GlobGlacier: A NEW ESA PROJECT TO MAP THE WORLD'S GLACIERS AND ICE CAPS FROM SPACE

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ABSTRACT

In this paper we provide an overview of the GlobGlacier project, a new data user element activity within ESA's Living Planet program. The main aim of the project is to map glaciers from key regions all over the world and to generate digital glacier outlines in large quantities in order to fill data gaps in currently existing databases (GLIMS and World Glacier Inventory, WGI). Further goals are to provide additional information (snow line, topography, elevation change, velocity) for a smaller number of glaciers in selected regions from space-borne sensors and to document the applied techniques for later use. Apart from a short description of the project and the products that are generated, an overview of available remote sensing techniques that have been used on glaciers and ice caps is given.

BACKGROUND

Glacier changes are key indicators of climatic changes as they show an enhanced and well recognisable reaction to even small climatic fluctuations, which results from their proximity to melting conditions (1). They have thus been selected together with ice caps as one of the essential climate variables (ECVs) in the implementation plan of the global climate observing system (2). Their monitoring is organised in a tiered strategy within the global terrestrial network for glaciers (GTN-G) which is operated by the world glacier monitoring service (WGMS). Within GTN-G, annual measurements of mass balance (about 50 glaciers at Tier levels 2 and 3) and length changes (about 550 glaciers at Tier 4) are performed (3). Detailed glacier inventory data (Tier 5) from the 1960s to 1970s exist as point information in the world glacier inventory (WGI) for c. 71,000 glaciers, which is about 40% of the estimated 160,000 glaciers worldwide. Thus, (a) the current sample of glaciers with annual measurements is very small and not necessarily representative for the changes at a global scale, and (b) the WGI is not complete and difficult to use for change assessment as, in general, the glacier perimeter related to the sampled point data is not known.

According to (4), melting glaciers and ice caps might provide an even larger contribution to the global sea level rise in the coming decades than the two continental ice sheets Greenland and Antarctica. Hence, there is an urgent necessity to generate more complete and representative data sets for global assessments (e.g., 5,6). The GCOS report 'Systematic observation requirements for satellite based products for climate change' (7) and the IGOS cryosphere theme report (8) have confirmed the important contribution of satellite observations to monitor glacier and ice caps around the world. In this respect, the Global Land Ice Measurements from Space (GLIMS) initiative has started to compile glacier outlines in a digital vector format from satellite data and other sources in a publicly accessible database (9).

In 2007, the European Space Agency (ESA) has initiated a new activity within its data user element (DUE) programme that augments ongoing activities: the GlobGlacier project. Its major aim is to establish services for glacier monitoring from space, building upon, complementing and strengthening the existing network and services (GLIMS, WGMS) of global glacier monitoring (10). According to ESA standards, the set-up of the data processing will be worked out in phase 1 (16 months) and the application and data generation will mostly take place during phase 2 (20 months). The project started in Nov 2007 for a period of three years, is led by the University of Zurich, has four partners (Table 1) and ten user group members (Table 2) which will be actively involved in the project (e.g. for product evaluation) and represent different interest groups. The project will map glaciers from key regions all over the world, generate digital outlines in large quantities, and obtain additional information for a smaller number of representative regions. The selection criteria for the key regions are given by the Statement of Work from ESA and the requirements of the user group. Among others, the criteria were: to fill the gaps in the WGI and the GLIMS database, select regions with a potential strong contribution to sea level rise or as a (regional) water resource, include sites with glacier related hazards, and compile glacier data from all continents.

Table 1: The consortium of GlobGlacier.

Name	Affiliation (Abbreviation)	Country	Products
F. Paul	Dept. of Geography, University of Zurich (GIUZ)	CH	Outlines, terminus
A. Kääb	Dept. of Geoscieneces, University of Oslo (GUIO)	NO	Topography
H. Rott	Environmental Earth Observation, Innsbruck (ENVEO)	AU	Snow lines
A. Shepherd	School of Geosciences, University of Edinburgh (SGUE)	UK	Elevation change
T. Strozzi	Gamma Remote Sensing, Gümligen (Gamma)	CH	Velocity fields

Table 2: The members of the GlobGlacier user group, their affiliation, role and region of expertise (m.: modelling).

Name	Institute	Role	Region
M. Zemp	UZH	WGMS	global
B. Raup	NSIDC	GLIMS	global
M. Citterio	GEUS	Arctic	Greenland
R. Wheate	UNBC	WC2N	Canada
P. Mool	ICIMOD	Hazard	Himalaya

Name	Institute	Role	Region
L. Andreassen	NVE	Hydrologic m.	Norway
S. Kotlarski	MPI	Climate m.	global
R. Braithwaite	IMAU	Sea level rise	global
H. Oerlemans	SED	Cryospheric m.	global
T. Khromova	RAS	CliC	Russia

GLOBGLACIER WORKFLOW AND PRODUCTS

Workflow

The organisation and workflow of the project is illustrated in Figure 1. The upper part of the diagram illustrates the consolidation of the user requirements (in close cooperation with the user group) and the selection of key regions (based on the above criteria and the available satellite data). The middle part shows the individual work packages (which are related to the requested products), the responsible consortium members, and the relation between the data products. Glacier outlines from work package 1 (WP1) will be provided to all other WPs for consistent product creation. A subset of the satellite scenes selected for WP1 will also be used to perform the snow classification in WP2. In principle, two different types of products (deliverables) will be generated by GlobGlacier: Text documents and a certain quantity of data products (Table 3). While the former will summarise the methodological and technical aspects of the project, the latter will make a major contribution to existing databases (GLIMS, WGMS).

A major aim of GlobGlacier is to aid in completing the WGI and supplementing the existing point information (1D) in the WGI with digital vector outlines (2D) of glaciers and ice caps. This requires a close coordination with currently ongoing activities, in particular with the GLIMS initiative. Further goals of GlobGlacier are an extension of the currently observed glacier fluctuations (mass and length changes) from direct satellite measurements (products terminus and elevation change), as well as indirect means that could be useful to estimate glacier mass balance (snow lines, velocity fields). As the products should satisfy very different demands from the members of the user group, the main product glacier outlines have been subdivided into three levels of detail (L0 to L2). The topographic information (i.e., a digital elevation model, DEM) as provided by workpackage 3 (WP3) is required to derive most of the other products (e.g. topographic glacier inventory data or altitude of the snowline). In Table 3 a short overview of the created data products is given.

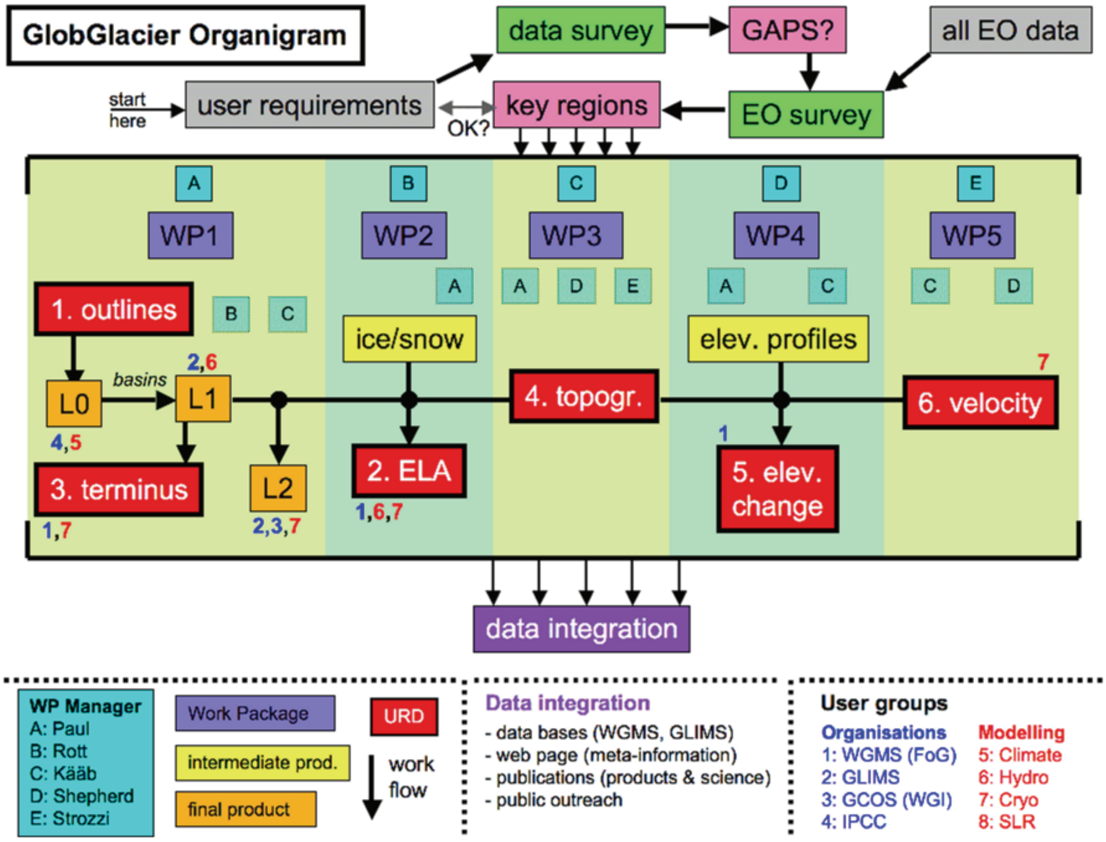

Figure 1: Organigram of GlobGlacier as developed for the proposal. WP is work package, URD is user requirements document. After the first user group meeting it has been decided that the end product of WP2 will be the late summer snow line (LSSL) rather than ELA.

Table 3: Proposed product quantities for the total project duration and in phase 1 / 2

	Outline	Terminus	Snow line	Topography	Elevation ch.	Velocity
WP	1	1	2	3	4	5
Phase 1	2000	2000	500	1000	200	40
Phase 2	18000	18000	4500	4000	800	160
Total	20000	20000	5000	5000	1000	200

Products

Outlines (WP1)

Digital glacier outlines will be created from multispectral sensors (mainly Landsat, ASTER, and SPOT) with well-established methods (band ratio) combined with manual editing and GIS-based data fusion at three different levels of detail:

- Level 0 (L0): Glacier outlines corrected for misclassification (e.g. debris, shadow, water) and consisting of one polygon for each contiguous ice mass (i.e. no individual basins). This product may include (perennial) snow fields and no selection will be made.
- Level 1 (L1): Individual glaciers that result from combining the L0 outlines with hydrologic divides. These divides will also be used to deselect snow fields (as far as possible) and select the glacier sample. This will be the (counted) major output of the project (and GLIMS input).

- Level 2 (L2): In regions with DEM data (from WP3), the combination with L1 outlines will result in topographic glacier inventory data for each glacier (e.g. incl. min./mean/max. elevation, slope, aspect, hypsography, etc.). This will be the counted topography product.

Terminus (WP 1)

The terminus position will mostly be derived from the intersection of a central flowline with the L1 glacier outlines and stored as a glacier specific point with a certain elevation. When such a point is difficult to identify (e.g. at an irregular terminus), a line will be defined instead (e.g. a calving front) or the glacier is not considered. The terminus position will facilitate the subsequent calculation of glacier length changes.

Snow line (WP 2)

In a first step the snow covered area (SCA) will be mapped from optical sensors, preferably from the end of the ablation period, i.e. using mostly the same satellite data as selected for the outlines. In a second step, the SCA will be combined with the L1 glacier outlines (from WP1) and DEM data (from WP3) to obtain glacier specific elevations of the transient snowline (TSL). In cases when the TSL is similar to the equilibrium line, its altitude (ELA) might be used as a proxy for the glacier mass balance.

Topography (WP 3)

Topographic information for the glaciers will be compiled from readily available resources (mostly the SRTM3 DEM and maybe the forthcoming global ASTER DEM) that are complemented in some regions by satellite derived DEMs, either from multispectral stereo sensors (e.g. ASTER, SPOT) or interferometric SAR data (e.g. from the ERS1/2 tandem mission). The DEMs will also be used for geometric and radiometric correction of the satellite data (e.g., orthorectification and albedo calculation), to derive topographic data for each glacier (L2 outlines) or snow line elevation, and they will partly serve as a reference for the determination of elevation changes.

Elevation change (WP 4)

Changes in glacier surface elevation will be obtained by differencing DEMs from two epochs in time (e.g. InSAR, stereo-photogrammetry) and from time-series of satellite (and partly airborne) altimetry data (e.g. RADAR, LiDAR). Additionally, methods for spatial extrapolation of point measurements to the entire glacier surface will be developed.

Velocity (WP 5)

Velocity fields for glaciers can be obtained either from feature tracking of repeat-pass optical imagery or from microwave sensors using differential SAR interferometry or offset-tracking. The time period analysed will depend on the available satellite data and vary from short term (a few days) to annual means. Apart from the calculation of balance velocities, the velocity fields will also be used to identify flow divides in flat accumulation regions.

Quantities

The major aim of the project is to apply well-established (i.e. validated) techniques to large quantities of archived satellite data (Table 3). The first three products have a reduced quantity in phase 1 as several document deliverables will be prepared at the same time. Where possible, results from previous/ongoing studies (by the consortium or the user group) will be included.

Validation activities

A sub-set of each generated product will also be validated with a number of different methods (see below). The major focus with respect to validation will be on methodological aspects. The techniques and data sets that could be applied for technical validation depend on the product and include the following methods:

- Cross validation (CV): generating the same product from different sensors or sources and comparison of the data sets;

- Higher spatial resolution data sets (HR): using aerial photography, Quickbird/Ikonos, airborne LIDAR or -DEMs from national mapping agencies, and
- Field observations (FO): measurements of mass balance, length changes and GPS surveys.

For the individual products, the following methods (in brackets) could be used: Outline (HR, CV), terminus position (FO), snow line (FO, CV), topography (HR, CV), elevation change (FO, CV), and velocity (CV, FO). While for some of the products also internal accuracy measures will be applied (e.g., for DEM generation), others will be controlled by visual inspection (glacier outlines).

METHODS

Glacier outlines and terminus

The method for glacier mapping from multispectral satellite sensors is based on the sharp contrast in spectral reflection of snow and ice versus other materials in the shortwave infrared (SWIR) part of the spectrum (around 1.5 µm). Here, snow and ice have a very low reflectance while it is very high in the visible part (11). The spatial resolution of most SWIR sensors (20-30 m) is sufficient to map glaciers as small as 0.02 km^2 (about 30 pixels) accurately (12). In principle, the method that is easiest to perform (thresholded ratio image on the raw digital numbers with the TM equivalent bands 3 or 4 and 5) yields the most accurate results (13,14). The most problematic regions (debris cover, shadow, snow fields, lakes) have to be edited manually in any case (Figure 2). As such, the thresholds for the mapping will be selected to minimise the workload for manual corrections, at best in regions of cast shadow where the threshold is most sensitive.

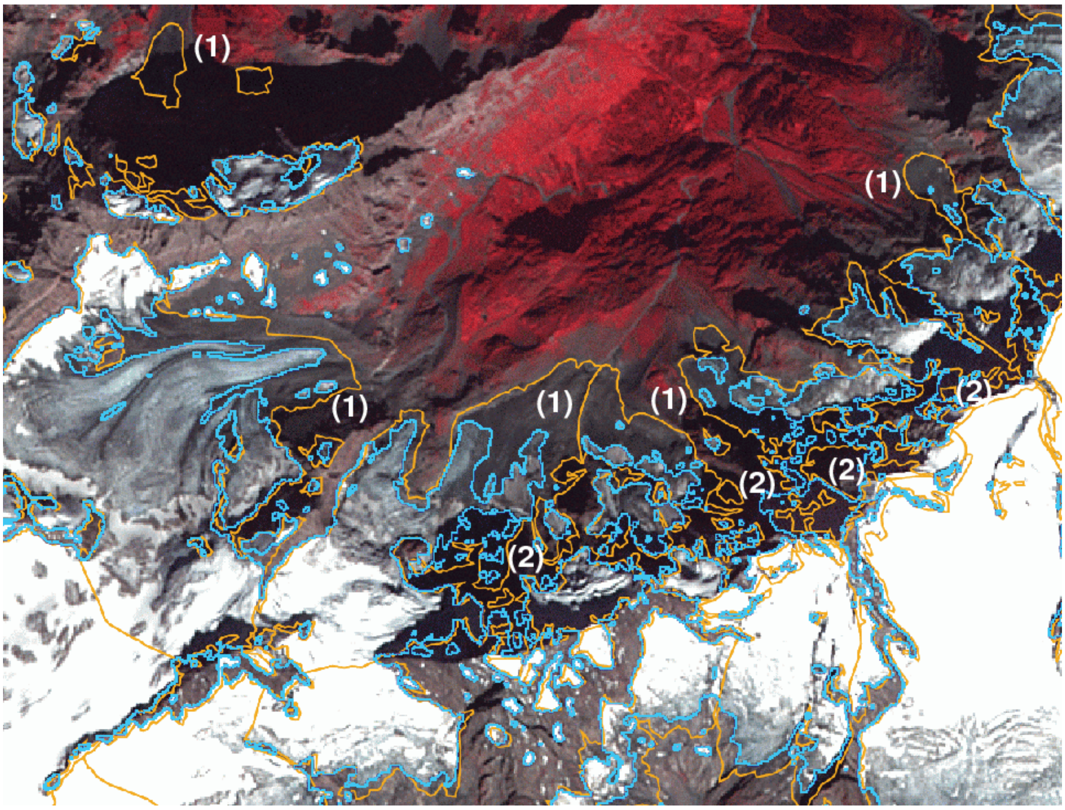

Figure 2: Maybe the most challenging region for glacier mapping in the Alps, the end of the Lauterbrunnen Valley as seen from ASTER on 8 Sep 2004. Glacier outlines as mapped with ASTER (band 2/4 ratio) are in blue, and from the digitised 1973 glacier inventory in orange. Numbers denote: (1) debris covered regions that are hardly recognisable, (2) cast shadow with nearly invisible snow patches.

Apart from the automated glacier mapping, satellite sensors have some more advantages compared to traditional techniques like aerial photography: a) large regions are covered at the same time, b) a large amount of appropriate (with respect to clouds and snow conditions) historic scenes are available on a global scale and in a digital format, and c) the sensors are calibrated and allow conversion to physical units like radiance or reflectance values. For an overview of the applied techniques and results see (9,15,16,17). Further studies have been performed (18,19,20,21,22,23). Accuracy and performance assessments are described by (13,14,24,25). In (26), an overview of deriving glacier terminus positions and length changes from the air and space is given.

Snow lines and firn area

For Alpine glaciers, the snowline at the end of the ablation period (the late summer snow-line, LSSL) corresponds approximately to the equilibrium line, EL, the boundary between the ice and/or firn area and the snow accumulated during the last year. The EL altitude (ELA) is an important indicator for mass balance and can be derived for each glacier by combining the mapped snow covered area with glacier outlines and a DEM. However, in years of very negative mass balance the boundary between snow and ice can be very complex and the accumulation area thus very patchy (22). In this case the ELA could be better derived from the area-altitude curve taking into account the size of the accumulation and ablation area. Both approaches will be applied in the project.

In GlobGlacier, the focus is on mapping the LSSL from optical imagery using differences in surface albedo or reflectance. In general, glacier ice has a lower albedo than snow, and the albedo of firn (névé) is usually also lower than that of snow from the current mass balance year (22). A semi-automated algorithm will be applied for mapping the LSSL in multi-spectral satellite imagery, based on top-of-atmosphere (TOA) or at-satellite reflectance. An important processing step is the compensation of topographic illumination effects (27). Several parametric approaches like the Minnaert or C-factor correction will be tested and the most suitable method will be applied. The resulting reflectance map will then be the basis for the classification of snow covered regions using selected thresholds. This is an efficient solution for the analysis of large data sets, requiring only a DEM and TOA reflectance as an input. For validation purposes, a comparison will be made with the full solution of a radiative transfer model that calculates spectral irradiance at the surface, the scattering contribution of the atmosphere, and atmospheric extinction losses. As this method requires data on atmospheric aerosol and water vapour content, it will only be applied to selected test sites where such data are available (e.g. Ötztal Alps, Austria; Jotunheimen, Norway). As an example, Figure 3 shows surface types on glaciers and ice-free regions based on a multi-threshold classification of albedo values as derived from Landsat 5 TM data. In this case, a DEM and the radiative transfer model were applied to calculate local spectral irradiance and atmospheric path radiance for every pixel. The reflectance of snow exhibits an increasing forward scattering component towards lower solar elevation (28). These angular variations in snow reflectance are described by the Bidirectional Reflectance Distribution Function (*BRDF*). The related (small) reduction in reflectance (28) is not considered here.

Topography

For certain GlobGlacier regions DEMs will be readily available from the SRTM (29, 30) or from national agencies. However, a number of DEMs will have to be newly produced, either due to the lack of suitable DEMs or in order to obtain multitemporal DEMs. Spaceborne DEMs will be produced from SAR interferometry, optical stereo data, and laser altimetry. Altimetry, namely from the ICESat GLAS, is not suitable for deriving area-wide glacier topography, but rather for measuring elevation differences (see below) and for additional ground control for optical stereo data and SAR interferometry (31,32).

Glacier topography from repeat-pass SAR interferometry can most probably only be expected within GlobGlacier from the ERS-1/2 tandem mission between 1995 and early 2000, and the 3-day repeat ice phase during several months in 1992 and 1993. Such data will represent an important time slice set for change detection purposes. ERS-1 SAR triplets from the 3-day repeat phases or two pairs of ERS-1/2 SAR images from the tandem phase with assumed similar displacement allow the estimation of the ice surface topography with a 25 m resolution (e.g., 33,34). The vertical error for an ERS-derived DEM is typically in the range 5 to 20 m.

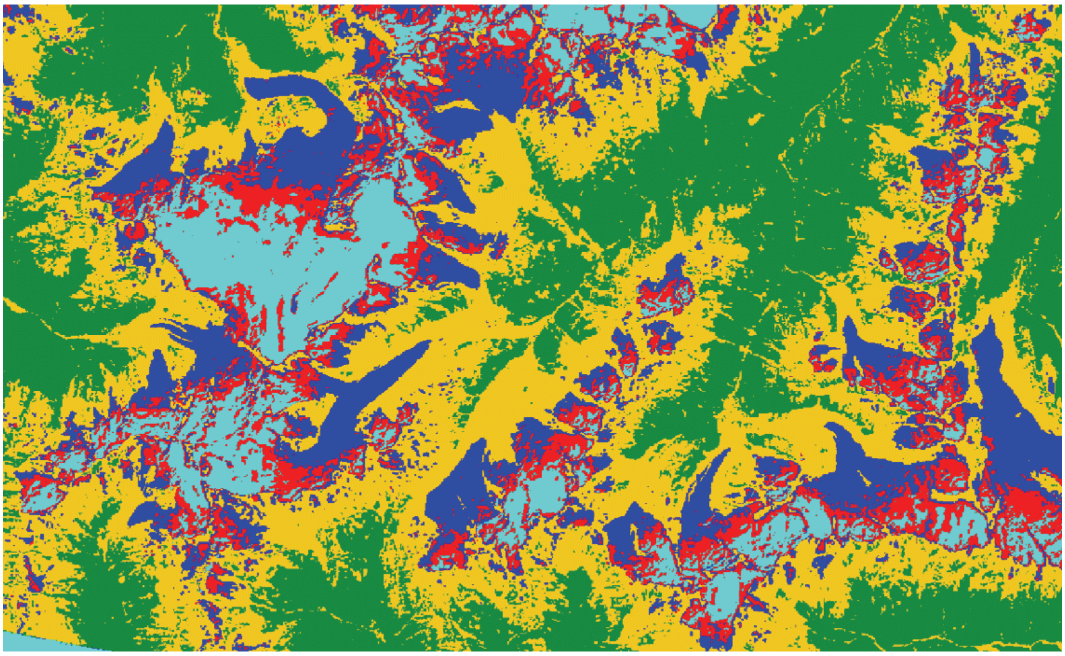

Figure 3: Classification of surface types on glaciers and ice free areas, based on surface albedo derived from Landsat 5 TM data of 16 Aug 1992, Ötztaler Alpen, Austria. Blue: glacier ice; red: firn (névé); cyan: snow; green: alpine vegetation; yellow: moraine and rocks. The combination with glacier outlines provides glacier specific values of the accumulation area ratio (AAR).

Optical satellite stereo is highly valuable alone and in complementing above-mentioned SAR methods (35). Under high-mountain conditions where surface properties can change quickly, along-track optical stereo is highly preferable over cross-track stereo. Suitable sensors are mainly ASTER, and the new ALOS PRISM instrument. Along-track stereo data from SPOT 5 is in general not available for customers, but corresponding DEMs are provided for commercial purposes or even free of charge in the framework of the IPY project SPIRIT for certain regions in the Arctic and Antarctic. ASTER data, for example, proofed very useful for DEM generation over glaciers, in spite of their medium spatial resolution of 15 m (16,35,36). A comparison of the SRTM DEM and an ASTER derived DEM is depicted in Figure 4. Vertical accuracy of individual terrain elevations (RMSE) is in the order of the image pixel size, for sufficient optical image contrast. DEMs from optical stereo are produced using photogrammetric principles and algorithms. Methods for error detection and filtering of DEMs from satellite optical stereo are available as well as methods for combining optical and InSAR-derived DEMs (30,35,37).

Elevation change

Changes in the elevation of glacierised surfaces could be used as a measure of changes in snow and ice mass (e.g. 38) and, in consequence, are an important method for assessing the state of the cryosphere. In order to survey elevation (and volume) changes with sufficiently fine spatial and temporal resolution, a range of techniques could be applied. In GlobGlacier, two methods are employed using both optical and microwave instruments: (a) differencing continuous elevation models (or profiles) at two or more discrete epochs, and (b) sampling discrete elevations at frequent and regular time intervals.

Accuracy of digital elevation models

In GlobGlacier, elevation changes will be analysed at a horizontal resolution in the range 20 - 100 m. A practical estimate of the required accuracy in elevation can be obtained by considering improvements to the certainty of the global sea level contribution due to melt of glaciers and ice caps (0.2 to 0.4 mm yr^{-1} in (39)). To survey the mass changes within a sea level equivalent of 0.1 mm yr^{-1} corresponds to an average elevation change accuracy of 5 cm yr^{-1}. This certainty could be achieved by surveying a representative sample of 100 independent glaciers to an accuracy of 50 cm yr^{-1}.

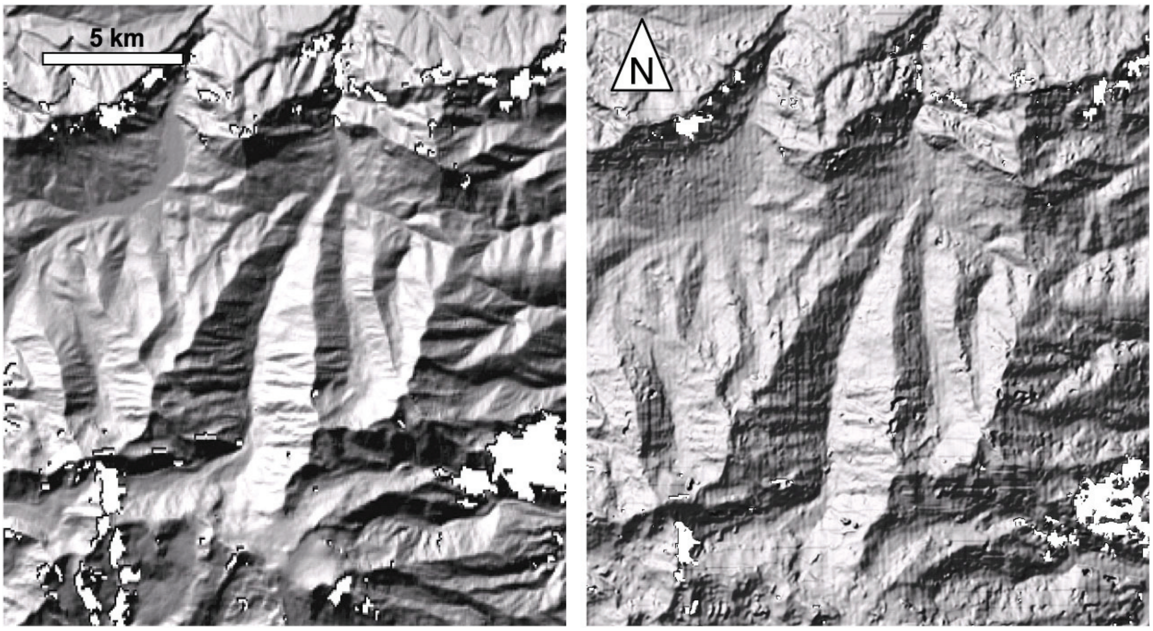

Figure 4: Shaded reliefs of DEMs from the SRTM (left) and ASTER (right) satellite optical stereo over the Kasbek area, Caucasus. Some striping is evident in the ASTER DEM, apart from this the quality of both DEMs as well as the location of data voids is comparable.

A number of observation systems meet the spatial-resolution criterion (Figure 5, left), including the ERS and EnviSat InSAR missions (80 m) over the period 1991-present (33), the SPOT and ASTER optical stereo missions (5 m and 25 m, respectively) over the period 1986-present (40,41), and the SRTM InSAR mission (30-90 m) in 2000 (42). The temporal separation criterion for discrete elevation models, coupled with their respective certainties, governs the accuracy with which elevation trends may be derived. Estimates of the vertical accuracy of these techniques are ~6 m for SPOT (43), ~16 m for SRTM (29), and ~30 m for InSAR (33). According to the survey period, combinations of these techniques are therefore able to determine elevation changes with accuracies in the range 30 to 300 cm yr^{-1} (e.g., 44).

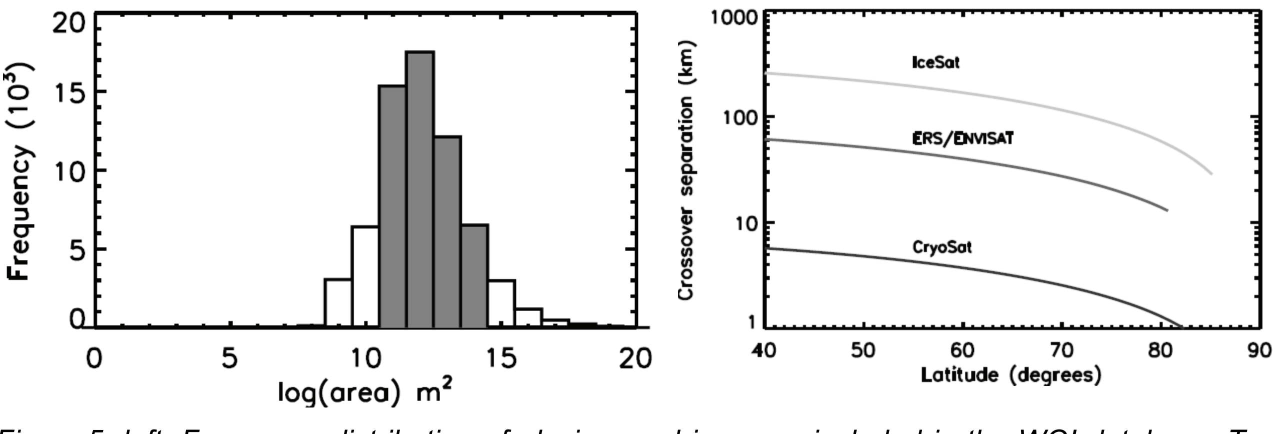

Figure 5, left: Frequency distribution of glaciers and ice caps included in the WGI database. Targets that may be resolved by radar altimetry (e.g., ERS, EnviSat), laser altimetry (e.g. ICESat) or interferometric synthetic aperture radar altimetry (e.g. CryoSat), and differential gridded elevation models (e.g., ASTER, InSAR), are highlighted in light grey, dark grey, and white, respectively. Right: Spatial separation of orbit crossing points for ICESat, ERS and CryoSat.

Time series of elevation change

One practical means of developing regular time-series of surface elevation changes is through satellite altimetry at orbit crossing points. This is achieved by computing elevation changes at the crossing points of ascending and descending satellite orbits (45). In this way, the effects of surface gradients are eliminated. The existing satellite dataset comprises a series of comparable pulselimited radar altimeters (Seasat, Geosat, ERS, Envisat) and a beam-limited laser altimeter (ICESat), with ground footprints of ~5-10 km and 70 m, respectively. For comparison, at a latitude of 60º the average separation of ICESat, ERS/ENVISAT, and CryoSat orbit crossing points (where elevation trends may be determined) is 175 km, 35 km, and 2 km, respectively (Figure 5, right). In addition, where elevation changes are substantially larger than topographic undulations, it is possible to use repeat-pass altimetry in the absence of orbit crossing points.

Traditionally, repeated aerial photography is used to assess overall changes in glacier thickness and volume for alpine type glaciers over time periods of a decade (46,47). Moreover, direct mass balance measurements have to be calibrated after a decade in order to correct systematic errors and to obtain the overall volume change (e.g., 48,49). In regions where DEMs of sufficient accuracy from earlier periods are available, the SRTM DEM makes it now possible for the first time to calculate elevation changes for large glacier ensembles at the same time (e.g., 50,51) and to assess the representativeness of the few glaciers selected for direct mass balance measurements for entire mountain ranges (48). In Figure 6 an assessment of elevation changes for two ice caps is shown that combines the elevation data available from traditional mapping (contour lines) with those obtained from an ASTER derived DEM and ICESat elevation profiles.

Figure 6a: ASTER satellite image from two ice caps in Eastern Svalbard indicating the used ICESat ground tracks used (dotted).

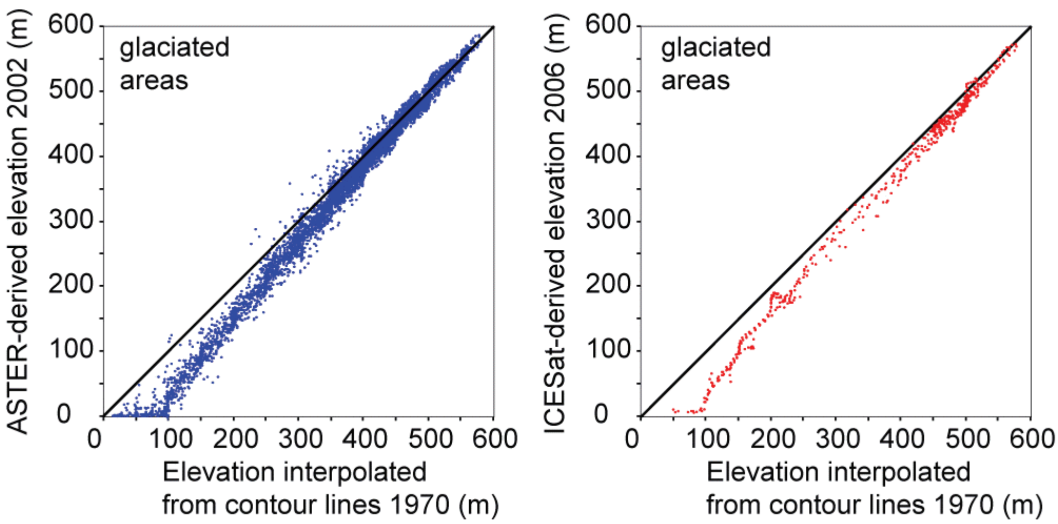

Figure 6b: Derived elevation changes between contour lines from topographic maps 1970 and an ASTER-derived DEM (left) and ICESat GLAS derived elevations from 2006 (right). After Kääb (52).

VELOCITY

Ice flow components can be derived from space by matching of SAR interferometry, repeat SAR images (offset tracking) and repeat optical images. In Figure 7 examples are given for the latter two. The techniques that are used for digital comparison between multitemporal images are: block (or area-based) matching techniques and feature matching techniques. Matching blunders are detected and eliminated from the analysis of the correlation coefficients and from the application of constraints, such as the expected range for flow speed and direction. In the case of coherent displacement fields, additional spatial filters may be applied such as median or RMS thresholds. Digital motion measurements from repeat satellite optical imagery have been applied for ice sheets (e.g., 53), Arctic glaciers (e.g., 37), and alpine glaciers (e.g., 35,54).

Interferometric SAR (InSAR) combines two SAR images acquired from slightly different orbit configurations and/or at different times to exploit the phase difference of the signals (55,56). An external DEM or the differential use of two interferograms with similar displacement can be employed to remove the topography-related phase from the interferogram to derive a displacement map (57,58). Most of the InSAR ice studies used winter data from ERS-1 with 3-day repeat cycles during the ice missions in 1992/94 and from ERS-1/2 during the tandem phase from 1995 to 2000 with a one-day acquisition interval. For ERS data, estimated errors are on the order of a few centimetres, but the maximum detectable rate is limited by signal decorrelation due to glacier flow. Despite the availability of a large ERS-1/2 SAR archive, only few studies have been performed over alpine glaciers (59, 60, 61), where the rugged topography causes incomplete coverage due to layover and shadowing. GlobGlacier will utilise the vast potential of the ERS-1/2 SAR tandem acquisitions to assess the surface velocity of alpine glaciers on a global scale.

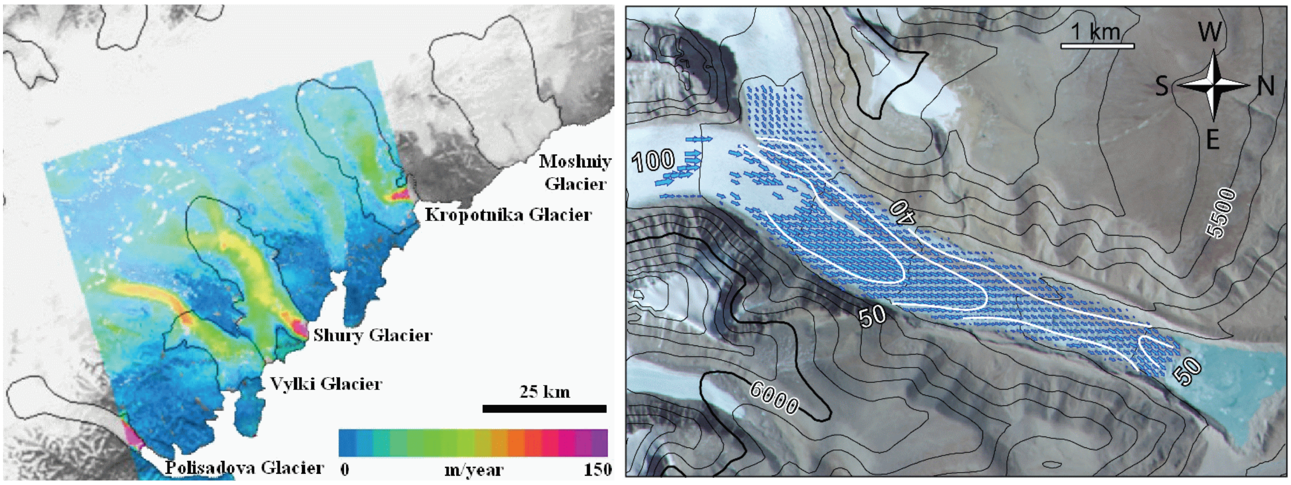

Figure 7, left: Horizontal displacement for Novaya Zemlya from ALOS offset tracking between PALSAR images of 6 Dec 2006 and 21 Jan 2007. In the background a MODIS image from 29 July 2003 is shown. Ice divides and outlet glaciers boundaries are after (62). Right: Velocity field on an unnamed glacier in Bhutan derived from matching of repeat pass ASTER data. Ice velocity is also indicated by isolines.

When InSAR is limited by incoherent flow and large acquisition time intervals, offset-tracking is a good alternative (63,64,65). With offset tracking the registration offsets of two SAR images are generated with a normalised cross-correlation in both slant-range and azimuth directions and used to estimate the displacement of glaciers. The successful estimation of the local image offsets depends on the presence of nearly identical features in the two SAR images at the scale of the employed patches. If the speckle pattern of the two images is correlated, tracking with image patches of about 1 km in size can be performed to remarkable accuracy. Studies were performed with ERS-1/2, ENVISAT, RADARSAT-1, JERS-1 SAR, and ALOS PALSAR data separated by a full orbital cycle over many Arctic regions with expected errors on the order of 10 to 20 m/year (66,67).

EXPECTED RESULTS

Apart from the input to the GLIMS and WGMS databases, it is expected that a major impulse from GlobGlacier will be related to the document deliverables. They will help to define standards, assess data quality and provide workflows to generate the products from the respective sensors. In view of the envisaged operational monitoring services (7,8,9), such documents will greatly facilitate this goal. When the proposed product quantities could be achieved during the project duration, the databases should consist of a much more representative sample of glaciers and their changes around the world. This will give a higher confidence in the results from all kinds of modelling studies with a global perspective (e.g., sea level rise). GlobGlacier will also assess the status quo of the databases and provide an overview of current satellite data holdings. These documents could also be used after the end of the project to identify future work. The change assessment that will be performed in many key regions will help to quantify climate change impacts in yet uncovered regions and thus to give a higher confidence in currently observed trends. Requirements for future space-borne glacier monitoring will be reported as well.

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