Towards a global glacier inventory from satellite data

Recent efforts and challenges to complete the global glacier inventory with modern geoinformatic techniques

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1 Introduction

Glaciers and their changes have drawn the attention of the public and the media for several years now. Today, it is widely recognized that glacier changes are key indicators of climatic change (e.g. Intergovernmental Panel on Climate Change - IPCC 2007). They serve as unique demonstration objects of climate change effects for a wide public and act as independent proxies for small but global changes in temperature (e.g. Oerlemans 2005). The reason for the monitoring of glaciers and assessment of their overall distribution in a glacier inventory has thus changed from a hydrologic purpose (how much water is stored in the glaciers?) during the international hydrologic decade in 1965 to 1974 (e.g. Ohmura 2009) to climate change detection since the 1990s (Haeberli 2006). Recently, hydrologic aspects are again of high interest for several reasons: among others are, for example, the hydrologic significance of glacier meltwater in arid regions (e.g. Vergara et al. 2007), and the larger contribution of meltwater from glaciers and icecaps to global sea-level rise in the next decades compared to the two polar ice sheets Greenland and Antarctica (e.g. Meier et al. 2007). For both global sea-level rise calculations and assessment of glacier changes, detailed regional inventories are mandatory (e.g. Andreassen et al. 2008; Hock et al. 2009). Without them, large errors due to imprecise upscaling procedures have to be taken into account (e.g. Radic & Hock 2010; Raper & Braithwaite 2006), or overall changes must be deduced from isolated observations that might not be representative for an entire mountain range (Fountain et al. 2009; Paul & Haeberli 2008).

To overcome such deficiencies, the global terrestrial network for glaciers (GTN-G) has recommended the compilation of glacier inventory data from spaceborne sensors with a repetition after a few decades which is the typical response time of glaciers to climate change (e.g. Haeberli 2006). Today, basically two global glacier inventories exist: (a) the tabular data in the World Glacier Inventory (WGI) that was compiled during the 1970s to 1980s from aerial photography and topographic maps acquired in the 1940s to 1980s (WGMS 1989), and (b) the vector outlines stored in the GLIMS (Gobal Land Ice Measurements from Space) glacier database (GDB) at the National Snow and Ice Data Center (NSIDC), that are compiled by several regional centres from satellite data and partly also digitized from maps (Raup et al. 2007). Though detailed instructions for data compilation are available for both inventory types (Paul et al. 2009a; Raup & Khalsa 2007; UNESCO 1970), the inventories are geographically incomplete and partly include preliminary information that lack the level of detail (i.e. topographic attributes for each glacier entity) required for global assessments (e.g. Braithwaite 2009). Despite the possibility for (semi-)automated generation of glacier inventory data by digital combination of glacier outlines with a digital elevation model (DEM) (e.g. Paul et al. 2002), large and heavily glacierized regions (e.g. Alaska, Canadian Arctic) remain uncovered in the present GDB (see www.glims.org).

2 Available data sets

2.1 Glacier inventories

It is possible to differentiate between three types of data structure in current inventories: (1) point information, (2) vector outlines and (3) grid or raster data sets. The WGI (WGMS 1989), and its extended format, the WGI-XF (Cogley 2009), belong to category (1); the GDB and the digital chart of the world (DCW) to category (2); and the 1 by 1 degree GGHydro dataset by Cogley (2003) to category (3). Among other points, these data sets differ in the area covered, degree of completeness, level of detail, available data entries and period of acquisition. Accordingly, when global completeness is required, for example for sea-level rise calculations, a wide range of strategies is applied by different authors to fill these gaps (Hock et al. 2009; Radic & Hock 2010; Raper & Braithwaite 2006; Zuo & Oerlemans 1997). The same applies for the estimation of the total area covered by glaciers and ice caps on Earth, which varies between 520 million km^2 when excluding local glaciers on the Antarctic Peninsula and Greenland (Ohmura 2004; Raper & Braithwaite 2006) and 540 million km^2 (Dyurgerov & Meier 2005; Meier & Bahr 1996). The number of glaciers on Earth is largely unknown and Meier & Bahr (1996) applied a scaling technique to come to an estimation of 160’000. This number does strongly depend on the smallest glacier size considered, as there is in most inventories a strong (exponential) increase of glacier number towards smaller glaciers (e.g. Bolch et al. 2010). However, the rough number

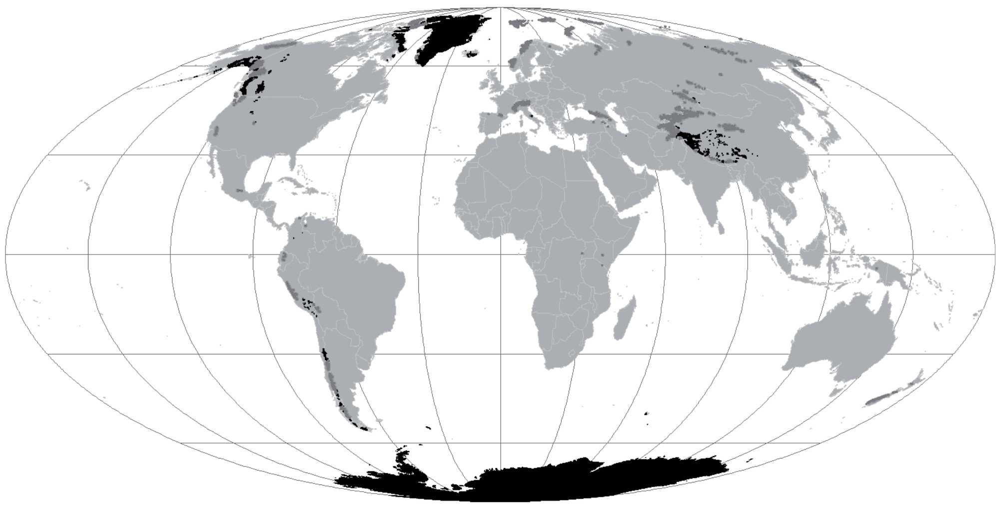

Fig. 1: Regions represented in the World Glacier Inventory - WGI (dark grey) on the glacier cover from the Digital Chart of the World (black), which also includes the two polar icesheets.
Regionen, die im Weltgletscherinventar (WGI) verzeichnet sind (dunkelgrau), auf einer Karte der Gletscherbedekkung gemäss der Digital Chart of the World (schwarz). Diese beinhaltet auch die beiden polaren Eisschilde.
Régions figurant dans le World Glacier Inventory (WGI) (gris foncé) représentées sur la couverture des glaciers du Digital Chart of the World (noir). Les deux calottes polaires sont également indiquées.
Source: The image was kindly provided by M. Zemp, World Glacier Monitoring Service

of 160'000 alone indicates that only about 44% and 62% of all glaciers are included in the WGI and GDB, respectively (Ohmura 2009).

While a large number of glaciological parameters can be calculated using the tabulated WGI data (e.g. Evans & Cox 2005; Haeberli & Hoelzle 1995), accurate change assessment requires knowledge of the precise extent of a glacier (incl. the drainage divides) as used for area determination in the former inventory. Printed schematic maps are often too imprecise for accurate transfer of drainage divides (e.g. Paul & Andreassen 2009). For this reason, the glacier extents in the GDB are based on vector outlines. Both datasets (WGI and GDB) overlap to some degree but have still large gaps when combined (Ohmura 2009). On the other hand, the DCW was digitized from topographic maps, the outlines are freely available online (www.maproom.psu.edu/dcw), the accuracy is approximately comparable to a one kilometre grid, and the dataset is globally nearly complete (with some local gaps and artefacts). The DCW has not yet been used for global calculations, but is frequently used for visualization of global glacier distribution (Fig. 1). From such an overlay the regions with the largest data gaps in the WGI or GDB are well visible. The two ice sheets covering Greenland and Antarctica are generally not considered in the inventories but the surrounding ice masses should be included nevertheless. Due to its global completeness, the most popular data set for global calculations (e.g. sea-level rise) is the gridded GGHydro data set. It can be easily combined with gridded climate data (e.g. Hock et al. 2009). However, its spatial resolution is poor (cell size is about 125 km) and too coarse for regional scale applications.

2.2 Satellite data

Satellite data have been used for glaciological applications for decades, starting with the c. 80 m resolution Landsat Multispectral Scanner (MSS) sensor in the 1970s (e.g. Østrem 1975; Rott 1976). The use of satellite data for mapping of glacier extent was proposed by Rundquist et al. (1980) and glacier inventory compilation from satellite data was introduced by Howarth & Ommanney (1986). In the 1990s, several authors applied the higher resolution Thematic Mapper (TM) sensor onboard Landsat 4 and 5 for mapping of glacier extent (e.g. Aniya et al. 1996; Bayr et al. 1994), snow facies (e.g. Hall et al. 1987; Williams et al. 1991) and change assessment (e.g. Jacobs et al. 1997). The special advantage of this sensor is its wide swath width (180 km), its comparably high resolution (30 m), a band in the blue part of the

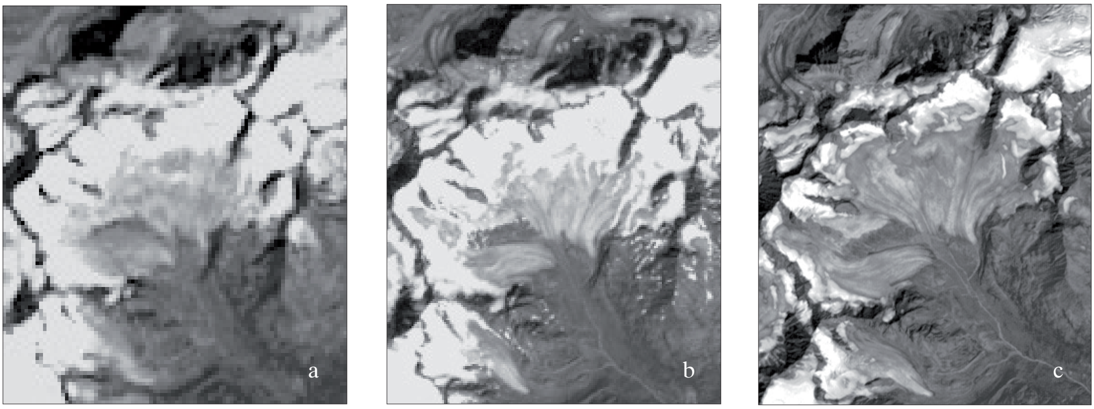

Fig. 2: The glacier Vernagtferner in the Oetztaler Alps, Austria, as seen in the green band with three different sensors: a) with MSS on 13.9.1973, b) with ETM on 13.9.1999, and c) with ASTER on 23.8.2003.
Der Gletscher Vernagtferner in den Ötztaler Alpen, Österreich, wie er im grünen Kanal von drei verschiedenen Sensoren gesehen wird: a) mit MSS am 13.9.1973, b) mit ETM am 13.9.1999 und c) mit ASTER am 23.8.2003.
Le glacier Vernagtferner dans les Alpes autrichiennes (Oetztal), vu dans la bande verte par trois différents capteurs: a) avec MSS le 13/09/1973, b) avec ETM le 13/09/1999, et c) avec ASTER le 23/08/2003.

spectrum, and the possibility to spectrally discriminate snow from clouds as well as glaciers from other terrain with a band in the shortwave infrared (see Section 3). The disadvantage at that time was the high costs per full scene (about € 5000). This prevented application for extended regions. Even with the strongly reduced costs of about US$ 475 per scene after 2000, global-scale applications were still too expensive to be realized.

In the following years, automated glacier mapping algorithms were developed and compared (Albert 2002; Paul 2002), and GIS-based data processing for glacier inventory creation was established (Kääb et al. 2002; Paul et al. 2002). During this period, data from the ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer) sensor on-board the Terra satellite became available and could be used for free within the framework of GLIMS (Raup et al. 2000). A shortcoming of this sensor was the much smaller area covered (60 km by 60 km) compared to Landsat. However, a backward-looking telescope allowed the acquisition of along-track stereo images that could be converted to digital elevation models (DEMs) using photogrammetric techniques (e.g. Toutin 2002). In the following years, the ASTER sensor was used for a large number of glaciological applications (e.g. Kääb et al. 2003; Kargel et al. 2005; Toutin 2008), including the creation of glacier inventory data (Bown et al. 2008; Svoboda & Paul 2009). A comparison of all three sensors (MSS, TM, ASTER) for a region in the Austrian Alps is depicted in Fig. 2.

With the release of the global orthorectified «Geocover» data set in 2002 (Tucker et al. 2004), free Landsat scenes became available for (repeat) glacier mapping on a global scale. Though only few of the available scenes had good conditions for glacier mapping, some of them were nearly perfect and have been used for this purpose (Citterio et al. 2009). Presumably the by far largest breakthrough for completing a global glacier inventory from satellite data came with the opening of the entire Landsat archive of the United States Geological Survey (USGS) for the public (United States Geological Survey - USGS 2008). Now, all scenes can be downloaded for free in an already orthorectified version in Geotif-format from glovis.usgs.gov and other websites. Though not all regions are fully included in the USGS archive, several initiatives have been started to map glacier outlines with these data (cf. Paul et al. 2009b) in view of completing the global inventory.

2.3 Topographic information

A basic requirement for creation of a detailed glacier inventory (i.e. including topographic parameters) is a DEM, at best acquired in the same year (or on the same day as with ASTER) as the satellite image that is used for glacier mapping (Paul et al. 2009a). Today, there are two DEMs available for global applications: the SRTM (Shuttle Radar Topography Mission) DEM from February 2000 with about 90 m spatial resolution between 60°N and 57°S (Farr et al. 2007), and the new first release of the ASTER-

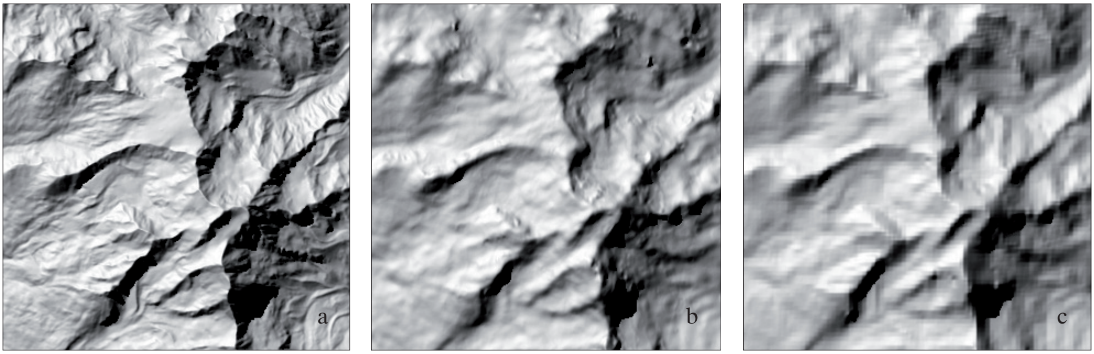

Fig. 3: Comparison of three different digital elevation models (DEMs) in a hillshade view for the Weissmies region (Switzerland). Black areas indicate regions of cast shadow: a) DEM25 from swisstopo, b) ASTER GDEM, c) SRTM3.
Vergleich von drei verschiedenen digitalen Höhenmodellen (DHM) in Reliefdarstellung für die Weissmiesregion (Schweiz). Schwarze Bereiche kennzeichnen Regionen mit Schlagschatten: a) DHM25 von Swisstopo, b) ASTER-GDEM, c) SRTM3.
Comparaison de trois différents MNT pour la région de Weissmies (Suisse). Les zones noires sont les régions situées à l'ombre: a) DEM25 de swisstopo, b) ASTER GDEM, c) SRTM3.
Source: The DEM25 is reproduced with permission from swisstopo (BA100522).

GDEM as a composite of scenes from 1999-2006 with 30 m resolution and near global coverage (Hayakawa et al. 2008). Both DEMs have local artefacts, for example data voids due to radar shadow in the case of SRTM or regions with low contrast (snow, shadow) or clouds for ASTER. However, glaciers are often located outside the radar shadow of SRTM due to their more gently sloped terrain (Paul & Haeberli 2008).

A comparison of the DEMs from SRTM, ASTER (GDEM) and national sources (Swisstopo) is presented in Fig. 3. The level of detail is clearly different in all three DEMs, but for creation of topographic glacier inventory data all three are suitable. Due to the rapid geometric changes of glaciers in the recent past (e.g. Paul et al. 2007), a good temporal match of the DEM with the satellite data can be more important for accurate inventory data than the influence of local artefacts of the DEM. While the creation of topographic glacier inventory data will be the focus of applications with these DEMs in the future, several studies have used the SRTM DEM to derive glacier elevation changes and hence volume changes by comparison with an earlier national DEM (e.g. Larsen et al. 2007; Paul & Haeberli 2008; Schiefer et al. 2007). These studies have substantially improved knowledge about overall glacier mass changes and their spatial variability in entire mountain ranges.

3 Methods and challenges

The surface of a glacier is, apart from debris and water, mostly composed of ice and snow. As glacier ice originated from snow through metamorphosis, the spectral properties of glacier ice are very similar to those of snow with large grain sizes. While snow has a high reflectance in the visible spectrum, its reflectance decreases in the near infrared, and is very low in the shortwave infrared (SWIR), in particular for large grain sizes (Dozier 1989). This peculiar reflectance curve allows snow, firn and glacier ice to be separated from other terrain with a threshold applied to a ratio image (e.g. with bands TM3/TM5) or the normalized difference snow index (NDSI), i.e. (TM2-TM5)/(TM2+TM5). The basic rule for threshold selection is to minimize workload for manual corrections (Paul & Hendriks 2010). Compared to full manual delineation, the automated mapping approach has some advantages: (a) the entire sample of glaciers is included, independent of their size, (b) the results are reproducible, and (c) the outlines are not generalized and the quality is comparable for all parts of a scene.

The band ratio technique for glacier mapping is simple (it works best on the raw digital numbers), robust (the threshold is not very sensitive) and more accurate than other methods (e.g. Albert 2002; Paul & Kääb 2005). It is thus, along with the NDSI, widely applied for glacier mapping (Racoviteanu et al. 2008). Clean

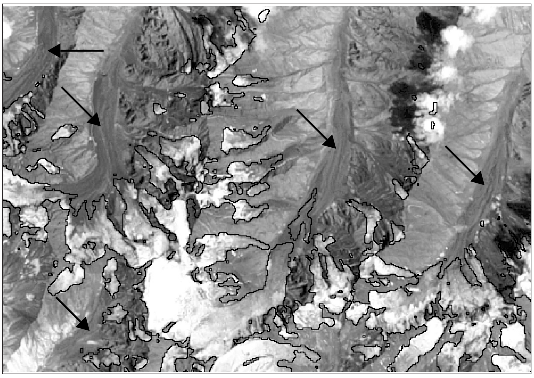

Fig. 4: The identification of debris-covered glacier tongues (arrows) can be very demanding when solar elevation is high (i.e. no illumination differences) and spectral properties are similar to the surrounding terrain. The example is from Landsat ETM+ scene 147-38 acquired on 2.8.2002 over the western Himalaya (India). Black lines are the result of the automated glacier classification.
Die Identifikation von schuttbedeckten Gletscherzungen (Pfeile) kann extrem aufwendig sein, wenn die Sonne hoch steht (d.h. es gibt kaum Beleuchtungsunterschiede) und die spektralen Eigenschaften ähnlich wie die des umgebenden Geländes sind. Das Beispiel zeigt eine Region im westlichen Himalaya (Indien) in einer Landsat ETM+ Szene (147-38) vom 2.8.2000. Schwarze Linien kennzeichnen das Ergebnis der automatischen Klassifikation.
L'identification des langues glaciaires couvertes de débris (flèches) peut être très compliquée lorsque le soleil est haut (pas de différence d'illumination) car les propriétés spectrales sont alors similaires au terrain environnant. Exemple sur l'image Landsat ETM+ (147-38) acquise le 02/08/2002 au-dessus de l'ouest de l'Himalaya (Inde). Les lignes noires sont le résultat de la classification automatique des glaciers.

ice and snow under optically thin clouds or located in cast shadow are generally accurately mapped (Paul & Andreassen 2009). Further, dirty but sunlit glacier ice is often correctly classified. Glacier ice under debris cover cannot be mapped from optical sensors alone and several semi-automated methods have been developed (e.g. Bishop et al. 2001; Bolch et al. 2007; Paul et al. 2004). When the contrast is reduced due to high solar elevation, even manual delineation of debris-covered glaciers is difficult (Fig. 4). From the available cloud-free images, only the scenes with the smallest amount of seasonal snow should be selected for glacier mapping, otherwise determination of glacier outlines is very time consuming or even impossible (Fig. 5a). In local topographic depressions perennial snow fields might exist that are difficult to distinguish from seasonal snow (Fig. 5b), even by multitemporal image analysis (Paul & Andreassen 2009).

Before glacier inventory data can be calculated for each glacier from digital intersection with a DEM (cf. Paul et al. 2002), they need to be separated into individual entities. This can be rather difficult (Fig. 6), even when DEM-derived flow-direction grids or drainage basins from watershed analysis are available (Bolch et al. 2010). Delicate questions include icecaps with radial flow, only loosely connected tributaries and multiple glacier tongues emerging from the same accumulation region (cf. Racoviteanu et al. 2009).

4 Outlook and conclusions

This study presented an overview of past and ongoing activities to map glaciers from satellite data in view of creating a more complete global inventory. While the perspectives to achieve this ambitious goal are now better than ever before due to the freely available satellite data from USGS, near global DEMs from ASTER and SRTM, and well established algorithms and data compilation procedures, still large amounts of manual work (on-screen digitization) remains to be done. For a regular update of glacier inventory data in the near-term, the outlook is less promising, as the currently used sensor Landsat TM is far beyond its expected lifetime (> 25 years now in orbit!) and the Terra ASTER sensor is starting to degrade rapidly. However, in the mid-term these sensors can hopefully be replaced with the upcoming Landsat Data Continuity Mission (LDCM) and the proposed ESA (European Space Agency) Sentinel 2 spacecraft. It can also be expected that improved DEMs (higher spatial resolution, less artefacts) will be available for free in the future as several missions for this purpose are planned or have started. Combined with standards for glacier entity identification and the possibility of regionally representative change assessment from repeat inventories, the impacts of climate change on glaciers can be determined on a global scale and operational spaceborne glacier monitoring might become feasible.

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References

Albert, T. (2002): Evaluations of remote sensing tech-

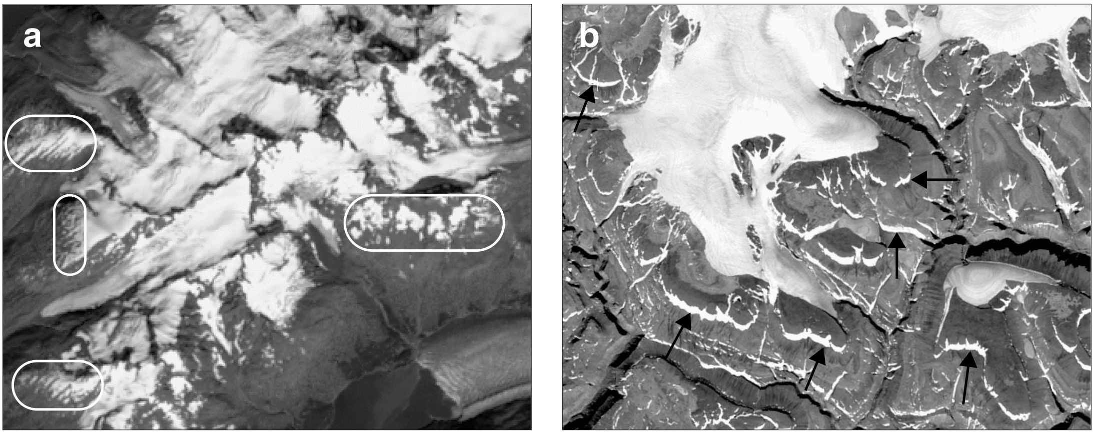

Fig. 5: Challenging snow conditions for glacier mapping: a) subset of a Landsat ETM+ scene (67-17) from 1.8.2002 covering Chugach Mts. (Alaska, USA). Abundant seasonal snow patches (white circles) hide several glacier perimeters; b) subset of a Landsat ETM+ scene (40-7) from 29.7.2000 covering the southwestern part of Devon Icecap (Canada). Elongated perennial snow fields (black arrows) in topographic depressions and attached to icecaps are difficult to discern from seasonal snow.
Schwierige Schneeverhältnisse für die Gletscherkartierung: a) Ausschnitt aus einer Landsat ETM+ Szene (67-17) vom 1.8. 2002, welche die Region der Chugach Mountains (Alaska, USA) zeigt. Viele Gletscherabgrenzungen werden durch saisonale Altschneereste (weisse Kreise) verdeckt; b) Ausschnitt aus einer Landsat ETM+ Szene (40-7) vom 29.7.2000, welche den südwestlichen Bereich der Devon-Eiskappe (Kanada) zeigt. Langgestreckte, ganzjährige Schneefelder (schwarze Pfeile) in topographischen Mulden und teilweise mit der Eiskappe zusammenhängend sind nur schwer von saisonalem Altschnee zu unterscheiden.
Exemples de conditions d'enneigement rendant la cartographie des glaciers difficile: a) extrait de l'image Landsat ETM+ (67-17) du 01/08/2002 couvrant les montagnes Chugach (Alaska, Etats-Unis). Abondantes zones de neige (cercles blancs) masquant de nombreux périmètres de glaciers; b) extrait de l'image Landsat ETM+ (40-7) du 29/07/2000 couvrant la partie sud-ouest de la calotte Devon (Canada). Les champs de neiges pluriannuelles (flèches noires) dans les dépressions topographiques et attachés aux calottes sont difficiles à discerner des neiges saisonnières.

niques for ice-area classifications applied to the tropical Quelccaya Ice Cap, Peru. – In: Polar Geography 26, 3: 210-226.

Aniya, M., Sato, H., Naruse, R., Skvarca, P. & G. Casassa (1996): The use of satellite and airborne imagery to inventory outlet glaciers of the Southern Patagonia Icefield, South America. – In: Photogrammetric Engineering and Remote Sensing 62, 12: 1361-1369.

Andreassen, L.M., Paul, F., Kääb, A. & J.E. Hausberg (2008): Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s. – In: The Cryosphere 2: 131-145.

Bayr, K.J., Hall, D.K. & W.M. Kovalick (1994): Observations on glaciers in the eastern Austrian Alps using satellite data. – In: International Journal of Remote Sensing 15, 9: 1733-1742.

Bishop, M.P., Bonk, R., Kamp, U. & J.F. Shroder, Jr. (2001): Terrain analysis and data modeling for alpine glacier mapping. – In: Polar Geography 25, 3: 182-201.

Bolch, T., Buchroithner, M.F., Kunert, A. & U. Kamp (2007): Automated delineation of debris-covered glaciers based on ASTER data. – In: Gomarasca, M.A. (ed.): GeoInformation in Europe. Proceedings of the 27th Symposium of the European Association of Remote Sensing Laboratories, Bolzano, Italy, 4-7 June 2007. – Rotterdam: Millpress: 403-410.

Bolch, T., Menounos, B. & R. Wheate (2010): Landsat-based glacier inventory of western Canada, 1985-2005. – In: Remote Sensing of Environment 114, 1: 127-137.

Bown, F., Rivera, A. & C. Acuna (2008): Recent glacier variations at the Aconcagua basin, central Chilean Andes. – In: Annals of Glaciology 48: 43-48.

Braithwaite, R.J. (2009): After six decades of monitoring glacier mass balance we still need data but it should be richer data. – In: Annals of Glaciology 50, 50: 191-197.

Citterio, M., Paul, F., Ahlstrøm, A.P., Jepsen, H.F. & A. Weidick (2009): Remote sensing of glacier change

Fig. 6: Ice-covered ridges and complex structured, compound-basin glaciers make the correct distinction of individual glacier entities difficult (example from the northern part of Baffin Island, ETM+ scene 28-9 from 10.8.2000).
Eisbedeckte Grate und komplex zusammenhängende, aus mehreren Einzugsgebieten zusammengesetzte Gletscher machen die korrekte Abgrenzung von individuellen Gletschern schwierig (Beispiel des nördlichen Teils der Baffin-Insel, ETM+ Szene 28-9 vom 10.8.2000).
Les crêtes englacées et les structures complexes telles que les glaciers composés rendent difficile la distinction correcte des glaciers individuels (exemple de la partie au nord de l'Ile de Baffin, image Landsat ETM+ (28-9) du 10/08/2000).

in West Greenland: accounting for the occurrence of surge-type glaciers. – In: Annals of Glaciology 50, 53: 70-80.
Cogley, J.G. (2003): GGHYDRO - Global Hydrographic Data, Release 2.3, Peterborough, Ontario, Trent University, Department of Geography. – In: Trent Technical Note 2003-1.
Cogley, J.G. (2009): A more complete version of the World Glacier Inventory. – In: Annals of Glaciology 50, 53: 32-38.
Dozier, J. (1989): Spectral signature of alpine snow cover from Landsat 5 TM. – In: Remote Sensing of Environment 28: 9-22.
Dyurgerov, M.B. & M.F. Meier (2005): Glaciers and the changing earth system: a 2004 snapshot. – In: Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, Boulder.
Evans, I.S. & N.J. Cox (2005): Global variations of local asymmetry in glacier altitude: separation of north-south and east-west components. – In: Journal of Glaciology 51, 174: 469-482.
Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. & D. Alsdorf (2007): The Shuttle Radar Topography Mission. – In: Reviews of Geophysics 45, RG2004, doi:10.1029/2005RG000183.
Fountain, A.G., Hoffman, M.J., Granshaw, F. & J. Riedel (2009): The «benchmark glacier» concept – does it work? Lessons from the North Cascade Range, USA. – In: Annals of Glaciology 50, 50: 163-168.
Haeberli, W. (2006): Integrated perception of glacier changes: a challenge of historical dimensions. – In: Knight, P.G. (ed.): Glacier science and environmental change. – Oxford: Blackwell Publishing: 423-430.
Haeberli, W. & M. Hoelzle (1995): Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. – In: Annals of Glaciology 21: 206-212.
Hall, D.K., Ormsby, J.P., Bindschadler, R.A. & H. Siddalingaiah (1987): Characterization of snow and ice zones on glaciers using Landsat Thematic Mapper data. – In: Annals of Glaciology 9: 104-108
Hayakawa, Y.S., Oguchi, T. & Z. Lin (2008): Comparison of new and existing global digital elevation models: ASTER G-DEM and SRTM-3. – In: Geophysical Research Letters 35, L17404, doi:10.1029/2008GL035036.
Hock, R., Woul, M. de, Radic, V. & M. Dyurgerov (2009): Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution. – In: Geophysical Research Letters 36, 7, L07501, doi:10.1029/2008GL037020.
Howarth, P. & C.S.L. Ommanney (1986): The use of Landsat digital data for glacier inventories. – In: Annals of Glaciology 8: 90-92.
Intergovernmental Panel on Climate Change - IPCC (2007): Fourth Assessment Report. – Cambridge and New York: Intergovernmental Panel on Climate Change.
Jacobs, J.D., Simms, E.L. & A. Simms (1997): Recession of the southern part of Barnes Ice Cap, Baffin Island, Canada, between 1961 and 1993, determined from digital mapping of Landsat TM. – In: Journal of Glaciology 43, 143: 98-102.
Kääb, A., Paul, F., Maisch, M., Hoelzle, M. & W. Haeberli (2002): The new remote-sensing-derived Swiss glacier inventory: II. First Results. – In: Annals of Glaciology 34: 362-366.
Kääb, A., Paul, F., Huggel, C., Kieffer, H., Kargel, J.S. & R. Wessels (2003): Glacier monitoring from ASTER imagery: accuracy and applications. EARSeL Workshop on Remote Sensing of Land Ice and Snow, Bern, 11.-13.3.2002. – In: EARSeL eProceedings 2: 43-53.
Kargel, J.S., Abrams, M.J., Bishop, M.P., Bush, A., Hamilton, G., Jiskoot, H., Kääb, A., Kieffer, H.H.,

Lee, E.M., Paul, F., Rau, F., Raup, B., Shroder, J.F., Soltesz, D., Stainforth, D., Stearns, L. & R. Wessels (2005): Multispectral imaging contributions to Global Land Ice Neasurements from Space. – In: Remote Sensing of Environment 99, 1-2: 187-219.

Larsen, C.F., Motyka, R.J., Arendt, A.A., Echelmeyer, K.A. & P.E. Geissler (2007): Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. – In: Journal of Geophysical Research 112, F01007.

Meier, M.F. & D.B. Bahr (1996): Counting glaciers: use of scaling methods to estimate the number and size distribution of the glaciers on the world. – In: Colbeck, S.C. (ed.): Glaciers, ice sheets and volcanoes: a tribute to Mark F. Meier. – Cold Regions Research and Engineering Laboratory (CRREL) Special Report 96-27: 89-94.

Meier, M.F., Dyurgerov, M.B., Rick, U.K., O'Neel, S., Pfeffer, W.T., Anderson, R.S., Anderson, S.P. & A.F. Glazovsky (2007): Glaciers dominate eustatic sea-level rise in the 21st century. – In: Science 317: 1064-1067.

Oerlemans, J. (2005): Extracting a climate signal from 169 glacier records. – In: Science 308: 675-677.

Østrem, G. (1975): ERTS data in glaciology – an effort to monitor glacier mass balance from satellite imagery. – In: Journal of Glaciology 15, 73: 403-415.

Ohmura, A. (2004): Cryosphere during the twentieth century. – In: Sparks, R.S.J. & C.J. Hawkesworth (eds): The state of the Planet: frontiers and challenges in geophysics. – Geophysical Monograph Series 150, AGU, Washington, D.C.: 239-257.

Ohmura, A. (2009): Completing the world glacier inventory. – In: Annals of Glaciology 50, 53: 144-148.

Paul, F. (2002): Changes in glacier area in Tyrol, Austria, between 1969 and 1992 derived from Landsat 5 TM and Austrian Glacier Inventory data. – In: International Journal of Remote Sensing 23, 4: 787-799.

Paul, F. & A. Kääb (2005): Perspectives on the production of a glacier inventory from multispectral satellite data in the Canadian Arctic: Cumberland Peninsula, Baffin Island. – In: Annals of Glaciology 42, 1: 59-66.

Paul, F. & W. Haeberli (2008): Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models. – In: Geophysical Research Letters 35, L21502, doi:10.1029/ 2008GL034718.

Paul, F. & L.M. Andreassen (2009): A new glacier inventory for the Svartisen region, Norway, from Landsat ETM+ data: challenges and change assessment. – In: Journal of Glaciology 55, 192: 607-618.

Paul, F. & J. Hendriks (2010): Optical remote sensing of glaciers. – In: Pellikka, P. & W.G. Rees (eds): Remote sensing of glaciers: techniques for topographic, spatial and thematic mapping of glaciers. – Leiden: CRC Press, Taylor and Francis Group: 137-152.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T.W. & W. Haeberli (2002): The new remote-sensing-derived Swiss glacier inventory: I. Methods. – In: Annals of Glaciology 34, 1: 355-361.

Paul, F., Huggel, C. & A. Kääb (2004): Combining satellite multispectral image data and a digital elevation model for mapping of debris-covered glaciers. – In: Remote Sensing of Environment 89, 4: 510-518.

Paul, F., Kääb, A. & W. Haeberli (2007): Recent glacier changes in the Alps observed from satellite: consequences for future monitoring strategies. – In: Global and Planetary Change 56, 1-2: 111-122.

Paul, F., Barry, R.G., Cogley, J.G., Frey, H., Haeberli, W., Ohmura, A., Ommanney, C.S.L., Raup, B., Rivera, A. & M. Zemp (2009a): Recommendations for the compilation of glacier inventory data from digital sources. – In: Annals of Glaciology 50, 53: 119-126.

Paul, F., Kääb, A., Rott, H., Shepherd, A., Strozzi, T. & E. Volden (2009b): GlobGlacier: mapping the world's glaciers and ice caps from space. – In: EARSeL eProceedings 8, 1: 11-25.

Racoviteanu, A.E., Williams, M.W. & R.G. Barry (2008): Optical remote sensing of glacier characteristics: a review with focus on the Himalaya. – In: Sensors 8: 3355-3383.

Racoviteanu, A.E., Paul, F., Raup, B., Khalsa, S.J.S. & R. Armstrong (2009): Challenges in glacier mapping from space: recommendations from the Global Land Ice Measurements from Space (GLIMS) initiative. – In: Annals of Glaciology 50, 53: 53-69.

Radic, V. & R. Hock (2010): Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. – In: Journal of Geophysical Research 115, F01010, doi:10.1029/2009JF001373.

Raper, S.C.B. & R.J. Braithwaite (2006): Low sea level rise projections from mountain glaciers and icecaps under global warming. – In: Nature 439: 311-313.

Raup, B.H., & S.J.S Khalsa (2007): GLIMS analysis tutorial. – Online from http://www.glims.org/MapsAndDocs/assets/GLIMS_Analysis_Tutorial_a4.pdf 7.7.2010.

Raup, B., Kieffer, H.H., Hare, T.M. & J.S. Kargel (2000): Generation of data acquisition requests for the ASTER satellite instrument for monitoring a globally distributed target: glaciers. – In: IEEE Transactions on Geoscience and Remote Sensing 38, 2: 1105-1112.

Raup, B., Racoviteanu, A., Khalsa, S.J.S., Helm, C., Armstrong, R. & Y. Arnaud (2007): The GLIMS geospatial glacier database: a new tool for studying glacier change. – In: Global and Planetary Change 56, 1-2: 101-110.

Rott, H. (1976): Analyse der Schneeflächen auf Gletschern der Tiroler Zentralalpen aus Landsat-Bildern. – In: Zeitschrift für Gletscherkunde und Glazialgeologie 12: 1-28.

Rundquist, D.C., Collins, S.C., Barnes, R.B., Bussom, D.E., Samson, S.A. & J.S. Peake (1980): The use of Landsat digital information for assessing glacier inventory parameters. – In: IAHS 126: 321-331.

Schiefer, E., Menounos, B. & R. Wheate (2007): Recent volume loss of British Columbian glaciers, Canada. – In: Geophysical Research Letters 34, L16503.

Svoboda, F. & F. Paul (2009): A new glacier inventory on southern Baffin Island, Canada, from ASTER data: I. Applied methods, challenges and solutions. – In: Annals of Glaciology 50, 53: 11-21.

Toutin, T. (2002): Three-dimensional topographic mapping with ASTER stereo data in rugged topography. – In: IEEE Transactions on Geoscience and Remote Sensing 40, 10: 2241-2247.

Toutin, T. (2008): ASTER DEMs for geomatic and geoscientific applications: a review. – In: International Journal of Remote Sensing 29, 7: 1855-1875.

Tucker, C., Grant, D.M. & J.D. Dykstra (2004): NASA's global orthorectified Landsat data set. – In: Photogrammetric Engineering and Remote Sensing 70, 3: 313-322.

UNESCO (1970): Perennial ice and snow masses: a guide for compilation and assemblage of data for the World Glacier Inventory. – In: Technical Papers in Hydrology 1.

United States Geological Survey - USGS (2008): Opening the Landsat Archive. USGS Factsheet 2008-3091. – URL: http://pubs.usgs.gov/fs/2008/3091/pdf/fs2008-3091.pdf 7.7.2010.

Vergara, W., Deeb, A.M., Valencia, A.M., Bradley, R.S., Francou, B., Zarzar, A., Grünwaldt, A. & S.M. Haeussling (2007): Economic impacts of rapid glacier retreat in the Andes. – In: EOS, Transactions American Geophysical Union 88, 25: 261 and 264.

WGMS (1989): World Glacier Inventory – Status 1988. – Haeberli, W., Bösch, H., Scherler, K., Østrem, G. & C.C. Wallén (eds), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland.

Williams, R.S., Jr., Hall, D.K. & C.S. Benson (1991): Analysis of glacier facies using satellite techniques. – In: Journal of Glaciology 37, 125: 120-127.

Zuo, Z. & J. Oerlemans (1997): Contribution of glacier melt to sea-level rise since AD 1865: a regionally differentiated calculation. – In: Climate Dynamics 13: 835-845.

Abstract: Towards a global glacier inventory from satellite data. Recent efforts and challenges to complete the global glacier inventory with modern geoinformatic techniques

There is a major need for a complete and detailed global glacier inventory that is freely available in a digital format (vector outlines with attribute data) for all kinds of glaciological assessments, e.g. sea level rise, hydro-power, run-off and natural hazards. However, such an inventory is not yet available and the uncertainties due to the missing data for related calculations are large. While the existing World Glacier Inventory offers tabular data that were compiled from aerial photography and maps during the 1960s to 1970s for about 72'000 glaciers, current efforts are being exerted within the framework of the Global Land Ice Measurements from Space (GLIMS) initiative to compile vector outlines from satellite data and combine them with digital elevation models (DEMs). At this point, inventory data from about 100'000 of the estimated 160'000 glaciers are available in the GLIMS database. Due to the now free availability of satellite data from the United States Geological Survey's archive and near global DEMs with appropriate spatial resolution, a globally complete and detailed glacier inventory appears viable. This contribution provides an overview of past and ongoing activities related to the creation of glacier inventory data from satellite sensors, along with the methods employed and the challenges encountered in different parts of the world.

Keywords: glacier inventory, satellite data, GIS, DEM, GLIMS, GlobGlacier

Zusammenfassung: Auf dem Weg zu einem globalen Gletscherinventar aus Satellitendaten. Aktuelle Bemühungen und Herausforderungen zur Vervollständigung des globalen Gletscherinventars mit den modernen Methoden der Geoinformatik

Ein global vollständiges und detailiertes Gletscherinventar, welches frei verfügbar ist und in einem digitalen Format vorliegt (Vektorumrisse mit Attributdaten), ist von grosser Wichtigkeit für eine Vielzahl von glaziologischen Anwendungen, z.B. Meeresspiegelanstieg, Wasserkraft, Abfluss und Naturgefahren. Leider ist ein solches Inventar noch nicht verfügbar, und die durch die fehlenden Daten bedingten Unsicherheiten für die entsprechenden Berechnungen sind gross. Abgesehen von den tabulierten Daten im Weltgletscherinventar, welches aus Luftbildern und Karten der 1960er bis 1970er Jahre für etwa 72000 Gletscher zusammengestellt wurde, fokussieren die derzeitigen Bemühungen auf eine Erfassung von Vektorumrissen aus Satellitendaten, kombiniert mit digitalen Höhenmodellen (DHM) im Rahmen der sogenannten *Global Land Ice Measurements from Space* (GLIMS)-Initiative. Zurzeit sind die Inventardaten von etwa 100'000 der geschätzten 160'000 Gletscher in der GLIMS-Datenbank gespeichert. Durch die nun freie Verfügbarkeit von Satellitendaten aus dem *United States Geological Survey* (USGS)-Archiv und digitalen Höhenmodellen (DHM) mit beinahe globaler Abdeckung und ausreichender räumlicher Auflösung scheint ein global vollständiges und detailliertes Gletscherinventar machbar. Dieser Beitrag gibt einen Überblick über die vergangenen und gegenwärtigen Aktivitäten bezüglich der Erstellung von Gletscherinventaren aus Satellitendaten und behandelt ebenfalls die verwendeten Methoden sowie die in verschiedenen Regionen der Welt angetroffenen Schwierigkeiten.

Schlüsselwörter: Gletscherinventar, Satellitendaten, GIS, DHM, GLIMS, GlobGlacier

Résumé: Vers un inventaire global des glaciers à partir de données satellitaires. Efforts récents et défis en vue de compléter l'inventaire global des glaciers avec les techniques modernes de géo-informatique
Pour répondre aux différentes problématiques glaciologiques, telles que la hausse du niveau de la mer, la production hydroélectrique, l'écoulement et les catastrophes naturelles, il est nécessaire de disposer d'un inventaire des glaciers qui soit complet et détaillé tout en étant librement accessible et dans un format vectoriel (limites des glaciers avec données attributaires). Toutefois, ce type d'inventaire n'est pas encore disponible et les incertitudes dans les calculs restent grandes, principalement à cause des données manquantes. Mis à part les données tabulaires disponibles dans le WGI (*World Glacier Inventory*) qui ont été compilées à partir de photographies aériennes et de cartes durant les années 1960 et 1970 (environ 72 000 glaciers), les efforts actuels se focalisent sur la création des contours des glaciers en utilisant des images satellitaires et des modèles numériques de terrain. Ces efforts s'intègrent dans le cadre de l'initiative GLIMS (*Global Land Ice Measurement from Space*). Aujourd'hui, des données portant sur près de 100 000 glaciers sur les 160 000 estimés sont disponibles dans la base GLIMS. Grâce à la récente mise à disposition libre des archives de données satellitaires par l'*United States Geological Survey* (USGS) et à des modèles numériques de terrain disponibles quasiment à l'échelle globale, un inventaire global et complet des glaciers semble désormais réalisable. Cette contribution fournit une vue d'ensemble des activités passées et présentes relatives à la création d'inventaires des glaciers à partir de données satellitaires ainsi que des méthodes et défis rencontrés dans différentes parties du monde.

Mots-clés: inventaire des glaciers, données satellitaires, SIG, MNT, GLIMS, GlobGlacier

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