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

Andrea Fischer[1], Bernd Seiser[1], Martin Stocker Waldhuber[1,2], Christian Mitterer[1], Jakob Abermann[3,4]

Correspondence to: Andrea Fischer (andrea.fischer@oeaw.ac.at)

[1] {Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Technikerstrasse 21a, 6020 Innsbruck, Austria}

[2] {Institut für Geowissenschaften und Geographie, Physische Geographie, Martin-Luther-Universität Halle-Wittenberg, Von-Seckendorff-Platz 4, 06120 Halle, Germany}

[3] {Commission for Geophysical Research, Austrian Academy of Sciences}

[4] {now at Asiaq - Greenland Survey, 3900 Nuuk, Greenland}

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 outlines of the Little Ice Age maximum state (LIA) have 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 of variable length 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 mean glacier size decreased from 0.69 km² (GI 1) to 0.46 km² (GI 3) with 47% of the glaciers being smaller than 0.1 km² in GI 3 (22%).

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 one compiled by participants of 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, 2014). Based on the glacier inventories, ice volume has been modelled with different methods, partly as a basis for future sea level scenarios (Huss and Farinotti, 2012; Linsbauer et al., 2012; Radić et al., 2014, Grinsted, 2013). 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), as well as future glacier evolution. All this research is based on the most accurate mapping of glacier area and elevation at a particular point in time.

Satellite remote sensing is the most frequently applied method for large-scale derivation of glacier areas and outlines, (Rott, 1977, Paul et al., 2010, 2011b, 2013). For direct monitoring of glacier recession over time, the linkage of the loss of volume and area to local climatic and ice dynamical changes, and the spatial extrapolation of local observations, 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, such as topographic maps, 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 (Pfeffer et al., 2014, 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 the Alps. 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 four 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 period 1985-2010.

For the Austrian Alps, glacier inventories so far have been compiled and published for 1969 (Patzelt, 1980, Kuhn et al., 2008, Patzelt, 2013; GI 1) and 1998 (Lambrecht and Kuhn, 2007, Kuhn et al., 2008; 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 answered by this study 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

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. perennial 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. A number of different flight campaigns were 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 error 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 recorded glacier elevation by LiDAR DEMs was compiled from a single date per glacier , although acquisition times of the DEMs vary from glacier to glacier. 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. Mapping snow fields connected to the glacier as glacier area leads to an underestimate of glacier area changes if they increase in size and an overestimate if they melt.

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 a good 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 a minimum size for including glaciers in inventories, was also 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 illumination 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. Within this study, no experiment on quantifying differences between manual digitizing of different observers has been performed, as a number of studies with a high number of participants have already been carried out for VIS remote sensing data (e.g. Paul et al, 2013).

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 disappeared by 1969, might be missing in the LIA inventory. Groß (1987) accounted for these lost glaciers by adding 6.5% to the LIA area, estimated from a comparison of historical maps and images as well as moraines. We decided to include this consideration in the discussion on uncertainties, although we think that this estimate is based on the best available evidence.

4 Results

4.1 Total glacier area

Austrian glaciers cover 941.1 km² (100%) in GI LIA, 564.9 km² (60%) in GI 1, 471.7 km² (50%) in GI2 and 415.1 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 4.4 km² smaller than the 945.5 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 et al., submitted).

4.2 Absolute and relative changes of total area

The absolute loss of glacier area 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 yearThe glacier inventory periods can include subperiods with glacier advances and retreats, so that the calculated annual mean area change must be treated as an average value. 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, including 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. Within 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. Excluding retreat or advance periods for individual glaciers could show different annual area gain or loss rates. The numbers shown here represent the average annual area changes, without distinguishing between advance or retreat periods.

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, but 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). As shown by Abermann et al. (2009), relative area changes differ for specific glacier sizes and periods, so that regional differences can also be interpreted as related to the specific glacier types and their geomorphology.

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 area-weighted mean elevation of the glacier area is 2921 m a.s.l. in GI 2 and 2943 m a.s.l in GI 3. As an approximation to a theoretical AAR, 70% of the glacier area is located abvove 3029 ma.s.l. in GI 2 and above 3046 m a.s.l in GI 3.

The most severe absolute 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 percent of the area losses happened 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 (> 10 km²) in GI 1 and 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 0.002% (0.01 km²) of the total glacier area. In GI 2, 16 very small glaciers cover 0.024% (0.11 km²) of the total glacier area, and in GI 3 26 very small glaciers contribute 0.033% (0.14 km²) of the total glacier area.

5 Discussion

The uncertainties of the derived glacier areas are estimated to be highest for the LIA inventory, and decrease with time to 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 ±11.2km² or ±2.7%.

In case of changing observers, differences in the interpretation of the glacier boundaries must be taken into account. Various studies exist on that topic, e.g. by Paul et al. (2013) who investigated the accuracy of different observers manually digitizing glacier outlines from high (1 m) and medium resolution (30 m) remote sensing data and from automatic classification. They found high variabilities (up to 30%) for debris-covered parts and about 5% for clean ice parts. In contrast, in the presented study, all data have a spatial resolution of less than 5 m, GI 1 and GI 2 have been digitized manually by two observers and GI 3 followed their basic interpretation. The results of Paul et al. (2013) for changing observers, resolutions or methods thus do not directly apply to this study.

The period length between GI 2 and GI 3 differs, as both glacier inventories show some temporal variability. The shortest period length was two years in the very small Verwall group (3.66 km², 0.88% of the total glacier area). Only 1% of the total area of GI 3 was recorded less than five years after GI 2, 1.3% less than eight years later and 5.3% less than nine years later. Gardent et al. (2014) and Paul et al. (2011) found increasing change rates for short inventory periods, as they found the uncertainties in the area assessment higher than the change rates. For the present study, the change rate in the shortest periods GI2 to GI 3 (<5 years) is -18% to -22% of the GI 2 area, and thus much larger than the mapping accuracy of 2.7%. As the contribution of areas with short periods to the total area is small, the effect on the total area is also small.

Including seasonal or perennial snow fields attached to the glacier can introduce significant errors in calculating the glacier areas, affecting also area change rates when comparing inventories. The errors depend on the extent of the snow cover. As currently no operational method is available to identify snow covered ground or perennial snow fields from VIS imagery, the only possibility to minimize these errors is to use remote sensing data with minimum snow cover, which requires some additional information on the development of snow cover in the respective season from meteorological or mass balance time series. For future developments, radar imagery in L-band or tomographic radar as well as airborne ice thickness measurements could fill these gaps. As the firn and snow at the end of ablation season, when the minimum snow cover occurs and the perennial snow fields should be identified, still contains a high amount of liquid water, radar penetration depth decreases. An application to temperate glaciers as found in the Alps is therefore not feasible. . Another important point is the often small extent of perennial snow fields and their location in small structures, such as gullies or troughs, which might be beyond the spatial resolution of low frequency airborne or spaceborne radar systems.

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 and 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. In the present study, only the total glacier area in the mountain ranges has been compared.

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 1.7 % /year for 1999 to 2005, and 0,8 % /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. For the Swiss glaciers Maisch (1999) found an annual relative area change of -0.2%/year for 1850 to 1973 and about -1%/year between 1973 and 1999. For the Alps Paul et al. (2004) reported an annual relative area change rate of -1.3%/year for the period 1985 to 1999. All the above named periods differ in length and temporal occurrence, and the length and time of advance and retreat of glaciers vary. Therefore, even annual relative area change will not be fully comparable for the various inventories, but also include regional and geomorpholocial variabilities.

The glacier inventories presented here show i) high spatial resolution of the data base used to derive the glacier outlines ii) inclusion of additional information, such as ground truth data, snow cover maps from mass balance surveys and time lapse cameras as well as meteorological data iii) minimal snow cover at the time of the flights and iv) consistent nomenclature and ice divides for all four inventories. Given legal and monetary limitations, it might be difficult or even impossible to acquire the data used for this inventory time series for all glaciers in the world. The acquisition of airborne data might be more expensive and time-consuming than buying satellite data. 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 km² 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 might be a matter of spatial scales, debris cover, shadows and different definitions applied, and has no further implication.

6 Conclusions

This time series of glacier inventories presents a unique document of glacier area changes since the Little Ice Age. Total glacier area shrunk by 66 % between LIA maximum and GI 3, at increasing annual rates rising from 0.3%/year (LIA – GI 1), 0.6/year (GI1 – GI 2) to 1.2%/year (GI 2 – GI 3). During parts of the first two periods, some of the Austrian glaciers advanced, so that the latest period is the only one without glacier advances. The area changes vary for different mountain ranges and periods, with highest annual relative losses in the latest period GI 2- GI 3 for the small ranges Verwallgruppe (-5.9%/year) Samnaungruppe (-5.6%/year) and Karnische Alpen (-4.5%/year). 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 for the latest period, are smaller than 1%/year. Although the relative annual losses have generally increased since the LIA, some groups, for example Silvrettagruppe and Rätikon, exhibit a decrease in the latest period. The only glacier in Salzburger Kalkalpen region, Übergossene Alm, is currently disintegrating with annual relative area losses of 6.2 % and will thus likely vanish in the near future. The area-weighted mean elevation increased from 2921 m a.sl. in GI 2 to 2943 m a.sl. in GI 3, with highest absolute area losses taking place in elevations between 2700 and 2750 m a.s.l. The number of glaciers in the smallest size class (< 0.1 km²) increased between GI 1 and GI 3, the number of glaciers in the largest size class (> 10 km²) decreased. The 10 glaciers in the two largest size classes still cover 25% of the total glacier area. In GI 3, 49% of the glaciers are in the smallest size class, but cover only 5% of the total glacier area.

For deriving a statistics for specific glaciers, a discussion of the implications of disintegration of glacier tributaries is needed, including more data from various climate regions. We encourage the use of the presented data basis for further studies and investigations of glacier response to climate change.

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610

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 Year	GI III Year	Data source	LIA km²	GI-I km²	GI-II km²	GI-III 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.

Mountain 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: Absolute and relative 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
Number of glaciers in %							
in GI 1	22	50	14	12	1	1	100
in GI 2	43	37	10	9	1	0	100
in GI 3	49	33	8	8	1	0	100
% 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
Area in class in km²							
in GI 1	11.30	96.03	79.08	220.30	84.73	73.43	564.88
in GI 2	18.83	80.01	65.89	192.97	65.89	47.07	470.67
in GI 3	20.77	70.63	49.86	170.34	70.63	33.24	415.47

Figures

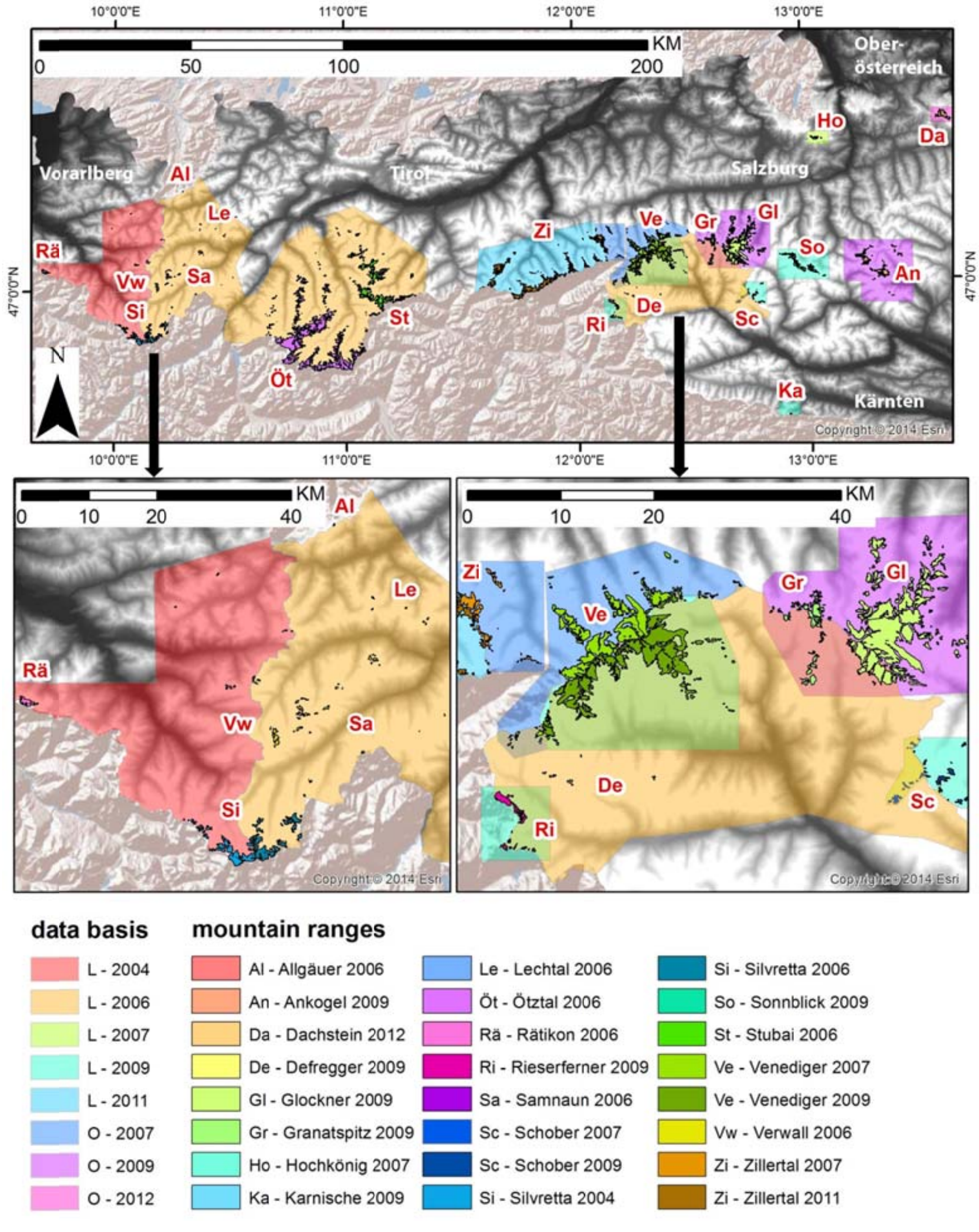

Figure 1: Austrian glaciers displayed on a DEM (Jarvis et al., 2009) color-coded by mountain ranges, with polygons showing data type and date used for deriving GI 3 and GI LIA (Mountain ranges and survey dates can also be found in Fischer et al. submitted).

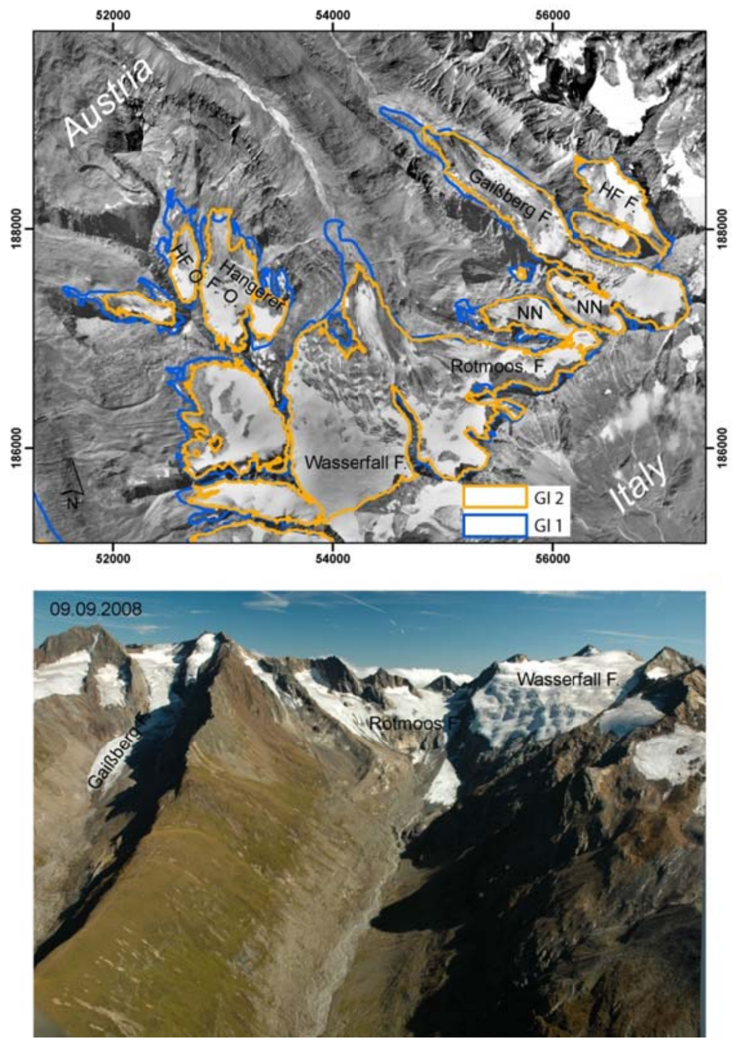

Figure 2: GI 1 and GI 2 glacier margins superimposed on a GI 2 orthophoto with an oblique photograph of the area in Ötztal Alps. HF O…Hangerer Ferner Ost, HF F…Hochfirst Ferner, NN …not named.

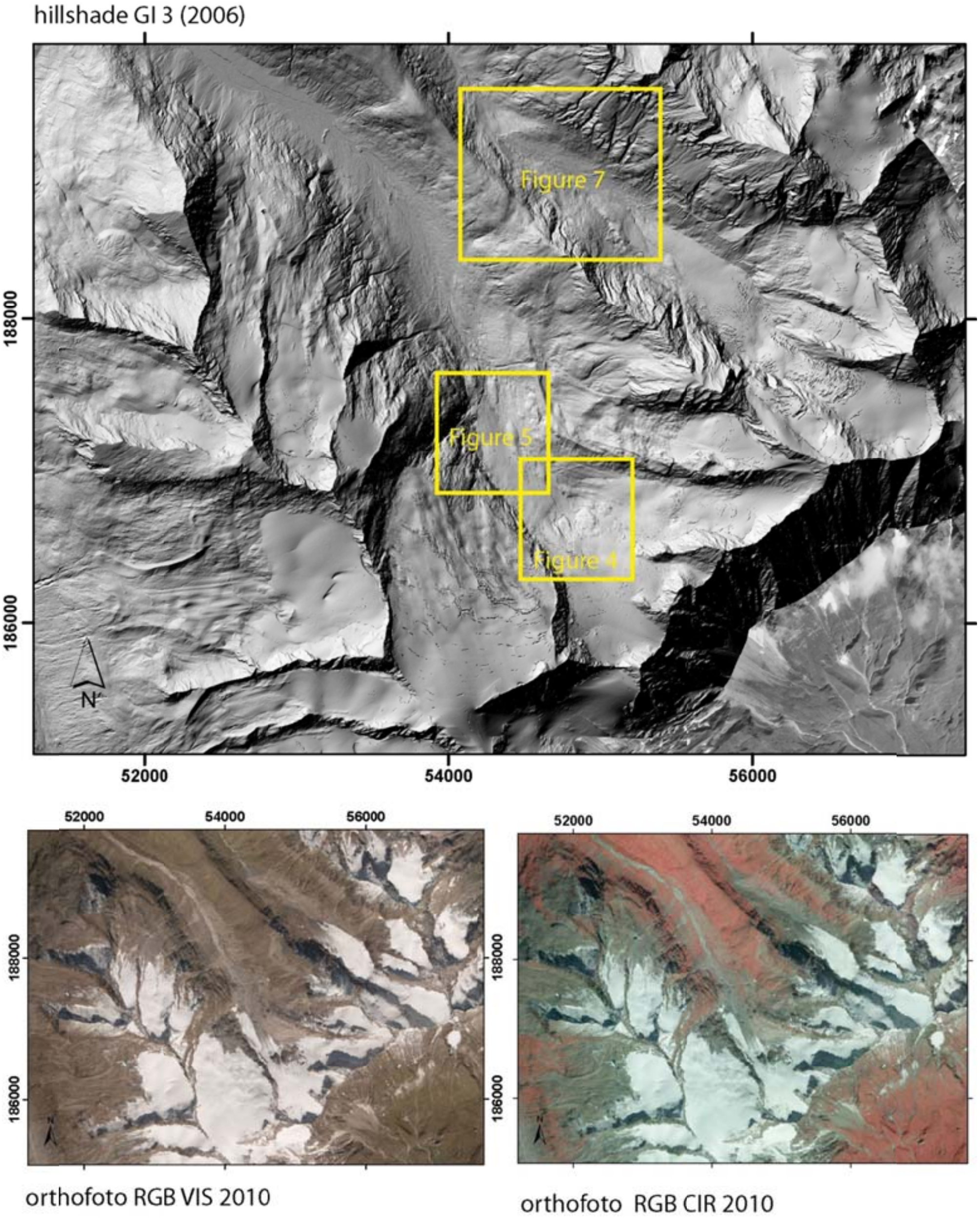

Figure 3: Example of an LiDAR hillshade (2006) of the same area as in Figure 2 with VIS and CIR RGB orthophotos from 2010 for comparison. The inserts show the position of the subsets shown in Figure 4 (lower right rectangle) and Figure 5 (upper left rectangle).

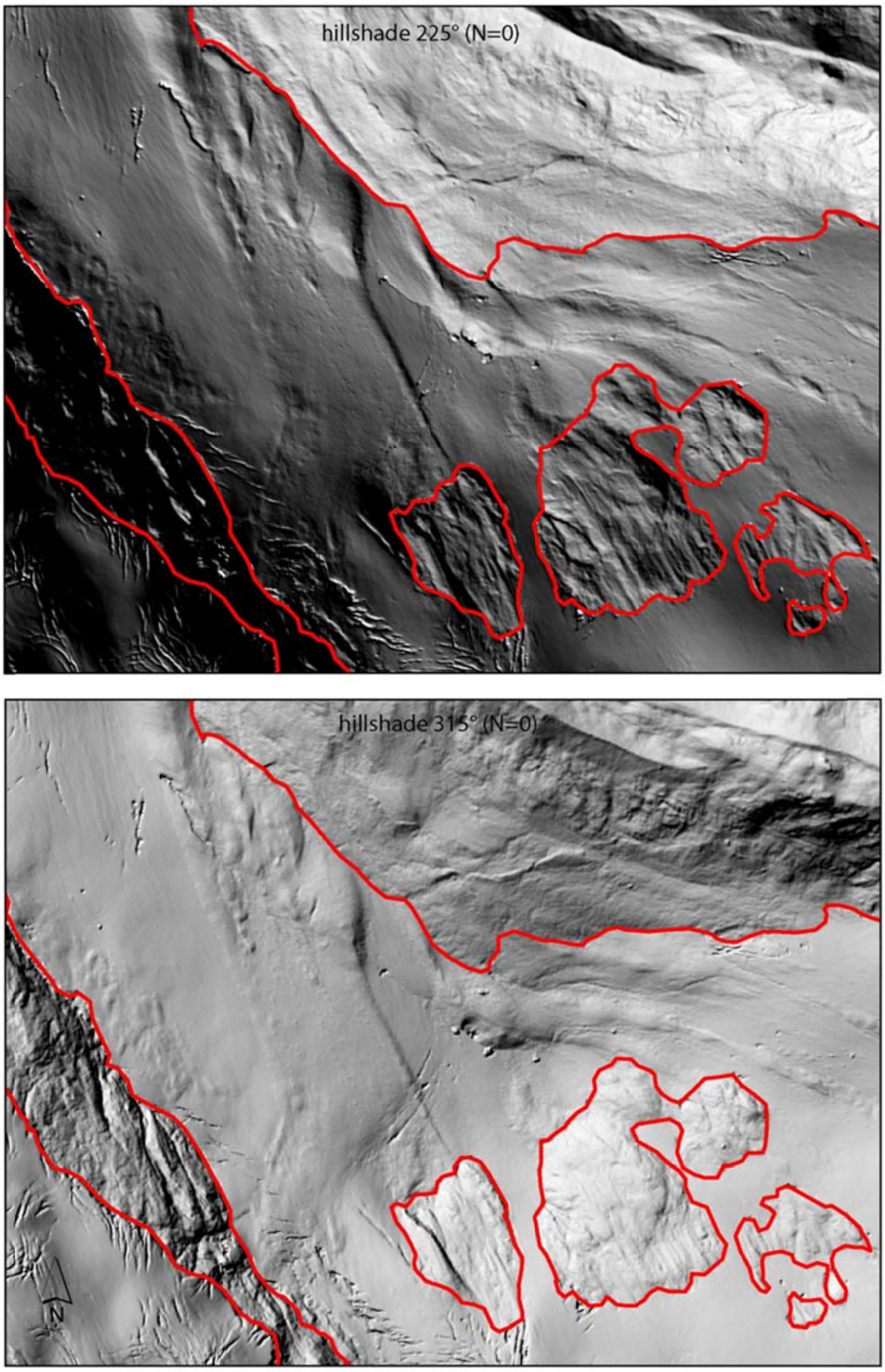
hillshade 225° (N=0)
hillshade 315° (N=0)
N

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

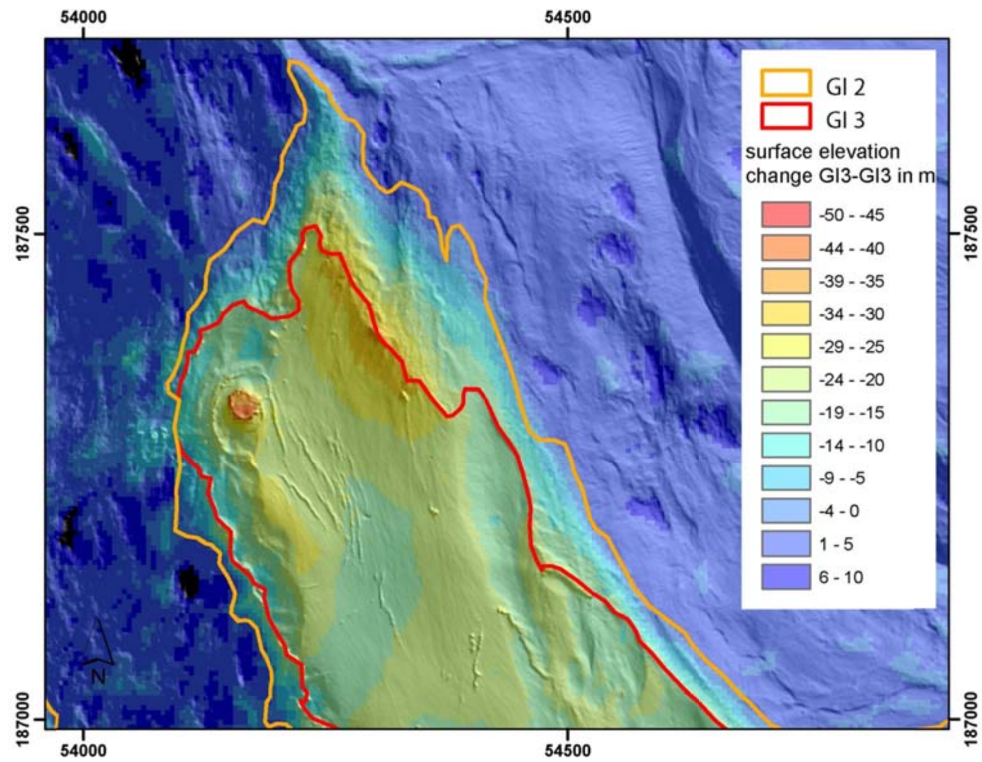

Figure 5: The elevation change between GI 2 and GI 3 superimposed on a hillshade shows that the elevation changes can help to delineate the actual (maximum elevation change) and previous (outer minimum of elevation change) position of the glacier margin (position of the subset shown in Figure 3).

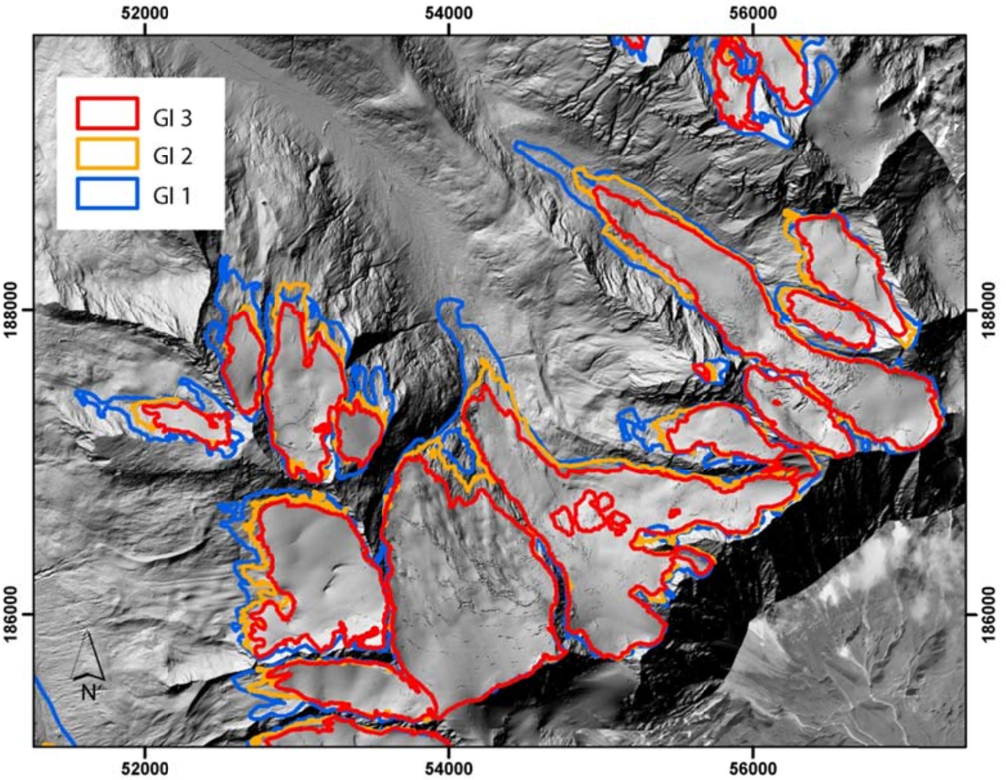
52000
54000
56000
GI 3
GI 2
GI 1
188000
186000
N

Figure 6: GI 3 glacier boundaries superimposed on LiDAR hillshade with GI 1 and GI 2 boundaries (same site as in Figure 2).

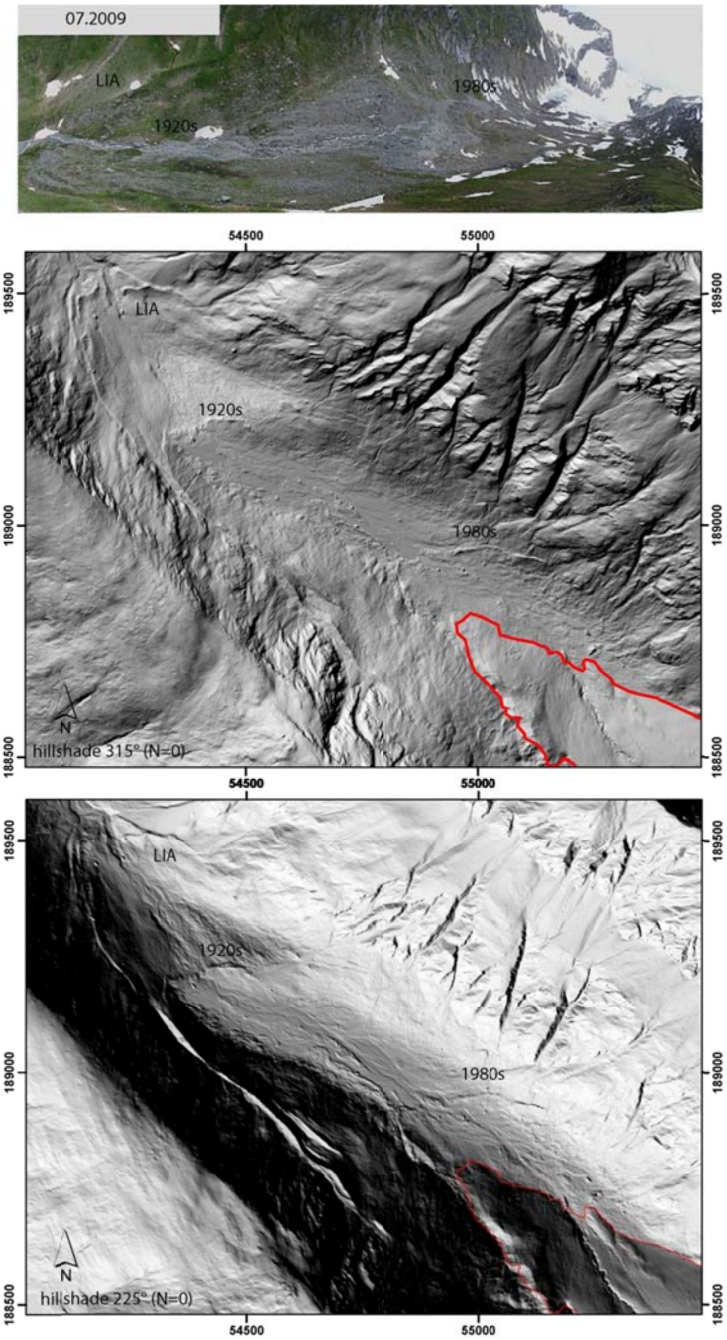

Figure 7: Periglacial area of Gaißbergferner with moraines dating from LIA, 1920 and 1980 (position of the subset: see Figure 3).

689

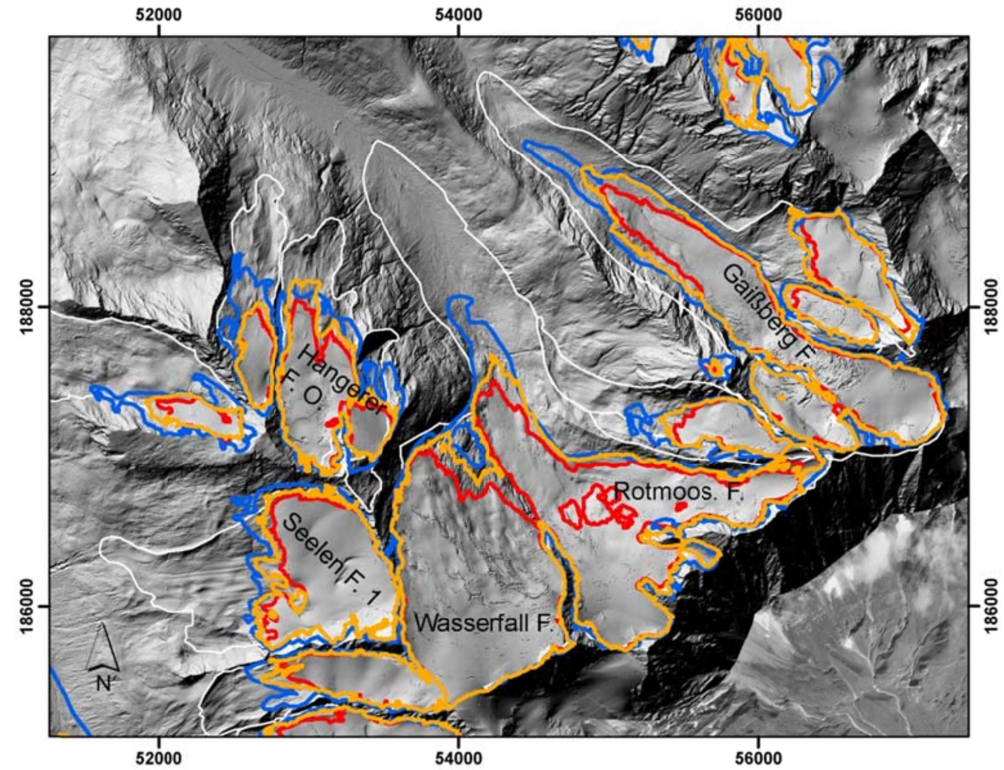

Figure 8: Resulting LIA glacier areas (white) with several modern glaciers contributing to the LIA Rotmoos Ferner and LIA Gaißbergferner (all glacier names: see Figure 2).

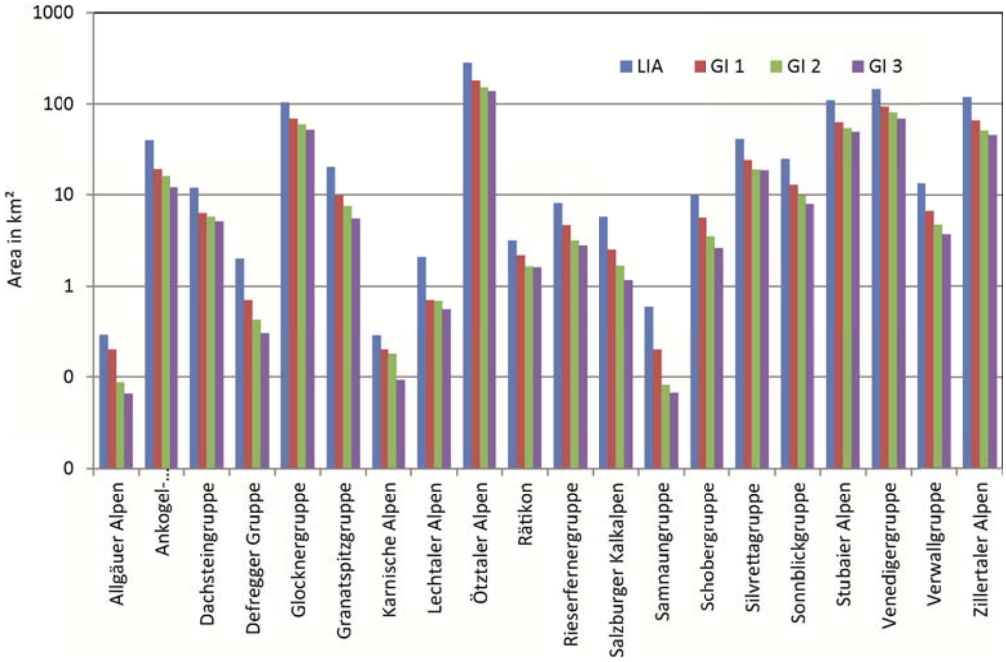

Figure 9: Glacier areas for specific mountain groups in GI LIA to GI 3.

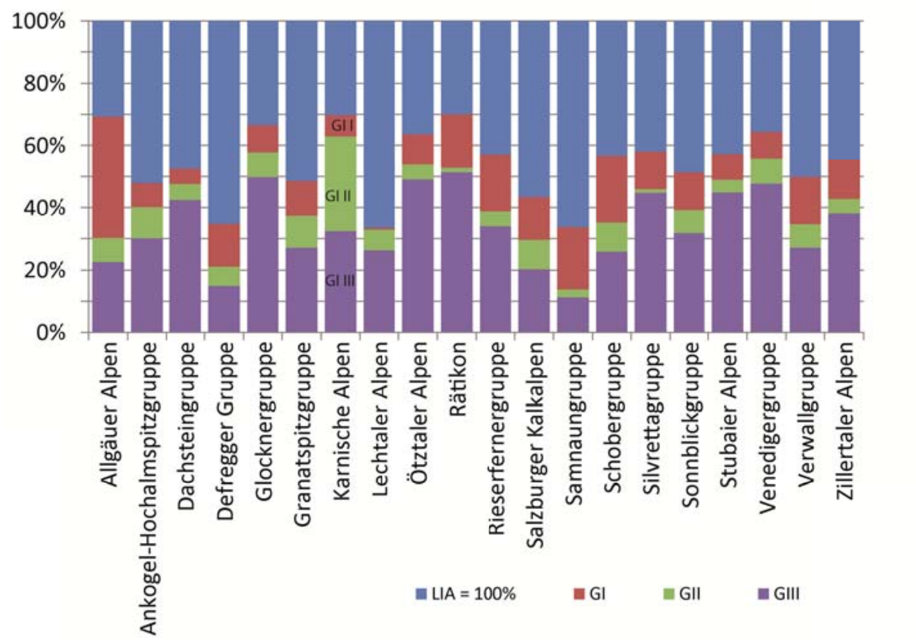

Figure 10: Area changes of specific mountain ranges in percentage of their LIA area.

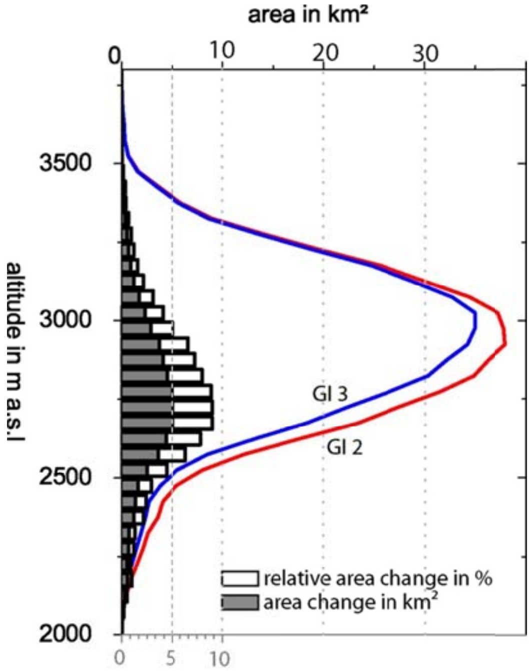

Figure 11: Altitudinal distribution of areas in GI 2 and GI 3 with absolute and relative area changes.

second federal survey (1816-1821) third federal survey (1869-1887)

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.