→ CLIMATE CHANGE INITIATIVE

Glaciers CCI Newsletter

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Figure 1: Oberaarglacier in Switzerland (Photo: F. Paul)

Glaciers and Ice Caps

Changes in glaciers and ice caps are key indicators of climate change. Satellite data help to monitor them at a global scale.

Glaciers are considered as key indicators of climate change and thus play a most important role in globally coordinated and climate-related monitoring programs like the Global Climate Observing System (GCOS). They are frequently in the focus of the public and the media, as their strong changes in length as a reaction to small changes in climate reflect impacts of climate change in an extraordinarily clear and understandable way. As glacier changes are widely reported with related adverse impacts when errors in the observations occur, they must be performed with great care and should be quality checked. Complementary to the field-based measurements of changes in glacier length and mass on selected glaciers world-wide, satellite data offer the unique possibility to cover entire mountain ranges with a consistent method thus helping to create a more complete and representative picture of ongoing changes. This is only possible due to the vector nature of the derived outlines that allow for a consistent analysis with modern geoinformatic techniques. But melting glaciers were also responsible for a substantial contribution to sea-level rise over the past decade, and the need for a detailed and globally complete glacier inventory for a more precise calculation of this contribution became an urgent demand. This demand is also expressed in several scientific publications and international documents so that the creation of such an inventory is a key task for the Glaciers_cci project.

But satellite data can provide much more than glacier outlines. From the large number of possible observations, Glaciers_cci selected three of them: Glacier area, elevation changes and velocity fields. While elevation changes provide direct information about ongoing vertical mass changes, flow velocity gives additional information for horizontal changes (i.e. mass transport to the terminus). This is in particular important for calving glaciers, which can lose substantial parts of their mass by calving. Another interesting aspect of the products is the complimentary nature of the satellite sensors to create them. They differ strongly in regard to spectral properties (optical, microwave, LIDAR), spatial resolution, temporal coverage, repeat interval, etc. and each sensor has its specific field of application. In this first newsletter we will provide an overview on the products and how they are created and the data sources to be used by the project.

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The products

A wide range of glacier-related products can be created from satellite data. Glaciers_cci focuses on three of them: Glacier area, elevation change and velocity.

Based on the user survey presented in the user requirements document (URD), the following three products will be created by the project: Glacier area, elevation changes and velocity fields. Available data sources and algorithms (see below) are all in a very mature state to envisage creation of these products globally and regularly. However, to achieve a certain quality level of the products, manual intervention is required at several stages of the processing. The particular aims for each of the products are thus rather different and are shortly described in the following.

The **glacier area** product is basically a vector outline of a glaciers perimeter. This outline is derived by raster-vector conversion of a glacier map that is derived from classification of a multispectral (optical) satellite image (see below). This raw outline (Level 0a product) will be corrected for misclassification in the post-processing stage (becoming L0b) and then upgraded to two further processing levels. At the first level (L1) drainage divides as derived from a digital elevation model (DEM) are digitally intersected with the outlines to separate contiguous ice masses into individual glacier polygons so that each glacier receives its own identifier (ID). In the second step the L2 product is created by adding topographic attributes (e.g. minimum, mean, and maximum elevation) as derived from a DEM to each entity. This product is the final glacier inventory that will be provided to the GLIMS database for free access. A major point to consider for this product is that it will be largely generated by the global community participating in GLIMS rather than by Glaciers_cci. The project will, however, support creation of L2 products in the required key regions, provide guidelines for consistent data generation, improve algorithms, and perform accuracy assessments, among others.

The **elevation change** product is calculated using two complementary methods, one that is derived from differencing two DEMs obtained over a c. 10-20 year time interval, and another that is derived from long-term (decadal) satellite altimeter measurements that are repeated over much shorter intervals (a few months). DEM differencing can cover glaciers completely, and tends to perform best in areas of rugged high-mountain topography. In contrast, satellite altimetry provides sparse measurements at points or along lines, and tends to perform best over large and flat ice masses (e.g. ice caps). While the point accuracy of elevation measurements from altimetry is much higher than DEMs (a few centimetres compared to a few metres), the accuracy of glacier elevation change products derived from each technique can be quite similar once spatial and temporal sampling is considered. The elevation change of the glacier surface is directly related to the annual atmospheric conditions, and the mean change over the entire glacier multiplied with its area gives the volume change. In the case of calving glaciers, surface velocity measurements help to determine the mass loss due to calving.

The **flow velocity** at the surface of a glacier provides important complimentary information (the horizontal components) about the elevation changes of a glacier at a point as well as for mass loss by calving. It also helps to identify drainage divides on very flat glaciers or ice caps and gives information about glacier health (e.g. where the ice is stagnant). Velocity fields can be derived from different methods (e.g. offset tracking and interferometry) and sensors (optical and microwave) providing different averaging periods (from days to years), but the final product is basically the same (surface displacement per year). As for the elevation change product, also this product requires satellite data obtained from two points in time (repeat pass) that cover the same region and are properly co-registered. In regard to the spectral properties of a glacier (composed of snow, ice, rock and water at the surface, see Fig. 1), the regions of a glacier that can be properly tracked by a specific sensor, varies with the contrast and the conditions of the ice (see methods).

The data sources

Satellite data provide not only images, but also three-dimensional information. Digital elevation models (DEMs) are a key input data set for all three products.

The input data sets required to generate the Glaciers_cci products can be distinguished in some main categories, but actually they overlap to some extent. Satellite data can be distinguished from DEMs, image data from altimeter tracks and optical from microwave sensors. However, altimeters can operate with optical (ICESat GLAS) and microwave instruments (e.g. EnviSat RA-2), and DEMs can be created from spaceborne instruments (e.g. SRTM, GDEM) or from aerial photography (most national DEMs). So the categories used below to describe the available data sets are only indicative rather than exclusive.

Satellite data from **optical sensors** provide the main input for the glacier area and the velocity product (with about annual temporal resolution for the latter). While for the glacier area product the most important requirement of the sensor is a spectral band in the shortwave infrared (SWIR) around 1.5 µm, it is a high-spatial resolution for velocity. Several sensors have a SWIR band and partly provide data since 1984 (Landsat 5) as the timeline in Fig. 2 illustrates. The two Landsat sensors TM and ETM+ are actually the backbone of glacier mapping, as their data are available free of charge (at glovis.usgs.gov) and a huge region of about 180 by 180 km is covered in each scene (i.e. 9 times the area covered by SPOT or ASTER). This also helps to create glacier inventories over large regions from the same point in time.

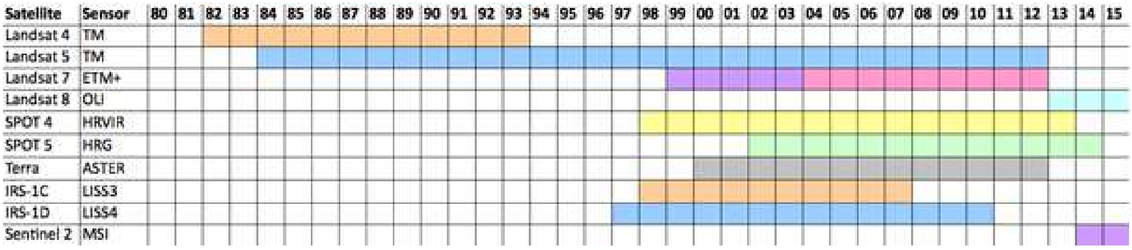

Figure 2: Timeline of currently available and scheduled future (Landsat 8, Sentinel 2) optical satellite data with at least one band in the short wave infra-red of at least 30 m spatial resolution. The change in the colour for ETM+ indicates the scan-line-corrector failure in 2003.

The now 27 year time-series of Landsat is also exceptional in regard to its potential for change assessment. No other sensor provides a similar long continuous record of the Earth's surface at 30 m spatial resolution. For the velocity product the 15 m resolution pan band of Landsat 7 and the visible and near infrared bands (VNIR) of ASTER are particularly useful. For all optical sensors cloud cover results strongly limits data availability. In this regard, the higher repetition rate of future sensors (Sentinel-2) will be an important benefit compared to current sensors.

Satellite data from **microwave sensors** are used to create the velocity product. In contrast to optical sensors, these sensors have the main advantage of being largely independent from cloud cover. They illuminate the analysed region directly and record travel times and the complex (intensities and phase) of the return signal. They have thus a component related to the topography (influencing travel times) and one that is based on material properties and the local geometry compared to the wavelength of the beam (e.g. causing scattering). An important criteria to differentiate the available datasets is the repeat interval. This influences the technique that can be applied to derive the product, as glacier flow and changes in the physical properties of the glacier surface cause changes in the reflection of the beam (see methods). So the available data (see timeline in Fig. 3) spanning a repeat cycle from a few days to several weeks can all be used to generate the product, but constraints result in regard to the further data processing and the averaging period.

Altimeters use either optical (infrared wavelength) laser pulses or microwaves (Ku band) to precisely track the distance of the satellite from the Earth's surface. From a repeat track close by and the known position of the sensor in the orbit, the change in elevation at specific points can be followed (it is not necessary to record the absolute height of the surface). Sensors suitable for this purpose have been flown onboard the ERS-1 and ERS-2, IceSat, Envisat, and CryoSat-2 satellite platforms since 1991. While the IceSat laser altimeter system is the most precise of these instruments, its repeat cycle of 91 days is about three times longer than that of the remaining sensors. The prospect of densely sampled glacier elevation change data from Cryosat-2 (Figure 6) offers an exciting opportunity for studies of glacier imbalance.

DEMs are available globally from a variety of sources. They differ in regard to the area covered, the spatial resolution, the acquisition type (satellite / aerial images / maps) and mode (optical / microwave), the time stamp, and their shortcomings (e.g. artifacts or data voids). Apart from the SRTM DEM, the ASTER GDEM and the GLS2000 DEM (used by USGS to orthorectify the Landsat images with their near global coverage), several more regional DEMs are available e.g. the NED for the US, the CDED for Canada and the collection of DEMs from viewfinderpanoramas.org by J. de Ferranti. While some of these DEMs are sufficiently accurate and temporarily focused that they can be used to determine elevation changes of glaciers over decadal periods, most of them are at least sufficient to determine drainage divides and/or for calculation of topographic inventory parameters. The basic issue is thus to select the most appropriate DEM for the study region from the available sources in view of its application. It is possible that a DEM is well suited to derive drainage divides (in the accumulation region of glaciers), but much less appropriate for the topographic parameters as surface elevation has changed too strongly in the ablation area since DEM acquisition. Several measures to assess the quality of a DEM are in place and can be investigated before the respective DEM is applied. With the future availability of the TanDEM-X DEM many of the currently required DEM comparison and evaluation schemes might become obsolete.

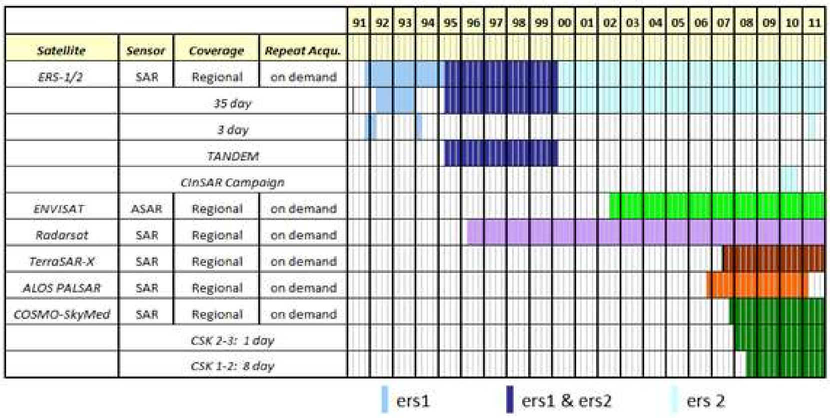

Figure 3: Timeline of available SAR sensors and corresponding mission phases since 1991.

The methods

The degree of sophistication of the algorithms to be applied for each product varies greatly. But all have a pre-, main- and post-processing stage in common.

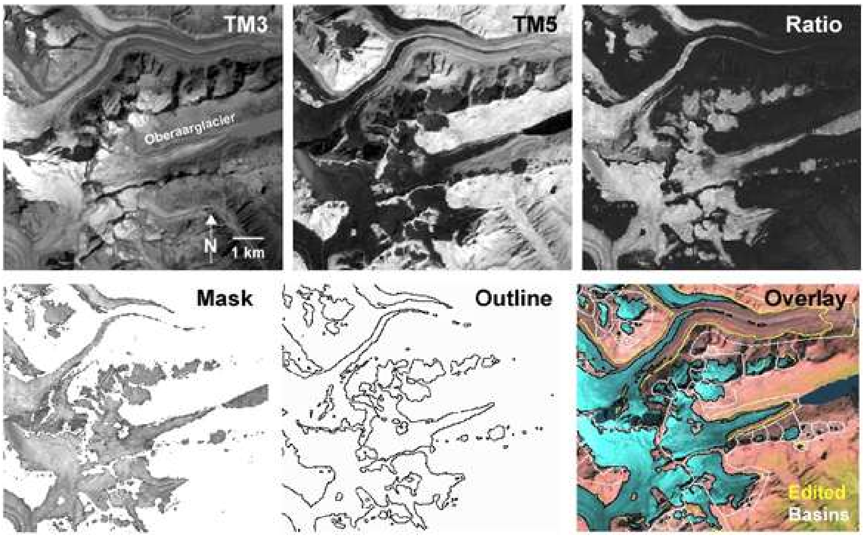

Fig. 4: Steps of creating the glacier area product from a TM3 / TM5 ratio image (upper row): A glacier map results from applying a threshold to the ratio image and raster-vector conversion creates the raw glacier outlines. They are manually edited and intersected with drainage divides as a final step (lower row).

Glacier area
The pre-processing stage of the glacier area product includes selection of the most appropriate scene in regard to cloud and snow conditions, download, format conversion (from geotiff to the format of the software used) and creation of RGB composites for correction of the outlines in the post-processing stage. The main processing is based on a very simple algorithm, division of the grey values (or digital numbers) from the red band by the SWIR band and application of a threshold to the ratio image (cf. Fig. 4). This threshold is best-selected manually, but is normally around 1.8. So in principle, glaciers are mapped where the grey values in the red band are at least 1.8 times higher than in the SWIR. An additional threshold in the blue band (or green if not available) helps to improve the classification in cast shadow. The algorithm is based on the very different spectral properties of ice and snow in the SWIR (where both are nearly black, i.e. absorb all radiation from the sun) compared to shorter wavelengths (Fig. 4, upper row). Finally, the glacier map is converted to glacier outlines by raster-vector conversion. In the post-processing stage, the outlines are corrected in regions of misclassification (Fig. 4, lower row). First, for gross errors (e.g. water surfaces, ice clouds or ice bergs), then for details (e.g. shadow, debris). This is done by using one of the contrast enhanced band composites in the background. Each glacier outline is thus quality controlled, but the interpretation of the satellite image requires special training and experience of the analyst.

DEM differencing
The most important pre-processing step when determining elevation changes from DEM differencing is the accurate co-registration of both DEMs. Otherwise a systematic shift directly impacts on the difference values and results in a product of poor quality (Fig. 5). Furthermore, the DEM needs to be investigated for data voids, artefacts and regular patterns (e.g. from the interpolation applied during its creation). Both DEMs should also have the same spatial resolution. This often requires resampling of one of the DEMs which may lead to unwanted artefacts or biases. The subtraction itself is then a very simple step in the main processing stage and zonal averaging with glacier entities directly provides mean elevation changes per glacier. Of course, artefacts, data voids etc. need to be carefully checked for each glacier to be sure that the value makes sense. This can be automated to some extent, for example by excluding all glaciers from the further analysis that are covered by data voids for more than 10% of their area.

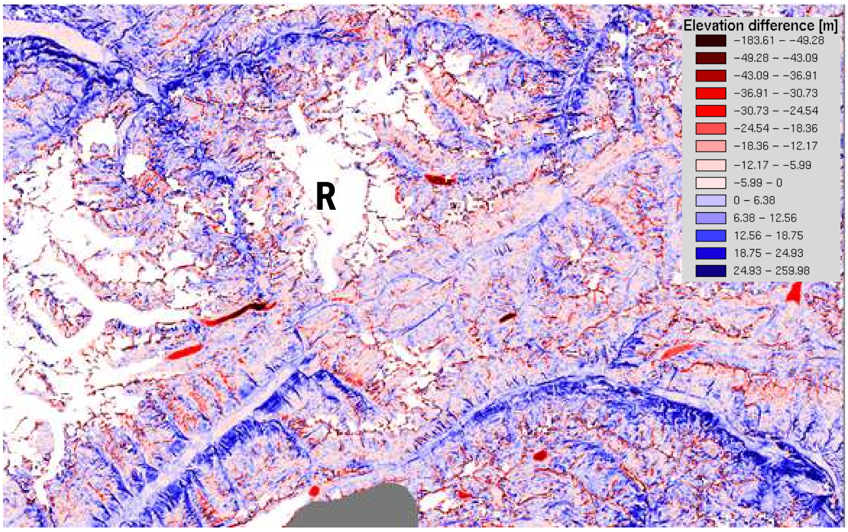

Fig. 5: After proper co-registartion of the two DEMs to be subtracted, the differences are independent of terrain aspect and only differences in the 'stable' terrain remain. For this region in Switzerland around Rhoneglacier (R), we have masked all glaciers and data voids (white). Hydro-power lakes (dark red) and forest stands (dark blue) clearly show up due to the different seasons of acquisition (summer/winter) and DEM types.

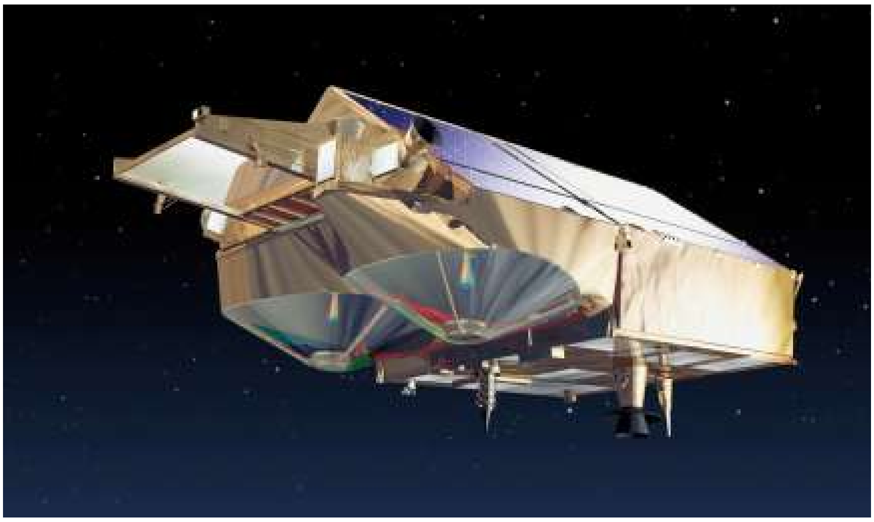

Fig. 6: The CryoSat-2 satellite altimeter was launched by the European Space Agency in 2010. CryoSat-2 is the most advanced satellite altimeter mission to date and was specially designed with two antennas to monitor changes of the Earth's cryosphere with unprecedented accuracy (Image: ESA).

Altimetry

Satellite altimeter data are assembled over the survey region from the continuous record of measurements acquired by a succession of satellite altimeter missions that began in 1992. There are two basin approaches for calculating glacier elevation changes from these data; either at the intersections of crossing satellite orbit ground tracks, or along parallel repeated ground tracks after taking account of their misalignment due to orbital drift. The altimeter data are adjusted using precision orbit corrections, and are corrected for distor-tions introduced by the ionosphere, the lower atmosphere, the scattering properties of the glacier surface, the tidal pull of the sun and moon, and the tectonic motion of the Earth. Observations recorded by successive satellite missions are combined by taking account of elevation differences recorded during periods of mission overlap. When calculating glacier elevation changes at orbit crossing points, altimeter measurements recorded in north-bound and southbound orbits are combined at monthly intervals. When calculating glacier elevation changes along parallel repeat orbits, the altimeter measurements are first cor-rected for errors associated with orbit drift using models of the glacier surface slope. This might require that data are grouped into yearly time periods. After both datasets are assembled, the resulting measurements are averaged across the glacier target to compute the average elevation change.

Velocity

Methods for deriving glacier velocity from satellite images are abundant and vary significantly depending upon each individual study. Pre-processing steps such as orthorectification of the images, application of filters or interest operators, though important, will not be the main focus for Glaciers_cci as these steps are either standardized (in the case of orthorectification) or are highly specific to the images used and glaciers studied (in the case for filtering). Nevertheless, there are numerous image matching algorithms available operating in both the spatial and frequency domain and it remains to be determined in which situations certain algorithms perform best. The potential window sizes used in these algorithms vary significantly and must be determined for each case or algorithm. Large potential exists for developing algorithms to operate using adaptive window sizes within a scene pair, though this process is computationally expensive. In summary, while the implementations of image matching algorithms vary significantly and are not at all standardized, the algorithms themselves perform variably in different glacier and imaging conditions. By inter-comparing these possible algorithms, Glaciers_cci aims to outline best-case scenarios for providing glacier velocity estimates from repeat image analysis.

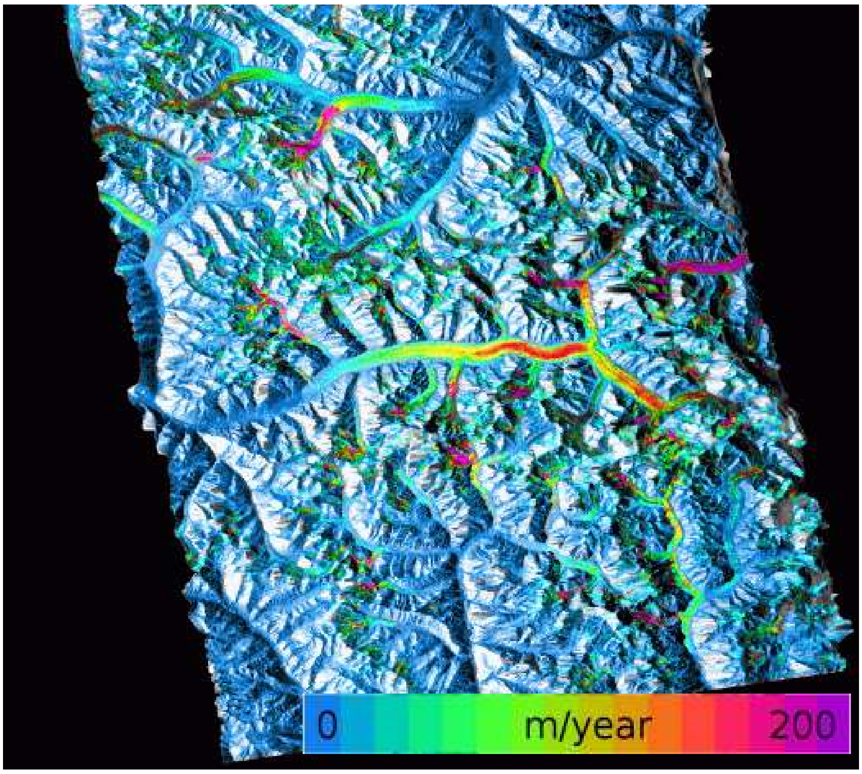

Fig. 7: Velocity of glaciers in the Karakorum derrived from offset-tracking based on ALOS PALSAR scenes from 10.8. and 25.9. 2007 image width is c. 100 km.

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The team

As the Glaciers_cci project is working with satellite data from optical, microwave and altimetry sensors to derive three types of products (glacier outlines, elevation changes and velocity fields), the consortium must have expertise in all these disciplines. We have thus decided to continue the work in this project with the team from the GlobGlacier project (Table 1). The associated Climate Research Group (CRG) is led by a specialist in glacier modelling and has experts for hydrologic and climate modelling, representatives from key science bodys (WGMS, GLIMS), and experts for glacier mapping . For further information about the project and the team, please visit our website www.esa-glaciers-cci.org/.

Table 1: The consortium and the climate research group

Name	Affiliation	Acronym	Role
The consortium			
Frank Paul / Tobias Bolch	Dept. of Geography, University of Zurich, Switzerland	GIUZ	Science Lead / Project Manager
Tazio Strozzi / Andreas Wiesmann	Gamma Remote Sensing AG, Gümligen, Switzerland	Gamma	EO Team / System Engineering
Thomas Nagler / Kilian Scharrer	Environmental Earth Observation, Innsbruck, Austria	Enveo	EO Team
Andreas Kääb / Christopher Nuth	Department of Geosciences, University of Oslo, Norway	GUIO	EO Team
Andrew Shepherd / Fransceca Ticconi	School of Earth and Environment, University of Leeds, United Kingdom	SEEL	EO Team
Tony Payne	School of Geographical Sciences, University of Bristol, United Kingdom	SGS	CRG Lead
The climate research group			
M. Zemp	Wold Glacier Monitoring Service, Zurich, Switzerland	WGMS	Key science body
B. Raup	National Snow and Ice Data Centre (NSIDC), Boulder (CO), USA	GLIMS	Key science body
S. Kotlarski	Institute for Atmosphere and Climate, ETH Zurich, Switzerland	IAC-ETH	Climate Modelling
L. Braun	Commission for Glaciology, Bavarian Academy of Sciences and Humanities, Munich, Germany	KfG	Hydrological modelling
L.M. Andreassen	Norwegian Water Resources and Energy Directorate, Oslo, Norway	NVE	Glacier mapping
P. Mool	International Centre for Mountain Development, Kathmandu, Nepal	ICIMOD	Glacier mapping

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Abbreviations

ALOS	ALOS Advanced Land Observing Satellite	InSAR	Interferometric SAR
ASAR	Advanced Synthetic Aperture Radar	IRS	Indian Remote Sensing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer	LISS	Linear Imaging and Self Scanner sensor
DEM	Digital Elevation Model	MSI	Multi Spectral Instrument
ERS	European Remote Sensing Satellite	OLI	Operational Land Imager
ETH	Federal Institute of Technology	PALSAR	Phased Array type L-band SAR
ETM+	Enhanced Thematic Mapper plus	SAR	Synthetic Aperture Radar
GLAS	Geoscience Laser Altimeter System	SPOT	System Pour l'Observation de la Terre
GDEM	Global DEM	SRTM	Shuttle Radar Topography Mission
GLIMS	Global Land Ice Measurements from Space	SWIR	Short Wave InfraRed
HRG	High Resolution Geometric	TM	Thematic Mapper
ICESat	Ice, Cloud, and land Elevation Satellite		