Tracing glacial disintegration from the LIA to the present using a LIDAR-based hi-res glacier inventory in Austria

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Abstract

Glacier inventories provide the basis for further studies on mass balance and volume change, relevant for local hydrological issues as well as for global calculation of sea level rise. In this study, a new Austrian glacier inventory has been compiled, updating data from 1969 (GI 1) and 1998 (GI 2) based on high resolution LiDAR DEMs and orthophotos dating from 2004 to 2012 (GI 3). To expand the time series of digital glacier inventories in the past, the glacier inventory of the Little Ice Age maximum state (LIA) has been digitalized based on the LiDAR DEM and orthophotos. The resulting glacier area for GI 3 of 415.11±11.18 km² is 44% of the LIA area. The annual relative area losses are 0.3 %/year for the ~119 year period GI LIA to GI 1 with one period with major glacier advances in the 1920s. From GI 1 to GI 2 (29 years, one advance period in the 1980s) glacier area decreased by 0.6 %/year and from GI2 to GI 3 (10 years, no advance period) by 1.2 %/year . Regional variability of the annual relative area loss is highest in the latest period, ranging from 0.3 to 6.19 %/year. The specific glacier sizes decreased from LIA to the latest period, so that 47% of the glaciers are smaller than 0.1 km² in GI 3.

1 Introduction

The history of growth and decay of mountain glaciers affects society in the form of global changes in sea level and in the regional hydrological system as well as through glacier-related natural disasters. Apart from these direct impacts, the study of past glacier changes reveals information on palaeoglaciology and, together with other proxy data, palaeoclimatology and thus helps to compare current with previous climatic changes and their respective effects.

Estimating the current and future contribution of glacier mass budgets to sea level rise needs accurate information on the area, hypsography and ice thickness distribution of the world's glacier cover. In recent years the information available on global glacier cover has increased rapidly, with global glacier inventories compiled for the IPCC Report 2013 (Vaughan et al., 2013) complementing the world glacier inventories (WGMS, 2012) and the GLIMS initiative (Kargel et al., 2013). These global inventories serve as a basis for modelling current and future global changes in ice mass (e.g. Gardner et al., 2013; Marzeion et al., 2012; Radić and Hock, 2011). Based on the glacier inventories, ice volume has been modelled with different methods as a basis for future sea level scenarios (Huss and Farinotti, 2012; Linsbauer et al., 2012; Radić et al., 2014). On a regional scale, these glacier inventory data are used for calculating future scenarios of current local and regional hydrology and mass balance (Huss, 2012). All this research is based on the most accurate mapping of glacier area and elevation at a particular point in time.

For large-scale derivation of glacier surfaces, satellite remote sensing methods are most frequently applied (Paul et al., 2010, 2011b, 2013). For direct monitoring of glacier recession over time, and the linkage of the loss of volume and area to local climatic and ice dynamical changes, time series of glacier inventories are needed. Time series of remote sensing data naturally are limited by the availability of first satellite data (e.g. Rott, 1977), so that time series of glacier inventories have been limited to a length of several decades (Bolch et al., 2010). Longer time series (Nuth et al., 2013; Paul et al., 2011a; Andreassen et al., 2008) can only be compiled from additional data with varying error characteristics (e.g. Haggren et al., 2007) and temporally and regionally varying availability.

Although the ice cover of the Alps is not a high portion of the world's ice reservoirs, scientific research on Alpine glaciers has a long history which is important in the context of climate change. Apart from the Randolph glacier inventory data (Ahrendt et al., 2012) and a pan-Alpine satellite-derived glacier inventory (Paul et al., 2011b), several national or regional glacier inventories are available. For Italy, only regional data are available, for example for South Tyrol (Knoll and Kerschner, 2010) and the Aosta region (Diolaiuti et al., 2012). For the five German glaciers, time series of glacier areas have been compiled by Hagg et al. (2012). For the French Alps, glacier inventories have been compiled for 4 dates between 1967/71 and 2006/09 by Gardent et al (2014). For Switzerland, several glacier inventories have been compiled from different sources. For the year 2000, a glacier inventory has been compiled from remote sensing data (Kääb et al., 2002; Paul et al., 2004), for 1970 from aerial photography (Müller et al., 1976) and for 1850 the glacier inventory was reconstructed by Maisch et al. (1999). Elevation changes have been calculated between 1985 and 1999 for about 1050 glaciers (Paul and Haeberli, 2008) and recently by Fischer et al. (2014).

For the Austrian Alps, glacier inventories so far have been compiled for 1969 (Patzelt, 1980; GI 1) and 1998 (Lambrecht and Kuhn, 2007; GI 2) on the basis of orthophoto maps. Groß (1987) estimated glacier area changes between 1850, 1920 and 1969, mapping the extent of the Little Ice Age (LIA) and 1920 moraines from the orthophotos of the glacier inventory of 1969. As the Austrian federal authorities made LiDAR data available for the major part of Austria after years of very negative mass balances after 2000, these data have been used for the compilation of a new glacier inventory based on LiDAR DEMs (Abermann et al., 2010). As the high resolution data allow detailed mapping of LIA moraines, the unpublished maps of Groß (1987) have been used as the basis for an accurate mapping of the area and elevation of the LIA moraines, based on the LiDAR DEMs and the ice divides/glacier names used in the inventories GI 1 and GI 2.

The pilot study of Abermann et al. (2009) in the Ötztal Alps identified a pronounced decrease of glacier area, but differing for different size classes. The aim of this study was to update the existing Austrian glacier inventories 1969 (GI 1) and 1998 (GI2) to a GI 3 and complement this as consistently as possible with a LIA inventory based on new geodata (Figure 1) and the mappings of Groß (1987). The overarching research question is the variability of Austrian glacier area changes and change rates by time, region, size class and elevation.

2 Data

2.1 Austrian Glacier inventories

Patzelt (1980) and Groß (1987) derived the first Austrian glacier inventory GI 1 based on orthophotos from 1969 (shape files: Patzelt, 2013). Groß (1987) compiled glacier inventories for the LIA maximum and 1920 from the GI 1 geodata and field surveys mapping the moraines of the respective glacier adavances.

Lambrecht and Kuhn (2007) used othophotos between 1996 and 2002 to update the glacier inventory 1969 (GI 1), which they also digitized (Figure 2). In the first, analogue, evaluation of the 1969 orthophotos the glacier area in 1969 was determined as 541.7 km². The glacier areas have been delineated manually by Lambrecht and Kuhn (2007) and Kuhn et al. (2008) as recommended by UNESCO (1970), i.e. snow patches directly attached to the glacier have been mapped as glacier area. The digital reanalysis of the inventory 1969 (GI 1) by Lambrecht and Kuhn (2007) found a total glacier area of 567 km², including also areas above the bergschrund. For the GI 2 (Kuhn et al., 2013), Lambrecht and Kuhn (2007) used the same definition, so that a number of different flight campaigns was necessary to acquire cloud-free orthophotos with a minimum snow cover. Therefore, GI 2 dates from 1996 to 2002, but the main part of the glaciers were covered during the years 1997 (43.5% of the total area) and 1998 (38.5% of the total area). Lambrecht and Kuhn (2007) estimated the effect of compiling the glacier inventory from data sources of different years by calculating an area for the year 1998. The temporal homogenization of glacier area was done by upscaling or downscaling the recorded inventory area in specific altitude bands with a degree day method to the year 1998. The difference between the recorded area and the area calculated for the year 1998 was only 1.2 km² They found a glacier area of 470.9 km² for the summed areas of different dates, and 469.7 km² for a temporally homogenized area for the year 1998. All the orthophoto maps and glacier boundaries are published in a booklet (Kuhn et al, 2008), showing also the low amount of snow cover on the orthophotos. The maximum area of the glacier area is estimated to be ±1.5% (Lambrecht and Kuhn, 2007). About 3% of the glacier area of 1969 have not been mapped and several very small glaciers were still missing in GI II. GI I and GI II comprise surface elevation models, with a vertical accuracy of ±1.9 m (Lambrecht and Kuhn, 2007).

2.2 LiDAR data

Airborne laser scanning is a highly accurate method for the determination of surface elevation in high spatial resolution, allowing the mapping of geomorphologic features, such as moraines (Sailer et al., 2014).

The LiDAR DEMs were compiled from a single campaign so that the recorded glacier elevation corresponds to one date only, although the acquisition times of the DEMs differ for the specific mountain ranges. The sensors and requirements on point densities are listed in Table 1. Vertical and horizontal resolution also depends on slope and elevation, nominal mean values for flat areas are better than ±0.5 m (horizontal) and ±0.3 m (vertical) accuracy.

The point density in one grid cell of 1x1 m ranges from 0.25 to 1 point per square metre. The vertical accuracy depends on slope and surface roughness and ranges from few cm to some dm in very steep terrain (Sailer et al., 2014). LiDAR has a considerable advantage over photogrammetric DEMs where fresh snow or shading reduce vertical accuracy. As the high spatial resolution also reflects surface roughness, smooth ice-covered surfaces can be clearly distinguished from rough periglacial terrain. The flights were carried out during August and September in the years 2006 to 2012, when snow cover was minimal and the glacier margins snow free.

2.3 Orthophotos

Orthophotos were used for the delineation of glacier margins where no LiDAR data were available. All orthophotos used are RGB true colour orthophotos with a nominal resolution of 20x20 cm. Orthophotos from 2009 were used for Ankogel- Hochalmspitzgruppe, Defreggergruppe, Glocknergruppe, Granatspitzgruppe, the western part of Schobergruppe and the East Tyrolean part of Venedigergruppe. Glacier margins in the eastern part of Zillertaler Alpen and the northern part of Venedigergruppe, located in Salzburg province, were determined using orthophotos from the year 2007. Orthophotos from 2012 were used for Dachsteingruppe.

3 Methods

3.1 Applied basic definitions

The compilation of the glacier inventory time series aims at monitoring glacier changes with time. Therefore, ice divides and specific definitions regarding what is considered a glacier were kept unchanged, although they could have been changed for compiling single inventories. To make the definitions used in this study clear, the definition of glaciers, as well as glacier area and the separation by ice divides are specified here. Naturally, inventories which serve purposes other than compiling inventory time series will use other definitions, for example mapping changing ice divides instead of constant ones.

The ice divides remain unchanged in all glacier inventories and are defined from the glacier surface in 1998. Although ice dynamics are likely to change between the inventories, leaving the position of the divides unchanged has the advantage that no area has shifted from one glacier to another.

The parent data set for this study is the GI 1, so that the unique IDs in GI 1 were kept in later inventories. If a glacier had disintegrated in the inventory of 2006, one ID refers to polygons consisting of several parts of a formerly connected glacier area. For the disintegration of glaciers, the parent and child IDs as used in the GLIMS inventories (Raup et al, 2007; Raup et al, 2010) are an excellent solution. Going backwards in time, e.g. to where several parents of the GI 1 are part of a larger LIA glacier, would consequently need the definition of a grandparent or the division of the LIA glacier in different tributaries to allow a glacier-by glacier comparison of area changes.

No size limit was applied for the mapping of glaciers in the 2006 inventory, i.e. glaciers whose area has decreased below a certain limit are still included in the updated inventory. This avoids an overestimate of the total loss of ice-covered area as a result of skipping small glaciers included in older inventories. The area of glaciers smaller than 0.01 km², which is often considered as a threshold for including glaciers in inventories, was quantified.

3.2 Mapping the glacier extent in GI 3 from LiDAR

Abermann et al. (2010) demonstrated in a pilot study for the Ötztal Alps that LiDAR DEMs can be used with high accuracy for mapping glacier area. Figure 3 shows a LiDAR hillshade of glaciers in the Ötztal Alps dating from 2006 with orthofotos in VIS and CIR RGB from 2010 for comparison. The update of the glacier shapes from the inventory of 1998 was done combining hill shades with different angles calculated from LiDAR DEMs (Figure 4, location of the subset see Figure 3), analysing the surface elevation changes between the GI 2 and GI 3 inventories (Figure 5, location of the subset see Figure 3) and by comparison with orthophoto data, where available. The surface elevation change shows a maximum close to the position of the GI 3 glacier margin and should be zero outside the GI 2 glacier margin (apart from permafrost phenomena or mass movements). The resulting glacier boundaries are shown in Figure 6. Abermann et al. (2010) quantify the accuracy of the areas derived by the LiDAR method to ±1.5 % for glaciers larger than 1 km² and up to ±5% for smaller ones. The comparison with glacier margins measured by DGPS in the field for 118 points showed that 95% of these glacier margins derived from LiDAR were within an 8 m radius of the measured points and 85% within a 4 m radius.

3.3 Mapping the glacier extent in GI 3 from orthophotos

Where no LiDAR data was available (cf Figure 1, Table 2), the GI 2 glacier boundaries have been updated with orthophotos. As the nominal resolution of the orthophotos used for the manual delineation of the glacier boundaries is similar to GI 2, the estimated accuracy of the glacier area of ±1.5% is considered to be valid also for GI 3.

3.4 Deriving the LIA extent

The LIA maximum extents were mapped based on previous mappings by Groß (1987) and Patzelt (1973), which were adapted to fit the moraine positions reorded in modern LiDAR DEMs and orthophotos. Groß and Patzelt mapped the LIA extents of 85% of the Austrian glaciers based on field surveys and the maps and orthophotos of the 1969 glacier inventory. Their analogue glacier margin maps had been stored for several decades and suffered some distortion of the paper, so that the digitalization could not reproduce the position of the moraines according to the LiDAR DEMs. Therefore we decided to remap the LIA glacier areas, basically following the interpretation of Groß and Patzelt, but remaining consistent with the digital data. Figure 7 shows the hillshades of the tongues of Gaißbergferner with pronounced LIA, 1920 and 1980 moraines, which are ice cored on the orographic left side. The basic delineation of Groß (1987) was adapted to fit the LIA moraine in the LiDAR hillshade (Figure 8).

Nevertheless, some smaller glaciers, which had wasted down until 1969, might still be missing in the LIA inventory. Groß (1987) accounted for these disappeared glaciers by adding 6.5% to the LIA area. We decided to include this consideration in the discussion on uncertainties, although we think that this estimate is fairly accurate.

4 Results

4.1 Total glacier area

Austrian glaciers cover 941.13 km² (100%) in GI LIA, 564.88 km² (60%) in GI 1, 471.67 km² (50%) in GI2 and 415.11 km² (44%) in GI 3 (Table 2). The GI LIA was not corrected for glaciers which completely disappeared before GI 1, so that the area in this study is a bit lower than the 945.50 km² found by Groß (1987). Only four glaciers have wasted down completely between GI 2 and GI 3.Shape files of GI 3 can be downloaded via the Pangaea data base (Fischer, in prep).

Kommentar [x1]: Should be ready for download end of January 2015

4.2 Absolute and relative changes of total area

The absolute loss of glacier area, which is interesting from a hydrological perspective, was 376 km² between GI LIA and GI 1, 94 km² between GI 1 and GI 2, and 55 km² between GI 2 and GI 3 (Table 2). Relative changes of the total area are 40% (GI LIA to GI 1), 17% (GI 1 to GI 2) and 12 % (GI 2 to GI 3). These numbers need a reference to the different period length for a comparison or interpretation, which is usually done by calculating relative changes per year, neglecting glacier advances in the periods. The calculation of annual relative losses between GI LIA and GI 1 is based on the simplification that the LIA maximum occurred in

1850, so that the length of this period is 119 years. Then the relative area change per year is calculated to be 0.3 %/year, neglecting glacier advances around 1920 (Groß, 1987) and the temporal variability of the occurrence of LIA glacier maximum. The area weighted mean of the number of years between GI 1 and GI 2 is 28.7, resulting in an anual relative change of total area of 0.6 %/year. In this period, a high portion of Austrian glaciers advanced (Fischer et al., 2013). The latest period, GI 2 to GI 3, showed a general glacier recession without significant advances, resulting in an annual relative area loss of 1.2%/year for the area weighted period length of 9.9 years. Therefore, overall annual relative area losses in the lastest period are twice as large as for GI 1 to GI 2 and four times as large as GI LIA to GI 1.

4.3 Results for specific mountain ranges

The absolute areas recorded for specific mountain ranges are shown in Figure 9 and Table 2. Highest absolute glacier area decrease between GI 2 and GI 3 was observed in the Ötztaler Alpen (-13.9 km², 24% of total area loss), the Venedigergruppe (-11.7 km², 20.9% of total area loss), Stubaier Alpen (8.2 km², 4.5%) and Glocknergruppe (-8.17 km², 14.6% of total area loss). These mountain ranges contribute 74.2% of the total Austrian glacier area. Their contribution to the area loss is lower than their share of glacier area, and is only 60.4% of the area loss. The contribution of the Ötztaler Alpen, Silvretta, Zillertaler Alpen and Stubaier Alpen to the total Austrian area loss decreased between the LIA and today, the contribution of Glocknergruppe and Venedigergruppe increased by more than 4% of the total area loss for each mountain range. The relative area loss since the LIA maximum differs between the specific groups: Whereas only 11% of the LIA area is left in the Samnaun Gruppe, 51 to 45% of the LIA area is still ice covered in Rätikon, Ötztaler Alpen, Venedigergruppe, Silvretta, Glocknergruppe and Stubaier Alpen (Figure 10).

While the annual relative area losses in the first period vary between -0.3 and -0.6 %/year, the regional variability of the relative annual area loss in the two latest periods is much higher the later (and shorter) the period (Table 3).

The highest annual relative area loss was observed in Karnische Alpen (-4.5%/year), Samnaungruppe (-5.6%/year), and Verwallgruppe (-5.9%/year) for GI 2 to GI 3. These are groups with a high portion of small glaciers.

4.4 Altitudinal variability of area changes

In GI 2, 88% of the total area was located at elevations between 2600 and 3300 m.a.s.l (Figure 11). In GI 3, the proportion of glacier area located at these elevations was still 87%. The largest portion of the area is located at elevations between 2850 and 3300 m.a.s.l (41% in GI 2 and 58% in GI 3), 42% of the area was located in regions above 3000 m in GI 2, decreasing to 39% in GI 3.

The most severe losses took place in altitudinal zones between 2650 and 2800 m.a.s.l., with a maximum in the elevation zone 2700 to 2750 m.a.s.l. Fifty of the area losses took place at altitudes between 2600 and 2900 m.a.s.l. Therefore the main portion of the glacier covered areas are stored in regions above the current strongest area losses.

4.5 Area changes for specific glacier sizes

The interpretation of the recorded glacier sizes has to take into account that not all glaciers which are mapped for newer inventories are part of the older inventories, as the total number of glaciers in Table 4 shows. Although some smaller glaciers are missing in GI 1, the number of glaciers smaller than 0.1 km² has been increasing, replacing the area class between 0.1 and 0.5 km² as the most frequent one. At the other end of the scale, 11 glaciers were part of the largest size class in GI 1and only 8 were left in GI 3.

For GI 3, the glaciers in the largest size class of 5 – 10 km² cover 41% of the area (Table 4). All other size classes range between 8 and 17% of the total area, but glaciers of the smallest size class cover only 9% of the total glacier area.

The percentage of area contributed by very small glaciers (<0.01 km²) is small. In GI 1, 1 glacier covers 0.0015% of the total glacier area. In GI 2, 16 very small glaciers cover 0.024% of the total glacier area, and in GI 3 26 very small glaciers contribute 0.033% of the total glacier area.

5 Discussion

The uncertainties of the derived glacier areas are estimated to be highest for the LIA inventory, and lowest for GI 3. For all glacier inventories, debris cover and perennial snow fields or fresh snow patches connected to the glacier are hard to identify, although including information on high resolution elevation changes and including additional information from different points in time reduces this uncertainty (Abermann et al., 2010). The high-resolution data were only available for GI 3, so that the interpretation of debris and snow can still be regarded as an interpretational range of several percentage points for the area in GI 1 and 2. The nominal accuracy of the method (Abermann et al., 2010) results in an area uncertainty of ±11.2% or ±2.7%.

For the interpretation of the LIA inventory, temporal and spatial indeterminacy has to be kept in mind. The temporal indeterminacy is caused by the asynchronous occurrence of the LIA maximum extent. In extreme cases the occurrence of the LIA maximum deviated several decades from the year 1850, which is often used as synonymous with the time of the LIA maximum.

The spatial indeterminacy varies between accumulation areas and glacier tongues: The moraines which confined the LIA glacier tongues give a good indication for the LIA glacier margins in most cases as they are clearly mapped in the LiDAR DEMs and changing vegetation is visible in the orthophotos. In some cases, lateral moraines standing proud for several decades eroded later, so that the LIA glacier surface will be interpreted as wider, but also lower than it actually was. In some cases, LIA moraines were subject to mass movements caused by fluvial or permafrost activities. In a very few cases, ice cored moraines developed and moved from the original position. Altogether these uncertainties are small compared to the interpretational range at higher elevations, where no significant LIA moraines indicate the ice margins. Moreover, historical documents and maps often show fresh or seasonal snow cover at higher elevations. For example the federal maps of 1816-1821 and 1869-1887 in Figure 12 show surfaces where it is not clear if they are covered by snow, ice or firn. Therefore we cannot even be sure to have included all glaciers which existed during the LIA maximum. Groß (1987) calculated LIA maximum glacier areas of 945.50 km² without, and 1011.0 with disappeared glaciers (i.e. 6.5 % disappeared glaciers). According to this estimate, 6.5 % of the LIA maximum area is possibly missing from our inventory. Taking this a general mapping error of 3.5% into account we estimate the accuracy of the total ice cover for the LIA as ±10%. Figure 12 illustrates that the maps of the third federal survey, together with other historical data, provide some information on the glacier area also in higher elevations. In any investigation of large system changes, as between LIA and today, the definition of the term ‘glacier’ is difficult, as it is not clear if it makes sense to compare one LIA glacier with the total area of its child glaciers with totally different geomorphology and dynamics, or if it would make more sense to split the LIA glacier into tributaries according to the present situation. Regarding the presented annual rates of area change, it has to be born in mind that all periods apart from GI 2 to GI 3 contain at least one period (around 1920 and in the 1980s) when the majority of glaciers advanced (Groß, 1987; Fischer et al, 2013). Thus a higher temporal resolution of inventories might result in different absolute and relative annual area change rates, as the length change rates, for example during the 1940s, have previously been in the same range as those after 2000.

The development of area change rates is similar to the ones found for the Aosta region by Diolaiuti et al., (2012), who arrived at 2.8 km^2/year for 1999 to 2005, and 1.1 km^2/year for 1975 to 1999. The maximum relative area changes in the period of the Austrian GI 2 to GI 3 exceed the ones summarized by Gardent et. al. (2014). The periods for which area changes have been calculated for the French Alps by Gardent et al. (2014) are no exact match of the Austrian periods, but the total loss of 25.4% of the glacier area between 1967/71 and 2006/09 is similar to the Austrian Alps, despite the higher elevations of the French glaciers. A common finding is the high regional variability of the area changes.

Compared to global satellite remote-sensing-based glacier inventories, the glacier inventories presented here show i) high spatial resolution ii) inclusion of additional information iii) minimal snow cover at the time of the flights and iv) consistent nomenclature and ice divides for all four inventories. The high resolution data used in this study is neither available for a global inventory, nor is the high resolution beneficial for global studies, so that global inventories will naturally use satellite remote sensing data. As the Alps often are used as an open space laboratory in glaciology, it nevertheless might make sense to compare results of global inventories with this regional inventory. The Randolph inventory RGI Version 3.2, released 6 September 2013 and downloaded from http://www.glims.org/RGI/rgi_dl.html contains 737 glaciers and a glacier area of 364 km^2 for the year 2003. These numbers are lower than the ones recorded in the Austrian inventories (GI 2 before 2003 and GI 3 after

2003), although cross-border glaciers were not delimited for the comparison. This is clearly a matter of spatial scales, and has no further implication.

6 Conclusions

This time series of glacier inventories presents a unique document of glacier area change since the Little Ice Age. The regional variability of glacier area loss since the LIA maximum is high, ranging from 89% loss of LIA glacier area for the small glaciers of the Samnaun group to half of the LIA glacier area remaining in a number of other groups. Small groups like Salzburger Kalkalpen and Karnische Alpen show the highest annual losses. The only glacier in Salzburger Kalkalpen region, Übergossene Alm, is currently disintegrating with annual relative area losses of 6.2 %. It seems likely to vanish in the near future. Nevertheless, for some of the largest glacier regions like Stubaier Alpen, Ötztaler Alpen and Silvrettagruppe as well as for the small Rätikon, annual relative changes even in the latest period are smaller than 1%/year. Although generally the relative annual losses increased since the LIA, some groups, for example Silvrettagruppe and Rätikon, exhibit a decrease in the latest period. The reason for that might be found in small scale mass balance variabilities in the shortest period analysed, or topographic or dynamical responses. For a meaningful interpretation of annual relative losses the length of the periods and the occurrence of positive mass balances and advances must be taken into account. We hope that the presented data basis will be used for further studies and investigations of glacier response to climate change.

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Table 1: Sensor and point densities.

	sensor	point density/m²
Tirol	ALTM 3100 and Gemini	0.25
Salzburg	Leica ALS-50, Optech ALTM-3100	1.00
Vorarlberg	ALTM 2050	2.50
Kärnten-Karnische Alpen	Riegl LMS Q680i and Riegl LMS Doublescansystem	1.00
Kärnten-other	Leica ALS-50/83 and Optech Gemini	1.00

Table 2: Acquisition times of the glacier inventories with glacier areas for specific mountain ranges shown in Figure 1; L means LiDAR ALS data and O means orthophoto.

group	GI II	GI III	data source	LIA	GI-I	GI-II	GI-III
	year	year		km²	km²	km²	km²
Allgäuer Alpen	1998	2006	L	0.29	0.20	0.09	0.07
Ankogel-Hochalmspitzgruppe	1998	2009	O	39.94	19.17	16.03	12.05
Dachsteingruppe	2002	2012	O	11.95	6.28	5.69	5.08
Defregger Gruppe	1998	2009	O	2.01	0.70	0.43	0.30
Glocknergruppe	1998	2009	O	103.58	68.93	59.84	51.67
Granatspitzgruppe	1998	2009	O	20.08	9.76	7.52	5.48
Karnische Alpen	1998	2009	L	0.29	0.20	0.18	0.09
Lechtaler Alpen	1996	2004/06	L	2.09	0.70	0.69	0.55
	1996	2006	L				0.36
	1996	2004	L				0.19
Ötztaler Alpen	1997	2006	L	280.35	178.32	151.16	137.58
Rätikon	1996	2004	L	3.12	2.19	1.65	1.61
Rieserfernergruppe	1998	2009	L	8.07	4.60	3.13	2.75
Salzburger Kalkalpen	2002	2007	L	5.68	2.47	1.68	1.16
Samnaungruppe	2002	2006	L	0.59	0.20	0.08	0.07
Schobergruppe	1998	2007/09	L/O	9.88	5.60	3.49	2.57
	1998	2007	L				0.96
	1998	2009	O				1.61
Silvrettagruppe	1996	2004/06	L	41.27	23.96	18.97	18.48

		2006	L				9.86
		2004	L				8.62
Sonnblickgruppe	1998	2009	L	24.81	12.76	9.74	7.91
Stubaier Alpen	1997	2006	L	110.10	63.05	53.99	49.42
Venedigergruppe	1997	2007/09	L/O	145.20	93.44	81.01	69.31
	1997	2007	O				29.85
	1997	2009	L				39.47
Verwallgruppe	2002	2004/06	L	13.41	6.70	4.65	4.08
	2002	2006	L				3.66
	2002	2004	L				0.41
Zillertaler Alpen	1999	2007/11	L/O	118.42	65.64	50.64	45.24
	1999	2007	O				4.73
	1999	2011	L				40.51
total area				941.13	564.88	470.67	415.47
% of LIA area				100.00	60.02	50.01	44.15

Table 3: Relative and relative annual area changes.

group	GI 1-GI 2	GI 2 - GI 3	LIA-GI 1	GI 2-GI1	GI3-GI2	LIA-GI 1	GI 1-GI2	GI2-GI3
	years	years	%	%	%	%/year	%/year	%/year
Allgäuer Alpen	29	8	-31	-55	-22	-0.3	-1.9	-2.8
Ankogel-Hochalmspitzgruppe	29	11	-52	-16	-25	-0.4	-0.6	-2.3
Dachsteingruppe	33	10	-47	-9	-11	-0.4	-0.3	-1.1
Defregger Gruppe	29	11	-65	-39	-30	-0.5	-1.3	-2.7
Glocknergruppe	29	11	-33	-13	-14	-0.3	-0.5	-1.2
Granatspitzgruppe	29	11	-51	-23	-27	-0.4	-0.8	-2.5
Karnische Alpen	29	11	-31	-10	-50	-0.3	-0.3	-4.5
Lechtaler Alpen	27	8,10	-67	-1	-20	-0.6	-0.1	-2.2
Ötztaler Alpen	28	9	-36	-15	-23	-0.3	-0.5	-2.6
Rätikon	27	8	-30	-25	-25	-0.3	-0.9	-3.1
Rieserfernergruppe	29	11	-43	-32	-22	-0.4	-1.1	-2.0
Salzburger Kalkalpen	33	5	-57	-32	-18	-0.5	-1.0	-3.5
Samnaungruppe	33	4	-66	-60	-22	-0.6	-1.8	-5.6
Schobergruppe	29	9,11	-43	-38	-19	-0.4	-1.3	-1.8
Silvrettagruppe	27	8,10	-42	-21	-25	-0.4	-0.8	-2.7
Sonnblickgruppe	29	11	-49	-24	-21	-0.4	-0.8	-1.9
Stubaier Alpen	28	9	-43	-14	-23	-0.4	-0.5	-2.6
Venedigergruppe	28	10,12	-36	-13	-22	-0.3	-0.5	-2.0
Verwallgruppe	33	2,4	-50	-31	-22	-0.4	-0.9	-5.9
Zillertaler Alpen	30	8,12	-45	-23	-23	-0.4	-0.8	-2.0

Table 4: Number and areas of glaciers per size class.

Size classes [km²]	<0.1	0.1 to 0.5	0.5 to 1	1 to 5	5 to 10	>10	total
number of glaciers							
in GI 1	177	401	116	99	11	5	809
in GI 2	401	343	92	79	7	3	925
in GI 3	450	307	77	77	8	2	921
% of total area in class							
in GI 1	2	17	14	39	15	13	100
in GI 2	4	17	14	41	14	10	100
in GI 3	5	17	12	41	17	8	100

Figures

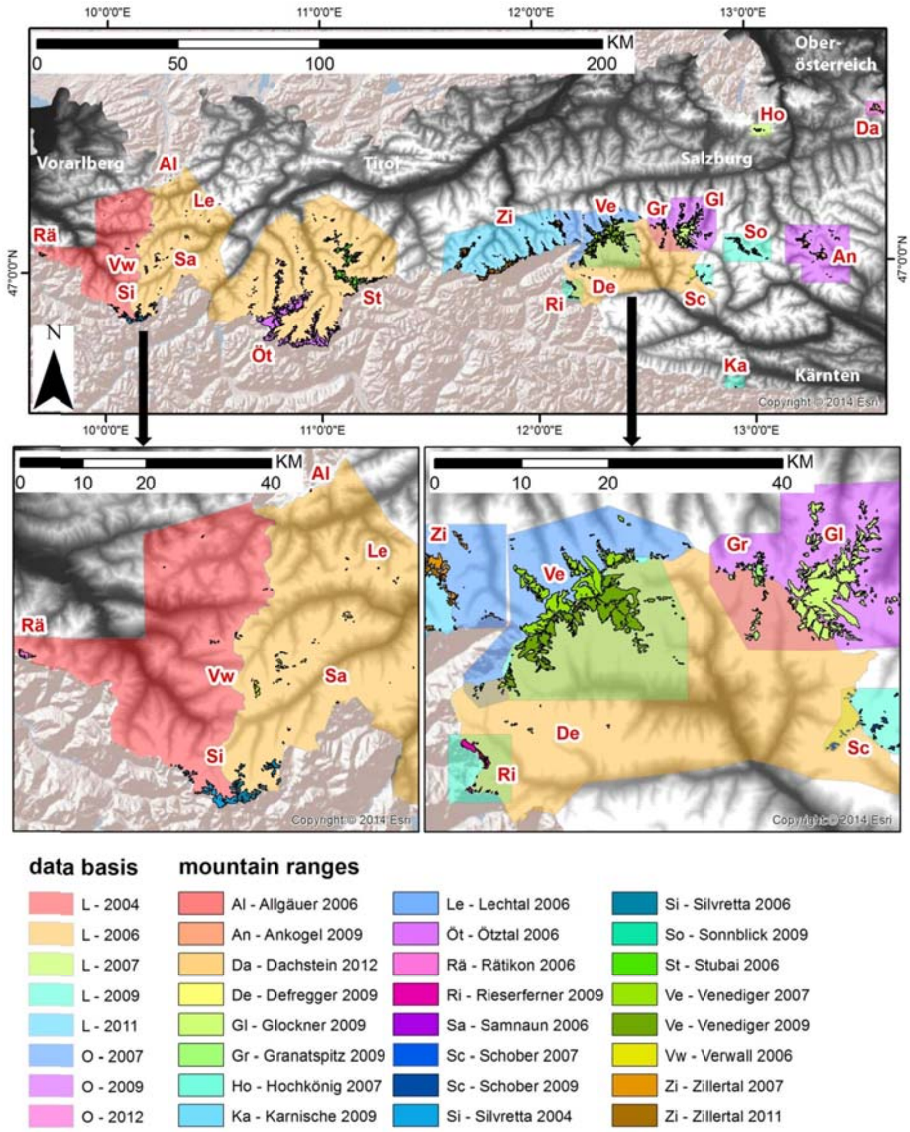

Figure 1: Austrian glaciers displayed on a DEM (Jarvis et al., 2009) color-coded by mountain ranges, with polygons showing data type and date used for deriving GI 3 and GI LIA.

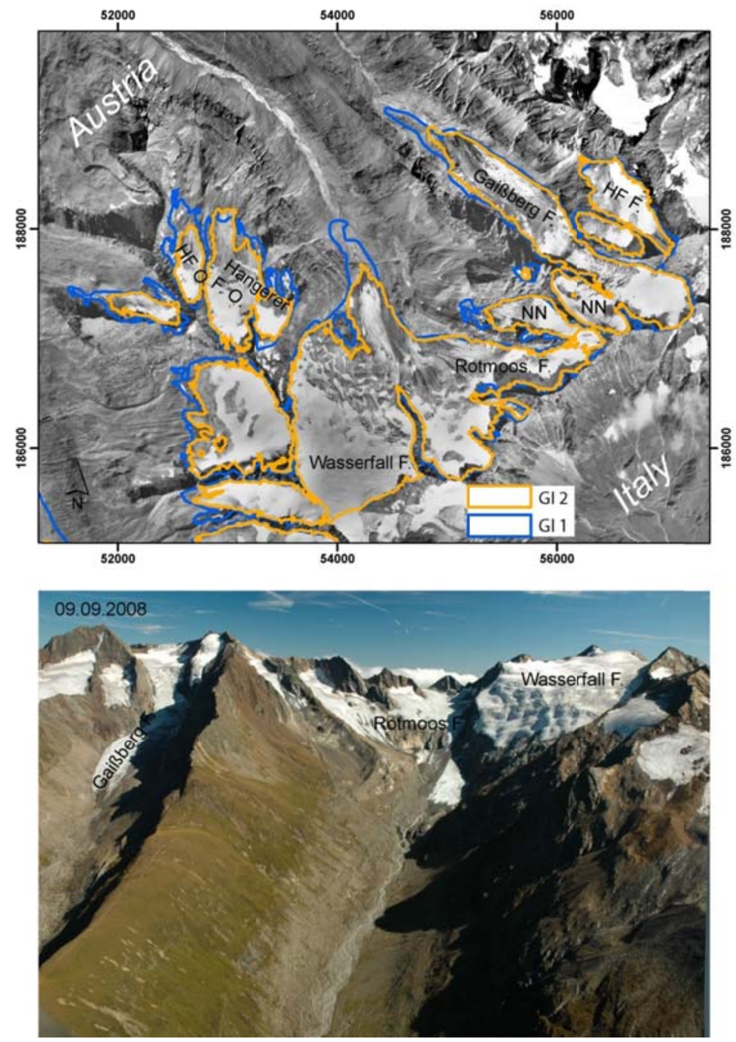

Figure 2: GI 1 and GI 2 glacier margins superimposed on a GI 2 orthophoto with an oblique photograph of the area in Ötztal Alps. HF O…Hangerer Ferner Ost, HF F…Hochfirst Ferner, NN …not named.

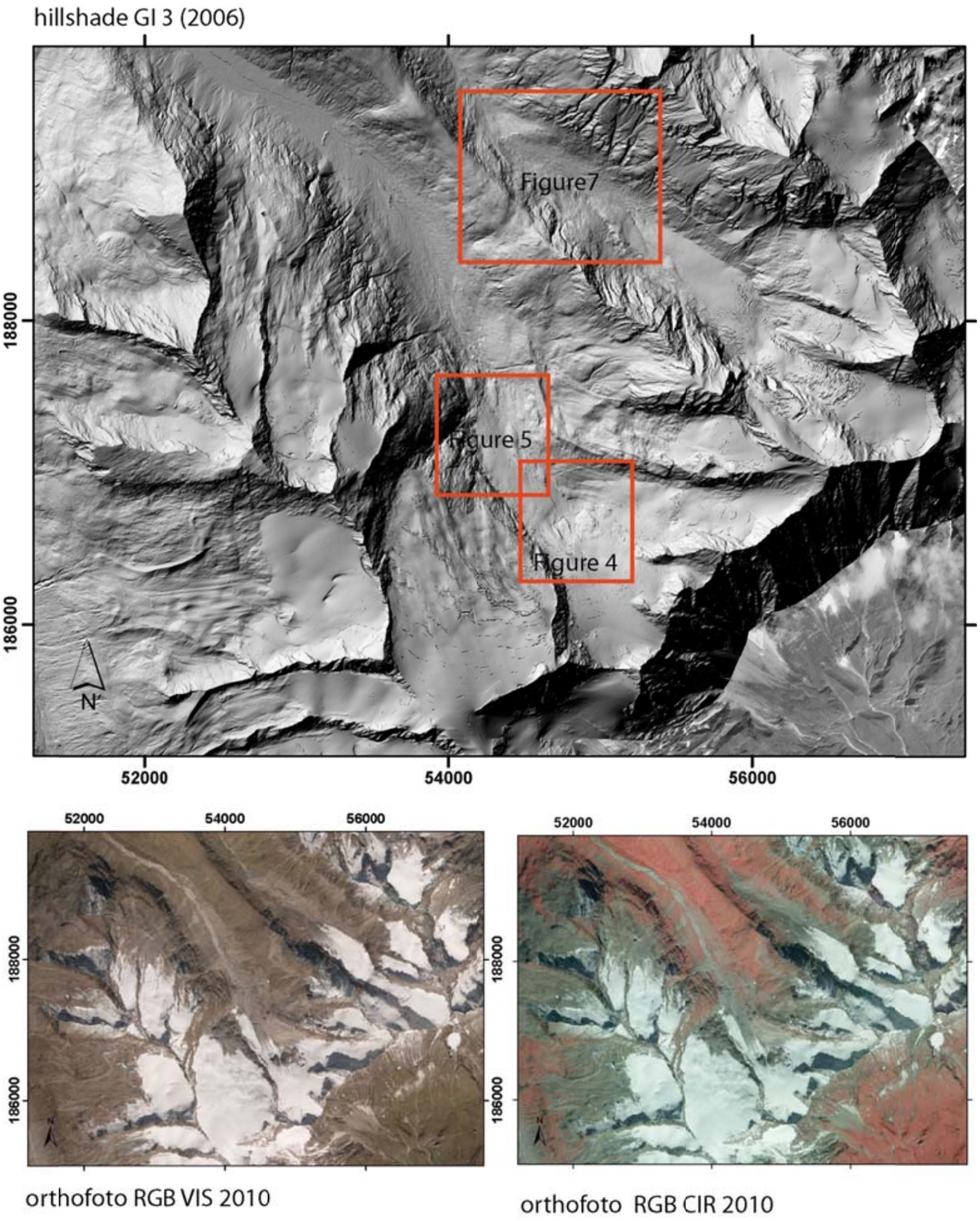

Figure 3: Example of an LiDAR hillshade (2006) of the same area as in Figure 2 with VIS and CIR RGB orthophotos from 2010 for comparison. The inserts show the position of the subsets shown in Figure 4 (lower right rectangle) and Figure 5 (upper left rectangle).

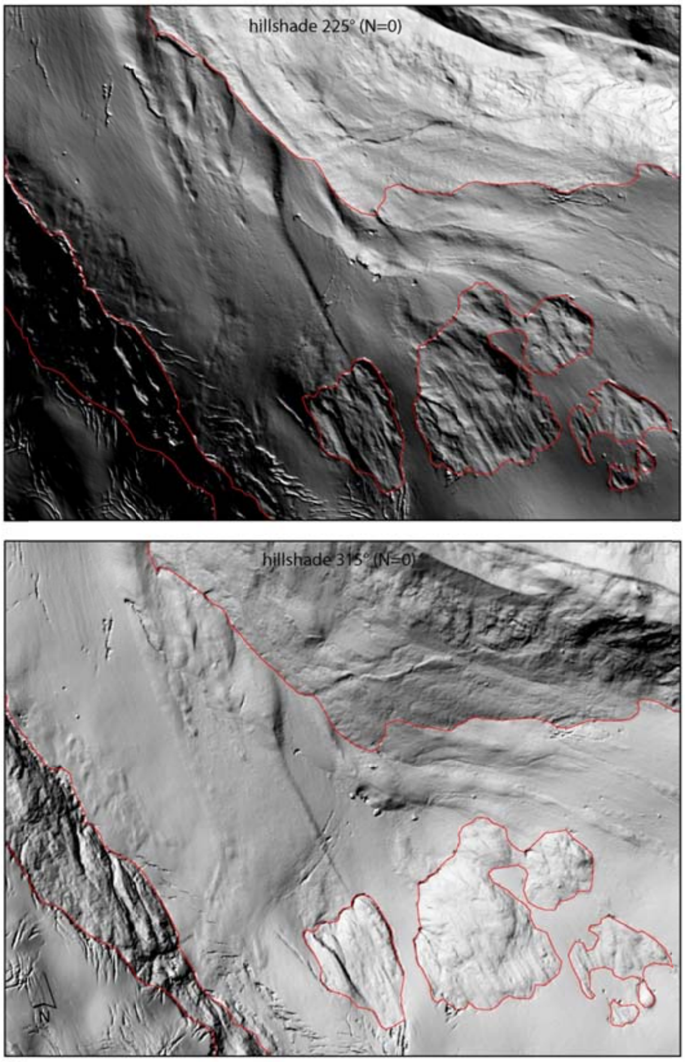

Figure 4: Hillshades from different view angles allow to distinguish smooth glacier surfaces from bedrock (position of the subset shown in Figure 3).

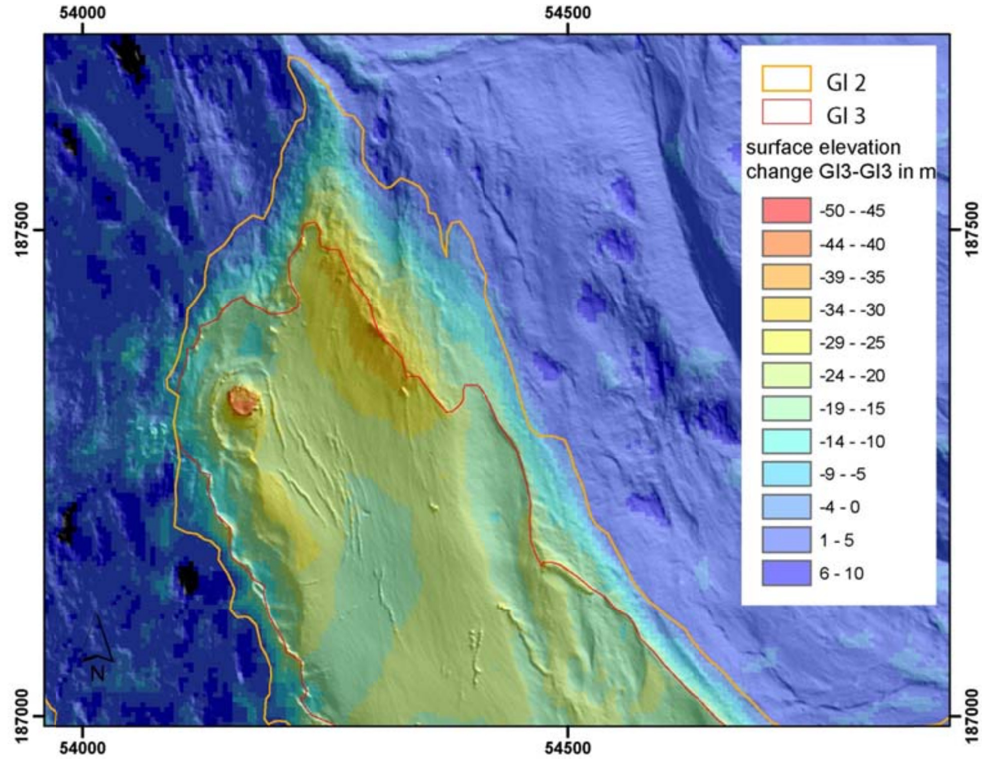

Figure 5: The elevation change between GI 2 and GI 3 superimposed on a hillshade shows that the elevation changes can help to delineate the actual (maximum elevation change) and previous (outer minimum of elevation change) position of the glacier margin (position of the subset shown in Figure 3).

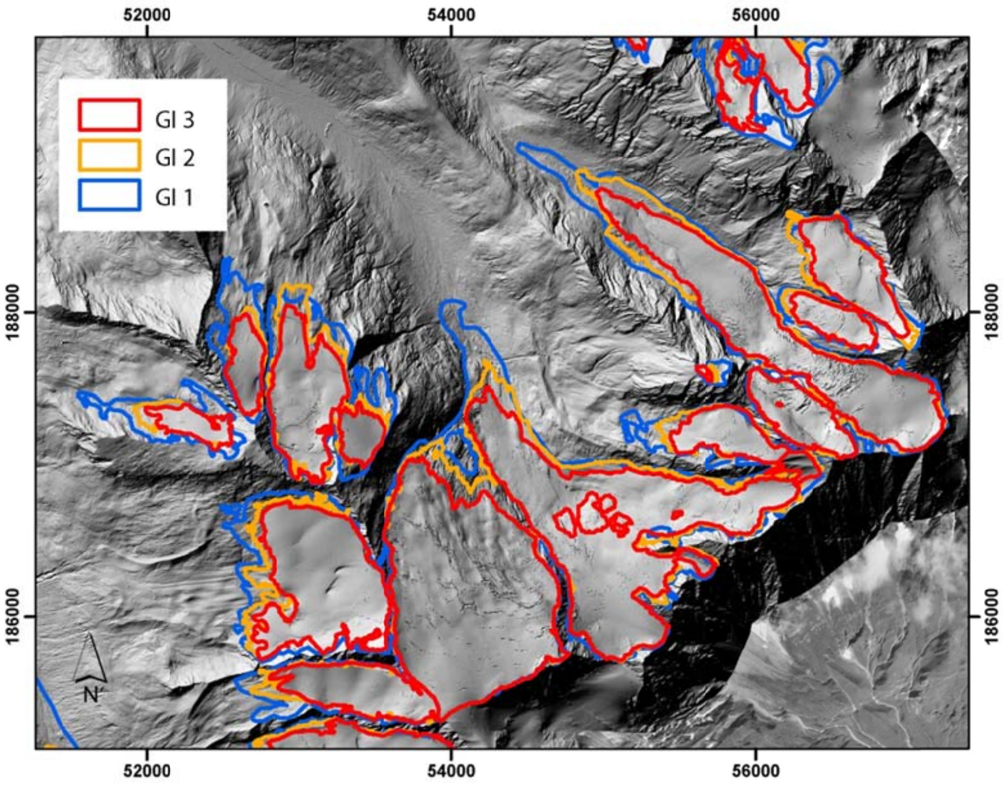

Figure 6: GI 3 glacier boundaries superimposed on LiDAR hillshade with GI 1 and GI 2 boundaries.

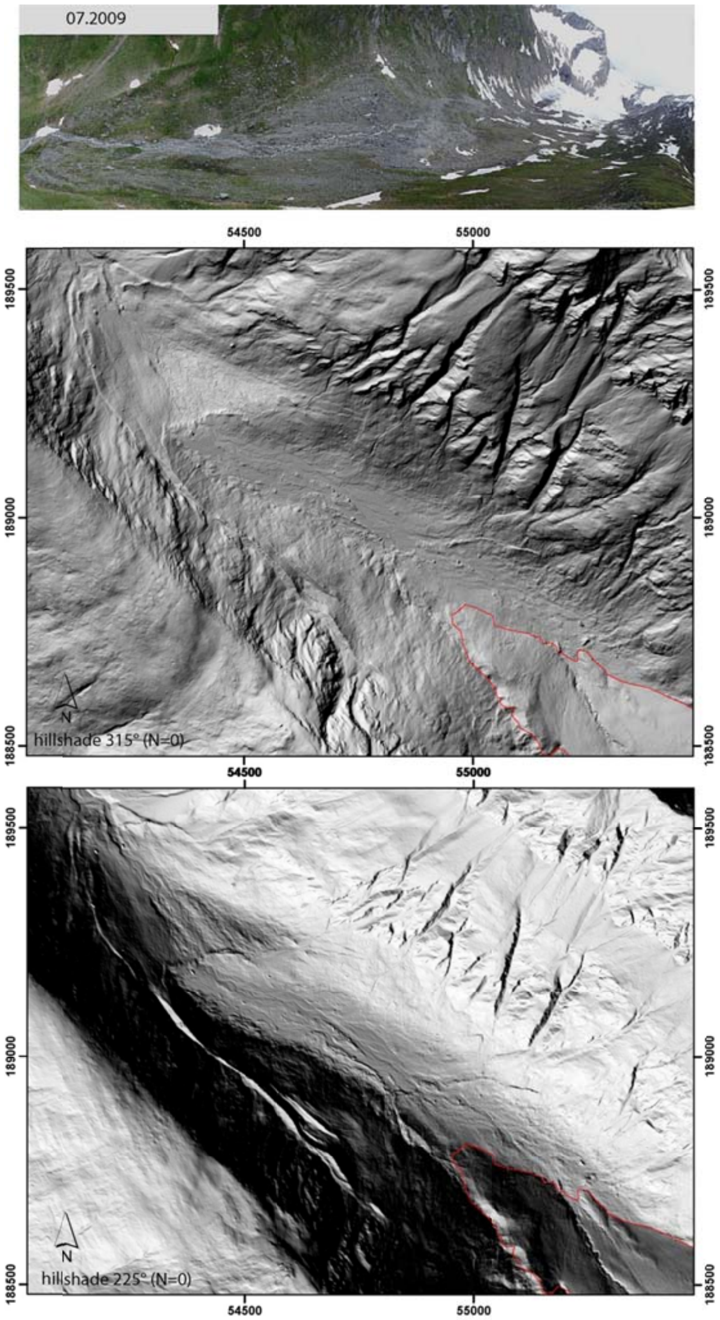

Figure 7: Periglacial area of Gaißbergferner with moraines dating from LIA, 1920 and 1980 (position of the subset: see Figure 3).

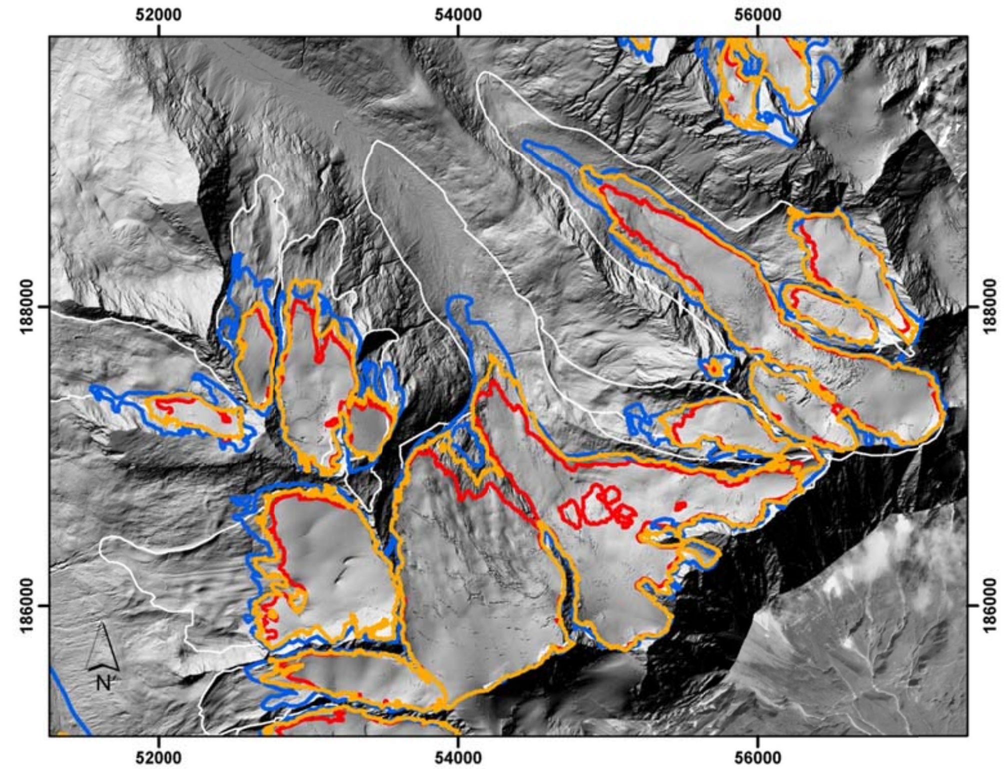

Figure 8: Resulting LIA glacier areas (white) with several modern glaciers contributing to the LIA Rotmoos Ferner and LIA Gaißbergferner.

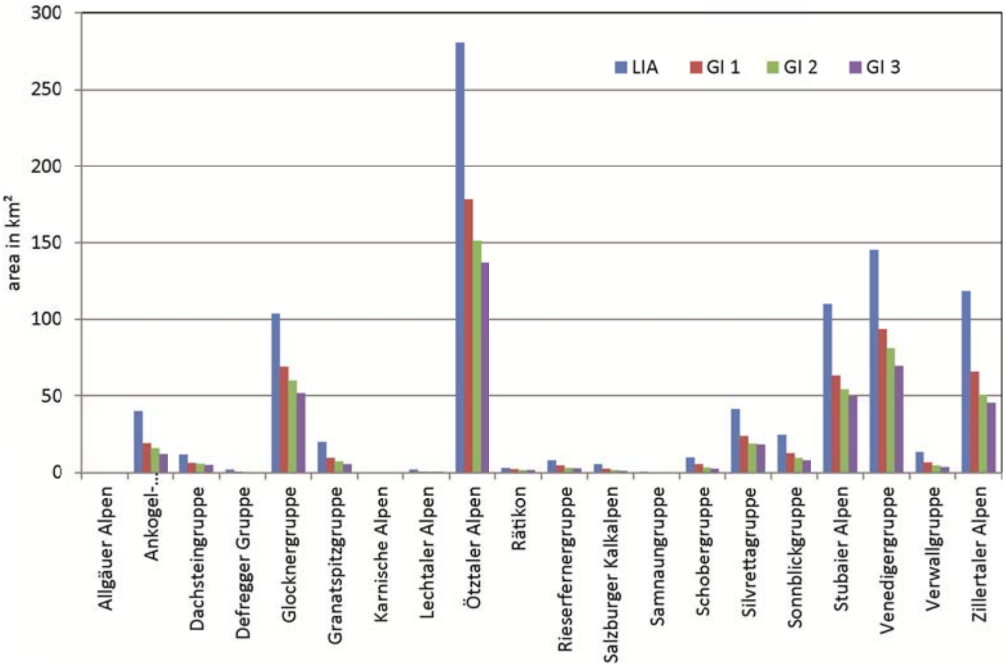

Figure 9: Glacier areas for specific mountain groups in GI LIA to GI 3.

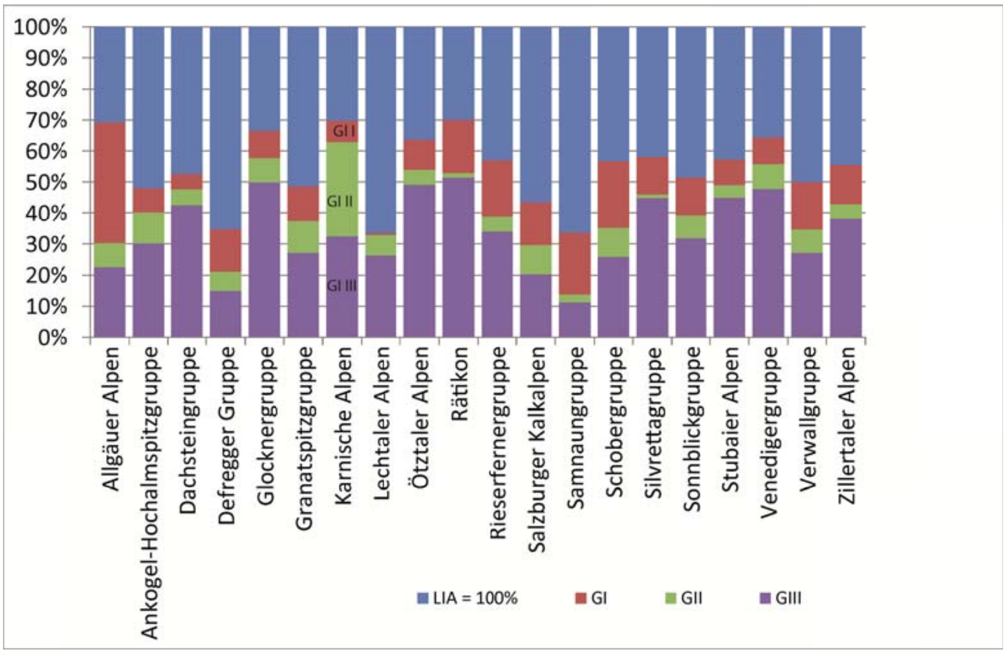

Figure 10: Area changes of specific mountain ranges in percentage of their LIA area.

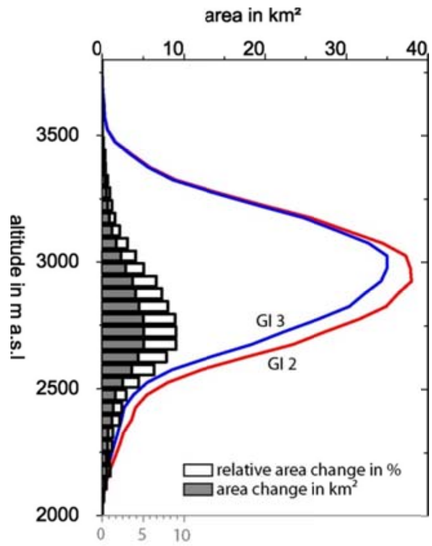

Figure 11: Altitudinal distribution of areas in GI 2 and GI 3 with absolute and relative area changes.

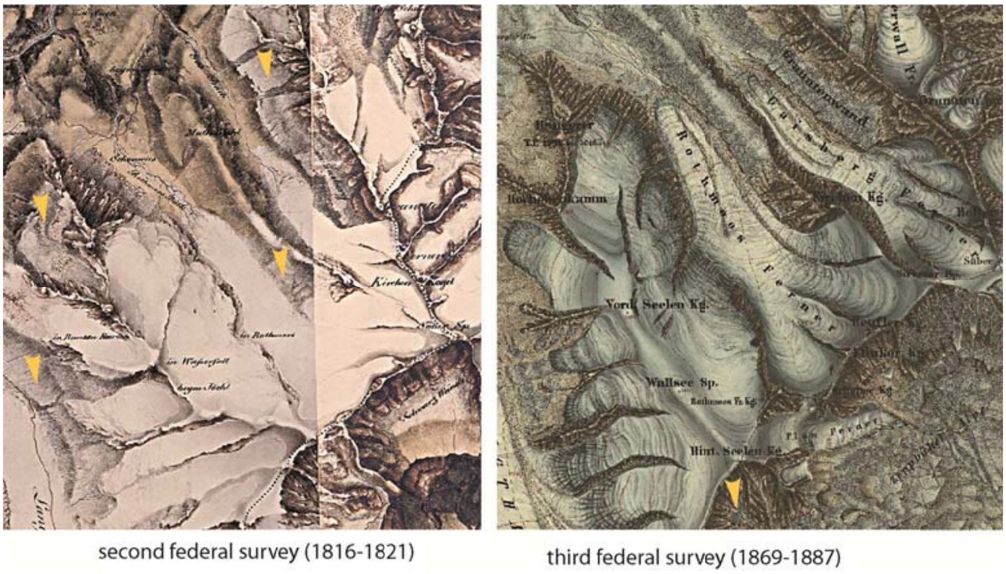

Figure 12: Federal maps of the second and third federal survey (before and after the LIA maximum) show uncertainties in differentiation of snow, firn and glacier (arrows) but give some general impression on LIA glaciers.