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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Reconciling high altitude precipitation in the upper Indus Basin with glacier mass balances and runoff" *by* W. W. Immerzeel et al.

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General
The discussion paper presents an analysis of precipitation estimation by inverse precipitation-stream flow modeling, aimed at proving that a) precipitation gauged by valley stations and b) TRMM remote sensing estimates of precipitation for the Upper Indus Basin (UIB) grossly underestimate actual precipitation. As an alternative to TRMM and gauged data, the authors use ERA-interim and MERRA reanalysis products to derive basin-wide mean annual precipitation. The products are artificially corrected, whereby closure of the basin-scale mean annual mass balance equation Q=P-ET+MB serves as a constraint. Losses to groundwater and buffer effects due to longer residence times of water in alluvial deposits (generally composed of silt, sand and gravel) are neither addressed nor mentioned. The discharge Q is the observed long-term mean annual stream flows for various sub-catchments, ET is estimated from reanalysis data or an energy balance model, while glacier mass balance accounting (MB) is based on ICESAT satellite altimetry (25 sqkm resolution). In the inverse model, precipitation P is considered as the dependent variable. The analysis window is 2003-2007. The verification of the mass balance closure is achieved by means of a grid-based distributed hydrological model (PCGLOB) (1 sqkm grid resolution, daily time step), which estimates net precipitation (P-ET) and contains glacier mass balance accounting (MB) with the aim to reproduce observed flows (Q) at a series of observation points. From modeling and an uncertainty analysis in which several precipitation correction model parameters are drawn by Monte Carlo analysis, it is concluded, that the mean annual precipitation over the basin must equate 913$\pm$323mm/year. This value is approximately a factor three higher than the estimates stated in several earlier publications (Immerzeel et al. 2009, 2010; Bookhagen and Burbank 2010). Actual evaporation is estimated as an average of four widely disparate products, including ERA Interim evaporation (i), MERRA reanalysis evaporation (ii), an estimate using an energy balance model (iii) and an estimate computed by PCGLOB via soil moisture accounting (iv). The average value and spread between the four products is 359$\pm$107mm/yr. In the works by Immerzeel et al. (2009, 2010) and Bookhagen

Burbank (2010) evaporation is neglected.

Observations

The paper seems to be another attempt (e.g., Immerzeel et al. 2012a, 2013) to come up with more realistic results than those first published in Immerzeel et al. (2009), where a mass balance analysis of the UIB was performed using basin-average TRMM precipitation estimates of 300 mm/year for the 2001-2005 period to drive the SRM hydrological model (Martinec, 1975). From the modeling results at that time, the authors reached the conclusion that to close the mass balance at Besham Quila gauging station (upstream of the basin outlet at Tarbela Reservoir), where 460 mm/year is the observed long-term mean annual flow, the supplementary discharge required to close the water balance must come from non-renewable glacier wastage at a rate of 1% per year. The authors cited these results in another sequel article (Immerzeel et al., 2010). In Immerzeel et al. (2012b), the Indus basin was labelled as "hot spot" based on the 2010 findings, including the water supply perspective. In Immerzeel et al. (2009) actual evaporation as a forcing term is set to zero. If included, it would lead to a higher (and even more unrealistic) glacier melting rate to close the water balance. In our view, the discussion paper suffers from a series of conceptual shortcomings:

Firstly, the authors continue to look at a very short time window (2002-2007), ignoring longer, climatic, time scales. For instance, when the 50-year trend of the observed Indus flows at the inlet of Tarbela Reservoir, downstream of Besham Quila, is considered, it should have become outright apparent that flow data exhibit an essentially stable trend from 1961 to date, as indicated by Reggiani and Rientjes (2015) and Mukhopadhyay and Khan (2015a). Moreover, the cumulative reservoir inflow volumes at Tarbela for the 1999-2009 decade were actually 4% below the 1961-2009, 50-year average (see Table 2 in Reggiani and Rientjes, 2015), the same

time window for which Kääb et al. (2012) estimated a non-renewable ice mass loss from ICESAT altimetry data equivalent to 231$\pm$ 46 m3/s of mean annul discharge at Tarbela. This equivalent discharge is 10% higher than the observed long-term mean annual flow and casts doubts on the reliability of the satellite-based ice mass estimates for the UIB. As a result, one should question if the satellite-derived mass balance estimates can be considered and used as an estimator variable for glacier mass balance accounting, and as in this case, to derive inferences about precipitation.

Secondly, different studies have addressed the issue of estimating realistic precipitation and actual evaporation rates. For the Upper Indus Basin (UIB), a large number of gridded rainfall products have been examined. For instance Palazzi et al. (2013) and Reggiani Rientjes (2015) studied several precipitation reanalysis products showing that the basin-average precipitation in the UIB is indeed at least double the rates indicated by the TRMM 3B43 product in Immerzeel et al. (2009; 2010) and in the order of 675$\pm$ 100 mm/yr, thus significantly higher than those recorded at valley stations (Archer and Fowler, 2004). Several studies with weather stations placed over limited periods at high altitudes have indicated that actual precipitation in the high altitude mountainous areas is significantly higher, reaching up to 2000 - 3500 mm and higher of w.e. per year (e.g. Wake 1989, Cramer 2000, Kuhle 2005, Winiger 2005), to then decrease higher up, an already well-known phenomenon (see Fig. 8 in Mukhopadhyay Khan, 2014a). Also, estimates of actual evaporation are provided, which have been presented in literature based on few field experiments at highly glaciated mountain ranges including the Himalayas at large (Buthyani, 1999, Khattak et al., 2011) and valley-based stations (see Fig. 7 in Mukhopadhyay and Khan, 2014a). In particular, Buthyani (1999) indicated a mean annual total evaporation rate in the order of 200 mm/yr for Siachen glacier based on glacier mass balance. In the discussion paper the authors rely on i) gridded estimated actual evaporation with mean values which are at least a factor two higher than observed in glaciated areas in the Himalayas, ii) possibly inconsistent satellite-based glacier mass estimates, iii) and short-term flow records as independent variables to draw inferences about precipitation. The more robust approach would be to rely on evaporation and precipitation estimates and trends to infer on glacier mass balance. In this case, it would become apparent that satellite-derived mass balances are not sufficiently reliable to serve as support in inverse modeling of precipitation.

Thirdly, the authors chose to ignore long-term observed flow time series. An inverse modeling attempt like the one proposed here, with multiple uncertain independent variables (i.e. ET, MB), cannot replace or serve as a substitute to any sound analysis of observed stream flow data. Neither does an inverse steam flow modeling on a time window of half a decade convey a sense of confidence when conclusions need to be drawn on long-term, climate-controlled glacier mass storage. An analysis of longer flow records in space and time would provide considerably more insights into the mass balance of the basin than numerical modeling alone (in this context we recall that satellite-altimetry derived mass balance in glaciers in extreme topography (Kääb et al., 2012) is essentially an application of reflected electromagnetic wave signal interpretation, which has not undergone any thorough validation for the particular region yet). Rising trends of August flows in the central and eastern Karakoram imply decreasing glacial storage at rates of 0.553 – 0.645 mm/day/year and 0.186 – 0.217 mm/day/year in the Shigar and Shyok watersheds respectively, whereas in the western Karakoram (Hunza watershed) falling trend of August flows implies increasing glacial storage at a rate of 0.552 – 0.644 mm/day/year (Mukhopadhyay Khan, 2014b; Mukhopadhyay et al., 2014; Mukhopadhyay Khan, 2015b). Such rates should be reconciled with the precipitation trends to infer changes in the regionally- averaged glacier mass balance.

Fourth, the distribution of the various parameters in the uncertainty analysis of precipitation are assumed with a (log-)Gaussian distribution, which the authors have not demonstrated to relate to actual empirical distributions in the region that could in

principle be quite different (e.g. bi-modal, skewed, non-Gaussian etc.). The analysis only yields the uncertainty of their precipitation correction model which they have assumed and inserted into the model “a priori” based on values taken from the literature and not necessarily the actual uncertainty of precipitation, which is yet unknown. The precipitation uncertainty analysis pursued in this way is thus akin to a prediction that directly or indirectly causes itself to become true, by the very terms of the prophecy itself (Merton, 1948).

Conclusions

The research and results presented in the paper do not provide relevant benefit towards understanding the hydrological balance in UIB. Findings on gridded precipitation and actual evaporation products are significantly higher than those shown in recent publications, whereas long-term streamflow analysis and aspects of glacier mass storage are not analyzed. The underlying assumption that the water balance can be closed by inversely estimating precipitation results in basin-average precipitation estimates that are likely overrated. Given the essentially stable (or statistically insignificant falling) long-term trend in observed stream flows at the basin outlet, the truly important scientific issue is not an estimation of the absolute value of the basin wide mean annual precipitation, which can hardly be achieved in this terrain, but validation of glacier mass loss estimates against the background of a hydrological balance of the basin and spatial patterns and trends in precipitation, as a function of summer and winter seasons. Such an analysis is needed to validate the mass balance of the glaciers and melting rates variously given in Immerzeel et al. (2009), Kääb et al. (2012) and Gardelle et al. (2012, 2013). Consequently, the discussion paper opens more questions than it provides answers, while the methodological approach does not contribute much of value in this respect.

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