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An improved topographic database for King George Island: compilation, application and outlook

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Abstract: A new topographic database for King George Island, one of the most visited areas in Antarctica, is presented. Data from differential GPS surveys, gained during the summers 1997/98 and 1999/2000, were combined with up to date coastlines from a SPOT satellite image mosaic, and topographic information from maps as well as from the Antarctic Digital Database. A digital terrain model (DTM) was generated using ARC/INFO GIS. From contour lines derived from the DTM and the satellite image mosaic a satellite image map was assembled. Extensive information on data accuracy, the database as well as on the criteria applied to select place names is given in the multilingual map. A lack of accurate topographic information in the eastern part of the island was identified. It was concluded that additional topographic surveying or radar interferometry should be conducted to improve the data quality in this area. In three case studies, the potential applications of the improved topographic database are demonstrated. The first two examples comprise the verification of glacier velocities and the study of glacier retreat from the various input data-sets as well as the use of the DTM for climatological modelling. The last case study focuses on the use of the new digital database as a basic GIS (Geographic Information System) layer for environmental monitoring and management on King George Island.

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Key words: Antarctic Peninsula, Digital Terrain Model, environmental management, Geographic Information System, King George Island, satellite image map

Introduction

Since the earliest days of human activities south of 60°S King George Island (KGI), located north of the Antarctic Peninsula (Fig. 1), has been one of the most visited and most densely populated areas in Antarctica. William Smith discovered the South Shetland Islands including KGI in 1819 (Miers 1950, Jones 1975) and made his landfall in Esther Harbour (Hattersley-Smith 1991). Sealers and whalers followed and used the sheltered natural harbours of the island. One of the first overwinterings in Antarctica is also reported to have taken place on the island's coast in 1821 (Headland 1989). The first permanent station (Base G) on the island was installed at Admiralty Bay by the former Falkland Island Dependency Survey (FIDS) in 1947 and maintained until 1961 (Headland & Keage 1985). Today nine permanent bases and several research cabins have been constructed and every year at least 85 people (1989–90) overwinter. Due to the easy access by plane via the Chilean air strip (Base Teniente Rodolfo Marsh) and by ship the number of island inhabitants can rise to 500 (1989–90) during summer months (Harris 1991a). In the years 1989/90 to 1998/99, the number of tourists visiting the island in summer increased from about 3200 to 4200, with a maximum of more than 7000 visitors in the season of 1994/95 (IAATO 1999). Altogether, the activities of tourists and of the scientific and station personnel impact the local ecosystems considerably.

To protect fragile ecosystems in ice-free areas and to counterbalance the heavy human impact on KGI several protected areas were established by the Antarctic Treaty Consultative Parties. First, in 1966 an area of 28 km² on Fildes Peninsula was made a Specially Protected Area. A few years later the protected status was almost completely revoked near the stations and three other sites on the island were designated as Sites of Special Scientific Interest (SSSI) (Headland & Keage 1985). At present, five areas with SSSI status are located on King George Island. Furthermore, Brazil and Poland, in coordination with Ecuador and Peru, proposed to the XX Antarctic Treaty Consultative Meeting (ATCM) in 1996 the creation of the first Antarctic Specially Managed Area (ASMA) in Admiralty Bay (ATCM XX 1996).

Despite numerous activities on the island and current mapping requirements, the island still lacks an accurate topographic database. Cartographic work started with the beginning of exploration, but focussed on coastlines and harbours (Gould

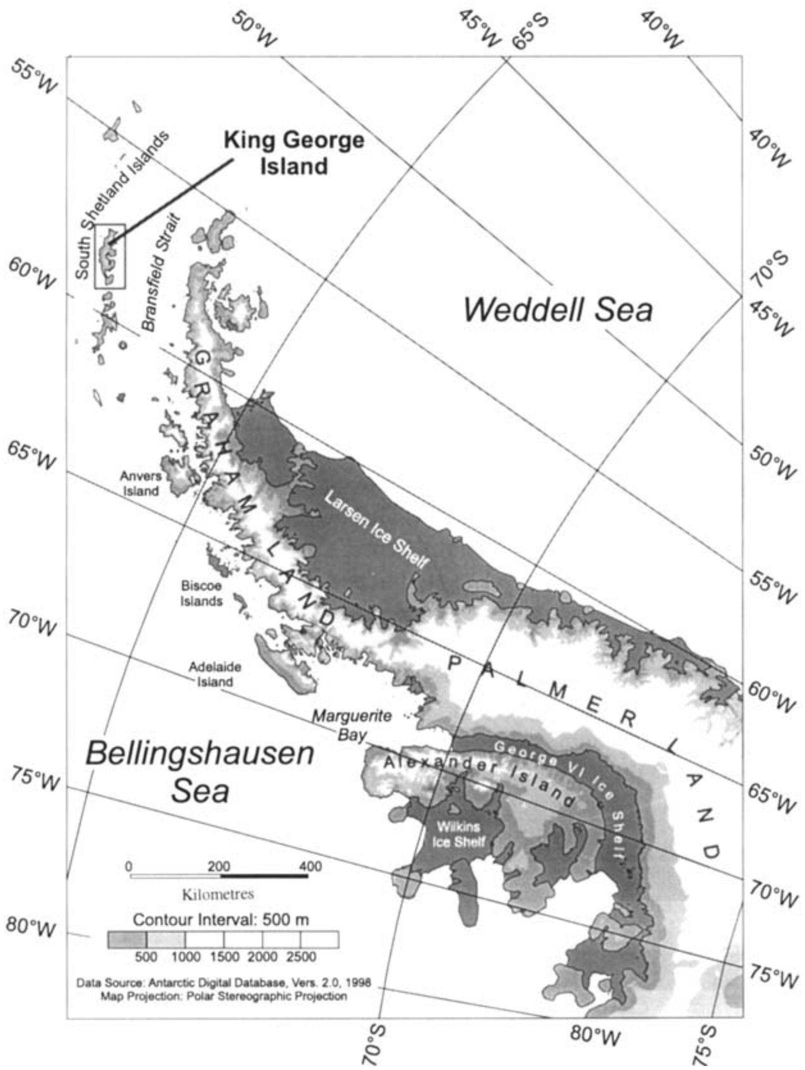

Fig. 1. Location of King George Island with respect to the Antarctic Peninsula.

1941, Roberts 1952). During FIDS activities from Base G (1947–60) topographical surveys were conducted by several sledge parties. As result, the trigonometric points of KGI and the other South Shetland Islands were connected and more accurate maps of KGI were produced. The first aerial photography survey was carried out in January 1952 by Argentina followed by overflights during the Falkland Island Dependency Aerial Survey Expedition in 1956. In recent years, larger scale maps have been published by various nations (e.g. Instituto Geográfico Militar de Chile 1996) for the ice-free areas of the island, but the need of a continuous, digital topographic database for the entire island at a scale larger than 1:200 000 still remains. Harris (1991b) has called for an easily accessible GIS as database to support environmental monitoring and management. However, only a few uncoordinated attempts have been made by different groups in the following years focussing again only on small parts of KGI (e.g. ATCM XXI 1997, Jiaxiang & Tianjie 1997). In 1998, the Working Group of Geodesy and Geographic Information (WG-GGI) of the Scientific Committee on Antarctic Research (SCAR) started an initiative for the implementation of a GIS for KGI, the KGIS project. As a major outcoming of the first workshop on KGIS held in June 2000 it was agreed to develop a standardized data model, data quality standards and a data inventory (WG-GGI 2000).

This paper presents the compilation of a digital terrain model (DTM) and an improved topographic map of the entire King George Island based on a comprehensive differential GPS (DGPS) survey, on data from the Antarctic Digital Database (ADD) (British Antarctic Survey 1998), and on large-scale maps of different parts of the island. All data was assembled in a GIS and present-day coastline was derived from a SPOT satellite mosaic. The following section gives a description of the applied methodology, followed by results and discussion. Several case studies demonstrate the potential applications of the new database for scientific investigations and administrative work.

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Methodology

Existing database and requirements for an improved map

Several large-scale maps exist for ice free areas on King George Island. However, they use different geographic reference systems and scales. Therefore, a combination of the data cannot be accomplished easily. At present, only small-scale maps are available for ice covered areas (1 158 km²). The topography of the ice field is poorly defined due to the lack of aerial photo coverage. Elevations differ from map to map and are sometimes ambiguous. Furthermore, elevation data is not available in digital format with the exception of the ADD, which uses the BAS map at 1:200 000 (British Antarctic Survey 1968). Therefore, the authors' intention was to compile an improved topographic database of the island that should fulfil the following requirements:

a) represent the current topography and coast lines as exactly as possible,

b) connect and combine data from different large scale maps,

c) use a common reference system,

d) include important topographic feature and place names,

e) include information on elevation accuracy,

f) show the distribution of ice and ice free areas,

g) give an immediate impression of the island's topography,

h) be available in digital format, and

i) be easily available and easy to handle for potential users.

To meet these, the use of a heterogeneous data-set was necessary including the most accurate topographic information available for each part of the island. A satellite image mosaic was chosen as base for the new map in order to improve the visual appearance. Height information was digitized from

Table I. Maps, aerial photography and satellite images used for DTM and satellite image map compilation.

Title	Date	Scale / Resolution	Source	Projection and geoid model	Input data
Isla Rey Jorge, Peninsula Fildes	1996	1 : 10 000	Instituto Geográfico Militar de Chile and Instituto Antártico Chileno	UTM, WGS84, mean sea level	Geodetic reference points by GPS 1994–95, aerial photography 1983 and 1984
Admiralty Bay	1990	c. 1 : 65 000	Nakladem Instytutu Ekologii Polskiej Akademii Nauk	Gauß-Krüger-coordinate system and geographic coordinates, Krassowski geoid, 1942	ground survey by theodolite and aerial photography from 1979
King George Island	1986	1 : 100 000	Antarctic Place Names Committee Foreign and Commonwealth Office	Lambert conformal conic projection	
Antarctic Digital Database, Ver. 2.0	1998		SCAR homepage	Stereographic projection	
DTM Potter Peninsula	1996	10 m	Fachbereich Kartographie und Vermessungswesen, Fachhochschule Karlsruhe		photogrametric evaluation of FIDASE aerial photography 1956
DGPS height points	1997/98		Institut für Geophysik, Universität Münster; Institut für Physische Geographie, Universität Freiburg, Germany	UTM, WGS84	mobile DGPS survey of 1997/98 Brazilian-German Antarctic Expedition
DGPS height points	1999/00		Institut für Physische Geographie, Universität Freiburg, Germany; Laboratório de Pesquisas Antárticas e Glaciológicas, Porto Alegre, Brazil	UTM, WGS84	mobile DGPS survey of 1999/00 Brazilian-German Antarctic Expedition
SPOT-3 XS Satellite Image	26/11/94	20 m	SPOTIMAGE, Frame No. 725-478	georeferenced to UTM, WGS84	
SPOT-3 XS Satellite Image	29/03/95	20 m	SPOTIMAGE, Frame No. 725-477	georeferenced to UTM, WGS84	
SPOT-4 XS Satellite Image	23/02/00	20 m	SPOTIMAGE, Frame No. 5 - 725-477	georeferenced to UTM, WGS84	

large-scale maps of Admiralty Bay (Nakladem Instytutu Ekologii 1990), Fildes Peninsula (Instituto Geográfico Militar de Chile 1996), and from the map King George Island 1:100 000 (Antarctic Place Names Committee Foreign and Commonwealth Office 1986). The ADD (British Antarctic Survey 1998), a high resolution DTM of Potter Peninsula, and data from two comprehensive DGPS surveys on the major ice cap of King George Island were already available in digital format. Table I summarizes the properties of the maps and images used in this project.

The first step of the study was the generation of a satellite image mosaic from three multispectral SPOT scenes to determine the current coastline. Next, all data-sets were integrated into a GIS to enable reprojection to a common reference system and the compilation of a continuous DTM for the entire island. Subsequently, the contour lines derived from the DTM were superimposed on the mosaic image to produce a satellite image map. Place names were included for easy identification of the main topographical features of the island.

Satellite image mosaic

Due to the fact that landmarks were best visible in the SPOT satellite image from 26 November 1994, this image was used for geo-rectification. Using 12 reference points and seven control points from maps and GPS observations in Admiralty Bay, on Fildes Peninsula and on Stigant Point, the root mean square error (RMS error) could be minimised to 1.2 pixels, i.e. *c.* 24 m, for that scene. Subsequently, the remaining SPOT images (Table I) were coregistered to that image with RMS errors between 1 and 2 Pixels (20 m to 40 m, respectively). Finally, the images were merged to a satellite image mosaic covering the entire island. The coverage of the scenes is given in Fig. 2.

Table II. Estimated vertical accuracy of data layers used to generate the DTM of King George Island.

Database	Estimated vertical accuracy
DGPS height points	2 m
DTM Potter Peninsula	5 m
Coastline from SPOT mosaic	5 m
Map: Admiralty Bay, 1:65 000	*c.* 20 m
Map: Fildes Bay, 1:50 000	30 m
Antarctic Digital Database	100 m

Digital terrain model

The DTM was generated using point and line elevation data from different sources with varying spatial resolutions and accuracy. Layers of data with low accuracy were clipped where more precise and reliable data existed. Since the heterogeneous database of contour lines and spot elevations requires an algorithm capable of processing these different data types, the TOPOGRID module of ARC/INFO was chosen to compile the DTM. This tool is especially designed to integrate different data types into a single DTM. It uses an iterative finite difference interpolation technique and is especially suited to create DTMs for hydrological modelling. TOPOGRID is based on the ANUDEM algorithm (Hutchinson 1988, 1989, 1996). It is optimised to have the computational efficiency of local interpolation methods, such as inverse distance weighted interpolation, without losing the surface continuity of global interpolation techniques like splines or kriging (ESRI 1995). To preserve the accuracy of the DGPS data collected during our own fieldwork, these data were gridded separately by a kriging algorithm. The resulting grid was then inserted without further modification into the grid generated by TOPOGRID. Similarly, the DTM of Potter Peninsula was included after resampling from 10 m to 100 m resolution. To match the accuracy of the input data and to meet the needs of DTM users, a horizontal resolution of 100 m was chosen. The contribution of each data layer to the DTM

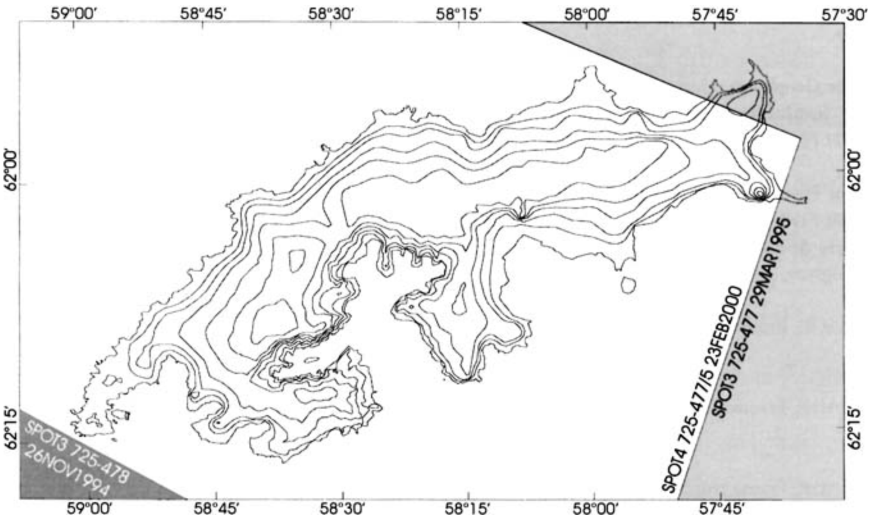

Fig. 2. Coverage of the satellite images used for the generation of the satellite mosaic.

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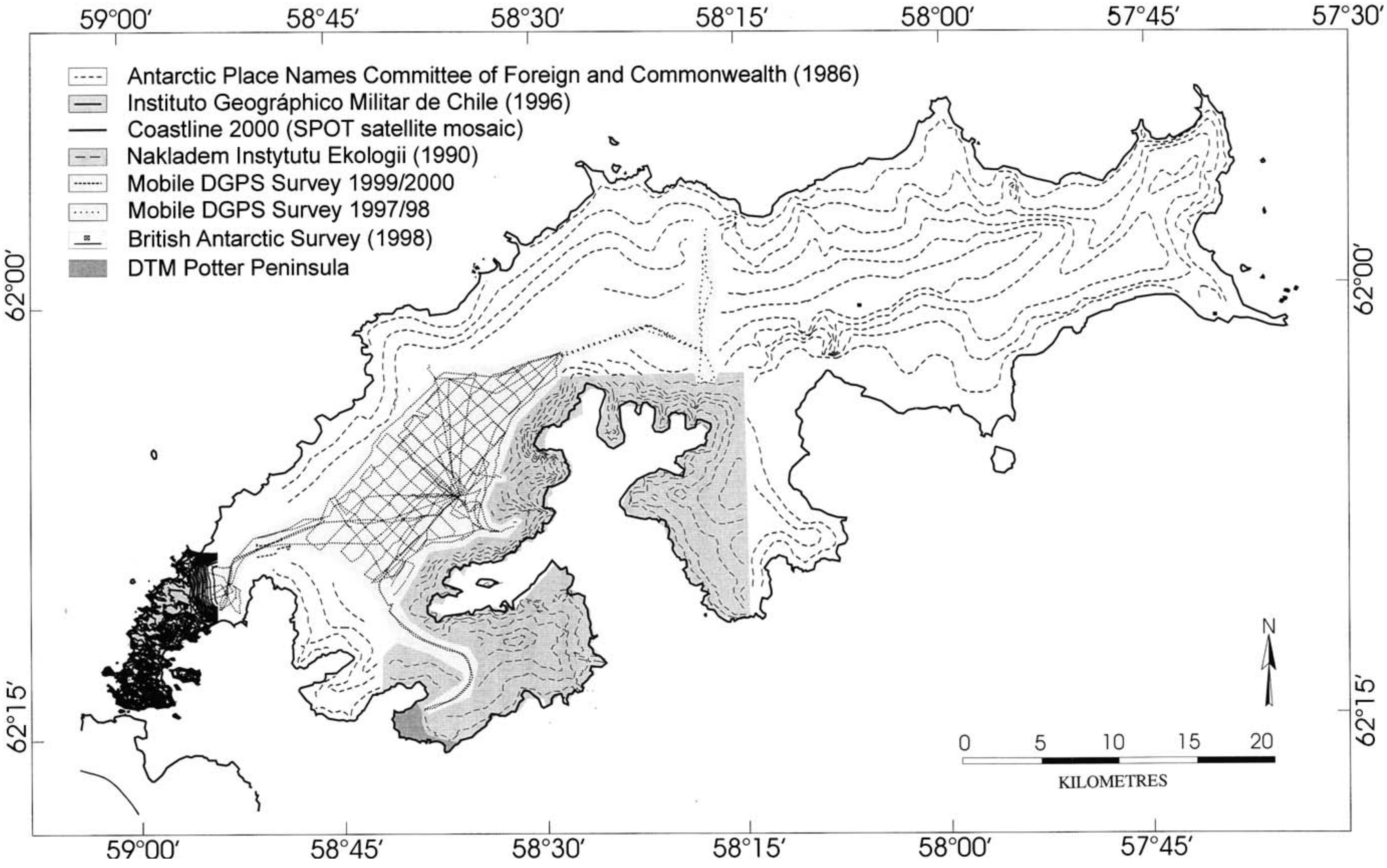

Fig. 3. Spatial coverage of the data layers used for DTM generation. Estimated elevation accuracies of the different layers are given in Table II. Note the scarce data coverage on the eastern part of the island.

is shown in Fig. 3. Additional information on the quality of the input data is given in Table II, which should be regarded as integral part of the topographic database.

Satellite image map

A Lambert Conformal Conic Projection was used for the satellite image map as proposed by Sievers & Bennat (1989). Contour lines were generated in 50 m intervals from the DTM and combined with the SPOT mosaic. Due to the large number of nations which undertake fieldwork on KGI, the use of location names is exceptionally complicated. It is common to find various names for a single feature, as for example, the island's name itself: it is referred to as "King George Island", "Isla Rey Jorge", "Isla 25 de Mayo" or "Waterloo Island". In order to avoid ambiguities, place names were selected from the Composite Gazetteer Antarctica (Working Group of Geodesy & Geographic Information 1999). In case of duplicate names the suggestion "one name per feature" by Sievers & Thomson (1998) was applied. They give priority to the first recorded name, unless:

a) it has disappeared in the actual Gazetteer Antarctica, then a lack of formal approval by the relevant naming authorities was assumed,

b) the name raises confusion with a name applied to a different, more widely known feature,

c) more detailed surveys indicate a misleading description,

d) a person's name was spelt incorrectly,

e) the feature name is now widely used in scientific literature, and

f) the historic name has too many specific components.

The history of locations of place names for King George Island was mainly obtained from Hattersley-Smith (1991). Further information on names and locations were taken from Birkenmajer (1980, 1984), Antarctic Place Names Committee Foreign and Commonwealth (1986), the composite Gazetteer of Antarctica (Working Group of Geodesy and Geographic Information 1999) and from the maps listed in Table I.

Results and discussion

Ice surface morphology

The main King George Island ice field (Arctowski Icefield) is characterised by three major ice domes reaching a maximum elevation of 707 m a.s.l. (Fig. 4). The smooth slopes of the north-western coast contrast with the precipitous fjord-like southern inlets. Here, the ice field drains into fast flowing and strongly convergent outlet glaciers with abrupt icefalls. Ice divides and outlet glaciers are well marked on the satellite image map. The subglacial bedrock topography of the north-western part of the island was mapped by an extended ground penetrating radar (GPR) survey. The results show that the ice surface is mostly controlled by the bedrock topography. A major subglacial ridge in SW–NE direction, Barton Horst (Birkenmajer 1997, Tokarski 1987) forms the base for the highest elevations of the island.

Accuracy of the DTM and the satellite image map

When comparing the contour lines calculated from the DTM with the topography visible in the satellite mosaic, it is obvious that the DTM has higher accuracy in the south-western part of the island than in the north-eastern one (Fig. 4). Around Admiralty Bay, on Fildes and Potter Peninsula, and the Arctowski Icefield, the contour lines fit very well to the mosaic relief and shading. Only Barton and Weaver Peninsula are poorly represented. This can clearly be attributed to a lack of topographic information. For the north-eastern half of the island, the latitudinal information is based only on the Antarctic Place Name Committee map contour lines and few spot heights from the ADD. Consequently, the data-set is poor in that area and the contour lines do not, for example, show the Barton Horst ridge. Moreover, the isolated spot elevation of Melville Peak corrupted the elevation data in this area. In the present study the incorrect contour lines of the DTM were not adjusted to the satellite mosaic, as previously done by British Antarctic Survey & Institut für Angewandte Geodäsie (1996) for the satellite image map "Trinity Peninsula, 1:250 000, SP 21-22/13". An adjustment would probably improve the elevation information only very little. An improvement of the topographic database for the eastern part of the island will be a task for further field work or the use of radar interferometry.

Both, the sketch map indicating the data-layers used (Fig.3) and the estimated vertical accuracy table (Table II) are placed on the map. This enables the user to construct an accuracy map. Further information comprises satellite image identification and precision of image geo-rectification. All metadata is given in four languages (English, German, Portuguese and Spanish) to embrace the work of the large number of nations operating on the island.

Case studies

Due to the GIS integration of the present database a wide range of possible applications in scientific investigations and for administrative purposes is facilitated. To demonstrate its capabilities we present three case studies from glaciology, climatology and environmental management. In the glaciological example, the contour lines are used to validate measured ice velocities with the superficial topography of an outlet glacier and to determine the limits of the glacier drainage basin. Moreover, the different stages of ice front retreat of the Lange Glacier since 1956 have been derived from various input data-sets and additional sources. In another study, the spatial distribution of net radiation on the King George Island ice field was computed. In this case the DTM was used for

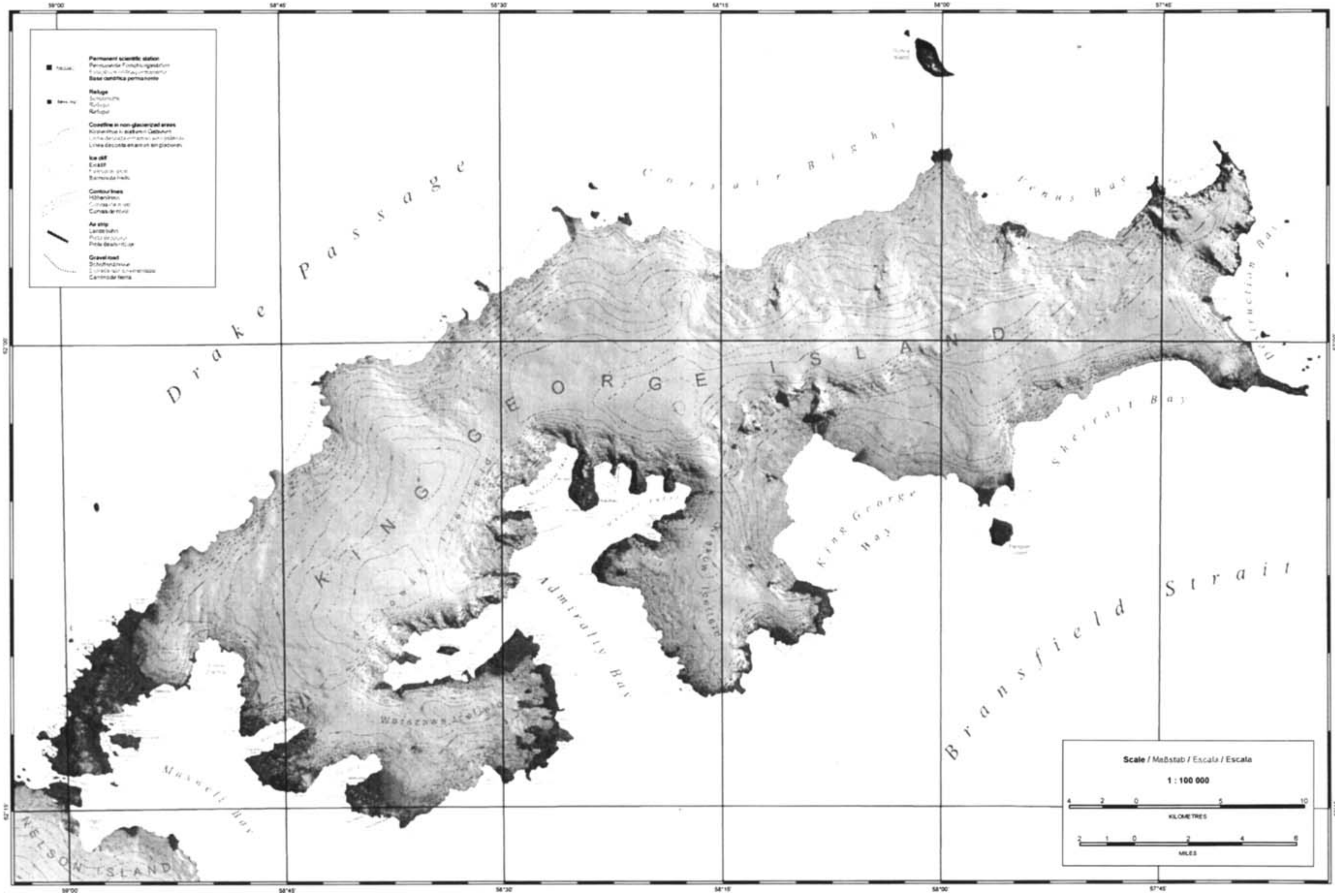

Fig. 4. Black and white overview of the new satellite image map of King George Island. The original map will be printed in a scale 1:100 000, the contour interval is 50 m.

climatological modelling. The last example demonstrates the use of the map and the DTM for an improved delimitation of protected areas established by ATCM and as a basic GIS-layer for environmental management applications.

1) *Supporting glaciological studies and verifying the climate sensitivity of the King George Island ice masses*

The Lange Glacier is a fast flowing tidewater glacier that drains into Admiralty Bay. It is one of the major outlets of the Arctowski Icefield. The glacier flow velocities have been measured by stationary DGPS during the field work in the summer 1997/98 and extrapolated to yearly movement rates. Ice velocity vectors in the upper part of the drainage basin (30.3 km²), shown in Fig. 5, coincide well with the relief represented by the 20 m contour lines and confirm the position of the ice divide as established from the satellite mosaic. A mean elevation of this drainage basin of 440 m is relatively high compared to a mean elevation of the entire island of 280 m. The flow vectors obtained are in good agreement with the surface topography derived from the 20 m contour lines. Similar studies from other places along the Antarctic Peninsula report comparable glacier velocities (Noble 1965, Casassa 1989, Wunderle & Schmidt 1997).

In the polar regions, glacier retreat is a crucial parameter in environmental studies since new ice free areas are formed that enable colonisation and the development of new communities. Moreover, this can also affect the aquatic systems and is regarded as an indicator of climate change. The impressive retreat of the glacier terminus of Lange Glacier since the 1950s, as determined from aerial photography, maps and satellite images, is shown in Fig. 5. A first phase of retreat (440 m) is recorded for the period between 1956 and 1975. Even more striking is the retreat in the short time period between 1975 and 1979. Together, these two periods led to an ice cliff retreat of about 880 m, i.e. a loss of *c.* 1 km². This process continued between 1979 and 1988, when the glacier retreated an additional 280 m, thus losing 0.36 km². Between 1988 and 1995 the glacier retreated 180 m, i.e. it lost an area of 0.2 km². In total, the glacier retreated 1340 m (± 30 m) from 1956 to 1995, thus losing *c.* 1.56 km².

It should be noted that a comparison of the satellite scenes of February 1988 (late summer) and November 1994 (spring) does not indicate a glacier retreat for this period. However, one has to be cautious when interpreting these data as steady state or advance of the glacier terminus. When comparing ice front states of Stenhouse Glacier (also draining into Admiralty

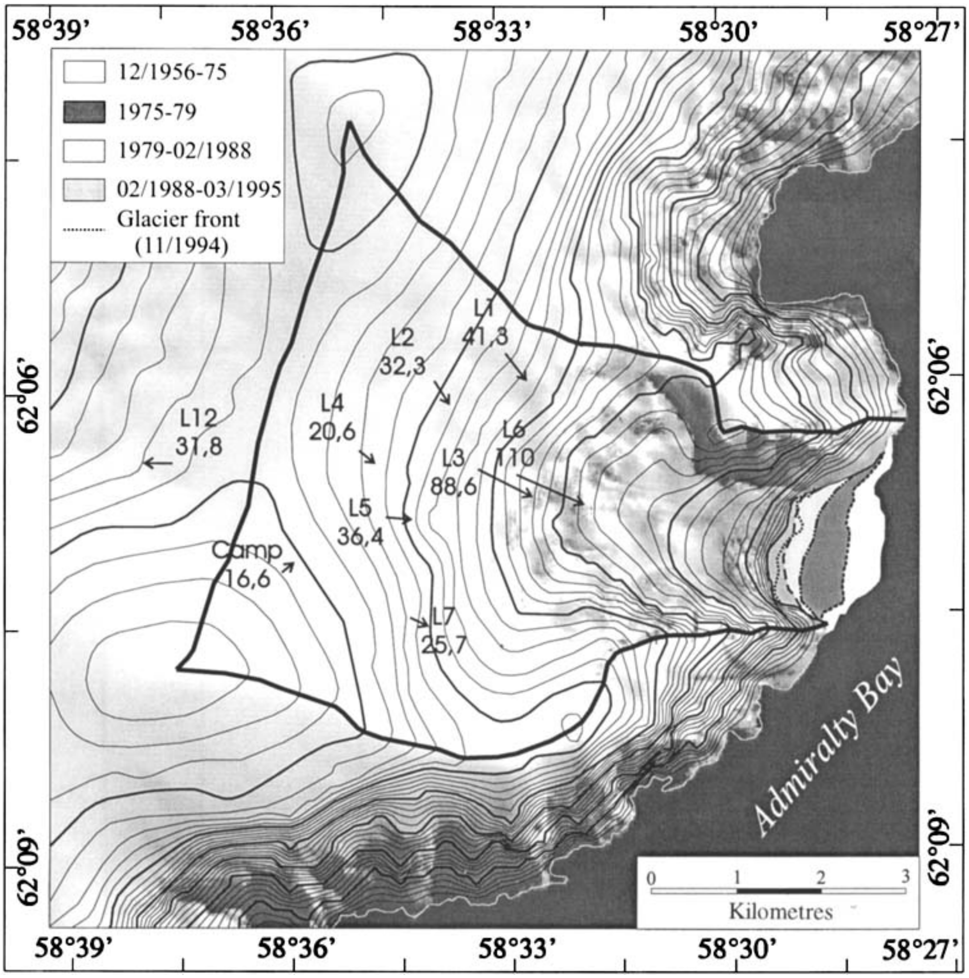

Fig. 5. Ice front retreat and surface glacier velocity vectors of Lange Glacier as measured in summer 1997/98. Arrows indicate the velocity vectors and letters the stake-ID (L1-L12 and camping site). The velocity are given in ma⁻¹. The ice retreat between 1956 (white) and 03/1995 (solid black) is indicated as grey area. Ice front locations from 1979, 1988 and 11/1994 are marked with dotted-dotted-dashed, dashed and dotted lines respectively.

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Bay) during 1957/58 a strong oscillation of the glacier terminus position depending on the season could be observed (Noble 1965). In February/March 1957 massive calving led to ice front retreat while during winter the glacier terminus advanced 150 m before the next spring. This was followed again by a retreat of the terminus in the summer months. Keeping this yearly cycle in mind the acquisition date of aerial and satellite images becomes crucial when small changes in glacier extent are monitored.

Recent studies indicate that the King George Island ice field mass balance may be very sensitive to climatic changes (Bintanja 1995, Braun *et al.* in press). From 1956 to 1995 vast glacier retreats have been reported by various authors for the entire King George Island (e.g. Simões & Bremer 1995, Wunderle 1996, Simões *et al.* 1999). These observations seem to be associated with the observed increase in surface air temperatures (Park *et al.* 1998). Based on ice-flow modelling, Knap *et al.* (1996) proposed that an increase in mean surface air temperature by 1°K would result in 36% loss of total ice volume. Given a current warming trend of 0.38°K per decade (King 1994), the effects on the mass balance of the KGI ice cap will be clearly recognisable in the near future. The highly accurate ice surface topography of the main ice dome of KGI as revealed from the two DGPS surveys will facilitate the verification of the ice flow modelling results by remeasuring in a few years.

2) *Radiation balance of King George Island ice field, 2 January 1998*

One of the most important meteorological parameters in environmental sciences is the net radiation balance since it constitutes the major energy flux at the earth's surface. Snow melt on the King George Island ice field for example is controlled by the radiation balance (Bintanja 1995, Braun & Schneider 2000, Braun *et al.* in press). Modelling the spatial distribution of radiation fluxes requires information on topographic features such as elevation, aspect and slope. Therefore, an accurate DTM of the area of interest is required. The spatial distribution of the net radiation was calculated according to an algorithm suggested by Hock (1998) using the modelled clear sky irradiance, measured global radiation, albedo and net radiation values from an automatic weather station. Figure 6 shows the model results of net radiation averaged over the period 3 December 1997 to 11 January 1998. Influence of shading can only be seen in the steep Ezcurra Inlet whereas the lower elevations show highest net radiation values. The highest snowmelt rates are also observed in these areas (Braun *et al.* in press).

3) *Delimitation and management of protected areas*

According to Article 5.3, Annex V of the Protocol on Environmental Protection to the Antarctic Treaty, proposed management plans for protected areas require, *inter alia*, maps and photographs that show clearly the boundary of the area in relation to surrounding features and key features within the area. At present, five areas on King George Island have SSSI status. Some of them cover only small regions such as SSSI no. 5 (1.8 km^2) on Fildes Peninsula. Their delimitation requires large scale maps (e.g. Instituto Geográfico Militar de Chile 1996). Often protected areas cover large regions. In case of the Admiralty Bay Antarctic Specially Managed Area (ASMA), prior to this study only an imprecise description of its borders

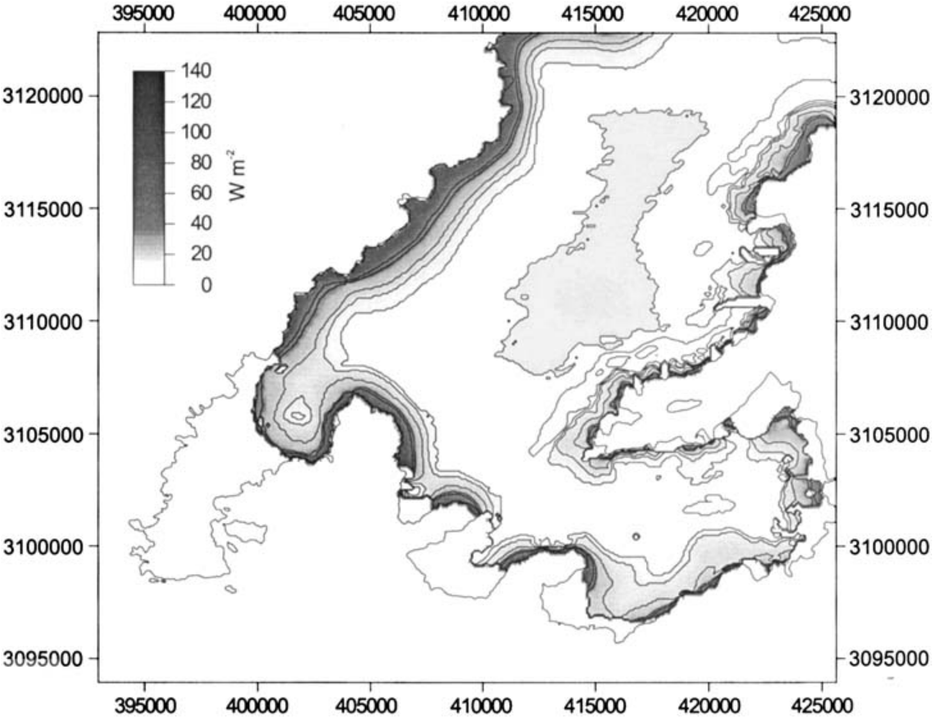

Fig. 6. Modelled net radiation averaged over the period 3 December 1997 to 11 January 1998 over the glaciated area of north-western King George Island. Coordinates are in UTM projection.

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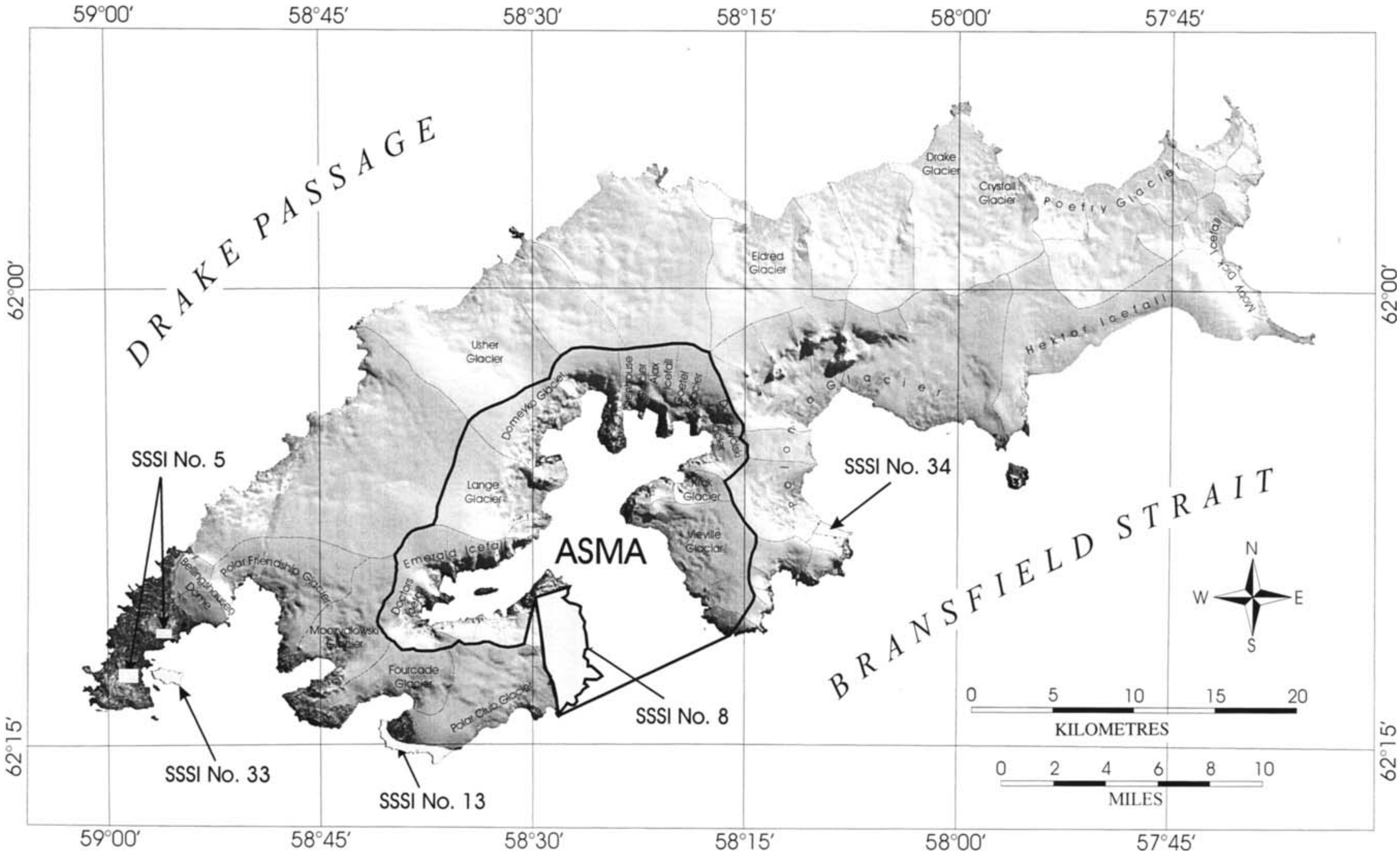

Fig. 7. SPOT mosaic with major drainage basins (after Simões *et al.* 1999). The ASMA/SSSI areas are highlighted in bright grey. Due to the limited space in this figure, not all glaciers are labelled.

existed, which was based on the British Antarctic Survey (1968) map at scale 1:200 000. This deficiency was overcome using the satellite image map (Fig. 7) where the limits of the ASMA are marked as defined at the XX ATCM in Utrecht (ATCM 1996). It comprises "the area considered to be immediately within the glacial drainage basin of Admiralty Bay as well as part of the present SSSI no. 8, which is adjacent to this region but outside the drainage basin" (Foreign & Commonwealth Office 1997). The total area of the ASMA was redetermined and now amounts to 362 km^2 (against former 370 km^2). 32 km^2 of this area are ice-free and 168 km^2 are covered by snow and ice. The remainder is water surface in the bay and the adjacent Bransfield Strait.

The topography, place names, ice divides, current and historic ice front positions, location of stations and boundaries of specially protected areas form the first layers in a GIS for the Admiralty Bay ASMA. A further extension will include vegetation cover, breeding sites of birds and mammal colonies, geological and geomorphological features and bathymetry. Such a GIS will assist in the identification of conflicting interests of environmental protection, scientific work, tourism and the requirements of logistic support. It will also serve as a pre-eminent source of spatial information for research purposes. The GIS will follow the data standards and the data model under development by SCAR WG-GGI. The improved topographic database may therefore form a major input to the SCAR WG-GGI project.

Conclusion

The topographic database for King George Island could be significantly improved by integrating a satellite image mosaic and elevation information from various sources. From these data-sets a DTM and a new satellite image map were generated. Extensive meta information about the map compilation, including data accuracies, data sources, satellite image identification and criteria for place name selection is presented to the user on the map in four languages. Deficiencies of accurate topographic measurements in the eastern parts of the island were identified that can only be overcome by additional topographic surveying or by radar interferometric techniques. An easy updating and extension of the database is guaranteed by the integration into a GIS. The DTM and the satellite image map will facilitate administrative activities and future studies, in particular those that require spatially distributed modelling. Demonstrations of possible applications were given in three case studies from glaciology, climatology and environmental management. These basic topographic GIS layers from the map will be extended using the SCAR WG-GGI standards to form a major base of spatial information for the entire King George Island within the KGIS project. It is intended to make the database available for other working groups on the World Wide Web.

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