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Interactive
Comment

Interactive comment on "Brief Communication: Contending estimates of early 21st century glacier mass balance over the Pamir-Karakoram-Himalaya" *by* A. Kääb et al.

A. Kääb et al.

kaeaeb@geo.uio.no

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Dear Paolo Reggiani and Tom Rientjes

We would like to provide an initial response to this comment in order to facilitate open discussion. Specific responses will be prepared after the discussion phase together with the response to other comments and a revised version of the manuscript.

First of all we would like to thank you for your engaged and detailed comments. We will certainly clarify our manuscript in the light of these comments, in order to better describe our intentions and avoid potential misunderstandings. Here we discuss what we believe are your two major concerns: (1) Validation of ICESat satellite laser altimetric glacier mass changes (2) Hydrological implications of our glacier mass changes

(1) Validation of ICESat satellite laser altimetry

(1.1) It is specifically not clear which independent method for glacier mass change estimation reveals the most accurate time series. In-situ glacier mass changes are logistically limited to a few points over a few glaciers regionally, while geodetic volume change estimates can be estimated regionally. In fact, the higher temporal resolution in-situ glacier mass balance time series is often checked and sometimes calibrated to the geodetically derived volume changes (e.g. Zemp et. al., 2013). There are only a few comparisons available between glaciological glacier mass changes and ICESat altimetry (e.g. Kropáček et al. 2014; Fig S6, Supplement of Kääb et al., 2012) and it remains open to what extent the in-situ measurements are presentative of a whole region (see Cogley, 2012). Glacier volume changes are commonly estimated using repeat DEMs and continuous altimetry; the latter samples continuously in space but limited in time. Altimetry samples at higher temporal resolutions but is spatially limited to satellite orbits. Altimetry has therefore been used statistically to estimate trends in glacier elevation changes over the lifetimes of the altimeters, most commonly for the ice sheets, but also for mountain glacier regions (Nuth et al., 2010; Moholdt et al., 2010; Kääb et al., 2012, etc). In conclusion, often the best practice of validation is cross comparison between sensors and methods, which we have described in elaborate detail within the Supplement of Kääb et. al., 2012 (for open-access version: http://folk.uio.no/kaeaeb/publications/nature_finalmanus.pdf)

In the following two points, we discuss the accuracy of the satellite sensor and the ability of it to produce reliable glacier mass changes.

(1.2) ICESat elevations are well calibrated/validated over flat terrain and a number of studies over ice, water and salars indicate elevation accuracies of a few centimetres to decimetres under ideal conditions (see http://nsidc.org/data/icesat/publications/index.html, and the ICESat Algorithm Theoretical Basis Documents, also linked from the latter page). New ICESat releases are still produced and published with improved accuracy, even several years after the ICESat life time (e.g. Borsa et. al., 2014). Also, a number of studies outside the Himalayas investigated and characterized the accuracy and performance of ICESat over rough topography (e.g., Kääb, 2008; Nuth et al., 2010; Moholdt et al., 2010; Nuth and Kääb, 2011; Kropacek et al. 2014, to name only a few. See above NSIDC link for more). These studies confirm that ICESat data can actually be used over rough topography, of course at reduced accuracy compared to flat surfaces, and thus typically rather for regional scales than over single glaciers. (See also the interactive discussion on the Phan et al. TCD paper, http://www.the-cryosphere-discuss.net/8/2425/2014/tcd-8-2425-2014.html)

(1.3) A strict validation of ICESat-derived glacier changes from independent, and temporally and spatially coincident data over the Himalayas is impossible because the mission ended in 2009, and the current available archives of available DEMs (i.e. ASTER) from this time period are not of high enough accuracy and do not cover the large regions that are used to integrate our ICESat elevation change trends into glacier mass changes. For these reasons, we have spent considerable effort to test and characterise ICESat performance and ability over the Himalayas in the Supplement of Kääb et al. (2012) and through the comparison to satellite DEMs in Gardelle et al. (2013). Within the limitations given in the Kääb et al. (2012) Supplement and within the error bars given in the paper discussed here and in Kääb et al. (2012), we (and others, e.g., Gardner et al., 2013; Neckel et al., 2014) believe ICESat measurements are valid to estimate glacier volume changes at*** regional scales *** in the Himalayas. We are not aware of a study that contradicts these conclusions.

(2) Hydrological implications

(2.1) First of all, our intention to compare discharge equivalent glacier mass change (DE) to average annual river run-off is far from investigating any hydrological budget or balance closure. (A short communication would indeed not be the right format for that). Rather, we want to roughly highlight the relative importance of glacier mass change for the river flow in different zones over our study area. This might have been a misunderstanding and we will clarify that.

(2.2) The proposal to compare glacier mass change to changes in river flow is, no doubt, a valuable approach towards a hydrological budget and used by a number of authors. But for our aim of the relative importance between DE and river flow, rough run-off averages are sufficient. Uncertainties or temporal trends in these average values will have little effect on the regional pattern highlighted in our Fig. 2. Adding uncertainties for the river discharge used (not done as indicated in the Supplement) as root-sum-square to the uncertainties of the DE would change the values in Fig. 2 only marginally.

(2.3) To use a hydrological budget to validate geodetic mass balances is to our understanding problematic, at least in the Himalayas, as horizontal and vertical patterns in precipitation are too poorly known and the few valley stations hardly representative (Immerzeel et al., 2012, 2014; Reggiani and Rientjes, 2014). We expect that the resulting uncertainty in total precipitation over these high-mountain catchments is at least on the same order or even exceeding the uncertainty of the ICESat-derived glacier mass changes. In consequence, other authors (e.g., Immerzeel et al. 2012) find it a good approach to actually investigate the representativeness of the few valley precipitation measurements against the geodetic glacier mass changes using a hydrological budget, not vice-versa. In some regions of our study area, even the existence of major glaciers alone can hardly be explained by measured precipitation amounts (Immerzeel et al., 2012). Ultimately, we certainly agree with your comment about the "importance of exploiting and integrating information from alternative hydro-meteorological and ice-storage data sources such as satellite remote sensing, atmospheric reanalysis and ground-based products…". But such work would exceed by far the purpose of this Brief Communication, and is already underway by other, better specialised groups.

(2.4) We were not aware of Reggiani and Rientjes (2014) before your comment and

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find it very valuable in highlighting and discussing the problems in closing the Upper Indus Basin (UIB) hydrological balance. We will certainly include a reference to the paper and the issues discussed in our revised manuscript. As a side-comment, we would like to stress again that the 'Karakoram anomaly' (i.e. glacier mass stable or even increasing) is not spatially coincident with the UIB. Actually, the UIB is only on the slope of such anomaly, which explains why we obtain significantly negative glacier mass change for the entire UIB. This is therefore one of the important results of our study and has to our best knowledge not been shown clearly before.

(2.5) We believe that the largely unchanged long-term river run-off trend at Tarbela dam cannot be compared to or used to validate our ICESat-derived mass changes:

- Our measurements cover 5 years and we hope to have it made very clear that these 5 years need by no means to be representative for longer time periods. Cutting out just 2003-2008 from Fig. 2 of Reggiani and Rientjes (2014) illustrates that comparing our 5-year trend to the long-term variation in run-off is problematic. Actually, comparing the temporal variation of run-off at Tarbela dam (Fig 2 of Reggiani and Rientjes) with the variation of glacier thickness from ICESat (Fig. 2, panel JK, Kääb et al., 2012; the UIB variation resembles JK) reveals some encouraging similarity.

- The UIB is a large area and stretches over several glacier systems with different climatic and glaciological characteristics. It is possible that the pattern and amount of glacier mass change (negative and positive) have spatio-temporally interfered in the UIB over the recent decades in a way that leaves the total glacier mass loss and its DE largely unchanged. For instance, large glacier shrinkage in one area could have been compensated by mass gain at other areas at the same time, whereas in another period all glaciers could have changed little, both leading to the same total (in the example: low) DE.

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