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Rapid disintegration of Alpine glaciers observed with satellite data

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[1] Analyses of multispectral satellite data indicate accelerated glacier decline around the globe since the 1980s. By using digitized glacier outlines inferred from the 1973 inventory and Landsat Thematic Mapper (TM) satellite data from 1985 to 1999, we obtained area changes of about 930 Alpine glaciers. The 18% area reduction as observed for the period 1985 to 1999 (-1.3% a^{-1}) corresponds to a seven times higher loss rate compared to the 1850–1973 decadal mean. Extrapolation of area change rates and cumulative mass balances to all Alpine glaciers yields a corresponding volume loss of about 25 km^3 since 1973. Highly individual and non-uniform changes in glacier geometry (disintegration) indicate a massive down-wasting rather than a dynamic response to a changed climate. Our results imply stronger ongoing glacier retreat than assumed so far and a probable further enhancement of glacier disintegration by positive feedbacks. *INDEX TERMS:* 1630 Global Change: Impact phenomena; 1640 Global Change: Remote sensing; 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827). **Citation:** Paul, F., A. Kääb, M. Maisch, T. Kellenberger, and W. Haeberli (2004), Rapid disintegration of Alpine glaciers observed with satellite data, *Geophys. Res. Lett.*, *31*, L21402, doi:10.1029/2004GL020816.

1. Introduction

[2] Changes in mountain glaciers are among the best natural indicators of climate change [*Houghton et al.*, 2001; *Oerlemans*, 1994]. Their monitoring is now organized in the Global Terrestrial Network for Glaciers (GTN-G) as a part of the Global Terrestrial/Climate Observing System (GTOS/GCOS) [*Haeberli et al.*, 2000]. However, due to the remote location or the large size of glaciers, direct measurements are difficult to perform and the sample of observation sites available is sparse compared to the estimated 160,000 glaciers worldwide [*Dyurgerov and Meier*, 1997]. Calculations of sea level rise [*Van de Wal and Wild*, 2001] have to rely on scaling-paradigms applied to non-representative samples [*Bahr*, 1997], because a detailed worldwide glacier inventory is far from being accomplished [*Braithwaite and Raper*, 2002]. One way to obtain data for a global glacier inventory is the use of multispectral Landsat Thematic Mapper (TM) data, which are available since 1982 at 30 m spatial resolution and have widely been used for automated glacier mapping [*Aniya et al.*, 1996; *Jacobs et al.*, 1997]. The required international cooperation for a long term program of spaceborne glacier monitoring was recently initiated by the project Global Land Ice Measurements from Space (GLIMS) [*Kieffer et al.*, 2000; *Bishop et al.*, 2004].

[3] In the extraordinary warm decade of the 1990s many glaciers experienced large reductions in area [*Paul*, 2002b; *Khromova et al.*, 2003] and volume [*Arendt et al.*, 2002; *Rignot et al.*, 2003] with unknown magnitude at a global scale [*Dyurgerov*, 2002]. Glaciers in the European Alps are comparably small and their melt will not contribute significantly to global sea level rise [*Van de Wal and Wild*, 2001]. However, they are sensitive indicators of climatic change at a relevant time scale (a few decades), and they serve as benchmark glaciers for many global applications. Their disappearance might have large economic and societal impacts, for example on the hydrologic regime, tourism and natural hazards; in particular as the Alps are the most densely populated high-mountain region in the world [*Haeberli and Beniston*, 1998].

[4] Here we report results from the new Swiss Glacier Inventory 2000 (SGI 2000), a pilot study for worldwide glacier inventory compilation that has been obtained from multitemporal TM data and digitized glacier outlines. The latter were inferred from the previous Swiss glacier inventory that has been compiled from vertical aerial photographs acquired in September 1973 [*Müller et al.*, 1976]. Data processing is performed within a Geographic Information System (GIS) to facilitate operational application for global assessments [*Paul*, 2003].

2. Methods and Data

[5] The very low reflectance of ice and snow in the middle infrared has widely been used for glacier classification, for example with thresholded ratio images from TM bands 4 and 5 [*Bayr et al.*, 1994; *Paul*, 2002a]. This technique has proven to be simple, robust and accurate [*Sidjak and Wheate*, 1999; *Paul et al.*, 2002; *Albert*, 2002] and is applied for the SGI 2000 as well. The resulting glacier maps were converted to a vector format for further GIS-based processing. In combination with a digital elevation model (DEM) glaciologically relevant parameters (e.g., equilibrium line altitude, slope, aspect, hypsography) were derived [*Kääb et al.*, 2002].

[6] The specific analysis of glacier change presented here is based on the years 1850 and 1973 (digitized inventories), as well as 1985, 1992 and 1998/9 (TM data). The 1985 and 1992 data sets use a 50% southward shifted scene 195-27 (path-row) from 30 September 1985 and 17 September 1992, respectively. The 1998/9 data sets include two scenes: (A) scene 195-27/8 from 31 August 1998 with 713 glaciers, and (B) scene 194-27/8 from 12 September 1999 including 225 glaciers. As a result of the glacier partition during the last 25 years, the calculation of changes in area or hypso-

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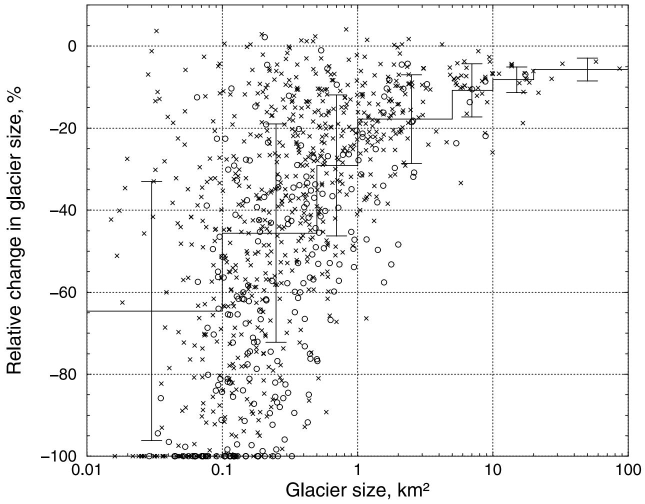

Figure 1. Scatterplot showing relative change in glacier size from 1973 to 1998/99 versus glacier size. This sample includes the 713 glaciers from data set A (crosses) as well as the 225 glaciers from set B (circles). Mean values of glacier area change for both sets combined (thick line) is given together with one standard deviation for seven distinct area classes (in km^2: <0.1, 0.1–0.5, 0.5–1.0, 1.0–5.0, 5.0–10.0, 10.0–20.0, >20.0).

graphy summarizes all individual glacier parts within the formerly specified basin.

3. Results

[7] The pattern of relative changes in glacier area as depicted in Figure 1 displays a strongly increasing scatter towards smaller glaciers. This implies that only a large sample of glaciers, covering all size classes, provides reliable information on the overall changes in glacier area. The decreasing mean towards smaller glaciers implies that the average change obtained for a greater region depends on the glacier size distribution considered in a specific sample. From 1973 to 1998/99 we found relative changes in area of −14% for set A, −31% for set B and −16% for both sets combined (Table 1). Glaciers smaller than 1 km^2 contribute about 44% to the total loss of area in this period, although they cover only 18% of the total area in 1973 (cf. cumulative change in Table 1). This is a direct consequence of their strong shrinkage combined with their large number. Hence, neglecting small glaciers in national inventories could introduce significant errors in the assessment of regional glacier change. For a subset of 471 glaciers from set A, changes in glacier size are also derived for the periods 1973 to 1985 (−1%), 1973 to 1992 (−11%) and 1973 to 1998 (−19%), reflecting the observed advance period of Alpine glaciers from about 1970 to 1985 and the strong retreat thereafter.

[8] Typical changes of individual glaciers are illustrated for the Rheinwald region (46.5°N, 9.1°E, Grisons, Switzerland) in Figure 2 with glacier extent given for the years 1850, 1973 and 1999. From 1850 to 1973 all glaciers lost large parts of their former area or even disappeared. From 1973 to 1999 the full spectrum of glacier area changes occurs, ranging from minor retreat to complete disappearance, although the entire region is assumed to be influenced by similar climate conditions. The 52% area reduction of the Paradiesgletscher (P) since 1973 is caused by a detachment of its tongue which was initiated by emerging rock outcrops at a steep slope. Such non-uniform changes in glacier geometry can be observed throughout the entire Alps. They indicate that down-wasting has been the dominant process of glacier mass loss since 1985 and measurements of length changes may not fully reflect corresponding area changes, in particular not for such small glaciers. Thus, the problems associated with the parameterization of such high spatial variability by numerical modelling will make the assessment of future glacier change rather difficult. However, the highly-individual area changes of small glaciers can be documented most efficiently from multitemporal satellite imagery in combination with GIS-based data processing [*Paul*, 2002b].

[9] Glaciers in the northeastern part of Switzerland are poorly represented in the SGI 2000 (due to snow cover) and many glaciers smaller than 0.1 km^2 have not been considered. In order to obtain full coverage the average relative changes for the seven area classes used, are linearly extrapolated to the entire Swiss data set (2057 glaciers), yielding a −18% change in area from 1973 to 1999 (cf. Table 1). If the extrapolation is applied to all 5422 Alpine glaciers (covering 3010 km^2) the change is 675 km^2 or −22%. Assuming a moderate climate-change scenario, the latest overall assessment predicts a −30% change in Alpine glacier area from 1980 to 2025 [*Haeberli et al.*, 2002]. However, the loss of about −22% calculated here for

Table 1. Summary of Glacier Data for the 1973–1998/9 Period[a]

	Swiss Glacier Inventory 2000					Switzerland			Alps		
Class		Area [km^2]		Change	Cum.		Area	Change		Area	Change
[km^2]	Count	1973	1998/9	[%]	[%]	Count	[km^2]	[km^2]	Count	[km^2]	[km^2]
0.1	164	10.1	3.6	−64.6	3.4	1022	40.1	−25.9	1971	101.2	−65.4
0.5	448	110.7	60.3	−45.6	30.2	673	153.9	−70.1	2411	533.2	−242.9
1.0	131	89.6	63.5	−29.1	44.1	151	104.1	−30.3	465	324.8	−94.6
5.0	141	264.2	217.1	−17.9	69.1	157	296.0	−52.8	470	952.5	−170.0
10.0	36	260.7	233.6	−10.8	84.0	35	249.4	−26.9	71	497.7	−53.6
20.0	13	210.0	192.8	−8.2	93.1	14	216.3	−17.7	27	387.9	−31.7
100	5	225.9	213.0	−5.7	100.0	5	225.9	−12.9	7	293.6	−16.8
Total	938	1171.2	982.8	−16.1	100.0	2057	1285.7	−236.7	5422	3090.9	−675.0

[a] ‘Class’ gives maximum glacier size within each area class. ‘Cum.’ gives cumulative part on the absolute change in glacier area. Absolute change in area for ‘Switzerland’ (column 9) and ‘Alps’ (column 12) is calculated by multiplication of column 5 with the respective area in each class (columns 8 and 11, respectively).

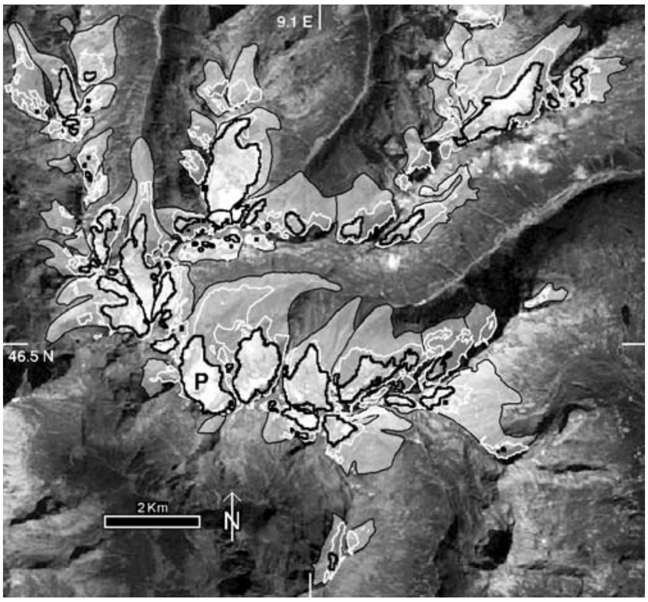

Figure 2. Glacier extent in 1850, 1973 and 1998 in the Rheinwald mountain group. Glacier outlines from 1850 (black with hatched areas) and 1973 (white) have been digitized manually, 1999 outlines (thick black) are derived automatically from TM (without correction for debris cover). The background shows a contrast stretched TM band 2 image from 12 September 1999, P is Paradiesgletscher. See color version of this figure in the HTML.

the period 1973–1998/9 is already in this range, indicating a much faster glacier melt than previously expected. Multiplication of the average cumulative mass balance for eight Alpine glaciers (about −9 m water equivalent) with the mean of the 1973 and 1998 total Alpine glacier area (2753 km^2) gives about −25 km^3 for the corresponding volume loss. For geometrical reasons (thickness loss), the relative change in volume is likely to have been larger than the corresponding relative change in area. If we conservatively assume a relative volume change of −25%, the total 1973 Alpine glacier volume results in 100 km^3 or less, much lower than the 130 km^3 suggested earlier [*Haeberli and Hoelzle*, 1995].

[10] The acceleration of glacier retreat has also been proven by a comparison of the decadal area change for the period 1850–1973 [*Maisch et al.*, 2000] with 1973–1998 (cf. Table 2): In total the area change has increased by a factor of three for the latter period, whereas it is about a factor of seven for the period 1985–1998. Again, the rate of area loss for small glaciers is even larger. Numerical modelling of length fluctuations for specific valley glaciers (areas >10 km^2) from a 2000-year simulation with a global climate model, suggest that their retreat since 1850 has exceeded their internal variability [*Reichert et al.*, 2002]. However, such large glaciers exhibit only small relative area changes since 1973 in our assessment, implying that the glacier shrinkage observed in the Alps since 1985 relates to an extraordinary climatic anomaly.

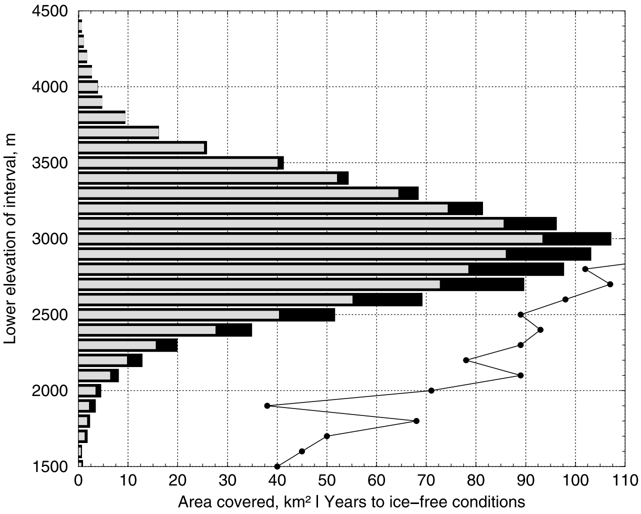

Figure 3. Changes in distribution of glacier area with elevation. The bars give values summarized in 100 m elevation intervals for 1973 (black) and 1998 (grey). The black line indicates the number of years after 1998, until the respective elevation interval will be ice-free, assuming the mean 1973 to 1998 retreat rates.

[11] For a selection of 683 glaciers from set A the hypsography at 100 m bins is calculated from the 1973 and 1998 outlines and a DEM with 25 m spatial resolution (Figure 3). While highest absolute changes in area of up to 20 km^2 take place where most of the glacierized area is located (from 2700 to 3100 m a.s.l.), highest relative changes occur below 2000 m a.s.l. Based on the rate of change in each elevation interval for the entire 1973–1998 period, the number of years to ice-free conditions has been

Table 2. Average Glacier Change Per Decade for 1850–1973, 1973–1998 and 1985–1998[a]

	1850		1850–1973		1973–1998/9		1985		1985–1998	
Class		Area	Change/10a		Change/10a			Area	Change/10a	
[km^2]	Count	[km^2]	[km^2]	[%]	[km^2]	[%]	Count	[km^2]	[km^2]	[%]
0.1	297	17.3	−0.8	−4.5	−2.6	−25.9	79	4.2	−2.0	−46.2
0.5	715	181.3	−7.9	−4.3	−20.2	−18.2	227	53.7	−15.1	−28.1
1.0	249	172.5	−6.3	−3.6	−10.4	−11.6	75	51.0	−10.0	−19.6
5.0	253	524.4	−14.0	−2.7	−18.9	−7.1	76	135.0	−17.2	−12.7
10.0	26	195.5	−3.1	−1.6	−11.3	−4.3	11	79.3	−5.8	−7.3
20.0	18	259.9	−3.0	−1.2	−6.9	−3.3	3	49.1	−2.3	−4.6
100.0	9	270.5	−2.6	−1.0	−5.2	−2.3	0	0	0	0
Total	1567	1621.4	−38.3	−2.2	−75.4	−6.4	471	372.2	−52.2	−14.0

[a] 'Class' gives maximum glacier size within each class. Count and area for the 938 glaciers of the 1973 sample are given in Table 1. The 1985 sample holds only glaciers smaller 20 km^2.

calculated (Figure 3, black line). Regions below 2000 m a.s.l. will be ice-free by 2050 and below 2500 m a.s.l. by 2100. An even faster area loss is assumed for at least four reasons: (1) The interval used for this extrapolation includes the intermittent growth period 1973–1985 with little variation in glacierized area. If the retreat period 1985–1998 is used for extrapolation, the change is two times faster. (2) The eastern part of Switzerland (data set B) experienced stronger area reduction but is not considered. (3) Positive feedbacks due to thermal radiation emitted from now ice-free bare rock surfaces or the general decrease in glacier albedo after several years with strongly negative mass balances will further accelerate glacier melt. (4) With respect to the characteristic response time of Alpine mountain glaciers to climatic changes (about 10–20 years), an accelerated retreat as a reaction to the extraordinary warm 1990–2000 decade is still to come.

4. Conclusions

[12] Analysis of global mass balance data [*Haeberli et al.*, 1999; *Dyurgerov and Meier*, 2000], recent direct measurements with new technologies [*Arendt et al.*, 2002; *Rignot et al.*, 2003] and latest studies with satellite data [*Paul*, 2002b; *Khromova*, 2003] confirm that current rates of glacier retreat have strongly increased above long-term averages. In the Alps, the observed non-uniform changes in glacier geometry (e.g., emerging rock outcrops, separation from tributaries, disintegration) indicate a massive downwasting since 1985 rather than a dynamic glacier response to a changed climate. Further enhancement of glacier decay is expected from positive feedbacks related to the changed radiation regime. The processing of the archived TM data sets with the efficient methodologies available today, is a promising way to assess glacier area changes in full and at a global perspective.

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