The Cryosphere, 7, 445–449, 2013
www.the-cryosphere.net/7/445/2013/
doi:10.5194/tc-7-445-2013


The Cryosphere Open Access

# *Brief communication*
# "The aerophotogrammetric map of Greenland ice masses"

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Received: 6 August 2012 – Published in The Cryosphere Discuss.: 18 September 2012
Revised: 2 February 2013 – Accepted: 4 February 2013 – Published: 11 March 2013

**Abstract.** The PROMICE (Programme for Monitoring of the Greenland Ice Sheet) aerophotogrammetric map of Greenland ice masses is the first high resolution dataset documenting the mid-1980s areal extent of the Greenland Ice Sheet and all the local glaciers and ice caps. The total glacierized area excluding nunataks was 1 804 638 km$^2$ ± 2178 km$^2$, of which 88 083 ± 1240 km$^2$ belonged to local glaciers and ice caps (GIC) substantially independent from the Greenland Ice Sheet. This new result of GIC glacierized area is higher than most previous estimates, 81 % greater than Weng's (1995) measurements, but is in line with contemporary findings based on independent data sources. A comparison between our map and the recently released Rastner et al. (2012) inventory and GIMP (Greenland Ice Mapping Project) Ice-Cover Mask (Howat and Negrete, 2013) shows potential for change-assessment studies.

## 1 Introduction

Glaciers and ice caps are important contributors to present-day sea-level rise (Jacob et al., 2012) but uncertainty about the area covered by GIC (glaciers and ice caps) is an obstacle to modelling their contribution (Kaser et al., 2006). The aim of this study is to produce a highly detailed map of the entire margin of the Greenland ice sheet and all surrounding GIC from a time preceding the last decade of widespread availability of high-resolution satellite imagery. Such a dataset would serve as reference for detecting long-term trends, and also contribute to the decades-long debate on the combined areal extent of GIC in Greenland. The Landsat 1, 2 and 3 missions allowed Weidick (1995) to assemble a comprehensive visual documentation of Greenland's ice cover using scenes of Greenland acquired between years 1972 to 1982 (see plate in Weidick, 1995). Based on a new 1 : 2 500 000 scale map, Weng (1995) measured the total ice-covered area of Greenland as 1 755 637 ± 100 km$^2$, with 1 707 038 ± 100 km$^2$ for the Greenland ice sheet, not including nunataks. He measured an extent of 48 599 km$^2$ for 301 of the larger glaciers situated outside the margin of the Greenland ice sheet on the main island (44 838 ± 100 km$^2$) and on coastal islands (3761 ± 100 km$^2$). Weidick and Morris (1998) suggested a GIC area of 70 000 km$^2$ and discussed whether – and how – several peripheral ice units, which appear to behave independently from the ice sheet proper, should be considered separately. Values between 49 000 km$^2$ (Ohmura, 2009, derived from the map of Weng, 1995) and 163 000 km$^2$ (Sharp, 1953) can be found in the literature.

Until recently, glacier mapping in Greenland was only regional and mostly limited to the early work by Jiskoot (2002) on central East Greenland and the inventory of Disko Island, Nuussuaq and Svartenhuk peninsulas (Citterio et al., 2009). The WGGI (West Greenland Glacier Inventory) (Weidick et al., 1992) included printed maps and tables, but only the tables are available in digital form. Jiskoot et al. (2012) produced a new detailed inventory in central East Greenland from 2000–2001 Landsat 7 and ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer) imagery and differenced it against GEUS (Geological Survey of Denmark and Greenland) map data from the 1980s to investigate the fluctuations of tidewater glaciers in the Geikie Plateau region.

The GIMP (Greenland Ice Mapping Project) 15 m Ice-Cover Mask (Howat and Negrete, 2013) has recently become available. Even more recently, Rastner et al. (2012) proposed an inventory based on Landsat scenes between 1999 and 2002 covering all of Greenland and, above 80° N, complemented by the GIMP mask, improved based on MODIS (MODerate resolution Imaging Spectroradiometer) imagery to correct obvious errors. The Rastner et al. (2012) dataset is especially interesting not only because it has been extensively controlled manually, but also because the issue of splitting ice masses in contact with the ice sheet is thoroughly discussed and addressed.

In this brief communication we introduce the new PROMICE (Programme for Monitoring of the Greenland Ice Sheet) aerophotogrammetric map of Greenland ice masses, based on images acquired between 1978 and 1987, we provide a new estimate of the total area covered by GIC, and compare the glacier margins in our new dataset to the recent GIMP Ice-Cover Mask. We identify as local glaciers and ice caps (GIC) all ice masses essentially independent from the Greenland ice sheet with regard to their accumulation area and ice flow. Ambiguities can arise in some local settings, and overall we have been more conservative than Rastner et al. (2012) in splitting some ice masses adjacent to the ice sheet. In particular, our "disconnected ice masses" and "local ice masses" are comparable, respectively, to the CL0 and CL1 connectivity levels of Rastner et al. (2012), while their "strong connection" CL2 ice masses remain part of our "ice sheet" polygon.

## 2 Data sources

The ice-margin vectors in the PROMICE dataset derive from aerophotogrammetric maps at scales of 1 : 100 000 and 1 : 250 000, referred to as G100 and G250 in the following. It is worth noting that older datasets at the same scales have been published over the past decades, mostly under the G/100 and G/250 denomination. A detailed discussion of the origin of each dataset is beyond the scope of the present paper, but a historical overview can be found in Nielsen et al. (1995). These maps provide land-cover type, hydrology and elevation contour lines over the island of Greenland with the exception of the interior of the ice sheet, and are based on 1 : 150 000 scale vertical aerial photographs acquired between 1978 and 1987 (Fig. 1). The camera and lens were a Wild RC10 and Wild Super Aviogon-II with nominal focal length of 88 mm and film size of $230 \times 230$ mm. The maps were produced by GEUS (Geological Survey of Denmark and Greenland), formerly GGU (Greenland Geological Survey) using a Kern PG2 analogue stereoplotter and later a LH-Systems DPW digital workstation, and by KMS (Danish National Survey and Cadastre). KMS also surveyed the vast majority of geodetic ground control points.

Vectors based on GEUS and GGU aerophotogrammetric products and KMS ground control points have xyz error better than 10 m rms. KMS ground-control points were not available in the eastern part of Hans Tausen Ice Cap and Heinrich Wild Ice Cap (Peary Land), and in a N–S strip centred on Kejser Franz Joseph Fjord in East Greenland occasionally, resulting in a degraded horizontal accuracy of 30 m rms (W. Weng, personal communication, 2012). Maps over South-East and North-West Greenland were only available in raster format from KMS, and a larger error can be expected due to the additional digitisation step (Fig. 1, lines labelled as "KMS"). Part of these KMS scanned maps, particularly in NW Greenland, were produced using older aerial photographs than the 1978–1987 campaigns (Korsgaard, personal communication, 2012). With reference to the topological length of the lines defining the boundaries of the "ice" polygons, 98 % of the G100 source vectors are from the GEUS or GGU products, compared to 67 % for the G250 dataset. However, the latter provides for complete coverage of Greenland. Both scales have been used as source data for the compilation of the PROMICE dataset, and the source map and scale of each individual polygon is provided as metadata information.

## 3 Production of the PROMICE ice margin vectors

The original G100 and G250 surface land-cover polygons were checked out from the GEUS geospatial database in June 2010 and reprojected to a Lambert azimuthal equal area coordinate system in order to maintain equal-area properties over the large region. Gaps in the G100 coverage were filled in with data from G250. Supraglacial lakes were dissolved into the 'ice' polygons, while proglacial and ice-marginal lakes were excluded. Known surging glaciers were marked but not edited. Missing areas of debris-covered ice were included when possible. Frontal, lateral and occasionally medial moraines improperly mapped as 'land' were reclassified, based on the operator's interpretation of the topography and one or more snow-free satellite image. Landsat 4 to 7 and Terra ASTER imagery were obtained from http://glovis.usgs.gov and http://reverb.echo.nasa.gov on an as-needed basis. Typically, the satellite images would be significantly more recent than the original data. Therefore, care was exercised not to directly digitize features from the imagery, and the satellite scenes were only used as visual aids to correctly interpret the landscape. Manual editing was only undertaken for issues significant enough to justify the uncertainties involved in interpreting an older landscape based on a satellite image of much lower detail than the original aerial photographs.

Both G100 and G250 are tiled to match the extent of the paper map sheets, requiring adjacent polygons to be dissolved into single ice masses. The classification of ice masses into "disconnected ice mass", "local ice mass" and "ice sheet" described above was enforced at this stage by manually digitizing ice divides to split local ice masses topologically in contact with the ice sheet. The polygons were flagged accordingly. Elevation contour lines produced from the same aerophotogrammetric stereo pairs were used to digitize the

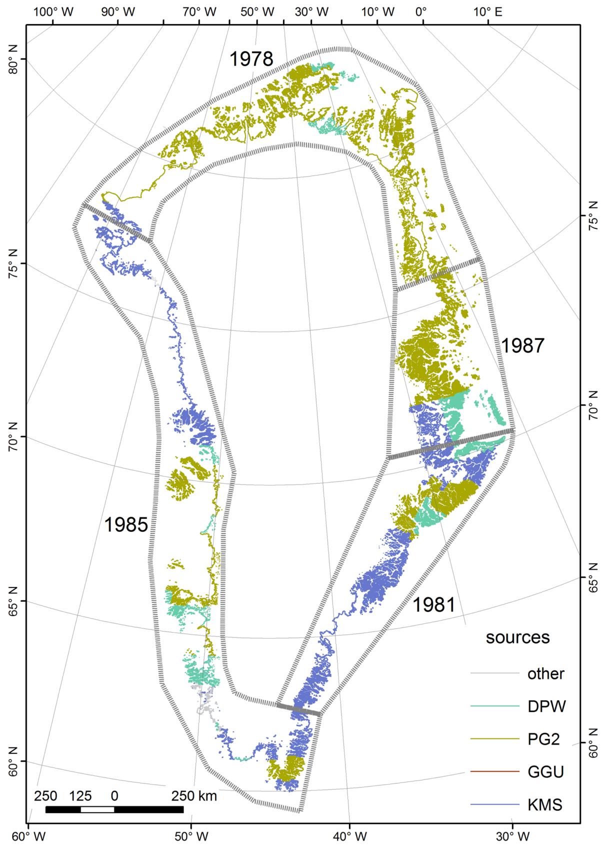


**Fig. 1.** Small-scale overview showing the margins of all ice masses in the PROMICE map, colour coded according to the data sources used to produce it (DPW: GEUS, digital workstation; PG2 GEUS, analogue stereoplotter, GGU: Geological Survey of Greenland, analogue stereoplotter, KMS: National Survey and Cadastre). The actual year and geographic coverage of each flight campaigns is shown. Especially in the north-west, and occasionally in other regions, vectors identified as "KMS" are based on aerial photographs older than 1978–1987 (see text for details).

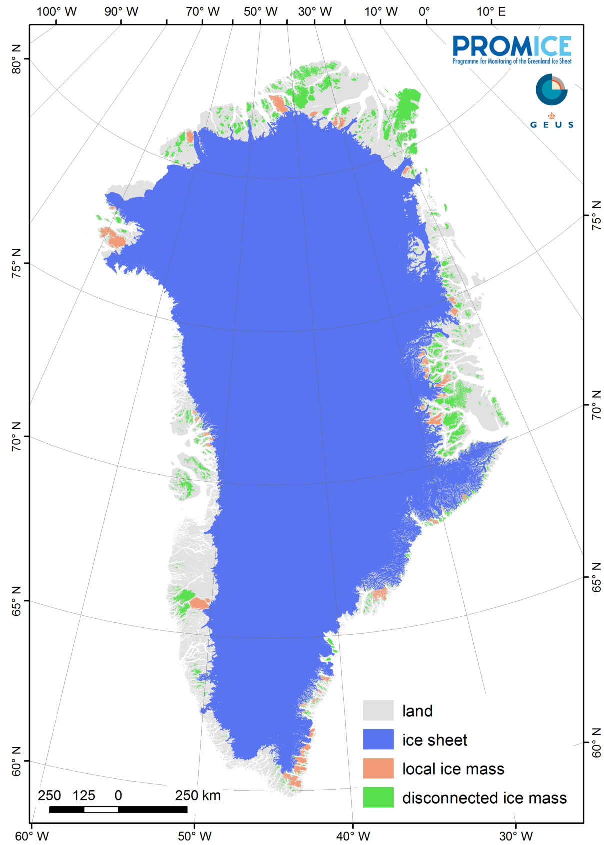


**Fig. 2.** Small-scale overview of the PROMICE aerophotogrammetric map of Greenland ice masses, colour coded according to our classification of "disconnected ice mass", "local ice mass" (collectively referred to as GIC in this paper) and "ice sheet".

ice divides. The final step was to calculate and store the area of all polygons, and to estimate the error, which was defined here as the area of a 10-m buffer around the entire perimeter of the ice masses, as discussed in the following section.

## 4 Accuracy considerations

We lack a suitable reference dataset to properly validate the PROMICE ice margins product. In this section we will therefore discuss the three error sources likely to be dominant.

The first source of uncertainty is the quality of the ground control points for the rectification of the aerial photographs. This limits the absolute geodetic accuracy of the mapped topologies, which is important when different datasets must be aligned. In the PROMICE dataset the absolute accuracy of the underlying photogrammetric map is preserved. Furthermore, area estimates are insensitive to constant offsets in the horizontal plane.

A second source of uncertainty is inherent in the tracing of the ice margin by the stereoplotter operator. It has been found that the digitizing accuracy on satellite imagery is comparable to the pixel size (Paul et al., 2012). The smallest resolvable detail in the 1978–1987 aerial photographs is about one order of magnitude smaller than Landsat 7 imagery, and the stereoplotter operator benefits from the stereoscopic view. It is therefore reasonable to neglect any stereoplotter operator tracing error when comparing the PROMICE ice margins derived from GEUS and GGU aerophotogrammetric data with anything of coarser resolution than SPOT-5. Bjørk et al. (2012) scanned the subset of 1981 and 1985 aerial photographs covering SE Greenland at an equivalent ground resolution of 2 m and produced a digital ortorectified mosaic with 4-m pixel size. They reported digitisation accuracy nominally equal to the 4-m pixel size.

The third factor limiting the accuracy of our product include the operator's bias toward mapping, e.g. seasonal snow as glacierized area, or debris-covered ice as land. This

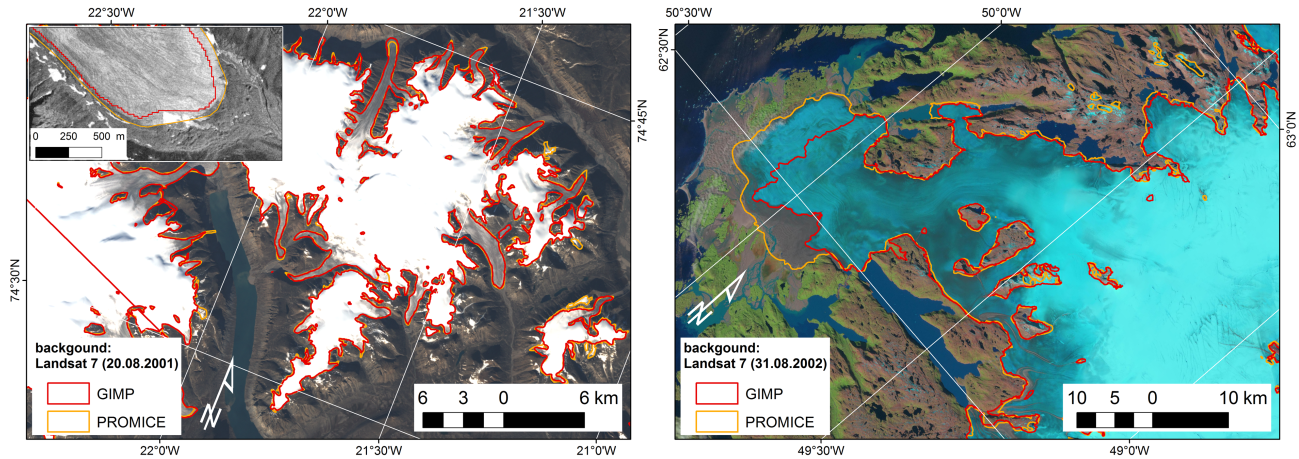


**Fig. 3. (A)** Overlay of the PROMICE and GIMP datasets showing advancing and retreating glacier termini at the A. P. Olsen ice cap (NE Greenland) between 1987 and ca. year 2000. The inset shows a detail view of a glacier terminus with the PROMICE and GIMP glacier outlines overlaid to the orthorectified aerial photograph from 1987. GIMP omits some smaller polygons included in the PROMICE dataset, and the partly frozen surface of the ice dammed lake is misclassified as glacier (visible to the east of the outlet glacier magnified in the inset); **(B)** comparison of PROMICE and GIMP ice margin polygons in the Frederikshåb Isblink area exemplifies the difficulty of properly classifying debris-covered ice in GIMP ver. 1.2. A substantial ($> 70\,\mathrm{km}^2$) sector of the terminus where no debris-cover exists is also omitted.

operator-dependent effect has the potential to introduce large systematic biases, and to produce regional patterns when the operator, snow conditions or image quality vary. This same issue exists in all semi-automatic workflows with manual editing and clean-up by an operator.

We conclude this section by suggesting that, at least for estimating the combined area of the local glaciers and ice caps, as well as the total glacierized area of Greenland, a conservative error estimate can be obtained by drawing a 10-m wide buffer around the entire perimeter of the mapped ice masses. A width of 10 m appears reasonable because it is intermediate between the expected digitizing accuracy of the stereoplotter operator (in the orders of a few meters) and the 15-m pixel size of the pan-sharpened Landsat 7 images used during the checking and editing of the G100 and G250 vectors.

## 5 Results

The final PROMICE ice margins vector product (Fig. 2) is a polygon layer depicting the shape of all the glacier-ice masses mapped in Greenland. Because of the underlying source data, it is diachronous (1978–1987) at the scale of the entire Greenland but essentially synchronous over large subareas of Greenland: either 1978 in the North-East, 1981 in the southeast, 1985 in the West or 1987 in the central East, with the North-West and some local areas mainly in South-West Greenland where source data from older flights and maps are included (Fig. 1).

Preliminary versions of the PROMICE dataset have been used to derive glacier length information (Leclercq et al., 2012), and to estimate a net combined area loss of $2560 \pm 260\,\mathrm{km}^2$ between the mid 1980s and 2011 (Kargel et al., 2012). To obtain this result, a preliminary version was updated using 250 m resolution MODIS imagery to summer 2011 at 128 sites of large observed change (primarily at tidewater outlet glacier termini).

Here, we calculate the total glacierized area including the ice sheet and all local glaciers and ice caps to be $1{,}804{,}638 \pm 2{,}178\,\mathrm{km}^2$, which do not include the area of nunataks. The Greenland ice sheet accounted for $1\,716\,555 \pm 947\,\mathrm{km}^2$ and the local glaciers and ice caps substantially independent from the ice sheet covered $88\,083 \pm 1{,}240\,\mathrm{km}^2$. Within the stated uncertainties, this GIC area is undistinguishable from the $89\,273 \pm 2767\,\mathrm{km}^2$ extent of "no and weak connection" CL0 + CL1 connectivity levels in Rastner et. al. (2012). Of all GIC glacierized area, $67\,143 \pm 1057\,\mathrm{km}^2$ belonged to ice masses completely separated from the ice sheet, which is comparable to the extent of $65\,474 \pm 2029\,\mathrm{km}^2$ covered by "no connection" CL0 ice masses of Rastner et al. (2012).

As a way to provide at least a qualitative impression of the PROMICE ice margin vectors, we overlay them to two Landsat 7 scenes and the highest detail dataset currently available for all of Greenland, the GIMP Ice Cover Mask ver. 1.2 available from http://bprc.osu.edu/GDG/icemask.php (Howat and Negrete, 2013). The GIMP mask is a 15 m pixel binary grid over all of Greenland based on Landsat 7 panchromatic band imagery and RADARSAT-1 Synthetic Amplitude Radar (SAR) from 1999 to 2001. Figure 3 shows two examples of overlaying the two raw datasets. The two locations were selected to display interesting features of the datasets. The two raw dataset align well, and significant changes can be detected. Figure 3a over A. P. Olsen ice cap in NE Greenland shows that the northern outlet advanced markedly since the 1987 aerial photographs (yellow line), while most other tongues retreated. It is also clearly visible that the GIMP dataset omits some relatively small polygons. Figure 3b displays a common issue with dark glacier surfaces not detected as ice, but also what seems to be an error clipping a significant portion of Frederikshåb Isblink.

## 6 Conclusions

The new PROMICE aerophotogrammetric map of Greenland ice masses is the only complete and high detail map documenting the margin of both the Greenland Ice Sheet and the surrounding local glaciers and ice caps in the 1980s. The total area covered by local glaciers and ice caps ($88\,083 \pm 1240\,\mathrm{km}^2$) is substantially larger than previous estimates (88 % more than the widely cited measure by Weng, 1995). The appearance of other high resolution and wide coverage glacier masks (Rastner, 2012; Howat and Negrete, 2013) capturing the position of the ice margins at the turn of the century will make it possible to detect glacier change over all of Greenland. The provided metadata must be used to properly account for diachronicity, especially in regions covered by KMS data.

The PROMICE dataset will be publicly available through the GLIMS (Global Land Ice Measurements from Space) Glacier Database. Future extension of the dataset may include metadata identifying the individual aerial photographs covering each polygon feature.

*Acknowledgements.* The authors acknowledge financial support from the Danish Energy Agency through the Programme for the Monitoring of the Greenland Ice Sheet (PROMICE). Comments by Richard S. Williams Jr., Bruce Raup and an anonymous reviewer in the open discussion, and by the scientific editor Dorothy K. Hall helped improve the manuscript. Niels J. Korsgaard (Natural History Museum of Denmark) and Willy Weng (GEUS) provided valuable information on the the temporal and spatial coverage of the input data. The GLIMS Project is acknowledged for providing access to ASTER data. Landsat 7 imagery is available from the US. Geological Survey. The GIMP dataset is available from Byrd Polar Research Center at the Ohio State University. Published with the permission of the Geological Survey of Denmark and Greenland.

Edited by: D. Hall

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