climate change initiative

→ GLACIERS NEWSLETTER

Special Issue: COP-21 | September 2015

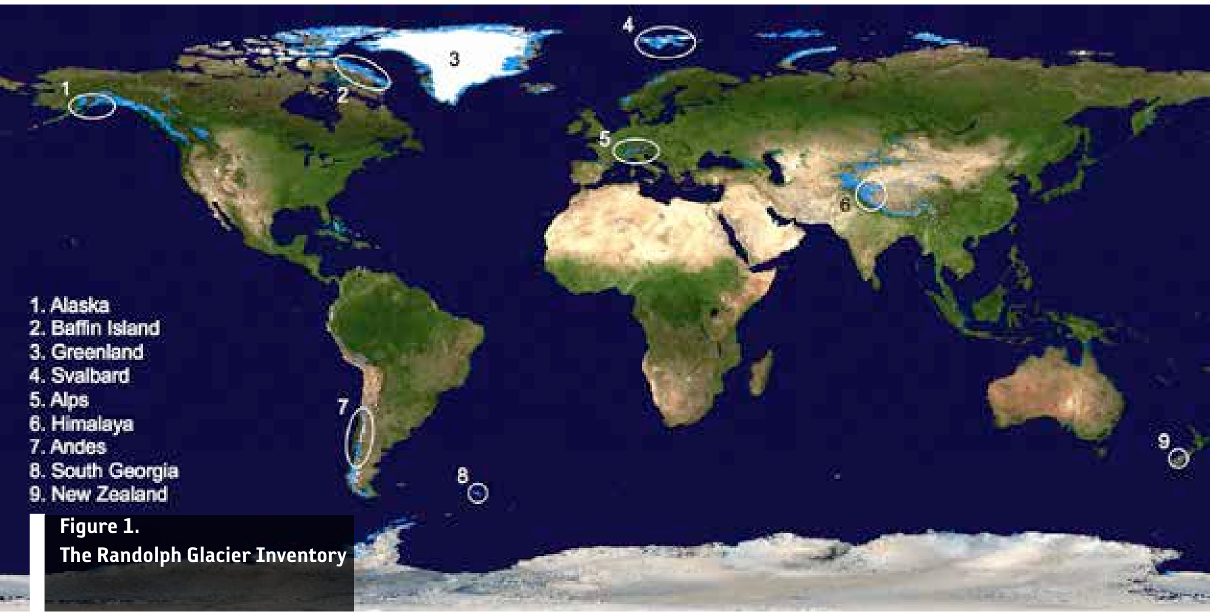

Figure 1.
The Randolph Glacier Inventory

In this issue:

The Randolph Glacier Inventory (RGI)

The RGI was used as a key input dataset for numerous applications of relevance for IPCC AR5.

The Glaciers_cci project contributed substantially to completing the RGI (Fig. 1) that was finalized just in time for applications by the glaciological community in support of the Fifth Assessment Report (AR5) of the IPCC (Vaughan et al. 2013). Glacier outlines from the RGI were assimilated into models developed by the hydrological and glaciological communities to answer key research questions of the changing cryosphere, as for example:

- What is the total area, number and volume of the glaciers on Earth?
- How have glaciers changed in the past or will change in the future?
- What was and will be their contribution to global sea level?

The first step to answer these questions was achieved by generating a glacier inventory that is both globally complete and available in a digital vector format. In a second step the outlines were combined with a digital elevation model (DEM) to derive drainage divides for a separation of glacier complexes into individual glaciers and the calculation of glacier-specific topographic parameters, such as minimum and maximum elevation or mean slope and aspect (Pfeffer et al. 2014). The RGI outlines and a DEM were also used to calculate the ice thickness distribution for all glaciers (Huss and Farinotti 2012).

In combination with re-analysis data and climate models the available datasets were integrated in glaciological models determining past, current and future glacier extents and their contribution to sea level (e.g. Marzeion et al. 2012). Such calculations were not possible before and the improved quality and completeness of the RGI can be seen as a quantum leap compared to the datasets available before. Accordingly, uncertainties in previous calculations that are based on an incomplete dataset could be largely reduced for IPCC AR5 (Vaughan et al. 2013).

The RGI is a multi-source and fused product that combined the already existing glacier outlines of the GLIMS database with several recently created datasets (e.g. by Glaciers_cci). With the latest release of the RGI (v5.0) a further substantial quality improvement for glaciers in High Mountain Asia could be achieved thanks to the release of the 2nd Chinese Glacier Inventory and outlines for the entire Karakoram produced by Glaciers_cci.

Further improvements of data quality and consistency (e.g. correct interpretation of debris cover and seasonal snow) in the RGI are on-going and Glaciers_cci will further contribute to both aspects in close cooperation with the IACS working group on the RGI, CRG members and the glaciological community. These efforts will strongly benefit from the higher spatial resolution and denser temporal coverage of Sentinel-2A/B.

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Glacier changes in Greenland, Northern Patagonia and the Karakoram

The identification of glaciers that are peripheral to the Greenland Ice Sheet is a challenging task. But once they are assigned, their changes can be observed in full detail.

Key products of Glaciers_cci are glacier outlines in a digital vector format (shape-file) and full glacier inventories as a higher-level derivative. While the outlines are generated with automated methods from optical satellite data for clean ice, they require manual correction of omission (e.g. debris-covered ice) and commission (e.g. icebergs) errors. Once the outlines are corrected, the resulting glacier complexes are separated along drainage divides into glacier entities.

This is rather challenging for the numerous ice caps on Greenland, as they have a highly variable shape and near circular and uniform structures should not be separated to keep their ice cap nature. We have thus developed a set of rules to decide if and how ice caps and other glacier complexes are separated along drainage divides (Rastner et al. 2012). As both glaciers and ice caps (GIC) could be connected to the ice sheet to a variable degree (either in their accumulation or ablation region), we have further assigned an ice sheet connectivity level (CL0: none, CL1: weak, CL2: strong) to each of them (Fig. 2, left). This allowed us for the first time to determine elevation and mass changes of the GIC peripheral to the ice sheet (with CL0 and CL1) separately from it (that includes CL2 GIC for consistency with previous assessments).

The resulting mean specific (per m²) mass changes for ten sectors and the individual elevation changes are shown in Fig. 2, right. Overall, we found that GIC contributed about 30 Gt per year or 12% of the Greenland total (about 250 Gt per year) to the mass loss over the 2003-2008 period (Bolch et al. 2013). A slightly higher value of 40 Gt per year was found by Gardner et al. (2013), who used a different density assumption for converting volume into mass changes. The highest specific mass losses are found in the SE sectors while the changes in the north sector of Green-land are rather small.

Apart from elevation changes, we also started with time-series analysis for assessment of area changes in selected key regions. A first study for glaciers in northern Patagonia mapped glacier extents in 1985, 2000 and 2011 and found a 293 km2 (or -25%) decrease in glacier area over the full time period (Paul and Mölg, 2014). In total, more than 370 glaciers disappeared and at the same time over 100 lakes newly formed and more than 60 grew in size (total area gain 11.6 km2). Different from all other regions in the world, the highest relative area loss (-37%) was found for the largest size class (glaciers >10 km2), indicating a strong down-wasting of large glacier tongues at low elevations (Fig. 3).

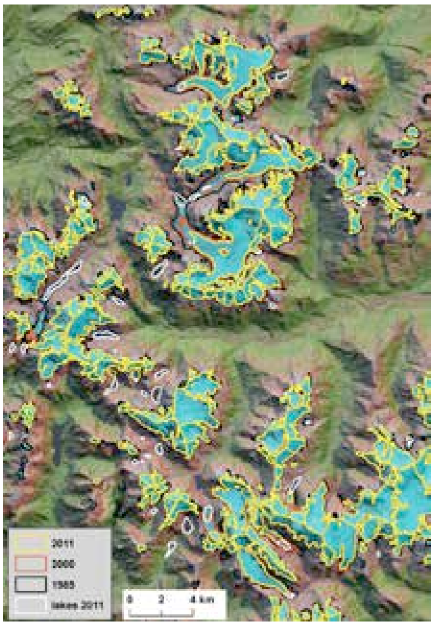

Figure 3: Glacier area changes for a part of northern Patagonia from 1985 to 2000 and 2011 (from Paul and Mölg 2015).

Seemingly opposite to this trend is the behaviour of glaciers in the Karakoram, which showed either only minor changes over a similar time period (1989-2014) or they strongly advanced or retreated in the cases where they are of surge-type. For this region we have created a new inventory (for the year 2000) that is already integrated in the latest release of the RGI (v5.0) and created animations for 4 sub-regions showing 22 years of glacier flow and terminus changes compressed into one second, i.e. about 700 million times faster (Paul 2015).

These animations show for the first time what glacier flow really looks like and reveal several further insights such as the interactions with tributaries, the short-lived nature of supra-glacial lakes, or the variable dynamics of surging glaciers. A more detailed investigation of the latter will be strongly facilitated by the higher spatial resolution and more frequent coverage of the Sentinel 2A/B satellites.

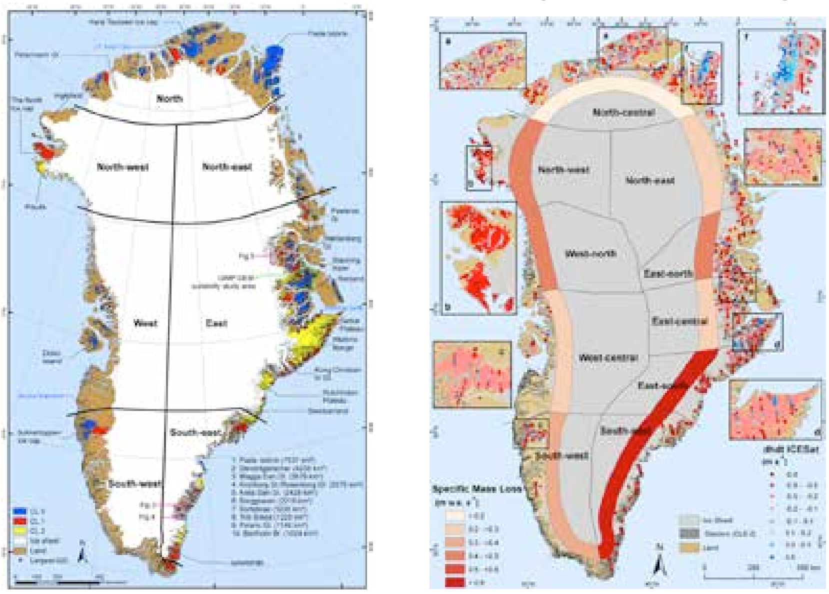

Figure 2, left: The glaciers & ice caps surrounding the Greenland ice sheet colour-coded according to their connectivity level (CL) (Rastner et al. 2012). Right: Mean specific mass changes for ten sectors & individual elevation changes for the ICESat tracks used to calculate the sector mean values (Bolch et al. 2013).

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High variability of glacier changes in the Karakoram, High Mountain Asia and on Svalbard

Elevation changes derived from laser altimetry and DEM differencing reveal a complex pattern of glacier changes in the region. The same applies to glaciers in Svalbard.

Elevation changes in Karakoram and High Asia

There are several ways to determine elevation changes of glaciers: (a) repeat altimetry (e.g. using the ICESat sensor) as described for Greenland in the section before, (b) a combination of altimetry and a DEM (with a well-defined acquisition day), and (c) the

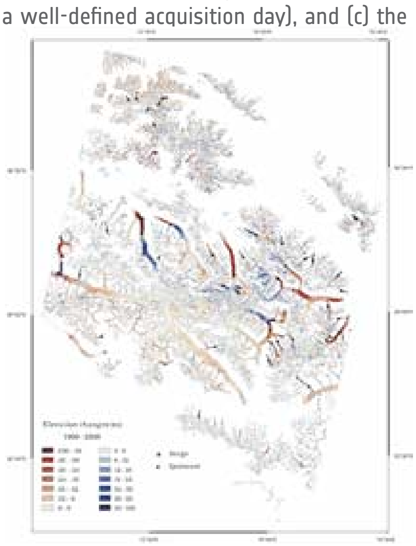

Figure 4: Elevation changes for a part of the Karakoram range obtained from differencing two DEMs (from Gardelle et al. 2013)

direct subtraction of two DEMs obtained at two different dates. While methods (a) and (b) require some inter- and extrapolation to obtain values over entire glaciers, method (c) directly provides volume changes. By applying method (c) to the central Karakoram using the SRTM DEM from 2000 and a DEM derived from the SPOT stereo sensor in 2008, the spatially inhomogeneous elevation changes related to the many surging glaciers becomes evident (Fig. 4). They generally show sharply separated positive (blue) and negative (red) changes that are very different from other glaciers, which are only getting thinner. Interestingly, many of the latter glaciers are heavily debris covered, indicating a limited influence of debris on overall volume changes (Gardelle et al. 2013).

The rather special elevation changes of glaciers in the Karakoram are confirmed by two studies (Kääb et al. 2012 and 2015) using method (b) for larger parts of High Mountain Asia (Fig. 5). While thickness loss is most pronounced over the eastern Nyainqentanglha mountain range and loss is dominating in nearly all other regions, the Karakoram and western Kunlun Shan stand out with zero to slightly positive elevation changes. This signal even persists when excluding surge-type glaciers, indicating a climatic reason for the rather stable conditions in this region (e.g. in-creased precipitation).

Flow velocities and glacier dynamics in the Karakoram and Svalbard

When flow velocities (e.g. mean annual values) are calculated for different points in time and the resulting grids are subtracted or values are shown as profiles in the same plot, changes in flow dynamics can be revealed that might indicate instable flow or surge-type glaciers. Such a multi-temporal comparison has been performed in the study by Heid and Kääb (2012) for glaciers in the Karakoram using repeat optical images for the 2000-2001 and 2008-2009 period. Several glaciers started to surge over this period resulting in a strong increase in flow velocities for specific glacier parts.

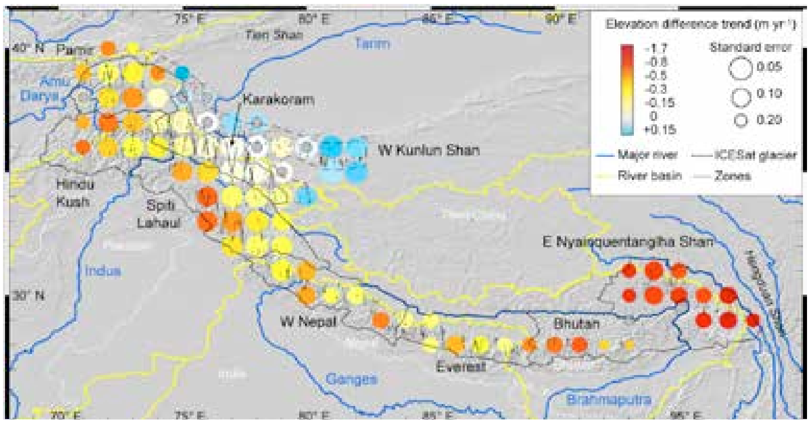

Figure 5: Elevation trends averaged over 2 by 2 degree grid cells as derived from ICESat in combination with the SRTM DEM for the southern part of High Mountain Asia. Grey circles inside a coloured circle marks trends that are statistically not significant (from Kääb et al. 2015).

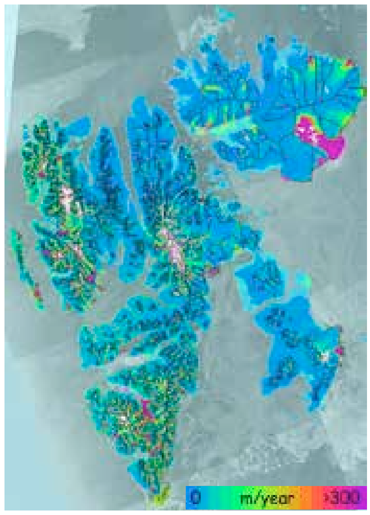

Figure 6: Glacier flow velocities for entire Svalbard derived from Sentinel 1a data of January - February 2015.

Glaciers with such unstable flow dynamics might also be detected from velocity fields alone. When comparing maps from different periods gradual or sudden increase in flow velocity can be detected. Several of such regions with locally high flow velocities (pink, >300 m/a) have been revealed for glaciers on Svalbard by analysis of recent Sentinel 1a scenes (Fig. 6). The most prominent of these regions are the two large glaciers on the north-east and south of the archipelago. Where the zone of highest velocity is restricted to the glacier front, glaciers are likely calving into the ocean rather than surging.

When combined, the area, velocity and elevation change products that can be derived from satellite sensors, provide a most complete picture of glacier dynamics that is readily suitable for in-depth scientific analysis and understanding of the governing processes.

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Publications

The Glaciers_cci team has produced a large number of publications (see webpage for a full list) together with the community and related to the generated products and techniques. We also list publications by other scientists that are based on the RGI.

Generated data-sets

Andreassen, L.M., Winsvold, S.H., Paul, F. and Hausberg, J.E. (2012): Inventory of Norwegian Glaciers. Norwegian Water Resources and Energy Directorate, Rapport 38-2012, 240 pp.

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N., and Stoffel, M. (2014): Ice volume estimates for the Himalaya–Karakoram region: evaluating different methods. The Cryosphere 8: 2313-2333.

Heid, T. and Kääb, A. (2012): Repeat optical satellite images reveal widespread and long term decrease in land-terminating glacier speeds. The Cryosphere, 6, 467-478.

Kääb A., Berthier, E., Nuth, C., Gardelle, J. and Arnaud, Y. (2012): Contrasting patterns of early 21st century glacier mass change in the Hindu Kush - Karakoram - Himalaya. Nature, 488, 495-498.

Le Bris, R. and Paul, F. (in press): Glacier-specific elevation changes in western Alaska. Annals of Glaciology, 56 (70).

Paul, F. (2015): Revealing glacier flow and surge dynamics from animated satellite image sequences: Examples from the Karakoram. The Cryosphere Discussions, 9, 1-27.

Paul, F. and N. Mölg (2014): Hasty retreat of glaciers in northern Patagonia from 1985 to 2011. Journal of Glaciology, 60 (224), 1033-1043.

Pfeffer, W.T., and 18 others and the Randolph Consortium (2014): The Randolph Glacier Inventory: a globally complete inventory of glaciers. Journal of Glaciology, 60 (221), 537-552.

Neckel, N., Kropacek, J., Bolch, T., Hochschild, V. (2014): Glacier elevation changes on the Tibetan Plateau between 2003 – 2009 derived from ICESat measurements. Environmental Research Letters, 9, 014009.

Nuth, C., Kohler, J., König, M., von Deschwanden, A., Hagen, J. O., Kääb, A., Moholdt, G., and Pettersson, R. (2013): Decadal changes from a multi-temporal glacier inventory of Svalbard, The Cryosphere, 7, 1603-1621.

Rastner, P., T. Bolch, N. Mölg, H. Machguth, R. Le Bris and F. Paul (2012): The first complete inventory of the local glaciers and ice caps on Greenland. The Cryosphere, 6, 1483-1495.

Joint studies with the CRG and community

Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D.P., Srivastava, D., Pratap, B. (2012): Heterogeneity in glacier response in the Shyok valley, northeast Karakoram. The Cryosphere, 7, 1384-1398.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, H., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M. (2012): The state and fate of Himalayan glaciers. Science, 336, 310-314.

Bolch, T., Sørensen, L. S., Mölg, N., Rastner, P., Machguth, H., and Paul, F. (2013): Mass loss of Greenland's glaciers and ice caps 2003-2008 revealed from ICESat data. Geophysical Research Letters, 40, 875-881.

Carturan, L., and 10 others (2013): Area and volume loss of the glaciers in the Ortles-Cevedale group (Eastern Italian Alps): controls and imbalance of the remaining glaciers. The Cryosphere, 7, 1339-1359.

Gardelle, J., E. Berthier, Y. Arnaud and A. Kääb (2013): Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011. The Cryosphere, 7, 1263-1286.

Gardner, A.S., and 15 others (2013): A consensus estimate of glacier contributions to sea level rise: 2003 to 2009. Science, 340 (6134), 852-857.

Kääb, A., Treichler D., Nuth C. and Berthier E. (2015): Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya. The Cryosphere, 9, 557- 564.

Kargel, J.S., Leonard, G.J., Bishop, M.P., Kääb, A., Raup, B.H. (Eds.) (2014): Global Land Ice Measurements from Space. Springer Praxis Books, 876 pp.

Paul, F., and 19 others (2013): On the accuracy of glacier outlines derived from remote sensing data. Annals of Glaciology, 54 (63), 171-182.

Paul, F. and 24 others (2015): The Glaciers Climate Change Initiative: Algorithms for creating glacier area, elevation change and velocity products. Remote Sensing of Environment, 162, 408-426.

Application of the RGI by others

Giesen, R.H. and Oerlemans, J. (2013): Climate-model induced differences in the 21st century global and regional glacier contributions to sea-level rise. Climate Dynamics.

Grinsted, A. (2013): An estimate of global glacier volume. The Cryosphere, 7, 141-151.

Huss, M., and D. Farinotti (2012): Distributed ice thickness and volume of 180,000 glaciers around the globe. Journal of Geophysical Research, 117, F04010.

Marzeion, B., A. H. Jarosch, and M. Hofer (2012): Past and future sea-level change from the surface mass balance of glaciers. The Cry-osphere, 6, 1295-1322.

Radic, V., A. Bliss, A. C. Beedlow, R. Hock, E. Miles, and J. G. Cogley (2013): Regional and global projections of the 21st century glacier mass changes in response to climate scenarios from GCMs. Climate Dynamics.

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