Proposal for a

IACS Working Groupon glacier ice thickness estimation methods

submitted by

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1. MOTIVATION

Knowledge of the ice thickness distribution and the total volume of a glacier is one of the most important prerequisites when addressing a number of glaciological and hydrological problems: It is essential for determining the subglacial topography of a glacier, which is a necessary boundary condition for ice-flow modeling, and ultimately limits the amount of stored water, which is central for questions linked to water availability, hydrology, or sea level change. Despite this importance, knowledge about the ice thickness distribution of the various glaciers around the globe is remarkably limited. This fact is mainly due to the difficulties in measuring glacier ice thickness directly. To overcome the problem, a series of methods that aim at inferring the total volume and/or the ice thickness distribution of a glacier from the characteristics of its surface have been developed.

So-called scaling approaches explore empirical relations between the area and the volume of a glacier (e.g. Chen and Ohmura, 1990; Bahr et al., 1997), partially including other attributes such as glacier length or mean surface slope (e.g. Lüthi, 2009; Radić and Hock, 2011; Grinsted, 2013). Such approaches, however, only yield an estimate of the total volume of a glacier, leaving the question about its spatial distribution unanswered. Nye (1952) noted that for the case of an idealized glacier of infinite width, ice thickness can be calculated from the surface slope when knowing the basal shear stress and assuming perfect plastic behavior. Nye (1965) successively extended the considerations to valley glaciers of idealized shapes, whilst Li et al. (2012) extended the method in order to account for the effect of the side drag from the glacier margins. In these relations, that are all capable of yielding distributed information about the ice thickness, the required basal shear stress has often been assumed to be constant (e.g. Schilling and Hollin, 1981). Haeberli and Hoelzle (1995) therefore proposed to parameterize the basal shear stress as a function of the glacier elevation range, and this parameterization has now been used in a series of works (e.g. Paul and Linsbauer, 2012; Linsbauer et al., 2012, Frey et al, 2014; Baubin et al., submitted). Alternative methods based on rigorous inverse modeling of glacier ice flow have often focused on inferring additional properties at the glacier base besides ice thickness (e.g. Gudmundsson et al., 2001; Thorsteinsson et al. 2003; Raymond-Pralong, 2011). Early approaches that take into account mass conservation and ice flow dynamics go back to Budd and Allison (1971) or Rasmussen (1988), an idea further developed by Fastook et al. (1995) or Farinotti et al. (2009). The latter approach was successively extended by Huss and Farinotti (2012) in order to present the first estimate of the ice thickness distribution for every single glacier on Earth. The approach by Clarke et al. (2009), on the other hand, estimates subglacial topography exploring the concept of neural networks, and can be considered unique in its kind.

In the recent past, the number of additional methods that aim at estimating the glacier bedrock topography from characteristics of the surface has been increasing at a rapid pace: Methods that include additional data such as surface velocities and mass balance have been presented (e.g. McNabb et al., 2012; Farinotti et al., 2013, 2014; Huss and Farinotti, 2014) as well as approaches that make iterative use of more complex forward models of ice flow (e.g. Van Pelt et al., 2013; Michel et al., 2013, 2014). This has led to a rather confused situation, in which a wealth of approaches are potentially available, but no assessment that compares the relative strengths and weaknesses of the models exist. Additionally, the few estimates available for the total glacier volume at the global scale are based on a very limited number of methods only and their reliability is thus difficult to assess. A further inconvenience when investigating the accuracy of the individual models, is that measurements for individual glaciers are scattered across the literature, and are partly inaccessible.

The proposed working group (WG) aims to shed light on the above topics by (A) conducting a model intercomparison and validation experiment, (B) working towards a consensus assessment of the total ice volume of the glaciers and ice caps around the globe, and (C) continuing the efforts recently initiated by the World Glacier Monitoring Service (WGMS) in centralizing the ice thickness measurements available worldwide. By coordinating its activities with the recently established IACS WG on "the Randolph Glacier Inventory and infrastructure for glacier monitoring" (RGI-WG from now on), moreover, the WG aims at establishing a homogenized, freely accessible data base, which will serve as the reference for the characterization of the world's glaciers and ice caps, including information about ice thickness.

2. OBJECTIVES OF THE WG AND PLAN OF ACTION

The proposed WG will aim to:

A) PERFORM A MODEL INTERCOMPARISON AND VALIDATION EXPERIMENT

The aim of the experiment is to perform a thorough comparison of the various models available in the literature for estimating the total ice volume and ice thickness distribution of individual glaciers. The general plan of action for the experiment is as follows:

A.1) Define a suitable set of benchmark glaciers. Suitability will be defined through the representativeness of the individual glaciers and the availability of data for model input and validation. The set will comprehend 10 to 20 real-world glaciers located in various regions around the globe, as well as a set of 5 to 10 synthetic glaciers. A wide range of glacier types including valley glaciers, ice caps, land or marine terminating glaciers, as well as glaciers located in different climatic regimes will be considered. For each glacier, at least the following data should be available: i) a digital glacier outline, ii) a digital elevation model of the glacier surface, iii) a set of ice thickness measurements for validation of the model output. Additional data such as information about surface mass balance, the rate of ice thickness change, and/or surface flow velocities, will be sought as well. For the set of synthetic glaciers, full control over the above mentioned parameters will be possible, thus allowing in-depth model validation. The WG leaders will be in charge of retrieving and homogenizing the necessary data.

A.2) Perform a round-robin experiment for ice thickness estimation models. This step aims at generating independent estimates of the total ice volume and the ice thickness distribution of the glaciers defined in point A.1 with as many models as possible. To this end, an open call for participation will be posted (on "cryolist" and via the IACS website), whilst authors of published methods will explicitly be invited (see also section 3). In a first phase, the experiment will be performed blindly, i.e. the participants will be asked to generate their estimates for ice thickness and volume without having access to the ice-thickness measurements necessary for validation. In order to ensure as much fairness as possible (i.e. preventing the tempting possibility of using published data for partially calibrating the models already), the set of real-world glaciers will include a subset of glaciers for which ice-thickness measurements are not available yet, but are planned to be collected in the near future. In a second phase, which will start after having collected the results of the first phase, the ice thickness data will be released, and the participants be asked to include those data in their estimates. The results of this second phase will be used to construct a consensus "best guess" that will serve as reference. In both steps, the additional data mentioned in A.1 will be available to models that require or are able to include such information, and serve as additional means for validation.

A.3) Perform a model validation and intercomparison. In this step, the results generated in A.2 will be validated against the direct measurements (real-world glaciers) or the known bedrock topography (synthetic glaciers) and the results of the different models be compared to each other. The aim is to answer the following questions: i) How well do the individual models perform? ii) How well do the individual models perform for different types of glaciers? iii) What is the minimal input required for a given model? iv) How does the accuracy of the models evolve when additional data are used? v) How do the results of the individual models compare to each other? vi) Is it possible to detect a "best model", or give an advice for which model should be used in a particular situation? The task of answering these questions will be assigned to a core team including but not limited to the WG leaders.

A.4) Present the results to the community. The results of the various steps mentioned above will be made accessible and presented to the community in the form of one or more scientific publications, and in the frame of a specific session organized at one major international assembly (e.g. AGU, EGU, or IUGG). The preparation of the scientific publications will be taken over by the core team mentioned in A.3, whilst the organization of a conference session will be task of the WG leaders.

B) ASSOCIATE AN ESTIMATE OF THE ICE THICKNESS DISTRIBUTION TO EVERY GLACIER OF THE RGI

Building upon the work and the results of objective A, the WG aims at providing an estimate of the ice thickness distribution and the total volume to every glacier included in the Randolph Glacier Inventory (RGI), thus updating the results presented in Huss and Farinotti (2012). To this end, models that have the capability of dealing with a global data set and that have proven their reliability in the validation experiment will be asked to generate an according data set. For accomplishing this objective, close collaboration will be sought with the RGI-WG, which is in charge of updating, improving, and extending a data base of glacier outlines that is anticipated to become the reference at the global level. The aim will be to directly embed the newly derived ice thickness estimates in the RGI-WG data base, thus further strengthening its role as freely accessible, reference source of homogeneous quality. This step will include the elaboration of a suitable technical document in which the methods with which the ice thickness estimates are derived will be described in detail and with consistent notation. This task will be taken over by a second core team that will, again, include but not be limited to the WG leaders.

C) CONTINUE THE WGMS EFFORT IN THE COLLECTION OF ICE THICKNESS MEASUREMENTS

The WGMS is currently promoting an effort in order to collect and centralize published ice thickness measurements around the globe, and plans to release a first version of the data base in the course of the current year (pers. comm. Michael Zemp, Feb. 2014). The leaders of the here proposed WG have verbally agreed to help in the continuation of the initiated work. In this respect, the WG aims at i) helping with updates (at least one during the WG life span) and extensions of the data base that is currently in compilation, and ii) linking the available data to the RGI data base. Similarly as for objective B, the second point aims at promoting the build-up of one single data source for the global characterization of individual ice masses. The objective will be achieved by installing a third core team that will join the WGMS effort. The core team will again include at least one of the WG leaders, and will work closely with the RGI-WG.

3. ORGANIZATION OF THE WG

The WG will be led by Dr. Huilin Li and Dr. Daniel Farinotti (mentioned above as the "WG leaders"), and will work along a four year road map (see section 4).

As agreed with the secretary general of IACS, an "advisory board (AB)" consisting of Dr. G. Hilmar Gudmundsson and Dr. Matthias Huss will supervise the activities of the WG. The AB will serve as the primary source of advice in questions of both scientific and administrative nature. The AB will not have an active function in the steering of the WG in general, but act upon request of either the WG leaders or the IACS Executive. As member of the RGI-WG, Dr. M. Huss will additionally serve as the primary link between the two IACS WGs (i.e. the RGI-WG and the WG proposed here), although direct interaction with the RGI-WG leaders (Prof. Regine Hock and Prof. Graham Cogley) is foreseen.

The additional persons (group members) that will actively contribute in achieving the objectives exposed in section 2 will form the actual WG. In this respect, a series of persons have already been contacted during the elaboration of this proposal (see table below), and additional group members are anticipated to join once the WG is becoming active. The various “core teams” mentioned in section 2 will be formed from the pool of group members, the AB, and the WG leaders. The exact composition of the core teams will be decided at due time and will depend upon the commitment of the individual group members.

Table 1: List of persons involved in the WG, including their function “fct” (L=lead, AB=advisory board, GM=group member). GMs are listed in alphabetical order, and have all confirmed their engagement.

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4. DELIVERABLES, MILESTONES, AND TIME SCHEDULE

The WG plans its activities during standard four year term, which will allow it to align with the schedule proposed by the RGI-WG. The milestones and deliverable foreseen during this time period are listed hereafter and grouped according to the objectives stated in section 2. “NLT” stands for “not later than”; “FB” stands for “from the beginning of the formal existence of the WG”. Figure 1 visualizes the planned time schedule.

4.1 Deliverables, milestones and time schedule for achieving Objective A

Milestone 1 (NLT 6 months FB): The set of benchmark glaciers for the model intercomparison and validation experiment is defined, the necessary data retrieved and homogenized, the exact rules according to which the experiment will take place designed.

Deliverable 1(NLT 7 months FB): An open call for participation in the model intercomparison and validation experiment is posted.

Milestone 2 (NLT 8 months FB): The final composition of the WG members is defined through the commitment of individual persons in participating to the experiment.

Milestone 3 (NLT 12 months FB): The results of the first phase of the experiment are delivered to the WG leaders. The data for the second phase are released.

Milestone 4 (NLT 16 months FB): The results of the second phase are delivered to the WG leaders.

Deliverable 2 (NLT 20 months FB): A workshop is organized for presenting and discussing the various results obtained from the different models.

Milestone 5 (NLT 25 months FB): The analysis of the results is completed; a draft of the publication is circulated amongst the participants.

Deliverable 3 (NLT 30 months FB): A scientific publication relative to the intercomparison and validation experiment is submitted to an international, open-access journal.

4.2 Deliverables, milestones and time schedule for achieving Objective B

Milestone 6 (NLT 25 months FB): The models suitable for calculating an ice thickness distribution for every glacier around the globe are defined; the final composition of the core team working on objective B is defined.

Milestone 7 (NLT 36 months FB): The results necessary for achieving objective B are available.

Deliverable 4 (NLT 48 months FB): The results of Milestone 7 are embedded in the RGI data base.

4.3 Deliverables, milestones and time schedule for achieving Objective C

Milestone 8 (NLT 4 months FB): The core team that will join the efforts of the WGMS is defined, and the contact to the group active currently is established.

Milestone 9 (NLT 12 months FB): The strategy for including the data into the data base elaborated by the RGI-WG is defined.

Deliverable 5 (NLT 24 months FB): The first version of the data is embedded in the RGI data base.

Deliverable 6 (NLT 48 months FB): The RGI data base is updated with a second release.

Objective	Year 1	Year 2	Year 3	Year 4
	01 02 03 04 05 06 07 08 09 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24	25 26 27 28 29 30 31 32 33 34 35 36	37 38 39 40 41 42 43 44 45 46 47 48
A	①❶② ③	④ ❷	⑤ ❸	
B			⑥ ⑦	❹
C	⑧ ⑨	❺		❻

Figure 1: Time schedule of the proposed WG. White (black) circles refer to milestones (deliverables). The numbers in the second row (counted from top) are "months FB".

5. CONCLUDING REMARKS

The two WG leaders (and others) have submitted a session proposal for the upcoming IUGG assembly in Prague (June/July 2015) entitled "Advances in estimating and measuring glacier ice thicknesses". If accepted, the event could serve as natural occasion for reporting on the WG progress to the scientific audience.

The success of the WG as well as the speed with which progress will be achieved will strongly depend on the efforts of the individual group members. The time schedule exposed in section 4 is set up taking into account that all participants will work on a voluntary basis.

The time schedule for objectives B and C is tentative and will be adjusted according to the progress of the RGI-WG. In particular, the timing for the release of the individual data sets will be aligned to the planned RGI releases.

REFERENCES

Bahr, D., Meier, M., and Peckham, S. (1997). The physical basis of glacier volume-area scaling. Journal of Geophysical Research, 102(B9):20355–20362.

Baubin, C., Rowan, A., Fuchs, H.-J., Glasser, N., Quincey, D., and Cook, S. (submitted). Volume estimates for five Himalayan glaciers. Submitted to Geomorphology.

Budd, W. and Allison, I. (1975). An empirical scheme for estimating the dynamics of unmeasured glaciers. In Proceedings of the Moscow Symposium ”Snow and Ice”. International Association of Hydrological Sciences. Publication No. 104, 246–256.

Chen, J. and Ohmura, A. (1990). Estimation of alpine glacier water resources and their change since the 1870s. In Lang, H. and Musy, A., editors, Hydrology in Mountainous Regions, pages 127–135. IAHS Publ. No. 193. Proceedings of two Lausanne symposia.

Clarke, G., Berthier, E., Schoof, C., and Jarosch, A. (2009). Neural networks applied to estimating subglacial topography and glacier volume. Journal of Climate, 22:2146–2160.

Farinotti, D., Corr, H., and Gudmundsson, G. (2013). The ice thickness distribution of Flask Glacier, Antarctic Peninsula, determined by combining radio-echo soundings, surface velocity data, and flow modelling. Annals of Glaciology, 54(63):18–24. doi: 10.3189/2012AoG63A603.

Farinotti, D., Huss, M., Bauder, A., Funk, M., and Truffer, M. (2009). A method to estimate ice volume and ice thickness distribution of alpine glaciers. Journal of Glaciology, 55(191):422–430. doi: 10.3189/002214309788816759.

Farinotti, D., King, E., Albrecht, A., Huss, M., and Gudmundsson, G. (2014). The bedrock topography of Starbuck Glacier, Antarctic Peninsula, as measured by radio-echo soundings. Annals of Glaciology, 55(67):22-28. doi: 10.3189/2014AoG67A025.

Fastook, J., Brecher, H., and Hughes, T. (1995). Derived bedrock elevations, strain rates and stresses from measured surface elevations and velocities: Jakobshavns Isbrae, Greenland. Journal of Glaciology, 41(137):161–173.

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N., and Stoffel, M. (2013). Ice volume estimates for the Himalaya Karakoram region: evaluating different methods. The Cryosphere Discussions, 7(5):4813–4854. doi: 10.5194/tcd-7-4813-2013.

Grinsted, A. (2013). An estimate of global glacier volume. The Cryosphere,7:141–151. doi: 10.5194/tc-7-141-2013.

Gudmundsson, G. H., Thorsteinsson, T., and Raymond, C. F. (2001). Inferring bed topography and stickiness from surface data on ice streams. Eos Trans. AGU, 82(47). Fall Meet. Suppl., Abstract IP21A-0687.

Haeberli, W. and Hoelzle, M. (1995). Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Annals of Glaciology,21:206–212.

Huss, M. and Farinotti, D. (2014). A high-resolution bedrock map for the Antarctic Peninsula. The Cryosphere Discussions, 8(1):1191–1225. doi: 10.5194/tcd-8-1191-2014.

Linsbauer, A., Paul, F., and Haeberli, W. (2012). Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. Journal of Geophysical Research, 117:F03007. doi: 10.1029/2011JF002313.

Luethi, M. (2009). Transient response of idealized glaciers to climate variations. Journal of Glaciology, 55(193):918–930.

McNabb, R., Hock, R., O’Neel, S., Rasmussen, L., Ahn, Y., Braun, M., Conway, H., Herreid, S., Joughin, I., Pfeffer, W., Smith, B., and Truffer., M. (2012). Using surface velocities to calculate ice thickness and bed topography: A case study at Columbia Glacier, Alaska. Journal of Glaciology, 58(212):1151–1164.

Michel, L., Picasso, M., Farinotti, D., Funk, M., and Blatter, H. (2013). Estimating the ice thickness of mountain glaciers with an inverse approach using surface topography and mass-balance. Inverse Problems, 29:035002.doi: 10.1088/0266-5611/29/3/035002.

Michel, L., Picasso, M., Farinotti, D., Funk, M., and Blatter, H. (2014). Estimating the ice thickness of shallow glaciers from surface topography and mass-balance data with a shape optimization algorithm. Computers& Geosciences, 66:182–199. doi: 10.1016/j.cageo.2014.01.012.

Nye, J. (1952). The mechanics of glacier flow. Journal of Glaciology,1(12):82–93.

Nye, J. F. (1965). The flow of a glacier in a channel of rectangular, elliptic or parabolic cross-section. Journal of Glaciology, 5(41):661–690.

Paul, F. and Linsbauer, A. (2011). Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM. International Journal of Geographic Information Sciences, 26(7):1173–1190.

Radić, V. and Hock, R. (2011). Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. Nature Geoscience,4:91–94. doi: 10.1038/ngeo1052.

Rasmussen, L. (1988). Bed topography and mass-balance distribution of Columbia Glacier, Alaska, U.S.A., Determined from sequential aerial photography. Journal of Glaciology, 34(117):208–216.

Raymond-Pralong, M. and Gudmundsson, G. (2011). Bayesian estimation of basal conditions on Rutford Ice Stream, West Antarctica, from surface data. Journal of Glaciology, 57(202):315–324.doi:10.3189/002214311796406004.

Thorsteinsson, T., Raymond, C. F., Gudmundsson, G. H., Bindschadler, R. A., Vornberger, P., and Joughin, I. (2003). Bed topography and lubrication inferred from surface measurements on fast-flowing ice streams. Journal of Glaciology, 49(167).

van Pelt, W., Oerlemans, J., Reijmer, C., Pettersson, R., Pohjola, V., Isaksson, E., and Divine, D. (2013). An iterative inverse method to estimate basal topography and initialize ice flow models. The Cryosphere, 7:987–1006. doi: 10.5194/tc-7-987-2013.