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Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models

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[1]   Massive glacier thinning in the Alps during the past 20 years is documented by direct mass balance measurements on nine regularly observed glaciers. How representative this limited sample of glaciers is for the entire Alps, however, remained uncertain. The near-global digital terrain model from the SRTM enables a closer analysis of this question, which is of fundamental importance to assess overall glacier volume change. Here we present elevation changes from 1985 to 1999 for about 1050 glaciers in the Swiss Alps. The analysis reveals extreme thickness losses (>80 m) for flat/low-lying glacier tongues and a strong overall surface lowering. The mean cumulative mass balance of the nine glaciers with direct measurements (-10.8 m w.e.) agrees well with the mean change of the entire region from DEM differencing (-11 m w.e.) and can thus be considered to be representative. Mean thickness change of individual glaciers is correlated with their size, elevation, and exposure to solar irradiation. This implies that mass losses of large glaciers can be underestimated when they are directly inferred from values measured at much smaller glaciers. **Citation:** Paul, F., and W. Haeberli (2008), Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models, *Geophys. Res. Lett.*, *35*, L21502, doi:10.1029/2008GL034718.

1.   Introduction

[2]   Rapid decline in Alpine glacier area from 1985 to 1999 (-1.4% per year) has been observed by analysis of multitemporal Landsat Thematic Mapper (TM) data [*Paul et al.*, 2004]. This strong glacier shrinkage has continued as visual inspection of 2003/04 satellite imagery revealed [*Paul et al.*, 2007]. In parallel, nearly continuous negative mass balances have been measured since 1980 in the Alps, reaching cumulative values up to -33 m water equivalent (w.e.) until the year 2005 and displaying a trend towards increasingly negative values [*Zemp et al.*, 2005; *Haeberli et al.*, 2007]. This trend indicates that glaciers have not yet adapted their size to the new climate and are still far away from a steady-state. Under such conditions large parts of the ablation area become stagnant and melt down rapidly. Indeed, down-wasting and disintegration has become a common observation [*Paul et al.*, 2007]. For the lower reaches of many glacier tongues this massive decrease in surface elevation since the 1980s is now much larger (exceeding -80 m) than the standard error of many digital elevation models (DEMs), even considering their reduced accuracy in high-mountain topography.

[3]   In particular the Shuttle Radar Topography Mission (SRTM) DEM has a reported error smaller than this [e.g. *Brown et al.*, 2005] and provides an efficient means to assess elevation changes over large areas where a precise earlier DEM is available. Such calculations allow to evaluate the representativeness of the few glaciers selected for direct mass balance measurements [*World Glacier Monitoring Service* (*WGMS*), 2007; cf. also *Dyurgerov and Meier*, 2005] for an entire mountain range. Thereby, this would also help to constrain uncertainties in estimated glacier contributions to global sea level rise as currently mass balance data from comparably small glaciers (e.g. <10 km^2) have to be used to extrapolate glacier melt over entire mountain ranges, including those with large ice masses (e.g. >100 km^2) that most essentially contribute to sea level rise [*Kaser et al.*, 2006; *Raper and Braithwaite*, 2006].

[4]   In the recent past, several studies have utilized the SRTM DEM for calculation of glacier elevation and volume changes by comparison with earlier topographic data [e.g., *Aizen et al.*, 2006; *Larsen et al.*, 2007; *Rignot et al.*, 2003; *Surazakov and Aizen*, 2006; *Schiefer et al.*, 2007]. They found a considerable elevation loss at the lower parts of the investigated glaciers and a recent acceleration of trends. However, the representativeness of the glaciers selected for long-term mass balance measurements with respect to the variability of elevation changes from a large sample of glaciers remains to be explored. Here we utilize the SRTM DEM from 2000 and a 25 m resolution DEM from c. 1985 to calculate glacier thickness changes and its spatial variability for a sample of about 1050 glaciers in the Swiss Alps. Digital glacier outlines and GIS-based processing are used to calculate overall and glacier-specific changes automatically [*Paul et al.*, 2002].

2.   Data Sources and Processing

[5]   The used base DEM is the level 1 DEM25 (25 m grid spacing) from swisstopo that was created from aerial photographs acquired around 1985. The vertical accuracy varies with the map sheet but is in general better than 8 m in rugged high-mountain topography [*Rickenbacher*, 1999]. It covers entire Switzerland and small parts of neighbouring countries and its projection is the Swiss geodetic system (oblique transverse Mercator) with the Bessel 1841 ellipsoid and a user defined datum. The recent DEM is the SRTM3 DEM with 3″ or 90 m resolution that was acquired in February 2000 with InSAR techniques [*Farr et al.*, 2007] and is available for free from a NASA ftp site. The many data voids due to radar shadowing and layover in rugged topography have a limited influence in this study, as glaciers are often located outside the voids due to their more gentle

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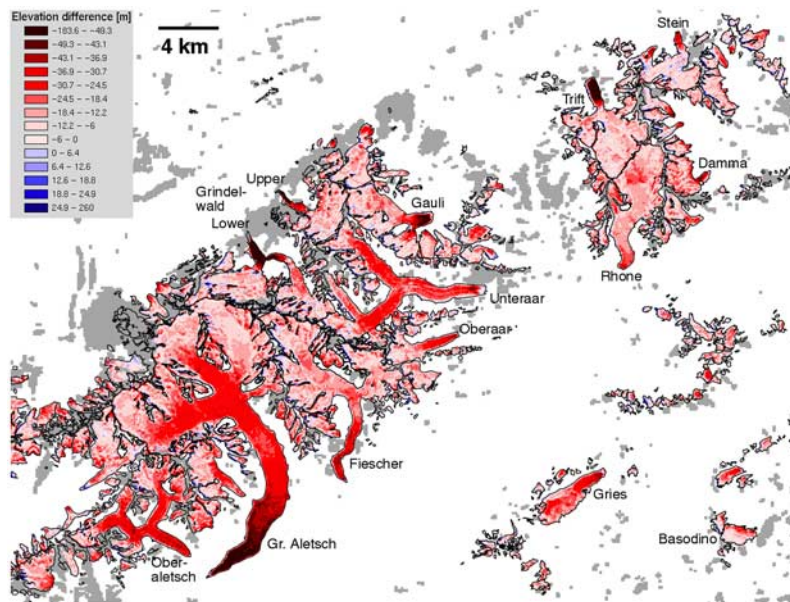[1]Department of Geography, University of Zurich, Zurich, Switzerland.

Figure 1. DEM difference image (SRTM3-DEM25) depicting glacier elevation changes from c. 1985 to 1999 in the region around Aletsch and Rhone glaciers (see Figure 3 for location). Glacier outlines from 1973 (black) and data voids including a 50 m buffer zone (grey) are also shown. The DEM25 is reproduced by permission of swisstopo (BA081539).

slopes (Figures 1 and S1[1]). Digitized glacier outlines from 1973 are used to assess glacier-specific elevation changes from 1985 to 1999 as only small area changes (−1%) have taken place in the Alps from 1973 to 1985 [cf. *Paul et al.*, 2004]. The SRTM3 DEM refers to the 1999 glacier surface, as it is assumed that the C-band radar penetrated the winter snow pack [*Rignot et al.*, 2001].

[6] The SRTM3 tiles are merged to cover the entire test site and are reprojected to the Swiss map projection with a 25 m cell size and bilinear interpolation. The reprojected SRTM3 DEM is horizontally adjusted to the DEM25 by minimizing the standard deviation of the DEM differences. Data voids are buffered with a two pixel (50 m) wide zone to reduce artefacts, and outlines of 1053 glaciers (>0.1 km^2) are converted to a 25 m grid for calculation of glacier specific mean changes. From this sample, 265 glaciers are excluded from a more detailed analysis (yielding 786 glaciers) as they are covered to more than 20% by data voids. Elevation changes are converted to volume changes by multiplication with the respective glacier area and to mass changes by multiplication with the density of glacier ice (0.9 g/cm^3), i.e. assuming that only ice has melted [*Andreassen*, 1999]. The changes refer to a fixed geometry (reference surface mass balance) which is in general more negative than the measured (hydrologic) mass balance, that refers to the actual glacier surface [*Elsberg et al.*, 2001].

[7] The cumulative mass balances from the two Swiss glaciers Gries and Silvretta are not used for a direct comparison as the methods of determination differ (reference area, firn density) and the so far reported values had (partly large) errors. Due to the different methods applied and time periods analysed we could also not compare our results directly with the study by *Bauder et al.* [2007].

Instead, the arithmetic mean value of cumulative mass balances from nine glaciers that represent the Alpine mean [*Zemp et al.*, 2005] is used for a comparison with SRTM-derived changes. The latter are calculated by two methods: (A) the arithmetic mean of 786 individual mean elevation change values for a direct comparison with the measured glaciers, and (B) a mean value for the entire area covered by glaciers, i.e. the 786 glaciers are taken as one large glacier.

3. Results

[8] In Figure 1 the results of the DEM differencing for the region around Grosser Aletsch and Rhone Glacier are presented, including the location of data voids and 1973 glacier outlines (see Figure S1 for a further example). The difference image exhibits the extreme thinning (locally exceeding −80 m) at several flat and/or low lying glacier tongues (Grosser Aletsch, Lower and Upper Grindelwald, Gauli, Trift) as well as strong overall melt for heavily debris-covered glacier tongues (Oberaletsch, Fiescher, Unteraar). Indeed, for these glaciers the strong changes are supported by field evidence (tongue collapse, revised mountain-hut access routes, rock wall destabilisation, etc.). In Figure 1, there is also a reduced elevation change visible on the lateral parts of some glacier tongues (Damma, Unteraar). Such subtle spatial variability is visible on several glaciers and reflects local melt protection due to avalanche activity.

[9] An increase in thickness loss towards lower elevations is visible from Figure 2 which displays mean elevation changes at 50 m bins for eleven selected glaciers versus altitude. Most of the glaciers have their highest loss about 100 m above the terminus position [*Schwitter and Raymond*, 1993]. Despite their different locations and topographic setting, the values are similar for discrete elevation bands. Above 3000 m a.s.l. the changes vary only between 0 and
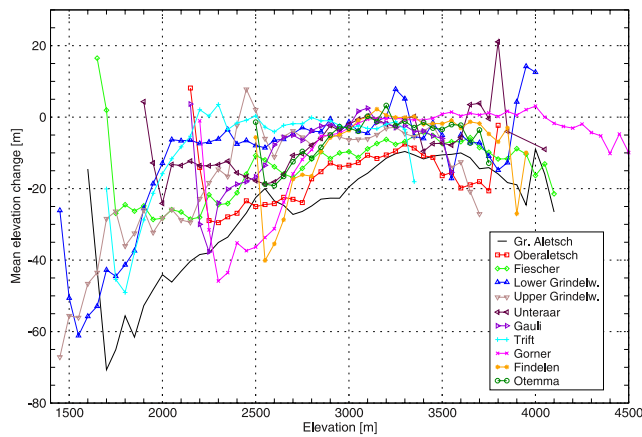
Figure 2. Elevation changes from c. 1985 to 1999 for eleven larger glaciers in Switzerland averaged over 50 m elevation bins.

−20 m and at the highest glacier points they increase again due to smoothing effects at steeper slopes in the coarser SRTM3 DEM. The related Figure S2 displays the mean profile for the 786 glaciers (method B) and confirms the changes described above.

[10] The mean thickness change per glacier (method A) has been calculated to analyse the spatial variability within the Alps and is visualized in Figure 3 for the sample of 786 glaciers. The analysis reveals that large (or flat) glaciers exhibit the greatest mean changes and that there is no dependence on geographic location. The strong thinning observed at the tongues of Trift and both Grindelwald Glaciers (Figure 1) is compensated by little loss in their accumulation regions. Based on the arithmetic mean of the 786 glaciers (method A), the obtained 1985–1999 mean change of −7.0 m w.e. (±6.43 m) is less negative than the measured mean value (−10.8 m w.e.) from the nine Alpine mass balance glaciers. However, based on the entire area (method B) the mean change from SRTM is −10.95 m w.e. which is almost the same. While the mean value for Silvretta Glacier (−9.3 m w.e.) is slightly less negative than

the overall mean from method (B), the value for Gries Glacier is much more negative (−17.8 m w.e.). Corresponding correction factors with respect to the mass loss of the entire glacier ensemble would be 1.18 for Silvretta and 0.62 for Gries.

[11] The dependence of mean thickness change on glacier size (Figure 4a) or mean potential global radiation in summer (Figure 4b) is more pronounced (correlation in both cases is −0.5) than regional effects. This supports the evidence that larger glaciers (reaching further down) and less topographically shielded glaciers have lost more mass (cf. *Hoelzle et al.* [2003] for the size effect). While there is a certain increase in scatter towards smaller glaciers for the size dependence (Figure 4a), the scatter is more normally distributed for the radiation dependence (Figure 4b).

4. Validation

[12] A systematic bias (underestimation of elevation) in the SRTM3 DEM has been found by *Berthier et al.* [2006] and *Schiefer et al.* [2007] for non-glacierized regions above a certain elevation. For glaciers, this would lead to an overestimation of thickness loss in the accumulation area and thus of the mean thickness change. However, we have not corrected the data for two reasons: (1) A separate study [cf. *Paul*, 2008] revealed that the underestimation of terrain height outside of glaciers and above a certain elevation could also be explained by the coarser spatial resolution of the SRTM DEM combined with the increase of steep slopes/mountain ridges (where elevations are underestimated at lower spatial resolutions) towards higher elevations. Subtracting a fine resolution DEM from its coarse resolution version gives nearly the same bias. (2) A systematic increase of SRTM elevations above 2700 m would result in numerous glaciers with mass gains in the accumulation region (cf. Figure 2). For the time period 1985–1999 this is unlikely as it contradicts climatic conditions and glacier-related observations (e.g. the loss of firn reserves).

[13] Compared to the results obtained by *Bauder et al.* [2007] for Grosser Aletsch Glacier, the SRTM-derived changes agree well in the ablation region, but are up to

Figure 3. Mean elevation change per glacier for Swiss glaciers larger than 0.1 km^2 with less than 20% of their area covered by data voids (786 glaciers). The black squares in the inset denote the location of the region (dashed) and the subregion of Figure 1 (solid).
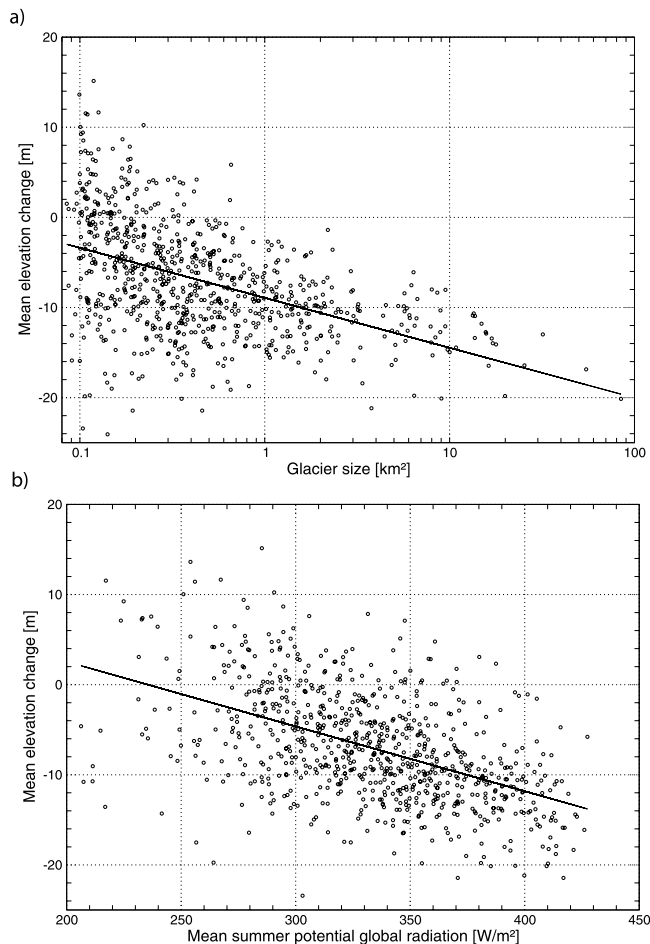
Figure 4. (a) Glacier size vs. mean elevation change and (b) potential global radiation in summer vs. mean elevation change for the sample of 786 glaciers.

10 m more negative in the accumulation region. However, a direct comparison is difficult as different time periods are analysed, the used density values for firn are not known and the snow conditions of the used images are not reported (a snow surface could lead to large errors in the derived DEM when stereo correlation fails [e.g., *Toutin*, 2008]). We have thus decided to compare SRTM elevations only on flat terrain and used reported levels of four hydro-power lakes located between 1900 and 2500 m a.s.l. and 14 not regulated lakes (from 1800 to 2800 m a.s.l.). For the former, elevation differences are mostly within ±2 m, for the latter within ±3 m and a systematic difference with altitude is not found. Compared to the recently revised cumulative mass balance values of Gries and Silvretta Glacier [*Huss et al.*, 2008], the SRTM-derived elevation changes are in good agreement (±2 m w.e.).

5. Discussion and Conclusions

[14] Our analysis reveals extreme thickness losses (partly exceeding −80 m) from 1985 to 1999 for Alpine glaciers which confirms results from other studies [e.g., *Bauder et al.*, 2007; *Haeberli et al.*, 2007] and observations of spectacular events accompanying the loss (e.g. collapsing rock walls). However, the general and uniformly strong surface lowering of large parts of flat glaciers, even under

thick debris cover, as revealed by the DEM comparison was not obvious so far. The fine spatial details of local thickness changes that are visible (and realistic) point to a high accuracy of the SRTM3 DEM. Based on the results of this and some other studies [e.g., *Larsen et al.*, 2007; *Paul*, 2008; *Möller et al.*, 2007], we have not corrected the previuosly reported bias in SRTM3 elevations.

[15] The comparison with the mean cumulative mass balance of nine Alpine glaciers (−10.8 m w.e.) demonstrated that the way of calculating the mean value has a strong impact on the value itself. When the same methods (A) are compared, the SRTM-derived mean value (−7.0 m w.e.) is less negative. When the overall change (method B) is used for comparison (−11 m w.e.), the agreement is very good and the mean of the field-measured values could thus be used for Alpine-wide extrapolations [e.g., *Haeberli et al.*, 2007; *Paul et al.*, 2004]. The differences between the two methods could be explained with increasing thickness losses towards lower elevations and because the largest glaciers (e.g. Aletsch, Gorner, Unteraar) have large portions of their area at low elevations. The observed decrease in mean thickness loss towards small glaciers could be explained with their better protection from global radiation and that their ablation regions are generally located at higher elevations. This result is in contrast to the assumed overestimation of melt from small glaciers made in the study by *Kaser et al.* [2006]. The average mass loss of the nine regularly observed glaciers in the Alps is similar to the entire glacier ensemble (method B), primarily because of extremely negative balances at the glaciers Caresèr and Sarennes [*Carturan and Seppi*, 2007; *WGMS*, 2007].

[16] We conclude that the extrapolation of measured mass balances from individual glaciers to other glaciers of an entire mountain range is not straight forward, as glacier size, hypsography and topographic conditions have to be considered. The differencing of the SRTM3 DEM with an earlier DEM, however, provides an efficient means to determine the required correction factors and to assess the representativeness of mass balance observations in entire mountain ranges.

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