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Discussions

Interactive comment on "Density assumptions for converting geodetic glacier volume change to mass change" *by* M. Huss

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C. Nuth and T. Schuler are acknowledged for their constructive comments. In response to their points, more discussion of important topics of this paper and additional model experiments were added to the manuscript. My responses to the their comments (in *italic*) are given, including proposed changes to the text (in quotation marks).

First, eq. 4 and the model applied only refer to land-terminating glaciers. This derivation of a conversion factor requires that mass is conserved and the modeling approach is basically solving for variations in the glacier wide average density through time. For marine terminating glaciers, a (often large) proportion of the volume change

may be through calving which would raise the conversion factor.

This is an important point that needs to be mentioned in the paper – thanks. Some sentences were added that discuss the restriction of the study to land-terminating glaciers and values of $f_{\Delta V}$ in the case of calving glaciers.

In general, the processes and results derived with the simple firn densification model for land-terminating glaciers are assumed to also be valid for calving glaciers although numbers might be subject to changes.

I do not agree that for calving glaciers volume-mass change conversion factors would be higher as implied in the Interactive Comment: A higher percentage of the surface of marine-terminating glaciers is covered by firn (ablation not only by melt, but by calving). Consequently, I expect changes in firn volume and density to be even more important in the case of calving glaciers.

"All evaluations refer to land-terminating glaciers. Ice volume loss by calving is not included in the model and would require the description of ice flow dynamics. General concepts, such as the dependence of $f_{\Delta V}$ on the time period considered, and the high variability of the conversion factor for particular cases, are however assumed to be valid for marine-terminating glaciers as well."

Second, since the idealized glacier geometry contains only constant glacier widths (slab of ice), it is difficult to assess how applicable these results are to geodetically measured volume changes of real glaciers with significantly varying geometries. For example, it is stated on Pg 233 (Line 6-7) that 'the area-elevation distribution of the glacier has a minor influence on $f_{\Delta V}$.' How could these experiments lead to this conclusion when glacier width is held constant? It could be expected that the accumulation area ratio (AAR) has a large influence on this factor as it defines approximately *the magnitude of the firn volume in relation to the total glacier volume and we assume that the larger the AAR the larger sensitivity on volume to mass conversions using a constant. Thus, the results obtained from idealized glacier geometry may not be explicitly applicable to geodetically measured volume changes of real glaciers.*

The same comment was also made by Reviewer #2. To assess the impact of the area-elevation distribution on calculated $f_{\Delta V}$, an additional sensitivity experiment is performed in which the glacier width (accumulation area) is varied (see more details on how this issue was addressed in the response to Reviewer #2). The impact on the results is relatively small. This corresponds to the results of the model application to real data of Gries- and Silvrettagletscher.

The abstract and conclusions of this study suggest (even recommend!) a constant conversion factor of 850±60 kg m-3. Where does this number come from? Interpreting Figure 4 and 5 shows that the conversion factor is not at all constant, but rather varies significantly the shorter the time interval between geodetic acquisitions. In fact, the error bar on the conversion factor will also vary significantly with time. It would be beneficial, and possible with the data in this study, to calculate a variable error of the density conversion dependent upon time. Then readers may get an idea of the magnitude potential of such errors in their data given the time span between geodetic surveys.

This is a very important comment which will be addressed in the revised paper. Indeed, the recommended value of 850±60 kg m^{-3} was a bit 'magical'. Actually, the entire paper is about showing that the conversion factor is *not* constant and that caution is required when converting volume change to mass change. So the recommendation of a constant value really seems strange at first sight.

Figure 4 and Table 1 exactly provide what is suggested By C. Nuth and T. Schuler ('a variable error of the density conversion dependent upon time'). These numbers however come from experiments with idealized mass balance forcing and synthetic glaciers and will not be generally valid, i.e. they will not be useful as look-up tables for field data studies. The application to real data shows that the variability in $f_{\Delta V}$ can be strong for some cases due to accumulation variations several decades back in time.

In practice, scientists using the geodetic method (DEM differencing) will not apply a firn densification model as the one described here to all of their volume change surveys. Accounting for changes in accumulation rates and variability over time is not possible due to a lack of data although this is indispensable to correctly capture the dynamics of firn volume and density changes. Therefore, I have decided to recommend one average value for a straightforward use in glaciological studies – with further stressing the caveats (!) which is also proposed by Reviewer #2. The origin of the number 850 kg m^{-3} as well as the uncertainty range ±60 kg m^{-3} is discussed in more detail in the revised paper. See response to Reviewer #2.

To summarize, it is difficult (and dangerous) to suggest and apply the constant conversion factor directly to any geodetically measured volume change. Results of this study show that the conversion factor varies greatly for short time periods between geodetic measurements and supposedly if more realistic glacier geometries and a more sophisticated densification model had been used, this variation may increase even more. In addition, only land terminating glaciers are represented in this study. Therefore, the title claiming to assess 'density assumptions for converting geodetic volume changes to mass changes' does not describe what is actually accomplished in this study. One title suggestion: 'Sensitivity of assuming Sorge's Law for converting volume to mass changes of land terminating glaciers'.

As stated above, the recommended value for $f_{\Delta V}$ is now restricted more explicitly to three cases (as proposed by Reviewer #2). These cases were already stated in the abstract, the discussion and the conclusions of the TCD manuscript.

I do not agree that this paper suggests and applies a constant conversion factor as implied by this Interactive Comment. It is rather the contrary: The paper clearly (and for the first time) shows how strongly the conversion factor $f_{\Delta V}$ can vary. See e.g. P 235, L 8-10 of the TCD paper: "... but highlights the strong variability, the underlying processes and the problems inherent to assuming a constant factor to convert geodetic volume change and mass change".

Based on the findings of this study, a mean value (with an uncertainty estimate) which is fine for most cases (which are now clearly specified), is extracted and provides a number that can be useful to volume change studies that do not apply a specific model for assessing firn density changes.

Related to my above responses, I also disagree that the present title is misleading. The paper investigates the 'density assumptions for converting geodetic volume change to mass change'. This title does neither imply that the conversion factor is constant, nor that this value should be applied to any glacier type. In my opinion, the suggested title 'Sensitivity of assuming Sorge's Law for converting volume to mass changes of land terminating glaciers' would strongly understate the scope of the study. Of course, only calculations for land-terminating glaciers are performed but all findings are also relevant for calving glaciers. So there is no reason of including this restriction in the title. For the above reasons the title of the paper was not changed.

We think the results would allow analyzing a hitherto unexplored point, namely to separate the effects on bulk glacier density related to changes in the firn volume, △firn, from those caused by changes in the firn density, △firn. The outcome may have important implications: if changes in $f_{\Delta V}$ were dominated by △Vfirn, the costly

(and uncertain, see comments by Referee #1) computation of △firn could be omitted. △Vfirn may be estimated using remote sensing methods (at least the change of firn area). This would open possibility for a more accurate conversion from △V to △M than relying on a single constant $f_{\Delta V}$.

The question whether firn density change or firn volume change is dominant driver is really interesting but a sound analysis would require more (and repeated) field measurements (see e.g. Zdanowicz et al., 2012). The evolution of both firn volume and firn density are calculated by the model. However, these variables cannot simply be separated (as implied in the Comment), as changes in the firn density will affect firn volume and vice versa.

I do not agree that firn volume change △Vfirn can easily be measured and thus be used to calculate $f_{\Delta V}$: Most of the recent studies on regional geodetic mass changes (Nuth et al., 2010, Moholdt et al., 2010, Kääb et al., 2012, Gardelle et al., 2012, Bolch et al., 2013 etc.) determine their conversion factors by separately evaluating volume changes in the accumulation and the ablation area. A volume change above the ELA is thus regarded as a firn volume change △Vfirn (for which a certain density is assumed). This would however only be true if no (!!) ice flow is present. As glaciers are dynamic, elevation (or volume) changes in different zones of the glacier cannot be regarded separately. In fact, this issue might lead to a significant underestimation of the uncertainties in state-of-the-art mass change assessments based on the geodetic method.

Pg 226-227: Maybe list the experiments in bullets. This would aid the reader easily recover what exactly is being done in Figure 4.

Done.

Section 3.2., Fig 5: Which mass balance series was used for Silvrettagletscher? Was it the homogenized series or the series that did not fit with the geodetic assessments? In both cases, I do not understand how then the conversion factor was calculated since both series are either no longer independent, or that the two series are significantly different.

See also the response to the comment of Reviewer #2. The homogenized series (Huss et al., 2009) was used in order to provide a realistic surface mass balance forcing. Volume changes are calculated (!) with the firn compaction model, and not based on observed geodetic mass balances.
These issues are clarified in the revised version of the manuscript.

Interactive comment on The Cryosphere Discuss., 7, 219, 2013.