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Quantifying changes and trends in glacier area and volume in the Austrian Ötztal Alps (1969–1997–2006)

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Abstract

In this study we apply a simple and reliable method to derive recent changes in glacier area and volume by taking advantage of high resolution LIDAR (light detection and ranging) DEMs (digital elevation models) from the year 2006. Together with two existing glacier inventories (1969 and 1997) the new dataset enables to quantify area and volume changes over the past 37 years at three dates. This has been done for 81 glaciers (116 km^2) in the Ötztal Alps which accounts for almost one third of Austria's glacier extent. Glacier area and volume have reduced drastically with significant differences within the individual size classes. Between 1997 and 2006 an overall area loss of 10.5 km^2 or 8.2% occurred. Volume has reduced by 1.0 km^3 which accounts for a mean thickness change of −8.2 m. The availability of three comparable inventories allows a comprehensive analysis of glacier changes over all size classes but lacks a high temporal resolution. We therefore used glacier length as well as mass balance measurements from all available glaciers within the study area to analyse the potential temporal course of glacier changes in terms of area and volume which allows a rough estimation of mean annual area and volume changes and thus acceleration trends. Comparing the net retreating period between 1969 and 1997 with the period 1997 to 2006, the analysis reveals that mean annual absolute area losses have remained constant. Relative area losses have accelerated slightly whereas volume as well as mean thickness losses have accelerated significantly.

1 Introduction

For the past 40 years a general trend of glacial mass and area loss has been observed all over the world with only minor exceptions (e.g. Lemke et al., 2007; Oerlemans, 2005; Dyurgerov and Meier, 2000; Haeberli, 1999) and especially in the Alps (Lambrecht and Kuhn, 2007; Citterio et al., 2007; Kääb et al., 2002). In order to document the glacier resources, various national glacier inventories have been produced in recent years using different remote sensing techniques (e.g. photogrammetry (Lambrecht and Kuhn, 2007; Schneider et al., 2007), satellite data (Paul et al., 2002; Andreassen et al., 2008) or LIDAR (Knoll and Kerschner, 2009)). In Austria, two complete glacier inventories exist on the basis of analogue (1969) and digital (1998) airborne photogrammetry, respectively. The first one (1969) has been compiled by Patzelt (1980) and Groß (1987) and has later been digitised during the compilation of the second Austrian inventory 1998 (Lambrecht and Kuhn, 2007). Between these dates only maps of selected glaciers in the study area have been produced (e.g. Hintereisferner: Kuhn (1979) or Vernagtferner: Heipke et al. (1994), Endres (2001)).

The strong area and volume loss of the last decade raised the interest in an updated glacier inventory. Based on LIDAR-DEMs this was developed for the glaciologically well investigated southern part of the Austrian Ötztal Alps and is presented in this study. Besides forming an important source for the determination of glacier extent as its main purpose, periodically updated glacier boundaries are a necessary input for accurate mass balance studies (Elsberg et al., 2001), as well as any future glacier extent modelling approach.

A sequence of glacier inventories provides information on area and volume evolution between the respective datasets. However, it is not directly possible to extract trends of changes in a higher temporal resolution out of glacier inventory data directly (e.g. on a decadal basis). This is especially true, if, as in this study, a period of general area and volume loss was interrupted by a glacier advance around 1980 (Patzelt, 1985).

Therefore we used all available length change as well as mass balance measurements within the study area that have been measured annually during the whole investigation period to approach a higher resolution of area and volume changes. This information, however, is not directly convertible into area and volume changes and only exists for several glaciers that are not always representative for the study area.

Our first aim in this study is thus to present area and volume changes that occurred in the Ötztal Alps during the last decade, derived from LIDAR-DEMs in combination with former inventories, including altitude-dependent trend considerations. Secondly, we use the glacier inventories, with a high spatial but comparably low temporal resolution, in combination with the existing length and mass balance records (low spatial but high temporal resolution) to quantify higher resolved trends of glacier changes in terms of relative and absolute area, volume and mean thickness changes. The approach to relate the length and mass balance evolution to the area and volume trends allows a size-dependent analysis that covers all glaciers in the study area.

2 Study area

The Ötztal Alps are located in a central-alpine dry region at around 47° N and 11° E (Fliri, 1975). Their Austrian part is situated on the northern slope of the main alpine divide. Figure 1 shows the study area with the glacier extent of all Austrian Ötztal glaciers in 1997 (grey) and all updated glaciers in 2006 (red). In total, 81 glaciers of all size and exposition classes were remeasured, chosen simply by the extent of the DEM used, covering all well studied glaciers in this area. This new inventory accounts for 84% of the glacier area in this mountain range (1997: 151.2 km^2) and represents approx. 27% of the whole Austrian glacier area (1998: 469.7 km^2).

3 Data

3.1 Glacier inventory data

Two existing inventories were used for the determination of area and volume changes of the past four decades. The first one was established using aerial photographs of the year 1969 (Patzelt, 1980; Groß, 1987) and has been digitized later on (Lambrecht and Kuhn, 2007). In the years 1996–2002 a new inventory has been produced by means of digital photogrammetry. The results for all Austrian glaciers were then temporally homogenized for the year 1998 using a degree-day approach (Lambrecht and Kuhn, 2007). The DEMs of the Ötztal Alps for the second inventory have been acquired on the basis of 1997 – orthophotos (acquisition date: 11 September 1997), therefore we refer to this date further on. The vertical accuracy of these DEMs in general is better than ±1.9 m, according to Lambrecht and Kuhn (2007) and Eder et al. (2000). Only in extreme cases accuracies can exceed this value (Abermann et al., 2007).

Several studies show that LIDAR or ALS (airborne laser scanning) is a powerful tool to generate DEMs from glaciated as well as non-glaciated areas (e.g. Kennett and Eiken, 1997; Baltsavias et al., 2001; Geist et al., 2005; Geist and Stötter, 2007; Kodde et al., 2007; Geist and Stötter, 2009). The DEMs of 2006 were acquired by high resolution airborne LIDAR. The survey flights have been undertaken by the Regional Government of Tyrol between 23 August 2006 and 9 September 2006. This makes them well comparable with the data of 11 September 1997 both being close to the minimum snow extent. Details about the technical specifications of the used DEMs including general remarks of glacier boundary delineation out of DEMs are summarized in Abermann et al. (2009).

3.2 Glacier length change measurements

Variations of glacier lengths are determined annually by the length change measurement service of the Austrian Alpine club for a large number of glaciers with the results published annually in the club's magazine (until: 2003/2004: e.g. Patzelt, 2005; from 2004/2005: e.g. Patzelt, 2006). Within the study area length change measurements are performed annually on 16 glaciers since 1969. Glacier names, size and location of these glaciers are summarized in Table A1 (Appendix A).

3.3 Mass balance measurements

To estimate annual averages of volume and mean thickness changes between the inventories we used the temporal course of the available mass balance measurements. On three glaciers within the study area (Hintereisferner, Kesselwandferner and Vernagtferner) direct mass balance measurements are performed annually.

4 Methods

4.1 Area and volume changes

Abermann et al. (2009) proposed a method to delineate glacier boundaries by using hillshades of high-resolution DEMs as a primary data source and including information of multi-temporal DEMs as well as orthophotos to increase accuracies in ambiguous areas. Applying this method, we updated the glacier boundaries of 2006 on the basis of the 1997-inventory.

We kept ice divides constant during the delineation since they have not significantly changed over the past 40 years compared to the strong changes in the ablation area and thus played a somewhat negligible role in our considerations. Furthermore, we address overall changes in ice cover rather than changes of individual glaciers, therefore a shift of an ice divide does not change the results. We also remained consistent with the former inventories by including dead ice bodies and debris covered areas to the glacier area. If it was not possible to decide whether adjoining snow and firn areas cover ice or rocks, we included them to the glacier area as proposed in UNESCO (1970). The resulting glacier masks were identified according to the nomenclature of 1969 which is based on a systematic numbering within drainage areas. Thus, glaciers have not been renamed, even if they have disintegrated since the last inventory.

For the calculation of volume changes we first resampled all DEMs to the same cell size (5 m). This is done to avoid apparent accuracies. Then we subtracted one DEM from the other and multiplied the elevation difference per cell with the cell-size (5×5 m) to obtain volume changes.

The calculation of the mean thickness change has been performed by dividing the total volume change by a mean area of the respective period, which gives

$$\Delta \overline{z}_{1969-1997} = \frac{\Delta V_{1969-1997}}{0.5 \cdot (A_{1969} + A_{1997})} \quad (1)$$

for the period 1969–1997, or

$$\Delta \bar{z}_{1997-2006} = \frac{\Delta V_{1997-2006}}{0.5 \cdot (A_{1997} + A_{2006})} \tag{2}$$

for the period 1997–2006.

Abermann et al. (2009) estimated the accuracy of the applied method to be ±1.5% of the total area for glaciers larger than 1 km^2 and up to ±5% for smaller glaciers.

4.2 Estimating mean annual changes

4.2.1 Mean annual area changes

All length change measurements within the study area which cover the whole investigation period (16 glaciers, for details see Table A1, Appendix A) are plotted in Fig. 2 (crosses). The solid line displays their arithmetic mean. Individual glaciers respond very differently to changes in the climatic conditions: there are glaciers that have not reached the initial state of 1969 before 2003 after a period of significant advance and others that only responded with a decreased rate of negative length changes but show a continuous retreat since 1969. The temporal course of the arithmetic mean has been used to define the mean onset of the general glacier advance (1976, indicator 1), as well as the year in which the same length as at the beginning of the advance has been reached again (1989, indicator 2). This has been done because for an application to the glacier inventory data covering longer periods we are interested in a net loss. To estimate the mean annual area loss in the period between the first two inventories (1969 and 1997) we divided the absolute area changes by 16 which is the number of years with net area reduction.

For the period 1997–2006 a continuous area loss occurred. Therefore we derived estimates for a mean annual area change by dividing the overall changes by $9(\Delta A/\Delta t_{97-06\_\mathrm{retr}})$.

Changes in length and area are not to be compared between two different periods directly since they do not refer to the same absolute length/area. For this reason we also assess relative area changes by subtracting the average annual area change value ($\Delta A/\Delta t_{69-97\_\text{retr}}$ and $\Delta A/\Delta t_{97-06\_\text{retr}}$) from the initial glacier area for each timestep (year). This gives the opportunity to calculate a mean annual percentile area change, referring to a shrunken absolute value for each year. This has been performed with all individual size classes during both investigated periods again considering the same periods of net-area loss and results in $\Delta A/dt_{97-06\_\text{retr}\_\%}$ and $\Delta A/\Delta t_{69-97\_\text{retr}\_\%}$.

4.2.2 Mean annual volume and thickness changes

Figure 3 shows the temporal evolution of the cumulative mean specific mass balance of three glaciers within the study area and their arithmetic mean. To estimate average annual volume and mean thickness change values we extracted the year of the onset of mean mass gain (1973, indicator 3). The gain in mass during the positive mass balance years was finally compensated in 1985 by several negative years (indicator 4). Therefore we divided the overall volume changes for the period 1969–1997 by 17 years (17 out of 28 years contributed to the observed volume loss). For the second period (1997–2006) only one year has shown a sum of positive specific mass balance (2001). Therefore we divided the overall volume change for this period by 8, to derive mean annual values of the volume reduction within the respective period ($\Delta V/\Delta t_{97-06\_\text{retr}}$). Since the mean thickness change is directly connected with the volume loss (Eq. 1), we used the same length of intervals to derive mean annual values of $\Delta z/\Delta t_{69-97\_\text{retr}}$ and $\Delta z/\Delta t_{97-06\_\text{retr}}$.

5 Results

Glacier area, all other glacier inventory parameters, absolute and relative area changes, as well as absolute volume and mean thickness changes have been determined and calculated for each individual glacier within the study area for the year 2006 (81 glaciers, 116 km^2). Three out of originally 84 glaciers (1997) in the study area have shrunken below the minimum size of 0.01 km^2 to be accounted for as a glacier (UNESCO, 1970).

Figure 4a shows the area-altitude distribution of all updated glaciers for 1969, 1997 and 2006. Areas with the largest ice cover are between 3100 and 3200 m a.s.l. The minimum altitude of ice cover has risen from 2060 m a.s.l. to 2120 m a.s.l. between 1969 and 2006. It is worth noting, that the elevation of maximum ice-cover of the study area, as shown in Fig. 4a, is about 200 m higher (approx. 3200 m) than of all Austrian glaciers (Lambrecht and Kuhn, 2007, Fig. 3). This is due to the central-alpine dry climate of the Ötztal Alps as well as due to the comparably large areas that are available for potential glaciation in these high altitudes.

The absolute area changes (Fig. 4b) show that for both periods the strongest area loss occurred at about 3000 m a.s.l. There are, however, some significant differences considering the distribution over the entire altitude range. Up to approximately 2900 m a.s.l. both periods show similar values of absolute area changes, while in higher elevations the area reduction is about one third weaker for the period 1997–2006 than for 1969–1997. This means that for lower elevations a similar absolute area change has occurred within the last decade as it was observed within the 28 years before.

Figure 5a shows an example of area changes for Rotmoos- and Wasserfallferner in the southern Ötztal Alps. The glacier boundaries of the three dates (1969, 1997 and 2006) are plotted over the hillshade. Large rock outcrops developed on Rotmoosferner between 1997 and 2006. In 2005 the two glaciers separated, a phenomenon that is observed on various alpine glaciers during the glacier retreat of the past decades (e.g. Knoll and Kerschner, 2009; Paul et al., 2004). Elevation changes between 1997 and 2006 are plotted in Fig. 5b. An interesting detail is the slightly positive thickness change on Wasserfallferner which could be due to changed glacier dynamics after the separation.

The quantitative results are summarized in Table A2 and A3 (Appendix A). For this purpose the glaciers are divided into size classes based on their area in 2006. An overall absolute area change of −17.6 km^2 between 1969 and 1997 and −10.5 km^2 for 1997–2006 has been derived. This corresponds to a relative area change of −12.2% for 1969–1997 (referring to 1969) and −8.3% for 1997–2006 (referring to 1997). The respective values for the volume changes for these periods are −1.3 km^3 and −1.0 km^3 and −9.5 m and −8.2 m for the mean thickness changes. In general our results are similar but slightly more negative than the values that are derived by Knoll and Kerschner (2009) for the south Tyrolean glaciers (mean thickness change 1997–2006: −7.0). In the period 1969–1997 the relative area loss decreases with glacier size as plotted in Fig. 6. The largest values are observed for the smallest class (<0.1 km^2, −52.2%). The second period shows the strongest relative area losses for glaciers that are between 0.1 and 0.5 km^2 in area (−16.5%) whereas the smallest class lost significantly less in this second period (−11.8%).

To compare trends of area and volume changes we propose scaled parameters defined by

$$F_A = \frac{\frac{\Delta A_{97-06\_retr}}{\Delta t_{97-06\_retr}}}{\frac{\Delta A_{69-97\_retr}}{\Delta t_{69-97\_retr}}}, \tag{3}$$

$$F_{A\%} = \frac{\frac{\Delta A_{97-06\_retr\%}}{\Delta t_{97-06\_retr\%}}}{\frac{\Delta A_{69-97\_retr\%}}{\Delta t_{69-97\_retr\%}}}, \tag{4}$$

$$F_V = \frac{\frac{\Delta V_{97-06\_\mathrm{retr}}}{\Delta t_{97-06\_\mathrm{retr}}}}{\frac{\Delta V_{69-97\_\mathrm{retr}}}{\Delta t_{69-97\_\mathrm{retr}}}}, \tag{5}$$

$$F_{\bar{z}} = \frac{\frac{\Delta \bar{z}_{97-06\_\mathrm{retr}}}{\Delta t_{97-06\_\mathrm{retr}}}}{\frac{\Delta \bar{z}_{69-97\_\mathrm{retr}}}{\Delta t_{69-97\_\mathrm{retr}}}}. \tag{6}$$

These scaled parameters allow the direct comparison of glacier area and volume evolution within size classes and enable to contrast trends in absolute area change with relative, volume and mean thickness changes. They all refer to the net-retreating periods as derived above. A scaled parameter larger than 1 means that mean annual area losses have increased referring to the net-retreating periods. Figure 7 shows a size-dependent plot of the scaled parameters F_A, F_A%, F_V, and $F_{\bar{z}}$.

F_A shows that the mean absolute annual area changes remained the same during the retreating period 1969–1997 compared with 1997–2006. Only in the three largest classes (>5 km^2) an acceleration of approximately 10 to 20% (F_A=1.1 to 1.2) occurred. This means that for large glaciers the absolute area loss is slightly stronger in the time period 1997 to 2006 than for the 14 years with net area reduction (within a total of 28 years) before. The very small glaciers have decelerated significantly in terms of mean absolute annual area changes (F_A=0.2). We point out that a direct comparison of absolute values of area changes is critical. Their relative impact on overall glacier changes depends on the absolute glacier extent they refer to which may have changed between two periods.

Therefore we propose the use of relative area changes (F_A%) in order to enable a comparison between time periods and also between size classes. The mean annual relative area change increased by about 10% between the two periods (F_A%=1.1). This means, that an overall deceleration trend of absolute area has to be interpreted as a moderate acceleration trend relative to the remaining glacier area. Again the lowest values are observed for the smallest glaciers ($F_A\%=0.2$). The strongest increase in relative annual glacier area loss ($F_A\%=1.3$) occurs for the glaciers between 1 and 10 km^2 in size.

The mean annual ice volume changes have increased by more than 50% ($F_V=1.5$), while the mean annual thickness changes by more than 60% ($F_{\overline{z}}=1.6$). Analysing the different size classes reveals that the strongest changes occurred for glaciers between 0.5 and 1 km^2, where the mean annual volume change as well as the mean annual thickness change more than doubled ($F_V=2.2$, $F_{\overline{z}}=2.4$) compared to the net-retreating period within 1969 to 1997. Again, glaciers of the smallest size class show a decrease in mean annual volume changes compared to the earlier period ($F_V=0.7$). This is in line with trends in area changes that have been highlighted earlier.

6 Discussion and conclusion

A reliable and sufficiently accurate method has been applied to derive recent glacier area and volume changes in the Ötztal Alps out of two existing glacier inventories as well as high-resolution LIDAR-DEMs. An important prerequisite is the application of consistent methods and decision rules (e.g. concerning ice divides, debris-covered areas, snow and ambiguous areas), in order to create comparable inventories.

Additional information as continuous length change and mass balance measurements has been used to derive estimates for the evolution of mean annual area and volume changes. The limited number of glaciers for which this additional information exists and thus the unequal distribution over the size classes of continuously measured glaciers allows only generalised estimates for the individual periods, but no year-by-year analysis of glacier changes. Therefore no annual area and volume changes for a selected year can be calculated for the entire inventory, but rather longer-term trends (e.g. decadal means of annual changes) were compared.

Length and area changes are linked but do not necessarily follow exactly the same pattern. It depends on the topography of the individual glacier how different length and area respond to a climatic change but the sign of this evolution is likely to be the same. Since we only extract the temporal evolution of the length change and relate them qualitatively to the observed area change we feel confident enough to do so.

The fact that the smallest class (<0.1 km^2) has decelerated to retreat in terms of area change suggests that these glaciers are now in a state closer to equilibrium than they used to be in the previous period. Differences in area change between the two periods are very large in this class (Table A2, Figs. 6 and 7) therefore we draw this conclusion even though interpretation uncertainties are larger for small glaciers.

Glacier area losses in low elevations have increased stronger than in high elevation as shown in Fig. 4b. This may be due to changes in energy balance (e.g. air temperature, albedo, turbulence) and in the fraction of solid precipitation of the overall precipitation that have a stronger effect on glacier changes in low elevations since these regions are generally closer to melting conditions. Furthermore, ice motion slowed down significantly during recent years which slows down dynamic ice supply of glacier tongues (e.g. Abermann et al., 2007).

The comparison of the scaled parameters discussed reveals that the parameters connected with volume changes (F_V, $F_{\bar{z}}$) are significantly larger than the ones connected with area changes (F_A, F_A%). This means that mean annual volume and mean thickness changes have increased more than mean annual area changes across all size classes compared to the respective values for the period (1969–1997). Taking an extensive data set of ice thickness measurements in the study area into consideration we found that the larger valley glaciers still have a considerable ice thickness in low elevations (a typical value for glaciers within the study area between 1 and 5 km^2 is 60 m at the tongue in 2700 m a.s.l., larger glaciers up to 150 m (Span et al., 2005; Fischer et al., 2007)). This geometric constellation results in the fact that mean annual volume or mean thickness changes (thick glacier tongues melt down) increase strongly while mean annual area changes do not increase significantly. This particularly affects the size class of glaciers that are within 0.5 and 1 km^2 where the mean relative annual area change has not changed (F_A%=1.0) but the mean annual volume change as well as the mean annual thickness change more than doubled (F_V=2.2, $F_{\overline{z}}$=2.4). It can be anticipated that this trend may reverse as soon as the tongues have become thin enough to melt away and loose large areas within few years without losing a lot of volume. This point in time is individual for each glacier and should be evaluated further together with ice volume data and an energy balance model.

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References

Abermann, J., Fischer, A., Lambrecht, A., and Geist, T.: Multi-temporal airborne LIDAR-DEMs for glacier and permafrost mapping and monitoring, The Cryosphere Discuss., 3, 383–414, 2009, http://www.the-cryosphere.net/3/383/2009/.

Abermann, J., Lambrecht, A., and Schneider, H.: Analysis of surface elevation changes on Kesselwand glacier – Comparison of different methods, Zeitschrift für Gletscherkunde und Glazialgeologie, 41, 147–168, 2007.

Andreassen, L. M., Paul, F., Kääb, A., and Hausberg, J. E.: Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s, The Cryosphere, 2, 131–145, 2008, http://www.the-cryosphere-discuss.net/2/131/2008/.

Baltsavias, E.P., Favey, E., Bauder, A., Bösch, H., and Pateraki, M.: Digital Surface Modelling by Airborne Laser Scanning and Digital Photogrammetry for Glacier Monitoring, Photogramm. Rec., 17(98), 243–273, 2001.

Citterio, M., Diolaiuti, G., Smiraglia, C., D'Agata, C., Carnielli, T., Stella G., and Siletto, G. B.: The fluctuations of Italian glaciers during the last century: a contribution to knowledge about Alpine glacier changes, Geogr. Ann. A, 89(A), 167–184, 2007.

Dyurgerov, M. B. and Meier, M. F.: Twenthieth century climate change: Evidence from small glaciers, PNAS, 97, 1406–1411, 2000.

Eder, K., Würländer, R., and Rentsch, H.: Digital photogrammetry for the new glacier inventory of Austria, IAPRS International Archives of Photogrammetry and Remote Sensing, 33, 1–15, 2000.

Elsberg, D. H., Harrison, W. J., Echelmeyer, K. A., and Krimmel, R. M.: Quantifying the effect of climate and surface change on glacier mass balance, J. Glaciol., 47(159), 649–658, 2001.

Endres, J.: Farborthophotokarte "Vernagtferner 1999" aus Amateur-Luftbildern, Diploma thesis technical university of Munich, Munich, 2001.

Fischer, A., Span, N., Kuhn, M., and Butschek, M.: Radarmessungen der Eisdicke österreichischer Gletscher, Band II: Messungen 1999 bis 2006, Österreichische Beiträge zu Meteorologie und Geophysik, 39, Zentralanstalt für Meteorologie und Geodynamik, Wien, 2007.

Fliri, F.: Das Klima im Raume von Tirol, Universitätsverlag Wagner, Innsbruck-München, 1975.

Geist, T., Elvehoy, H., Jackson, M., and Stötter, J.: Investigations on intra-annual elevation changes using multitemporal airborne laser scanning data – case study Engabreen, Norway, Ann. Glaciol., 42, 195–201, 2005.

Geist, T. and Stötter, J.: Documentation of glacier surface elevation change with multi-temporal airborne laser scanner data – case study: Hintereisferner and Kesselwandferner, Tyrol, Austria, Zeitschrift für Gletscherkunde und Glazialgeologie, 41, 77–106, 2007.

Geist, T. and Stötter, J.: Laser scanning in glacier studies, in: Remote Sensing of Glaciers, Taylor & Francis Ltd., London, 2009.

Gross, G.: Der Flächenverlust der Gletscher in Österreich 1850–1920–1969, Zeitschrift für Gletscherkunde und Glazialgeologie, 23, 131–141, 1987.

Haeberli, W., Frauenfelder, R., Hoelzle, M., and Maisch, M.: On rates and acceleration trends of global glacier mass changes, Geogr. Ann. A, 81(A), 585–591, 1999.

Heipke, C., Rentsch, H., Rentsch, M., and Würländer, R.: The digital orthophoto map Vernagtferner 1990, Zeitschrift für Gletscherkunde und Glazialgeologie, 30, 109–117, 1994.

Kääb, A., Paul, F., Maisch, M., and Häberli, W.: The new remote-sensing-derived Swiss Glacier Inventory: II, First results, Ann. Glaciol., 34, 362–366, 2002.

Kennett, M. and Eiken, T.: Airborne measurement of glacier surface elevation by scanning laser altimeter, Ann. Glaciol., 24, 293–296, 1997.

Knoll, C. and Kerschner, H.: A glacier inventory for South Tyrol, Italy, based on airborne laser scanner data, Ann. Glaciol., 50(53), submitted, 2009.

Kodde, M., Pfeiffer, N., Gorte, B., Geist, T., and Höfle, B.: Automatic Glacier Surface Analysis from Airborne Laser Scanning, ISPRS Workshop Laser Scanning 2007, XXXVI Part 3/W52, 221–226, 2007.

Kuhn, M.: Begleitworte zur Karte des Hintereisferners 1979, 1:10 000, Zeitschrift für Gletscherkunde und Glazialgeologie, 16, 117–124, 1979.

Lambrecht, A. and Kuhn, M.: Glacier changes in the Austrian Alps during the last three decades, derived from the new Austrian glacier inventory, Ann. Glaciol., 46, 177–184, 2007.

Lemke, P., Ren, J., Alley, R. J. et al.: Observations: Changes in Snow, Ice and Frozen Ground, in: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M. et al., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Oerlemans, J.: Extracting a climate signal from 169 glacier records, Science, 308, 675–677, 2005.

Patzelt, G.: The Austrian glacier inventory: status and first results. Riederalp Workshop 1978 – World Glacier Inventory, IAHS, 1980.

Patzelt, G.: The period of glacier advances in the Alps, 1960 to 1985, Zeitschrift für Gletscherkunde und Glazialgeologie, 21, 403–407, 1985.

Patzelt, G.: Gletscherbericht 2003/2004, Sammelbericht über die Gletschermessungen des Oesterreichischen Alpenvereins im Jahre 2004, Mitteilungen des Oesterreichischen Alpenvereins, 60(130), 24–31, 2005.

Patzelt, G.: Gletscherbericht 2004/2005, Sammelbericht über die Gletschermessungen des Österreichischen Alpenvereins im Jahre 2005, Bergauf, 2, 6–11, 2006.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., and Häberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31(21), L21402, doi:10.1029/2004GL020816, 2004.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T. W., and Häberli, W.: The new remote-sensing-derived Swiss Glacier Inventory: I, methods, Ann. Glaciol., 34, 355–361, 2002.

Schneider, C., Schnirch, M., Acuña, C., Casassa, G., and Kilian, R.: Glacier inventory of the Gran Campo Nevado Ice Cap in the Southern Andes and glacier changes observed during recent decades, Global Planet. Change, 59(1–4), 87–100, 2007.

Spa, N., Fischer, A., Kuhn, M., Massimo, M., and Butschek, M.: Radarmessungen der

Eisdicke österreichischer Gletscher, Band I: Messungen 1995 bis 1998, Österreichische Beiträge zu Meteorologie und Geophysik, 33, Zentralanstalt für Meteorologie und Geodynamik, Wien, 2005.

UNESCO: Perennial ice and snow masses: a guide for compilation and assemblage of data for a world inventory, Technical Paper Hydrology 1, UNESCO/IASH, 1970.

Table 1. Name, size and coordinates of the glaciers for which annual length change measurements are available for the whole investigation period (1969–2006).

Name	size 2006 [km^2]	Lon [° E]	Lat [° N]
Diemferner	2.34	11.07	46.83
Gaissbergferner	1.03	11.02	46.78
Gepatschferner	16.62	10.95	46.81
Großer Guslarferner	1.40	10.91	46.79
Hintereisferner	7.49	10.86	46.77
Hochjochferner	6.07	10.82	46.79
Kesselwandferner	3.82	10.76	46.80
Langtalerferner	2.62	10.79	46.84
Mutmalferner	0.56	10.80	46.85
Niederjochferner	1.87	10.82	46.88
Rettenbachferner	1.48	10.88	46.88
Rofenkarferner	1.14	10.93	46.93
Sexegertenferner	1.96	10.76	46.85
Taschachferner E	5.71	10.71	46.85
Vernagtferner	8.32	10.85	46.90
Weisseeferner	2.59	10.80	46.89

Table 2. Summary of absolute and relative area changes as well as mean annual changes and proportional factors, 1969–2006.

Class [km^2]	Count 06	A 69 [km^2]	A 97 [km^2]	A 06 [km^2]	ΔA 69–97 [km^2]	%	ΔA 97–06 [km^2]	%	$\Delta A/\Delta t$ 6997_retr [km^2/a]	$\Delta A/\Delta t$ 9706_retr [km^2/a]	F_A	$\Delta A/\Delta t$ 6997_retr_% [%/a]	$\Delta A/\Delta t$ 9706_retr_% [%/a]	$F_{A\%}$
<20	1	18.0	17.2	16.6	−0.8	−4.4	−0.5	−3.1	−0.1	−0.1	1.1	−0.3	−0.3	1.2
<10	7	64.5	57.8	53.2	−6.7	−10.4	−4.6	−8.0	−0.5	−0.5	1.2	−0.7	−0.9	1.3
<5	15	38.7	34.3	31.3	−4.4	−11.4	−3.0	−8.7	−0.3	−0.3	1.1	−0.7	−1.0	1.3
<1	11	10.1	8.2	7.3	−1.8	−18.2	−0.9	−10.9	−0.1	−0.1	0.8	−1.2	−1.3	1.0
<0.5	25	10.1	7.8	6.5	−2.4	−23.3	−1.3	−16.5	−0.2	−0.1	0.9	−1.6	−1.9	1.1
<0.1	22	2.8	1.4	1.2	−1.5	−52.2	−0.2	−11.8	−0.1	−0.0	0.2	−4.3	−1.9	0.2
All	*81*	*144.2*	*126.6*	*116.1*	*−17.6*	*−12.2*	*−10.5*	*−8.3*	*−1.2*	*−1.2*	*1.0*	*−0.8*	*−0.9*	*1.1*

Table 3. Summary of volume and mean thickness changes as well as mean annual changes and their proportional factors, 1969–2006.

Class [km^2]	ΔV 69–97 [$\times 10^6$m^3]	ΔV 97–06 [$\times 10^6$m^3]	$\Delta V/\Delta t$ 69–97_retr [$\times 10^6$m^3/a]	$\Delta V/\Delta t$ 97–06_retr [$\times 10^6$m^3/a]	F_V	$\Delta\bar{z}_{69-97}$ [m]	$\Delta\bar{z}_{97-06}$ [m]	$\Delta z/\Delta t$ 69-97_retr [m/a]	$\Delta z/\Delta t$ 97-06_retr [m/a]	$F_{\bar{z}}$
<20	−129	−78	−8	−10	1.2	−7.4	−4.6	−0.5	−0.6	1.2
<10	−688	−554	−43	−69	1.6	−11.2	−10.0	−0.8	−1.3	1.7
<5	−331	−239	−21	−30	1.4	−9.1	−7.3	−0.6	−0.9	1.5
<1	−57	−61	−4	−8	2.2	−6.2	−7.8	−0.4	−1.0	2.4
<0.5	−63	−52	−4	−7	1.7	−7.0	−7.4	−0.5	−0.9	2.0
<0.1	−19	−7	−1	−1	0.7	−9.3	−5.1	−0.6	−0.6	1.0
All	*−1286*	*−990*	*−80*	*−124*	*1.5*	*−9.5*	*−8.2*	*−0.6*	*−1.0*	*1.6*

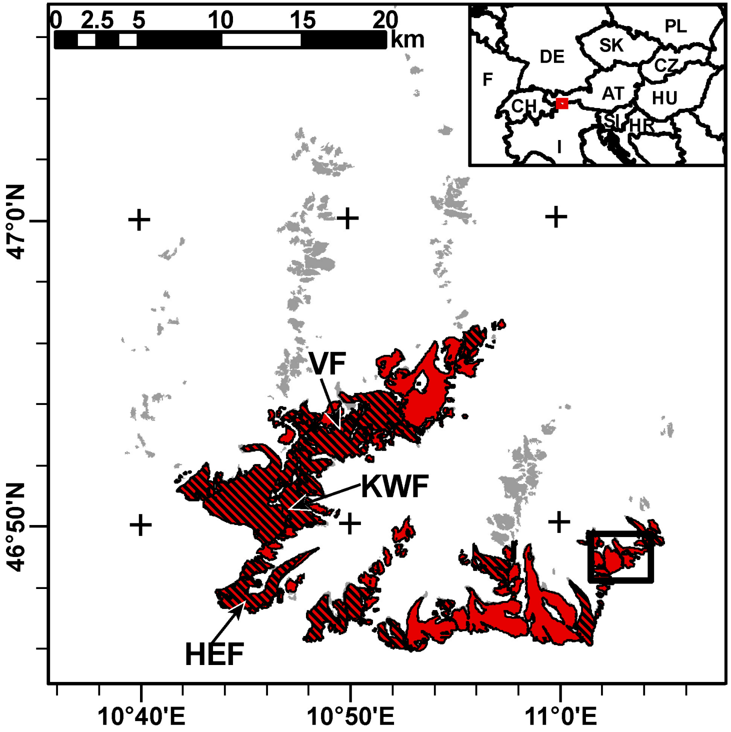

Fig. 1. Study area Ötztal Alps (Grey: glacier extent 1997, red: updated glacier extent 2006, dashed: glaciers with length measurement records in the study area, black rectangle: extent of Fig. 4). HEF, KWF and VF refer to three glaciers with mass balance records (Hintereisferner, Kesselwandferner and Vernagtferner).

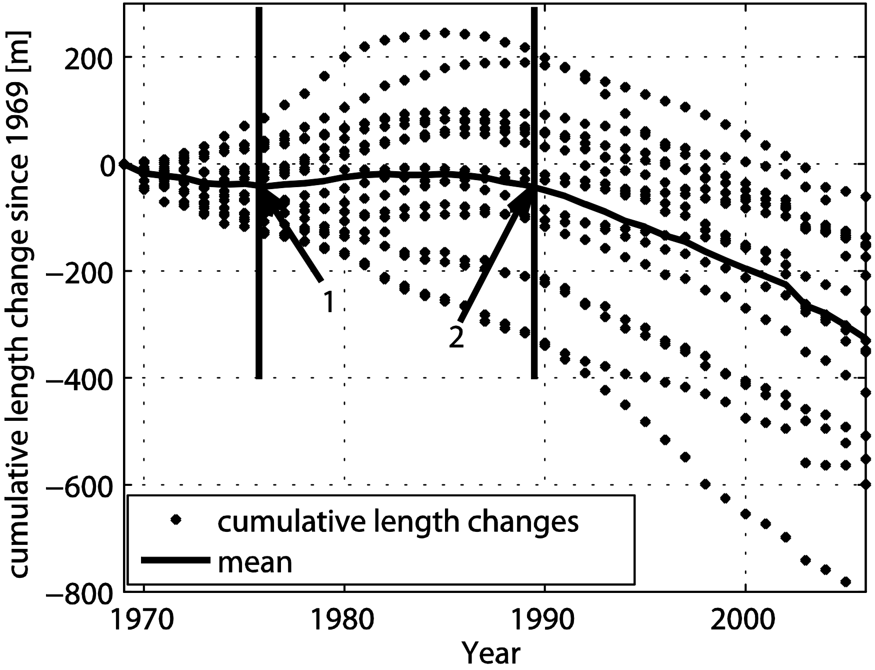

Fig. 2. Cumulative length change for all glaciers that cover the entire period (crosses) and the arithmetic mean over these curves (solid). Arrow 1 indicates the derived onset of the advance period (1976), arrow 2 the state where the same cumulative length as in 1 has been reached again (1989).

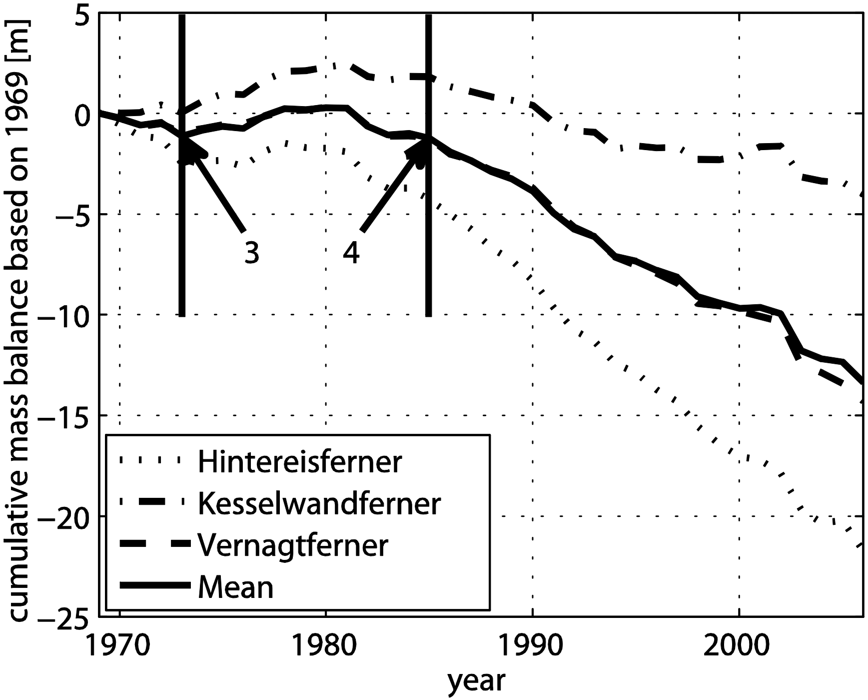

Fig. 3. Cumulative mean specific mass balance of the glaciers Hintereisferner, Kesselwandferner and Vernagtferner and their mean refering to 1969. It is pure coincidence, that the cumulative balance values of the mean and of Vernagtferner follow almost exactly the same temporal course. Arrow 3 indicates the year when an overall mass gain starts (1973) and by the year 1985 (arrow 4), the same volume was reached again.

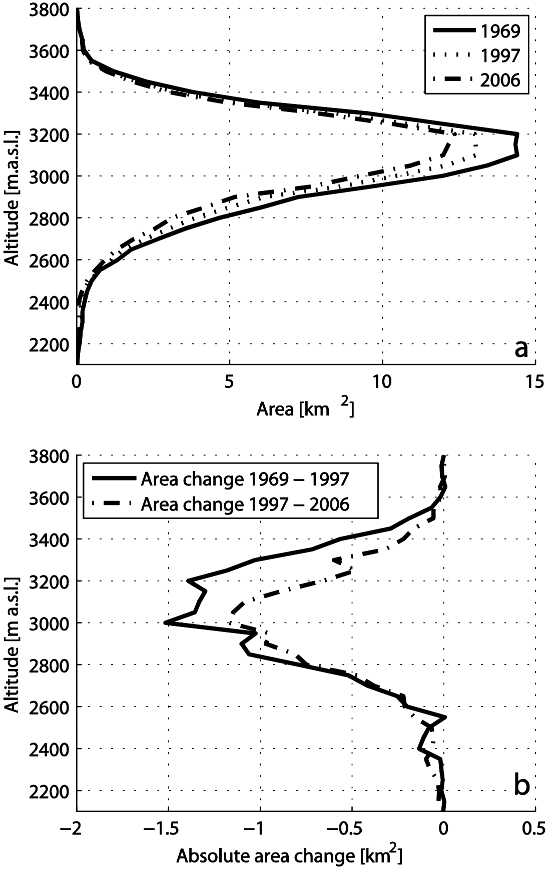

Fig. 4. Area-altitude distribution in 50m-intervals of all updated glaciers for 1969, 1997 and 2006 **(a)** and absolute area changes of the 50m-intervals for the periods 1969–1997 and 1997–2006 **(b)**.

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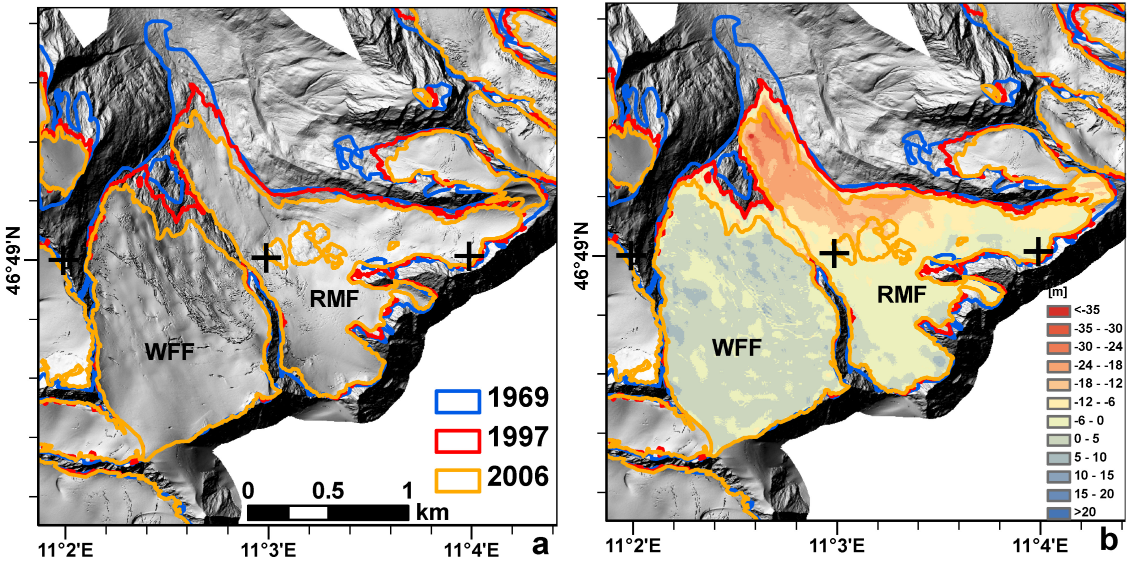

Fig. 5. Rotmoosferner (RMF), Wasserfallferner (WFF) and their surrounding glaciers: Hillshade and glacier boundary 1969, 1997 and 2006 **(a)**; glacier boundaries as well as thickness change 1997–2006 **(b)**.

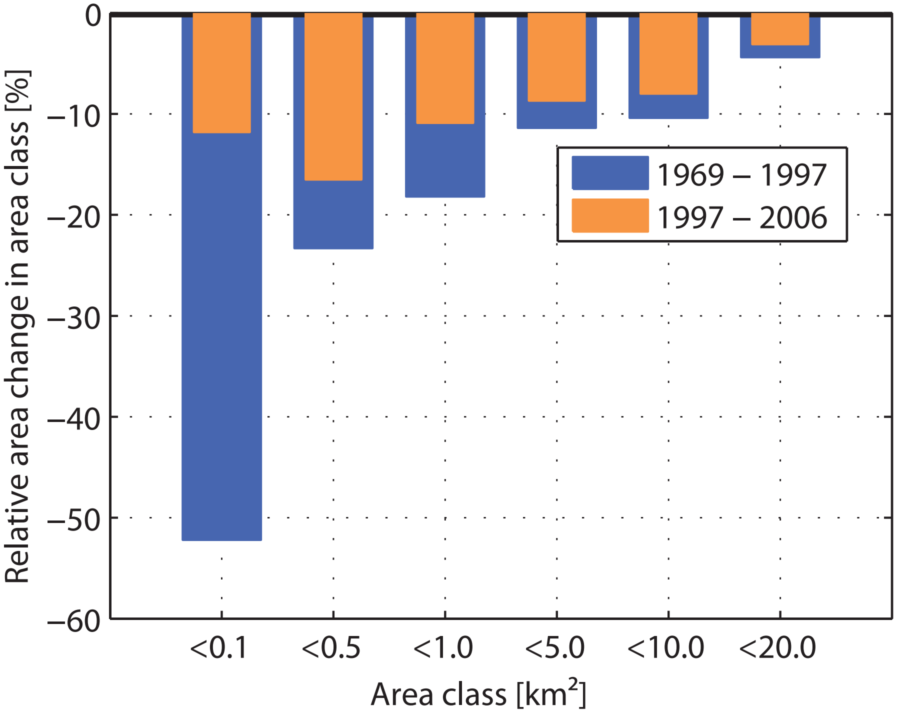

Fig. 6. Relative area changes for the period 1969–1997 (blue) and 1997–2006 (orange) for the individual size classes.

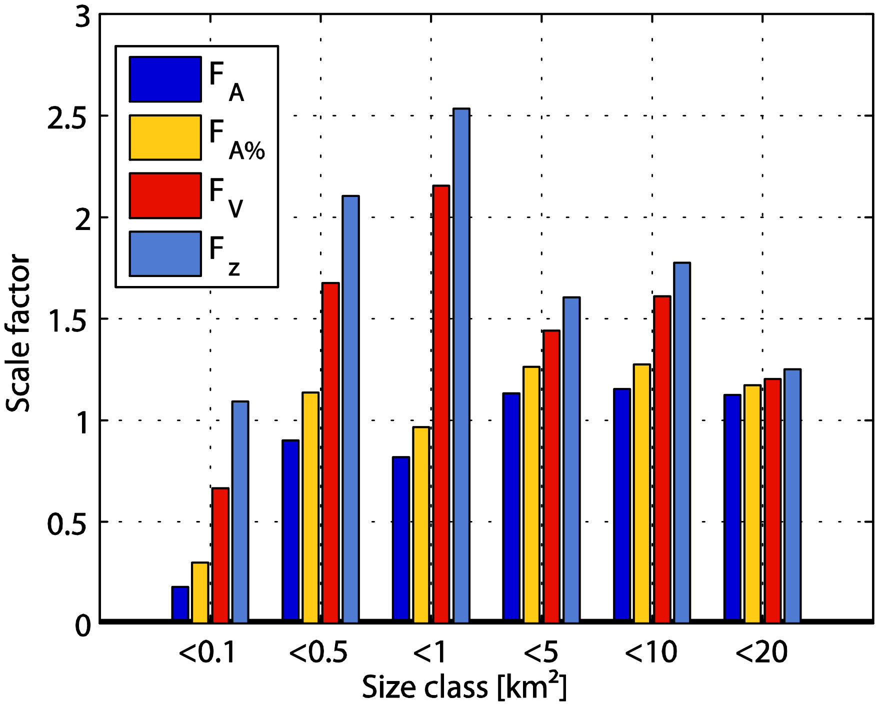

Fig. 7. Scaled parameters referring to mean annual area (absolute and relative) as well as volume and mean thickness changes. The length of the periods, the means are derived with, are extracted out of Figs. 2 and 3 as explained in 4.2.