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A GIS-BASED GLACIER INVENTORY FOR THE ANTARCTIC PENINSULA AND THE SOUTH SHETLAND ISLANDS ——A FIRST CASE STUDY ON KING GEORGE ISLAND

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ABSTRACT The aim of the international project "Global Land Ice Measurements from Space (GLIMS)" headed by the US Geological Survey is to establish a world wide glacier inventory based on satellite imagery. This data set will form a first digital baseline study for future glacier monitoring. The presented GIS-based glacier inventory for King George Island is a case study for the area of the Antarctic Peninsula. In the database of the glacier inventory topographic information, specific glaciological parameters as well as metadata will be included. The topographic data consists of drainage basin limits, basin areas, altitudinal ranges, perimeters and mean lengths. Glaciological data sets should comprise information on glacier retreat in different periods, glacier velocities, ice thickness and bedrock topography as well as derived parameters. Modelled and measured mass balance parameters could be included as additional data layers. In particular, these metadata records must comprise background information on data accuracy and data sources and should be compatible with a future data model for the King George Island GIS (KGIS). Three examples illustrate that the GLIMS database will not only contain information valuable for glaciological applications, but also other environmental studies on the island will benefit from this standardised remote sensing data sets. Therefore, a very close link between the data models of KGIS and GLIMS has to be established to enable these synergisms. Finally, better access to historic aerial photography would enable a continuous record of glacier retreat from the beginning of the 1950's onward.

1 Introduction

The Working Group on Geodesy and Geographic Information (WG-GGI) of the Scientific Committee on Antarctic Research (SCAR) launched the project King George Island GIS (KGIS). In order to provide an operational system, a data model, data accuracy standards and a data inventory have to be developed and compiled. As within other Antarctic and global GIS projects data and metadata standards are already established, it is highly desirable to achieve a compatibility of the KGIS to these databases.

Glacial systems on King George Island have considerable impact on their adjacent environments, e.g. the freshwater supply to permafrost sites, new ice free areas for vegetation succession or sediment transport with glacier melt water in fjords and bays. Consequently, glaciers have to be considered in geo-ecological and environmental impact studies. As about 93% of King George Island are glacierised and the KGIS will be designed primarily for the

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above-mentioned scientific and administrative purposes, glaciers must be included in a KGIS.

In this paper, the principle project and database structure of the international project "Global Land Ice Measurements from Space" (GLIMS) headed by the US Geological Survey (USGS) (Kieffer, *et al.*, 2000) is outlined. King George Island is used as a first case study for the setup of a GIS-based glacier inventory for the Antarctic Peninsula. King George Island was selected because numerous glaciological and topographic data sets are available. Furthermore, intensive glacier retreat has already been reported by various authors and attributed to the climatic changes observed in that region. In several case studies, the potential of the GLIMS remote sensing data sets are demonstrated and the links and compatibility between this glaciological baseline study and the KGIS project are pointed out.

2 Indicators for climatic changes along the Antarctic Peninsula

In recent years, indicators for on-going climatic changes have been detected in the region of the Antarctic Peninsula (Fig. 1). The long-term meteorological records show a drastic increase of surface air temperatures at almost all permanent stations (e. g. King, 1994; Stark, 1994; Smith, *et al.*, 1996; Harangozo, *et al.*, 1997; Skvarca, *et al.*, 1998). Moreover, the review of climatological records from early expeditions to the peninsula showed temperatures significantly lower than those recorded today (Jones, 1990). He suggested that the observed warming trends extend back to at least 1900. A general increase of degree-days since the 1960's was detected for the Marguerite Bay (Fox & Cooper, 1998). They attributed the reduction in the extend of perennial snow patches to this. These findings are further supported by observations of Smith, *et al.* (1998) with a lowering of the ice ramp near Rothera base, the disintegration of the ice ramp on Stonington Island (Splettstoesser, 1992), and the measured surface lowering on Moraine Corrie Glacier, Alexander Island (Morris, 1999). Evidence for a linkage between Antarctic Peninsula air temperature increase, atmospheric circulation and interaction with sea ice were presented by King (1994) and King & Harangozo (1998). Pressure indices and statistical analysis indicated that especially during the winter month a more frequent advection of warm humid air masses from northerly directions occurred. This is in good agreement with findings by Turner, *et al.* (1997) which show a systematic increase in the number of precipitation events at Faraday/Vernadsky station since the 1950s. The relation between atmospheric circulation and snow and glacier melt have been investigated by Braun & Schneider (2000). They showed that especially northerly advection of warm humid air masses causes highest summer ablation rates on the west coast of the Antarctic Peninsula and on King George Island.

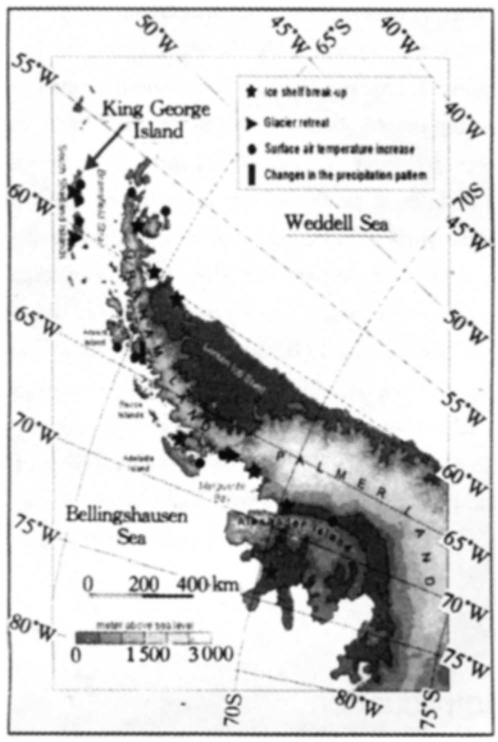


Fig. 1 Indicators for a climatic change in the region of the Antarctic Peninsula

The enormous disintegrations of ice shelves along the Antarctic Peninsula during the last decade might be a direct consequence of the weakening of the ice shelves along fracture zones caused by extreme surface melting during several consecutive extraordinary warm ablation seasons (Hulbe, 1997). Doake & Vaughan (1991), Doake, *et al.* (1998), Lucchitta & Rosanova (1998) and Rott, *et al*. (1996, 1998) documented and explained possible reasons for the spectacular collapses of these ice shelves. Glacier retreat was also reported from several locations on the Antarctic Peninsula (e. g. Calvet, *et al*., 1992; Park, *et al*., 1998; Simões, *et al*., 1999; Wunderle, 1996). As glacier mass balance is strongly triggered by the prevailing meteorological conditions, changes in the climatological settings will also affect the glacial systems. Glaciers are therefore regarded as good indicators for climate change. Many attempts have been made to estimate the sea level raise induced by changes in the glacial systems. All these studies require a representative selection of glaciers (Bahr, 1997; Bahr & Meier, 2000). However, until today, for the entire world no accurate and complete inventory is available.

3 The GLIMS initiative

The GLIMS objectives are to establish a global GIS database of land ice, including surface topography, to measure changes in the extent of glaciers and, where possible, their surface velocities. As a result, the first digital inventory of ice extend will be established. It will form a baseline for future comparison. The world's glaciers will be monitored primarily using data from the ASTER instrument (Advanced Spaceborne Thermal Emission and Reflection Radiometer) aboard the EOS Terra spacecraft, launched in December, 1999. It is intended to have image acquisition on an annual basis using 3 to 5 imaging attempts per year. However, data from other satellites and aerial photography will be mandatory due to the frequent cloud coverage in the region of the Antarctic Peninsula and for the analysis of historic glacier front positions. Detailed planning of data acquisition and analysis are huge tasks that can only be done in cooperation of many institutions. Therefore, the USGS has developed a regional center concept that is illustrated by Fig. 2. Each Regional Center (RC), as e. g. the Institut für Physische Geographie (Universität Freiburg) for the Antarctic Peninsula, will be responsible for the coordination of the mission planning in a region, including the use of their local knowledge of seasonal weather conditions, and the analysis within the region. The analysis will be done by the RC associates themselves, or by "Stewards" (individuals or

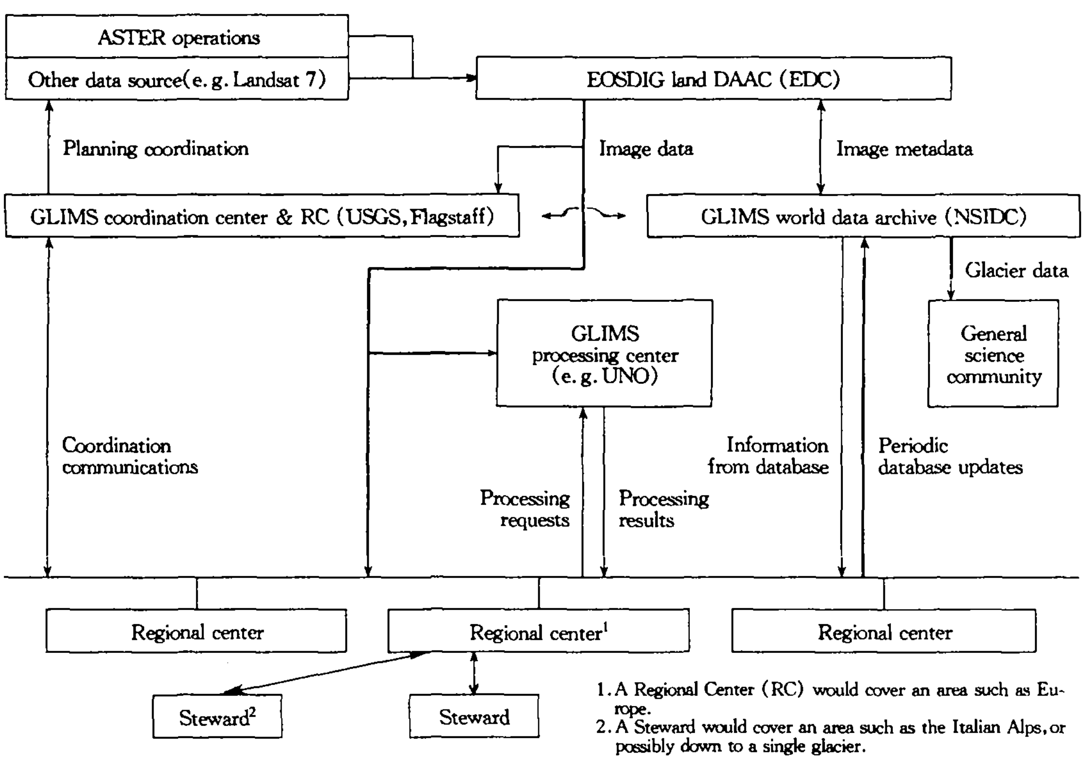


Fig. 2 Organizational block diagram of the GLIMS project
<http://wwwflag.wr.usgs.gov/GLIMS/blockdiag-big html>

groups) interested in smaller areas within a region. The derived products will be archived by the National Snow and Ice Data Center (NSIDC), Boulder, Colorado, already acting as a World Data Center for Glaciology.

4 Database on King George Island

Due to the historic importance of King George Island, the easy access during the winter months and the numerous nations operating permanent research stations on the island, a large amount of aerial photography and satellite imagery are already available, shown in Fig. 3 where data known to exist or to be acquired, but not disposable for analysis and integration into the GIS are marked in grey. King George Island is one of the most intensively surveyed areas of Antarctica. From the time bar below it is obvious that during recent years the amount of satellite imagery increased drastically. However, imagery before the 1990's is especially valuable for the analysis of glacier retreat rates as will be demonstrated in a case study later in this paper. Hence, the availability of historic imagery of King George Island is crucial for this kind of study, which will form an exceeding database as input and verification of glacier flow models.

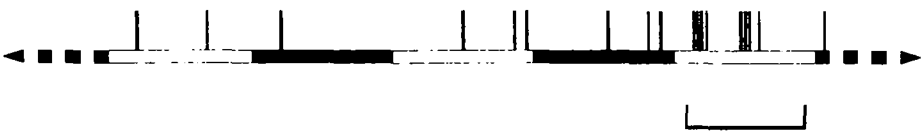


Fig. 3 Satellite imagery and aerial photography of King George Island as available (black)

5 The data model of the GLIMS glacier inventory

Generally, a GIS-integration requires the design of a data model. For the GLIMS project such a data structure is developed for all glaciers on the world. Therefore, an adaptation of this structure for or a compatibility with the KGIS would be desirable. In the GLIMS database, 9 data tables are planned. They comprise static and dynamic variables on glacier parameters, information on image tiepoints, image cube, instrument and ground control points. A detailed list is given in Table 1. For King George Island, more glaciological relevant data sets exist and an integration into the GIS is preferable. These data sets consist of bedrock topography, internal structures of the ice cap , as well as accumulation

Table 1 Extract of the database tables of the GIS-based glacier inventory within the GLIMS project <http://wwwflag.wr.usgs.gov/GLIMS/db-design.html>

Table No.	Table name	Parameters
1	Static	Time-independent glacier information, such as name, general location, glacier type etc.
2	dynamics	Time-dependent glacier information, such as boundaries, area, equilibrium line altitude, total glacier length, mean width of glacier, ablation area, glacier polygon, uncertainty in computed glacier area and polygon, etc.
3	Image Tiepoint Region Information	Information about non-glacierized regions near a glacier suitable for finding inter-image tiepoints
4	Image Cube	Information about a source image, including instrument, time/date, location, cloud severity, number of glaciers in this image
5	Instrument	Complete information about remote sensing instruments
6	Instrument Bands/Modes	Information about instrument bands, such as spatial and radiometric resolution
7	Displacement Vector Information	Vectors of ice displacement, as derived by comparison of multi-temporal images of the same glacier
8	Source Snow Regions	Information (e. g. boundaries) about snow regions from which glaciers derive, uncertainty of determination
9	GCPs/Reference Points	Information about control and reference points, such as latitude/longitude/elevation and their uncertainties

and ablation measurements. In order to guaranty the sustainable utilisation of these resources for a wide range of scientific and administrative applications, it is indispensable to provide detailed standardised descriptions of the various data sets. Particularly, these metadata records must include background information on data accuracy and data sources as precision of image rectification, glacier boundary polygons, or ground control point position.

6 Determination of glaciological parameters using remote sensing and GIS

Remote sensing enables the detection of many valuable glaciological parameters as demonstrated in the following examples. Beside the delimitation of glacial drainage basins, the analysis of glacier retreat, the determination of transient snow and firn line positions, information on the snow melt dynamics can be derived from the different kind of remote sensing data. All these parameters can be included in the GLIMS database, connected to the KGIS.

6.1 Example 1 Glacier retreat in the area of Admiralty Bay and Potter Cove

Aerial photography (FIDASE 1956), a map with the coastline from 1979, and 4 SPOT satellite images (from 19 February 1988, 23 November 1992, 21 December 1992 and 29 March 1995) were used to determine glacier retreat in the area of Admiralty Bay and Potter Cove between 1956 and 1995 as shown in Fig. 4, in which white areas indicate the area loss of the different glaciers basins. The delimitation of glacier drainage basins was taken from Simões, *et al*. (1999). Note the drastic retreat of the large tidewater glacier Fourcade Glacier in Potter Cove and Polar Club, Lange and Vieville Glacier. The small glaciers which end on land show smaller absolute retreat areas, however taking their total area in account, the reveal highest percentages of ice loss. The borders of the glacier drainage basins were taken from Simões, *et al*. (1999). Information on glacier retreat stages is required for the study of vegetation succession on new ice free areas. This information can be provided up to pixel accuracy from remote sensing data. Moreover, glaciers can be used as indicators for climatic changes . However , for many tidewater glaciers a

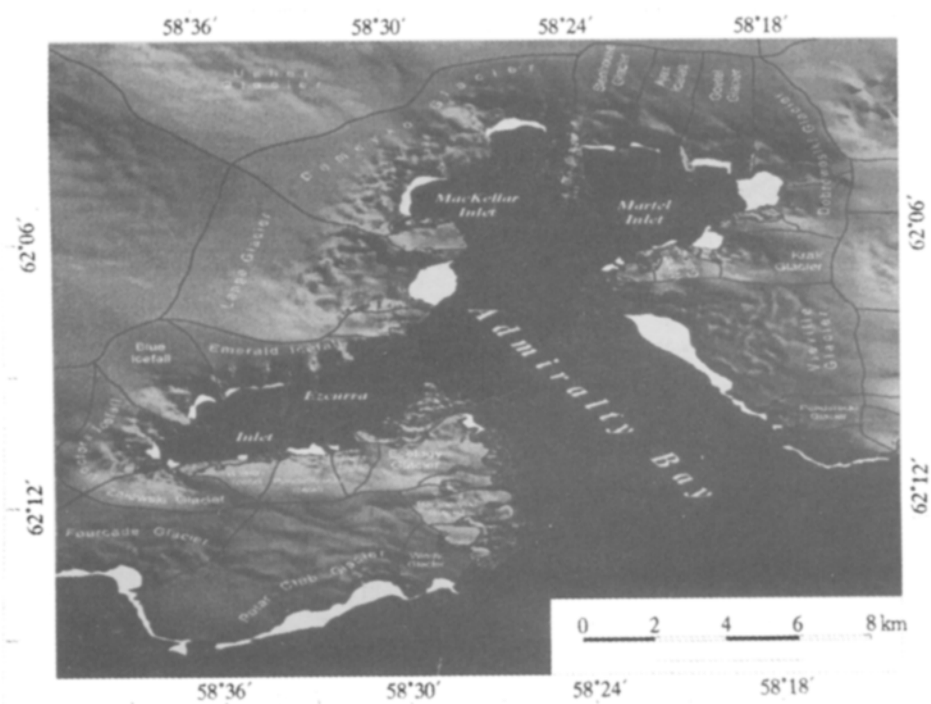


Fig. 4 Glacier retreat in the areas of Admiralty Bay and Potter Cove in the period 1956 to 1995

linear relationship between ice front retreat and climate signal (e.g. temperature increase) can not be assumed. Calving rates of tidewater glaciers depend, besides other factors, strongly on water depth (Warren, 1992). Therefore, drastic changes in glacier front positions of the large tidewater glaciers as seen in Fig. 4 (Lange Glacier, Polar Club Glacier and Vieville Glacier) can not be interpreted as mass balance changes of the same magnitude. Nevertheless, since the small glaciers on King George Island also show considerable retreat and highest percentages in relation to their total area a climatic trigger is quite probable as already stated by Park *et al.* (1998). A further refinement of the glacier retreat stages can be realized including additional data from the intermediate years as shown in Fig. 5 for Martel Inlet, where the different retreat stages are marked in greyscales.

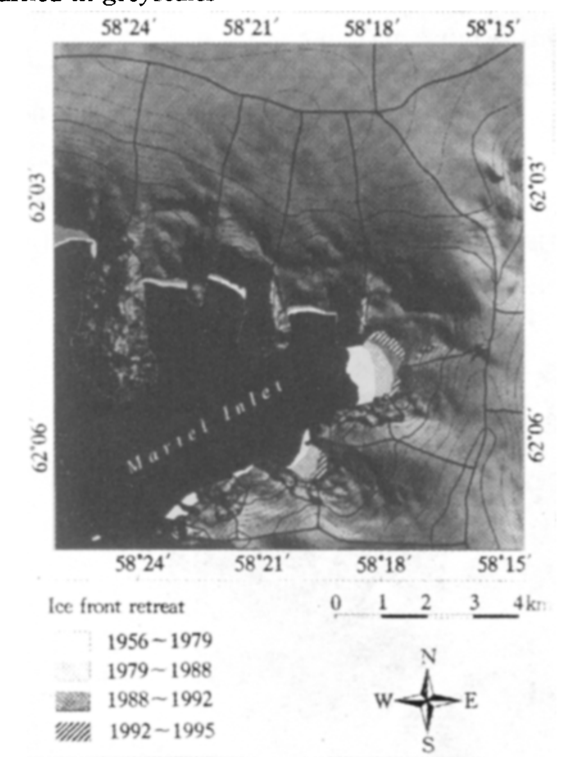


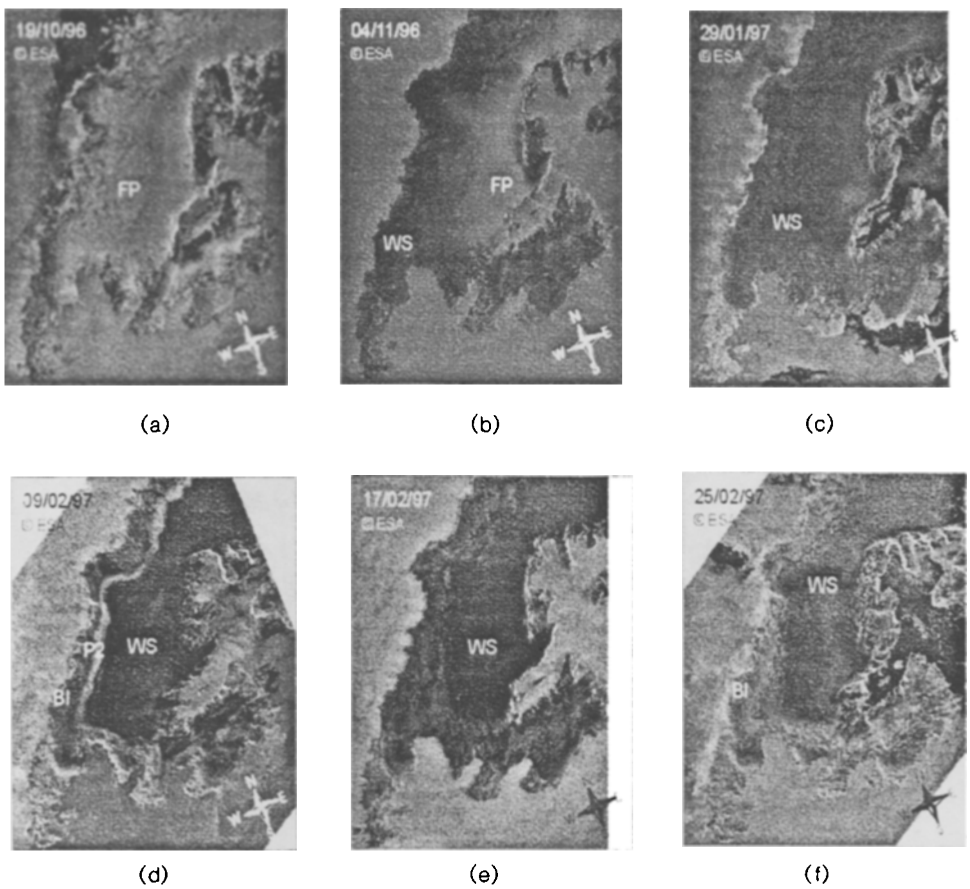
Fig. 5 Ice front positions in the area of Martel Inlet on King George Island

6.2 Example 2 Snowmelt dynamics on the King George Island ice cap

One of the major fresh water sources of the permafrost regions on King George Island is the glacier cover. Knowledge on the timing and intensity of the snow melt process provides additional information for geo-ecological studies. Furthermore, glacier mass balance studies and snowmelt modelling require spatially distributed data sets on snow covered and bare ice areas. Imagery from optical satellite systems as well as from active microwave (such as ERS-1/2 SAR) permits the determination of the transient snow and firn line positions. However, SAR offers the advantage of being weather independent since the radar beam is not affected by clouds and illumination. Additionally, the radar backscatter signal contains information on structure and liquid water content of the snow cover. In regions like the Antarctic Peninsula, SAR imagery is hence a very powerful tool to monitor snow melt patterns and firn line positions (Braun, *et al.*, 2000; Rau, *et al.*, 2000). For the year 1996~1997, snow cover dynamics as obtained from ERS-2 SAR imagery are shown in Fig. 6, in which WS denotes wet snow radar zone, FP, frozen percolation, and BI, bare ice radar zone. Firn line positions can be extracted from the imagery due to significant differences in the radar backscatter signal from bare ice (−7 to −12 dB) towards a wet snow cover (< −15 dB) or a frozen stratified snow cover (−8 to −3 dB). Applying this technique on the ERS-1/2 SAR archive available for King George Island since 1991, the firn line position in several consecutive mass balance years can be extracted. As the firn line only occasionally coincides with the equilibrium line, is a limited proxy for mass balance. However, it is an essential parameter for the initialisation and verification of glacier melt models, because bare glacier ice and snow covered areas show considerable differences in albedo and therefore melt rates.

6.3 Example 3 Sediment plumes and melt water input from the glacier cover into the fjords and bays of King George Island

SPOT multi-spectral imagery enables the determination of sediment plumes originating from the glaciers. The sediments are transported with the glacier melt water and affect the biological life cycle in the bays and fjords (Rakusa-Suszczewski, 1993). They alter the transmisivity of light to the lower strata in the sea. Since freshwater with the associated suspended sediments is subject to wind-driven circulation, the positions of these sediment plumes change fast. Several ground based investigations have been performed to measure sediment



Orbit parameters:		
1996-10-19 descending	1996-11-04 descending	1997-01-29 descending
1997-02-09 ascending	1997-02-17 descending	1997-02-25 ascending
Radar glacier zones:		
FP: frozen-percolation radar zone	BI: bare-ice radar zone	P2: roughened and metamorphosed wet-snow radar zone
WS: wet-snow radar zone		

Fig. 6 Snow melt patterns during the mass balance year 1996~1997 as revealed from ERS-2 SAR imagery

concentrations in Admiralty Bay and Potter Cove (e. g. Klöser, *et al.*, 1994; Klöser & Arntz 1994; Rakus-Suszczewski, 1995). However, they always lack spatially distributed data concurrently obtained under similar conditions. The analysis of satellite imagery can support these studies as shown in Fig. 7, although the optical satellite sensors are influenced by cloud cover and no quantitative sediment volumes can be derived.

7 Conclusions

Using King George Island as a first case study, it is shown that a GIS-based glacier inventory for the island will result in a considerable gain of information. The glaciological data sets of the GLIMS project will not only be very useful for climate monitoring, but also for ecological studies. In several case studies, the impact of the glacial environment on other subjects was demonstrated. The melt water supply of the permafrost areas is strongly dependent on the snow and ice melt. Multi-temporal radar remote sensing can provide information on the snowmelt dynamics. Sediment plumes in the bays and fjords are induced by melt water currents from the glaciers and have impact on the aquatic life cycle. Their spatial distribution can be monitored with optical satellite data. As a further example, the study of plant succession on the newly ice free areas requires a detailed archive on glacier retreat stages. Only from the combination of historic maps , aerial photography and satellite imagery this

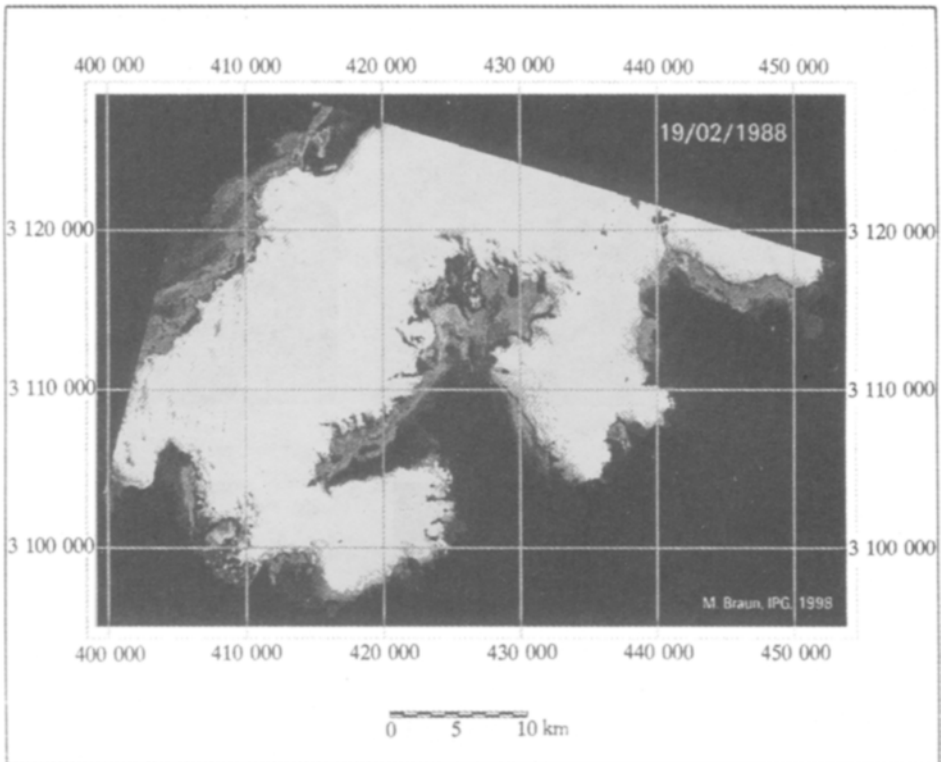


Fig. 7 Sediment plumes as derived from a SPOT satellite image from February 19,1998

information can be obtained. As remote sensing will be the primary source of information gain within the GLIMS project, not only studies of the glacierised areas will benefit from the setup of such a database. The new multi-temporal and multi-spectral imagery from ASTER will also support the extraction of information of related scientific subjects. Therefore, it is proposed to include the GLIMS information and data structure into the KGIS in order to enable these synergisms. The GLIMS database tables will contain a data on static and dynamic glacier parameters as well as comprehensive metadata on imagery and data accuracy. Further glaciological data sets (e. g. mass balance data) could be included into the GIS-based glacier inventory for King George Island and made available to other users. Especially further access to remote sensing data before the 1990's would complete the database for glacier retreat studies.

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