Submitted: 20.11.2019. Revised: 21.12.2019. Accepted: 18.01.2020.

Proposal for an

IACS Working Group on the Randolph Glacier Inventory (RGI) and its role in future glacier monitoring and GLIMS

Co-chairs:
Fabien Maussion, University of Innsbruck, Innsbruck, Austria
Regine Hock, University of Alaska Fairbanks, Fairbanks, USA

Steering committee:
Frank Paul, University of Zurich, Zurich, Switzerland
Philipp Rastner, University of Zurich, Zurich, Switzerland
Bruce Raup, National Snow and Ice Data Center, Boulder, USA
Michael Zemp, World Glacier Monitoring Service, Zurich, Switzerland

+co-chairs

1. EXECUTIVE SUMMARY

The Randolph Glacier Inventory (RGI) is a globally complete collection of digital glacier outlines, excluding the polar ice sheets. It has become a pillar of glaciological research at global and regional scales. After its creation in 2012, the dataset's further development has been coordinated by an IACS Working Group (WG) from 2014 to 2019. During this period it has become clear that a continuation within an established international framework is still needed to further improve the quality of the dataset, add further attributes required by modelers and facilitate and guide the generation of future RGI releases from the GLIMS database. Thus we propose a 4-year follow-up IACS working group focused on the RGI to accomplish those tasks.

2. CONTEXT AND MOTIVATION

2.1 STATUS OF THE RGI

The RGI (RGI Consortium, 2017; Pfeffer et al., 2014) was created with limited resources to meet the needs of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) for e.g. estimates of recent and future glacier changes, mass balance, and sea-level contributions on a global scale. Priority was given to complete coverage, if necessary at reduced quality. Continuing this effort, a WG was created in 2014 for a period of 4 years that was later extended for one year, effectively ending in 2019.

The success of the RGI and therefore also of the WG is tremendous. The dataset has been used extensively since its first release in 2012, and it forms the basis of numerous global and regional studies, as shown e.g. by the number of citations of Pfeffer et al. (more than 500 in Google scholar at the time of writing). The latest version of the RGI (V6) was released on July 28, 2017: in these five years the dataset's quality increased considerably, and it was amended with several important attributes (see Appendix A) useful for numerical modelling and statistical studies. Since then, the RGI V6 has been extended with even more attributes thanks to recent developments of global methods in glaciology (debris cover mask by Scherler et al., 2018; ice thickness distribution by Farinotti et al., 2019). Its latest version is, besides from the Global Land Ice Measurements from Space (GLIMS) webpage, now also available from the Copernicus Climate Data Store (CDS).

In the following, we briefly review and discuss the three main goals of the previous WG:

"*A) To maintain and develop the Randolph Glacier Inventory as a resource for global and regional scale mass-balance assessments and projections"*

This objective has been followed effectively, as seen by the continuous improvements to the RGI. At the same time, it is undesirable for the dataset to be frozen at this stage as several major issues remain (see Appendix B for a discussion of the current known problems in RGI V6). Many improvements to the dataset are still possible, motivating our proposal to pursue the work of the WG for another 4-yr period.

"*B) To work towards merging the RGI into GLIMS"*

The GLIMS database is the reference database for multi-temporal glacier outlines. The merging of the RGI into GLIMS is now fully achieved; however, additional work is needed to generate releases of future RGI versions out of the GLIMS database (Section 2.2).

"*C) To develop a model for medium-term support of the RGI, for example for purposes of the next IPCC assessment"*

This objective was only partly reached: as of today, there is no single infrastructure or institution leading the development of future RGI versions. This is due to several factors, and we mention the most important here:

- The past development of the RGI relied on an ad-hoc, manual workflow. This had the advantage of allowing frequent and significant improvements to the database, since automation is costly and not trivial. Recent advances in open-source data processing chains would allow a partial automation in the near future: for example, GLIMS has worked towards automated outlines extraction, and open-source geospatial and glaciological tools (e.g. rasterIO, rgitools, OGGM, ASMAG, see references below) are targeting specifically the large scale processing of geospatial datasets.
- Limited community engagement: since the dataset development happened manually, few scientists actually had access to the original data and tools, giving the wrong impression that the RGI development is a blackbox and simply 'happens'. Using open workflows and discussion platforms after the example of the open-source model will engage more users and developers for the RGI and GLIMS.
- Lack of time and financial support: developing an automated and sustainable workflow was a goal too ambitious for such a short period of time (this was in fact acknowledged in the previous WG proposal). In the proposed WG continuation, we will continue to work towards this main objective, and aim for a semi-automated data generation workflow.

2.2 STATUS OF THE GLIMS DATABASE

Since 2000, glacier outlines have been archived at the U.S. National Snow and Ice Data Center (NSIDC) as part of the GLIMS initiative launched in 1995. Multi-temporal outlines are available, allowing glacier change detection. During the previous WG funding period, the RGI was fully incorporated into GLIMS, i.e. GLIMS is now globally complete and effectively more comprehensive than the RGI. However, there is currently no way to extract an “RGI-like” dataset out of GLIMS. GLIMS was not created for such a task, which means one must make their own choices about which outline to choose for each glacier. Furthermore, the RGI also has other unique features related to its format and attributes.

GLIMS recently made considerable progress towards this goal: the tools allowing for automated outline extraction per attribute (e.g. date) are now in the testing phase (Raup, 2019), and will provide the basis for future RGI versions. One of the goals of our continued WG will be to support GLIMS in the successful implementation of the “RGI-on-demand” feature, making of GLIMS the single entry point to access future RGI versions, thus meeting the needs identified above.

2.3 MOTIVATION

The RGI is undoubtedly a centerpiece of many glaciological studies. However, a series of informal consultation with RGI users showed a widespread agreement that the RGI V6 can (and needs) to be improved further to remain useful to the wider scientific community (see also Appendix B). Examples include data quality (wrong/outdated outlines, ice divides) but also attributes (hypsometries, morphology, etc.). If updates to the RGI will not be made available, there is a high risk of fragmentation and duplication of effort as the current RGI becomes progressively outdated: users from e.g. the remote-sensing, geodetic and modelling communities will need more recent outlines in the near future. Additionally, there is also a demand for consistent historic glacier outlines (e.g. from the mid-1980s or earlier) to facilitate validation of glacier evolution models or transient mass balance calculations. The community is willing to help to tackle these tasks, provided that a clear path forward is presented. The main role of the new WG will be to develop and provide this guidance.

3. CHALLENGES AND OPPORTUNITIES FOR THE RGI

After 7 years of existence and being well established as a commonly used dataset, the RGI faces similar challenges as other freely available products, such as the Fluctuations of Glaciers (FoG) or GLIMS databases. These challenges can be summarized around three central themes: (1) pressure from the research community that these products have to be improved and should always be available; (2) maintaining such datasets requires a considerable investment which is not rewarded by traditional academic measures (e.g. publications); (3) the lack of institutional support and associated funding.

The main purpose of the proposed WG continuation is to address these issues by means of global coordination, communication and outreach.

In particular, outreach towards funding agencies and data providers will be necessary. There are very strong arguments in favor of the RGI as an irreplaceable requirement for present and future expensive data acquisition programs. For example, modern satellite products such as ICESat-2 or the Sentinel series are much less valuable without the RGI and GLIMS, since glacier change detection studies require a previous glacier inventory in the first place. It is also important to note that, to date, there is no freely available, gap-free global digital elevation dataset, probably for lack of commercial applications. Tasks such as glacier mapping, outline quality check, basin delineation or attribute generation can only be tackled with dedicated worker-time: these necessary costs should be split between working groups and funding agencies, especially because they are such a central piece of our daily research.

We propose this WG as a means to ensure that these global challenges are addressed in a coordinated way and with wide international participation. It will complement and strengthen the work of other international groups and institutions (see also Section 7).

Another goal of this WG will be outreach and education: by bringing awareness on global challenges and bringing together the communities of users, data providers, modellers and remote sensing specialists, the WG will be at a unique position to raise awareness to present and future global challenges in glaciological research.

4. OBJECTIVES

The proposed continuation of the WG will have the following general objectives:

A. Make GLIMS the single entry point to access future RGI versions

a. Develop tools in GLIMS to allow outline selection by date and possibly other attributes (e.g. analyst) at the global level.
b. Automate the process of glacier attribute generation and data formatting, so that future RGI versions can be generated semi-automatically (manual intervention will be necessary but limited to outline selection and quality check).
c. Discuss and propose a way to implement a sustainable release cycle for the various RGI products, which will depend on long-term institutional funding.

B. Extend the RGI to more attributes and use cases

a. Provide different “snapshots” of the RGI by date: e.g. around 2000, 2015, 1985, or select glacier outlines by proximity to given date, i.e. to match that of a reference elevation model (SRTM, Arctic DEM, TanDEM-X, national DEMs).
b. Provide glacier outlines in various levels of data precision and geometrical complexity (i.e. including ice divides, or ‘merged’ entities).
c. Continue to extend the RGI with new and improved attributes: debris cover, ice thickness (i.e. incorporate the output of the now finished IACS WG “Glacier ice thickness estimation”), snow line altitudes (Rastner et al., 2019), snow cover fractions, glacier length, bathymetry of calving glaciers, surface flow velocities, etc. These developments will depend on the involvement of the community.

C. Engage a sustainable community around the open development of the RGI

a. Whenever possible, provide the tools used to realize objectives A and B in open online repositories, in order to encourage code reviews and improvements from the community.

b. Open a discussion platform for users and developers to come together and discuss issues around the RGI. This platform should be inclusive and ideally replace private e-mails for all discussions related to the RGI dataset itself: it can take the form of open meetings, open meeting notes, and a low-maintenance online forum (e.g. GitHub issues).
c. Regularly invite members of the broader glaciological community to contribute to GLIMS and the RGI with improvement to either data or tools. Provide educational material about the RGI and related products.
d. Communicate with universities, research centres, employers, funding agencies and scientific journals to raise awareness about the usefulness of the RGI and to encourage its sustainable development.

5. DELIVERABLES

D1 Publication of an updated version of the RGI based on a new, semi-automated GLIMS extraction and attribute generation workflow (Version 7).
D2 Publication of an online platform for open discussions related to the RGI - this can be based on existing tools such as GitHub or GitLab or may be hosted at GLIMS.
D3 Publication of open-source tools for automated glacier attribute generation (where possible). A prototype is already available (rgitools; Maussion and Landmann, 2019).
D4 Updated technical notes for the RGI to accompany each release of a new RGI version hosted at GLIMS.
D5 Glacier mapping guidelines to increase the consistency in interpretation.
D6 Educational material about the RGI in the form of online tutorials and workshops.
D7 Publication of new RGI products (RGI2015 and RGI1985) as unprecedented time-dependent global inventories to be extracted from the GLIMS database.
D8 A long-term plan for sustainable continuation of the RGI past the end of this WG in partnership with GLIMS.

6. WORKING GROUP ORGANISATION AND MEMBERSHIP

The governance of the previous RGI WG was re-organized after co-chair Graham Cogley's passing. A steering committee was formed that included the co-chairs and four representatives of the main data centers. This model has proven effective and more sustainable than leadership merely resting with the chair(s). We propose to keep the same organizational form so that the WG includes:

1. Two co-chairs (Maussion, Hock)
2. A steering committee (co-chairs + four additional members: Paul, Rastner, Raup, Zemp)
3. Additional members (to be determined following an open call for participation).

The ***co-chairs*** will oversee the overall work of the WG, serve as liaisons to IACS and are responsible for reporting back to IACS (including annual reports). The ***steering committee*** will discuss day-to-day business, and decide the specifics and next steps to meet the WG's goals. The steering committee will discuss WG business every 1-2 months via teleconference. ***Members*** will contribute to the deliverables and provide feedback, and are encouraged to contribute with ideas about how to meet the WG's goals and deliverables. Many previous RGI WG members have expressed their interest to contribute to this follow-up WG. Membership will be open and we will invite members through international calls (e.g., through CRYOLIST, GLIMSLIST) once the WG is approved. An annual meeting (typically at an international conference) will be held with all WG members and the steering committee to discuss plans and progress. The WG will strive for wide international participation and diversity regarding geographic spread, gender and career stage. The previous RGI WG had 24 members from 11 countries. We are confident that this new WG will also attract a broad and diverse membership following our open call for participation.

The steering committee will also establish specific groups ("task forces") to reach our goals:

Task 1: WG leadership (Maussion, Hock)
Management of milestones, organization of meetings, communication with IACS.

Task 2: GLIMS tools, Query tools (Raup, Paul, Zemp and relevant members)
Development of the necessary tools to extract updated frozen RGI versions from the GLIMS database.

Task 3: Glacier mapping (Paul, Rastner and relevant members)
Glacier mapping methods, extension of the GLIMS database, mapping of remaining nominal glaciers and problematic regions.

Task 4: Publication of the RGI versions (steering committee)
Production of the final RGI versions: compilation of outlines, quality checks, decisions on choice of outlines (time period; selection from multiple outlines, etc), beta testing.

Task 5: Attribute generation (Maussion, Rastner, Zemp and relevant members)
Software tools for automated topographic and morphologic attribute generation.

Task 6: Communication and outreach (all members)
Online tutorials, workshops, website, community engagement, scientific publications.

Task 7: International collaborations (all members)
Contact with international collaborators and institutions (see Section 7).

7. INTERNATIONAL COLLABORATIONS

The WG will work closely with the current (or recently finished) IACS WGs "Ice Thickness Estimation", "Debris Cover", and "Regional Assessments of Glacier Mass Change" to maximize synergies between the WGs. It will also work closely with the GLIMS core team, report regularly back to WGMS and the advisory board of GTN-G. The work of the WG will also be highlighted in projects providing funding for the activities of specific members of the WG, for example the Copernicus Climate Change Service (C3S) and the ESA Climate Change Initiative (CCI).

8. COLLABORATION WITH AND RELATION TO GLIMS

The RGI WG will closely work with GLIMS to accomplish the tasks above. Bruce Raup from GLIMS is included in the steering committee to maximize collaboration with GLIMS, avoid duplication and facilitate continued integration of the RGI into GLIMS. This ensures that GLIMS and this RGI WG will jointly work towards the ultimate goal of fully integrating the RGI functionality into the GLIMS framework. Some of the tasks will be done by GLIMS (task 2) or in close collaboration with GLIMS (task 4). This WG together with GLIMS will work towards a plan securing the future of RGI beyond this WG.

REFERENCES

Janke, J. R., Bellisario, A. C., & Ferrando, F. A. (2015). Classification of debris-covered glaciers and rock glaciers in the Andes of central Chile. Geomorphology, 241, 98–121. https://doi.org/10.1016/j.geomorph.2015.03.034

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., & Pandit, A. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nature Geoscience, 12(3), 168–173. https://doi.org/10.1038/s41561-019-0300-3

Maussion, F. & Landmann, J. (2019): OGGM/rgitools: v0.0.1, https://doi.org/10.5281/zenodo.3497112

Raup, B. (2019): Glacier maps for arbitrary years built on-demand from the GLIMS Glacier Database, IUGG Conference 2019 Abstracts, IUGG 2019, Montreal, Canada

Pfeffer, W.T., A.A. Arendt, A. Bliss, T. Bolch, J.G. Cogley, A.S. Gardner, J.O. Hagen, R. Hock, G. Kaser, C. Kienholz, E.S. Miles, G. Moholdt, N. Mölg, F. Paul, V. Radić, P. Rastner, B.H. Raup, J. Rich, M.J. Sharp and the Randolph Consortium (2014) The Randolph Glacier Inventory: a globally complete inventory of glaciers, Journal of Glaciology, 60(221), 537–552. https://doi.org/10.3189/2014JoG13J176

Rastner, P., Prinz, R., Notarnicola, C., Nicholson, L., Sailer, R., Schwaizer, G., & Paul, F. (2019). On the automated mapping of snow cover on glaciers and calculation of snow line altitudes from multi-temporal Landsat data. Remote Sensing, 11(12), 1–24. https://doi.org/10.3390/rs11121410

RGI Consortium (2017). Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, Colorado, USA. Digital Media. https://doi.org/10.7265/N5-RGI-60

Scherler, D., Wulf, H., & Gorelick, N. (2018). Global Assessment of Supraglacial Debris-Cover Extents. Geophysical Research Letters, 45(21), 11,798-11,805. https://doi.org/10.1029/2018GL080158

APPENDIX A: LIST OF RGI ATTRIBUTES

Global Glacier Inventory (shape file attributes)			
Item (short)	**Item (full)**	**Unit**	**Format**
GLIMS-ID	GLIMS-ID	n/a	txt
RGI-ID	RGI-ID	n/a	txt
O1 Region	First Order region in RGI	num	Integer
O2 Region	Second Order Region in RGI	num	Integer
Name	Glacier name (if available)	n/a	txt

Area	Glacier size	km^2	Float
BgnDate	Date of earliest dataset used	n/a	yyyymmdd
EndDate	Date of last dataset used	n/a	yyyymmdd
Zmin	Minimum elevation	m	Float
Zmax	Maximum elevation	m	Float
Zmed	Median elevation	m	Float
Slope	Mean surface slope	deg	Float
Aspect	Mean surface aspect	deg	Float
Lmax	Maximum length	m	Float
CenLon	Longitude of centre coordinate	deg	Float
CenLat	Latitude of centre coordinate	deg	Float
PI	Principle Investigator or Analyst	n/a	txt
Funding	Sponsoring Agency	n/a	txt
Reference	Details of related publication(s)	n/a	txt
Citation	How to cite the dataset	n/a	txt

Additional RGI datasets:
- tabular hypsometry (histograms) as separate CSV files
- ice thickness maps (Farinotti et al., 2019)
- debris cover maps (Scherler et al., 2018)

APPENDIX B: KNOWN ISSUES IN RGI V6

The list below provides examples of issues to be discussed and improved in the future.

(a) Poor quality outlines: In several regions the current RGI has quality issues, so that the outlines cannot be used for change assessment. Apart from missed glaciers under cloud cover and a wrong interpretation of glaciers under debris cover, the most serious problem leading to too large glacier extents is the inclusion of seasonal snow. Known regions are the entire Andes and several other maritime mountain ranges (Alaska, Rocky Mountains, New Zealand, Greenland, Svalbard, ...). The issue can only be solved when satellite scenes with better snow conditions become available. Also rough digitizing (high generalization) leads to poor quality outlines but here the effect is less systematic, i.e. glaciers can be digitized larger or smaller than they are. The cloud problem can be solved when using additional imagery but this is a tedious and time consuming work and might not always be successful.

(b) Missing regions and nominal outlines: For a few regions such as the Antarctic Peninsula or Dry Valleys glacier outlines are missing in the RGI. As related inventories exist in the GLIMS database, they can be integrated with the next release of the RGI. In other regions outlines have been digitized from coarse resolution source data or topographic maps of large scale (e.g. northern Greenland or Ellesmere Island, both are not covered by Landsat and Sentinel) with unknown dates. Without changing the orbits of these satellites there is little one can do to improve the situation (maybe with a hillshade of the Arctic DEM?). The situation is somewhat better for the remaining nominal glaciers (that are currently represented by simple circles of equivalent size in RGI V6): For these regions it should be possible to identify satellite scenes of sufficient quality and replace them in the next version of the RGI.

(c) Long aggregation period: In many regions of the world glacier outlines have been compiled from source data acquired over a very long time period, sometimes exceeding ten years. Although such differences can be handled by numerical models concerned with future glacier evolution (as long as a date is given), change assessment and other climate related applications are very difficult when there is such a large spread. This is particularly true for regions with rapid glacier change. It should thus be a further goal to temporarily constrain such outlines in a future version of the RGI. This is facilitated by the current LGAC project of USGS (insert link), that brings together satellite scenes from all receiving stations and processes them according to the same standard. The archive is thus steadily growing and a closer temporal time frame might be possible in the future. In a first step, it is not too important from which point in time the scenes are, but at a later step this should be considered.

(d) Debris-covered glaciers: ‘Correct’ mapping of debris-covered glaciers is not only the main bottleneck for a quick update of existing inventories, it is also nearly impossible to achieve as different definitions exist that lead to different extents without a clear consensus. At higher spatial resolution the problem is even enhanced as new features appear that can be interpreted differently. Whereas various techniques exist to identify the active ice of a glacier (e.g. using decorrelated SAR coherence images), a large amount of expertise, clear rules and consistent application is required. For the time being, it is assumed that illustrated guidelines as part of an updated GLIMS Analysis Tutorial would at least help increase the consistency in the interpretation. A further possibility is using specific flags in the attribute table to identify specifics of debris-cover mapping in one or the other way.

(e) Rock glaciers: They are creeping bodies of ice and rock that are often found below steep and ice-free slopes (providing the rocks) in regions of permafrost. Sometimes these features also originate from debris-covered glaciers or ice-cored moraines. As the ice content can be very high, they have locally and regionally an important function as a source of freshwater and run-off contributor. They are thus included in some glacier inventories. However, their response to climate change is very different from glaciers and it is thus important to properly flag them in the attribute table if mapped. The problem is that the transition from a debris-covered glacier to a rock glacier is continuous so that it is very difficult to digitize a 'correct' boundary between them (e.g. Janke et al., 2015). The best practical solutions to solve the identification issues have to be discussed with the wider community.

(f) Dividing glacier complexes into separate entities: Traditionally, glacier complexes are divided into entities using hydrologic divides. Today, these are derived by watershed analysis and manual editing. Neglecting here the problem that this is very difficult when the baseline data (satellite, aerial) have been orthorectified with a different DEM (resulting in a spatial mismatch), a key problem is that there is a demand for both separated and unseparated glacier complexes. The former are required for running more complex (dynamical) models (ice thickness, future glacier evolution), the latter can be more appropriate for scaling approaches or when an ice cap is surrounded by an ocean (and all parts are thus draining into the same hydrologic basin). A further complication is given when glacier topology changes through time, e.g. when a former tributary separates from a main glacier and becomes a dynamically independent unit (or vice versa). Whereas dynamic models would need separate entities, surface mass balance calculations should refer to the entire area.

This problem is enhanced in times of glacier downwasting, where large parts of the ablation area of a glacier is separated from the accumulation region by rock melt-out at a steep slope. According to the current GLIMS Analysis Tutorial, such separated lower parts can be considered as dead ice and have thus to be excluded from an inventory, but on the other hand they might still serve as an important fresh-water resource and exist for several decades (e.g. Pasterze tongue). This is also difficult to handle in a glacier inventory when it comes to topographic information (e.g. minimum, mean and maximum elevation of a glacier), as these are very different for the individual glacier parts when compared to the combined parts. How this should be handled is an open question as there is likely a demand for both options. In effect, one would need at least two inventories using the same outlines but once everything is divided and once not. This issue has to be discussed by the community (data users and producers).