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

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General

The comment addresses the necessity of validating satellite-geodetic glacier mass imbalance estimates in the Pamir-Karakoram-Himalaya (PKH) region via hydrological balance closure analysis. It also stresses the need of comparing glacier mass loss estimates against the expected rate of change of observed stream flow. The hydrological mass balance is proposed as solid approach for validating satellite altimetry-based glacier mass imbalance estimates in data-poor basins.

Introduction

Without valuing the merits of glacier mass imbalance estimates using space-borne information, such as derived from an inter-comparison of SRTM (2000) and ICESAT (2003-2008) altimetry data for the Pamir-Karakoram-Himalaya (PKH) region (Kääb et al. 2012, Gardelle et al., 2013), one of the most rugged regions on Earth, we feel the need to comment on Section 3 of the Communication concerned with glacier mass changes and discharge equivalent (DE), which are indicated as annual average glacier imbalance contribution to river runoff. We advocate hydro-meteorological and water balance analysis to support conclusions on changes of mean annual river flows and possible effects on sea levels:

The study essentially relies on non-validated satellite-altimetry based mass imbalance estimates as a way to infer on glacier ablation and stream flow changes in the PKH system. In our view, non-validated estimates on glacier mass imbalance should be cross-validated by means of ground-based altimetry surveys or hydrological analysis to substantiate their informative content and reliability. The lack of validation is in our opinion methodologically questionable and suggests that conclusions on glacier mass losses must be drawn with utmost care because of implications for climate impact assessments.

Given that flow records for a series of gauging stations are available in several of the basins addressed in the studies, one should use these jointly with precipitation and evaporation estimates to validate the glacier mass loss hypothesis "a priori" via a hydrological balance closure analysis, as done by Bhutyani (1999) at the scale of a single glacier or Reggiani and Rientjes (2014) at the scale of a basin. Instead the study takes uncertain altimetry mass imbalance estimates as point of departure to justify results "a posteriori".

The presentation of ratios of estimated mean annual flow from altimetry based glacier mass losses vs. mean annual flow data gauged in the river basins (Figure 2) is mislead-

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ing and lacks informative added value. Non-validated satellite-altimetry based glacier imbalance estimates (Table 1) are translated to equivalent mean annual discharges (DE) (m3s-1) for the observation period (Table 2), and subsequently DEs compared against observed specific mean annual flows (mmyr-1) (summarized in Table S1 in the Supplement of the Comment). To do so, DEs are converted to specific flows (mmyr-1) via normalization by contributing basin area. At this stage two observations are due:

Firstly, potential glacier mass losses should not be compared against long-term mean annual flows, but to the expected value of the rate of change of flow, which provides an indication if the water balance can be reconciled with the estimated glacier mass loss rates. The ratios presented independently of a hydrological balance, as in Figure 2, provide no added insights.

Secondly, the negative DE values in Table 2, effectively non-renewable glacier melt rates, need to be reported with opposite sign, as they represent supplementary discharge to renewable rates, and therefore are positive contributions to stream flow. This would also facilitate an inter-comparison of DEs for the 2000-2008 sub-period with recorded mean annual flows over longer periods, as done in Reggiani and Rientjes (2014) in the context of a hydrological balance.

The study seeks to justify DE values (Tables 2 and S1) by referring to the literature (e.g. Mukhopadhyay and Khan, 2014). In doing so, justifications become subjective and findings questionable. For instance in the Upper Indus Basin, which is the largest and most glaciated hydrological entity in the study area, DE numbers are compared with results by Savoskul and Smakhtin (2013), which were derived by a robust, albeit simple modeling approach. Moreover, the latter findings were based on published glacier inventories (e.g. World Glacier Monitoring System and the National Snow and Ice Data Centre) with indicated uncertainty of 30%-50% (Table 4 in Savoskul and Smakhtin, 2013), while in the study DE on the Indus (Table S1) is indicated with an uncertainty of 2%, thus an order of magnitude less. Finally, in Table 2 the exact location in the stream network, at which DE estimates are compared with literature data, is not stated. This missing information is very important because of i) the large size of the basin, and ii) for differences in contributing upstream catchment area delineation may occur, as shown for the Upper Indus basin in Reggiani and Rientjes (2014).

Proposed approach

As a more rigorous approach towards estimating glacier mass change and possible impacts on stream flow and water resources, we propose a water balance analysis with indication of the closure error to link various terms with respective uncertainties:

(E[dV)/(dt])=E[P-ET-Q-G] (1)

In Eq. (1) E[ ] is the expected value operator, Q is the streamflow at a control section, P is precipitation and desublimation, while ET is actual evaporation and sublimation. The net input for the system is given by P-ET, while G represents losses (i.e., recharge) to deeper groundwater. It is reasonable to assume that the expected value of the groundwater recharge flux E[G]$\approx$0, because on a mean annual basis subsurface water is flushed out of the system through fast near-surficial runoff or delayed return flows from shallow groundwater systems in alluvial formations. The overall mean annual loss attributable to G is can be considered stationary and within the uncertainty of the individual remaining terms and can thus be neglected. The expected rate of change of volume E[dV/(dt]) accounts for all water going into storage if the derivative is positive, or storage depletion if the derivative is negative. The averaging period of the equations (Reggiani et al., 1998) is at least a year, but typically a multi-decadal series of consecutive years should be used for change detection. We refer to Reggiani and Rientjes (2014) for a detailed application in the Upper Indus Basin. There it is shown that a DE value of 220 ± 26 m3s-1, as indicated in Table 2, is incompatible with the observed long-term mean annual stream flow at the basin outlet and with basin-average precipitation and evaporation.

We note that for high altitudes (>3500 m.a.s.l.) and inaccessible areas like the PKH, in-situ data is sparsely collected, which stresses the importance of exploiting and inte-

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grating information from alternative hydro-meteorological and ice-storage data sources such as satellite remote sensing, atmospheric reanalysis and ground-based products including the Climate Research Unit (CRU) and the Global Precipitation Climatology Centre (GPCC) datasets.

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