COMPARISON OF TM-DERIVED GLACIER AREAS WITH HIGHER RESOLUTION DATA SETS

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ABSTRACT

Within the new satellite-derived Swiss Glacier Inventory 2000 (SGI 2000) methods for automatic classification of glaciers and GIS-based extraction of glaciers and their 3D parameters from a DEM have been developed. Here, glacier areas derived from Thematic Mapper (TM) are compared to data from the 1973 Swiss glacier inventory and higher-resolution satellite imagery, in order to achieve two objectives: (a) analysis of the change in glacier area with pixel size and (b) evaluation of the accuracy of TM-derived glacier areas. Investigation (a) reveals a minimum glacier size suitable for comparison with the 1973 inventory, for a given sensor resolution and standard deviation (σ) (e.g. 0.1 km^2 for a 25 m pixel and σ below 3%). The area comparison (b) between SPOT and TM for 28 debris-free glaciers yields no significant differences.

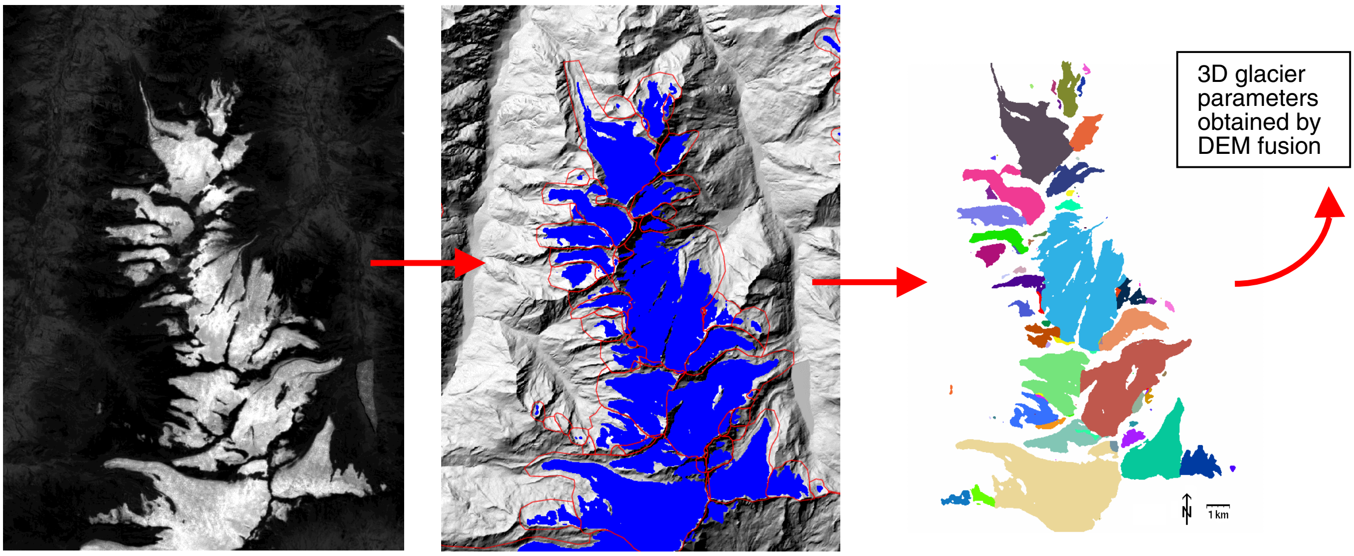
INTRODUCTION

Landsat TM data are widely recognized as highly valuable for glacier mapping (1, 2, 3). The large area covered (180 by 180 km) in combination with the high-spatial resolution of the sensor (30 m) enables accurate monitoring of even small alpine glaciers in large and remote areas (4, 5). This is also utilized in the world-wide effort of the USGS-led project GLIMS (Global Land Ice Measurements from Space), which aims at compiling a new global glacier inventory from space, mainly using the sensors ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer) on board Terra and ETM+ (Enhanced Thematic Mapper Plus) on board Landsat 7 (6). In this context, the SGI 2000 serves as a GLIMS pilot study by investigating the methods required for automated glacier mapping from TM data in a GIS environment (7, 8). The low reflectivity of snow and glacier ice in the middle infrared part of the spectrum allows glacier classification from segmentated TM band 4 and 5 ratio images (Fig. 1a), usually with a threshold near 2.0 (Fig. 1b). A comparison with results from other classification methods has shown that this method is best-suited with respect to the accuracy obtained and time exposure (9). For best results the threshold value should be selected interactively in regions with snow or ice in cast shadow, where the value is most sensitive. Apart from accurate orthorectification, further pre-processing (e.g. sensor calibration or atmospheric correction) is not required, as the method works best with the raw digital numbers. In Fig. 1c individual glaciers are shown after GIS-based intersection with glacier basins.

Within the SGI 2000, TM-derived glacier areas are compared to higher-resolution data sets such as the digitized 1973 inventory (which is originally derived from aerial photography) and SPOT pan imagery. This implies a possible difference in area for the same glacier if observed with different resolutions (or pixel sizes). Thus, the first part of this study will show the influence of sensor spatial resolution on glacier area by means of a GIS-based simulation. In the second part the comparison of TM-derived glacier outlines with higher-resolution satellite data is presented.

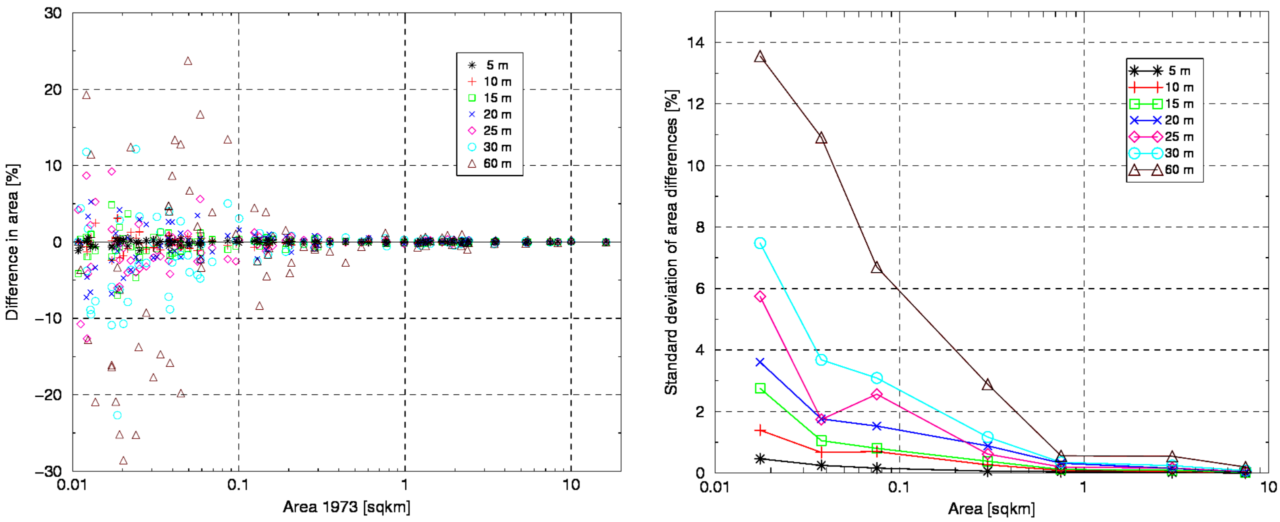
Influence of sensor spatial resolution

As glaciers are natural objects, their dimension is fractal and their area or perimeter depends upon the size of the yardstick used (10, 11). In order to assess how a change in spatial resolution will alter the glacier area, the vectorized glacier outlines are resampled to the following simulated cell sizes (corresponding sensor in brackets): 5 m (IRS-1C pan), 10 m (SPOT pan), 15 m (ASTER / ETM+ pan), 20 m (SPOT Xi), 25 m (TM, resampled), 30 m (TM, nominal), and 60 m (MSS, resampled).



a) b) c)

Figure 1: Glacier mapping with Landsat TM and a GIS. a) Ratio image from TM4 / TM5, b) derived glacier map after thresholding (blue) and overlay with digitized basins (red). Elevation data: DEM25, © Swiss Federal Office of Topography (DV002263.1), c) Individual glaciers after basin intersection (colour-coded) ready for DEM-fusion.



a) b)

Figure 2: a) Relative differences in glacier area between the digitized inventory and seven different sensor resolutions versus glacier area. b) Standard deviations of the area differences for seven area classes and seven sensor resolutions. Both graphs use the same data set with 102 glaciers of the Mischabel mountain range.

The relative difference between the digitized area and the resampled area versus glacier size is depicted in Fig. 2a for 102 glaciers of the Mischabel mountain range. Glacier size is in logarithmic scale (x-axis) to show values for smaller glaciers more clearly. For glaciers larger than 0.5 km^2 the scatter and the differences are very small, even for the 60 m pixel size. Scatter and absolute values, however, increase towards smaller glaciers, revealing a smallest appropriate glacier size in comparison with the digitized inventory, if area difference and sensor resolution is prescribed. For Fig. 2b glaciers are grouped into seven area classes and standard deviations (σ) of the area differences are calculated for each class. For TM-sized pixels (25 m) σ is below 3% if glaciers are larger than about 0.05 km^2. If ASTER-sized pixels can be used (15 m), σ is below 1% for such glaciers. As results may differ in other regions, a smallest glacier size of 0.1 km^2 is recommended for comparison of TM-derived areas with glacier inventory data derived from aerial photography.

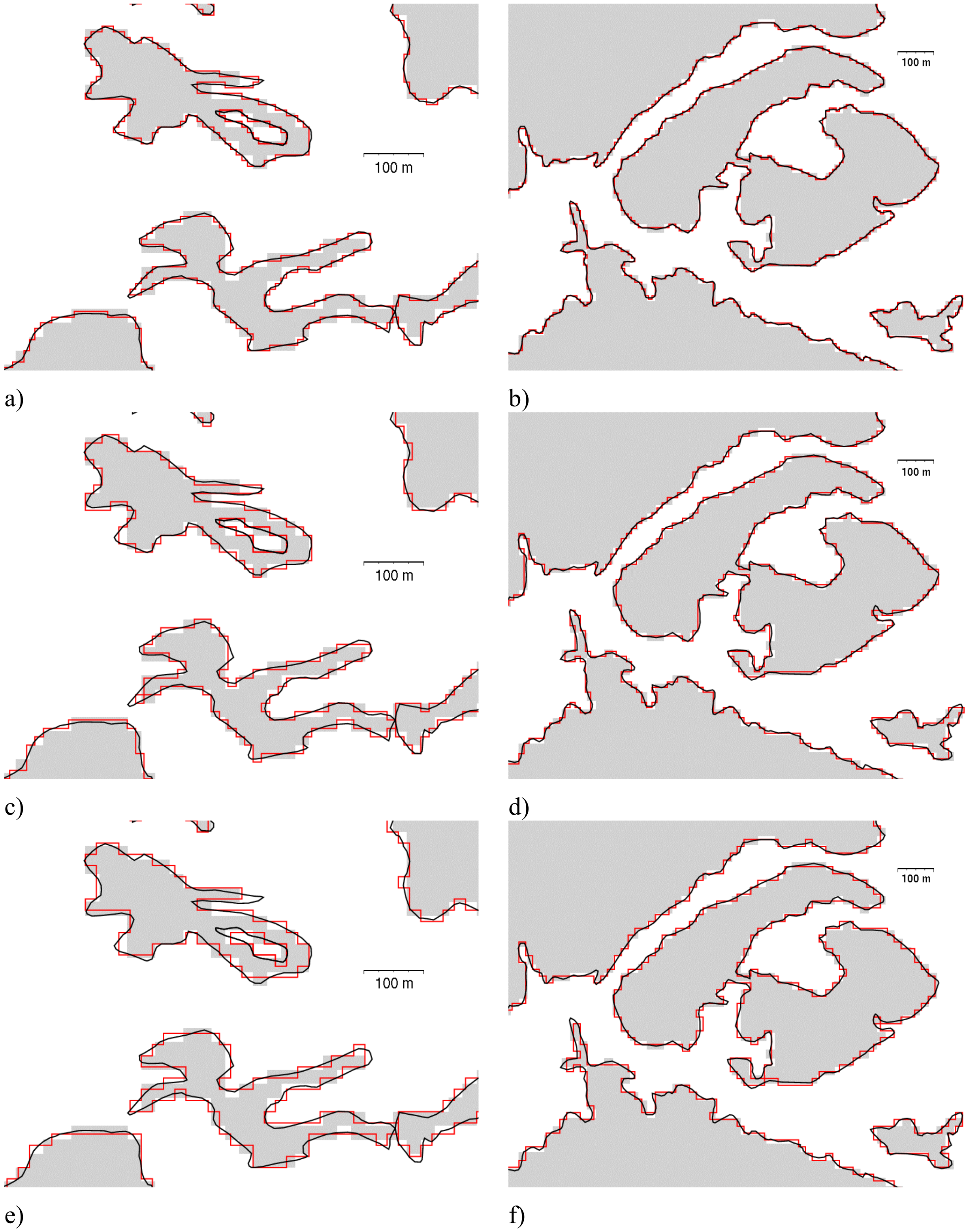


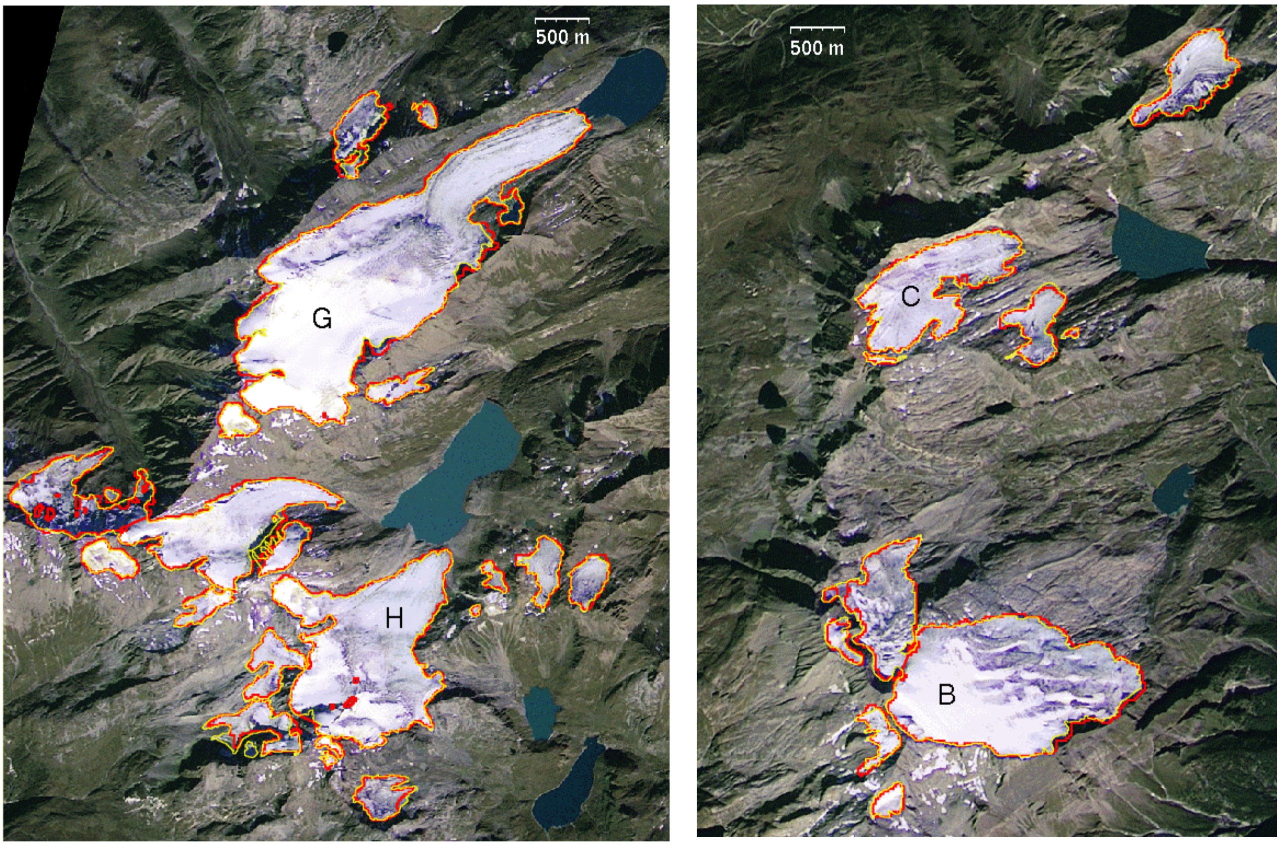
Figure 3: Overlay of glacier outlines as seen with different (simulated) spatial resolutions. The example in the left column shows two glaciers which are 0.04 km^2 in size, the connected glacier in the right column is 0.3 km^2 in size. The black outline is from the digitised 1973 glacier inventory, the grey areas result for a 25 m cell size (such as TM) and the red outlines represent 10 m (a and b), 15 m (c and d) and 20 m (e and f) cell size.

In order to illustrate the loss of fine spatial details with decreasing sensor resolution, six overlays are shown in Fig. 3 for glaciers of two different sizes (left column: each glacier is 0.04 km^2 in size, right column: the connected glacier is 0.3 km^2). In all images the grey areas represent 25 m pixels (TM), the black line is the digitised outline, and the red line depicts 10 m, 15 m and 20 m pixels. In particular the two small glaciers (left column) clearly demonstrate the limitations of a coarser pixel size. To resolve such fine details or complex structures, 15 m pixel sensors are required at minimum. Only if glaciers are more compact even 25 m resolution may be sufficient. If only glaciers larger than 0.1 km^2 are considered a fairly safe threshold is defined.

Comparison with high-resolution sensors

In this section we discuss the application of real satellite imagery with three different sensor resolutions to compare with TM-derived data. In general, image selection for glacier mapping is guided by: (a) acquisition at the end of the ablation period, (b) cloud-free conditions, and (c) lack of snowfields adjacent to glaciers. Thus, the number of available TM-scenes for glacier monitoring in the Alps since 1984 is rather limited (also considering the 16 days repeat cycle of Landsat). In order to facilitate comparison with other sensors snow conditions must be similar.

Automated glacier mapping from space depends on a spectral band in the middle infrared part of the spectrum (1, 12) and, thus, manual glacier delineation is the only possibility with all high-resolution panchromatic sensors. In order to enhance visibility of glacier boundaries, fusion by means of an RGB-IHS colour-space transformation with TM bands 1 to 3 is performed for SPOT and IRS-1C before the delineation, resulting in natural coloured 10 m pixel sized images. Debris-cover delineation according to the TM image is somewhat tricky, since mixed pixels are also mapped correctly by TM as 'glacier' but to a varying extent.



a) b)

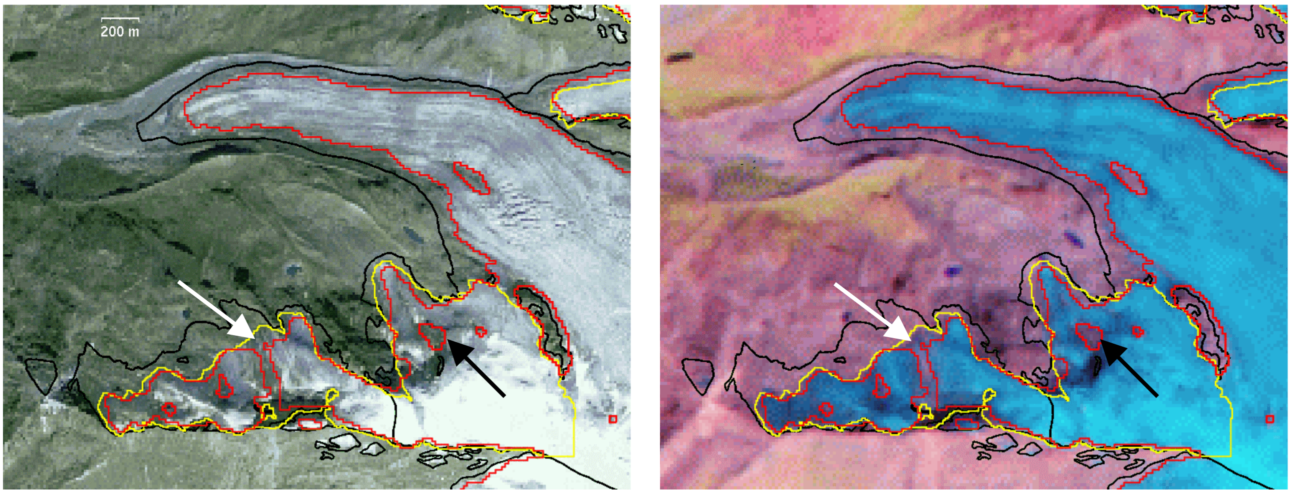
Figure 4: Overlay of glacier outlines digitized manually (yellow) and derived from TM (red) on a fused SPOT pan / TM image as background. a) Showing Gries (G) and Hohsand glacier (H) and b) with Cavagnoli (C) and Basodino glacier (B). SPOT data: © SPOTIMAGE.

Comparison with SPOT pan

This comparison uses a TM image from 15 September 1992 and a SPOT pan image acquired only two days later. For 28 glaciers located to the south of the 'Nufenenpass', manual delineation is carried out on the fused SPOT / TM image. Figure 4 displays the overlay of SPOT and TM-derived outlines. On average, the areas derived manually from SPOT are 1.7% smaller compared to TM (σ = 8.4%). As this value for σ is much larger than obtained from the theoretical assessment (comparing 10 m and 25 m resolution), the deviation cannot only be the result of the differing image scales. Moreover, the error is not from TM, because the area difference does not depend on glacier size (r= -0.03). Thus, the manual glacier delineation process must be responsible for the differences. In particular the wrong interpretation of snowfields and rock outcrops may cause deviations.

Comparison with IRS-1C

An IRS-1C image from 20 September 1997 with 5 m spatial resolution is re-sampled to 10 m and fused with a TM image from 31 August 1998. Manual glacier delineation is performed for about 30 glaciers of the Mischabel mountain range. The overlay of various outlines is displayed for a sub-set in Fig. 5a (fused image as background) and Fig. 5b (TM 543 composite) with the tongue of the Findelen glacier and some small glaciers facing north. Debris-covered glacier areas are not mapped with TM (white arrows), but also manual glacier delineation encounters problems, as correct interpretation of rock outcrops is difficult (black arrows). Since there was also some glacier retreat between 1997 and 1998 (in other regions), a quantitative error assessment is not carried out.

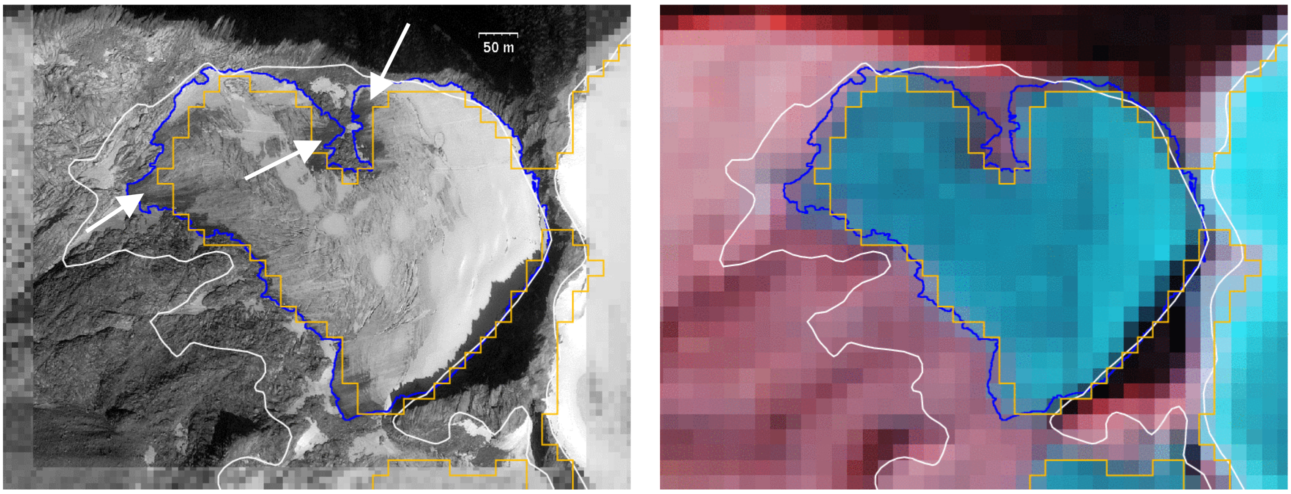


a) b)

Figure 5: Overlay of glacier outlines from the digitized 1973 glacier inventory (green), from IRS-1C (yellow) and from TM (red). a) The fused IRS-1C/TM image is used as background and in b) a TM 5, 4, 3 (as RGB) composite image is used. IRS-1C data: © NPOC.

Comparison with Ikonos

An Ikonos image with 1 m spatial resolution from 17 September 2000 is used for manual delineation of six small glaciers near Trift- and Rhoneglacier. Most of the small glaciers in the Ikonos image cannot be used for delineation, because snowfields hide the glacier perimeter. The glacier in Fig. 6 is 0.23 km^2 in size and shown together with the outlines from the digitised glacier inventory of 1973 (white), from Ikonos (blue) and from the TM-image (orange), which is acquired on 31 August 1998. From Fig. 6a (overlay with Ikonos), it is obvious that debris-covered glacier areas are not (or only partly) mapped with TM (white arrows), which is also confirmed in Fig. 6b (overlay with TM 543 composite) showing some bluish pixels outside the mapped perimeter. Apart from that, the overall correspondence with the Ikonos outline is satisfying.



a) b)

Figure 6: Overlay of outlines from the digitized 1973 glacier inventory (white), from Ikonos (blue) and from TM (orange). a) The Ikonos image as background and b) a TM 5, 4 and 3 (as RGB) composite image as background. Ikonos data: © Spaceimaging Europe / NPOC.

CONCLUSIONS

The comparison of glacier areas from different (simulated) sensor resolutions reveals: a smallest glacier size can be calculated if sensor resolution and standard deviation (σ) of area differences is prescribed. With σ = 3% the values obtained in this study are (resolution / minimum useful glacier size (in km^2)): 5 m / all, 10 m / 0.01, 15 m / 0.03, 20 m / 0.05, 25 m / 0.1, 30 m / 0.2, 60 m / 0.5. The comparison with higher-resolution satellite imagery reveals: (a) an overall good correspondence of the TM-derived glacier outlines with the manual delineation, (b) mapping of debris-covered glacier ice is not possible with TM data alone, and (c) also manual glacier delineation is problematic in the case of debris cover or snowfields. For the SGI 2000 the following conclusions are drawn:

- efficient and automated glacier mapping is possible with thresholded TM4 / TM5 ratio images,
- the accuracy achieved is sufficient for a glacier inventory (apart from debris-covered ice),
- the comparison of TM-derived glacier outlines with glacier inventory data should be restricted to glaciers larger than 0.1 km^2.

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