The GLIMS Glacier Inventory of the Antarctic Peninsula

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At the start of the new millennium, the climate in many parts of the polar regions is changing rapidly, and the influence of human-produced emissions of greenhouse gases is believed to be a major contributing factor. With temperature rises unequalled in the history of climatic observations, global climate of the 20th Century changed at an average rate beyond combined uncertainties and at a magnitude unprecedented in the last millennium. Although there is general agreement on the evidence of global warming, there is still much debate on the magnitude and the regional pattern of these changes and of the response of cryospheric systems to climate change.

A dramatic example of extraordinarily strong regional warming is observed around the Antarctic Peninsula. Even taking into consideration the extremely large interannual variabilities that characterize the meteorological records for this region, the warming rates identified on the western coast of the Antarctic Peninsula are greater than those found elsewhere in Antarctica. Furthermore, analysis of synoptic observation records and proxy values reveals that precipitation patterns on the Antarctic Peninsula are changing. These changes in temperature and precipitation in recent years directly result in fluctuations in the annual mass and energy balance cycles of the glacial systems of the Antarctic Peninsula. The consequences include the spectacular disintegration of ice shelves on both sides of the peninsula, acceleration of glaciers feeding those ice shelves, marked changes in the glacier frontal positions, and the retreat of grounding line positions of the floating ice tongues. Observational evidence suggests that there is much more spatial and temporal variability in the grounded and floating parts of local glacial systems than previously expected. Because of the extraordinary rate of warming on the Antarctic Peninsula and related changes in glaciers, the Intergovernmental Panel on Climate Change (IPCC) chose this region as one of eight key polar regions for detailed investigation.

The northern Antarctic Peninsula is dominated by an alpine glacial system consisting of an ice cap covering the central plateau region, which feeds numerous outlet glaciers draining to both sides of the peninsula. The majority of these flow into ice shelves or terminate as tidewater glaciers. In addition, isolated ice caps, mountain glaciers, and ice piedmonts characterize the margins of the peninsula and the adjacent islands. In contrast to the slow reaction of continental ice masses, the relatively small glaciers on the Antarctic Peninsula react with short response times (time scale: years to decades) to perturbations of their accumulation and ablation processes. These glaciers are therefore recognized to be superior indicators of the spatio-temporal variability of the regional climate system.

As part of the multi-national Global Land Ice Measurements from Space (GLIMS) project, the Department of Physical Geography of the University of Freiburg (Germany) monitors the glaciers of the Antarctic Peninsula. GLIMS was established to acquire satellite multi-spectral images of the world's glaciers and analyze them for glacier extent and changes, and to understand these change data in terms of climatic and other forcings—*www.glims.org*—GLIMS makes use of state-of-the-art imaging and image-analysis technology, and is designed to monitor the world's glaciers primarily using data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument aboard the EOS Terra spacecraft. Complementary image data from additional sensors such as Landsat, European Remote-sensing Satellite-1/2 (ERS-1/2), and CORONA, as well as information obtained from historic maps and air photographs are integrated into the general workflow. The project as a whole was originated and has been coordinated by the U.S. Geological Survey in Flagstaff, Arizona, but is now coordinated from the University of Arizona in Tucson, Arizona. GLIMS provides a global network for glaciologists from more than 60 scientific institutions across the globe.

The GLIMS consortium is organized into a system of Regional Centers (RCs), each of which is responsible for glaciers in their region of expertise. The standardized results of the glacier analyses are archived together with the corresponding meta-information in the GLIMS Glacier Database, which was designed and implemented at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado—*nsidc.org/glims/*.

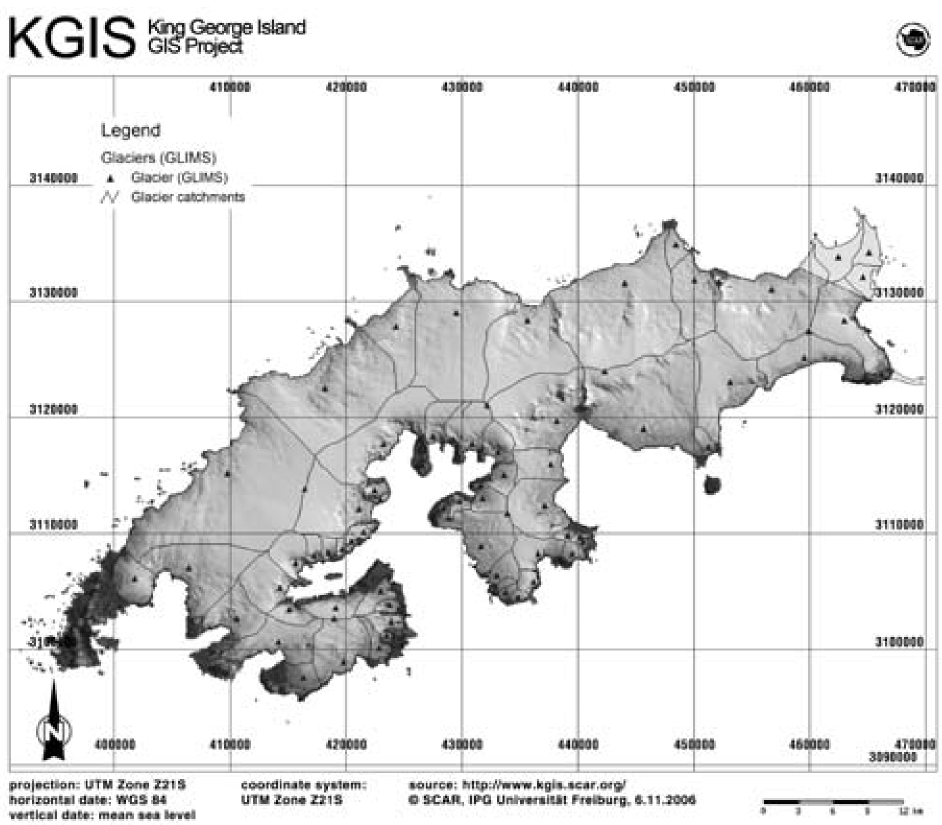
One of the main tasks of the RC of the Antarctic Peninsula hosted at the Department of Physical Geography of the University of Freiburg is the compilation of a glacier baseline inventory for the Antarctic Peninsula and the derivation of morphometric glacial parameters, which will facilitate a consistent glacier monitoring and geo-statistical analyses on the peninsula in the future. In its current version, the glacier inventory comprises more than 1100 entries of all glacial systems and individual glaciers from the Antarctic Peninsula north of 70° S and the adjacent islands.

The first step in compiling the glacier inventory is the identification of the individual glaciers. Because the Antarctic Peninsula is almost entirely covered in ice, and is quite complex glaciologically, a complete identification of absolutely all ice masses down to the smallest ice fringes, glacierets and snowfields is not possible. Consequently, all those glaciers definable from satellite images that meet at least one of the following criteria are defined as individual ice masses:

- Glaciers named on published maps or listed in the current version of the *Composite Gazetteer of Antarctica*—CGA; *www3.pnra.it/SCAR_GAZE*.
- Unnamed valley glaciers or outlet glaciers terminating as tidewater or terrestrial glaciers or draining into an ice shelf.
- Unnamed glaciers unrestricted by topography exceeding a minimum size—e.g. small island or mountain ice caps.
- Ice masses which are part of superior glacial systems and which are identifiable by an individual velocity field.
- Small glaciers of historic or scientific importance.

Most glaciers on the Antarctic Peninsula do not have official and internationally accepted names. The multinational history of scientific exploration and surveying on the Antarctic Peninsula, territorial claims, and the absence of a responsible naming authority under the Antarctic Treaty System, have resulted in numerous cases of multiple names for single features, and inconsistent practices in the recognition and use of existing names. To avoid further confusion and inconsistencies, and to bring some order to the local toponymy, the Scientific Committee on Antarctic Research (SCAR) promotes adoption of the general naming convention of *one name per feature* for all Antarctic geographic names. Therefore, all existing object names are checked in reference to the *Composite Gazetteer of Antarctica* and published maps. For objects with multiple names, a single name is fixed following the principle of historic priority. To provide highest compatibility with the *Composite Gazetteer of Antarctica*, maps and other publications, the synonyms are stored in addition to the approved object names in a supplemental data field together with a three-letter International Organization for Standardization (ISO) country code indicating the original source of each name.

Because each glacier record can point to a *parent ice mass* in the GLIMS Glacier Database, the representation of complex glacial systems with interconnections and relationships between different ice masses (e.g. an outlet glacier draining an ice cap) can be accomplished. The relation of each glacier to up- or downstream connecting ice masses is checked during the



The glacier inventory of the King George Island ice cap. King George Island is the largest of the South Shetland Islands located northwest of the Antarctic Peninsula. The island is home to about 80 glaciers, which are characterized in terms of their catchment boundaries and represented by an individual ID point (black triangles) located within the glacier polygon. Multi-spectral image classification techniques, morphometric analysis of digital terrain models, and personal experience from previous field campaigns were used to determine the surface area of the glaciers. Additional time-invariant and dynamic information on each glacier are stored in the geospatial relational GLIMS Glacier Database. The inventory presented is extracted from the *SCAR King George Island GIS Project* (KGIS, *www.kgis.scar.org/*), The image background is an ortho-rectified Système Pour l'Observation de la Terre (SPOT) image from February 2000.

glacier identification process. Ice masses such as ice caps, plateau glaciers, or ice fields were flagged as parent ice masses, while the ID of the appropriate parent ice mass was assigned to the individual subordinated glacial components—e.g. outlet glaciers, ice shelves.

Researchers use satellite imagery and supporting data from other sources—e.g, ground-based measurements —to extract information about the static and dynamic parameters of each glacier, and categorize each glacier using the modified GLIMS glacier classification scheme. In addition, the researchers use satellite imagery and Digital Elevation Model (DEM) output to develop datasets that contain information on the catchment and glacier boundaries. These datasets also include derived parameters, such as surface areas, length, and width, as well as additional information such as frontal position lines, center-lines, and snowline positions. All of this data is exported to the GLIMS-specific database ingest format.

Analysis of high resolution ASTER data co-registered to Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data provide information on glacier front variations between the years 1986 and 2002. In regional case studies, more than 300 glaciers were examined, covering a variety of glacial systems distributed over the northern Antarctic Peninsula. Of these, only 40 (12.8%) displayed advancing glacier fronts accounting for a gain of 7.1 km^2, while 171 (54.6%) showed retreating ice fronts accounting for a loss of 146.1 km^2. In addition, 102 (32.6%) were found to be in invariant conditions. The glaciers examined displayed no indications of dynamic flow instabilities. The observed glacial variations are therefore interpreted as direct consequences of the rapidly changing climatic conditions in the region that are affecting accumulation and ablation.

Beyond the overall trend toward retreating ice fronts, observations dating from the mid 1980s to 2001 reveal different patterns of glacier variation across the Antarctic Peninsula. An area of significant retreat is concentrated on the northeastern sectors of the peninsula—eastern coast of Trinity Peninsula and James Ross Island. Similarly, a consistent distribution of predominant glacial recession is also identifiable along the southwestern coasts of the study area—Graham Coast, Loubet Coast and Marguerite Bay. This is in sharp contrast with glacier frontal positions recorded in northwestern parts of the Antarctic Peninsula adjacent to Bellingshausen Sea, where only slight recessions and minor advances were recorded—western coast of Trinity Peninsula and Danco Coast. These observations from the northwest, which are presumed to be in the natural range of frontal fluctuations of tidewater glaciers, suggest relative dynamic stability of the glacial systems in this sector.

With long-term observations lacking from most parts of the Antarctic Peninsula, the high data availability on James Ross Island offers the possibility for a continuation of previous glacier monitoring activities. Analyzing the glacial variations on a larger perspective, a drastic acceleration of glacier recession could be determined on the island since 1988. In comparison to a retreat rate of 1.84 km^2/a from 1975 to 1988 (*Skvarca and others*, 1995), the annual reduction of glaciated areas doubled to 3.79 km^2/a from 1988 to 2001. Moreover, contrary to the situation in 1988, the majority of glaciers terminating on land in 2001 are now retreating. Over the entire period between 1975 and 2002, the glaciers on James Ross Island are found to have decreased by 78.8 km^2 corresponding to 3.9% of the previously ice-covered area.

These observations provide more evidence of the significant impacts of recent rapid climate change on the cryospheric environment of the Antarctic Peninsula. Furthermore, they highlight the importance of a consistent glacier monitoring in this region by means of high-resolution satellite image data. Innovative spaceborne sensors such as ASTER and new data acquisition and distribution strategies have led to a better coverage of the polar regions with satellite data in space and time, thus providing the required tools to accomplish the aim of establishing a functional monitoring program and to contribute the ongoing research efforts in the field of climate change.

References:

Kargel, J. S., M. J. Abrams, M. P. Bishop, A. Bush, G. Hamilton, H. Jiskoot, A. Kääb, H. H. Kieffer, E. M. Lee, F. Paul, F. Rau, B. Raup, J. F. Shroder, D. Soltesz, D. Stainforth, L. Stearns, R. Wessels, and the GLIMS Consortium (2005): Multispectral Imaging Contributions to Global Land Ice Measurements from Space. *Remote Sensing of Environment,* **99** (1/2), 187-219.

Rau, F., F. Mauz, H. De Angelis, R. Jaña, J. Arigony Neto, P. Skvarca, S. Vogt, H. Saurer & H. Goßmann (2004): Variations of glacier frontal positions on the Northern Antarctic Peninsula. *Annals of Glaciology* **39**, 525 - 530.

Raup, B., A. Kääb, J. S. Kargel, M. P. Bishop, G. Hamilton, E. Lee, F. Paul, F. Rau, D. Soltesz, S. J. Singh Khalsa, M. Beedle & C. Helm (in press): Remote Sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) Project. *Computers and Geosciences.*

Skvarca, P., H. Rott & T. Nagler (1995): Satellite imagery, a base line for glacier variation study on James Ross Island, Antarctica. *Annals of Glaciology* **21**, 291 - 296.