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Brief communication
"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"

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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 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 (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 overdeepened 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:

$$V_{\text{r}} = V_{\text{gic}} - V_{\text{s}} - V_{\text{l}}. \tag{1}$$

This effect has so far received little attention (Loriaux and Casassa, 2013) 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.

2 Thickness estimates for glaciers and ice caps

Only very few glaciers and ice caps in the world have measured ice thicknesses, from which volumes can be calculated. Various approaches have therefore been applied to estimate thicknesses and volumes of unmeasured perennial surface-ice bodies. The use of three-dimensional topographic information from detailed glacier inventories and digital elevation models (DEMs) has now 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 volume calculations 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 overdeepened parts of glacier beds.

3 Ice below sea level and below levels of potential lakes

Glacially sculpted landscapes are characterised by striking sequences of sills and overdeepened 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 (Figs. 2 and 3; Linsbauer et al., 2012; cf. Figs. 3 and 4 in Huss and Farinotti, 2012). The overdeepened parts of the terrain are sites of potential lake formation when exposed by vanishing glaciers (Figs. 1 and 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 regrowth 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 overdeepened parts of glacier beds does not immediately or directly contribute to sea level rise.

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 a 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). Photo: Michael Bütler, 10 August 2012.

The long profile of Taku Glacier provided in Fig. 3 of Huss and Farinotti (2012) 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).

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 difficult to obtain for a number of reasons, but the following rough order-of-magnitude estimate already indicates that $V_\mathrm{l} < V_\mathrm{s}$.

Linsbauer et al. (2012) present a detailed analysis of overdeepened bed parts and potential new lakes in the Swiss Alps (cf. Fig. 2). 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 $75 \pm 22\,\mathrm{km}^3$ for the time horizon (1973) of

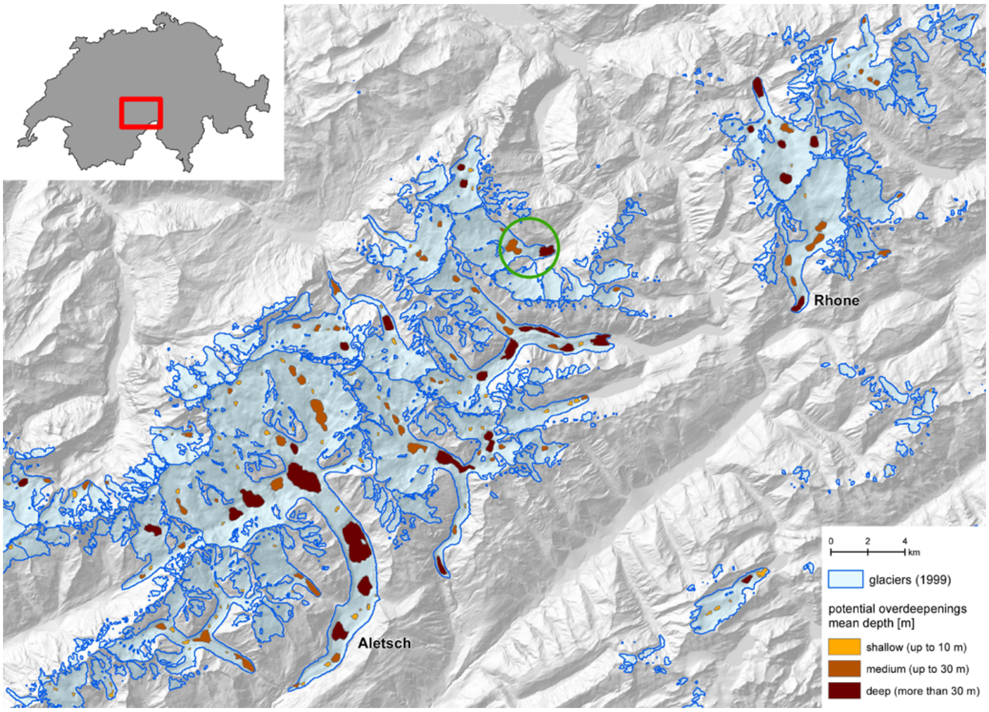

Fig. 2. Modelled overdeepenings and potential new lakes in the still glacierized region of the central Swiss Alps. Aletsch Glacier is in the lower left, and Rhone Glacier is in the upper right corner. Gauli Glacier with its new lake and another probably soon-forming lake is indicated with a green circle; 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).

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. The primary questions related to such estimates are (a) whether the calculated volume of the modelled overdeepenings corresponds to the future volume of water stored in them and (b) how representative such values from one high-mountain chain may be with respect to glaciers and ice caps worldwide. Because of possible 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 newly form or become enhanced artificially for hydropower production (Terrier et al., 2011) or naturally by landslide damming. 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. Overdeepened bed parts could be much larger in regions with networks of flat valley glaciers such as, e.g. central Alaska, the Canadian Rocky Mountains, parts of the Himalayas or the Patagonian ice fields (cf. Loriaux and Casassa, 2013, who estimate 10 % or even more for the Northern Patagonian Ice Field). 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. In view of all these uncertainties, the percentage value from the Swiss Alps can only be used for worldwide estimates as a very rough first approximation.

Ice below sea level of tidewater glaciers could constitute a far higher percentage of ice not contributing to sea level rise. In order to provide a rough order-of-magnitude estimate, we assume the following:

- 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's periphery) are Alaska 5 %, Antarctic and Subantarctic 10 %, Arctic Canada 10 %, Greenland periphery 10 %, Russian Arctic 5 %, Svalbard 5 %, and Patagonia 5 %.

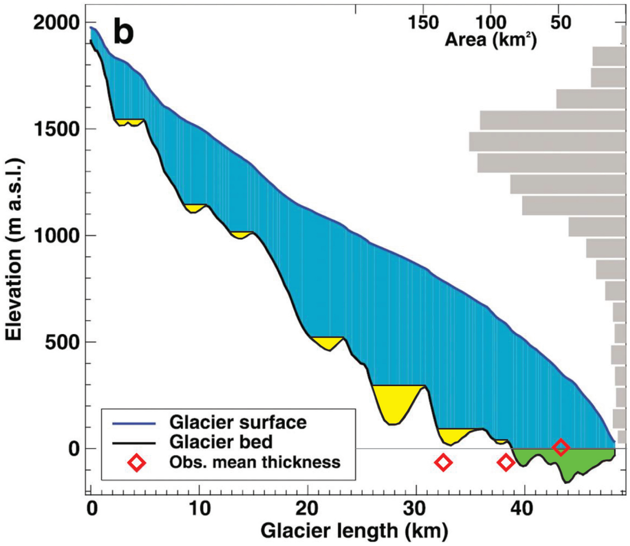

Fig. 3. Long profile of Taku Glacier adapted from Huss and Farinotti (2012; their Fig. 3). Ice in overdeepened bed parts and sites of potential lake formation are marked with yellow, ice below sea level with green.

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

By incorporating these assumptions (50 % (50 % (50 %))), we derive 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.

The two components V_s and V_l in principle discriminate between effects from (a) saltwater and freshwater, (b) below and above sea level and (c) marine- and land-terminating glaciers. At low elevations, however, transitions and combinations between the two exist. Some large lakes forming with retreating land-based glaciers and ice caps at low altitudes may have considerable parts of their volume below sea level (Fig. 3; Loriaux and Casassa, 2013). A striking example is lake-calving Yakutat Glacier, Alaska, where Harlequin Lake started to form in 1903 at a level of 28 m a.s.l., reached a surface area of 69 km^2 in the year 2010 and continues to expand rapidly as a consequence of the foreseeable collapse of the Yakutat Ice Field (Trüssel et al., 2013). The bottom of large newly exposed freshwater bodies like Harlequin Lake can easily be hundreds of meters below sea level. The case of Taku Glacier (Fig. 3) also shows that the vanishing of large glaciers can contribute to both, V_s and V_l. Future effects from V_s and V_l can therefore not always be strictly separated, and assessments concerning their relative influence unavoidably remain vague. It is therefore assumed here that the combined effect is probably somewhere between the two estimates, or about 5 to 10 % of the so far calculated contribution from the total remaining ice volume (around 0.2–0.6 m; Grinsted, 2013). 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.

5 Conclusions

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.

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