The Cryosphere Discuss., 6, 5169–5179, 2012
www.the-cryosphere-discuss.net/6/5169/2012/
doi:10.5194/tcd-6-5169-2012

The Cryosphere Discussions

Global glacier volumes and sea level – effects of ice below the surface of the ocean and of new local lakes on land

W. Haeberli and A. Linsbauer

Geography Department, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland

Received: 8 November 2012 – Accepted: 27 November 2012 – Published: 13 December 2012

Correspondence to: W. Haeberli (wilfried.haeberli@geo.uzh.ch)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The potential contribution of glaciers and ice caps to sea level rise is usually calculated by comparing the estimated total ice volume with the surface area of the ocean. Part of this total ice volume, however, does not contribute to sea-level rise, because it is below the surface of the ocean or below the levels of future lakes on land. The present communication points to this so far overlooked phenomenon and provides a first order-of-magnitude estimate. It is shown that the effect is small (most likely 1 to 5 cm sea-level equivalent) but systematic, could primarily affect earlier stages of global glacier vanishing and should therefore be adequately considered. Now-available techniques of slope-related high-resolution glacier-bed modelling have the potential to provide more detailed assessments in the future.

1 Introduction

The total possible contribution to sea-level rise from melting glaciers and ice caps other than the two continental ice sheets of Antarctica and Greenland is commonly calculated by estimating the total volume (V_{gic}) of such land-ice bodies, dividing the corresponding value by the value of the ocean area and applying a correction for the ice-water density difference. Parts of the ice in glaciers and ice caps, however, are located below sea level or below the levels of lakes potentially forming in over-deepened parts of their beds on land. The vanishing of such ice does not contribute to sea-level rise but will even slightly lower it due to the ice-water density difference. As a consequence, not the total volume of glaciers and ice caps but this volume minus the corresponding volume below sea level (V_s) and the volume below levels of potential lakes on land (V_l) constitutes the real volume (V_r) which affects sea level:

$$V_r = V_{gic} - V_s - V_l \qquad (1)$$

This effect has so far received little attention or may even have been completely overlooked (for instance, in the IPCC assessment reports). We here try to make a first order-of-magnitude estimate of the necessary correction. This rough approximation shows that the effect is small (probably a few centimetres sea-level equivalent in total) but nevertheless systematic and should no longer be ignored. Techniques of slope- and flux-dependent high-resolution glacier-bed modelling now open the way for more detailed assessments in the future.

2 Thickness estimates for glaciers and ice caps

The use of three-dimensional topographic information from detailed glacier inventories and digital elevation models (DEMs) has opened new dimensions for distributed modelling of ice thicknesses and volumes for large samples of glaciers and ice caps. The principle of an inverted flow law for ice (shear stresses as a function of strain rates governed by mass turnover) in combination with altitude information (elevation range) from tabular data in detailed glacier inventories was first applied in the 1990s (Haeberli and Hoelzle, 1995). It enabled slope-dependent estimates of average/maximum thicknesses and volumes concerning all glaciers of entire mountain ranges (cf. Paul and Svoboda, 2010). Globally available DEMs of sufficient spatial resolution and quality then paved the way for computing approximate slope-dependent thickness patterns and high-resolution bed topographies of individual glaciers (Farinotti et al., 2009; Li et al., 2012; McNabb et al., 2012), of all glaciers at regional scales (Linsbauer et al., 2012; Clarke et al., 2012) and – most recently and at somewhat lower spatial resolution – even for all glacier complexes around the world (Huss and Farinotti, 2012). Absolute values of ice depth for unmeasured glaciers thereby depend on highly uncertain assumptions about surface mass fluxes (especially accumulation, albedo/radiation, etc.; Machguth et al., 2008) and flow characteristics (especially basal sliding, rate factor in Glen's flow law). Calculated ice thicknesses can therefore deviate as much as ±30 % or even more from measured and inter-/extrapolated local values. In contrast, relative differences, i.e. the spatial patterns of the modelled ice thickness variability and corresponding bed topographies are primarily related via basal shear stresses to surface slope as contained in DEMs and, hence, are rather robust (Linsbauer et al., 2012). This helps in assessing the amount of ice existing below sea level and below levels of lakes that might potentially form in over-deepened parts of glacier beds.

3 Ice below sea level and below levels of potential lakes

Glacially sculpt landscapes are characterised by striking sequences of sills and over-deepened basins with inverse slopes. The bed topographies produced by the above-mentioned model approximations at various levels of sophistication consistently exhibit exactly this type of pattern (Fig. 2, 3; Linsbauer et al., 2012; cf. the Figs. 3, 4 in Huss and Farinotti, 2012). The over-deepened parts of the terrain are sites of potential lake formation when becoming exposed by vanishing glaciers (Fig. 1, 2; Frey et al., 2010). With continued if not accelerated global warming during the coming decades, the presently still existing glacier landscapes of mountain regions will indeed successively be replaced by landscapes with numerous lakes. As a re-growth of (at least large) glaciers during the coming centuries or even millennia is unlikely with rising long-term greenhouse-gas concentrations in the atmosphere, these new lake landscapes will most probably persist for many future generations. They have important implications for densely populated mountain regions because they relate to risks (e.g. flood hazards, cf. Frey et al., 2010; Künzler et al., 2010) and opportunities (e.g. hydropower production, cf. Terrier et al., 2011) but also have a (very) small effect on sea level: if replaced by lake water when vanishing, the ice presently flowing through over-deepened parts of glacier beds does not immediately or directly contribute to sea-level rise.

The long profile of Taku glacier provided in Fig. 3 of Huss and Farinotti (2012) also illustrates that even land-terminating glaciers can have bed parts well below sea level (Fig. 3). Large tide-water glaciers, which will continue influencing sea level for the near future in an important way (Meier et al., 2007), can occupy fjords many hundreds

TCD
6, 5169–5179, 2012

W. Haeberli and A. Linsbauer

of meters deep (McNabb et al., 2012). Replacing the corresponding (rather large) amounts of grounded ice below sea level by seawater again does not contribute to sea level rise. The density difference between ice and water even causes a lowering of sea level corresponding to about 10 % of the ice volume below sea level (cf. Meier et al., 2007).

4 Effects for estimates of potential contributions from glaciers and ice caps to sea level rise

The necessary corrections to be applied to the total volume of glaciers and ice caps concerning their potential contribution to sea-level rise relate to ice below sea level (V_s) and ice below levels of potential lakes on land (V_l). Exact numbers are not available yet but a rough order-of-magnitude estimate already shows that $V_l \ll V_s$.

Linsbauer et al. (2012) present a detailed analysis of over-deepened bed parts and potential new lakes in the Swiss Alps. Many of the new lakes will be small and shallow but lakes of considerable size and volume may form where large and flat glaciers disappear. The total potential lake volume in the Swiss Alps is estimated at 2 to 3 km^3 with a presently remaining ice volume of some 55 ± 10 km^3. The corresponding percentage of potential future lake volume is thus about 3 to 6 % of the presently remaining ice volume. Because of incisions at the downvalley side of new lakes, not all of the modelled overdeepenings may fill completely with water. Some lakes may irreversibly empty through moraine breaching and some of the lake volume may be replaced by sediment infill. Other lake volumes may be artificially enhanced for hydropower production (Terrier et al., 2011). Models for ice-thickness estimation, on the other hand, tend to strongly underestimate the depth of marked overdeepenings, for instance at Konkordiaplatz of Aletsch glacier or in the upper part of Rhone glacier (Farinotti et al., 2009; Linsbauer et al., 2012). Moreover, the larger and flatter glaciers are, the larger and deeper potential new lakes tend to be. Most of the glaciers in the European Alps are comparably steep (Paul et al., 2011) and thus thin (Haeberli and Hoelzle, 1995) with a limited potential for large lakes. Over-deepened bed parts could be much larger in regions with networks of flat valley glaciers such as, e.g. central Alaska, the Canadian Rocky Mountains or parts of the Himalayas. Taking half the 3 to 6 % estimated for the Swiss Alps – the so far only such estimate available – may be a reasonable first-order estimate of a *lower-bound value* concerning sea-level rise.

Ice below sea level of tide-water glaciers could constitute a far higher percentage of ice not contributing to sea level rise. Assuming very roughly that

- about 50 % of the sea-level contribution is from a number of large glaciers like Bering (Alaska) or O'Higgins (Patagonia) terminating in the sea or near sea level – rounded estimates of corresponding relative sea-level contributions from Table 2 in Huss and Farinotti (2012), and from Rastner et al. (2012) (for Greenland periphery) are: Alaska 5 %, Antarctic and Subantarctic 10 %, Arctic Canada 10 %, Greenland periphery 10 %, Russian Arctic 5 %, Svalbard 5 %, Patagonia 5 %,

- about 50 % of the ice in the lower parts of such large glaciers is below sea level (cf. McNabb et al., 2012), and

- these flat/thick lower glacier parts constitute about 50 % of the total ice volume in such glaciers (cf. McNabb et al., 2012; cf. Linsbauer et al., 2012)

may provide 10 to 15 % as a first-order estimate of an *upper-bound value* for effects from ice below sea level.

The combined effect is likely to be between the estimated upper- and lower-bound values, i.e. about 5 to 10 % of the so far estimated total remaining ice volume (around 0.4–0.6 m sea-level equivalent). The corresponding sea-level equivalent of a few (probably 1 to 5) centimetres for ice below the ocean surface plus millimetres for ice below future lake levels on land is comparable to roughly half the uncertainty range usually given with existing estimates relating to total ice volumes. This effect is small but nevertheless systematic. Moreover, continued atmospheric warming could strongly affect the stability of tide-water glaciers and lead to the disappearance of deep-water ice at an early stage of global glacier vanishing. The corresponding effect with respect to sea-level rise could primarily take place during the 21st century already. The phenomenon of ice below sea level therefore needs closer inspection and correct treatment. Modern techniques of slope-dependent high-resolution glacier-bed modelling for large glacier samples (Clarke et al., 2012; Huss and Farinotti, 2012; Linsbauer et al., 2012) now pave the way for more detailed assessments.

Acknowledgements. Thanks are due to Tobias Bolch, Holger Frey, Christian Huggel, Frank Paul, Philipp Rastner and Michael Zemp at the Geography Department of the University of Zurich, Switzerland, as well as Valentina Radić (TCD editor) for constructive feedback on an early draft of this communication.

References

Clarke, G., Anslow, F., Jarosch, A., Radić, V., Menounos, B., Bolch, T., and Berthier, E.: Ice volume and subglacial topography for western Canadian glaciers from mass balance fields, thinning rates, and a bed stress model, J. Climate., in revison, 2012.

Farinotti, D., Huss, M., Bauder, A., and Funk, M.: An estimate of the glacier ice volume in the Swiss Alps, Global Planet. Change, 68, 225–231, 2009.

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C., and Paul, F.: A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials, Nat. Hazards Earth Syst. Sci., 10, 339–352, doi:10.5194/nhess-10-339-2010, 2010.

Haeberli, W. and Hoelzle, M.: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, Ann. Glaciol., 21, 206–212; Russian translation in: Data of Glaciological Studies, Moscow, 82, 116–124, 1995.

Huss, M. and Farinotti, D.: Distributed ice thickness and volume of all glaciers around the globe, J. Geophys. Res., 117, F04010, doi:10.1029/2012JF002523, 2012.

Künzler, M., Huggel, C., Linsbauer, A., and Haeberli, W.: Emerging risks related to new lakes in deglaciating areas of the Alps, in: Mountain Risks: Bringing Science to Society, Proceedings of the “Mountain Risk” International ConferenceMalet, edited by: Malet, J.-P., Glade, T., Casagli, N., 24–26 November 2010, Firenze, Italy, CERG Editions, Strasbourg, France, 453–458, 2010.

Li, H., Ng, F., Li, Z., Qin, D., and Cheng, G.: An extended "perfect plasticity" method for estimating ice thickness along the flow line of mountain glaciers, J. Geophys. Res., 117, F01020, doi:10.1029/2011JF002104, 2012.

Linsbauer, A., Paul, F., and Haeberli, W.: Modeling glacier thickness distribution and bed topography over entire mountain ranges with Glab-Top: application of a fast and robust approach, J. Geophys. Res., 117, F03007, doi:10.1029/2011JF002313, 2012.

Machguth, H., Purves, R. S., Oerlemans, J., Hoelzle, M., and Paul, F.: Exploring uncertainty in glacier mass balance modelling with Monte Carlo simulation, The Cryosphere, 2, 191–204, doi:10.5194/tc-2-191-2008, 2008.

McNabb, R. W., Hock, R., O'Neel, S., Rasmussen, I. A., Ahn, Y., Braun, M., Conway, H., Herreid, S., Joughin, I., Pfeffer, W. T., Smith, B. E., and Truffer, M.: Using surface velocities to calculate ice thickness and bed topography: a case study at Columbia Glacier, Alaska, USA, J. Glaciol., 58, 1151–1164. doi:10.3189/2012JoG11J249, 2012.

Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., and Glazovsky, A. F.: Glaciers dominate eustatic sea-level rise in the 21st century, Science, 317, 1064–1067, doi:10.1126/science.1143906, 2007.

Paul, F. and Svoboda, F.: A new glacier inventory on southern Baffin Island, Canada, from ASTER data: I I. Data analysis, glacier change and applications, Ann. Glaciol., 50, 22–31, doi:10.3189/172756411799096295, 2010.

Paul, F., Frey, H., and Le Bris, R.: A new glacier inventory for the European Alps from Landsat TM scenes of 2003: challenges and results, Ann. Glaciol., 52, 144–152, doi:10.3189/172756411799096295, 2011.

Rastner, P., Bolch, T., Mölg, N., Machguth, H., and Paul, F.: The first complete glacier inventory for the whole of Greenland, The Cryosphere Discuss., 6, 2399–2436, doi:10.5194/tcd-6-2399-2012, 2012.

Terrier, S., Jordan, F., Schleiss, A. J., Haeberli, W., Huggel, C., and Künzler, M.: Optimized and adapted hydropower management considering glacier shrinkage scenarios in the Swiss Alps, in: Proceedings of the International Symposium on Dams and Reservoirs under Changing Challenges – 79th Annual Meeting of ICOLD, Swiss Committee on Dams, Lucerne, Switzerland, edited by: Schleiss, A., Boes, R. M., Taylor and Francis Group, London, 497–508, 2011.

Fig. 1. New lake which recently formed in a pronounced bed overdeepening of Gauli glacier, Bernese Alps, Switzerland, as a consequence of continued glacier retreat. Another lake is likely to form within the coming years to few decades in the probably overdeepened bed part indicated by the less inclined glacier surface above the bedrock sill with the present steep/thin glacier tongue (cf. Fig. 2 for model simulation/position and Frey et al., 2010 for morphological indications of bed overdeepenings). Foto: Michael Bütler, 8 Oktober 2012.

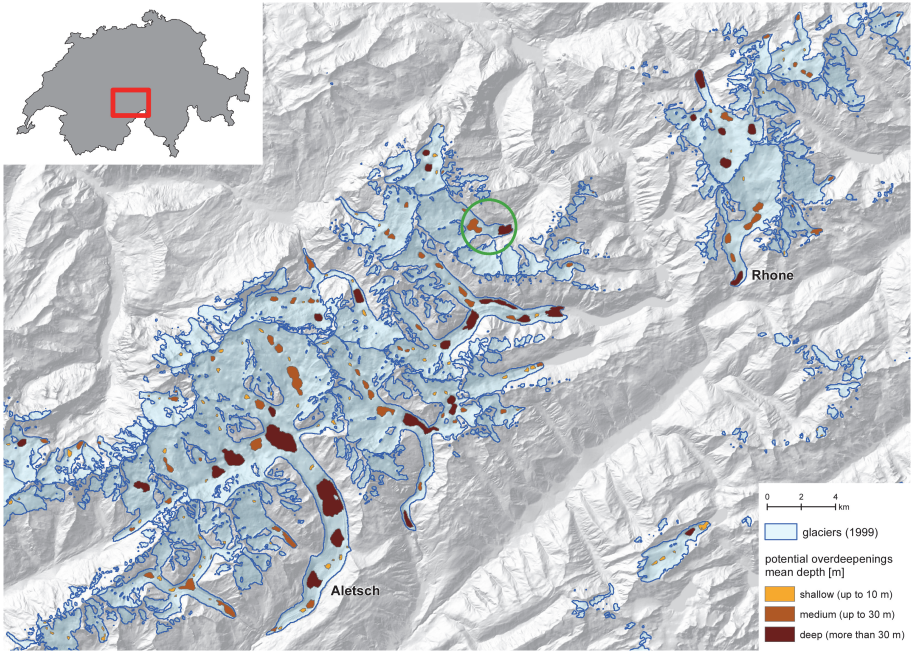

Fig. 2. Overdeepenings and potential new lakes in the still glacierized region of the central Swiss Alps. Aletsch glacier is in the lower left, Rhone glacier in the upper right corner. Gauli glacier with its new lake (cf. Fig. 1) and another probably soon forming lake is indicated with a green circle. Adjusted from Linsbauer et al. (2012).

TCD
6, 5169–5179, 2012

Ice below sea/lake levels

W. Haeberli and
A. Linsbauer

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

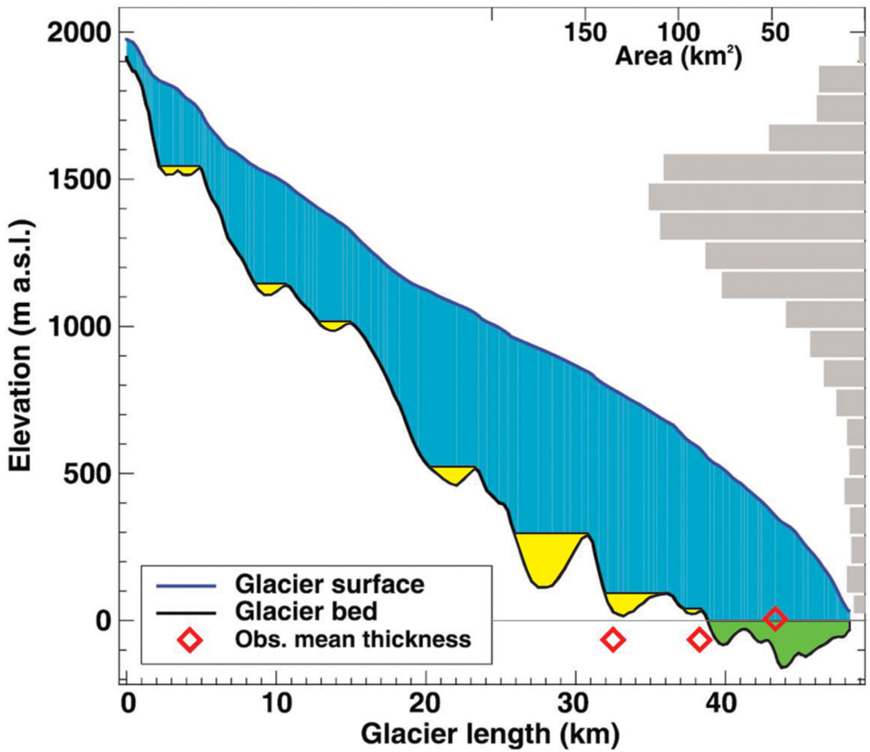

Fig. 3. Long profile of Taku glacier adapted from Huss and Farinotti (2012: Fig. 3). Ice in overdeepend bed parts and sites of potential lake formation are marked with yellow, ice below sea level with green.