USING AIRBORNE LASER SCANNER DATA FOR A GLACIER INVENTORY

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ABSTRACT
The IPCC depicts in its fourth assessment report that the behavior of glaciers is influenced by climatic conditions which are – among others – controlled by the emission of greenhouse gases. Monitoring glaciers can give valuable insights on glacier changes affecting the local economy, natural hazards and water supply. The spatial extent of glaciers can be half-automatically monitored with the help of raster data calculated from Airborne Laser Scanning (ALS) point data. Another feature could be the generation of mass balances of entire glacierized areas using two different ALS datasets.
The delineation of glacier outlines can be derived from ALS data by setting up a classification of the elevation model into the classes “glacier” and “non-glacier” area. The topographical smoothness as calculated from the ALS data is used as one classification criterion. The necessary data were acquired for the whole Southern Tyrolean Area, Italy, in the year 2005. The area of the Southern Stubai Alps in the north of Southern Tyrol was chosen for testing the algorithms because several different glacier types such as valley and mountain glaciers or glacierets can be found in that region. After identifying these glacier outlines the next step is to calculate the parameters of the glacier inventory based on the guidelines of the World Glacier Monitoring Service. The result is a highly accurate glacier inventory based on ALS raster data, which is methodically transferable to all regions in the world where such datasets are accessible.

Keywords: **glacier, glacier inventory, cryosphere, climate change, airborne laser scanning**

1. Introduction
As Hans Kinzl (1958) noted, glaciers are excellent climate indicators whose existence depend on climatic conditions of a mountainous region (e.g. Haeberli 1990 and 1994, Oerlemans 1994, IPCC 2001 and 2007). They are interesting phenomena to scientists, mountaineers, tourists and the people living in these glacierized areas. Worldwide, glaciers are important for the local economy, hydropower generation and water supply. The fluctuations of glaciers appear to be good indicators for the climate change (e.g. Oerlemans 1994, Paterson 1994, IPCC 2001, IPCC 2007).
Beside photogrammetry ALS has become one of the standard methods for the acquisition of topographic data for many applications in the last decade (i.e. Ackermann 1999). The method of Airborne Laser Scanning is characterized by a large degree of automation in terms of data recording and computer-aided data analysis methods, both, in Open Source e.g. with GRASS GIS or Windows-based e.g. with ArcGIS (Geist et al. 2003). With ALS, data can be recorded under meteorological conditions that are too poor for aerial photogrammetry (Albertz 2001).
Using ALS for glaciological purposes is still not as common (e.g. Favey et al. 1999, Favey 2001, Kennett and Eiken 1997, Geist and Stötter 2002, Geist et al. 2003, Lutz et al. 2005, Kodde et al. 2007) as in other fields of research. Some experiences using the techniques of laser profiling have been made in Greenland (e.g. Forsberg et al. 2001, Garvin and Williams 1993, Krabill et al. 2000, Krabill et al 2002, Rignot et al. 2004, Thomas et al. 2000) and in Alaska (e.g. Abdalati et al. 2004, Adalgeirsdottir et al. 1998, Echelmeyer et al. 1996, Sapiano et al. 1998) partially by the NASA.
In Europe, a few attempts have been made to utilize ALS for glaciological purposes (e.g. Baltsavias et al. 2001, Favey 2001, Favey et al. 2002). The Institute of Geography at the University of Innsbruck has also put an emphasis on researching the capabilities of ALS in glaciology in recent years (e.g. Geist and Stötter 2002, Lutz et al. 2003, Geist et al. 2003, Würländer et al. 2004, Geist et al 2005, Bucher et al. 2006, Lippert et al. 2006).

2. Data acquisition and data processing
All glaciers in the research area of the southern parts of the Stubai Alps in Southern Tyrol (see Figure 1) are located in high mountain regions which entails certain problems for the application of ALS. The rugged topography of these areas with large differences in the relief can cause serious troubles on ALS systems with a limited laser range, point density and spectral resolution for the data acquisition (e.g. Albertz 2001, Geist et al. 2003, Lutz et al. 2003).

The area of interest for this research comprises the entire glacier and remote firn areas. As this study is a derivative of an already existing algorithm of Kodde et al. (2007) it was necessary to adapt this so called “l.delineation algorithm” so that it works not just for a single glacier but for all possible glaciers in a raster data file.

Datasets were acquired using the "Optech" and the "Terrasys" scanner systems. Unfortunately detailed information about scanner types and their respective scanning areas, mean flying altitude, minimum or maximum slant range are not available for the raw data. An average point density of 8 points per 25 square meters for areas below 2000 m a.s.l. and 3 points per 25 square meters for areas above 2000 m a.s.l. was achieved. The vertical accuracy over a control area was s = 0.095 m. The full information of the collected data, i.e. information for first pulse, last pulse and intensity, will be stored in a separate dataset that has not been released and is not available for research yet.

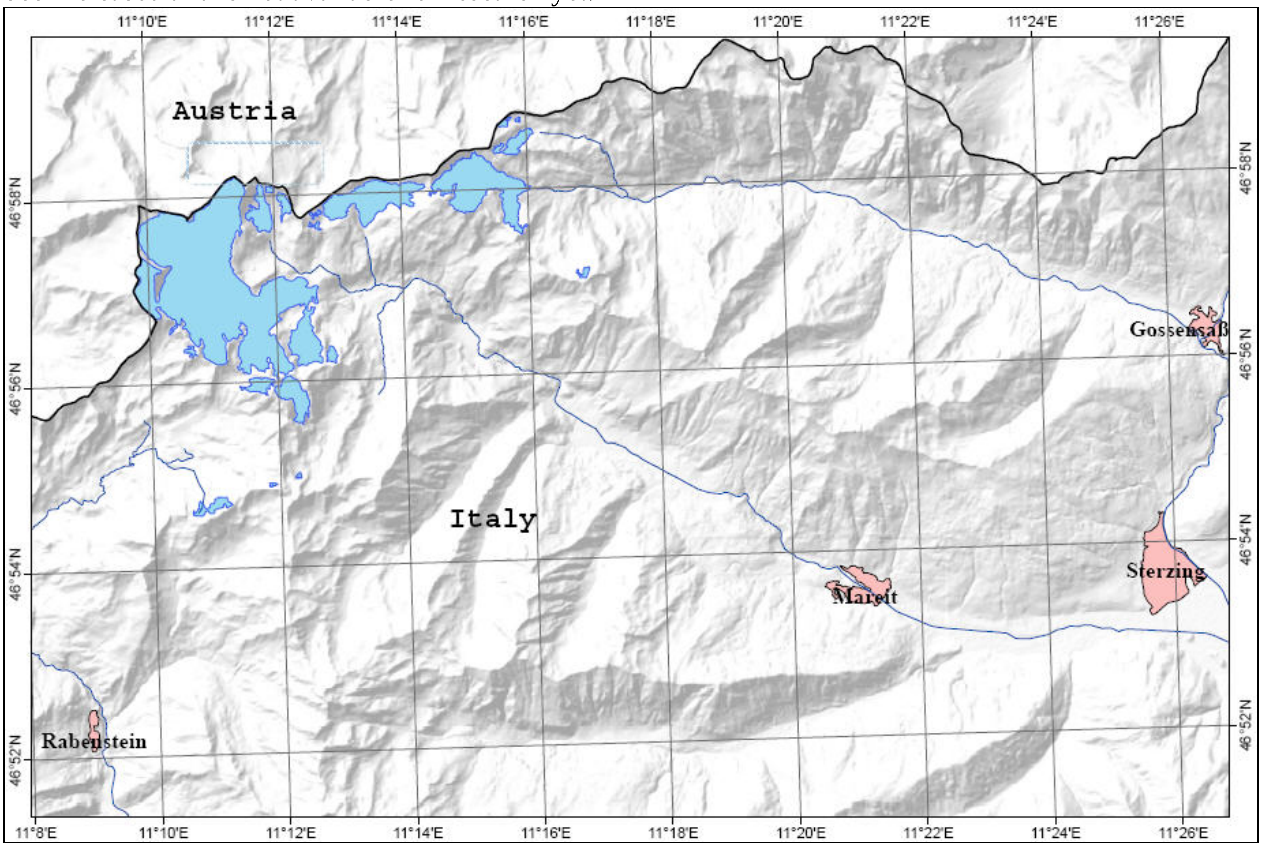

Figure 1: Research area in southern Stubai Alps, Southern Tyrol, Italy.

The digital elevation model (DEM) used is a 2.5m raster dataset of Southern Tyrol which is calculated out of ALS point data using a nearest neighbor interpolation method on the last pulse returns. These resulting raster data forms the input for the algorithms presented in the following sections (Kodde et al. 2007). The scanning flight took place in the end of summer of the year 2005 with an elevation accuracy of 0.4m below 2000m a.s.l. and 0.55m above 2000m a.s.l. This gives a sufficient accuracy for further calculations. For the correction of the glacier outlines ortho-images of the survey period of the year 2006 were used as for the recording year of the DEM no ortho-images are available.

3. Methodology

3.1. Detection of glacier boundaries

As the term “glacier” is ambiguous a clear definition was chosen. UNESCO (1970) defined glaciers as “a mass of ice with a minimum size of 1 hectare”. For the identification of debris-covered parts of the glaciers, the surface shape and roughness of the Laserscan DEM, as well as a hillshade of the Laserscan DEM and existing ortho-images were used. The final identification and correction of the glacier boundaries was done manually using the ESRI ArcGIS Software.

The glacier delineation was calculated with a GRASS GIS using the operating system LINUX. In Figure 2 the workflow is pictured. First the raster datasets of the DEM had to be imported into the GRASS database and the regions of the raster data had to be set for each raster tile to improve speed. In a second step the glacier delineation algorithm of Kodde et al. (2007) was improved in a way that it was possible to set the minimum size of a glacier to 1 hectare and to calculate all possible glaciers on a raster tile and not just the biggest one. The original algorithm was tested on Hintereisferner in the Ötz Valley, Austria, on a 1m raster dataset with good results (Kodde et al. 2007) but the improved algorithm worked on the 2.5m raster dataset of Southern Tyrol as well. The main difference is that the accuracy for the algorithm is limited by the raster size of the DEM but this loss of accuracy was corrected in the use of the ortho-images for the correction of the glacier outlines.

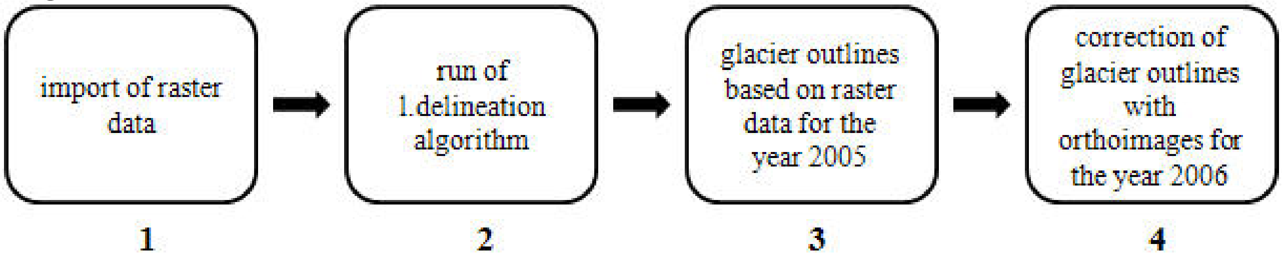

Figure 2: Workflow for a possible glacier inventory

The results of the improved algorithm (red in Figure 3) are good but not accurate enough especially in the ablation areas and so the results of the derivation were corrected with the ortho-images of the year 2006 (green in Figure 3).

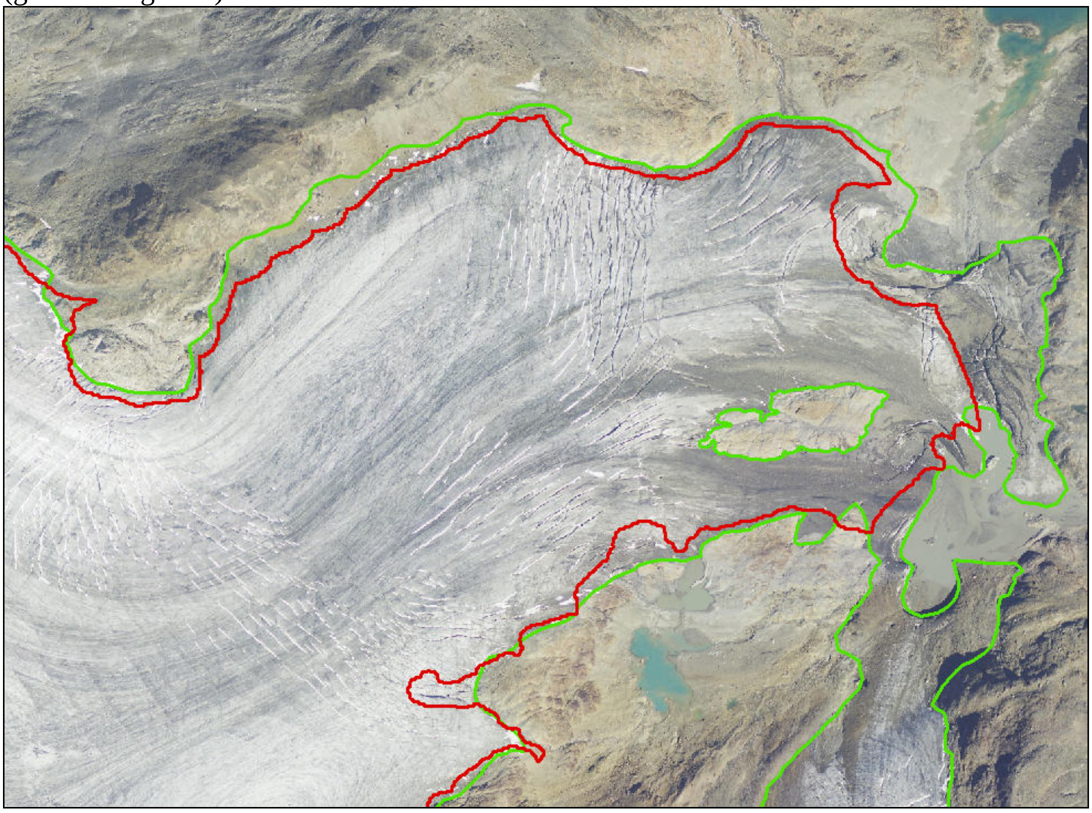

Figure 3: Results of l.delineation in the lower parts of the glacier (red) and their correction (green).

For the recording year of the DEM no ortho-images are available. So the glacier outlines were transformed into an ESRI polygon shapefile to import it into ESRI ArcGIS in work step 4. After importing the shapefiles into ESRI ArcGIS the glacier outlines were checked against the hillshade which was calculated from the DEM and the corresponding ortho-images. This has been done for the test area in the southern part of the Stubai Alps of Southern Tyrol. There the glaciers are located in the catchments of the Ridnaun Valley (including the Uebeltal Ferner, the largest glacier of Southern Tyrol), the Timmels Valley and the Pflerscher Valley.

The corrected glacier boundaries were used in ESRI ArcGIS, including additional information like drainage area, identification number, glacier name, glacier area, aspect of the ablation area, etc. Once the DEMs and the glacier boundaries had been determined additional information such as masks for individual glaciers, area–elevation distributions, minimum, maximum and mean elevation of the glaciers could be derived.

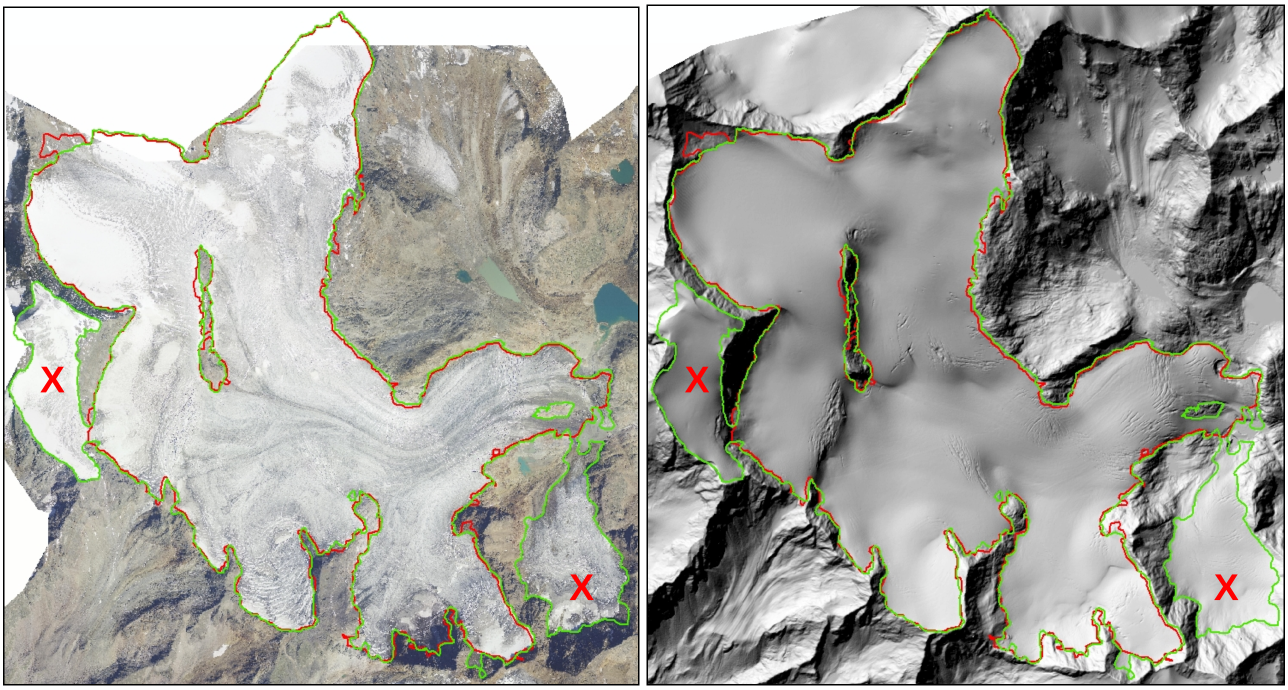

Figure 4: Results of the l.delineation algorithm (red) and the correction via ortho-images and hillshades (green).

3.2. Problems with the results of the l.delineation algorithm

This study is an advancement of the work of Kodde et al. (2007) but certain problems still remain unsolved. As the glacier delineation is based on criteria like the smoothness of the surrounding pixels, the connectivity and hydrological constraints (Kodde et al. 2007) it is still not possible to detect crevasses as parts of the glacier so human supervision is necessary to check against and correct errors. It has been the first time that this algorithm was tested for more than one glacier and for more glacier types than just the valley glacier. Good results were achieved for all three glacier types (valley glacier, mountain glacier and glacierete) that appear in the Southern Tyrolean Alps.

However the reconstruction of Uebeltal Ferner shows the main problem which needs further improvement. The results of the algorithm (red in Figure 4) are good but two extensive parts (see X in Figure 4) that enter the main glacier via crevasses are not identified as parts of a glacier. The corrected glacier extent (green in Figure 4) shows a result for the glacier that is just limited in its accuracy by the resolution of the raster dataset and the ortho-images.

4. Glacier development in the research area

4.1. Comparison of different datasets

The glacier inventory data for the year 1983 is not available digitally so a direct comparison and quantification of the glacier changes for that year is not possible. There are also no information available which glacier definition was used and if the firn boundaries are included.

For the inventory of the year 1996 shapefiles and tables are available. These shapefiles have been calculated by the Technical University of Munich under supervision of Hermann Rentsch via a Plancomp P1 system using aerial photographs of the year 1996.

For 2007 the situation is completely different. The whole dataset of the research area was calculated by the Institute of Geography at the University of Innsbruck and is described in chapter 3. The results of the inventory are shapefiles and tables.

4.2. Glacier changes between 1983, 1996 and 2006

In line with a global trend glacier recession in the area of investigation is dramatic and shows problems in compiling glacier inventories. A comparison of the three inventories (1983, 1996 and 2006) is difficult because of the multiple parting of a initially continuous ice mass. The biggest glacier in Southern Tyrol, the Uebeltal Ferner, split up into four parts of different sizes. In order to compare the three inventories it is necessary to consider all parts of the former glacier as one big ice mass. Each glacier has a worldwide unique inventory number and with this number the glaciers haven been dissolved in ESRI ArcGIS. A count of these

numbers a total of 25 glaciers in the research area for the year 1983. A count for 2006 gives a sum of 13 glaciers so in the last 23 years 12 glaciers collapsed and melted.
The analysis for the three different datasets shows an overall glacier area reduction of 26.3 %, from 14.3 km² to 10.5 km², for the period from 1983 to 2006. In the first 13 years from the first glacier inventory 1983 to the second inventory 1996, the loss was bigger (17.5% from 14.3 km² to 11.8 km²) than in the last ten years from the inventory of 1996 to new third glacier inventory of 2006 for the research area (10.7 % from 11.8km² to 10.5 km²). Our results show large variations for the extent of small glaciers (< 0.12 km²). These glaciers lost more than 75% of their area in average. For the larger glaciers (>0.12 km²) the mean area loss was 31%. Similar observations for small glaciers have been made by Lambrecht and Kuhn (2007) for the new Austrian glacier inventory and Paul et al. (2004) for the new Swiss glacier inventory.
A comparison of the area-elevation distribution is only possible for the glacier inventory 1996 and the inventory of the research area 2006 (Figure 5) as area-elevation distribution data for the year 1983 is missing. The results show the maximum glacierized area at elevations of 2700 - 2800 m for both, 1996 and 2006. The largest loss of area is between 2600 m and 2900 m where together 1.15 km² of glacier ice got lost.

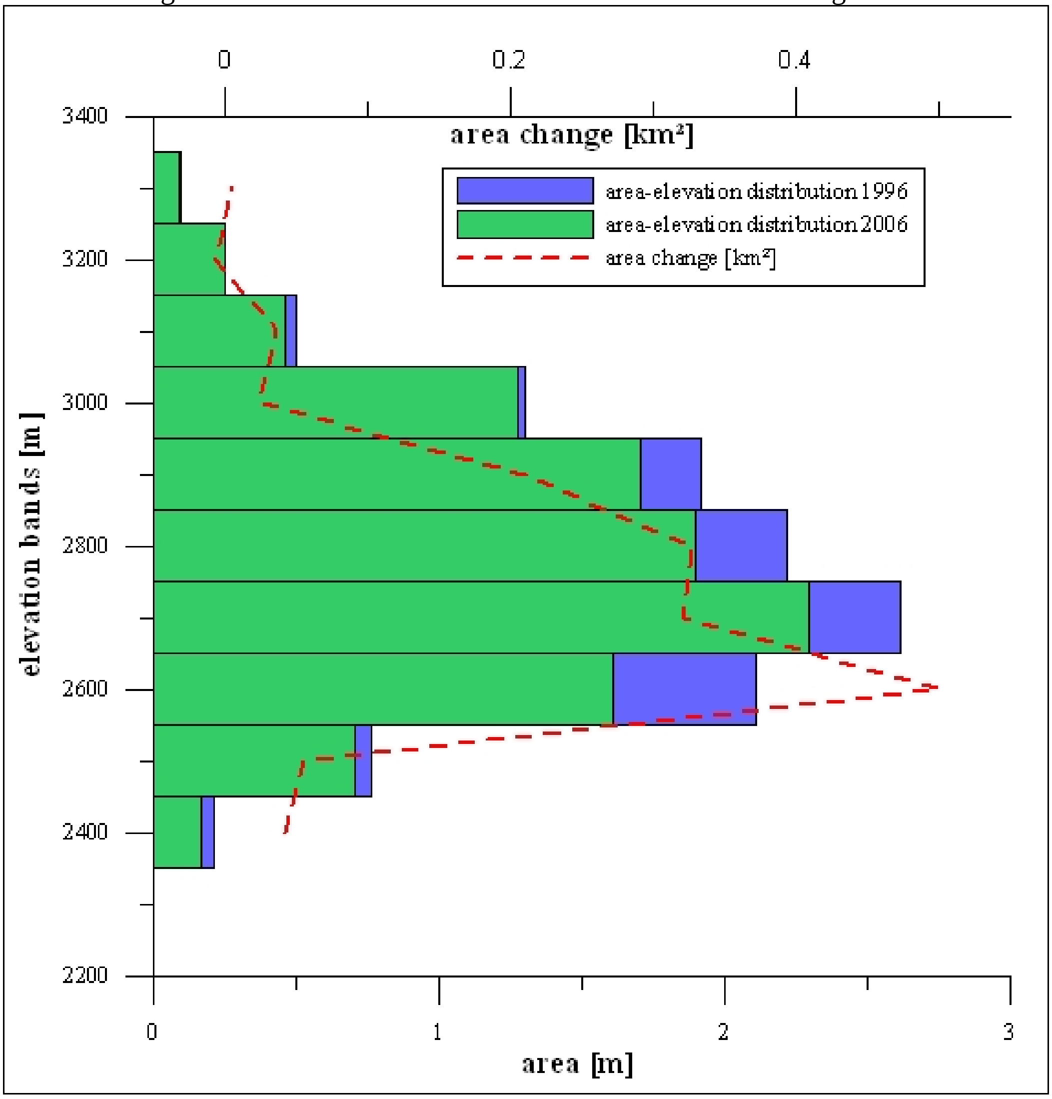

Figure 5: Area-elevations distribution for 1996 (blue) and 2006 (green) and the absolute area change between the two inventories in 100m elevation bands.

The mean glacier elevation in 1996 has been in an altitude of 2861 m. This elevation represents a change of 1.9 % to the year 2006 (2915 m).

5. Conclusions and perspectives

With the presented method a good and reliable tool for monitoring glaciers and their extent based on ALS data and ortho-images is created and it is also an excellent basis for further investigations. The accuracy is limited to the pixel size of the ALS raster data and the ortho-images.

One important conclusion can already be drawn. The glaciers in the research area of the Southern Stubai Alps are endangered by the worldwide processes of global warming. These glaciers have only a small height extension of three elevation bands or 300 m in average but this is also valid for almost all glaciers in Southern Tyrol. During the last 23 years glaciers have shown a strong reduction of area and number. 12 of them have melted, some of them have shrunken to an extension that is per definition not a glacier anymore and some are endangered of degeneration. Almost all elevations are affected by the melting process but elevations between 2600 m and 2900 m are especially affected. If the climatic conditions stay as how they are only the largest glaciers like the Uebeltal Ferner will survive.

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