely, they also demonstrate the potential of detailed analysis by using calibrated high-resolution SAR-data in combination with quicklook images. In turn, high-resolution SAR-data help to interpret the large-scale mosaics.

The remarkable sequence of backscatter variations in the coastal zone of various piedmont glaciers on the Biscoe Islands, Adelaide and Alexander Island, which was detected on both winter mosaics, initiated a detailed analysis of this phenomenon. Both, the absence of this pattern on Adelaide Island in the colder than average years, 1991 and 1996, and results of a backscatter model run support the assumption, that the observed pattern is linked to the seasonal removal of the snow cover of the lowermost areas of the glaciers. In agreement with MARSHALL et al. (1995), the upper boundary line is identified as the transient snowline at the end of the ablation period. This snowline may be regarded as an approximation of the equilibrium line. These observations will ultimately support glacier mass balance estimations. Additionally, direct mapping and tracking the inter-annual variations of the actual ablation zone becomes feasible by monitoring the transient snow line at the end of the summer season.

A more detailed analysis of the spatial variations of radar glacier zones requires radiometrically calibrated and geometrically corrected, co-registered images, as is demonstrated with two backscatter profiles, that cross the Antarctic Peninsula at 68 °S. The comparison of the 1993 and 1997 images reveals the relative stability of the dry snow lines in this time range thus indicating that the observed warming trend is not yet detectable with SAR-data in higher altitudes. Hereby, it should be noted, that any location change of the dry snow line has to be regarded as an indication for singular and extremely intense melt events.

King (1994) and King & Harangozo (1998) stated, that the winter months predominantly contribute to the variability and trend in annual mean temperatures. As a consequence of these higher winter temperatures, an extension of the ablation period might be expectable and has already been reported by Fox & Cooper (1998) for the inner Marguerite Bay. We thus regard the documentation of the beginning of snowmelt and the spatial evolution of the wet snow radar zone as an adequate tool for the detection of a changing climate on the Antarctic Peninsula. This is demonstrated by the third example from the South Shetland Islands, which documents the beginning of snowmelt and the short-time dynamics of radar glacier zones forced by the meteorological conditions at the beginning of the ablation season. Furthermore, as the wet snow line could be regarded as an approximation of the 0 °C isotherm (Smith et al. 1997), it provides directly information about the prevailing meteorological conditions.

## 7. CONCLUSION

Analysis of the 1992 and 1997 winter mosaics and the 1998 summer mosaic reveal the seasonal and spatial distribution of the major radar glacier zones on the Antarctic Peninsula. The boundary lines between these zones have been identified as sensitive indicators for climatic variations providing information on different time scales: (1) the transient snowline at the end of the ablation season documents the spatial extension of the ablation zone, (2) the dynamic wet snow line approximately coincides with the position of the 0 °C isotherm and (3) the dry snow line is a sensitive indicator for singular extreme melt events. Monitoring the temporal and spatial evolution of the wet snow radar zone during the summer, enables to determine the duration of the ablation period and to draw conclusions about the meteorological fluctuations.

The results obtained from the radar mosaics and the case studies emphasize the need for site-specific ground truth data, which remains indispensable for the evaluation of radar imagery. The large-scale interpretation of backscatter signatures was facilitated by snowpack data gathered during previous field campaigns to the Antarctic Peninsula. Ground truth data is also a prerequisite for the modelling of the snow cover properties and their backscatter characteristics. Concurrent meteorological data helps to reconstruct the meteorological conditions prior to and during the SAR-image acquisition and is crucial for understanding of the processes, which determine the formation of the different radar glacier zones. This stresses the importance of the establishment of study areas dedicated to monitoring purposes.

With the SAR-data archive, which has been build up since the launch of ERS-1 in 1991, and the continuation of polar-orbiting SAR-missions in the foreseeable future, the multi-temporal large-scale monitoring of glaciers and ice sheets has become feasible. It is therefore recommended, that a coordinated survey network for glacier monitoring is installed, where mass balance parameters and boundary positions of the different radar glacier zones will be monitored on a regular basis.

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*References*

*Benson, C.S.* (1962): Stratigraphic studies in the snow and firn of the Greenland ice sheet. Snow, Ice and Permafrost Establishment.- Research Report 70.

*Bindschadler, R. A. & Vornberger, P.L.* (1992): Interpretation of SAR imagery of the Greenland ice sheet using coregistered TM imagery.- Remote Sensing Environ. 42(3): 167-175.

*Budd, W. F. & Simmonds, I.* (1991): The impact of global warming on the Antarctic mass balance and global sea level.- In: G. WELLER, C.L. WILSON & B.A.B. SEVERIN (eds.), Proceedings of the International Conference on the Role of the Polar Regions on Global Change, University of Alaska, 489-494.

*Casassa, G.* (1989): Velocity, heat budget and mass balance at Anvers Island Ice Cap, Antarctic Peninsula.- Antarctic Record 33 (3): 341-352.

*Fahnestock, M.A.,Bindschadler; R.A., Kwok & Jezek, K.C.* (1993): Greenland ice sheet surface properties and ice dynamics from ERS-1 SAR imagery.- Science 262 (5139): 1530-1534

*Forster, R.R., Isacks, B.L. & Das, S.* (1996): Shuttle imaging radar (SIR-C/X-SAR) reveals near surface properties of the South Patagonian Icefield.- J. Geophys. Res. 101 (E10): 23169-23180.

*Fox, A.J. & Cooper, A.P.R.* (1998): Climate-change indicators from archival aerial photography of the Antarctic Peninsula.- Ann. Glaciol. 27: 636-642.

*Harangozo, S.A., Colwell, S.R. & King, J.C.* (1997): An analysis of a 34-year air temperature record from Fossil Bluff (71°S, 68°W), Antarctica.- Antarctic Sci. 9: 353-363.

*Jezek, K.C., Drinkwater, M.R., Crawford, J.P. Bindschadler, R. & Kwok, R.* (1993): Analysis of synthetic aperture radar data collected over the southwestern Greenland ice sheet.- J. Glaciol. 39/131: 119-132.

*King, J.C.* (1994): Recent climate variability in the vicinity of the Antarctic Peninsula.- Int. J. of Clim. 14: 42-53.

*King, J.C. & Harangozo, S.A.* (1998): Climate change in the western Antarctic Peninsula since 1945: observations and possible causes.- Ann. Glaciol. 27: 571-575.

*Marshall, G.J., Rees, W.G. & Dowdeswell, J.A* (1995): The discrimination of glacier facies using multi-temporal ERS-1 SAR data.- In: J. ASKNE (Ed.), Sensors and environmental applications of remote sensing, Balkema, Rotterdam, 263-269.

*Morris, E.M. & Vaughan, D.G.* (1992): Snow surface temperatures in West Antarctica.- In: E.M. MORRIS (ed.), The contribution of Antarctic Peninsula ice to sea level rise.- BAS Ice and Climate Spec. Rep. No.1. BAS, Cambridge, 17-24.

*Morrison, S.J.* (1990): Warmest year on record on the Antarctic Peninsula.- Weather. 45 (6): 231-232.

*O'Farrell, S.P. & Connolley, W.M.* (1998): Comparison of warming trends predicted over the next century around Antarctica from two coupled models.- Ann. Glaciol. 27: 576-582.

*Partington, K.C.* (1998): Discrimination of glacier facies using multi-temporal SAR data.- J. Glaciol. 44/146: 480-488.

*Paterson, W.S.B.* (1994): The physics of glaciers (3rd edition).- Pergamon Press.

*Peel, D.A.* (1992): Ice core evidence from the Antarctic Peninsula region.- In: R.S. BRADLEY & P.D. JONES (eds.): Climate since A.D. 1400. Routledge, New York, pp. 549-571.

*Rachlewics, G.* (1997): Mid-winter thawing in the vicinity of Arctowski Station, King George Island.- Polish Polar Res. 18/1:15-24.

*Rau, F. & Saurer, H.* (1998): Investigations into snow cover dynamics on two glaciers in the central Marguerite Bay (Antarctic Peninsula) using ERS and RADARSAT SAR imagery.- Proc. Final ADRO Symp., 13-15 October 1998, Montreal (in press).

*Rott, H., Rack, W., Nagler, T. & Skvarca, P.* (1998): Climatically induced retreat and collapse of northern Larsen Ice Shelf, Antarctic Peninsula.- Ann. Glaciol. 27: 86-92.

*Schneider, C., Wunderle, S. & Friedrich, M.* (1997): Snow cover investigations by means of ERS-SAR imagery on the Ant. Peninsula.- EARSeL Adv. in Rem. Sen., 1997, 5: 71-81.

*Shi, J. & Dozier, J.* (1993): Measurements of snow- and glacier-covered areas with single-polarization SAR.- Ann. Glaciol. 17: 72-76.

*Skvarca, P., Rack, W., Rott, H. & Ibarzábal y Donángelo, T.* (1998): Evidence of recent climatic warming on the eastern Antarctic Peninsula.- Ann. Glaciol. 27: 628-632.

*Smith, L.C., Forster, R.R., Isacks, B.L. & Hall, D.K.* (1997): Seasonal climatic forcing of alpine glaciers revealed with orbital synthetic aperture radar.- J. Glaciol. 43/145: 480-488.

*Stark, P.* (1994): Climatic warming in the central Antarctic Peninsula area.- Weather 49/6: 215-220.

*Turner, J., Colwell, S.R. & Harangozo, S.* (1997): Variability of precipitation over the coastal western Antarctic Peninsula from synoptic observations.- J. Geophys. Res. 102 (D12): 13999-14007.

*Vaughan, D.G. & Doake, C.S.M.* (1996): Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula.- Nature 39: 328-330.

*Winkler, J.B.,Schulz, F. & Kappen, L.* (1998): Seasonal variations of abiotic factors in terrestrial habitats.- Berichte Polarforsch. 299: 28-32.

*Wunderle, S., Saurer, H. & Goßmann, H.* (1998): Meteorological conditions and snow cover dynamics on Potter Peninsula, King George Island, Antarctica.- Berichte Polarforsch. 299: 15-27.

*Wunderle, S. & Saurer, H.* (1995): Snow properties of the Antarctic Peninsula derived from ERS-1 SAR images.- Proceedings of the 21 Annual Conference Remote Sensing Soc., 11-14 Sept. 1995, Southampton, 1231-1237.

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

*Wunderle, S.* (1996b): A comparison between the dry snow lines derived from meteorological data and ERS-1 SAR images on the Antarctic Peninsula.- In: E. PARLOW (ed.), Progress in environmental remote sensing research and applications. Proc. 15th EARSeL Symp. 4–6 September 1995, Basel, 249-252.