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

Response to *both* reviewers:

We thank the two reviewers for their constructive feedback and made the following adjustments to the text:

General:

Our contribution is a „brief communication“ not a full paper. Its main purpose is to make clear that the described phenomenon exists, is mall but systematic, should be correctly taken into account and can be roughly quantified (order of magnitude), even though large uncertainties exist and may continue to exist.

The title should not be alarming. We therefore changed it into:

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

We also slightly adjusted the estimation of lake to glacier volume by formulating (Page 5173, lines 15-18):

The total potential lake volume in the Swiss Alps is estimated at 2 to 3 km^3 with an ice volume of 75 ± 22 km^3 for the time horizon of the model calculation (1973) and with a presently (2012) remaining ice volume of some 55 ± 10 km^3. The corresponding percentage of potential future lake volume is thus about 5 ± 3 % of the assumed ice volume.

We added two most recent references: Cook and Swift (2012) for their extensive review on overdeepenings and Grinsted (2012) for his comparison of recent estimates of sea level equivalents related to glaciers and ice caps.

The assistance of the reviewers is mentioned in the acknowledgements.

Reviewer 1:

Page 5171, lines 3-5: The sentence is transferred to the new/short conclusion at the end of the text.

Page 5172, lines 15-17: The sentence has been adjusted following the recommendation.

Page 5173, line 1: "(rather large)" was deleted.

Figure 1: We would prefer to keep this image, because it relates to Fig. 2 (two modelled potential lakes in the green circle) and illustrates that the model calculations are quite realistic (the model calculation was done with a DEM, in which the lake of Fig. 1 did not exist yet but was covered by glacier ice – this is now mentioned in the caption to Fig. 1.

Reviewer 2 (Surendra Adhikari):

The title was adjusted to make it less "alarming" (see above).

Page 5170, lines 13 and 24: We agree with the comments but prefer to limit the formula (1) to the considered ice volume (rather than sea-level equivalent) in order to make things as simple and transparent as possible. The density effects, which must be taken into account for calculating sea-level change, are mentioned in the original text (lines 19-20; lines 32-33 in the revised MS). The remark about the influence of variable ocean area is justified but relates to considerations of sea level change in general and is, therefore, somewhat beyond the scope of our brief communication. We nevertheless added in the introduction that the value of the ocean surface is assumed to be constant for comparability (now line 29). We now also mention increased evaporation over new lake (and sea) surfaces in section 4 (page 5174, line 3) and provide a brief note about possible further effects within the terrestrial water cycle (lines 125-129 in the revised MS):

Additional losses of water may be caused by increased evaporation over new lake (and sea) surfaces as compared to earlier ice surfaces at the same sites. Like seepage, agricultural and industrial use, etc., such effects involve complex process chains and interactions within the water cycle, the consideration of which is beyond the scope of the present brief communication on ice volumes.

(The water used for agricultural and industrial purposes is not totally/permanently kept back but at least partially recycled. We prefer to focus here on glacier and lake effects.)

Page 5172, line 16: The sentence is adjusted (cf. remark of reviewer 1).

Page 5173, line 11: Our statement relates to our own estimation. The sentence now reads (lines 104-106 in the revised MS):

Exact numbers are difficult to obtain for a number of reasons but the following rough order-of-magnitude estimate already shows that $V_l << V_s$.

Page 5173, line 21: On average, a considerable volume of water is kept back in artificial lake reservoirs for hydropower production. Concerning the new lakes, artificial dams will locally to regionally increase the naturally forming lake volume.

Page 5174, line 3: we eliminated the sentence and avoid the terms "half" and "lower-bound value". The new 5 ± 3 % is now our best guess fort the lake component.

Page 5174, lines 14-20: The assumptions are: 50% of the sea-level contribution from glaciers and ice caps is from large tidal glaciers, which have 50% of their volume in low-flat glacier tongues and 50% of this low-flat glacier tongue is below sea level: $0.5^3 = 0.125$ or 10 to 15% of the total ice volume. We now avoid the term "upper-bound value" and reformulate the corresponding statement (lines 145-150 in the revised MS):

... may provide some 10 to 15% of the total ice volume as a first-order and probably rather high estimate for effects from ice below sea level.

In this estimate, V_l and V_s concern different parts of the total ice volume. Their percentages can, therefore, not be added. The combined effect is thus probably somewhere between the two estimates or about 5 to 10% of the so far estimated total remaining ice volume (around 0.2 – 0.6 m; Grinsted, 2012). The corresponding sea level equivalent is most likely a few (probably 1 to 6) centimetres, with millimetres rather than centimetres for V_l and centimetres rather than millimetres for V_s.

Wilfried Haeberli and Andreas Linsbauer

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

Wilfried Haeberli and Andreas Linsbauer

Geography Department, University of Zurich

Winterthurerstrasse 190, 8057 Zurich, Switzerland

e-mail: wilfried.haeberli@geo.uzh.ch

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 about 1 to 6 centimetres 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.

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 (assumed to be constant for comparability) 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. Techniques of slope- and flux-dependent high-resolution glacier-bed modelling now open the way for more detailed assessments in the future.

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.

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 (Cook and Swift, 2012). 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 figures 3 and 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 is unlikely with further rising long-term temperatures, 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, Haeberli 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 Figure 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 of meters deep (McNabb et al., 2012). Replacing the corresponding 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).

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 difficult to obtain for a number of reasons but the following rough order-of-magnitude estimate already shows that $V_l << V_s$.

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 an ice volume of 75 ± 22 km^3 for the time horizon (1973) of the model calculation and with a presently (2012) remaining ice volume of some 55 ± 10 km^3. The corresponding percentage of potential future lake volume is thus about 5 ± 3 % of the assumed ice volume. Because of incisions at the down-valley 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 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. Additional losses of water may be caused by increased evaporation over new lake (and sea) surfaces as compared to earlier ice surfaces at the same sites. Like seepage, agricultural and industrial use, etc., such effects involve complex process chains and interactions within the water cycle, the consideration of which is beyond the scope of the present brief communication on ice volumes.

Ice below sea level of tidewater 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 some 10 to 15% of the total ice volume as a first-order and probably rather high estimate for effects from ice below sea level.

In this estimate, V_l and V_s concern different parts of the total ice volume. Their percentages can, therefore, not be added. The combined effect is thus probably somewhere between the two estimates or about 5 to 10% of the so far estimated total remaining ice volume (around 0.2 – 0.6 m; Grinsted, 2012). The corresponding sea level equivalent is most likely a few (probably 1 to 6) centimetres, with millimetres rather than centimetres for V_l and centimetres rather than millimetres for V_s. Such values are 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 tidewater glaciers and therefore 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 therefore primarily take place during the 21st century already.

The phenomenon of ice below sea level 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 open the possibility for more detailed assessments.

Conclusion

The volume of glacier ice below the surface of the ocean and of potential future lakes (including related ice/water density effects) must be subtracted from the total volume of glaciers and ice caps for calculating sea level equivalents. A first rough order-of-magnitude estimate using information from recent slope-dependent ice thickness/volume calculations shows that the effect is small – probably a few centimetres sea-level equivalent in total – but nevertheless systematic and should be correctly taken into account.

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. Surendra Adhikari and an anonymous reviewer provided additional comments and suggestions which helped improving the quality of our contribution.

References

Clarke, G., Anslow, F., Jarosch, A., Radić, V., Menounos, B., Bolch, T., Berthier, E. (2012): Ice volume and subglacial topography for western Canadian glaciers from mass balance fields, thinning rates, and a bed stress model. Journal of Climate. doi:10.1175/JCLI-D-12-00513.1, in press.

Cook, S.J. and Swift, D.A. (2012): Subglacial basins: Their origin and importance in glacial systems and landscapes. Earth Science Reviews 115, 332-372.

Farinotti, D., Huss, M., Bauder, A. and Funk, M (2009): An estimate of the glacier ice volume in the Swiss Alps. Global and Planetary Change 68(3), 225–231.

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. and Paul, F. (2010): A multi level strategy for anticipating future glacier lake formation and associated hazard potentials. Natural Hazards and Earth System Science 10, 339-352.

Grinsted, A. (2012): An estimate of global glacier volume. The Cryosphere, 7, 141-151. doi:10.5194/tc-7-141-2013.

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. Russian translation in: Data of Glaciological Studies, Moscow, 82, 116-124.

Haeberli, W., Clague, J.J., Huggel, C. and Kääb, A. (2010): Hazards from lakes in high-mountain glacier and permafrost regions: Climate change effects and process interactions. Avances de la Geomorphología en España, 2008-2010, XI Reunión Nacional de Geomorphología, Solsona, 439-446.

Huss, M. and Farinotti, D. (2012): Distributed ice thickness and volume of all glaciers around the globe. Journal of Geophysical Research 117, F04010, doi:10.1029/2012JF002523.

Künzler, M., Huggel, C., Linsbauer, A. and Haeberli, W. (2010): Emerging risks related to new lakes in deglaciating areas of the Alps. In: J.-P. Malet, T. Glade, N. Casagli (eds) Mountain Risks: Bringing Science to Society. Proceedings of the 'Mountain Risk' International Conference, 24-26 November 2010, Firenze, Italy, CERG Editions, Strasbourg, France, 453-458.

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

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

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

McNabb, R.W., Hock, R., O'Neel, S., Rasmussen, l.A., Ahn, Y., Braun, M., Conway, H., Herreid, S., Joughion, I., Pfeffer, W.T., Smith, B.E. and Truffer, M. (2012): Using surface velocities to calculate ice thickness and bed topography: a case study at Columbia Glacier, Alaska, USA. Journal of Glaciology 58(212), 1151-1164. doi: 10.3189/2012JoG11J249

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. (2007): Glaciers dominate eustatic sea-level rise in the 21st century. Science 317(5841), 1064–1067, doi:10.1126/science.1143906.

Paul, F. and Svoboda, F. (2010). A new glacier inventory on southern Baffin Island, Canada, from ASTER data: II. data analysis, glacier change and applications. Annals of Glaciology 50(53): 22–31. doi: 10.3189/172756410790595921.

Paul, F., Frey, H. and Le Bris, R. (2011): A new glacier inventory for the European Alps from Landsat TM scenes of 2003: Challenges and results. Annals of Glaciology 52 (59), 144-152.

Rastner, P., Bolch, T., Mölg, N., Machguth, H. and Paul, F. (2012): The first complete glacier inventory for the whole of Greenland. The Cryosphere Discussion 6, 2399-2436.

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

Figure captions:

Figure 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, 10.08.2012.

Figure 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 and another probably soon forming lake is indicated with a green circle; the model run was done using a DEM in which the lower lake did not exist yet but was covered by glacier ice. Adjusted from Linsbauer et al. (2012).

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