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Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies

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Abstract

The new satellite-derived Swiss glacier inventory revealed that mean glacier area loss per decade from 1985 to 1998/99 has accelerated by a factor of seven compared to the period 1850–1973. Moreover, the satellite data display much evidence that down-wasting (i.e. stationary thinning) has become a major source of glacier mass loss, an observation that is confirmed by *in situ* mass balance measurements. Many of the observed changes (growing rock outcrops, tongue separation, formation of pro-glacial lakes, albedo lowering, collapse structures) are related to positive feedbacks which accelerate further glacier disintegration once they are initiated. As such, it is unlikely that the recent trend of glacier wastage will stop (or reverse) in the near future. In view of the rapid non-uniform geometry changes, special challenges emerged for the recently established tiered glacier monitoring strategy within the framework of the Global Climate/Terrestrial Observing System (GCOS/GTOS). The challenges include: (1) loss of mass balance series due to disintegrating glaciers, (2) problematic extrapolation of index stake measurements from a calibration period under different climate conditions, (3) critical evaluation of measured length changes, (4) establishment of an operational glacier inventorying strategy using satellite data and (5) the calculation of new topographic parameters after glacier split up that can be compared to previous parameters.

Keywords: Alpine glacier change; multispectral satellite data; glacier monitoring

1. Introduction

Changes in glacier length are widely recognized as the most reliable and most easily observed terrestrial indicators of climate change (IPCC, 2001; Haeberli, 2004). This is mainly due to the clearly recognizable retreat of many larger valley glaciers over more than 2 km in reaction to a temperature increase of only 1 K since 1850, which is hardly noticeable otherwise. This retreat signal has been of uniform and global character (Grove, 1988; Hoelzle et al., 2003) with short, intermittent periods of readvance in the 1920s and 1970s. The strong advance of several glaciers on the west coasts of Norway and New Zealand during the 1990s was mostly due to enhanced winter precipitation and does not contradict the general warming trend, as these maritime glaciers with a high mass turnover are much more sensitive to changes in precipitation than to

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temperature (Oerlemans and Reichert, 2000). In the Alps glacier fluctuations are well documented (paintings, photos, field surveys) due to a relative easy access (e.g. Zumbühl and Holzhauser, 1988), tourism (Zängl and Hamberger, 2004) and initiation of the length measurement network in 1893 by Forel (cf. Haeberli et al., 1998). The number of annually measured length changes increased from about 50 in the beginning to nearly 250 in 2000 with most glacier types being covered (Zemp et al., in press). However, there is a strong bias towards larger glaciers in the length measurement sample, due to the remote location of most small glaciers. As such, the changes of the latter are less well documented and the retreat signal is dominated by large valley and mountain glaciers. While the valley glaciers reflect the secular trend, mountain glaciers reveal decadal oscillations in the climate signal (Hoelzle et al., 2003), i.e. the advance period of the 1920s and 1970s. The related changes of small glaciers are best assessed by repeated inventories, that can be obtained from multispectral satellite data (e.g. Paul, 2002a; Paul et al., 2002).

Due to their function as terrestrial key indicators for climate change detection, glacier monitoring is implemented in the Global Climate/Terrestrial Observing System (GCOS/ GTOS) and follows a Global Hierarchical Observing Strategy (GHOST) of tiers that include: (1) intensive and integrated experimental sites (improvement of process understanding), (2) process-oriented mass balance studies within major climatic zones (with winter and summer balance measurements), (3) glacier mass changes within major mountain systems (calculating mass balance from reduced stake networks by spatial interpolation, about 50 glaciers worldwide), (4) long-term length change measurements at about ten sites within each mountain range (about 500 glaciers worldwide, also a key element for reconstructing past climate conditions, simple index), and (5) repeated glacier inventories from satellite data, that provide basic data sets for comparative studies (see Haeberli et al., 2000, 2002).

The recent analysis of satellite data revealed a strong acceleration of glacier shrinkage in the Alps since 1985, with a mean decadal rate of area reduction seven times higher than during the 1850–1973 period (Paul et al., 2004a). The strong acceleration of glacier shrinkage (in size and thickness) has also been observed in several other places around the world (Jianping et al., 2004; Khromova et al., 2003; Ramirez et al., 2001), by application of new technologies like laser profiling (Arendt et al., 2002), radar altimetry (Rignot et al., 2003) and analysis of global mass balance data (Haeberli et al., 1999; Dyurgerov and Meier, 2000). Although changes in glacier thickness can not be measured directly from optical satellite data, the analysis of image time series gives indirect evidence that down-wasting (i.e. stationary thinning) has become a major source of Alpine glacier mass loss during the past 20 years. This was also confirmed by the mainly negative mean mass balances of ten Alpine glaciers since 1980 (Frauenfelder et al., 2005). In particular, the extraordinary hot summer of 2003 (Schär et al., 2004) had major impacts on Alpine glaciers (Frauenfelder et al., 2005), by initiating adverse effects that are discussed in detail below.

In this paper we present examples for the observations made by Landsat Thematic Mapper (TM) and ASTER satellite data throughout the Alps, discuss the theoretical background of the analysis and show consequences for future glacier development. We close with a discussion of the resulting challenges for future glacier monitoring.

2. Study sites and methods applied

The satellite-based observations are exemplified for several test sites throughout the entire European Alps (Fig. 1). The examples discussed cover various climatic regions and include glaciers of different exposition and size. However, for better visibility of the changes, we have selected some of the more prominent examples. In principle, the changes can be observed in every region of the Alps, but not necessarily for all in the same region.

The analysis is based on multispectral, optical satellite data and relies on a spectral channel in the middle infrared part of the spectrum (around 1.5 μm), where snow and ice exhibit a very low reflection (cf. Fig. 3) compared to clouds and most other natural surfaces except water (e.g. Dozier, 1989). In order to study glacier changes, cloud-free images acquired at the end of the ablation season in a year without snow outside of glacier areas have to be used. Due to the often unstable weather conditions in the Alps during autumn, only a few years match all conditions. These years determine the selection of scenes presented here. The corpus of scenes analysed is summarized in Table 1.

2.1. Qualitative interpretation of image time series

A very efficient tool for rapid change detection analysis from Landsat Thematic Mapper (TM) raw data are animated image sequences (flicker images) from false colour composites using bands 5, 4 and 3 as red, green and blue, respectively. They show clouds in white,

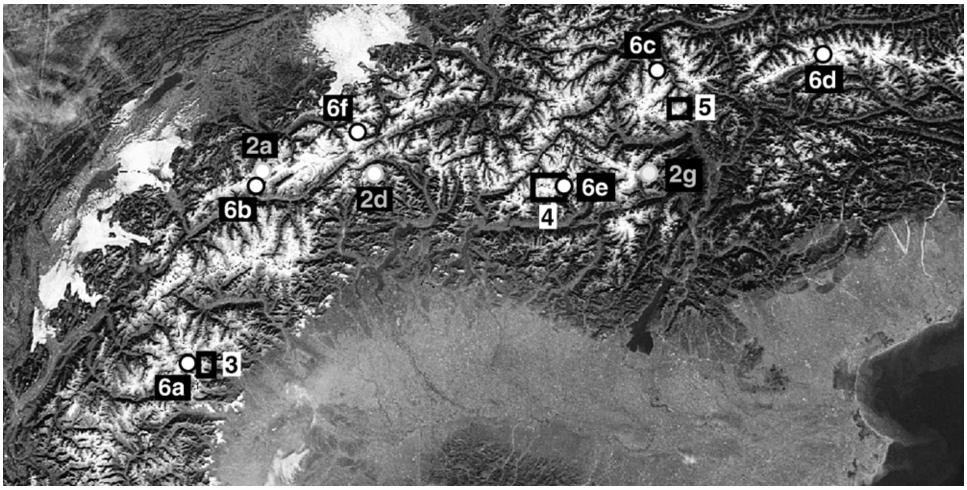

Fig. 1. Overview of the test sites selected for this study. The background image is acquired by MODIS at 1 November 2003 (© NASA, GSFC). The numbers indicate the respective Figures.

glaciers (i.e. snow and ice) in blue-green, lakes in blue, bare rock in pink to purple and vegetation in yellow to green. This band combination is also used for Figs. 2, 4 and 5) and widely applied for image quicklooks from TM data (e.g. http://glovis.usgs.gov) as the overall quality of a scene can be determined very easily. For Landsat TM data a relative image matching with a few unchanged ground control points (GCPs) works quite well, as the orbit of Landsat has been very stable for more than 20 years. If enough images are available, also more than two images can be animated to follow glacier change with time in more detail. However, the images should be acquired around the same date in the year to avoid too large changes of the cast shadow zones which disturb the visual analysis. One restriction is that the size of the image frames selected for animation must be smaller than screen size. For the comparably small glaciers in the Alps this is not a problem, as most individual mountain ranges are not exceeding 40 km, which is about 1200 pixels at the original resolution of about 30 m. Although resampling can be used to increase the covered area, the relative matching worsens for larger regions due to increasing geometric distortions (Paul, 2002a). The changes taking place are clearly visible even if the colour balance from the individual image frames is slightly different. Mostly, public domain image processing tools can be used to adjust the colours. Apart from changes in glacier length, in particular new rock outcrops and the formation of new lakes can be assessed quickly. In a high-speed mode, interesting details of individual glacier dynamics can be followed. They clearly indicate that frontal glacier recession is often coupled to a lateral glacier thinning of a similar magnitude. Another interesting application of such image sequences is provided by the Internet or computer presentations: apart from animated GIF images with a prescribed speed, both media allow an interactive change using a ‘mouse over’ command or a toggling (back and forth) between two slides (Kääb et al., 2003a). In summary, following glacier changes by animation of image sequences is much more instructive and plausible than overlay of outlines, as visual perception is trained to recognize changes (e.g. Bruce et al., 2003).

Table 1
Overview of the satellite scenes applied in this study

Nr.	Sensor	Date	Path-row	Figures
1	Landsat TM	30.9.1985	193–27	2g, 4a, 5a
2	Landsat TM	28.9.1985	195–28	2a, 2d, 3a
3	Landsat TM	13.9.1999	193–27	2h
4	Landsat TM	31.8.1998	195–28	2b, 2e
5	Landsat TM	30.7.2003	193–27	2i, 4b, 5b, 6e
6	Landsat TM	13.8.2003	195–28	2f, 3b, 6f
7	ASTER	23.8.2003	193–27	6c
8	ASTER	8.9.2004	195–27	2c, 6b
9	ASTER	8.9.2004	195–28	6a
10	ASTER	10.9.2004	192–27	6d

2.2. *Quantitative analysis from multispectral glacier classification*

In high-mountain topography exact orthorectification of satellite data is required if glacier outlines are combined with other sources of georeferenced information (e.g. other satellite sensors or digitized outlines of former glacier extent). This requires a high-resolution digital elevation model (DEM) of appropriate accuracy as well as accurate topographic maps for collection of GCPs (Paul, 2004). Both data sources are available for the countries of the Alpine region. However, accurate DEM data can be very expensive for the area covered by a single TM full scene. For glacier studies in other remote regions the availability of the SRTM 3 arc second (about 90 m) resolution DEM (Rabus et al., 2003), that can be down-loaded for free from an NASA ftp-server (ftp:// e0mss21u.ecs.nasa.gov/srtm/), was extremely valuable as it can also be used as a source of GCPs (Kääb, 2005). Where SRTM3 data is not available (voids, north of 61° N and south of 57° S) the DEM generation from ASTER stereo data has proven to be very useful for orthorectification and other purposes (e.g. Kääb et al., 2005; Paul and Kääb, 2005). Despite the somewhat higher resolution of an ASTER DEM (about 30 m) the accuracy of the elevation values obtained are similar to the SRTM3 DEM in high-mountain topography (Eckert et al., 2005; Kääb, 2005; Toutin, 2002).

Due to the distinct spectral properties of ice and snow, the classification of debris-free glaciers is quite easy from thresholded ratio images (e.g. Paul et al., 2002; Kääb et al., 2003b; Paul et al., 2003). Most effective for automated glacier mapping is a TM band 3/5 ratio (AST 2/4) in combination with an additional threshold in band TM1 (AST1) for discrimination of snow or ice in regions of shadow casted by the terrain from rock (Bishop et al., 2004; Paul and Kääb, 2005). Compared to the TM 4/5 ratio, which can also be applied efficiently (e.g. Jacobs et al., 1997; Sidjak and Wheate, 1999; Albert, 2002; Paul, 2002b), the TM3/5 ratio also maps all water bodies (clear and turbid) as glaciers, which requires additional post-processing. On the other hand, the interference with vegetation in shade is less pronounced and in very deep shadows ice is still mapped completely. Thus, the more suitable band combination (i.e. less work is required for post-processing) should be selected, depending on the image content (shadow, vegetation, water). Heavily debris-covered glacier parts cannot be mapped by either method due to their spectral similarity with the surrounding terrain. Some promising techniques that include DEM information and neighbourhood analysis (Bishop et al., 2001; Paul et al., 2004b) or utilize the thermal band (Taschner and Ranzi, 2002) have nevertheless been developed. The quantitative analysis of glacier change is strongly facilitated by application of GIS techniques (Paul, 2002b; Paul et al., 2002), which allow for the automated extraction of individual glaciers from the classified satellite map according to predefined glacier basins as well as the calculation of 3D glacier parameters (e.g. slope, aspect, lowest and highest glacier elevation) in combination with a DEM (Kääb et al., 2002; Paul, 2004).

3. Observed changes

3.1. The new Swiss glacier inventory 2000

Specific results of glacier changes in Switzerland from 1973 to 1985 to 2000 as well as an extrapolation to the entire Alps have been reported in Paul (2004) and Paul et al. (2004a). Thus, we will summarize here only the main results which support the observations made throughout the Alps. In Switzerland, glaciers lost about 18% of their area from 1985 to 1998/99 (from 1973 to 1985 the change is only −1%). This corresponds to an average relative area loss of 14% per decade, which is about seven times higher than the decadal loss rate between 1850 and 1973 (−2.2%). There is an even higher relative loss of area towards smaller glaciers, but the scatter among values increases as well, indicating a very specific behaviour of individual glaciers that are smaller than 1 km^2. Such small glaciers account also for a major part (44%) of the total area loss since 1973, although they cover only 18% of the total area in 1973. As most of these small glaciers are not covered by the length measurement network, satellite data are the most efficient way to assess their changes in full. Such data also reveal that non-uniform geometry changes (i.e. not related to active glacier retreat) can occur everywhere on a glacier. They are mainly indicated by increasing regions with rock outcrops inside of glaciers as well as a shrinkage along the entire glacier perimeter, including the accumulation area.

3.2. Down-wasting glaciers

According to the mass balance data from ten Alpine glaciers (IUGG(CCS)/UNEP/UNESCO/WMO, 2005) the mean cumulative specific mass loss was about 17 m water equivalent (we) between 1981 and 2003, corresponding to about −0.8 m we per year. This is about three times the long-term mean value for the 20th century of −0.27 m we (Haeberli and Hoelzle, 1995; Hoelzle et al., 2003). Apart from 3 years (1984, 1995 and 2001) with small mass gains, all years since 1981 exhibit mass losses. A linear trend line on the data points suggests an increasing speed of glacier mass loss, indicating that glaciers were not able to primarily adjust to the current climatic conditions by a dynamic retreat towards higher elevations with cooler temperatures.

Instead, the reduction in driving stress and flow facilitates down-wasting which even results in an elevation lowering of the glacier surface. The continuous mass loss has also diminished or even eliminated most of the firn reserves from previous years, as the equilibrium line was generally above its steady-state position and quite often even above the highest glacier point. Thus, the decreasing mass flux from the accumulation area has also steadily lowered the ice flow velocity (e.g. Herren et al., 2002) which in turn led to many of the observed disintegration features (hollows within a glacier, caves and deep tunnels at the glacier front).

3.3. Observations from satellite imagery

Although glacier thinning cannot be directly measured from Landsat or ASTER data (the latter allows at least the creation of a DEM that can be compared to previous DEMs, e.g. Berthier et al., 2004; Kääb, 2004), the observed changes provide evidence that massive glacier down-wasting took place during the past two decades. The major indicators of down-wasting that have been observed on Landsat images are: growing rock outcrops, separation from tributaries, formation of pro-glacial lakes, non-uniform geometry changes, e.g. disintegration and shrinkage along the entire perimeter. Such changes can be observed throughout the entire Alps, independent of the precipitation regime, glacier size or exposition. In some regions nearly all of these changes could be observed at the same time. In the following section, we discuss some of the more extreme examples for better visibility of the processes involved. However, it should be noted that individual glaciers with little or no change can often be found in the same region or even adjacent to a disintegrating glacier. The reason for this high-variability over short distances has not been determined yet.

3.4. Examples

In Fig. 2 we show smaller mountain glaciers located in three different regions (grey circles in Fig. 1) for three

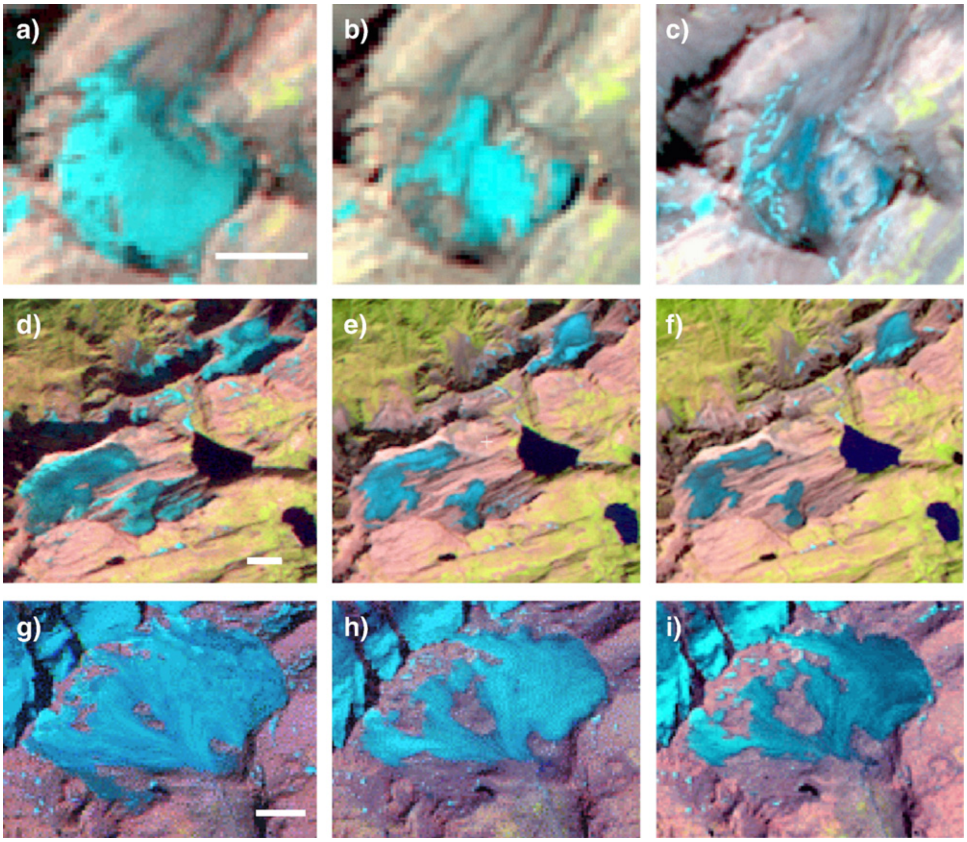

Fig. 2. Three small mountain glaciers which disintegrate due to down-wasting, the scale indicates 500 m. a) Taelli Glacier (46.5° N, 7.6° E) in 1985, b) in 1998 and c) in 2004 which has already disappeared. d) Cavagnoli Glacier (46.5° N, 8.5° E) in 1985, e) in 1998 and f) 2003 with an almost separated tongue (please note: the small Vallegia Glacier in the upper right is nearly unchanged). g) Caresèr Glacier (46.5° N, 10.7° E) in 1985, h) in 1999 and i) in 2003 displays increasing areas with rock outcrops that will separate the glacier into several smaller parts in the near future.

points in time (1985–1998/99–2003). The first is Taelli Glacier (Fig. 2a–c) in the Wildstrubel region which is situated at the northern rim of the Alps and receives high amounts of precipitation (Schwarb et al., 2001). The second one is Cavagnoli Glacier (Fig. 2d–f) which is located near the Nufenenpass and close to the two mass balance glaciers Gries and Basòdino, near a local maximum of annual precipitation (Schwarb et al., 2001). The third one is Caresèr Glacier (Fig. 2g–i) in the Ortler–Cevedale Group (Italy), which is located under somewhat more continental (drier) conditions. All three glaciers are placed at about the same geographical latitude (46.5° N) and clearly demonstrate how fast disintegration has proceeded in the last 20 years. While Taelli Glacier has already disintegrated into several small patches of ice remnants, Cavagnoli Glacier will likely follow next and the somewhat larger Caresèr Glacier shows rapidly growing regions with rock outcrops. Unfortunately, the latter is one of the few Tier 3 monitoring sites (Haeberli, 2004) with a long-term series of mass balance measurements starting in 1967 (Carturan, 2002). A common characteristic of all three glaciers is that they are comparably flat and not protected much by rock walls from direct solar radiation during summer. As such, their disintegration will most-likely continue in the following years as positive feedbacks can accelerate the down-wasting even further (see Section 4).

Somewhat larger regions are selected for Figs. 3–5 (black squares in Fig. 1). They are located in the Gran Paradiso mountain range (Fig. 3) in the southwestern part of the Alps (FR/I), the Bernina group (Fig. 4) in the central-southern part (CH/I) and in the Ötztaler Alps (Fig. 5) in the central-northern part (A/I). In all three regions several processes resulting from the overall glacier down-wasting or shrinkage are visible. The corresponding phenomena are marked by an arrow or circle and include: (L) formation or growing of pro-glacial lakes, (O) new rock outcrops, (T) tongue separation, (R) strong retreat, and (D) disintegration. Again, it is obvious that the observed changes took place on an Alpine-wide scale, but nearly unchanged glaciers can often be found within the same region. This aspect underlines the importance of satellite data for assessment of glacier changes, as the behaviour of an individual glacier might not optimally reflect the overall trend.

The final examples in Fig. 6 (black circles in Fig. 1) show recently formed pro-glacial lakes, which can clearly be detected by flicker-image analysis and which might already be or become a source of glacial hazards (Kääb et al., 2005). They are so numerous that an integrated approach of automatic detection from satellite data and classification of their hazard potential by means of GIS-based modelling should be applied (Huggel, 2004; Huggel et al., 2004). In this context, important

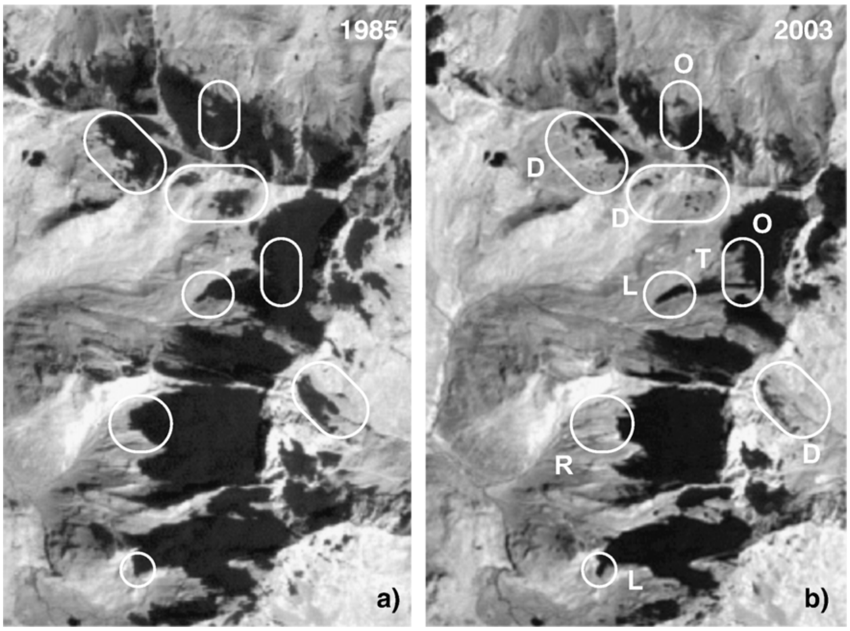

Fig. 3. The region around Sources de l' Arc Glacier (44.4° N, 7.2° E) in the Gran Paradiso Group (size is 7 by 9 km) as seen in TM band 5 in a) 1985 and b) 2003. Circles depict interesting regions of change and point to the same location in both images, letters denote: L = Lake formation/growth, O = rock Outcrops, T = Tongue separation, D = Disintegration, and R = strong Retreat.

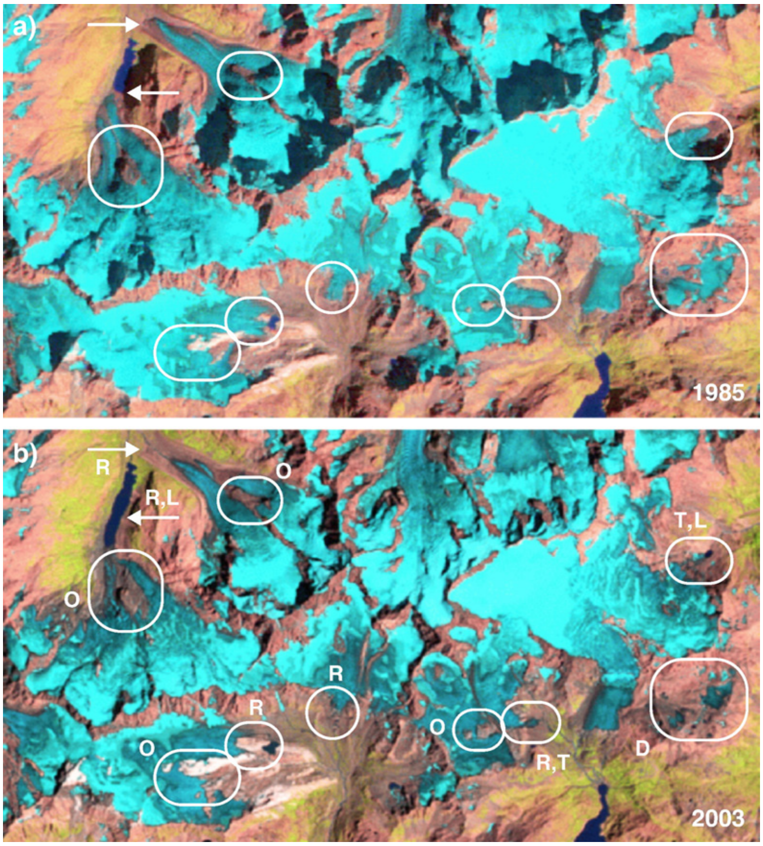

Fig. 4. The region along the Swiss/Italian border in the Bernina Region (image size is 15.3 by 8.4 km) in a TM 5, 4, 3 false colour composite with Piz Bernina near the image centre (46.4° N, 9.9° E) in a) 1985 and b) 2003. For the letter code see Fig. 3.

aspects for all lakes concern the question whether they are bounded by bed rock or morainic material, whether ice or rock avalanches from higher up can reach the lake and whether there is a potential for further growth (e.g. Huggel et al., 2003). However, for such studies DEM data must be analysed as well and this is not the scope of

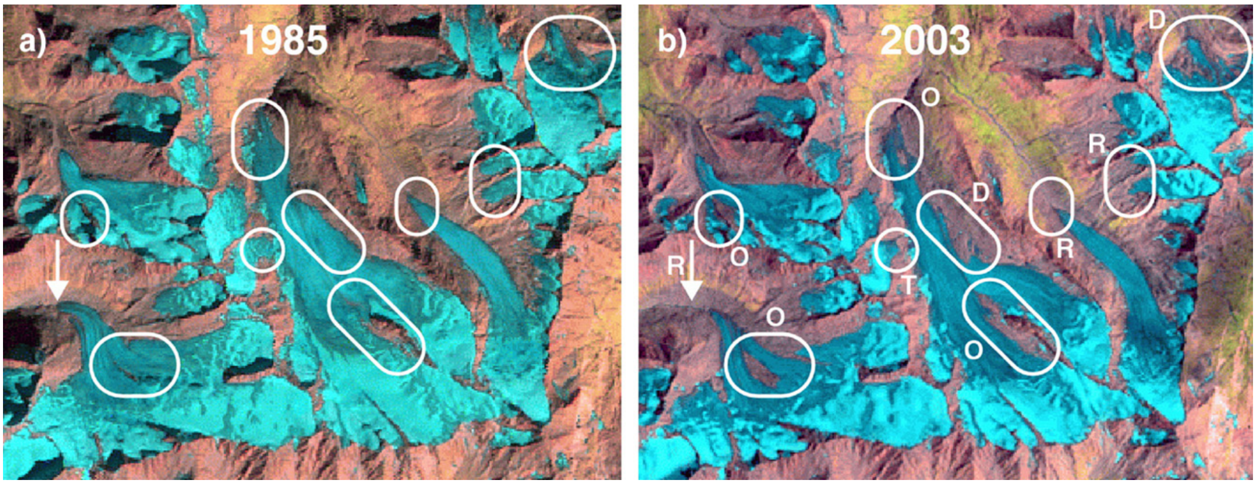

Fig. 5. The region along the Austrian/Italian border in the Ötztaler Alps (image size is 10.5 by 8.1 km) with the comparably large (ca. 10 km^2) valley glacier Gurgler Ferner (46.8° N, 10.9° E) in the image centre as seen from Landsat TM in a) 1985 and b) 2003. For the letter code see Fig. 3.

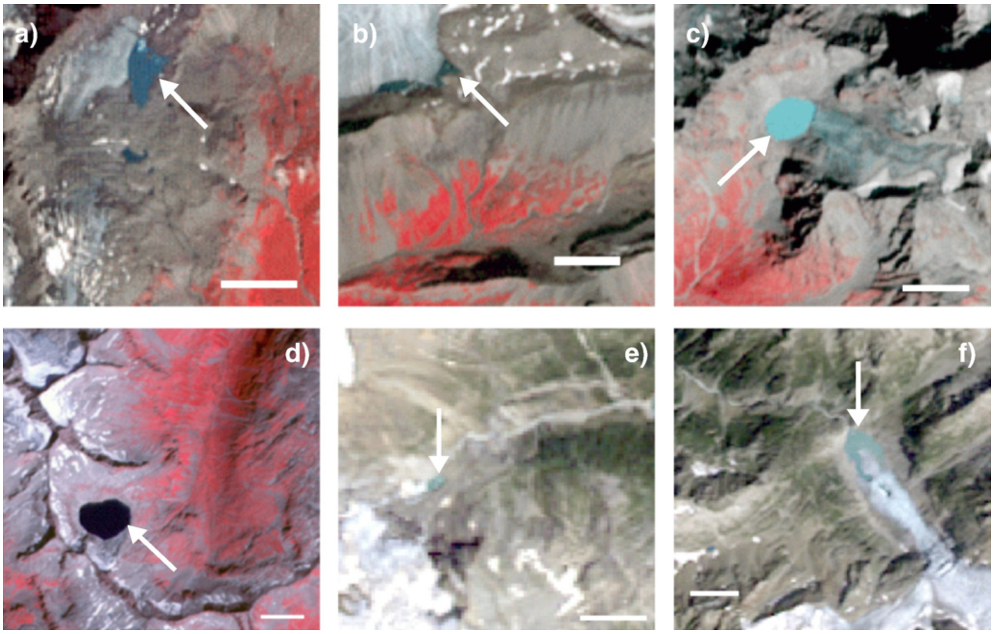

Fig. 6. Lakes that have been formed at several glaciers throughout the Alps (see Fig. 1 for location) in recent years due to glacier retreat, a) at Montet Glacier (Gran Paradiso, F), b) at Plaine Morte Glacier (Wildstrubel, CH), c) at the glacier front of Schweikart Ferner (Kaunertal, AU), d) at Seekar Glacier (Hohe Tauern, AU), e) at Palue Glacier (near Berninapass, CH) and f) at Trift Glacier (near Sustenpass, CH). The white scale bar on each figure indicates 500 m, north is always at top.

this study. While four lakes (Fig. 6a–d) are covered by recent 15 m resolution ASTER data (with AST 3, 2, 1 as RGB) from 2003/04, two other lakes (Fig. 6e and f) are depicted with TM data from 2003 (see overview in Table 1). All lakes shown were more or less completely covered by glacier ice in 1985 and the lake at Trift Glacier (Fig. 6e) did even not appear before 1998. Apart from the lake in Fig. 6d, there is a potential for further growth of all other lakes, as they are still in contact with retreating glaciers. An automatic camera has been installed to monitor the further evolution of Trift Glacier and its lake (http://people.ee.ethz.ch/~glacier/images/trift_acam.jpg).

4. Discussion

Most of the observed changes are related to positive feedbacks, i.e. once started they have the tendency to intensify further. The formation of pro-glacial lakes that are in contact with a glacier tongue often leads to rapid further growth, as the water can get warmer than 0° and cause additional ice melt (so called thermokarst). A thermally driven internal circulation erodes the ice at the waterline and leads to the formation of ice cliffs with the related calving events (Kääb and Haeberli, 2001). Rapid retreat of glacier tongues in the course of their flooding by artificial lakes (hydro-power) has been frequently observed. This process was also one reason for the recent rapid disintegration of an entire tongue at Trift Glacier (Fig. 6f). Where the growth of such lakes is not limited by topography (rising bedrock), the glaciers might shrink until they loose contact with the lake or until the ice flux is in balance with the enhanced melting.

Due to their lower albedo and thermal inertia, new rock outcrops heat up more quickly than the surrounding ice (or snow) and emit this heat also after local sunset and during night. This process can very efficiently create a small gap between the rock and the ice, which further grows by turbulent heat fluxes. As such, rock outcrops that appear somewhere within a glacier (depending on the bedrock topography) are very efficient in separating a glacier into smaller parts (Figs. 2–5). Once several rock outcrops have separated a part of a glacier from the accumulation area, the dead ice body will melt down quickly (at least if not protected by a thick debris cover). This is also due to the higher amounts of thermal heating from the surrounding rock and the larger parts of surface area exposed to turbulent heat fluxes. As a result of the overall down-wasting, the rock outcrops appear at first on steep slopes, where glaciers are relatively thin. At these locations glaciers can be separated very effectively from tributaries (which may have an accumulation region at higher elevations than the remaining glacier) or even loose their entire tongues. Both processes have been followed on multi-temporal satellite images for several glaciers (see examples in Figs. 2–5). All of the processes described above tend to considerably reduce the mass flux and may lead to further collapse structures (hollows, tunnels) that enlarge very fast by turbulent heat fluxes or accumulation of melt water. These structures can be observed today in many glaciers, but are difficult to detect on satellite imagery as they are generally quite small.

Another important aspect that could be observed is the gradual lowering of glacier albedo (in the ablation zone) in the course of the past 20 years, reaching values as low as 0.15 in 2003 (Paul et al., 2005). Apart from Saharian dust fall (occurring often in spring time) that could heavily decrease glacier albedo locally and temporarily, it seems that albedo decreased steadily as a result of the mainly negative mass balances since 1981. The effect is two-fold: one is the strong accumulation of soot, dust and other aerosols during long-lasting periods of fair weather (which are generally related to years with negative mass balance). Such particles could only be removed by very heavy precipitation events, as the material has a tendency to melt itself a few millimetres into the ice. The second aspect is the unveiling of dark firn bands from previous years, that are getting even darker since precipitation mostly falls as snow at these altitudes (no washing away of particles by heavy rain). In the Alps, glacier albedo exerts a major influence on the energy balance (e.g. Klok and Oerlemans, 2002; Paul et al., 2005) and thus on the summer ablation, which governs the variability of the annual balance for most glaciers (Oerlemans and Reichert, 2000). The decreasing glacier albedo is also part of a positive feedback that enhances glacier melt even more.

In total, all the processes observed here act together and in the same direction, leading to a self-acceleration of glacier decline. It can be assumed that it will be very difficult to stop this process for several reasons: (1) Most glaciers have lost all of their firn reserves from the 1970s and would need several years with large amounts of snow in winter (and little ablation in summer) to gain some mass that could then be redistributed by increased flow velocity to the glacier front. Although changes in precipitation are difficult to predict, it seems unlikely that the required increase of more than 50% (e.g. Kuhn, 1989) will take place. (2) There is a general trend of increasing temperatures in the future as predicted by nearly all climate models (e.g. Räisänen et al., 2004). This would further enhance the observed changes and also makes the required snowfall in summer less probable. (3) Even the still flowing and fast-reacting steeper mountain glaciers have response times of several years and their actual shape is not yet in balance with current climatic conditions. As such, they would continue to retreat for several more years even if temperatures are not increasing any further.

5. Consequences for future glacier monitoring

Important environmental changes must be expected to accompany further shrinkage or disappearance of mountain glaciers (e.g. landscape alteration, seasonality effects in the water cycle, slope stability and complex natural hazards; cf. Watson and Haeberli, 2004). Besides such aspects of general significance with respect to climate change, specific and new challenges result for the integrated multilevel (‘tiered’) glacier monitoring strategy as described in the introduction (Haeberli et al., 2000, 2002; Haeberli, 2004).

— Tier 1 observations along environmental gradients should strengthen the focus on interactions and feedbacks between elements with highly variable response characteristics (snow, glaciers, frozen ground, water cycle, soils, meadows, forests, etc.) within and between altitudinal belts in mountain areas in order to improve our understanding of disequilibrium which tend to develop more and more with increasing deviation of geo-and eco-systems from dynamic equilibrium conditions.

— Glaciers at tier 2 sites form the primary basis for development, calibration, and validation of numerical models, as much of the fundamental process understanding is generated here. Their study should continue as long and intensively as possible. However, it has to be taken into account that inter- and extrapolation of such measurements in space and time is getting more difficult due to rapidly and drastically changing glacier geometries: individual parts of Vernagtferner, for instance, are likely to separate in the near future, a fate which would be comparable to the evolution of Caresèr Glacier.

— At tier 3 sites, interpolation techniques applied to glaciers with index measurements should be re-evaluated in view of the new conditions compared to the calibration period (for instance, missing accumulation area) and rapidly changing geometries by using distributed mass balance models and corresponding interpolation schemes applied by using GIS techniques. This level of observation is becoming more important, because

— length change measurements analysed at tier 4 level are among the most heavily affected parts of modern monitoring strategies. In addition to selection criteria applied before (no flow instabilities, no calving/avalanching, no heavy debris cover, no disconnecting tongues), the transition from active retreat to downwasting or even collapse behaviour, increasingly limits possibilities of glaciological and climatological interpretation. The spatial representativity of observed glaciers can, and should, nevertheless be enhanced by using satellite measurements on a larger number of specifically selected glaciers at time intervals of roughly 10 years.

— Repeated glacier inventories (tier 5) from fast (operational) processing of satellite images and GIS-based post-processing including DEM fusion, should be repeated at a higher frequency (5 to 10 years) than previously planned (a few decades) in order to reveal collapse features or new lakes and to increase the number of observations. The separation of glaciers into many small glaciers thereby causes the need to design new (and consistent) hydrological numbering schemes, which allow the automated analysis of changing glacier parameters through time.

The fact that detailed baseline data for many climatologically interesting regions are still missing in the world glacier inventory (e.g. Arctic Canada) remains a special challenge for worldwide glacier monitoring. The project Global Land Ice Measurements from Space (GLIMS) is promising (Bishop et al., 2004), but it has become difficult to obtain global coverage from 60 × 60 km satellite scenes. As such, the huge archives with Landsat TM and undisturbed ETM + data (before the scan-line corrector fails) should be considered for generating glacier inventories as well.

6. Conclusion

The qualitative analysis of multispectral satellite imagery revealed clear but indirect evidence of massive glacier down-wasting in the European Alps since 1985. The changes can easily be detected with animated multi-temporal false colour images which only require relative image matching. Most of the observed changes (e.g. growing regions with rock outcrops, separation from tributaries, formation of pro-glacial lakes) are related to positive feedbacks, which will further accelerate glacier disintegration in the near future. A soon termination of this process is unlikely, as most glaciers are still far from a steady-state position, most firn reserves from previous years disappeared and climate models predict a further temperature increase in the future. This poses several new challenges for the recently established tiered glacier monitoring strategy, as the rapid changes in glacier geometry (up to disintegration) are difficult to cover. In particular tiers 2 to 4 suffer from the recent rapid changes. A large contribution could thus be made from the GLIMS project, by generating baseline glacier inventory data and DEM information through its regional centres for rapid assessment of ongoing changes.

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