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Multi-temporal airborne LIDAR-DEMs for glacier and permafrost mapping and monitoring

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Abstract

The proposed method presents a simple and robust way to derive glacier extent by using multi-temporal high-resolution DEMs (digital elevation models) as a main data source. For glaciers that are not debris covered, we perform the glacier boundary delineation by analysing roughness differences between ice and its surroundings. A promising way to distinguish dead ice, debris-covered ice or permafrost from its rocky surroundings is shown by taking elevation changes from DEMs of different dates into consideration. In case data has a high spatial and temporal resolution a good representation of the extent of debris cover and thus the overall ice covered area can be given. We use examples to show how potentially ambiguous areas can be treated decisively by the additional qualitative analysis of aerial photographs. Problems and limitations are discussed in comparison with selected other remote sensing techniques and accuracies are quantified. For glaciers larger than 1 km^2 an accuracy of ±1% of the glacier area could be assessed. The errors of smaller glaciers do not exceed ±5% of the glacier area.

1 Introduction

An overall glacier area and mass loss has been observed in the past decades throughout the world (e.g. Lemke et al., 2007; Dyurgerov and Meier, 2000; Haeberli, 1999; Oerlemans, 2005) as a result of climate change (e.g. Lemke et al., 2007; Trenberth et al., 2007). Many studies deal with mass-balance as well as run-off modelling to develop future scenarios of glacier extent and volume. These future states have large implications on the economy (water resources, tourism) of alpine regions. To quantify the recent changes and its current state in terms of area and volume, an actual dataset of glacier extent is thus mandatory. Additionally, a sound knowledge of the distribution of active rock glaciers is of interest for studies dealing with permafrost in a changing climate.

Mapping glacier extent and volume changes with remote sensing techniques is a widely used and powerful method. Various studies show the potential and limitations of using satellite data (e.g. Andreassen et al., 2008; DeBeer and Sharp, 2007; Paul et al., 2007), airborne techniques as photogrammetry (e.g. Patzelt, 1980; Würländer et al., 2004) or LIDAR (light detetction and ranging, e.g. Baltsavias et al., 2001; Favey et al., 2002; Geist et al., 2003; Geist and Stötter, 2007; Geist and Stötter, 2009). Automatic or semi-automatic classification algorithms (Kodde et al., 2007; Paul et al., 2002; Höfle et al., 2007) are used to classify glacier areas.

For both, automatic and manual methods, the mapping of debris covered glacier areas is a general problem (e.g. Knoll and Kerschner, 2009; Paul et al., 2002). Furthermore, the automatic mapping of small glaciers is difficult (e.g. Paul et al., 2002). Lambrecht and Kuhn (2007) showed that 79% of all Austrian glaciers are smaller than 0.5 km^2 and 43% smaller than 0.1 km^2.

These facts raised the need to develop a methodology for mapping and monitoring of all sizes of glaciers with and without debris cover and for the detection of rock glaciers.

In this paper, the use of high resolution DEMs for the monitoring of glacier and permafrost extent and volume changes is developed: The technique is applied to several test sites in the Austrian Alps, and compared to other mapping procedures.

2 Test sites and data

Three glaciers and one rock glacier in the Ötztal Alps were chosen as test sites. Hintereisferner in Ötztal Alps has been subject of extensive glaciological investigations for many years which results in a large number of DEMs, remote sensing data and field truth. Therefore, Hintereisferner was chosen as a test site for our method and compared with other remote sensing data. Since its tongue is partly debris covered we could evaluate the performance of the method on debris covered tongues. The nearby Mittlerer Guslarferner was chosen as an example for a small glacier with no debris cover. Problems with glacier boundary delineations in firn areas are highlighted with an example of Rotmoosferner. Reichenkar Rock glacier completes the test data set with a well investigated rock glacier (Krainer et.al, 2002; Krainer and Mostler, 2000). Figure 1 shows the study area with glaciers in the Ötztal and Stubai Alps (grey) and the exemplarily discussed glaciers (red).

For all test sites, DEMs with 10 m cell size acquired in 1997 and high resolution LIDAR-DEMs acquired in 2006 are available. The DEMs of 1997 were acquired during the compilation of the second Austrian glacier inventory by the means of digital photogrammetry (Lambrecht and Kuhn, 2007; Würländer and Eder, 1998). The LIDAR-DEMs of 2006 have been acquired by the regional government of Tyrol. The technical specifications of this LIDAR acquisition campaign are summarized in Table 1.

Another source of LIDAR-DEMs used covers a study area around Hintereisferner for which 14 DEMs have been produced between 2001 and 2007. Relative horizontal accuracies are better than 1 m and relative vertical accuracies better than 0.3 m according to Geist and Stötter (2007) where more technical specifications of this acquisition campaign are described. For the application of our method the survey flights 1 (10/2001), 11 (10/2004) and 12 (10/2005) have been chosen since they have been acquired in a similar time of the year (October) close to the minimum snow extent.

For the test site Hintereisferner, a direct comparison with other remote sensing data has been performed. Table 2 shows details on the acquisition dates of the data used and its accuracies as well as the spatial resolution.

3 Methodology

Ice thickness changes calculated from DEMs acquired at different times t_1 and t_2 can be used to gain important additional information for glacier extent mapping especially near the glacier tongue. Figure 2 shows the different temporal evolution of surface elevation schematically for a glacier without (a and c) and with debris cover (b and d).

After a period of glacier retreat, ice thickness losses of a glacier with no debris cover increase gradually with altitude from the glacier margin upwards. The maximum thickness loss is reached near the glacier margin at the time when the newer DEM was acquired (t_2, indicator 2).

A glacier with debris cover, as indicated schematically in Fig. 2b and d, evolves differently due to the fact that debris cover reduces ablation compared to bare ice (e.g. Kirkbride and Warren, 1999). For this reason, elevation differences between t_1 and t_2 are significantly smaller at the debris covered parts (between indicators 3 and 4) and instantly increase where debris cover meets bare ice (from 4 upwards).

We used these differences to gain information on the occurrence and, depending on the time between the acquired DEMs, the extent of debris-cover.

The work-flow of the applied methodology is highlighted schematically in Fig. 3. In a first step we calculated elevation differences between the two available DEMs of the respective region. In addition to that, we calculated two hillshades with different azimuth-angles for illumination (315° and 135°) through the ESRI-Software ArcMap to optimally visualize contrasts in different aspects. Taking advantage of the already existing glacier inventory of a former date (Lambrecht and Kuhn, 2007) we then analysed qualitatively in which way ice thickness has evolved from the former glacier terminus position upwards according to Fig. 2. The existence of former glacier boundaries is not mandatory but saves time since it shows where to expect glacier covered areas. Nevertheless, even if a former dataset of glacier boundaries exists, testing it with the difference raster is advisable. This is to avoid that a glacier that had not been captured in a previous study is not captured in a new study either.

In the case a gradual increase in ice thickness loss is observed from the former glacier tongue upwards, we set the glacier boundary directly by digitising the strongest roughness change in the hillshades.

If an abrupt increase in ice thickness loss can be detected, we use the hillshades to set the boundary between bare ice and dead ice or debris covered ice. The difference raster helps to investigate the extent of the debris covered areas in case the temporal resolution is high enough (e.g. 1 year). In case temporal resolution is lower (e.g. years – decades) we can derive a potential dead ice extent in areas where a significant thickness change has occurred.

In accumulation zones of glaciers, surface elevation changes are much smaller. We therefore could only partly take advantage of the difference raster and thus used the roughness changes in the hillshades as well as orthophotos to map the glacier extent in these areas.

4 Results

We now highlight the results of the applied method with exemplarily chosen reference glaciers of different characteristics.

4.1 Debris-free glacier tongues – e.g. Mittlerer Guslarferner

The small (0.5 km^2), debris-free Mittlerer Guslarferner shows a gradual ice thickness loss from the former glacier margin upwards (Fig. 4a); An optimal delineation of the glacier extent is performed by following the pronounced roughness changes in the hillshades as visualized in Fig. 4b.

4.2 Accumulation zone – e.g. Rotmoosferner

In large parts of the accumulation area we achieved good results by analysing roughness changes of the hillshades and could thus set the glacier boundary well. As suggested in UNESCO (1970) we included adjacent snow-covered areas to the glacier surface area. The acquisition date of the LIDAR-DEMs (October and late August, see Table 2) is optimal since it is close to the minimum snow cover in the Alps. In some cases also in the lower parts of the accumulation zone the analysis of surface elevation changes helped to decide which areas to include to the glacier extent. To decide about remaining ambiguous areas we also performed a qualitative analysis of aerial photographs. Figure 5a gives an example of the firn area of Rotmoosferner where it is not possible to tell whether this part is debris covered ice or only consists of rocks by simply analysing the hillshade of the DEM. Also the analysis of the surface elevation changes did not result in a distinct answer since surface elevation changes were very small in this region. In this case a qualitative comparison with an aerial photograph of 2003 taken by the regional government of Tyrol (Tirismaps, 2009) gives a good hint because crevasse patterns can be seen in this debris- or rock-covered part of the glacier (Fig. 5b).

4.3 Debris-covered glacier tongues – e.g. Hintereisferner

In case we identified an abrupt increase in elevation loss around the former glacier boundary we followed a different work-flow as indicated in Fig. 3. An example of this is given in Fig. 6 for Hintereisferner's tongue. Figure 6a shows the calculated differences between 2001 and 2005 and allows thus to define a potential dead ice extent by including all areas with a significant change. However, as UNESCO (1970) suggests, adjacent debris covered areas and dead ice bodies have to be included in glacier inventories. Therefore we included the areas where a significant elevation change occurred to a so-called "potential" glacier area. The significance of the potential glacier area depends on the temporal resolution of the multi-temporal DEMs. In case the two DEMs used have been acquired a long time apart from each other (e.g. decades) and during this period a significant ice volume loss has occurred, it can well be that ice that was stored beneath the debris cover has partly melted out by the time of the second acquisition date. In this case the additional use of multi-temporal DEMs should be seen as a hint of where ice could be below a debris cover. In case the period between the two DEMs is only short (e.g. years), we conclude that where an elevation change occurs we can assume there is ice below. In our study area around Hintereisferner we have the advantage of a very good temporal resolution, therefore the glacier extent can be determined very precisely using two DEMs with a one year time difference (Fig. 6c).

4.4 Rock glaciers – e.g. Reichenkar Rock glacier

Remote sensing techniques are not only applicable for the mapping and monitoring of glaciers and their changes but also of permafrost (e.g. Kääb, 2008a).

Figure 7 shows an example of Reichenkar rock glacier. We use it as an example to show that orthophotos (7a, 1997) as well as hillshades of high-resolution LIDAR-DEMs (7b, 2006) are appropriate datasets to derive rock-glacier's extents when they have a distinct snout. Both datasets result in a similar accuracy for the mapping of rock glacier extents. The calculation of volume changes from two successive DEMs is shown in Fig. 7c. The snout has advanced by ca. 25 m which can be seen in the elevation differences. In case two successive LIDAR-DEMs existed from this area, accurate mapping also of the upper areas of rock glaciers could be done as demonstrated with the debris-covered areas on Hintereisferner (Fig. 6). So far, subsequent LIDAR-DEMs are only available for a test region around Hintereisferner. Since elevation changes on rock glaciers are usually small apart from changes at the snout (e.g. Schneider and Schneider, 2001) a sequence of very accurate DEMs would be necessary to investigate volume changes over the entire rock glacier area. However, the difference raster can be taken as a method to distinguish active from fossile rock glaciers.

4.5 Accuracy

Assessing the accuracy of the proposed method quantitatively we point out that interpretation uncertainty is higher than horizontal errors of the DEMs (Table 2), therefore we neglected the latter. To estimate errors introduced by interpretation we first compared the results of two different persons for some glaciers. The deviance was less than 1% of the total area. Moreover, we evaluated some glaciers randomly out of different size classes and produced one maximum and one minimum extent by including all ambiguous areas and excluding them, respectively. The resulting glacier areas have deviated from the original values by not more than ±1.5% of the total glacier covered area for glaciers bigger than 1 km^2 and up to ±5% for smaller glaciers which remains the best estimate for the accuracy of the methodology.

5 Discussion

5.1 Hillshades and differences: cell-size

The influence of the cell-size of the DEM on the quality of the glacier boundary delineation with high-resolution DEMs as a main data source is highlighted in Figs. 8 and 9. We calculated three hillshades out of differently resampled DEMs (Fig. 8 a–c) of the same extent as in Fig. 4. The derivation of glacier boundaries by using the roughness changes out of hillshades as a main criterion is only applicable for DEMs that exist at a resolution better than 5 m. 1 m-DEMs are optimal and allow to omit the use of orthophotos or any other additional information for glaciers without debris-cover. A cell-size of 20 m or higher does not resolve roughness changes adequately (8 b and c).

Figure 9 shows analogously the calculated ice thickness changes out of differently resampled DEMs on Hintereisferner's tongue (same extent as Fig. 6). The differences between the rocky surroundings, the debris-covered part of the tongue and the debris-free ice is visible up to the 50 m resolution but since differences between the surface characteristics are small (compare noise in rocky surroundings with debris-covered part in 9b and c no significant conclusions can be drawn for cell-sizes larger than 5 m.

5.2 Exemplary comparison to other remote sensing techniques

Figure 10 shows an overview of the pixel size and the vertical accuracy of the discussed remote sensing data as well as orders of magnitudes of overall mean annual thickness loss (Lambrecht and Kuhn, 1997; Abermann et al., 2009), typical ice thickness loss of Hintereisferner's debris-covered as well as debris-free part between 2001 and 2005 and of the ice thickness loss at Hintereisferner's tongue between 1953 and 2003 (Fischer et al., 2009) on its right side. The remote sensing data outside the rectangular box (e.g. orthophotos and Landsat data) do not include topographic information. The applicability of ice thickness changes for the detection of glacier boundaries depends on the magnitude of elevation change (time difference, climate signal) compared to the sum of the vertical accuracies of the used DEMs. The use of LIDAR-DEMs together with the DEM 1997 is thus a comparably accurate option both in terms of the achieved pixel size as well as vertical accuracies. In the next parts, we will use the example of Hintereisferner's debris-covered tongue to qualitatively compare glacier boundary delineation with very high resolution DEMs (e.g. LIDAR) with other remote sensing data often used for this purpose.

5.2.1 Aerial photogrammetry

Many studies in the past use photogrammetrically derived orthophotos of varying pixel-sizes (e.g. 1 m: Lambrecht and Kuhn, 2007) as the main data source to obtain the glacier extent. This is a good method for debris-free glaciers and still provides the best results for glacier mapping in the accumulation zone where surface elevation changes are small. Photogrammetry also includes the opportunity to produce high-quality DEMs although their accuracy may be reduced in the accumulation zone due to oversaturation of the acquired images. Geist et al. (2003) and Würländer et al. (2004) pointed this out as a main advantage of LIDAR for glaciers.

Figure 11 shows an orthophoto of 2003 of Hintereisferner's tongue. In the debris-covered area it is not possible to detect the glacier boundary decisively simply by analysing the orthophoto. Although this orthophoto is taken in a different year (2003), it can be taken as an example that the dead ice boundary can not be extracted without additional information since we know from field surveys that there had been debris-covered ice around the margin already in 2003.

5.2.2 Multispectral remote sensing

The use of Landsat scenes as a main data source is widespread in literature and allows a mainly automatic glacier boundary detection (e.g. Andreassen et al., 2008; Paul et al., 2002). The pixel-size is 30 m for the relevant channels. Figure 12 shows the example of a Landsat-scene around Hintereisferner (NASA, 2004). With the combination of channels 4, 5 and 6 glacier ice can be distinguished from its rocky surroundings (Rott and Markl, 1989). The close-up rectangle in the upper left corner of Fig. 12 shows the discussed area of Fig. 6. Details as indicated in Fig. 6 (dead ice, detailed glacier boundary) are not possible to be detected with this data.

If Landsat-scenes are in use for glacier monitoring, additional remote sensing data have to be taken into account for the computation of DEMs in case volume changes are of interest.

SPOT

SPOT-Scenes reach a pixel-size of 2.5–20 m in various wavelengths (CNES, 2009). Figure 13 shows an example of the same study area again with a close-up rectangle in the upper left corner. Glacier boundary can be delineated well for debris-free glaciers although additional information as (a sequence of) high-resolution DEMs is eligible to enhance accuracies in ambiguous areas (e.g. debris-cover).

IKONOS

The IKONOS-satellite provides images of different bands in the visible range with comparable horizontal resolutions as the orthophotos used in this study (1 m). Sharov and Etzold (2007) evaluated IKONOS-data of Hintereisferner and derived horizontal accuracies of 17 m. Figure 14 shows a panchromatic IKONOS-scene of Hintereisferner's tongue of August 2003 (Sharov and Etzold, 2007). The potential to delineate the debris-cover extent is limited, comparable to the example of the orthophoto shown before.

ASTER

The ASTER-satellite provides images of cell-sizes between 15 and 90 m for wavelengths between 0.52 and 11.65 μm. The accuracies of the DEMs calculated from ASTER data (Kääb, 2008b) lack the accuracy to monitor short-term changes (e.g. years) of glaciers or permafrost. Concerning glacier boundary delineation similar success as well as limitations as shown for Landsat before occur due to its comparably large cell-size (Kääb et al., 2002).

6 Conclusions

The comparison of multi-temporal DEMs with a relative vertical accuracy significantly better than the ice thickness change over the investigated period enhance the accuracy of mapping glacier boundaries. The method is well-suited for study areas with a manageable extent where an accurate knowledge of glacier area and volume change is needed since it requires considerable manual digitisation effort. A great advantage compared to other remote sensing techniques is high accuracy for the delineation of small glaciers (e.g. $<0.5\,km^2$). The combination of additional information (e.g. multi-temporal DEMs and orthophotos) or other remote sensing data further improves the result.

The better the vertical accuracy and the horizontal resolution of the DEMs is, the shorter the time period between the acquisition of the DEMs can be chosen.

In a climate closer to a steady state of glaciers than today's climate, the application of this mapping procedure would be less successful since surface elevation changes would be smaller.

The accuracy of the glacier boundary delineation is higher in areas with large elevation changes, i.e. low elevations and bare ice.

There is also a high potential in using multi-temporal DEMs to map and monitor permafrost. So far, there is not sufficient data yet to perform detailed volume change analysis but it could be shown that rock glaciers can be mapped by taking LIDAR-DEMs into account. Long-term elevation changes allow also the distinction of active and fossile rock glaciers.

Compared to other remote sensing techniques, the use of multi-temporal LIDAR-DEMs implies the advantage of giving the possibility to derive glacier boundaries as well as volume change both in a high resolution without data gaps caused by the imaging geometry.

The application of multi-temporal DEMs for the detection of debris-covered glaciers in case large stone or debris mass turnovers which could have balanced or dominated possible vertical ablation depends on the horizontal and vertical resolution of the DEMs.

The use of multi-temporal DEMs will gain importance in future glaciological applications since the number of high-resolution DEMs is increasing and airborne as well as satellite data reaches higher accuracies. The prospected future climate change (Trenberth et al., 2007) will result in a continuing glacier volume and area loss and thus this method may be extended further.

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Table 1. Summary of technical specifications of the LIDAR acquisition campaign of the regional governement of Tyrol, 2006.

Sensor	Optech ALTM3100
Laser Wavelength	1064 nm
Scan Frequency	33 Hz
Scan angle	±20°
Point density	Minimum: 1 point/4 m^2
Measurement frequency	71 kHz
Average flight height	1100 m a.g.l.
Mode	Last Pulse
Interpolation software	SCOP++
Interpolation method	Moving Planes
Horizontal accuracy	±0.3 m
Vertical accuracy	±0.1 m

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3, 383–414, 2009

Table 2. Summary of the acquisition dates as well as resolutions and accuracies of the data used in this study. For references concerning the accuracies of LIDAR and Photogrammetry see above, Landsat, SPOT and IKONOS see Sect. 5.2.2.

Source data	Date	Band	Horizontal resolution [m]	Horizontal accuracy [m]	Vertical accuracy [m]
Aerial photography	11/9/1997		10	1	1.9
LIDAR	11/10/2001		1	<1	<0.3
LIDAR	5/10/2004		1	<1	<0.3
LIDAR	12/10/2005		1	<1	<0.3
LIDAR	23/08/2006		1	0.3	0.1
Landsat	10/09/2004	4,5,6 H	30	ca. 30	–
SPOT	17/07/1999	panchromatic	10	15	10
IKONOS	12/08/2003	panchromatic	2.5	17	3.5

TCD
3, 383–414, 2009

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

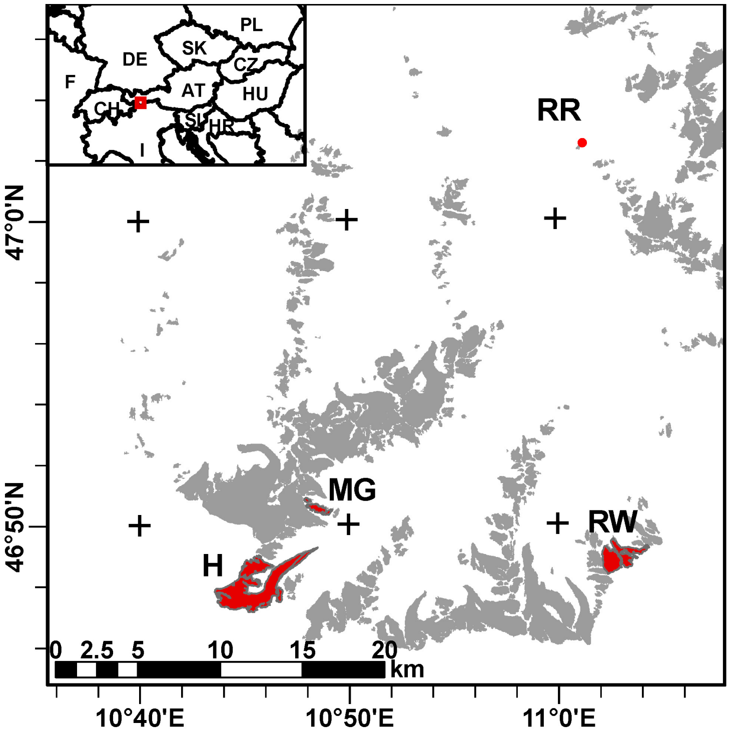

Fig. 1. The study area: Glaciers in the Ötztal and Stubai Alps (grey) with three reference glaciers (H: Hintereisferner, MG: Mittlerer Guslarferner, RW: Rotmoos- und Wasserfallferner) and one rock glacier (red, RR: Reichenkar rock glacier) to demonstrate special characteristics exemplarily.

TCD
3, 383–414, 2009

Multi-temporal airborne LIDAR-DEMs

J. Abermann et al.

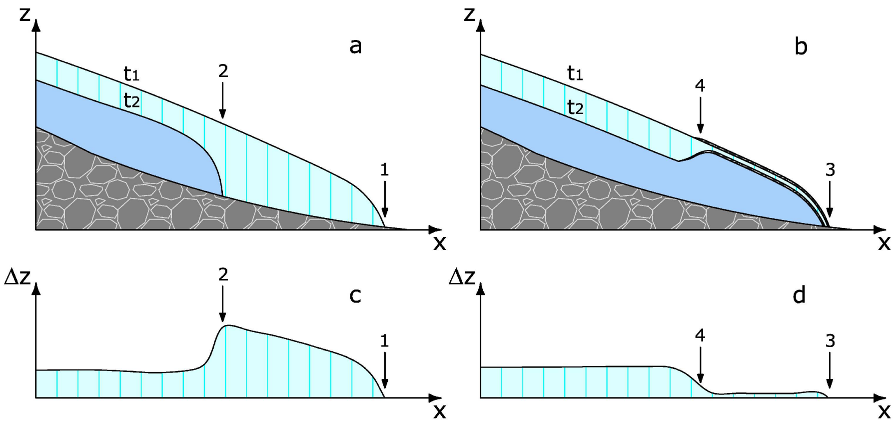

Fig. 2. Schematic model of surface evolution of a debris-free **(a)** versus a debris covered glacier **(b)**. Figures **(c)** and **(d)** indicate the respective surface elevation change according to the different surface conditions. Note the distinct increase in surface elevation change that occurs where debris cover meets bare ice in Fig. 2d at 4.

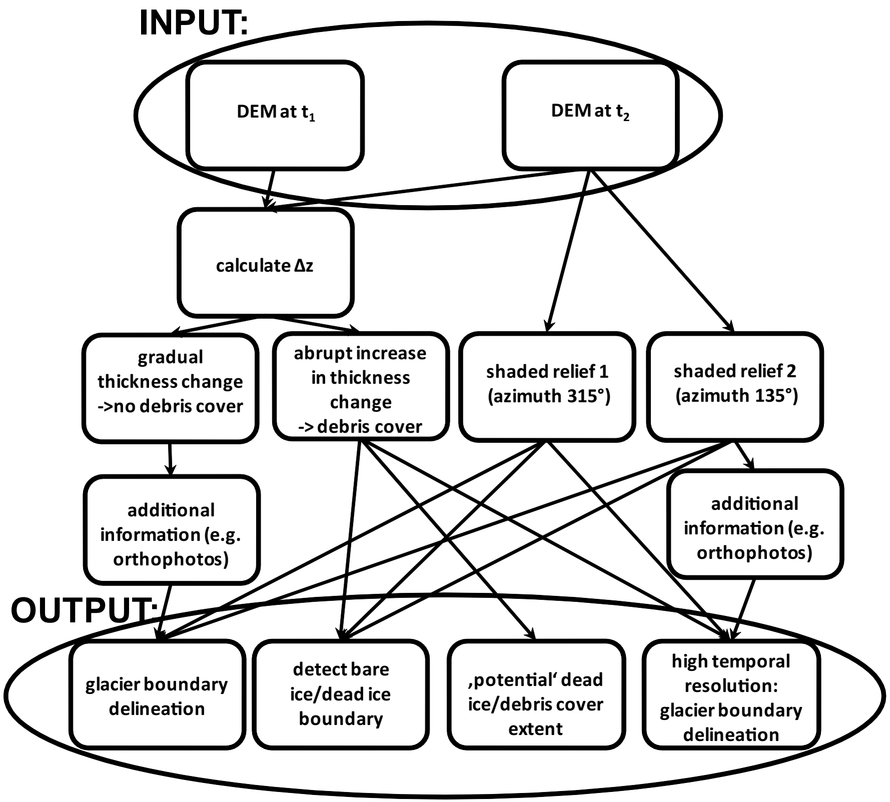

Fig. 3. Workflow of the methodology of mapping glaciers with multi-temporal high-resolution DEMs.

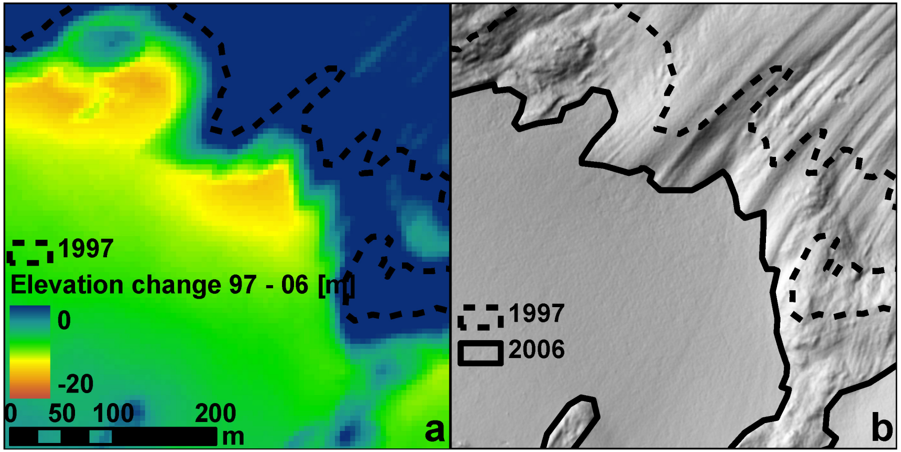

Fig. 4. Elevation change 1997–2006 with the glacier boundary of 1997 (dotted) on Mittlerer Guslarferner. To calculate elevation changes we resampled the DEM 2006 to 5 m cell-size **(a)**. **(b)** shows the hillshade of the same extent. By a qualitative analysis of roughness changes we performed the glacier boundary delineation manually.

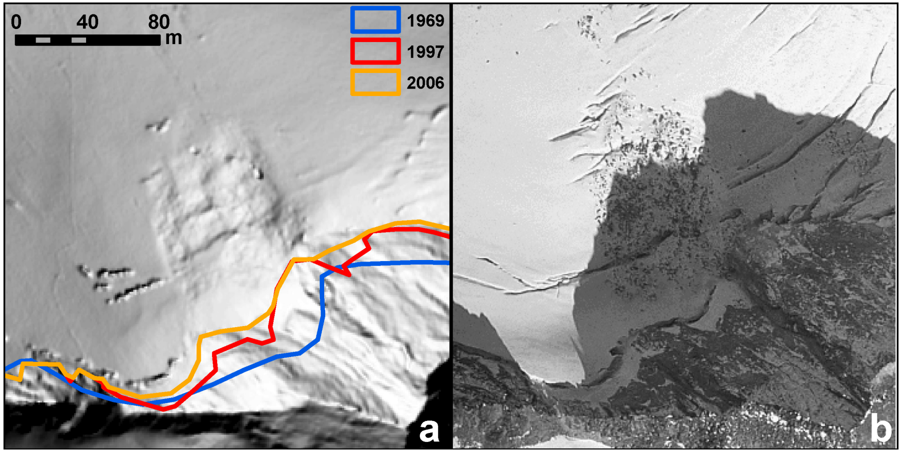

Fig. 5. Ambiguous glacier boundary at Rotmoosferner's firn area displayed as a hillshade of the 2006 DEM (azimuth angle: 315°) with glacier margins of 1996 (black, dashed), 1997 (orange, dots) and 2006 (yellow, solid) **(a)**. By simply taking the hillshade into consideration it is not possible to decide if to include or to exclude the ambiguous area but the aerial photograph from 2003 **(b)** reveals crevassed features which lead us to the decision to include the ambiguous area to the glacier area.

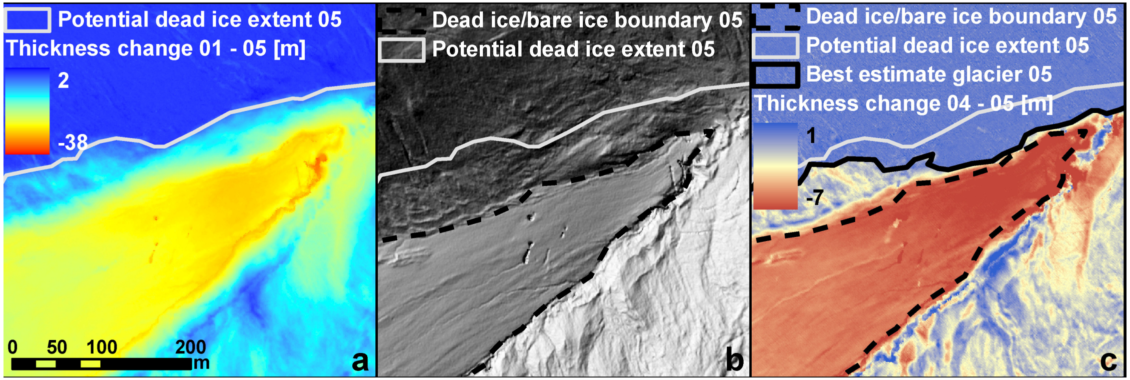

Fig. 6. In **(a)** the ice thickness changes between 2001 and 2005 are shown in a colour scheme. A potential dead ice extent can be delineated by considering changed surface elevations. The calculated hillshade from the 2005 DEM is shown in **(b)**. With this information it is only possible to detect the boundaries between dead ice and bare ice. The use of DEMs with a short time interval (e.g. 1 year) allows the detection of dead ice and thus the general ice-covered area well **(c)**.

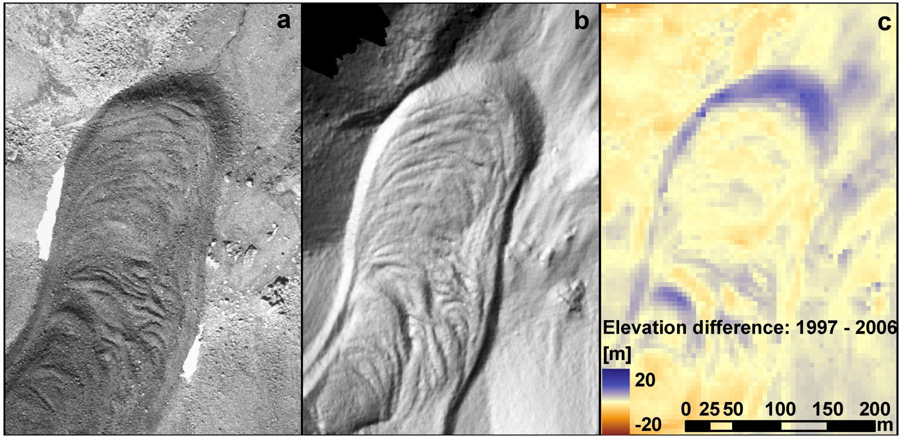

Fig. 7. Reichenkar rock glacier in the Stubai Alps. The orthophoto of its snout in 1997 **(a)**, a hillshade of the LIDAR-DEM 2006 **(b)** and the calculated elevation differences of the 1997 and the 2006 DEMs. Note, that the resolution of 9c drops to 5 m because of the resolution of the DEM 1997 (5 m).

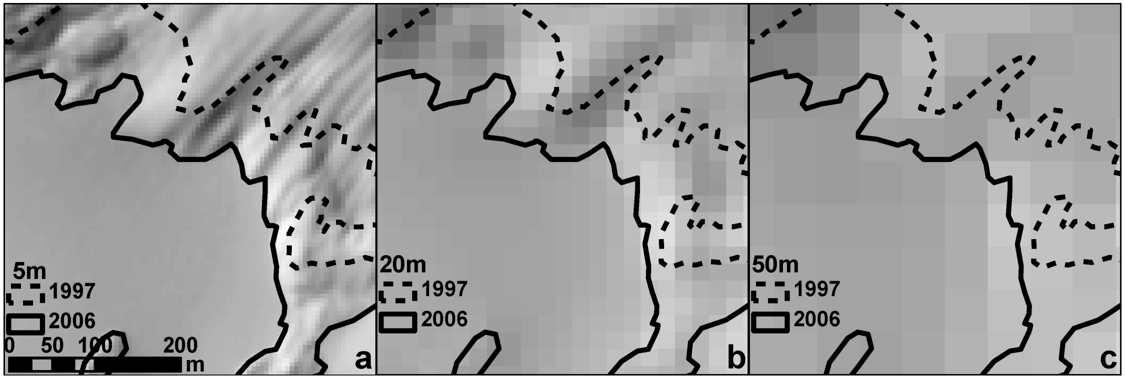

Fig. 8. Hillshades of Mittlerer Guslarferner's tongue calculated out of the LIDAR-DEMs with resampled 5 m **(a)**, 20 m **(b)** and 50 m resolutions **(c)**. In areas where no debris covered ice exists, the 1 m-resolution is high enough to distinguish glacier ice from its surroundings without any further information.

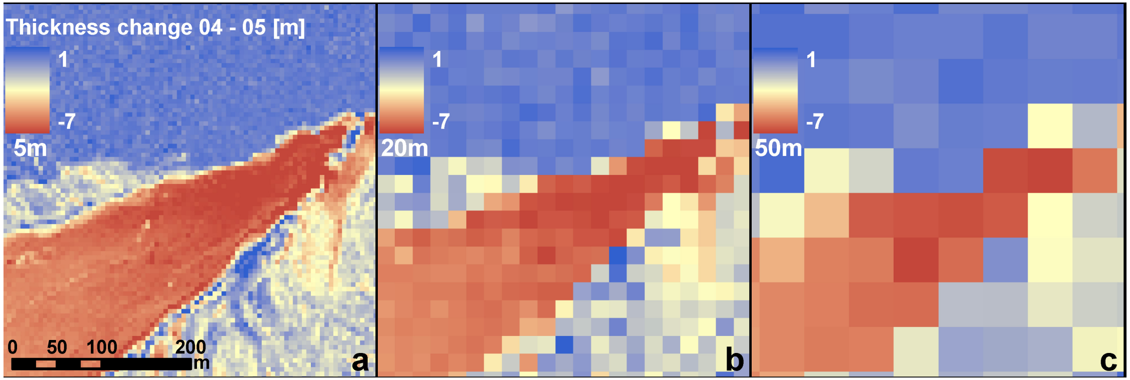

Fig. 9. Calculated ice thickness changes out of differently resampled DEMs with 5 m **(a)**, 20 m **(b)** and 50 m resolutions **(c)**.

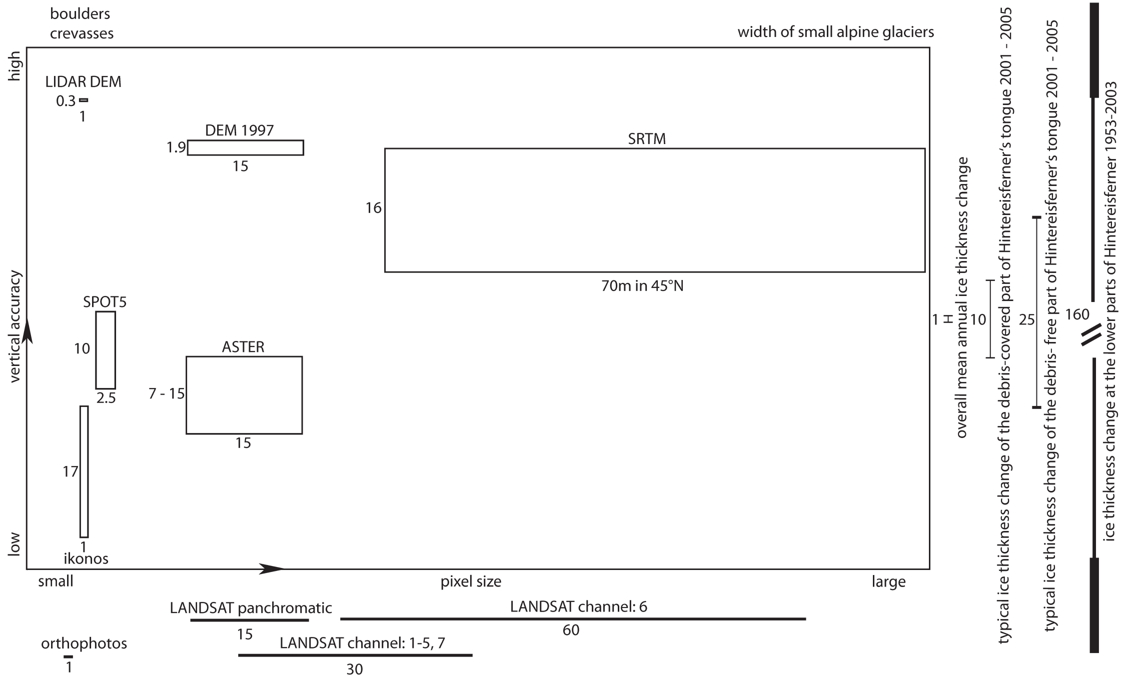

Fig. 10. Schematic distribution of pixel size vs. vertical accuracy of different applied remote sensing techniques. Orthophotos and Landsat-scenes do not include vertical information and the pixel size of the SRTM-DEM is more than one order of magnitude larger than the one of the LIDAR-DEMs. To better be able to evaluate potential and limitations of the use of multi-temporal DEMs we plotted overall mean annual ice thickness change of Austria's glaciers, typical values of ice thickness changes on debris- free and debris-covered parts of Hintereisferner's glacier tongue (2001–2005) as well as Hintereisferner's ice thickness loss 1953–2003 on the right. Lengths and widths of the boxes are scaled and all numbers are in meters.

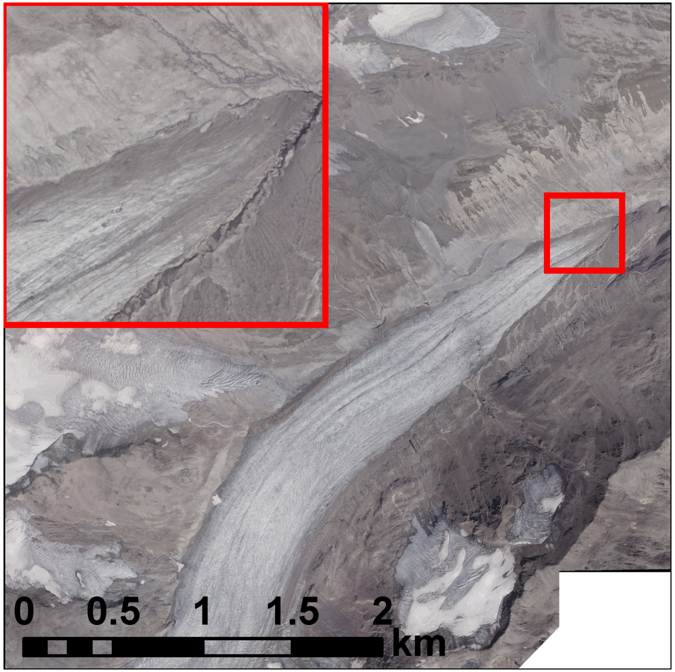

Fig. 11. The orthophoto (0.5 m pixel size) from 2003 of the same extent as in 6 with a close-up in the upper left corner.

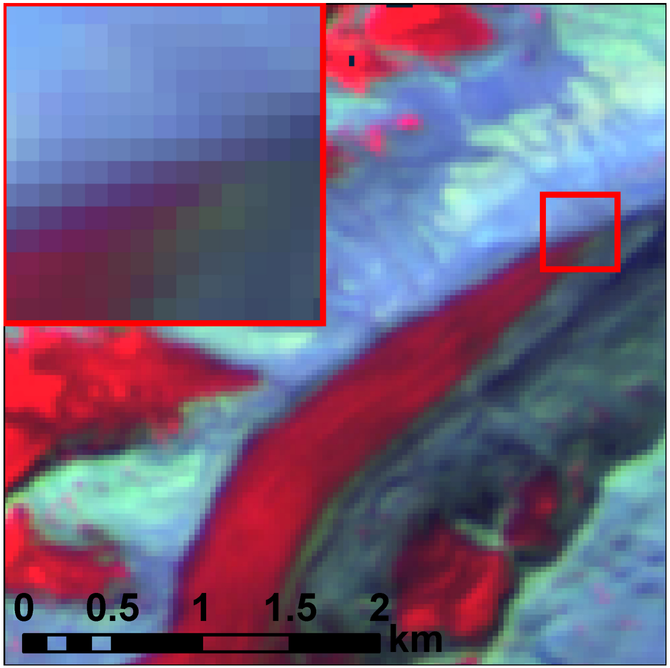

Fig. 12. Landsat 7 ETM+-scene of the area around Hintereisferner taken 10/09/2004 with the channels 4, 5,6 H as an RGB-composite. The red rectangle shows the extent of Fig. 6 with a close-up in the upper left corner.

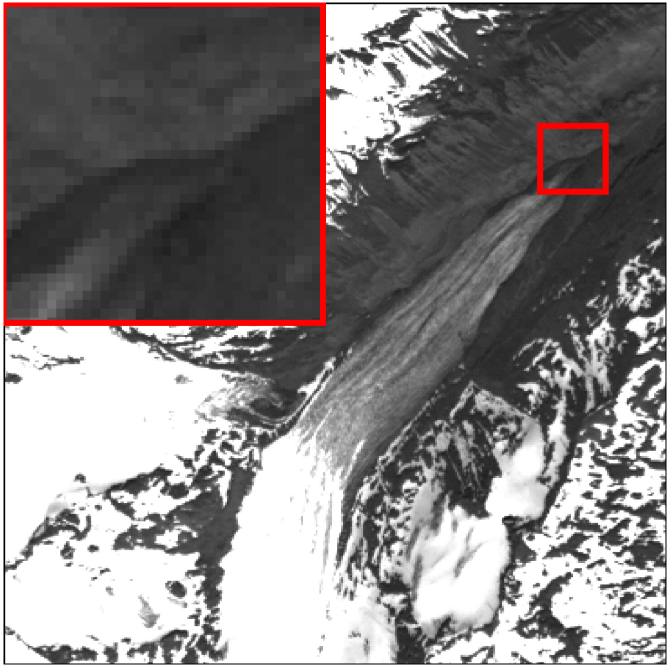

Fig. 13. SPOT panchromatic (0.51 to 0.73 μm) scene of the area around Hintereisferner 17.07.1999, with a pixel size of 10 m. The red rectangle shows the extent Fig. 6 with a close-up in the upper left corner.

TCD
3, 383–414, 2009

TCD

3, 383–414, 2009

Multi-temporal airborne LIDAR-DEMs

J. Abermann et al.

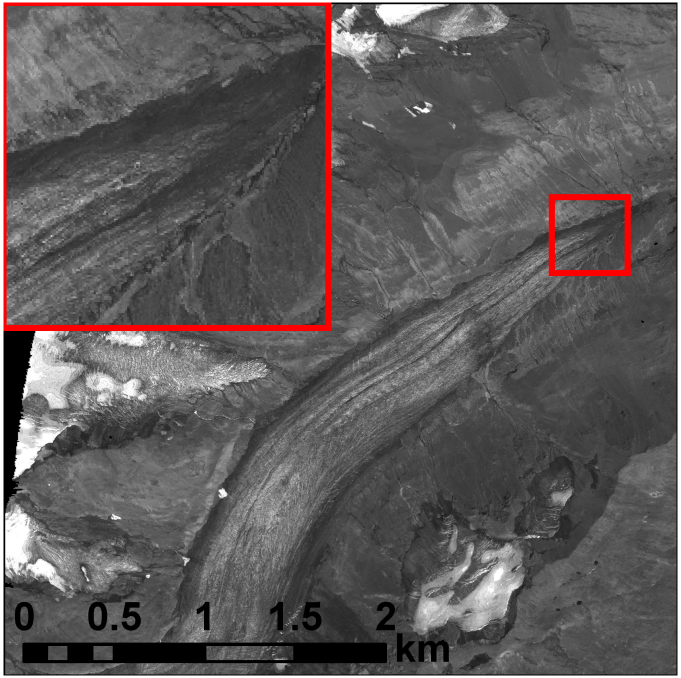

Fig. 14. Hintereisferner's glacier tongue, Ikonos 12.08.2003 (Sharov and Etzold, 2007). The red rectangle shows the extent Fig. 6 with a close-up in the upper left corner.