Module 1-AL (January 19-20, 2015)
Glacier volumes – assessment methods

Learning objectives

You are aware of the challenges of glacier mapping and creating glacier outlines/inventories.

You know how glacier ice thickness can be measured and about the bias of these measurements.

You know the difference between scalar and distributed glacier volume assessment methods and their problems and uncertainties. You can apply scalar approaches to glacier inventory data and know how you can use these results.

Terms and Concepts

WGI, GLIMS, RGI, manual and band ratio technique for glacier mapping, Drilling a bore hole, Seismic measurements, Geoelectric techniques, Radio-echo sounding (Radar), Scalar approaches, 3-dimensional ice thickness distributions, Approaches to model glacier volumes: (i) volume-area scaling, (ii) slope-dependent empirical relations, (iii) analogy: past as present, (iv) stress-dependent empirical relations, (v) balanced ice flux.

References and Further Reading

Literature

Paul (2010): about glacier mapping with remote sensing data

Clarke (1987): a history about measuring glacier ice thickness

Bolch et al. (2012): a review on the state and fate of himalayan glaciers

Frey et al. (2014): Ice volume estimates for the Himalaya: evaluating different methods

Chen and Ohmura (1990) and Bahr et al. (1997): the basis of Volume-Area scaling

Haeberli and Hoelzle (1995): parameterization scheme for calculations with inventory data

Clarke et al. (2009): subglacial topography derived with an neural network

Linsbauer et al. (2012): ice thickness distribution based on a stress dependent empirical relation

Farinotti et al. (2009): ice thickness distribution according to a balanced ice flux

Weblinks

World Glacier Monitoring Service (WGMS): www.wgms.ch

Global Land Ice Measurements from Space (GLIMS): www.glims.org

Randolph Glacier Inventory (RGI): www.glims.org/RGI

Additional Information

Glacier Inventories

In the context of the Hydrological Decade (1965-1974) the World Glacier Inventory (WGI) was established to assess the amount, distribution and variation of all snow and ice masses to better understand the role of the cryosphere in the global water balance. The World Glacier Monitoring Service (WGMS) maintains and collects information on glacier changes. More specifically, the tasks of the WGMS are to collect standardized observations on changes in mass, volume, area and length of glaciers with time (glacier fluctuations), as well as statistical information on the distribution of perennial surface ice in space (glacier inventories). At the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, the Global Land Ice Measurements from Space (GLIMS) initiative maintains a database of glacier inventories where the mapped glacier outlines are stored as polygons in a digital vector format, while the WGI data is available in a tabular format with up to 40 parameters per glacier, including geographic location, area, glacier type, topographic parameters, morphological classification, date, source material, and accuracy estimations.

In 2009, 54% of the global glacier area were covered by the WGI and GLIMS databases (WGI 46%, GLIMS 34%, overlap 26%). In the tabulated WGI data, a large amount of glacier information can be stored in an efficient manner and can be used for various applications that only require scalar information (e.g. the parameterization scheme from Haeberli and Hoelzle 1995). However, the WGI data are a 'snapshot' of the late 20th century, with partially unknown accuracy. Glacier outlines in a digital vector format (as stored in the GLIMS database) are a key dataset for hydrologic modeling, change assessment, and distributed mass balance modeling.

The Randolph Glacier Inventory (RGI 3.2) is a global inventory of glacier outlines. It is supplemental to the GLIMS initiative. Production of the RGI was motivated by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) and is being released initially with little documentation in view of the IPCC's tight deadlines during 2012. As resources allow, all these data will be incorporated into the GLIMS Glacier Database.

Glacier mapping

The surface of a glacier is, apart from debris and water, mostly composed of ice and snow. As glacier ice originated from snow through metamorphosis, the spectral properties of glacier ice are very similar to those of snow with large grain sizes. While snow has a high reflectance in the visible spectrum, its reflectance decreases in the near infrared, and is very low in the shortwave infrared (SWIR), in particular for large grain sizes. This peculiar reflectance curve allows snow, firn and glacier ice to be separated from other terrain with a threshold applied to a ratio image (e.g. with bands TM3/TM5) or the normalized difference snow index (NDSI), i.e. (TM2-TM5)/(TM2+TM5).

The basic rule for threshold selection is to minimize workload for manual corrections. Compared to full manual delineation, the automated mapping approach has some advantages: (a) the entire sample of glaciers is included, independent of their size, (b) the results are reproducible, and (c) the outlines are not generalized and the quality is comparable for all parts of a scene.

The band ratio technique for glacier mapping is simple, robust and more accurate than other methods. It is thus, along with the NDSI, widely applied for glacier mapping. Clean ice and snow under optically thin clouds or located in cast shadow are generally accurately mapped. Further, dirty but sunlit glacier ice is often correctly classified. Glacier ice under debris cover cannot be mapped from optical sensors alone and several semi-automated methods have been developed. When the contrast is reduced due to high solar elevation, even manual delineation of debris covered glaciers is difficult. From the available cloud-free images, only the scenes with the smallest amount of seasonal snow should be selected for glacier mapping, otherwise determination of glacier outlines is very time consuming or even impossible.

Before glacier inventory data can be calculated for each glacier from digital intersection with a DEM, they need to be separated into individual entities. This can be rather difficult, even when DEM-derived flow-direction grids or drainage basins from watershed analysis are available.

Glacier thickness - measuring and modeling

The knowledge of ice thickness distribution and volume of glaciers is fundamental for a variety of glaciological application, for instance for estimates of their contribution to sea-level rise, a more realistic modeling of glacier retreat, modeling future run-off from glacierized catchments, or to assess future hazard potential. While quantifying the ice thickness and especially its distribution all over the glacier is challenging, the glacier surface can be investigated directly (e.g., by photogrammetry). Ice thickness is only indirectly available by application of geophysical methods or by the drilling of bore holes. Recently, different estimation and modeling approaches have been developed to determine ice thickness and its distribution from glacier outlines and digital elevation models.

Measuring ice thickness

Clarke (1987) summarizes the evolution of investigating ice thickness, from the first glaciologists (L. Agassiz in 1948), who drilled through the glacier, to the various geophysical measurement approaches like seismic, gravimetric and electromagnetic methods as used until the middle of the 1980s. Nowadays the most often used technology to derive ice thickness measurements of glaciers is radio-echo sounding with ground penetrating radar (GPR).

Drilling a bore hole reveals an exact ice thickness at a distinct location (errors can occur due to a change in the angle of the bore hole). However, drilling is "a brutish approach to measuring ice thickness and as a mapping technique it is completely unsatisfactory" (Clarke 1987). In many cases the focus of hot-water or ice core drilling projects was not the measurement of the ice thickness directly, but analyses on temperatures, stratigraphy, isotopes, radioactivity contents and composition of gases.

Seismic measurements were the earliest used geophysical method to determine glacier ice thickness. It was for decades the preferred method to derive measurements about ice thickness. Despite the slow and troublesome business with seismics, an advantage of the method in contrast to radar sounding is that it can yield more complete information about the glacier substrate and the water content distribution. Therefore, the seismic method is still in use above all in investigating permafrost but partly also for glaciers.

Geoelectric techniques used to derive the ice thickness came into focus in the 1960s. On Grubengletscher in the Swiss Alps electrodes were placed in ice bore holes at the ice/bed interface to compare ice thickness with measurements from radio echo-sounding and to exploit the lithological characteristics of the bed. Although Clarke (1987) predicted a bright future, this technique was never employed extensively and became obsolete.

Radio-echo sounding (Radar) on glaciers was first used in the 1960s. The development of impulse radar systems, its application on temperate glaciers, and the subsequently airborne version were responsible for causing radar technology to become the routine method for measuring ice thickness since the 1980s. Ground Penetrating Radar (GPR) is now state of the art and extensive measurement campaigns were performed on glaciers all over the world resulting in more or less dense distribution of profile measurements over the glaciers. Compared with seismic techniques, radar profiling is easier and faster and allows researchers to carry out a larger amount of measurements with the same resources. In 2014 the WGMS internationally collected, standardized dataset on glacier thickness from in-situ and remotely sensed observations, based on literature review and airborne data from NASA's Operation IceBridge (http://www.gtn-g.org/glathida.html).

Nevertheless, the availability of direct ice thickness measurement data is still sparse. All methods are based on field work and are thus expensive, laborious and time-consuming. Increasingly GPR measurements are carried out airborne (with airplanes or helicopters) but still a large part of available measurements performed directly on glacier surfaces are restricted to accessible parts of glaciers. Measurements in very steep, crevassed, avalanche- or ice-/rockfall affected areas of a glacier are difficult to carry out. For simple logistical reasons, ice thickness measurements mainly cover the crevasse-free flat (and thick) parts of glaciers with compressing flow (often in overdeepend parts of the bed) and might thus not be representative of the entire glacier. The point density of measurements per km^2 of a glacier can vary within orders of magnitude and the bed between the measured data remains unknown and so has to be inter- and extrapolated and is thus a modeled product.

Modeling ice thickness / glacier volumes

To obtain information about subglacial topography, the glacier bed can be reconstructed from more or less dense field measurements of glacier thickness, by spatially inter- and extrapolating them to a continuous bed using a variety of methods. In principle, only the GPR profiles can be considered as validation data for results from other methods, as for regions without measurements glacier thickness is only a computed product and might thus be rather different from reality. Nevertheless, estimates of ice thickness and volume are also required for unmeasured glaciers. Hence, over the last decades several approaches have been developed to estimate or model ice thickness for individual as well as large samples of glaciers. Basically two different types of approaches can be distinguished:

- A: Scalar approaches yielding only one (mean thickness or total volume) value per glacier.
- B: Modeling and interpolation methods which provide 3-dimensional ice thickness distributions for each glacier.

These two classes can be further differentiated as outlined in Figure 1. The scaling approaches used in studies belonging to **A1** are originally based on empirical relations between measured surface areas and (geophysically) measured ice depths. In a wide range of studies the so-called area-volume scaling was applied to estimate ice volume and hence the potential sea-level rise contribution of glaciers at a global scale. This might be a suitable approach when applied to a large sample of glaciers (as the large uncertainties of the individual values average out), but deriving glacier volume (V) from its area (A) is problematic as it relates a variable (area) with itself (area in volume) resulting in high correlations and suppresses the large scatter, in particular when plotted with a double-logarithmic scale. So the problem of this method is not the physical basis of the scaling theory behind the approach (cf. Bahr et al. 1997), but the requirement to derive the scaling parameter c in $V = c\ A^{\gamma}$ from a statistical relation that correlates a variable with itself. A further problem when using area to determine glacier thickness or volume is that physically the variability of thickness is controlled by glacier slope and mass turnover rather than area. So approaches considering these factors (**A2**) in Figure 1 should give more realistic results than the others (**A1**) in Figure 1 for glaciers of the same size but with different mean slopes.

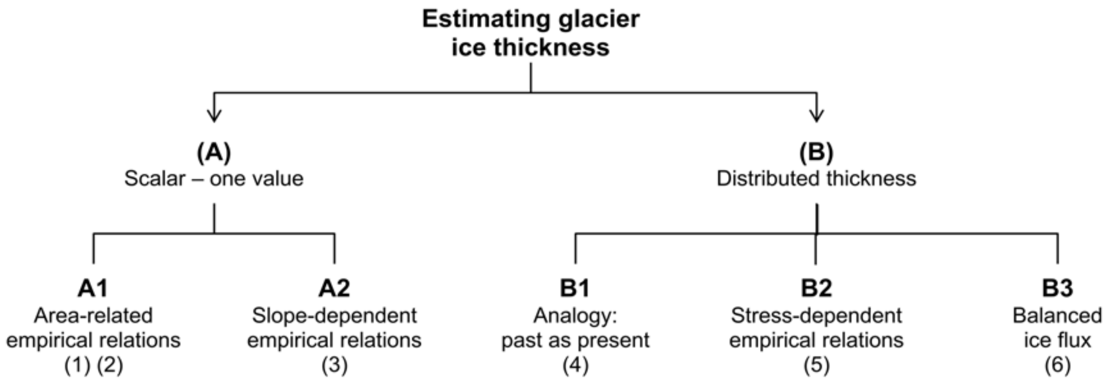

Figure 1: Classification scheme to separate different approaches to estimate glacier ice thickness. A selection of studies dealing with ice thickness assessment is denoted by numbers in brackets (1) Chen and Ohmura 1990, (2) Bahr et al. 1997, (3) Haeberli and Hoelzle 1995, (4) Clarke et al. 2009, (5) Linsbauer et al. 2012, (6) Farinotti et al. 2009.

With the topographic information available in detailed glacier inventories it is possible to use glacier length and elevation range to derive a slope-dependent mean thickness for large samples of glaciers (Haeberli and Hoelzle 1995). Studies applying this approach build the group **A2** in Figure 1. Corresponding thickness estimates for individual glaciers are considered to be more realistic than area-dependent estimates, because flow-related glacier thickness is strongly slope-dependent. In different studies, ice thickness and surface slope are related to stress, by applying the perfect-plasticity assumption to estimate the ice thickness of glaciers. The so-derived mean thickness of glaciers having the same size will get different values and volumes (in contrast to **A1**-approaches).

The area-related estimates and scalar methods from type **A** yield only one value per glacier (either a mean thickness or a total volume), but no information about subglacial topography. Simplified modeling approaches, based on application of DEMs in combination with vector outlines of glacier extent, were developed to obtain distributed ice thickness estimated and build type **B**.

The **B1**-class (Figure 1) represents approaches dealing with analogy of past and present glacierization. Clarke et al. 2009 trained an Artificial Neural Network (ANN) to transfer the characteristics of now ice free glacier beds to contemporary glaciers. The method yielded plausible, though not necessarily accurate, estimates of the bed surface. The obtained estimates of total glacier ice volume might be superior to the values calculated with **A**-approaches. Nevertheless, until today the ANN-approach was not further applied, because of the required workload and computational resources.

The concept of methods belonging to the **B2**-class (Figure 1) is based on the transformation of the perfect plasticity assumption of the **A2**-approaches averaged over the entire glacier to a spatially explicit reconstruction of the glacier bed. Thereby, ice thickness is computed as a function of local slope and a basal shear stress derived from the vertical glacier extent. Locally derived ice thickness are spatially interpolated and provide an approximated glacier bed. DEMs and polygons with glacier outlines basically provide all important information for this approach (Linsbauer et al. 2012).

Methods in the **B3**-class are based on mass conservation and principles of ice flow dynamics to estimate the ice thickness distribution. Farinotti et al. 2009 presented a method established on this foundation. In contrast to the approaches from **B1** and **B2** it requires a detailed parameterization of the involved physical processes and rough assumptions about several only vaguely determined processes (e.g., surface accumulation, mass balance gradient, rate factor in the ice flow law, basal sliding velocity). As a consequence, the model must be tuned for each glacier by comparing it with selected glacier cross sections derived from GPR profiles to make it realistic. The originally envisaged complexity and process understanding is thereby reduced to an empirically calibrated approach.

All ice thickness-estimation methods presented above have their shortcomings and uncertainties (e.g., not applicable to large samples, lack of data for application, complexity of the model, computational resources required, etc.). A critical step for the use of modeled glacier beds in other applications is the assessment of their quality, which requires a validation procedure with reference data. As the real glacier bed of still existing glaciers becomes only visible after the respective glacier has disappeared, validation data (i.e. bedrock information) has to be provided from field measurements. Such reference information is only sparsely available and in most cases biased towards crevasse-free, flat and thus thick glacier parts with compressing flow.

References

Bahr, D. B., Meier, M. F., and Peckham, S. D. (1997). The physical basis of glacier volum-area scaling. Journal of Geophysical Research, 102 (B9): 20,355–20,362. doi: 199710.1029/97JB01696.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., 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 (6079): 310–314. doi: 10.1126/science.1215828.

Chen, J. and Ohmura, A. (1990). Estimation of Alpine glacier water resources and their change since the 1870s. In: Hydrology in Mountainous Regions. I – Hydrological Measurements; the Water Cycle, (edited by Lang, H. and Musy, A.), vol. 193 of IAHS. Proceedings of two Lausanne Symposia, August 1990.

Clarke, G. (1987). A short history of scientific investigations on glaciers. Journal of Glaciology, Special Issue: 4–24.

Clarke, G. K. C., Berthier, E., Schoof, C. G., and Jarosch, A. H. (2009). Neural networks applied to estimating subglacial topography and glacier volume. Journal of Climate. doi: 10.1175/2008JCLI2572.1.

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

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N., and Stoffel, M. (2014). Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods, The Cryosphere, 8, 2313-2333, doi:10.5194/tc-8-2313-2014.

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.

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.