First Results on Monitoring Glacier Dynamics with the Aid of Terrestrial Laser Scanning on Pasterze Glacier (Hohe Tauern, Austria)

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Abstract

Terrestrial laser scanning is a quite new technique for glacier monitoring. Long-range laser scanners are able to acquire high-resolution 3D data of surface structures. They can achieve measuring distances up to a few kilometres of range with accuracy in the range of a few centimetres. We report on an integrated system that is capable of describing 3D motion and deformations of glacier (especially glacier fronts) within a single day's measurement campaign, including logistics and evaluation. The Pasterze glacier in the Hohe Tauern National Park (Central Alps, Austria) has been monitored during the last years beginning with 2001. Results give a clear picture of comprehensive modifications of the entire area. At least three zones of a collapsing of the ice body are detectable as well as a different behaviour of the bare ice and debris covered glacier tongue. Surface elevation changes in paraglacial areas such as adjacent slopes and newly developed kame terraces are available area wide for further analyses.

KEYWORDS: Monitoring glaciers, Terrestrial laser scanning, Pasterze Glacier, Hohe Tauern Range, Austria

1. Introduction

The Glockner Mountains comprise extensive glacier areas with the Pasterze Glacier as the longest glacier in the Eastern Alps (Central Alps, 47°04'N, 12°44'E, Figure 1). The glacier`s dimension changed from 1852 to 2002 as follows: length 11.4 km to 8.4 km (-26 %) and area 26.5 km² to 18.5 km²(-30 %). The dramatic loss of ice in the last decades is documented in a comprehensive modification of this alpine environment on the glacier itself as well as in the paraglacial area. Quantification of these changes such as spatial measurements of glacier surface changes are a primary task in the last 20 years with new remote sensing techniques using photogrammetric analyses (e.g. Kaufmann and Ladstädter, 2004), Airborne laser scanning (e.g. Geist et al., 2003; Kellerer-Pirklbauer et al., 2005) and radar-interferometry (e.g. Kaufmann et al., 2005). This article discusses first results of annual terrestrial laser scanning (TLS) campaigns at four epochs beginning in 2001 within the monitoring framework of the Pasterze glacier tongue. The selection of TLS on this part of the Pasterze glacier is due to following reasons providing several advantages:

- The steep terrain flanking the glacier tongue is unfavourable for airborne or satellite data resulting in a better resolution of terrestrial data
- Perfect accessibility keeps costs low (Großglockner-Hochalpenstraße/Franz-Josefs-Höhe)
- The lowest part of the glacier, i.e. the glacier termini, is object of an intense retreat which goes along with a massive modification of its proglacial landscape. In the upper part of the scanning area (at the "Seeland-Linie"-profile beneath the Hofmanns-Hütte) the glacier lost 38 % in width, 61 % of thickness, and 75 % in the cross-section (Wakonigg and Lieb, 1996; Krobath, 2003; Lieb, 2002, 2003, 2004).

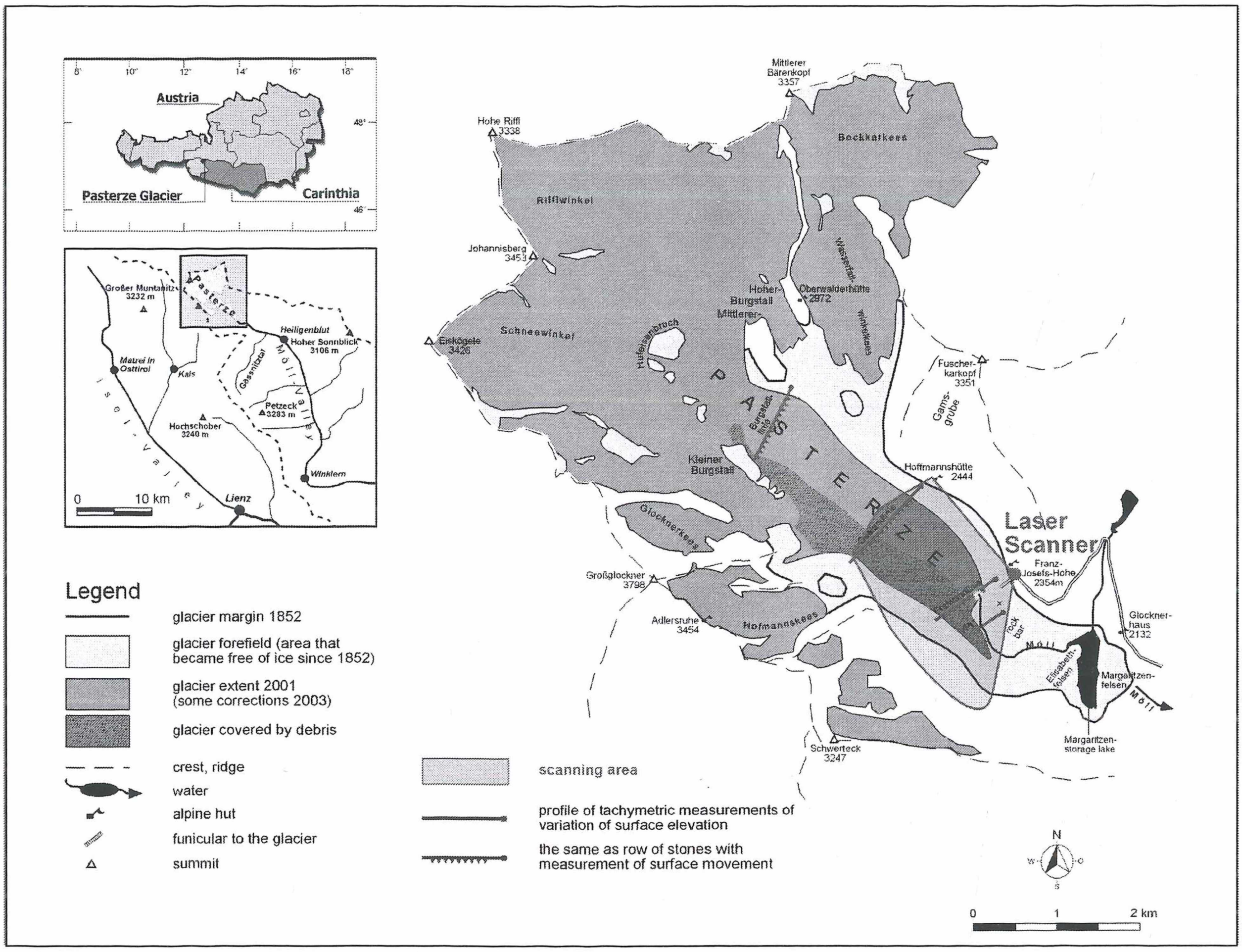


Figure 1: Location and setting of the Pasterze glacier, its spatial changes since the LIA, monitoring sites where glacier changes have been monitored within the framework of annual measurement campaigns as well as during scanning campaigns.

2. Methods

2.1. Terrestrial laser scanner

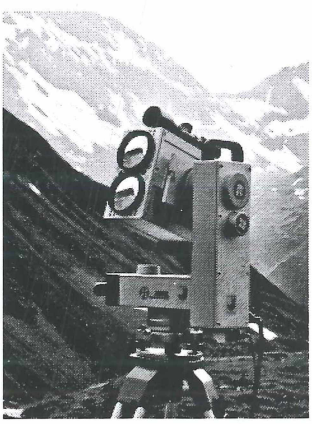
For the past few years, 3D TLS systems have been employed very successfully in the design and manufacturing industries as well as in industrial surveying (Pfeifer et al. 2004). Further development in terms of measurement speed, accuracy, range, field-of-view, and data sampling rate allow TLS to be applied in terrain surveying (Bauer et al., 2001, 2004, and 2005). TLS produce point clouds, sampled representations of 3D scenes, from range and angle measurements that are converted into accurate 3D models. The ability to acquire high-resolution 3D data of surface structures makes this technique a very interesting instrument for measuring glacier (Avian et al., 2005; Kellerer-Pirklbauer et al., 2005) as well as rock glacier dynamics (Bauer et al., 2003, 2005). The integrated measurement system is capable of describing 3D motion and deformation of glacier surface within a single day's measurement campaign including logistics and evaluation. Table 1 gives technical information concerning the used long range TLS Riegl LPM-2k. It is a time-of-flight system that measures the elapsed time of the pulse emitted by a photo-diode until it returns to the receiver optics. Maximum range depends on the reflectivity of surface (which is very good for snow and debris covered terrain), and atmospheric visibility (best for clear visibility, bad for haze and fog). A measuring range of up to 2000 m allows hazardous sites to be easily measured from a safe distance. Since each single measurement consists of a multitude of laser-pulses, different measurement modes ("first pulse", "last pulse", "strongest pulse") give proper results even on bad weather conditions and surfaces that may otherwise lead to ambiguous measurements like vegetated, moist or roughly structured terrain.

2.2. The measurement

Each individual measurement point consists of the distance to the surface, the exact angular positions, the reflectance, and an estimated root mean square error (RMSE) of the distance measurement for reliability check. Single time-of-flight measurements with distance accuracy of better than 5 cm are automatically combined to a measurement grid. Although the data generated by the measurement devices can in principle be directly used for measurement and further visualization, several methodological, technical, and logistic problems are to be encountered when establishing an integrated monitoring system. This includes, among others, the stability of device control software, the automatic sensor orientation, the high number of measurements, the compensation of weather influences, and the selection of reliable measurements. In addition it is of particular importance to consider the highly heterogeneous surface in terms of material (rock, vegetation, and humidity in general) and structure.

2.3. Data processing

To represent each measurement in a reference coordinate system a dense digital surface model (DSM) is generated of the scene to be surveyed. A DSM is a regularly spaced grid in desired resolution on an analytical model of the local surface, in the simplest case a horizontal or vertical plane. It is used to store the elevation as a vertical distance at the grid points. We generalize the DSM to an arbitrary reference surface, to be able to represent the surface data in best resolution, since most of the potentially insecure surfaces are characterized by steep fronts. This data structure well complies with the practical requirements such as difference measuring, volume change evaluation, and various visualization tasks. Neighbourhood relations of measurement data points are directly described in the DSM structure; therefore operating on DSMs allows



Scanner parameter	Value (range)
Measuring range for:	
- good diffusely reflective targets	up to 2500 m
- bad diffusely reflective targets	>800 m
Ranging accuracy	±50 mm
Positing accuracy	±0.01 gon
Measuring time / point	0.25 s to 1 s
Measuring beam divergence	1.2 mrad
Laser wavelength	900 nm
Scanning range	
- horizontal	400 gon
- vertical	180 gon
Laser safety class	3B, EN 60825-1
Power supply	11-18V DC, 10VA
Operation temperature range	-10 to +50°C

Table 1: Scanner parameters and values of the used instrumentation Riegl LPM-2k Long Range Laser Scanner.

quick access to the surface heights in a well-defined geometry. Direct mapping from the sensor spherical system to the DSM Cartesian coordinate space would result in a sparse and non-uniform elevation map, especially at large distances. To avoid interpolation artefacts, the Laser Locus Method (Kweon et al., 1992) for DSM (Bauer et al., 1999) generation proves to be a robust tool for data acquisition from flat angles, and supports error detection and utilization of additional confidence values provided by the range sensor. Since the DSMs of (temporally) different surface measurements are geo-referenced, simple differences between the DSMs reflect the changes in elevation. In consequence we can derive a full description of change in volume, spatial distribution of shape, or arbitrary profiles on the surface.

Single time-of-flight measurements are automatically combined to a measurement grid that enables the generation of a dense digital elevation model (DEM) of the glacier surface. Repeatable sensor orientation is performed using reflective targets fixed on stable surfaces somewhere in the spherical field of view of the sensor.

TLS measures the position of a theoretical stable point on the surface within a given reference-system. Resulting elevation differences do not reflect mass-losses at this particular point because surface velocity has not been taken into account yet.

3. Scanning Campaigns 2001-2004

Surface lowering and ongoing deglaciation of terrain were successfully measured four times resulting in three data-sets of surface elevation changing rates (xy-resolution 1 m, z-resolution 5 cm) at following dates:

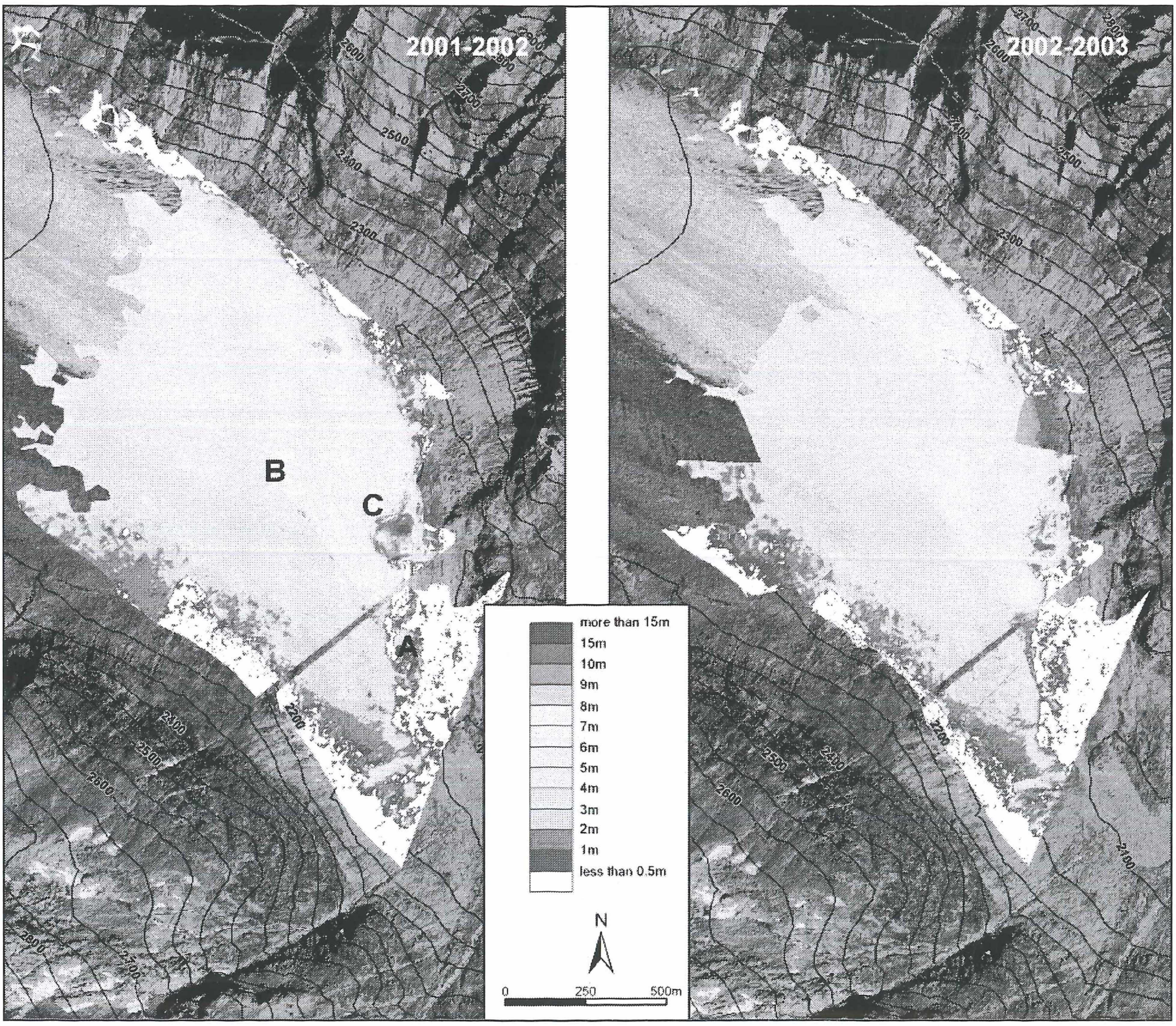


Figure 2: Spatial distribution of surface elevation changes on the Pasterze glacier in the period 2001/2002 and 2002/2003. Orthophotograph 1998, © Nationalpark Hohe Tauern.

- Campaign 1: 19./20.10.2001
- Campaign 2: 21./22.09.2002
- Campaign 3: 14./15./16.08.2003
- Campaign 4: 20./21.09.2004

2001-2002

This first year of measurements is mainly focused on the set up and instrumentation than taking into account glacial questions. The main question is to figure out the best increment for the different aspects in monitoring glaciers regarding time and resolution. As glaciers retreat recently deglaciated areas are characterized by high rates of sediment delivery (e.g. kame terraces) and deposit (e.g. sandur). This paraglacial area at the Pasterze is subject to conditions of comprehensive modifications at a mean magnitude from -1m to +1m in vertical surface elevation changes (max. up to -3.4 m, Figure2 left, A).

The debris covered, right part of the glacier shows a very interesting linear succession of surface lowering. Beginning at its right margin rates increase from around -1.5 m to -4.8 m at the supra-glacial meltwater channel marking the border between debris covered and bare ice part of the Pasterze glacier (Figure 2 left, B). This left part of the glacier is subject of dramatic modifications. Area wide surface elevation changes range from -6.2 m to -7.2 m and is very homogenous in terms of spatial distribution at the entire bar-ice glacier terminus. These rates do not include areas showing the beginning of intensive collapses of the ice body that mainly occurs at the left margin of the bare ice glacier surface. The lowest event in terms of absolute elevation is already visible due to developing crevasses near the fenced tourist areas (Figure 2 left, C; Figure 5 right), large areas show sinking rates over -12 m, maximum rates reach up to -19.2 m. Following the left glacier margin 550 m upwards an area of extraordinary sinking rates is detectable in the results (mean -7.8 m, max. -10.2 m). The magnitude of the sinking rates within this area exceeds surrounding rates by ~2.0 m. The occurrence of debris cover in some parts of the bare ice left part is visible in significant smaller sinking rates. Albedo of clean ice is about 40 % compared to shallow debris covered ice where albedo reaches values in the range of 10-15 %. Less energy is available for ablation on snow surfaces than on debris covered ice. Highest ablation rates occur at a thickness of debris cover of 0.3 cm; if debris cover increases to 5 cm, ablation rates on bare ice and debris covered parts are equal. Debris cover with a thickness of at least 7 cm is a significant protection against incoming short wave radiation (cf. Benn and Evans, 1998; Nakawo et al., 2000) The thickness of debris cover was not analysed particularly but rough estimations on the glacier during fieldwork provided results of around 10-15 cm.

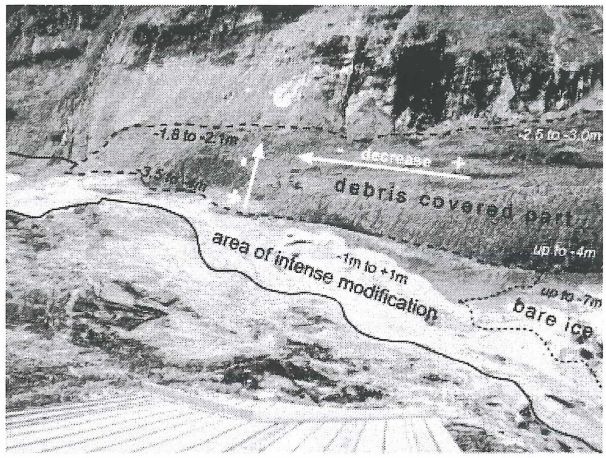


Figure 3: Lowest part of Pasterze glacier and paraglacial area. Note the decrease of surface elevation changes towards to glacier terminus (debris covered), and to the right margin of the debris covered glacier part. Image: Avian Michael (20.09.2004).

2002-2003

Dynamics of modification of paraglacial areas follows the retreating glacier terminus. Surface elevation changes decrease depending on the distance to the glacier terminus (as expected). Surface lowering probably connected to melting of dead ice bodies is also visible as in the previous period. The two mentioned collapsing areas still remain in extraordinary spatial dynamics, especially the upper one increases sinking rates (mean -8.3 m, max. -10.8 m; Figure 2 right; Figure 5. right). A new zone of massive surface lowering is developing another 400 m upwards on the left glacier margin (max. -9.5 m, mean -8.5 m, surrounding: -7.3 m). Ongoing increasing surface lowering towards the glacier terminus of the entire bare ice part is visible. This process is strongly influenced by a decrease of ice-supply due to reduced glacier surface velocities in the lower part since 1983 (Wakonigg and Lieb, 1996). Surface elevation changes at the debris covered part decrease mainly at the upper part, increase at the middle section and decrease to the lowest part. The mass loss on the debris covered glacier tongue is detectable at a magnitude of ~-3.5 m at lower edge decreasing to ~-2.1 m at the upper edge (Figure 3).

2003-2004

In 2004 we planned to increase the temporal resolution with measurements in the summer period at four epochs (mid of June, July, August, and September) to get a better picture of the inter-annual ablation dynamics. Complications due to unstable weather conditions and problems in sensor orientation inhibited the first three campaigns completely. Results were only carried out in September, where only 33 % of the area of 2001, 2002, and 2003 could be used for reasonable comparisons.

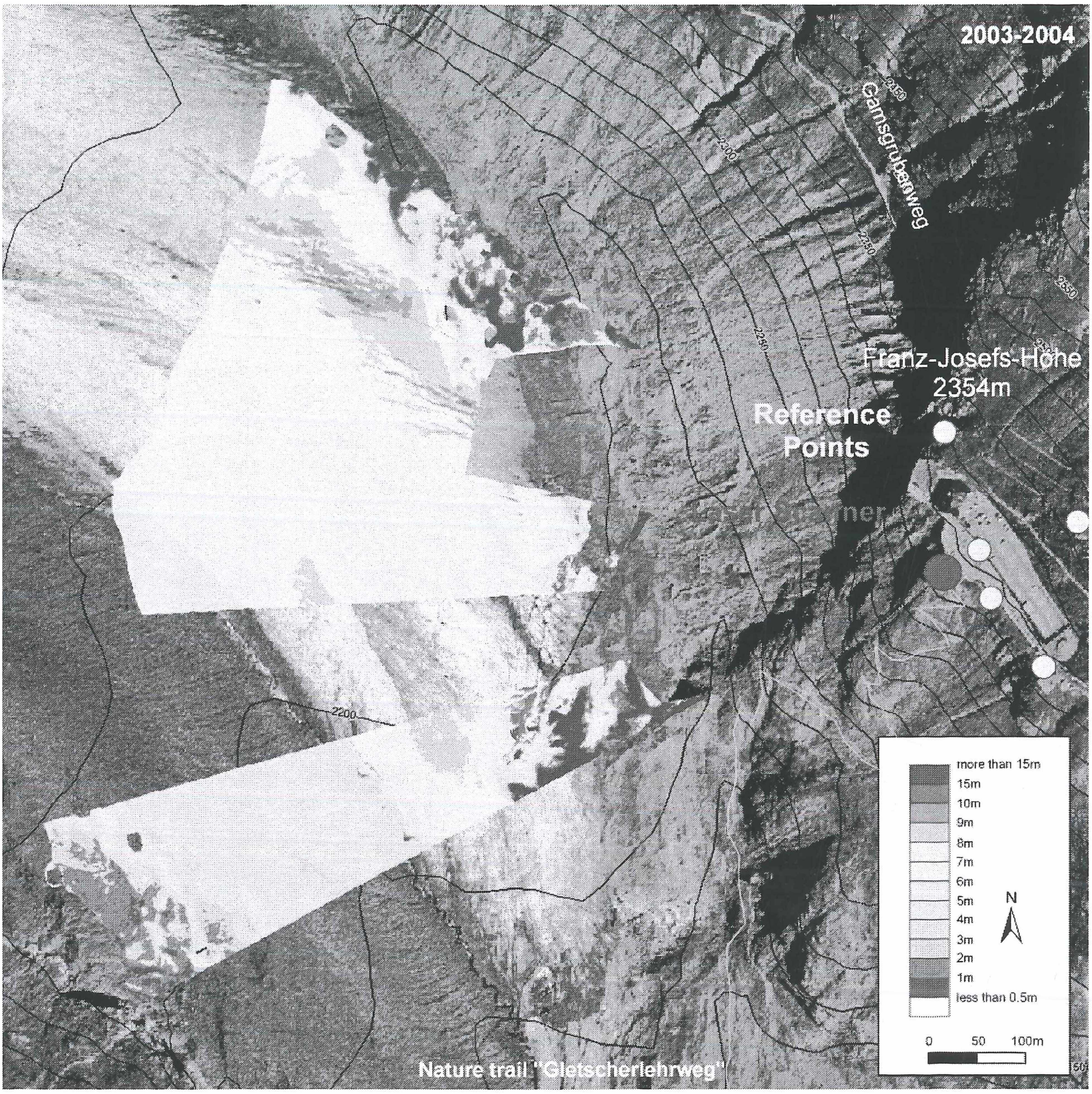


Figure 4: Spatial distribution of surface elevation changes on the Pasterze glacier in the period 2003-2004 with scanner position, reference points and tourist infrastructure. Orthophotgraph 1998, © Nationalpark Hohe Tauern.

The most obvious indication is a beginning of a comprehensive collapse of the entire left part of the bare ice glacier tongue. Gentle signs of this process are already visible in some parts since 2001, massive and homogenous surface lowering (over -9 m) as well as newly developed crevasses support this assumption (Figure 4; Figure 5). Mean sinking rates arise to -9.8 to 10.5 m with maximums in collapsed areas up to -20.5 m. The sub-glacial meltwater channel is visible a few meters (near the tourist-area) beginning to isolate several ice-bodies. The entire lowest part of the bare ice glacier part shows surface lowering with more than -7.7 m (Figure 4).

Adjacent slopes to the Franz-Josefs-Höhe also show surface lowering due to processes such as melting of dead ice and different types of mass movements. This part has not been measured consequently in the last periods but visual observations as well as the well known succession following glacier retreat support this assumption. Due to the lack of data on the debris covered part statements are not reasonable. Area wide information is not available, but the scanned sections show similar behaviour than in previous periods.

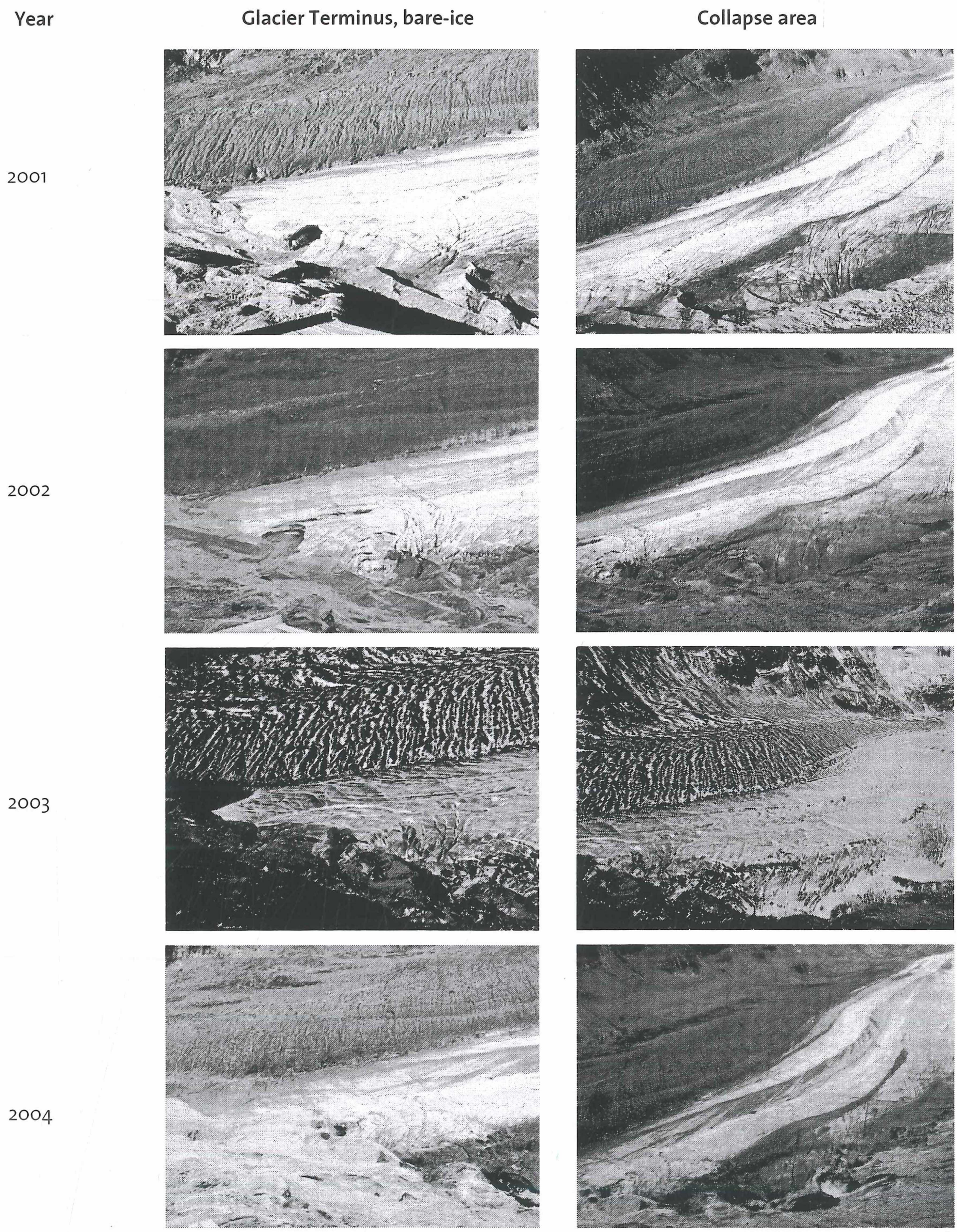


Figure 5: Progression of glacier retreat at the lowest part of Pasterze glacier. Images: Avian Michael (15.09.2002, 20.09.2004); Kaltenböck Alexander (19.10.2001), Kellerer-Pirklbauer Andreas (18.09.2003).

4. Conclusion

As expected from simultaneous tachymetric measurements all data sets show a clear trend in spatial variations of glacier retreat. There is a significant distribution of mass loss from the SW to the NE which also increases towards the glacier terminus on the bare ice glacier part. Here we can observe a clear leap in mass loss difference between the two obviously different glacier parts from the upper part to the lowest part. Debris cover with a thickness of at least 7 cm proofs to be a significant protection against incoming short wave radiation and therefore ablation. Another aspect in terms of different ablation rates of glacier parts is less potential radiation in the summer period due to the shadowing effect of the south-east facing, adjacent Großglockner ridge.

The left part of the entire bare ice glacier part is beginning to collapse comprehensively. The lowermost event is already visible in the last years with a dramatic landscape modification near the fenced off tourist area. The dynamics of the lowest event is already decelerating. Following the glacier upwards two further small "basins" flanked by circular to semi-circular crevasses are developing with a distance of 500 m from the lower one which seem to coalesce in 2004. All indications on the lowest bare ice part of the Pasterze glacier including the behaviour of the meltwater channel lead to the prediction that the entire footslope is about to collapse. The lower part of the adjacent slope facing to the "Gamsgrubenweg" is also getting increasingly unstable which is observable in mass losses already above dead ice. This part has not been measured consequently in the last years, no comparable rates are calculated.

The lowest part of the study area comprises the paraglacial area where a consequent decelerating of processes depending on the distance to the glacier as well as the outcrop of dead ice bodies is observable.

Terrestrial laser scanning proved to be a promising tool in monitoring local events with dimensions of 2-2.5 km. Single day´s campaigns of one person with consecutively short post-processing keep costs low and allow measures at short notice to react on dynamic processes.

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