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An appraisal of precipitation distribution in the high-altitude catchments of the Indus basin

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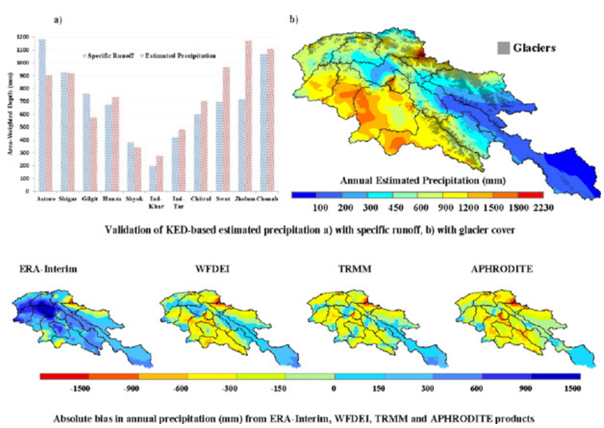
HIGHLIGHTS

- We developed an improved estimation of precipitation distribution over the upper Indus basin.
- Results show clear non-linear increases in precipitation with altitude.
- The estimated precipitation is much higher compared to previous studies and gridded products.
- The gridded precipitation products are unsuitable to force hydrological models in upper Indus.
- The basin-wide seasonal and annual correction factors can be used for hydrological models.

GRAPHICAL ABSTRACT



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ABSTRACT

Scarcity of in-situ observations coupled with high orographic influences has prevented a comprehensive assessment of precipitation distribution in the high-altitude catchments of Indus basin. Available data are generally fragmented and scattered with different organizations and mostly cover the valleys. Here, we combine most of the available station data with the indirect precipitation estimates at the accumulation zones of major glaciers to analyse altitudinal dependency of precipitation in the high-altitude Indus basin. The available observations signified the importance of orography in each sub-hydrological basin but could not infer an accurate distribution of precipitation with altitude. We used Kriging with External Drift (KED) interpolation scheme with elevation as a predictor to appraise spatiotemporal distribution of mean monthly, seasonal and annual precipitation for the period of 1998–2012. The KED-based annual precipitation estimates are verified by the corresponding basin-wide observed specific runoffs, which show good agreement. In contrast to earlier studies, our estimates reveal substantially higher precipitation in most of the sub-basins indicating two distinct rainfall maxima; 1st along southern and lower most slopes of Chenab, Jhelum, Indus main and Swat basins, and 2nd around north-west corner of Shyok basin in the central Karakoram. The study demonstrated that the selected gridded precipitation products covering this region are prone to significant errors. In terms of quantitative estimates, ERA-Interim is relatively

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close to the observations followed by WFDEI and TRMM, while APHRODITE gives highly underestimated precipitation estimates in the study area. Basin-wide seasonal and annual correction factors introduced for each gridded dataset can be useful for lumped hydrological modelling studies, while the estimated precipitation distribution can serve as a basis for bias correction of any gridded precipitation products for the study area.

1. Introduction

The Hindukush Karakoram Himalayan (HKH) mountain region and adjoining ranges of Pamirs and Tibetan Plateau (TP) hold the world's largest repositories of snow and ice mass outside the Polar Regions (Qiu, 2008; UNESCO-SCOPE-UNEP, 2011). The Indus River System (IRS), originating from TP and HKH mountain region and crossing through China, India, Afghanistan and Pakistan, sustains livelihoods of over 215 million people. Yet, little is known about environmental change and mountain hydrology in this highly diversified and complex mountain region (Immerzeel et al., 2012; Karki et al., 2011). There is limited understanding of quantitative and spatiotemporal distribution of precipitation, which provides the basic and critical input for hydrological assessment, mass balance and climate change studies. The current knowledge is mainly constrained by limited in-situ hydro-meteorological and cryospheric mass balance observations in the high-altitude catchments of Indus basin (Pellicciotti et al., 2012; Wake, 1987). Political environments, poor accessibility and harsh weather conditions pose serious challenges for such observations in this region. As a result, there are significant data, information and knowledge gaps in hydro-climatic aspects.

Precipitation in the high-altitude catchments of Indus basin is predominantly controlled by large-scale orography and remains highly variable in time, space and altitude. Its variability and distribution pattern mainly depends on the interactions and interplay of orographic features with large-scale atmospheric circulation systems, regional climatic processes and local evapotranspiration rates. Large changes in precipitation over short distances and within short periods of time are common and high amplitude events are often localized (Nesbitt and Anders, 2009). The zone of maximum precipitation is usually the function of enhanced moisture condensation and exponential reduction in the quantity of available moisture with increasing barrier height (Alpert, 1986). Hence, rainfall gradients in the complex terrains are often not linearly correlated with altitude (Singh and Kumar, 1997; Loukas and Quick, 1996). Nevertheless, several other studies indicated that precipitation in the HKH region exhibits a considerable vertical gradient (e.g. Pang et al., 2014; Winiger et al., 2005; Hewitt, 2011; Weiers, 1995; Wake, 1989; Dhar and Rakhecha, 1981; BIG, 1979; Decheng, 1978).

Precipitation is an important component of the hydrological cycle that governs the renewable water resources affecting agro-economic development, hydropower generation and environmental integrity. Therefore, accurate assessment of precipitation is essential as small errors in precipitation estimates may translate into major changes in surface runoff estimates and associated water allocations. Accurate assessment of precipitation requires good quality observations with adequate spatiotemporal coverage to assess the sub-basin or local scale variability. However, the existing rain gauge network in this region is not only inadequate but also biased towards valley bottoms (Fowler and Archer, 2006). The solid precipitation (snowfall) at higher altitudes is often difficult to accurately measure and generally susceptible to undercatch by 20–50% (Rasmussen et al., 2012). Furthermore, the Indus is an international river basin and the available observational data are usually fragmented and scattered with different organizations in four countries and are not freely accessible. Therefore, there is an ever-increasing trend of using the easily available global and/or regional scale gridded datasets for hydro-climatic assessment and mass balance studies (e.g. Lutz et al., 2014a; Sakai et al., 2014; Immerzeel et al., 2012, 2010, 2009; Tahir et al., 2011; Bookhagen and Burbank, 2006).

Indeed, the gridded datasets provide better information in terms of spatial coverage and temporal consistency, but with potentially large errors particularly in high-mountains where the resolution of the data is often larger than the spatial variability of precipitation and the adopted interpolation schemes add further uncertainty. Also, satellite observations underestimate precipitation in areas with significant snowfall (Andermann et al., 2011). Moreover, the gridded datasets covering the high-altitude areas of Indus basin use station data of only a few commonly available old observatories predominantly located at the valley floors, which do not reflect the topographical complexity and spatial variability of precipitation in these areas (Reggiani and Rientjes, 2015). Hence, the accuracy of gridded datasets is particularly questionable in this region requiring their correction and validation before use. However, the limitations and internal inconsistencies of the gridded datasets are often underestimated or overlooked in the hydro-climate studies; where underestimated precipitation is often compensated by underestimated evapotranspiration and/or overestimated snow/glacier melt rates (Lutz et al., 2014a; Pellicciotti et al., 2012; Schaefli et al., 2005). Ultimately, the inferences regarding precipitation distribution, snow/glacier cover dynamics and associated melt water contributions are inaccurately adjudicated. Point observations, on the other hand, provide relatively accurate local information, but their wider-scale use in hydro-climate studies is constrained by their restricted accessibility, limited spatiotemporal coverage and uneven distribution in both horizontal and vertical directions. Paucity of precipitation measurements in the high-altitude areas, where the bulk of precipitation falls, provides an incomplete picture of precipitation distribution. Auspiciously, there are few mass balance studies (e.g. Mayer et al., 2014, 2006; Hewitt, 2011; Shroder et al., 2000; Bhutiyani, 1999; Wake, 1989; Mayewski et al., 1984, 1983; Kick, 1980; BIG, 1979; Decheng, 1978; Qazi, 1973) that indirectly estimated net precipitation (as water equivalent) using snow pillows, snow pits, and ice cores from the accumulation zones of few important large glaciers in this region. These sparse but relatively accurate and high-altitude point observations can be combined and linked with the low-mid altitude observations to derive high-altitude precipitation and to verify and correct the gridded datasets developed through various means.

In addition, the specific runoffs (measured flow/drainage area) from all the high altitude catchments of Indus basin are significantly higher than the corresponding precipitation estimates by earlier studies (Immerzeel et al., 2012, 2015). This indicates that either the estimated precipitation is lower than the actual or these basins are receiving bulk of their runoff from snow/glacier melt in the absence of an adequate precipitation (snowfall) input to sustain the snow/glacier systems. The latter case certainly recognizes for tangible glacier retreat and loss of glacial mass. However, the scientific research on precipitation inputs and associated snow/glacier mass balance in the study area is uncertain and largely contradicting due mainly to paucity of in-situ precipitation and glacier mass balance data (Kaab et al., 2012; Immerzeel et al., 2009). Moreover, mass balance studies in this region are always difficult as most of the glaciers based at the high-altitude areas (above 4000 m) are often nourished by avalanches and redistribution by wind in addition to seasonal snow (Hewitt, 2013, 2011). While Kaab et al. (2015, 2012), Wiltshire (2014), Gardner et al. (2013), Jacob et al. (2012),