Climate Assessment Report (CAR)

glaciers cci

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Contact:
Frank Paul
Department of Geography
University of Zurich
frank.paul@geo.uzh.ch

Technical Officer:
Stephen Plummer
ESA ESRIN

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Author team:
Frank Paul (GIUZ), Andreas Kääb, Christopher Nuth (GUIO), Thomas Nagler, Helmut Rott, Kilian Scharrer (Enveo), Andrew Shepherd (SEEL), Tazio Strozzi (Gamma), Tony Payne (Bristol), and all contributors mentioned in Ch. 3.

Glaciers_cci Technical Officer at ESA:
Stephen Plummer

Table of Contents

1. Introduction

This is the Climate Assessment Report (CAR) of the Glaciers_cci project. According to the SoW, the CAR of Glaciers_cci describes:

- the feedback of users on the delivered ECV data products in respect of the behaviour globally and regionally of the time series of ECV data
- the science contributions (e.g. publications) to IPCC AR5 by the Glaciers_cci team and other authors having used Glaciers_cci data.

For ECVs where models are used:

- assessment of the contribution to the improvement of model performance with reference to the representation of observations based on current climate
- the approaches used to introduce the ECV products into the models
- any required model developments
- where changes in the model have been made the impact of such changes on the model outputs independent of the ECV products.
- comparison of the model with and without the ECV product
- the comprehensive error analysis derived through confrontation of the models and ECV products taking into account the inherent errors and uncertainty expressed in the URD, PSD and PVIR.

The glacier area product contributed mainly to the Randolph Glacier Inventory (RGI), that has in its second version (v2.0) been used extensively for a wide range of global-scale modelling applications (e.g. global number, area and volume of glaciers or their past and future mass balance and sea level contribution) in support of IPCC AR5. In essence, these applications have simply not been possible before or have been made using less detailed and/or roughly extrapolated input datasets. As previous estimates of the above quantities also refer to different regions (e.g. excluding glaciers on Greenland but including those on the Antarctic Peninsula), a direct comparison is not provided here.

In essence, the generation of the RGI allowed, for the first time, vector outlines of the individual glaciers combined with three-dimensional information from digital elevation models (DEMs) to be assimilated in global scale models (before planar information and coarse-resolution grid data were used). The availability of the RGI has also stimulated the development of a new class of models calculating climate change impacts on glaciers or their properties for each individual glacier globally.

The elevation change and velocity products that have been created and analyzed in cooperation with other institutions, had made their major impact through publications describing multi-annual trends of these variables in several key regions. Many of the related papers have been cited in IPCC AR5 as they were the first or most precise determinations to date. Important results of the related publications by the Glaciers_cci consortium are described in more detail in Section 2.2.

In the CAR of Glaciers_cci we provide in Ch. 2 an overview on the contribution of the glacier area product to the RGI and of the elevation change and velocity products (publications) to IPCC AR5. In Ch. 3 the feedback of the users on the delivered ECV data products are summarized. This includes a description of the status before the ECV datasets were available and how they have contributed to the improvement of model performance. Chapter 4 provides some more general conclusions and an outlook. In the last Ch. 5 we give an overview on the publications related to Glaciers_cci, either studies that are based on the provided datasets and are cited in IPCC AR5, or those authored or co-authored by consortium members. The latter relate to technical aspects as well as to the analysis of the created ECV time series.

2. Datasets contributed by Glaciers_cci

2.1 Contribution of glacier outlines to the RGI

The contributions of the Glaciers_cci project (and partly also GlobGlacier) to the RGI are described in the Technical Report to the RGI by Arendt et al. (2013) that can be downloaded here (http://glims.org/RGI/RGI_Tech_Report_V3.2.pdf). A general overview of the location of these regions is shown in Fig. 1. A table listing only the Glaciers_cci regions is given in Table 3.11 of the CRDP (Glaciers_cci, 2014) along with the overview map of the 19 main RGI regions. The RGI itself is a merged product that is largely based on the outlines from the GLIMS database, the digital chart of the world (DCW), and nominal outlines (size equivalent circles) from the World Glacier Inventory. In all cases the dataset with the best quality was chosen (for details see Pfeffer et al., 2014).

Due to temporal contraints imposed by the necessity to provide the globally complete dataset in time for modellers contributing to IPCC AR5, the RGI was created in a multi-stage process with continuous improvements through time. Glaciers_cci contributed to this process at all stages by providing datasets that were already created but not uploaded in the GLIMS glacier database (e.g. regions 2, 4 and 5 in Fig. 1), by generating datasets in regions that were simply lacking before (e.g. 3, 6 and 8), and by constantly improving the quality of datasets that were produced quickly for a first version of the RGI (e.g. regions 7 and 9). Due to this iterative improvement and update process, the work on the RGI is not yet finished and will continue through Phase 2 of the project.

Overall, the three ESA projects GlobGlacier, Glaciers_cci and Cryoland contributed about 1/3 of all glacier outlines in the RGI. This implies that the RGI would not have been finalized in time without the support of ESA and also that the global-scale assessments presented in the glaciers section of IPCC AR5 would not have been possible. Chapter 3 provides the related statements of the user community, IPCC lead authors and extracts from the IPCC report itself.

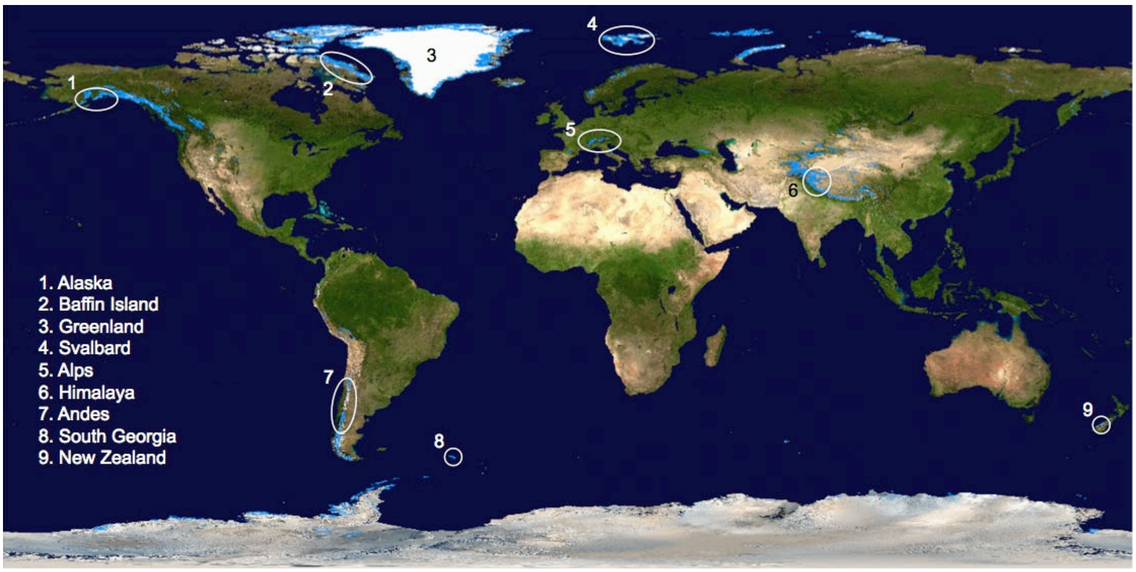

Fig. 1: Glacier outlines from the RGI (blue) with contributions from the Glaciers_cci project (circled), partly based on original work from GlobGlacier (regions 1, 2 and 5).

2.2 Elevation change and velocity products

Apart from the glacier area product that was provided to the RGI for use by others, the Glaciers_cci project produced also elevation change and velocity products jointly with the glaciological community and published the results of the time-series analysis in time for IPCC AR5. In the following we highlight some of the publications that contributed significantly to a better understanding of ongoing global glacier changes (see also Newsletter 3 for details).

Elevation changes derived from altimetry (ICESat data) by Sørensen et al. (2011) were digitally intersected with the glacier outlines for Greenland (Fig. 2) produced jointly by Glaciers_cci and the EU FP7 project ice2sea (Rastner et al., 2012), and further filtered to remove outliers to obtain for the first time the volume loss over the 2003 to 2008 period of the peripheral glaciers only (Bolch et al., 2013). This calculation allowed along with a modelled estimate of the firn an ice density a separation of the mass loss from the Greenland Ice Sheet and the peripheral glaciers (that contributed about 30 Gt or 12% to the total) so that the incomparable numbers from earlier assessments (maybe with double counting) could be avoided in IPCC AR5. The ICESat dataset used for the determination has also been made available on the Glaciers_cci website.

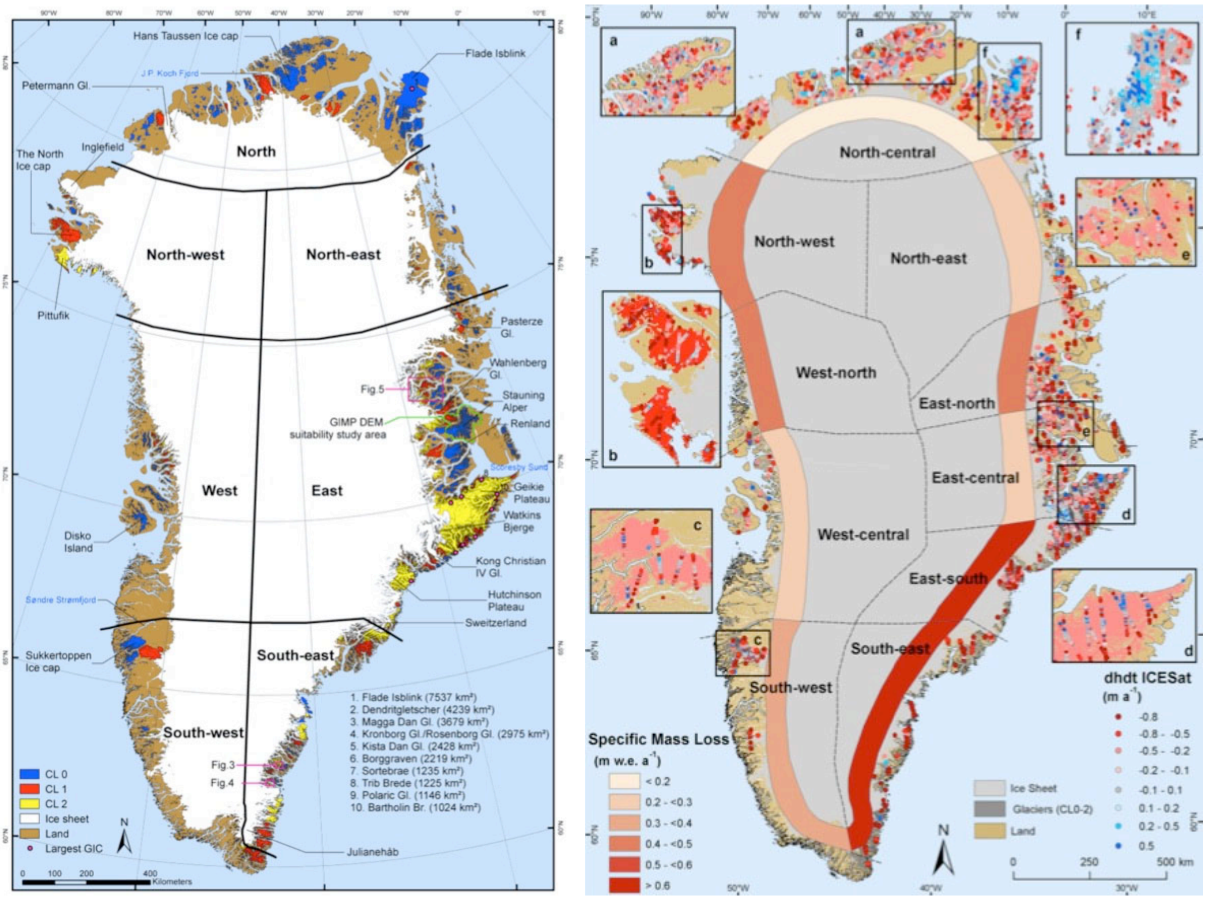

Fig. 2: The new glacier inventory for Greenland (left, Rastner et al. 2012) with the peripheral glaciers marked in blue (no connection to the ice sheet), red (weak connection), and yellow (strong connection). The former two classes were selected to calculate elevation changes from ICESat data (period 2003-2008) over all glacierized regions (right, Bolch et al. 2013).

The error about the future changes of glaciers in the Himalaya that was detected in the Working Group II report of IPCC AR4 pointed to a rather limited knowledge about the ongoing glacier changes in this region. A key contribution of Glaciers_cci by Kääb et al. (2012) helped clarifying the issue by revealing the spatial variability of glacier mass changes in the Himalaya - Karakoram mountain range based on elevation changes derived from ICESat altimetry data and the SRTM DEM (Fig. 3). For the first time these changes had been revealed on a large scale illustrating strong mass losses in most of the regions and zero changes to slight mass gains in the Karakoram range, confirming the so-called Karakoram anomaly. This study also helped to clarify the rather different results obtained in an earlier study by Jacob et al. (2012) using GRACE data. It could be concluded that the resolution of the gravimetric changes recorded by GRACE were simply too coarse to differentiate the signal in this region with a very heterogenous glacier cover. Later studies using DEM differencing (Gardelle et al., 2013) confirmed the spatial variability found by Kääb et al. (2012) with an even better spatial resolution, now resolving the rather peculiar changes of individual glaciers (e.g. the Karakoram has many surging glaciers where mass is quickly moved from the accumulation to the ablation region).

Another surprising finding of the Kääb et al. (2012) study was the very minor difference in elevation changes of debris free and debris-covered glaciers, indicating that the thermal and radiative protection of a thick debris cover has a very limited influence on the overall mass loss. This result stimulated several new investigations analysing the reasons for it. Overall, it is now clear that there is a high diversity of glacier response to climate change in this region that cannot be obtained by field observations of only a few glaciers and that process understanding (debris, surging) is still very limited in this region (Gardner et al., 2013).

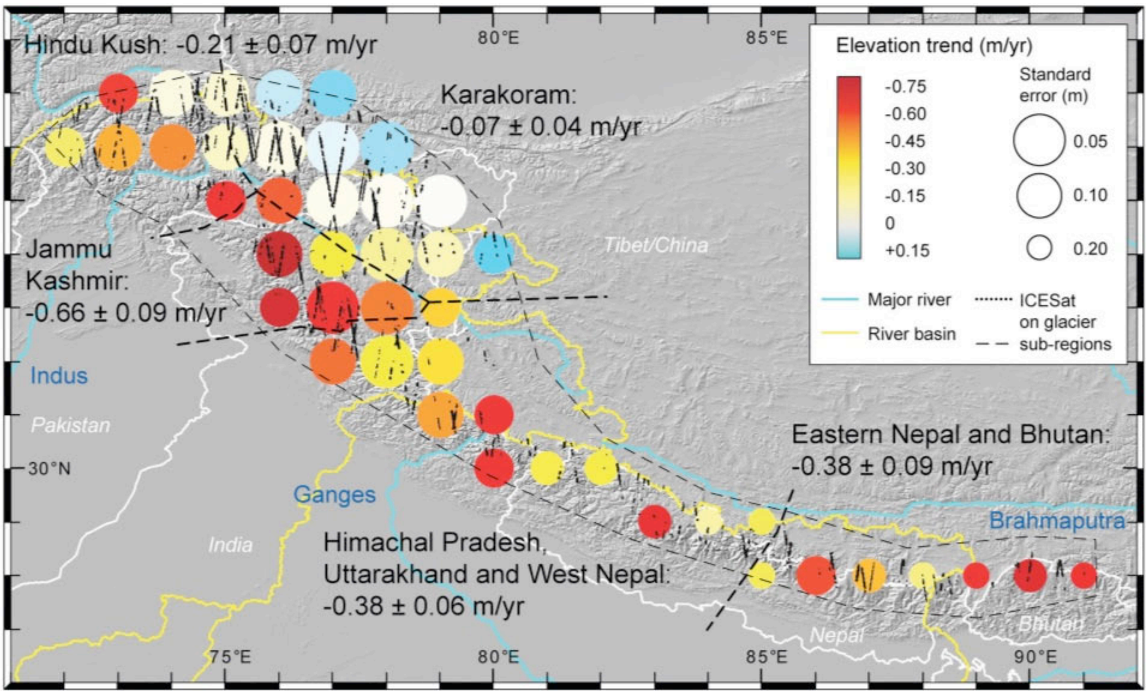

Fig. 3: Spatial variability of glacier mass changes in the Himalaya-Karakoram mountain range averaged for several sub-regions (after Kääb et al., 2012).

A final product that has been obtained in several test regions is the multi-annual time-series analysis of surface flow velocities. While flow velocities themselves provide information about glacier dynamics and mass fluxes (e.g. to obtain the contribution of calving to mass loss or to identify stagnant ice), the change in flow velocity through time on a multi-annual scale (i.e. not the well-known seasonal variations) can be related to impacts of climate change as flow speeds increase (decrease) after a period of increased mass gain (loss). The general decrease of flow speeds over the past decade could be shown for all but one region, the Karakoram (see Fig. 4). As mentioned above and shown in several earlier publications (e.g. Hewitt, 2007; Copland et al., 2011; Rankl et al., 2014), this region is full of dynamically unstable (i.e. surging) glaciers that tend to advance about a km per year with often abrupt increases in flow speed of a certain glacier part or tributary (dark blue tongues in Fig. 4). We are currently far away from understanding why the glaciers in this region show this peculiar behaviour. The in-depth analysis of further time series (area, elevation and velocity changes) in Phase 2 of Glaciers_cci should help to get a clearer picture of what is going on here.

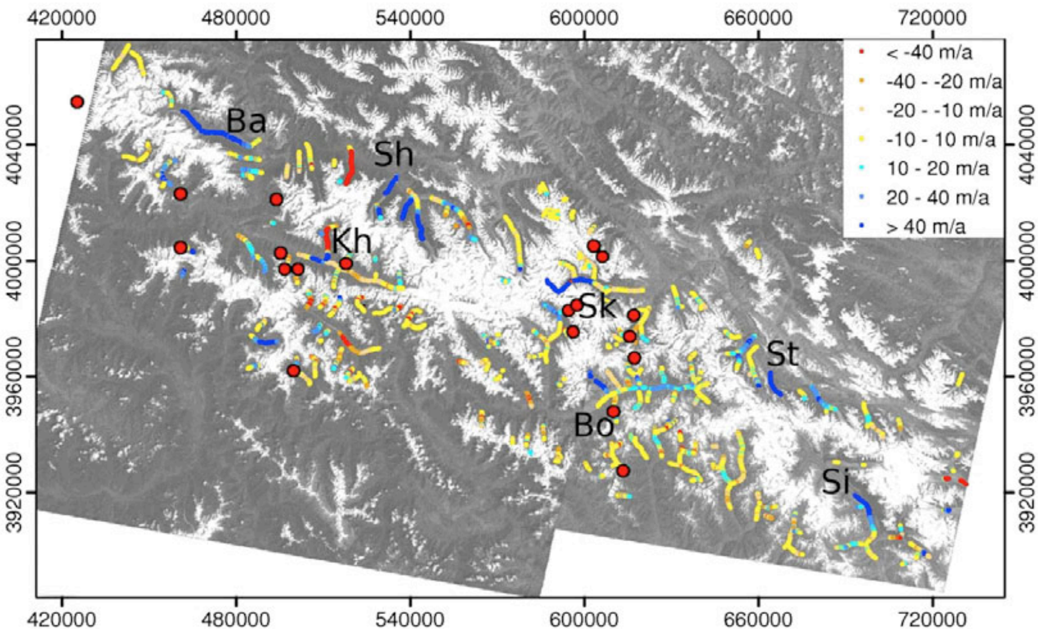

Fig. 4: Change in mean annual surface flow velocity over a ten-year period in the Karakoram mountain range revealing a large number of dynamically unstable (surging) glaciers (from Heid and Kääb, 2012).

3. Feedback on the RGI from the user community

3.1 Geir Moholdt[1]

1 Scripps Institution of Oceanography, La Jolla, CA, USA

Modern satellite techniques like GRACE gravimetry (2002-present) and ICESat altimetry (2003-2009) has for the first time made it possible to quantify glacier changes on a global scale in a consistent manner. I have been working on this using ICESat data in regions like Svalbard (Moholdt et al., 2010), the Canadian Arctic (Gardner et al., 2011) and the Russian Arctic (Moholdt et al., 2012). The main limitation of this work has not been the satellite data or processing, but rather the availability of complete inventory data for the major glacier regions of the world. This is a huge task and only possible through co-operation between investigators around the world. With the realization of the first version of the Randolph Glacier Inventory (RGI) in 2012, it was finally possible to do global glacier analyses of altimetry data. The first priority has been to quantify the recent sea level contribution from major glacier regions where prior studies have been geographically incomplete. The figure below show the results from an elevation change analysis over all glaciated mountain ranges in Central Asia (Gardner et al., 2013). This is the first region-wide study with altimetric data, and it would not have been possible without the collaborative effort of the RGI. Similar results have been obtained for the peripheral glaciers around the Greenland (Bolch et al., 2013) and Antarctic ice sheets, and they formed an important part of the global reconciliation of glacier mass balance and contribution to sea level rise (Gardner et al., 2013) and the IPCC 5th Assessment Report. But really, this is just a starting point for whole range of global applications, and I sincerely hope that RGI will keep developing with more detailed and up-to-date inventory data, made available for the entire scientific community.

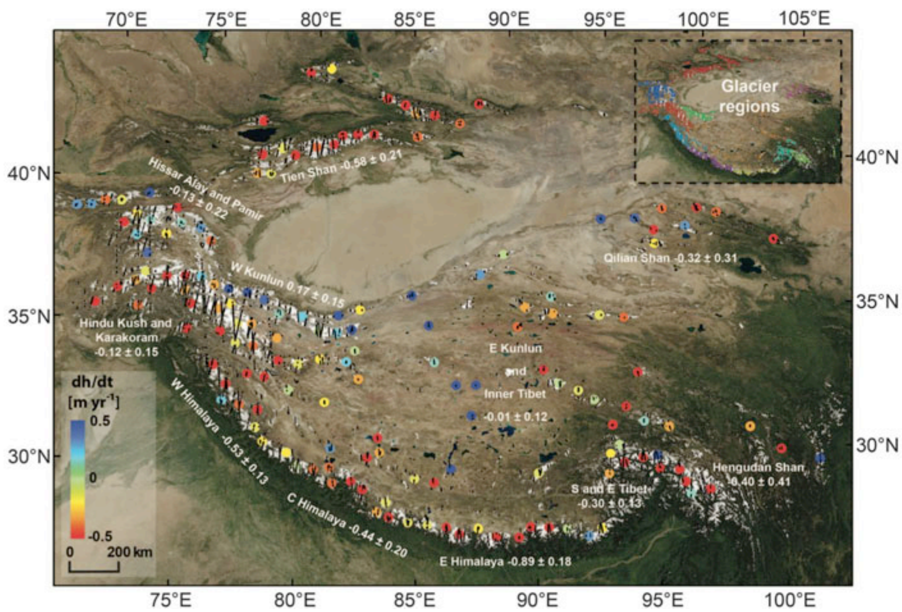

Fig. 5: Averaged elevation change rates (dh/dt) between October 2003 and October 2009 for high-mountain Asia. Each coloured dot represents an independent spatial average of a minimum of 50 dh/dt observations within a radius of 50 km. ICESat ground tracks over glaciers are shown with thin black lines. The inset image and text labels define a set of subregions for which we have estimated area-averaged elevation changes and mass budgets.

3.2 A. Cody Beedlow[1], Andy Bliss[1], and Regine Hock[1]

1 Geophysical Institute, University of Alaska, Fairbanks, USA

The Randolph Glacier Inventory (RGI) has dramatically reduced the uncertainties in our group's global and regional glacier surface mass balance modeling. The RGI allowed us to project the future volume changes for all glaciers in the world outside of the Antarctic and Greenland ice sheets using 14 different global circulation models running under the RCP 4.5 and 8.5 emission scenarios (Radić et al. 2013). Furthermore, the complete glacier inventory eliminated the need for upscaling of results to account for glaciers without outlines, thus eliminating the dominant source of uncertainty in previous modeling work (Radić and Hock, 2011). Accurate mass-balance modeling not only requires a complete global glacier inventory, but also additional data fields including glacier area, hypsometry, elevation range, and geographical coordinates; using the outlines from the RGI, we were able to derive these additional parameters. The RGI expands our modeling potential, allowing us to explore new methods and techniques that were not possible prior to the release of the RGI.

3.3 Ben Marzeion[1], Rianne Giesen[2], Aslak Grinsted[3], Valentina Radić[4]

1 Institute of Meteorology and Geophysics, University of Innsbruck, Austria
2 Institute for Marine and Atmospheric research Utrecht (IMAU), Utrecht University, The Netherlands
3 Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Denmark
4 Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada

The availability of a complete inventory of the glaciers on Earth has been the key to a number of recent advances in our understanding of how glacier changes have impacted the climate system in the past, and what future impacts we can expect. All contributors to the Randolph Glacier Inventory are to be commended for their efforts, not least for completing this tremendous task in time to allow publications to be prepared before the relevant deadlines of the 5th assessment report of the IPCC.

For global scale applications, in particular sea-level change assessments, lack of knowledge of the global distribution of glaciers was a significant, but very hard to quantify source of uncertainty. The consensus in projections of future glacier mass loss that is becoming apparent (Marzeion et al. 2012, Radic et al. 2013, Giesen and Oerlemans 2013) could probably not have been achieved without the RGI.

There is also emerging evidence that disagreement on the past contribution of glaciers to sea-level rise (Gregory et al., 2013) is related to different assumptions on the glacier distribution, which illustrates that the full benefits of having a complete glacier inventory are still being implemented.

Without doubt, the RGI constitutes a great leap ahead in our understanding of the glaciers in the climate system. Future improvements could include a narrowing down of the time span that is covered by the data in the RGI, i.e. bringing the inventory closer to representing a snapshot of the state of glaciers at a given time.

3.4 Yukiko Hirabayashi[1]

1 Institute of Engineering Innovation, University of Tokyo, Japan

Stock-type water resources such as glacier melt water and groundwater intake are missing link of global hydrological cycle because of the scarce information. Glacier melt water is particularly important to predict future water resources because of its contribution to low river flow in dry season and because of its recent acceleration of melting associated with the warming climate. The Randolph Glacier Inventory (RGI) provides spatial distribution of glaciers in global scale and enable hydrologist to include the effects of glacier melt on global water resources. For example, the estimation of glacier melt water at global 0.5-degree by Hirabayashi et al. (2013) relies on the location and area information of global glaciers derived from the RGI. The individual glacier information greatly improves the previous version of the model. Because of the inclusion of the complete global-scale inventory, the updated model could represent large-scale glacier mass losses in the future better than the old model. By calculating the mass changes in individual glaciers, HYOGA2 can simulate the timing of dissipation of small glaciers and ice caps and the associated shortage in water resources under future climate scenarios. This new calculation will be integrated to the current global hydrology and water resources model in near future.

In addition, glacier outlines of RGI are used for a research project to apply satellite remote sensing techniques to derive debris information on glaciers in large scale. The polygon shape file of individual glaciers by RGI is used to define glacier boundaries of satellite images where the glacier boundary is difficult to define from visible satellite images only because of the existence of debris (sand and rocks) on glaciers. The effect of thermal resistance change over the debris is then derived and applied to improve the calculation of glacier mass changes at such debris covered glaciers (Noguchi et al., 2013).

3.5 IPCC AR5 Lead authors

The impact of improved information on glaciers represented by the RGI is recognised in the following comments from IPCC AR5 lead authors:

Graham Cogley, Trent University, Canada
“This boost to the infrastructure means that people can now do research that they simply couldn’t do properly before”.

Tad Pfeffer, University of Colorado, USA
“I don't think anyone could have made meaningful progress on projecting glacier changes if the Randolph inventory had not been available”.

Georg Kaser, University of Innsbruck, Austria
“The data collection has considerably contributed to the knowledge gain of the IPCC report and its future benefits for glaciology has just started to emerge.”

3.6 Citations in IPCC AR5

The Cryosphere Chapter 4 in the Working Group I report of IPCC AR5 high-lighted the datasets and studies provided by Glaciers_cci consortium members at various places. Some key citations from the report are listed below.

All products
From the executive summary (P319):
"Since AR4, almost all glaciers worldwide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass (very high confidence). Measurements of glacier change have increased substantially in number since AR4. **Most of the new data sets, along with a globally complete glacier inventory, have been derived from satellite remote sensing**."

"Current glacier extents are out of balance with current climatic conditions, indicating that glaciers will continue to shrink in the future even without further temperature increase (high confidence)."

From the synthesis (P367/8):
"The number of in situ and satellite observations of cryospheric parameters has increased considerably since AR4 and **the use of the new data in trend analyses, and also in process studies, has enabled increased confidence in the quantification of most of the changes**."

"**Satellite data have provided the ability to observe large-scale changes in the cryosphere at relatively good temporal and spatial resolution throughout the globe**. Largely because of the availability of high resolution satellite data, **the first near-complete global glacial inventory has been generated, leading to a more precise determination of the past, current and future contribution of glaciers to sea level rise**. As more data accumulate, and as more capable sensors are launched, the data become more valuable for studies related to change assessment. The advent of new satellites and airborne missions **has provided powerful tools that have enabled breakthroughs in the capability to measure some parameters and enhance our ability to interpret results**. However, a longer record of measurements of the cryosphere will help increase confidence in the results, reduce uncertainties in the long-term trends, and bring more critical insights into the physical processes controlling the changes. **There is thus a need for the continuation of the satellite records**, and a requirement for longer and more reliable historical data from in situ measurements and proxies."

The importance of satellite observations was further stressed in FAQ 4.2:
"The Karakoram–Himalaya mountain range, for instance, has a large variety of glacier types and climatic conditions, and glacier characteristics are still only poorly known. ... However, **gaps in knowledge are expected to decrease substantially in coming years, thanks to increased use of satellite data (e.g., to compile glacier inventories or derive flow velocities)** ..."

Elevation change product
Fig. 4.11 (P341):
“Regional glacier mass budgets in units of kg m^{-2} yr^{-1} for the world’s 19 glacierized regions (Figure 4.8 and Table 4.2). Estimates are from modelling with climate data ... or airborne and/or satellite repeat topographic mapping (orange: Arendt et al., 2002; Rignot et al., 2003; Abdalati et al., 2004; Schiefer et al., 2007; Paul and Haeberli, 2008; Berthier et al., 2010; Moholdt et al., 2010, 2012; Nuth et al., 2010; Gardner et al., 2011, 2012; Willis et al., 2012; Björnsson et al., 2013; **Bolch et al., 2013**). Mass-budget estimates are included only for study domains that cover about 50% or more of the total regional glacier area. ...”

P342:
“The picture is also heterogeneous in High Mountain Asia (region 13 to 15) (e.g., Bolch et al., 2012; Yao et al., 2012), where glaciers in the Himalaya and the Hindu Kush have been losing mass (**Kääb et al., 2012**) while those in the Karakoram are close to balance (Gardelle et al., 2012).”

Glacier velocity product
Page 342:
“Several studies of recent glacier velocity change (**Heid and Kääb, 2012**; Azam et al., 2012) and of the worldwide present-day sizes of accumulation areas (Bahr et al., 2009) indicate that the world’s glaciers are out of balance with the present climate and thus committed to losing considerable mass in the future, even without further changes in climate.”

4. Conclusions and outlook

4.1 Conclusions

Despite the shortcomings in the regional quality of the RGI, this dataset had a tremendous impact not only on the improvements that could be made in IPCC AR5 over AR4, but also for the global modelling community (glaciological and hydrological) that has just started to explore the possibilities of global scale computations considering each individual glacier (i.e. assimilating vector data in their model). As a similar dataset has not been available before, there is at least a 100% improvement of the situation and a major goal from GCOS (2006), product T.2.1 'Maps of the areas covered by glaciers' could be achieved. This could also be seen as an important milestone in the practical implementation of GCOS goals via CEOS and the ESA Climate Change Initiative.

Judging the importance of the Glaciers_cci contribution to the RGI separately from the other contributions is challenging as the RGI was clearly a global endeavour (see Pfeffer et al., 2014). It might be possible that an RGI would have been accomplished also without Glaciers_cci (e.g. by using the Digital Chart of the World outlines for Greenland), but the quality of the datasets would have been much worse with an impact on all related calculations (e.g. glacier volume). From this perspective, the Glaciers_cci contribution can likely be seen as the 'go or no-go' part of the RGI and hence also of the glacier chapter in IPCC AR5. We have now for the first time an accurate estimate of the global number, area and volume of all glaciers worldwide, as well as their past and future contribution to sea-level rise.

In this regard, also the first analysis of the multi-annual time-series of the elevation change and velocity products from Glaciers_cci provided key contributions to IPCC AR5 as the related information (e.g. on elevation changes in the Himalaya) was simply not available before. For both products it was more the pattern of the change (i.e. the analysis of the results) rather than the data itself making the contribution. Doing this jointly with partners from other institutions and universities (e.g. the paper by Gardner et al., 2013) requires sometimes that data cannot be publicly shared from the beginning, however, in several cases we were able to provide them nevertheless.

4.2 Outlook

The products generated in Phase 1 of Glaciers_cci are a starting point. They have made important contributions to IPCC AR5 and were highly appreciated by the community. However, it is important now to go into data production and change assessment / trend analysis on a global scale for all products in Phase 2. A baseline dataset for all products will be a further improved version of the RGI. The still existing regional quality issues mentioned above (Section 4.1) have to be addressed as a first step before they can be used as a glacier mask for the other products. As a second step for the glacier area product it is required to increase the temporal consistency of the RGI to facilitate modelling and integrate the dataset in the GLIMS glacier database. For the other products further algorithm development is envisaged to integrate latest EO sensors (e.g. Sentinel-1, Cryosat-2, TanDEM-X) in the data processing chain. As a third step, data should be generated according to the predefined rules and their changes and trends through time should be determined globally. Where possible, all products should be generated in the same region to facilitate their joint analysis thus providing a better understanding of the reasons for the changes and their impacts on a regional scale.

5. References

5.1 Cited by the user community in Ch. 3

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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.

Gregory, J.M., White, N.J., Church, J.A., Bierkens, M.F.P., Box, J.E., van den Broeke, M.R., Cogley, J.G., Fettweis, X., Hanna, E., Huybrechts, P., Konikow, L.F., Leclercq, P.W., Marzeion, B., Oerlemans, J., Tamisiea, M.E., Wada, Y., Wake, L.M. and van de Wal, R.S.W. (2013): Twentieth-century global-mean sea-level rise: is the whole greater than the sum of the parts? J. Climate, 26, 4476-4499.

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Moholdt, G., C. Nuth, J. O. Hagen, and J. Kohler (2010): Recent elevation changes of Svalbard glaciers derived from ICESat laser altimetry. Remote Sens. Environ., 114(11), 2756-2767.

Noguchi, O., Zhang, Y., Watanabe, S and Hirabayashi, Y., 2013: Estimation of spatial distribution of debris cover on Caucasus glaciers using ASTER imagery. Journal of Japan Society of Civil Engineering, Ser. G (Env. Res.), 69 (5), I_45-I_51 (in Japanese with English abstract).

Radić, V. and Hock, R. (2011): Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. Nature Geosci., 4, 91-94.

Radić, V., Bliss, A., Beedlow, A., Hock, R., Miles, E. and Cogley, J.G. (2013): Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. Climate Dynamics, 1-22.

5.2 Cited in IPCC AR5

The following 14 publications have been cited in AR5. They have either used the RGI (see Ch. 2), describe it or involve Glaciers_cci consortium members (marked blue).

Arendt, A. et al. (2012): Randolph Glacier Inventory [v2.0]: A Dataset of Global Glacier Outlines, Boulder, Colorado, Digital Media.

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