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To
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c/o Dr. R. Woods

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Date November 12, 2015
Subject Second revision statement hess-2015-128

Our reference
WI/20151109

Dear Dr. Woods

I am pleased to submit our second revision of our paper "Reconciling high altitude precipitation in the upper Indus basin with glacier mass balances and runoff".

We have addressed the comments of reviewer 4 and reviewer 5. We have attached our pointwise reply below.

We hope the paper is now acceptable for publication in HESS and that it may contribute to the understanding of the complex hydrology of the upper Indus basin.

With kind regards,

Dr. W.W. (Walter) Immerzeel



Reviewer 4

The author answered the reviewer comments in good detail and modified the manuscript accordingly. The paper is conciser, easier to understand and the new figures add interesting new results. The new method sections summarize the used method very well (first paragraph) but it does not mention the ET estimates for validation (the authors might want to modify this).

Thanks. We do mention the ET estimates for validation as follows now in the first paragraph of the methods section:

“Estimated (annual) runoff, based on the corrected precipitation, actual evapotranspiration based on four gridded products and the observed glacier mass balance, is compared with an extensive set of UIB runoff observations. We also analyse the physical realism of our simulations by deriving a Turc-Budyko plot using precipitation, measured runoff and potential evapotranspiration.”

Detailed comment: HESS does not like (not accept) multi-letter variable names. Please distinguish between abbreviations (ET, MB) and variable names (i.e. ET and MB should be replaced by a variable in the equations). The same would in principle hold for the parameters, an exception might be possible here for parameters that are widely used in a multi-letter form.

We have discussed this with the scientific editor and given that the variables used in the equations and the abbreviations are used intermixed throughout the manuscript, we have decided to leave it as it is, because this is clearer to our opinion. We agreed that if this remains problematic during typesetting, we will correct it as suggested by the type setters.



Reviewer 5

This paper is an example of innovative research with a high practical impact on the water resources availability of millions of people. I found it interesting to review this paper. Despite the original thoughts and new insights, some corrections and amendments should be considered. While there is sufficient depth in the statistical analysis, the hydrological analysis requires more elaboration, especially the separation of UIB into different compartments with more local validation of stream flows and ET fluxes. With more proofs that the new rainfall correction makes sense, the whole work will get more attention and international support. The paper can be accepted for publication if the evidences are more localized and supported with other sources of information (local discharge measurements, local P-ET values that make sense, precipitable water column, atmospheric water balance).

We appreciate the positive feedback. We have done everything within our ability to collect as much local data as feasible within our extensive network in Pakistan. Our detailed response can be found below.

The authors used APHRODITE as the main source of rainfall information. In general terms, this rainfall product is not regarded as being accurate. It can certainly not be used as a reference for various type of gridded rainfall products. I advise the authors to include an analysis of CHIRPS data, that with 5 km resolution meet the authors concerns regarding the large cell size of other existing rainfall products. CHIRPS has build in corrections for rain gauge measurements and elevation, and although not verified, I expect this to be more realistic than APHRODITE.

APHRODITES is also based on rain gauges and the main problem, as we outline in our introduction and which is illustrated by panel B in Figure 1, is that there are only very few stations above 2000 meter. We have investigated the CHIRPS dataset and we have computed the average precipitation for 1998-2007 and we have plotted it below with the same legend as the other products compared in Figure 1 (panel C to E).

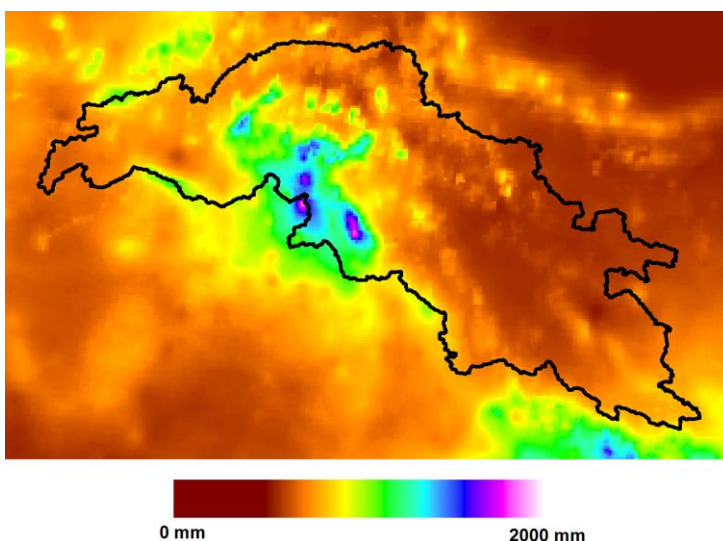


Figure 1 CHIRPS average annual precipitation from 1998 – 2007



Based on this analysis we decided not to use the CHIRPS product as a reference because (i) it seems even to be drier at high altitudes than the other products concerned and (ii) we observe some strange spatial patterns as part of the Himalayan arc, which is wet in all products is now quite dry and there are strange points / bulls eyes visible which is probably an artefact of the stations used in the algorithm.

The Ph.D. dissertation of Cheema from the Delft University of Technology shows that TRMM measurements in the Karakoram requires a 200 mm correction. This level of correction is sufficient for letting P exceed ET values in areas with brooks and gullies, revealing drainage processes. Hence, the local distribution of ET can be used to explain the under-reporting of rainfall (in addition to snowmass).

We have used the spatial distribution in our validation with the discharge data. We use the ETa estimates of 4 different products to estimate runoff at sub-basin level (Eq. 3 and Figure 9). Given the large variation between the four products and the difficulty of applying ET models to high altitude areas we believe that pixel based evaluations of P – ET at high altitude are of little added value in validating our results, but the sub-basin results are.

In addition, in the first revision we have done an additional analysis to check on the hydrological plausibility of our results using Turc-Budyko plots. Here we use potential ET, observed runoff and our corrected precipitation to check whether our results are physically realistic. The reviewer does not refer to these results, but we think they may address a lot of his concerns.

While UIB may not host flux towers for evapotranspiration, other parts of the Tibetan plateau are equipped with several towers, and these measurements under similar high altitude conditions can be used to validate the evapotranspiration estimates from the four different products. High elevation ET modelling may have its own sources of error, and knowledge on the uncertainty envelope could help to include also the spatially distributed ET data for inverse modelling of rainfall.

There are indeed no flux towers to our knowledge in the UIB, but there are indeed towers on the Tibetan plateau operated by the Institute for Tibetan Plateau research and the ITC in Enschede. However these towers are located in the interior of the Tibetan Plateau or in the south-eastern part. The climate in these regions is so distinctively different than the UIB that we believe that they cannot be used to make any claims on ET in the UIB based on these towers and we prefer to stick to the four products we have used in the present version of the manuscript.

The spatial variability of rainfall in UIB is significant, and the authors have made corrections over glacier areas. Did the corrections also include the forests and pastures due to the geo-statistical procedures applied?

We apply the correction only above HREF, which is randomly drawn for each of the 10000 runs using a log-Gaussian distribution with a standard deviation of 500 m. and an average altitude of 2500 m and there is a limited amount of pastures and forest above 2500 m. We



derive PGs for each of the large glacier systems and these PGs are statistically interpolated to the entire region above HREF as described in the methods. Moreover, there is no reason to assume that these PGs are not valid for other land use types.

The inflow into the main reservoirs (and especially for discharges $> 1000\text{m}^3/\text{s}$) is governed by the rainfall surplus (P-ET) over alpine forest and pastures. A separated set of gauging stations near glaciers should be used to validate glacier mass balances. This is probably already done, but the results are presented together with lower altitude gauging stations in Figure 9. I am not convinced that the mass balance of glaciers is controlling the inflow in Tarbella and other reservoirs. But if presented in a local context, then it will demonstrate the role of glacier mass balances on runoff.

The reviewer is right in the assumption that the further downstream one gets the less the influence of snow and glacier melt. However, for the Indus, even for Tarbela the contribution of snow and ice melt is around 60% of the total flow, and the remainder is groundwater runoff and direct rain runoff as we have shown in previous publications:

Immerzeel, W. W., Van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science (New York, N.Y.)*, 328, 1382–1385.

<http://doi.org/10.1126/science.1183188>

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., & Bierkens, M. F. P. (2014). Consistent increase in High Asia 's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, 4, 1–6. <http://doi.org/10.1038/NCLIMATE2237>

To suggestion to distinctly indicate the high altitude catchments is however very good and we have modified Figure 9 accordingly. Those box plots with a red outline are for catchments higher than 4000 m. and with a black outline lower than 4000 meter. The correlation coefficient for the high catchments between observed and simulated runoff is 0.98 and for the low catchment 0.76, so this confirms the assumption. We have added this to the manuscript:

“It is interesting to note that the higher catchment ($r = 0.98$, red outline) show a better correlation with the observed runoff than the lower catchments ($r = 0.76$, black outline)

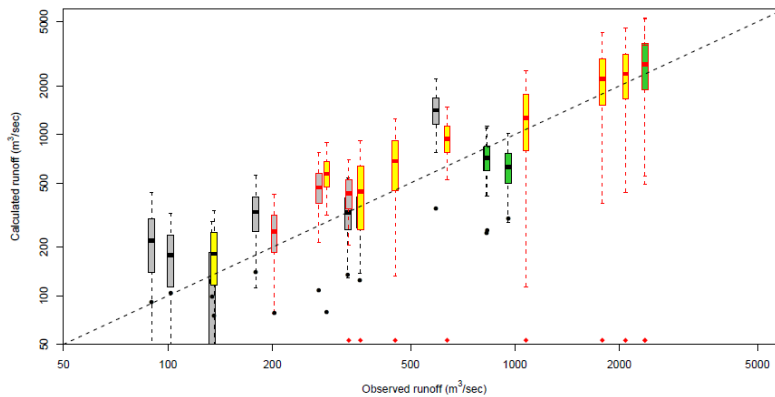


Figure 2 Updated top panel of Figure 9.

Another issue requiring more attention is the storage change in the unsaturated zone and in streams and lakes. The annual stream flow Q is not necessarily equal to $P-ET+MB$ due to storage changes. A longer period of several years is required for letting $P-ET+MB$ coincide with Q .

We are analyzing a period of 5 years (2003 until 2007) and it is safe to assume that the storage change in lakes and the unsaturated zone is negligible over such a period. The large lakes are mostly found on the Tibetan plateau outside the boundary of the UIB. We have discussed storage changes also in our reply to the first round of reviews and we have added a part regarding changes in groundwater storage to the discussion.

While the extra precipitation and snowfall might be correct, it should also match with the atmospheric moisture balance. Can this significantly higher rainfall be explained by the advection process? What is the source of this water? How does a doubled rainfall regime impact the leeward rainfall patterns? Is there continuous lateral transport of atmospheric moisture from evaporation of the plain areas, that sustain rainfall and snowfall? A double amount of rainfall should have a source or origin, and perhaps the atmospheric moisture recycling could explain this process? Adding some climatic analysis and explain the plausibility of double rainfall will improve the general acceptance of the results.

We have added the following discussion to the manuscript:

“Although the ERA-Interim dataset may not be used to reproduce the glacier mass balances it can be used to verify the atmospheric convergence as the product is based on a data assimilation scheme and the ECMWF IFS forecast model that includes fully coupled components for atmosphere, land surface and ocean waves including closure of the atmospheric water balance. The total precipitation sum from 1998 until 2007 of the ERA-Interim dataset over the entire UIB is 947 mm, which is very close to our corrected precipitation sum of 913 mm. This indicates that the westerlies and monsoon circulation transport sufficient moisture into the region to account for the precipitation we estimate. The source of precipitation in the upper Indus is a mixture of the Arabian Sea (westerlies), Bay of Bengal (Monsoon) and potentially also intra-basin moisture recycling (Tuinenburg et al., 2012;



Wei et al., 2013), however further research with atmospheric models is required to quantify these contributions further.”

Remarks

Where is the boundaries presented in Figure 1 based on?

The boundaries are based on the HydroSheds catchment boundaries derived from the SRTM DEM. The reference has been added to the caption of Figure 1.

The average monthly rainfall and ET values for the various algorithms should be reported in tabular format

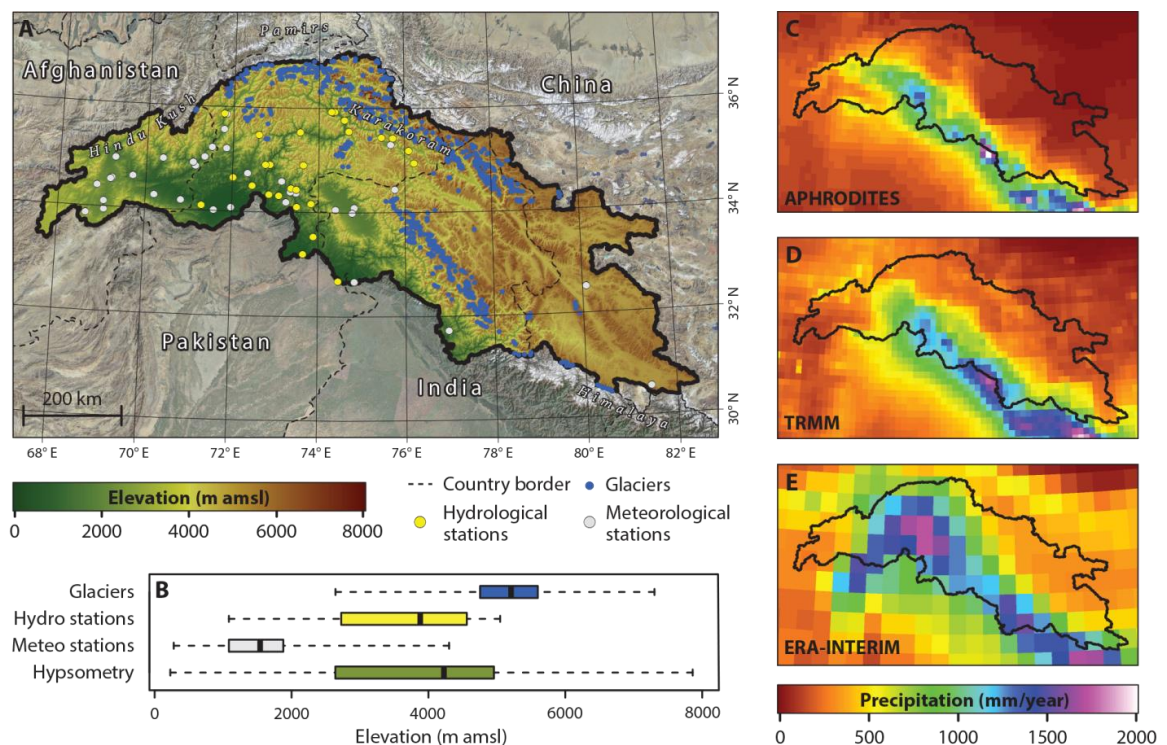
All relevant values are discussed in the text and given the already large number of figures and tables we propose to keep it as it is.

Can the elevation be added to Table 2 ?

Yes, the mean catchment elevation has been added for each discharge point.

A map with the location of the discharge gauging stations should be added

The locations of the stations have been added to Panel A of Figure 1. In panel B we have also added an extra box plot showing the catchment mean elevations.





The abstract should more reflect the average condition (double rainfall and snowfall), and not focus too much on the extreme corrections of a factor 10. This is somewhat misleading

OK, we have rephrased this into

“An independent validation with observed river flow confirms that the water balance can indeed only be closed when the high altitude precipitation on average is more than twice as high and in extreme cases up to a factor ten higher than previously thought.

The MODIS data sets also contain a number of atmospheric parameters, including precipitable water amounts. Analysis of the atmospheric composition could facilitate the existence of higher rainfall intensities in certain areas.”

We propose to stick to the analysis of ERA-Interim (see reply above) as this is based on a coupled model ensuring atmospheric mass conservation.

Figure 10 is a graphical confirmation of the inconsistency in mass balance discussed before. It does not contribute to the overall findings of the paper.

We think the reviewer means Figure 11 where we show the reconstructed mass balances. We propose to retain the figure as we use it to make our point that although ERA-Interim provides the right magnitude of precipitation the coarse resolution results in unrealistic glacier mass balances.

Reconciling high altitude precipitation in the upper Indus basin with glacier mass balances and runoff

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Abstract

Mountain ranges in Asia are important water suppliers, especially if downstream climates are arid, water demands are high and glaciers are abundant. In such basins, the hydrological cycle depends heavily on high altitude precipitation. Yet direct observations of high altitude precipitation are lacking and satellite derived products are of insufficient resolution and quality to capture spatial variation and magnitude of mountain precipitation. Here we use glacier mass balances to inversely infer the high altitude precipitation in the upper Indus basin and show that the amount of precipitation required to sustain the observed mass balances of large glacier systems is far beyond what is observed at valley stations or estimated by gridded precipitation products. An independent validation with observed river flow confirms that the water balance can indeed only be closed when the high altitude precipitation is on average is more than twice as high and in extreme cases up to a factor ten higher than previously thought. We conclude that these findings alter the present understanding of high altitude hydrology and will have an important bearing on climate change impact studies, planning and design of hydropower plants and irrigation reservoirs and the regional geopolitical situation in general.

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1 **1 Introduction**

2 Of all Asian basins that find their headwaters in the greater Himalayas, the Indus basin
3 depends most strongly on high altitude water resources (Immerzeel et al., 2010; Lutz et al.,
4 2014) The largest glacier systems outside the polar regions are found in this area and the
5 seasonal snow cover is the most extensive of all Asian basins (Immerzeel et al., 2009). In
6 combination with a semi-arid downstream climate, a high demand for water owing to the
7 largest irrigation scheme in the world and a large and quickly growing population, the
8 importance of the upper Indus basin (UIB) is evident (Immerzeel and Bierkens, 2012).

9 The hydrology of the UIB ($4.37 \cdot 10^5 \text{ km}^2$) is, however, poorly understood. The quantification
10 of the water balance in space and time is a major challenge due the lack of measurements and
11 the inaccessibility of the terrain. The magnitude and distribution of high altitude precipitation,
12 which is the driver of the hydrological cycle, is one of its largest unknowns (Hewitt, 2005,
13 2007; Immerzeel et al., 2013; Mishra, 2015; Ragetti and Pellicciotti, 2012; Winiger et al.,
14 2005). Annual precipitation patterns in the UIB result from the intricate interplay between
15 synoptic scale circulation and valley scale topography-atmosphere interaction resulting in
16 orographic precipitation and funnelling of air movement (Barros et al., 2004; Hewitt, 2013).
17 At the synoptic scale, annual precipitation originates from two sources: the south-eastern
18 monsoon during the summer and moisture transported by the westerly jet stream over central
19 Asia (Mölg et al., 2013; Scherler et al., 2011) during winter. The relative contribution of
20 westerly disturbances to the total annual precipitation increases from south-east to north-west,
21 and the anomalous behaviour of Karakoram glaciers is commonly attributed to changes in
22 winter precipitation (Scherler et al., 2011; Yao et al., 2012).

23 At smaller scales the complex interaction between the valley topography and the atmosphere
24 dictates the spatial distribution of precipitation (Bookhagen and Burbank, 2006; Immerzeel et
25 al., 2014b). Valley bottoms, where stations are located, are generally dry and precipitation
26 increases up to a certain maximum altitude (HMAX) above which all moisture has been
27 orographically forced out of the air and precipitation decreases again. In westerly dominated
28 rainfall regimes HMAX is generally higher, which is likely related to the higher tropospheric
29 altitude of the westerly airflow (Harper, 2003; Hewitt, 2005, 2007; Scherler et al., 2011;
30 Winiger et al., 2005).

31 Gridded precipitation products are the de facto standard in hydrological assessments, and they
32 are either based on observations (e.g. APHRODITES (Yatagai et al., 2012)), remote sensing

1 (e.g. the Tropical Rainfall Monitoring Mission (Huffman et al., 2007)) or reanalysis (e.g.
2 ERA-Interim (Dee et al., 2011)) (Fig. 1, panel C to E). In most cases the station data strongly
3 influence the distribution and magnitude of the precipitation in those data products; however
4 the vast majority of the UIB is located at elevations far beyond the average station elevation
5 (Fig. 1, panel A to B). The few stations that are at elevations above 2000 m are located in dry
6 valleys and we hypothesize that the high altitude precipitation is considerably underestimated
7 (Fig. 1, panel C to E). Moreover, remote sensing based products, such as TRMM, are
8 insufficiently capable of capturing snowfall (Bookhagen and Burbank, 2006; Huffman et al.,
9 2007) and the spatial resolution (25 to 75 km²) of most rainfall products (and the underlying
10 models) is insufficient to capture topography-atmosphere interaction at the valley scale (Fig.
11 1, panel C to E). Thus, there is a pressing need to improve the quantification of high altitude
12 precipitation, preferably at large spatial extents and at high resolution.

13 A possible way to correct mountain precipitation is to inversely close the water balance.
14 Previous studies in Sweden and Switzerland have shown that it is possible to derive vertical
15 precipitation gradients using observed runoff in a physically realistic manner (Valéry et al.,
16 2009; Valéry et al., 2010). Earlier work at the small scale in high mountain Asia suggested
17 that the glacier mass balance may be used to reconstruct precipitation in its catchment area
18 (Harper, 2003; Immerzeel et al., 2012a). Fig. 1 (panel A and B) shows that UIB glaciers are
19 located at high elevations that are not represented by station data. Therefore the mass balances
20 of the glaciers may contain important information on high altitude accumulation in an area
21 that is inaccessible and ungauged, but very important from a hydrological point of view. In
22 this study we further elaborate this approach by inversely modelling average annual
23 precipitation from the mass balance of 550 large (> 5 km²) glacier systems located throughout
24 the UIB. We perform a rigorous uncertainty analysis and we validate our findings using
25 independent observation of river runoff.

26 **2 Methods**

27 We estimate high altitude precipitation by using a glacier mass balance model to simulate
28 observed glacier mass balances. We use a gridded dataset from valley bottom stations as a
29 basis for our precipitation estimate and we compute a vertical precipitation gradient (PG (%
30 m⁻¹)) until observed mass balances match the simulated mass balance. We repeat this process
31 for the 550 major glacier systems in the UIB, and the resulting PGs are then spatially
32 interpolated to generate a spatial field that represents the altitude dependence of precipitation.

1 We use this field to update the APHRODITE precipitation and generate a corrected
2 precipitation field that is able to reproduce the observed glacier mass balance. We validate the
3 findings independently with a water balance approach. Estimated (annual) runoff, -based on
4 the corrected precipitation, actual evapotranspiration [based on four gridded products](#) and the
5 observed [glacier](#) mass balance, is compared with an extensive set of UIB runoff observations.
6 [We also analyse the physical realism of our simulations by deriving a Turc-Budyko plot using](#)
7 [precipitation, measured runoff and potential evapotranspiration](#). A rigorous uncertainty
8 analysis is also conducted on the six most critical model parameters including potential
9 effects of spatial correlation.

10 **2.1 Datasets**

11 2.1.1 Glacier mass balance and outlines

12 Glacier mass balance trends based on ICESat (Kääb et al., 2012a) are recomputed for the
13 period 2003 until 2008 for the three major mountain ranges in the UIB: the Karakoram, the
14 Hindu-Kush and the Himalaya Fig. 1. For each zone the mass balance is computed including
15 a regional uncertainty estimate (Kääb et al., 2012a). From the zonal uncertainty (σ_z) we
16 estimate the standard deviation between glaciers within a zone (σ_g) as

$$17 \quad \sigma_g = \sigma_z \sqrt{n} . \quad (1)$$

18 Where n is the number of glaciers within a zone. The σ_g values used in the uncertainty
19 analysis are shown in Table 1.

20 Glacier outlines area based on the glacier inventory of the International Centre for Integrated
21 Mountain Development (Bajracharya and Shrestha, 2011).

22 2.1.2 Precipitation and temperature

23 The daily APHRODITE precipitation (Yatagai et al., 2012) and air temperature datasets
24 (Yasutomi et al., 2011) from 2003 until 2007 are used as reference datasets to ensure
25 maximum temporal overlap with the ICESat based glacier mass balance dataset (Kääb et al.,
26 2012a). The precipitation dataset is resampled from the nominal resolution of 25 km^2 to a
27 resolution of 1 km^2 using the nearest neighbour algorithm. The air temperature dataset is then
28 bias-corrected using monthly linear regressions with independent station data to account for
29 altitudinal and seasonal variations in air temperature lapse rates (Fig. 3).

1 2.1.3 Runoff and evapotranspiration

2 We use runoff data, potential (ET_p) and actual evapotranspiration (ET_a) data for the
3 validation of our results. For runoff we compiled all available published data, which we
4 complemented with data made available by the Pakistan Meteorological Department and the
5 Pakistan Water and Power Development Authority.

6 Evapotranspiration is notoriously difficult to monitor and there are few direct measurements
7 of ET_a in the upper Indus. In earlier UIB studies, ET was estimated using an empirical
8 formulae based on air temperature but was only applied to the Siachen glacier (Bhutiyani,
9 1999; Reggiani and Rientjes, 2014). We take into account the uncertainty in ET in our stream
10 flow estimates and develop a blended product based on re-analysis datasets, a global
11 hydrological model and an energy balance model. Four gridded ET_a and three gridded ET_p
12 products were resampled to a 1 km² resolution at which we perform all our analyses:

- 13 • ERA-Interim reanalysis (Dee et al., 2011): ERA-Interim uses the HTESSEL land
14 surface scheme (Dee et al., 2011) to compute actual evapotranspiration (ET_a). For
15 transpiration a distinction is made between high and low vegetation in the HTESSEL
16 scheme and these are parameterized from the Global Land Cover Characteristics
17 database at a nominal resolution of 1 km².
- 18 • MERRA reanalysis (Rienecker et al., 2011): The MERRA reanalysis product of
19 NASA applies the state-of-the-art GEOS-5 data assimilation system that includes
20 many modern observing systems in a climate framework. MERRA uses the GEOS-5
21 catchment LSM land surface scheme (Koster et al., 2000) to compute actual ET. For
22 the MERRA product ET_p is not available.
- 23 • ET-Look (Bastiaanssen et al., 2012): The ET-Look remote sensing model infers
24 information on ET from combined optical and passive microwave sensors, which can
25 observe the land-surface even under persistent overcast conditions. A two-layer
26 Penman–Monteith forms the basis of quantifying soil and canopy evaporation. The
27 dataset is available only for the year 2007, but it was scaled to the 2003 – 2007
28 average using the ratio between the 2003 – 2007 average and the 2007 annual ET
29 based on ERA-INTERIM.

- PCRGLOB-WB (Wada et al., 2014): The global hydrological model PCRGLOB-WB computes actual evapotranspiration using potential evapotranspiration based on Penman-Monteith, which is further reduced based on available soil moisture.

The average annual ETa for the period 2003 – 2007 for each of the four products is shown in Fig. 2. The spatial patterns show good agreement, but the magnitudes differ considerably. The ensemble mean ETa for the entire upper Indus equals $359 \pm 107 \text{ mm y}^{-1}$.

2.2 Model description

We use the PC-Raster spatial-temporal modelling environment (Karssenberget al., 2001) to model the mass balance of the major glaciers in each zone and subsequently estimate precipitation gradients required to sustain the observed mass balance. The model operates at a daily time step from 2003 until 2007 and a spatial resolution of 1 km^2 . For each time step the total accumulation and total melt are aggregated over the entire glacier surface. Only glaciers with a surface area above 5 km^2 are included in the analysis (Karakoram = 232 glaciers, Hindu-Kush = 119, Himalaya = 204 glaciers) as the ICESat measurements do not reflect smaller glaciers. The model is forced by the spatial precipitation and temperature fields. The precipitation fields are corrected using a precipitation gradient (PG, $\% \text{ m}^{-1}$). Precipitation is positively lapsed using a PG between a reference elevation (HREF) to an elevation of maximum precipitation (HMAX). At elevations above HMAX the precipitation is negatively lapsed from its maximum at HMAX with the same PG according to:

$$P_{cor} = P_{APHRO} \cdot (1 + (H - HREF) \cdot PG \cdot 0.01) \quad \text{Eq. 1}$$

for $HREF < H \leq HMAX$, and:

$$P_{cor} = P_{APHRO} \cdot (1 + (((HMAX - HREF) + (HMAX - H)) \cdot PG \cdot 0.01)) \quad \text{Eq. 2}$$

for $H > HMAX$

1 HREF and HMAX values are derived from literature (Table 1) and uncertainty is taken into
2 account in the uncertainty analysis. HMAX varies per zone and lies at a lower elevation in the
3 Himalayas than in the other two zones (Table 1). We spatially interpolate HMAX from the
4 average zonal values to cover the entire UIB.

5 The melt is modelled over the glacier area using the positive degree day (PDD) method
6 (Hock, 2005), with different degree day factors (DDF) for debris-covered (DDFd) and debris-
7 free (DDFdf) glaciers derived from literature (Table 1). To account for uncertainty in DDF,
8 the DDFd and DDFdf are taken into account separately in the uncertainty analysis. At
9 temperatures below the critical temperature of 2 °C (Immerzeel et al., 2013; Singh and
10 Bengtsson, 2004) precipitation falls in the form of snow and contributes to the accumulation.
11 Avalanche nourishment of glaciers is a key contributor for UIB glaciers (Hewitt, 2005, 2011)
12 and to take this process into account, we extend the glacier area with steep areas directly
13 adjacent to the glacier with a slope over an average threshold slope (TS) of 0.2 m m^{-1} . This
14 average threshold slope is derived by analysing the slopes of all glacierized pixels in the basin
15 (Fig.4). To account for uncertainty in TS this parameter is taken into account in the
16 uncertainty analysis.

17 For each glacier system we execute transient model runs from 2003 until 2007 and we
18 compute the average annual mass balance from the total accumulation and melt over this
19 period. We make two different runs for each glacier system with two different PGs (0.3%
20 m^{-1} and 0.6% m^{-1}) and we use the simulated mass balances of these two runs and the
21 observed mass balances based on ICESat to optimize the PG per glacier, such that the
22 simulated mass balance matches the observed.

23 To interpolate the glacier-specific PG-values to PG spatial fields over the entire domain we
24 use geostatistical conditional simulation (Goovaerts, 1997). Simulated spatial fields of PG are
25 thus conditioned on the PGs determined at the glaciers centroid. The semi-variogram has the
26 following parameters: nugget = 0, the range = 120 km, sill = variance of PGs.

27 **2.3 Uncertainty analysis**

28 A rigorous uncertainty analysis is performed to take into account the uncertainty in parameter
29 values and uncertainty in regional patterns. To account for parameter uncertainty we perform
30 a 10,000 member Monte Carlo simulation on the parameters given in Table 1. For each run
31 we randomly sample the parameter space based on the average (μ) and the standard deviation

1 (σ), which are all based on literature values. For the positively-valued parameters we use a
2 log-Gaussian distribution and a Gaussian distribution in case parameter values can be
3 negative. We take into account uncertainty in the following key parameters (HREF, HMAX,
4 DDFd, DDFdg, TS) for the PG as well as uncertainty in the mass balance against which the
5 PG is optimized (MB). We randomly vary the 5 parameters (HREF, HMAX, DDFd, DDFdg,
6 TS) 10,000 times and calculate the PG for each glacier for each random parameter set drawn,
7 thus resulting in 10,000 PG-sets for each glacier considered. For each of the 10,000 PG-sets
8 we then use conditional simulation (see above) to arrive at 10,000 equally probable spatial
9 PG-fields, taking account of parameters uncertainty, mass-balance uncertainty and the
10 interpolation error. Note that for each of the 10,000 sets the variogram is scaled with the
11 variance of the PGs associated with the specific parameter combination drawn. Finally, based
12 on the results of the 10,000 simulations we derive the average corrected precipitation field
13 and the associated uncertainty in the estimates

14 Using the 10,000 combinations of parameters and associated PGs we ran a multi-variate linear
15 regression analysis to determine relative contribution of each parameter to the spread in the
16 PG to understand which parameter has the largest influence on the PG.

17 It is possible that certain parameters used in the model are spatially correlated. To account for
18 uncertainty in this spatial correlation and the presence of spatial patterns in the parameters we
19 perform a sensitivity analysis where we consider three cases:

- 20 • Fully correlated: we assume the parameters are spatially fully correlated within a zone,
21 e.g. for each of the 10,000 simulations a parameter has the same value within a zone
- 22 • Uncorrelated: we assume the parameters are spatially uncorrelated and within each
23 zone each glacier system is assigned a random value
- 24 • Intermediate case: we use geostatistical unconditional simulation (Goovaerts, 1997)
25 with a standardized semi-variogram (nugget = 0, sill = variance of parameter, range =
26 120 km) to simulate parameter values for each glacier system.

27 **2.4 Validation**

28 We estimate the average annual runoff (Q) for sub-basins in the UIB from

$$29 \quad Q = P_{cor} - ET + MB \quad (3)$$

1 Where P_{cor} is the corrected average precipitation, ET is the average annual evapotranspiration
2 based on the four products described above and MB is the glacier mass balance expressed
3 over the sub-basin area in $mm\ y^{-1}$. We then compare the estimated runoff values to the
4 observed time series (Table 2).

5 For the three zones (Himalaya, Karakoram and Hindu-Kush) we also perform a water balance
6 analysis to verify whether the use of the corrected precipitation product results in a more
7 realistic closure of the water balance. Finally we test the physical realism of the corrected
8 precipitation product using a non-dimensional Turc-Budyko plot as described in Valéry et al.
9 (2010). This plot is based on two assumptions: (i) the mean annual runoff should not exceed
10 the mean annual precipitation and (ii) the mean annual runoff should be larger than or equal to
11 the difference between precipitation and potential evapotranspiration. By plotting P/ETp
12 versus Q/P on catchment basis it is tested whether the use of corrected precipitation results in
13 more physically-realistic values.

14

15 **3 Results and discussion**

16 **3.1 Corrected precipitation**

17 The average annual precipitation based on 10,000 conditionally simulated fields reveals a
18 striking pattern of high altitude precipitation. The amount of precipitation required to sustain
19 the large glacier systems is much higher than either the station observations or the gridded
20 precipitation products imply. For the entire UIB the uncorrected average annual precipitation
21 (Yatagai et al., 2012) for 2003-2007 is $437\ mm\ y^{-1}$ ($191\ km^3\ y^{-1}$), an underestimation of more
22 than 200% compared with our corrected precipitation estimate of $913 \pm 323\ mm\ y^{-1}$ ($399 \pm$
23 $141\ km^3\ y^{-1}$ (Fig. 5)). The greatest corrected annual precipitation totals in the UIB ($1271\ mm$
24 y^{-1}) are observed in the elevation belt between $3750\ m$ to $4250\ m$ (compared to $403\ mm\ y^{-1}$ for
25 the uncorrected case). In absolute terms the main water-producing region is located in the
26 elevation belt between $4250\ m$ and $4750\ m$ where approximately $78\ km^3$ of rain and snow
27 precipitates annually.

28 In the most extreme case, precipitation is underestimated by a factor 5 to 10 in the region
29 where the Pamir, Karakorum and Hindu-Kush ranges intersect (Fig. 5). Our inverse modelling
30 shows that the large glacier systems in the region can only be sustained if snowfall in their
31 accumulation areas totals around $2000\ mm\ y^{-1}$ (Hewitt, 2007). This is in sharp contrast to

1 precipitation amounts between 200 and 300 $mm\ y^{-1}$ that are reported by the gridded
2 precipitation products (Fig. 1). Our results match well with the few studies on high-altitude
3 precipitation that are available. Annual accumulation values between 1000 and 3000 mm have
4 been reported for accumulation pits above 4000 m in the Karakoram (The Batura Glacier
5 Investigation Group, 1979; Wake, 1989; Winiger et al., 2005). Our results show that the
6 highest precipitation amounts are found along the monsoon-influenced southern Himalayan
7 arc with values up to 3000 $mm\ y^{-1}$, while north of the Himalayan range the precipitation
8 decreases quickly towards a vast dry area in the north-eastern part of the UIB (Shyok sub-
9 basin). In the north-western part of the UIB, westerly storm systems are expected to generate
10 considerable amounts of precipitation at high altitude.

11 Our results reveal a strong relation between elevation and precipitation with a median PG for
12 the entire upper Indus of 0.0989 $\% m^{-1}$, but with large regional differences. Median
13 precipitation gradients in the Hindu-Kush and Karakoram ranges (0.260 $\% m^{-1}$ and 0.119 $\%$
14 m^{-1} respectively) are significantly larger than those observed in the Himalayan range, e.g
15 0.044 $\% m^{-1}$ (Fig. 6). In the Hindu-Kush, for example, for every 1000 m elevation rise,
16 precipitation increases by 260% with respect to APHRODITE, which is based on valley floor
17 precipitation. In combination with a higher HMAX in the Hindu-Kush and the Karakoram
18 (e.g. 5500 m versus 4500 m in the Himalayas, [\(Hewitt, 2007; Immerzeel et al., 2014a;](#)
19 [Putkonen, 2004; Seko, 1987; Winiger et al., 2005\)](#)[\(Hewitt, 2007; Immerzeel et al., 2014a;](#)
20 [Putkonen, 2004; Seko, 1987; Winiger et al., 2005\)](#) this suggests that westerly airflow indeed
21 has a higher tropospheric altitude and that the interplay between elevation and precipitation is
22 stronger for this type of precipitation. Further research should thus focus on the use of high
23 resolution cloud-resolving weather models (Collier et al., 2014; Mölg et al., 2013) for this
24 region to further resolve seasonal topography-precipitation interaction at both synoptic and
25 valley scales.

26 The estimated precipitation is considerably higher than what was reported in previous studies.
27 Several studies have used TRMM products to quantify UIB precipitation (Bookhagen and
28 Burbank, 2010; Immerzeel et al., 2009, 2010) and they show average annual precipitation
29 values around 300 mm . It was also noted that the water balance was not closing and average
30 annual river runoff at Tarbela exceeded the TRMM precipitation [\(Immerzeel et al., 2009\).](#)
31 [\(Immerzeel et al., 2009\).](#) Two possible reasons have been suggested to explain this gap: (i) the
32 high altitude precipitation is underestimated, (ii) the glaciers are in a significant negative

1 imbalance (Immerzeel et al., 2009). Since the ICESat study and several other geodetic mass
2 balance studies (Gardelle et al., 2013; Kääb et al., 2012b) it has become clear that the glaciers
3 in this region are not experiencing a significant ice loss and that this cannot be the explanation
4 for the missing water in the water balance. This supports our conclusion that it is the high
5 altitude precipitation that has been underestimated. A study based on long term observations
6 of Tarbela inflow also confirm our results (Reggiani and Rientjes, 2014). In this study the
7 total UIB precipitation above Tarbela is estimated to be $675 \pm 100 \text{ mm y}^{-1}$ and the difference
8 remaining between our results may stem from the fact that the UIB we consider is twice the
9 size of the area above the Tarbela, the different approach used to estimate actual ET, the
10 different period considered and their assumption that ice storage has not changed between
11 1961 and 2009.

12 **3.2 Uncertainty**

13 We estimated the uncertainty in the modelled precipitation field with the standard deviation
14 (σ) of the 10,000 realizations (Fig. 5c). The signal-to-noise ratio is satisfactory in the entire
15 domain, e.g. the σ is always considerably smaller than the average precipitation with an
16 average coefficient of variation of 0.35. The largest absolute uncertainty is found along the
17 Himalayan arc and this coincides with the precipitation pattern found here. Strikingly, the
18 region where the underestimation of precipitation is largest, at the intersection of the three
19 mountain ranges in the northern UIB, is also an area where the uncertainty is small even
20 though precipitation gradients are large.

21 By running a multiple regression analysis after optimizing the PGs we quantify the
22 contribution of each parameter to the total uncertainty. The largest source of uncertainty in
23 our estimate of UIB high altitude precipitation stems from the MB estimates, followed by the
24 DDFdf, DDFd, TS, HREF and HMAX, although regional differences are considerable (Fig.
25 7). The MB constrains the precipitation gradients and thereby exerts a strong control on the
26 corrected precipitation fields, in particular because the intra-zonal variation in MB is
27 relatively large (Table 1). Thus, improved spatial monitoring techniques of the MB are
28 expected to greatly improve precipitation estimates.

29 Fig. 8 shows the result of uncertainty analysis associated to the spatial correlation of the
30 parameters, which reveals that the impact on the average corrected precipitation is limited.
31 Locally there are minor differences in the corrected precipitation amounts, but overall the

1 magnitude and spatial patterns are similar. However, there are considerable differences in the
2 uncertainty. The lowest uncertainty is found for the fully uncorrelated case, the fully
3 correlated case has the highest uncertainty whereas the intermediate case is in between both.
4 For the fully correlated case all glacier systems have the same parameter set for the specific
5 realization and this results in a larger final uncertainty. In the uncorrelated case each glacier
6 system has a different randomly sampled parameter set and this reduces the overall
7 uncertainty as it spatially attenuates the variation in precipitation gradients.

8 **3.3 Validation**

9 The corrected precipitation is validated independently by a comparison to published average
10 annual runoff data of 27 stations (Table 2). Runoff estimates based on the corrected
11 precipitation agree well with the average observed annual runoff (Fig. 9, top panel). It is
12 interesting to note that the higher catchment ($r = 0.98$, red outline) show a better correlation
13 with the observed runoff than the lower catchments ($r = 0.76$, black outline). The runoff
14 estimated for the uncorrected APHRODITE is consistently lower than the observed runoff,
15 and in some occasions even negative. Runoff estimates were also made based on the ERA-
16 INTERIM and TRMM precipitation products. The TRMM results yield a similar
17 underestimation as the uncorrected APHRODITES product, but the runoff estimates based on
18 the ERA-INTERIM precipitation ~~agre~~s agrees reasonably well with the observations.
19 However the coarse resolution ($\sim 70 \text{ km}^2$) (Fig. 1) is problematic and cannot be used to
20 reproduce the mass balance (Fig. 11). Averaged over large catchments the precipitation may
21 be applied for hydrological modeling, but at smaller scales there are likely very large biases.
22 As a result, the observed glacier mass balances cannot be reproduced when the ERA-
23 INTERIM dataset is used. Although the ERA-Interim dataset may not be used to reproduce
24 the glacier mass balances it can be used to verify the atmospheric convergence as the product
25 is based on a data assimilation scheme and the ECMWF IFS forecast model that includes
26 fully coupled components for atmosphere, land surface and ocean waves including closure of
27 the atmospheric water balance. The total precipitation sum from 1998 until 2007 of the ERA-
28 Interim dataset over the entire UIB is 947 mm, which is very close to our corrected
29 precipitation sum of 913 mm. This indicates that the westerlies and monsoon circulation
30 transport sufficient moisture into the region to account for the precipitation we estimate. The
31 source of precipitation in the upper Indus is a mixture of the Ariabian Sea (westerlies), Bay of
32 Bengal (Monsoon) and potentially also intra-basin moisture recycling (Tuinenburg et al.,

1 [2012; Wei et al., 2013](#)), however further research with atmospheric models is required to
2 [quantify these contributions further](#).

3 The zonal water balance analysis (Fig. 9, bottom panels) reveals that the water balance is
4 much more realistic when the corrected precipitation is used. Although the uncertainties are
5 considerable, our analysis shows that the Himalaya and Hindu-Kush zones are about twice as
6 wet as the Karakoram zone. For all three zones the glacier mass imbalance only plays a
7 marginal role in the overall water balance and about 60% of the total precipitation runs off
8 while 40% is lost through evapotranspiration. Notable are the values for *Corg*, which
9 represents the water balance gap in case the uncorrected precipitation is used, are
10 approximately 500 mm y^{-1} in all three zones. Our validation does not take into account
11 groundwater fluxes and we have assumed that over the observed period from 2003 until 2007
12 there is no net loss or gain of groundwater in the upper Indus basin. We do acknowledge that
13 groundwater may play an important role in the hydrology. A study in the Nepal Himalaya
14 shows that fractured basement aquifers fill during the monsoon and they purge in the post-
15 monsoon thus causing a natural delay in runoff (Andermann et al., 2012). However this does
16 not imply significant net gains or losses over multiple year periods, which is what we
17 consider. A second component that we have not considered and that may play a role in the
18 high altitude water cycle is sublimation. There are some indications that wind redistribution
19 and sublimation may play a considerable role in the high altitude water balance (Wagnon et
20 al., 2013). However our PGs are constrained on the observed mass balance, hence our
21 precipitation can be considered as a net precipitation and sublimation losses are thus
22 accounted for.

23 In Fig. 10 the Budyko-Turc plot is shown to confirm the physical realism of our results. Those
24 dots located in the hatched part of the graph are physically less realistic. For the uncorrected
25 case almost all dots (open dots) are above the $Q/P = 1$ line. For the corrected case the Q/P
26 values are much more plausible, however there many catchments which are located slightly to
27 the right side of the theoretical Budyko line, meaning that the Q is smaller than the difference
28 between P and ETp . Possible deviation can potentially be explained by uncertainties in
29 observed flows and ETp estimates, the fact the in glacierized catchments the theoretical
30 Budyko curve may be different because a glacier imbalance can be an additional water
31 balance term that is unaccounted for, a too short time period that is used to construct the water
32 balance and finally that some of the discharge observations do not align in time with the rest

1 of the water balance terms. Overall we conclude though that the use of the corrected
2 precipitation results in physically more realistic results, where the water balance could be
3 closed and no significant amount of precipitation input is missing.

4 Fig 11 shows how the average simulated zonal glacier mass balance using the corrected, the
5 APHRODITES, the ERA-Interim and the TRMM precipitation datasets. It shows that none of
6 the precipitation products can reproduce the observed mass balance. Mostly the mass balances
7 are underestimated which is consistent with and underestimation of the precipitation. The
8 ERA-Interim dataset overestimates the mass balance in the Himalaya, but underestimates the
9 mass balances in the other two zones as result of the coarse resolution.

10 **4 Conclusions**

11 In this study we inversely model high altitude precipitation in the upper Indus basins from
12 glacier mass balance trends derived by remote sensing. Although there are significant
13 uncertainties, our results unambiguously show that high altitude precipitation in this region is
14 underestimated and that the large glaciers here can only be sustained if high altitude
15 accumulation is much higher than most commonly used gridded data products.

16 Our results have an important bearing on water resources management studies in the region.
17 The observed gap between precipitation and streamflow (Immerzeel et al., 2009) (with stream
18 flow being larger) cannot be attributed to the observed glacier mass balance (Kääb et al.,
19 2012a), but is most likely the result of an underestimation of precipitation, as also follows
20 from this study. With no apparent decreasing trends in precipitation (Archer and Fowler,
21 2004) the observed negative trends in stream flow in the glacierised parts of the UIB should
22 thus be primarily attributed to decreased glacier and snow melt (Sharif et al., 2013) and
23 increased glacier storage (Gardelle et al., 2012). In a recent study the notion of negative trends
24 in UIB runoff was contested and based on a recent analysis (1985 - 2010) it was concluded
25 that runoff of Karakoram rivers is increasing (Mukhopadhyay and Khan, 2014b). The study
26 suggests that increase glacier melt during summer is the underlying reason, which in
27 combination with positive precipitation trends in summer does not contradict the neutral
28 glacier mass balances in the region. From all of these studies it becomes apparent that
29 precipitation is the key to understanding behaviour of glacier and hydrology at large in the
30 UIB. The precipitation we estimate in this study differs considerably, in magnitude and spatial
31 distribution, from datasets that are commonly used in design of reservoirs for hydropower and
32 irrigation and as such it may have a significant impact and improve such planning processes.

1 The water resources of the Indus River play an important geopolitical role in the region, and
2 our results could contribute to the provision of independent estimates of UIB precipitation.
3 We conclude that the water resources in the UIB are even more important and abundant than
4 previously thought. Most precipitation at high altitude is now stored in the glaciers, but when
5 global warming persists and the runoff regime becomes more rain dominated, the downstream
6 impacts of our findings will become more evident.

7 **Acknowledgements**

8 This study was funded by the Netherlands Organization for Scientific Research through their
9 VENI Program, User Support Program for Space Research and Rubicon program and by the
10 UK Department for International Development (DFID). This study was also partially
11 supported by core funds of ICIMOD contributed by the governments of Afghanistan,
12 Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan,
13 Switzerland, and the United Kingdom. The views and interpretations in this publication are
14 those of the authors and are not necessarily attributable to ICIMOD. The authors
15 acknowledge the Pakistan Meteorological Department and the Pakistan Water and Power
16 Development Authority for providing meteorological and hydrological data. The authors are
17 grateful to Andreas Kääb for calculating the zonal mass balances based on the ICESat data, to
18 Rianne Giesen for organizing the glacier mass balance data, to Samjwal Bajracharya for
19 providing the glacier boundaries and to Philip Kraaijenbrink for assisting with the figures.
20 ~~This study was also partially supported by core funds of ICIMOD contributed by the~~
21 ~~governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar,~~
22 ~~Nepal, Norway, Pakistan, Switzerland, and the United Kingdom. The views and~~
23 ~~interpretations in this publication are those of the authors and are not necessarily attributable~~
24 ~~to ICIMOD.~~

1 **References**

2 | Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P. and Gloaguen, R.: Impact
3 | of transient groundwater storage on the discharge of Himalayan rivers, *Nat. Geosci.*, 5(2),
4 | 127–132, doi:10.1038/ngeo1356, 2012.

5 | Archer, D.: Contrasting hydrological regimes in the upper Indus Basin, *J. Hydrol.*, 274(1-4),
6 | 198–210, doi:10.1016/S0022-1694(02)00414-6, 2003.

7 | Archer, D. R. and Fowler, H. J.: Spatial and temporal variations in precipitation in the Upper
8 | Indus Basin, global teleconnections and hydrological implications, *Hydrol. Earth Syst. Sci.*,
9 | 8(1), 47–61, doi:10.5194/hess-8-47-2004, 2004.

10 | Azam, M. F., Wagnon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A.,
11 | Pottakkal, J. G., Chevallier, P., Singh, V. B. and Berthier, E.: From balance to imbalance: a
12 | shift in the dynamic behaviour of Chhota Shigri glacier, western Himalaya, India, *J. Glaciol.*,
13 | 58(208), 315–324, doi:10.3189/2012JoG11J123, 2012.

14 | Bajracharya, S. R. and Shrestha, B.: *The Status of Glaciers in the Hindu Kush-Himalayan*
15 | *Region*, Kathmandu., 2011.

16 | Barros, A. P., Kim, G., Williams, E. and Nesbitt, S. W.: Probing orographic controls in the
17 | Himalayas during the monsoon using satellite imagery, *Nat. Hazards Earth Syst. Sci.*, 4(1),
18 | 29–51, doi:10.5194/nhess-4-29-2004, 2004.

19 | Bastiaanssen, W. G. M., Cheema, M. J. M., Immerzeel, W. W., Miltenburg, I. J. and Pelgrum,
20 | H.: Surface energy balance and actual evapotranspiration of the transboundary Indus Basin
21 | estimated from satellite measurements and the ETLook model, *Water Resour. Res.*, 48(11),
22 | W11512, doi:10.1029/2011WR010482, 2012.

23 | Bhutiyani, M. R.: *Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram*

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- 1 Himalaya, India, *J. Glaciol.*, 45, 112–118, 1999.
- 2 Bookhagen, B. and Burbank, D. W.: Topography, relief, and TRMM-derived rainfall
3 variations along the Himalaya, *Geophys. Res. Lett.*, 33(8), 1–5, doi:10.1029/2006GL026037,
4 2006.
- 5 Bookhagen, B. and Burbank, D. W.: Toward a complete Himalayan hydrological budget:
6 Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge, *J.*
7 *Geophys. Res.*, 115(F3), 1–25, doi:10.1029/2009JF001426, 2010.
- 8 Collier, E., Nicholson, L. I., Brock, B. W., Maussion, F., Essery, R. and Bush, a. B. G.:
9 Representing moisture fluxes and phase changes in glacier debris cover using a reservoir
10 approach, *Cryosph.*, 8(4), 1429–1444, doi:10.5194/tc-8-1429-2014, 2014.
- 11 Dee, D. P., Uppala, S. M., Simmons, a. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U.,
12 Balmaseda, M. a., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, a. C. M., van de Berg, L.,
13 Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, a. J., Haimberger, L.,
14 Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M.,
15 McNally, a. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P.,
16 Tavolato, C., Thépaut, J.-N. and Vitart, F.: The ERA-Interim reanalysis: configuration and
17 performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, 137(656), 553–597,
18 doi:10.1002/qj.828, 2011.
- 19 Gardelle, J., Berthier, E. and Arnaud, Y.: Slight mass gain of Karakoram glaciers in the early
20 twenty-first century, *Nat. Geosci.*, 5(5), 322–325, doi:10.1038/ngeo1450, 2012.
- 21 Gardelle, J., Berthier, E., Arnaud, Y. and Käab, A.: Region-wide glacier mass balances over
22 the Pamir-Karakoram-Himalaya during 1999–2011, *Cryosph.*, 7(4), 1263–1286,
23 doi:10.5194/tc-7-1263-2013, 2013.

- 1 | Goovaerts, P.: Geostatistics for Natural Resources Evaluation, Oxford University Press, New
2 | York - Oxford., 1997.
- 3 | Hagg, W., Mayer, C., Lambrecht, A. and Helm, A.: Sub-Debris Melt Rates on Southern
4 | Inylchek Glacier, Central Tian Shan, *Geogr. Ann. Ser. A Phys. Geogr.*, 90(1), 55–63,
5 | doi:10.1111/j.1468-0459.2008.00333.x, 2008.
- 6 | Harper, J. T.: High altitude Himalayan climate inferred from glacial ice flux, *Geophys. Res.*
7 | *Lett.*, 30(14), 3–6, doi:10.1029/2003GL017329, 2003.
- 8 | Hewitt, K.: The Karakoram anomaly? Glacier expansion and the “elevation effect,”
9 | *Karakoram Himalaya, Mt. Res. Dev.*, 25(4), 332–340, doi:10.1659/0276-4741, 2005.
- 10 | Hewitt, K.: Tributary glacier surges: an exceptional concentration at Panmah Glacier,
11 | *Karakoram Himalaya, J. Glaciol.*, 53(181), 181–188, doi:10.3189/172756507782202829,
12 | 2007.
- 13 | Hewitt, K.: Glacier Change, Concentration, and Elevation Effects in the Karakoram
14 | Himalaya, Upper Indus Basin, *Mt. Res. Dev.*, 31(3), 188–200, doi:10.1659/MRD-JOURNAL-
15 | D-11-00020.1, 2011.
- 16 | Hewitt, K.: The regional context, in *Glaciers of the Karakoram Himalaya*, pp. 1–33, Springer,
17 | Dordrecht., 2013.
- 18 | Hock, R.: Glacier melt: a review of processes and their modelling, *Prog. Phys. Geogr.*, 29(3),
19 | 362–391, doi:10.1191/0309133305pp453ra, 2005.
- 20 | Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., Hong, Y.,
21 | Stocker, E. F. and Wolff, D. B.: The TRMM Multisatellite Precipitation Analysis (TMPA):
22 | Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales, *J.*
23 | *Hydrometeorol.*, 8(1), 38–55, doi:10.1175/JHM560.1, 2007.

1 | Immerzeel, W. W. and Bierkens, M. F. P.: Asia's water balance, *Nat. Geosci.*, 5(12), 841–
2 | 842, doi:10.1038/ngeo1643, 2012.

3 | Immerzeel, W. W., Droogers, P., De Jong, S. M. and Bierkens, M.: Large-scale monitoring of
4 | snow cover and runoff simulation in Himalayan river basins using remote sensing, *Remote*
5 | *Sens. Environ.*, 113(1), 40–49, doi:10.1016/j.rse.2008.08.010, 2009.

6 | Immerzeel, W. W., Van Beek, L. P. H. and Bierkens, M. F. P.: Climate change will affect the
7 | Asian water towers, *Science*, 328, 1382–1385, doi:10.1126/science.1183188, 2010.

8 | Immerzeel, W. W., Pellicciotti, F. and Shrestha, A. B.: Glaciers as a proxy to quantify the
9 | spatial distribution of precipitation in the Hunza basin, *Mt. Res. Dev.*, 32(1), 30–38,
10 | doi:10.1659/MRD-JOURNAL-D-11-00097.1, 2012a.

11 | Immerzeel, W. W., Beek, L. P. H., Konz, M., Shrestha, A. B. and Bierkens, M. F. P.:
12 | Hydrological response to climate change in a glacierized catchment in the Himalayas, *Clim.*
13 | *Change*, 110, 721–736, doi:10.1007/s10584-011-0143-4, 2012b.

14 | Immerzeel, W. W., Pellicciotti, F. and Bierkens, M. F. P.: Rising river flows throughout the
15 | twenty-first century in two Himalayan glacierized watersheds, *Nat. Geosci.*, 6, 742–745,
16 | doi:10.1038/NGEO1896, 2013.

17 | Immerzeel, W. W., Kraaijenbrink, P. D. A., Shea, J. M., Shrestha, A. B., Pellicciotti, F.,
18 | Bierkens, M. F. P. and de Jong, S. M.: High-resolution monitoring of Himalayan glacier
19 | dynamics using unmanned aerial vehicles, *Remote Sens. Environ.*, 150, 93–103,
20 | doi:10.1016/j.rse.2014.04.025, 2014a.

21 | Immerzeel, W. W., Petersen, L., Ragetti, S. and Pellicciotti, F.: The importance of observed
22 | gradients of air temperature and precipitation for modeling runoff from a glacierised
23 | watershed in the Nepalese Himalayas, *Water Resour. Res.*, 50(3), 2212–2226,

1 doi:10.1002/2013WR014506, 2014b.

2 | Kääb, A., Berthier, E., Nuth, C., Gardelle, J. and Arnaud, Y.: Contrasting patterns of early
3 twenty-first-century glacier mass change in the Himalayas, *Nature*, 488(7412), 495–498,
4 doi:10.1038/nature11324, 2012a.

5 | Kääb, A., Berthier, E., Nuth, C., Gardelle, J., Arnaud, Y., Kaab, A., Berthier, E., Nuth, C.,
6 Gardelle, J. and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass
7 change in the Himalayas, *Nature*, 488(7412), 495–498, 2012b.

8 | Karssenberg, D., Burrough, P. A., Sluiter, R. and de Jong, K.: The PCRaster Software and
9 Course Materials for Teaching Numerical Modelling in the Environmental Sciences, *Trans.*
10 *GIS*, 5(2), 99–110, doi:10.1111/1467-9671.00070, 2001.

11 | Khattak, M., Babel, M. and Sharif, M.: Hydro-meteorological trends in the upper Indus River
12 basin in Pakistan, *Clim. Res.*, 46(2), 103–119, doi:10.3354/cr00957, 2011.

13 | Koster, R. D., Suarez, M. J., Ducharne, A., Stieglitz, M. and Kumar, P.: A catchment-based
14 approach to modeling land surface processes in a general circulation model structure, *J.*
15 *Geophys. Res.*, 105, 24809 – 24822, 2000.

16 | [Lehner, B., Verdin, K. and Jarvis, A.: New global hydrography derived from spaceborne
17 elevation data, *Eos Trans. AGU*, 89\(10\), 93–94, 2008.](#)

18 | Lutz, A. F., Immerzeel, W. W., Shrestha, A. B. and Bierkens, M. F. P.: Consistent increase in
19 High Asia ' s runoff due to increasing glacier melt and precipitation, *Nat. Clim. Chang.*, 4, 1–
20 6, doi:10.1038/NCLIMATE2237, 2014.

21 | Mihalcea, C., Mayer, C., Diolaiuti, G., Lambrecht, A., Smiraglia, C. and Tartari, G.: Ice
22 ablation and meteorological conditions on the debris-covered area of Baltoro glacier ,
23 Karakoram , Pakistan, *Ann. Glaciol.*, (1894), 292–300, 2006.

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- 1 | Mishra, V.: Climatic uncertainty in Himalayan Water Towers, *J. Geophys. Res. Atmos.* (in
2 | Press., doi:10.1002/2014JD022650, 2015.
- 3 | Mölg, T., Maussion, F. and Scherer, D.: Mid-latitude westerlies as a driver of glacier
4 | variability in monsoonal High Asia, *Nat. Clim. Chang.*, 4, 68–73, doi:10.1038/nclimate2055,
5 | 2013.
- 6 | Mukhopadhyay, B. and Khan, A.: A quantitative assessment of the genetic sources of the
7 | hydrologic flow regimes in Upper Indus Basin and its significance in a changing climate, *J.*
8 | *Hydrol.*, 509, 549–572, doi:10.1016/j.jhydrol.2013.11.059, 2014a.
- 9 | Mukhopadhyay, B. and Khan, A.: Rising river flows and glacial mass balance in central
10 | Karakoram, *J. Hydrol.*, 513, 191–203, 2014b.
- 11 | Nicholson, L. and Benn, D. I.: Calculating ice melt beneath a debris layer using
12 | meteorological data, *J. Glaciol.*, 52(178), 463–470, doi:10.3189/172756506781828584, 2006.
- 13 | Putkonen, J. K.: Continuous Snow and Rain Data at 500 to 4400 m Altitude near Annapurna ,
14 | Nepal, 1991-2001, *Arctic, Antarct. Alp. Res.*, 36(2), 244–248, doi:10.1657/1523-
15 | 0430(2004)036, 2004.
- 16 | Ragetti, S. and Pellicciotti, F.: Calibration of a physically based, spatially distributed
17 | hydrological model in a glacierized basin: On the use of knowledge from
18 | glaciometeorological processes to constrain model parameters, *Water Resour. Res.*, 48(3), 1–
19 | 20, doi:10.1029/2011WR010559, 2012.
- 20 | Reggiani, P. and Rientjes, T. H. M.: A reflection on the long-term water balance of the Upper
21 | Indus Basin, *Hydrol. Res.*, 46, 446–462, doi:10.2166/nh.2014.060, 2014.
- 22 | Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich,
23 | M. G., Schubert, S. D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A.,

1 da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson,
2 S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M.
3 and Woollen, J.: MERRA: NASA's Modern-Era Retrospective Analysis for Research and
4 Applications, *J. Clim.*, 24(14), 3624–3648, doi:10.1175/JCLI-D-11-00015.1, 2011.

5 Scherler, D., Bookhagen, B. and Strecker, M. R.: Spatially variable response of Himalayan
6 glaciers to climate change affected by debris cover, *Nat. Geosci.*, 4(1), 156–159,
7 doi:10.1038/ngeo1068, 2011.

8 Seko, K.: Seasonal variation of altitudinal dependence of precipitation in Langtang Valley,
9 Nepal Himalayas, *Bull. Glacier Res.*, 5, 41–47, 1987.

10 Sharif, M., Archer, D. R., Fowler, H. J. and Forsythe, N.: Trends in timing and magnitude of
11 flow in the Upper Indus Basin, *Hydrol. Earth Syst. Sci.*, 17(4), 1503–1516, doi:10.5194/hess-
12 17-1503-2013, 2013.

13 Singh, P. and Bengtsson, L.: Hydrological sensitivity of a large Himalayan basin to climate
14 change, *Hydrol. Process.*, 18(13), 2363–2385, doi:10.1002/hyp.1468, 2004.

15 The Batura Glacier Investigation Group: The Batura glacier in the Karakoram mountains and
16 its variations, *Sci. Sin.*, 22, 958–974, 1979.

17 [Tuinenburg, O. A., Hutjes, R. W. A. and Kabat, P.: The fate of evaporated water from the
18 Ganges basin, *J. Geophys. Res.*, 117\(D1\), 1–17, doi:10.1029/2011JD016221, 2012.](#)

19 Valéry, A., Andréassian, V. and Perrin, C.: Inverting the hydrological cycle: when
20 streamflow measurements help assess altitudinal precipitation gradients in mountain areas, ,
21 (September), 281–286, 2009.

22 Valéry, A., Andréassian, V. and Perrin, C.: Regionalization of precipitation and air
23 temperature over high-altitude catchments – learning from outliers, *Hydrol. Sci. J.*, 55(6),

Formatted: Normal, Space After: 7 pt, No widow/orphan control, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

1 928–940, doi:10.1080/02626667.2010.504676, 2010.

2 Wada, Y., Wisser, D. and Bierkens, M. F. P.: Global modeling of withdrawal, allocation and
3 consumptive use of surface water and groundwater resources, *Earth Syst. Dyn.*, 5(1), 15–40,
4 doi:10.5194/esd-5-15-2014, 2014.

5 Wagnon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Ménégoz, M.,
6 Gilbert, _a., Dumont, M., Shea, J. M., Stumm, D. and Pokhrel, B. K.: Seasonal and annual
7 mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007, *Cryosph.*, 7(6),
8 1769–1786, doi:10.5194/tc-7-1769-2013, 2013.

9 Wake, C. P.: Glaciochemical investigations as a tool to determine the spatial variation of
10 snow accumulation in the Central Karakoram, Northern Pakistan., *Ann. Glaciol.*, 13, 279–
11 284, 1989.

12 [Wei, J., Dirmeyer, P. A., Wisser, D., Bosilovich, M. G. and Mocko, D. M.: Where Does the](#)
13 [Irrigation Water Go? An Estimate of the Contribution of Irrigation to Precipitation Using](#)
14 [MERRA, *J. Hydrometeorol.*, 14\(1\), 275–289, doi:10.1175/JHM-D-12-079.1, 2013.](#)

15 Winiger, M., Gumpert, M. and Yamout, H.: Karakorum-Hindukush-western Himalaya:←
16 assessing high-altitude water resources, *Hydrol. Process.*, 19(12), 2329–2338,
17 doi:10.1002/hyp.5887, 2005.

18 Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H.,
19 Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B. and Joswiak, D.: Different glacier status with
20 atmospheric circulations in Tibetan Plateau and surroundings, *Nat. Clim. Chang.*, 2(9), 663–
21 667, doi:10.1038/nclimate1580, 2012.

22 Yasutomi, N., Hamada, A. and Yatagai, A.: Development of a Long-term Daily Gridded
23 Temperature Dataset and Its Application to Rain / Snow Discrimination of Daily

Formatted: Normal, Space After: 7 pt, No widow/orphan control, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

1 Precipitation, *Glob. Environ. Res.*, 3, 165–172, 2011.

2 | Yatagai, A., Yasutomi, N., Hamada, A., Kitoh, A., Kamiguchi, K. and Arakawa, O.:
3 | APHRODITE : constructing a long-term daily gridded precipitation dataset for Asia based on
4 | a dense network of rain gauges, *Geophys. Res. Abstr.*, 14(9), 1401 – 1415, 2012.

5 |

1 Table 1. Averages (μ) and standard deviations (σ) of predictors for the precipitation gradient.
 2 Values and ranges are based on literature as follows: HREF, HMAX: (Hewitt, 2007, 2011;
 3 Immerzeel et al., 2012b, 2014b; Putkonen, 2004; Seko, 1987; Winiger et al., 2005), DDFd,
 4 DDFdf: (Azam et al., 2012; Hagg et al., 2008; Immerzeel et al., 2013; Mihalcea et al., 2006;
 5 Nicholson and Benn, 2006), MB: (Kääb et al., 2012a)

Variable	Acronym	Distribution	μ	σ
Reference elevation (<i>m</i>)	HREF	log-Gaussian	2500	500
Maximum elevation (<i>m</i>)	HMAX	log-Gaussian		
<i>Himalaya</i>			4500	500
<i>Karakoram</i>			5500	500
<i>Hindu-Kush</i>			5500	500
Degree day factor debris covered glaciers ($mm\ ^\circ C^{-1}\ d^{-1}$)	DDFd	log-Gaussian	2	2
Degree day factor debris free glaciers ($mm\ ^\circ C^{-1}\ d^{-1}$)	DDFdf	log-Gaussian	7	2
Threshold slope ($m\ m^{-1}$)	TS	log-Gaussian	0.2	0.05
Mass balance ($m\ w.e.\ y^{-1}$)	MB	Gaussian		
<i>Himalaya</i>			-0.49	0.57
<i>Hindu-Kush</i>			-0.21	0.76
<i>Karakoram</i>			-0.07	0.61

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	34.31					
Phulra**	7	73.083	1106	<u>1613</u>	19.2	1969-1996
	34.50					
Daggar**	0	72.467	534	<u>1085</u>	6.9	1969-1996
	34.10					
Warsak****	0	71.300	74092	<u>2828</u>	593.0	1967-2005
	35.53					
Shatial Bridge**	3	73.567	189263	<u>4667</u>	2083.2	1983-1997

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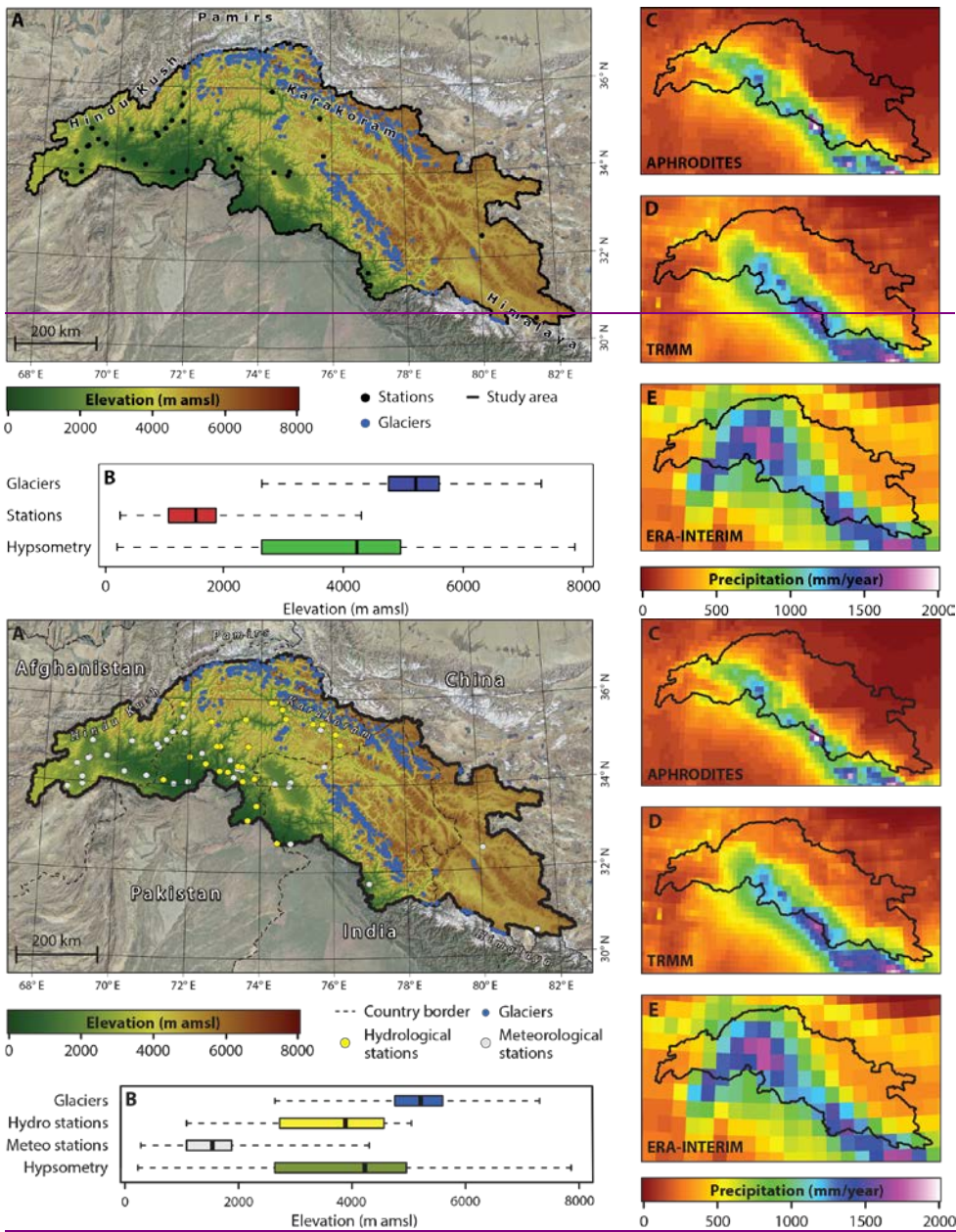
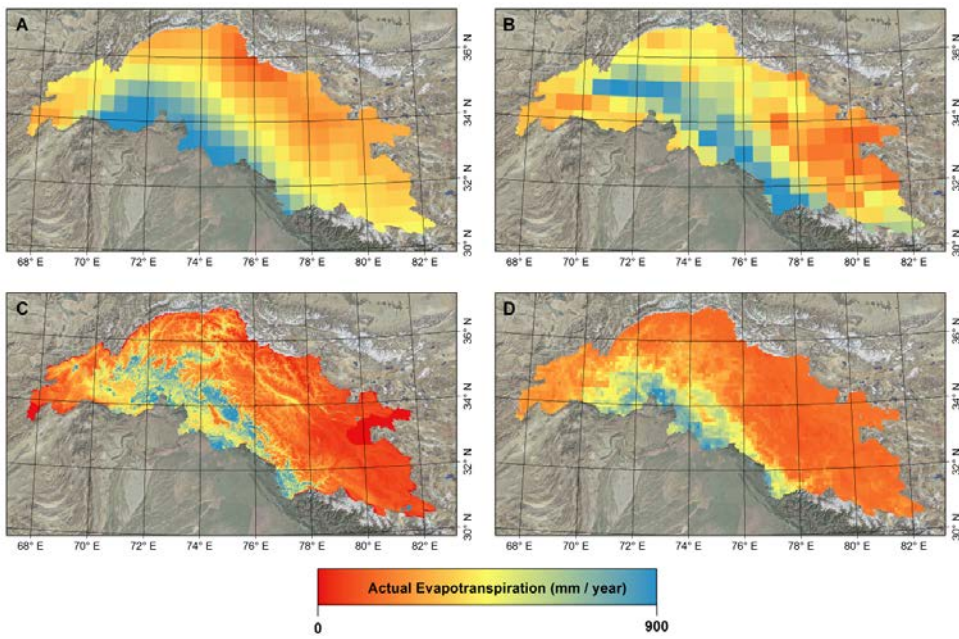
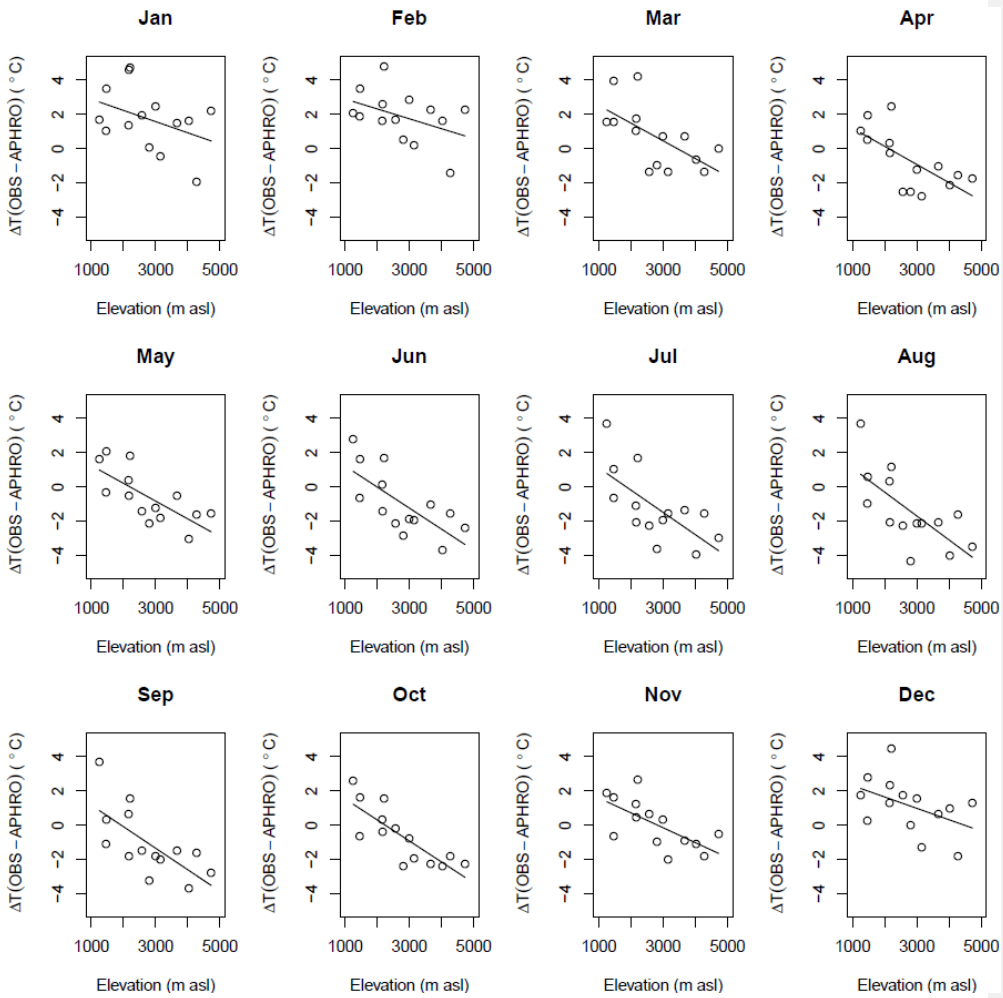


Figure 1. Overview of the UIB,

1 Figure 1. Overview of the UIB (Lehner et al., 2008), basin hypsometry and three gridded
2 precipitation products. Panel A shows the digital elevation model ~~and~~, the location of the
3 major glacier systems (area > 5 km²) ~~and~~, the available stations in the Global Summary of
4 the Day (GSOD) of the World Meteorological Organization (WMO) ~~and the hydrological~~
5 stations used for validation. Panel B shows boxplots of the elevation distribution of the basin,
6 the large glacier systems ~~and~~ the GSOD ~~stations~~ meteorological stations and the average
7 elevation of the catchment area of each hydrological station. Panel C to E show the average
8 gridded annual precipitation between 1998-2007 for the APHRODITE (Yatagai et al., 2012),
9 TRMM (Huffman et al., 2007) and ERA-INTERIM (Dee et al., 2011) datasets.

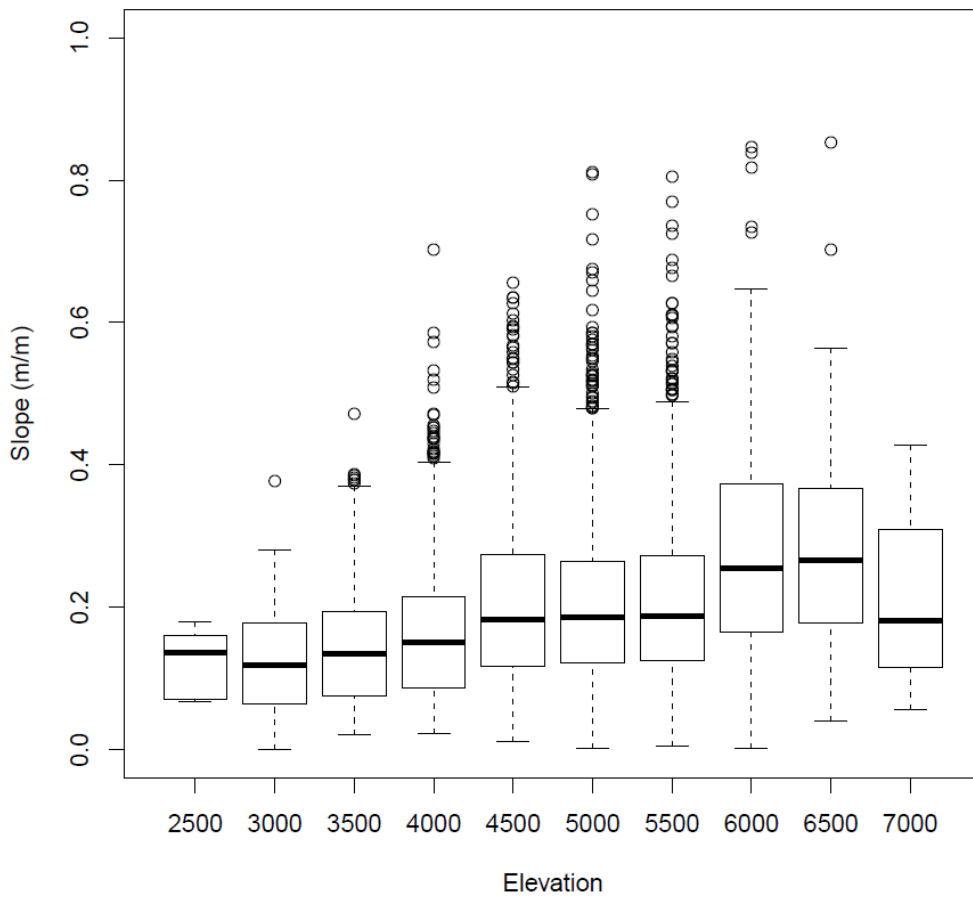


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 2 Figure 2. Average annual actual evapotranspiration between 2003 and 2007 for ERA-Interim
 3 (A), MERRA (B), ET-Look (C) and PCRGLOB-WB (D).
 4

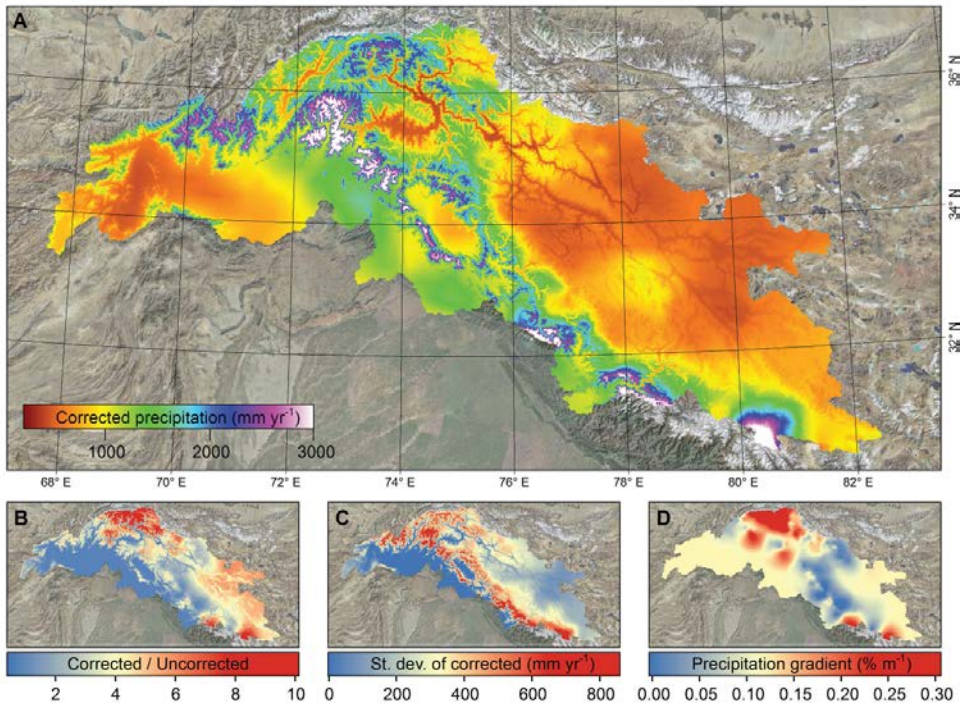


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 2 Figure 3. Monthly relation between observed temperatures at meteorological stations (OBS)
 3 and the APHRODITE temperature fields (APHRO) (Yasutomi et al., 2011).

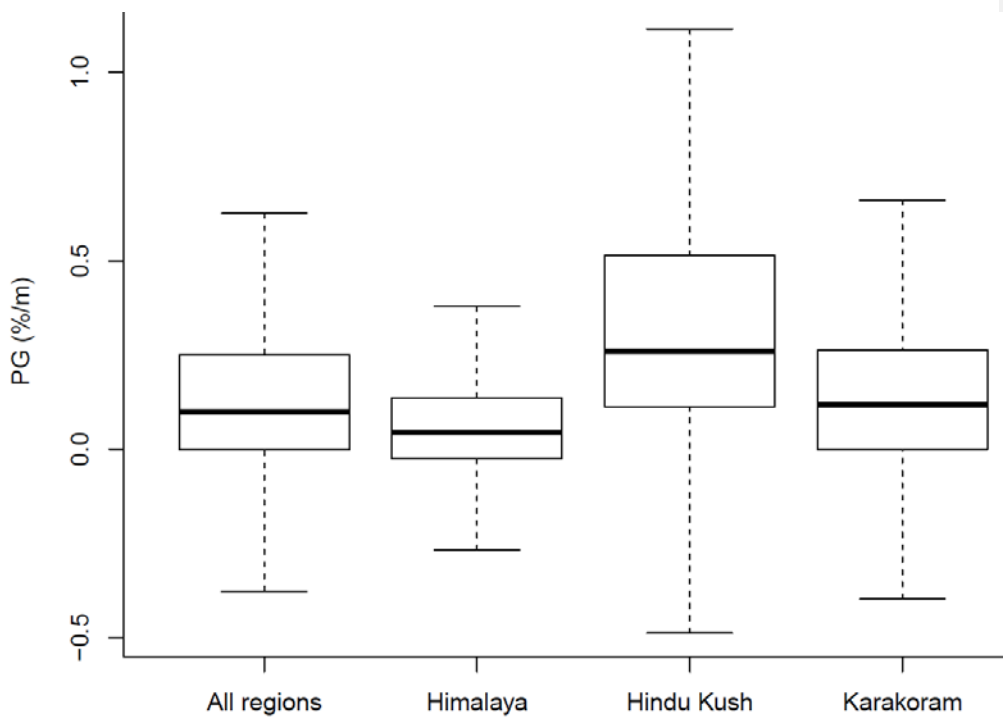
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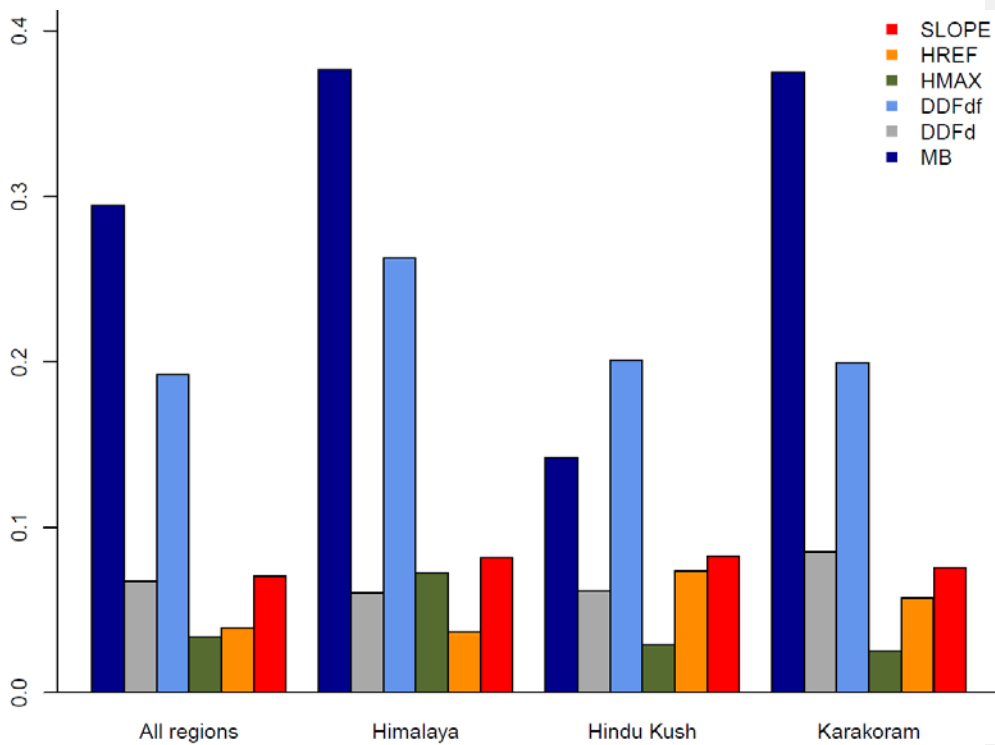
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 2 Figure 4. Boxplots of slopes of glacierised areas per elevation bin.
 3



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 2 Figure 5. Corrected precipitation and estimated uncertainty for the UIB for the case with
 3 intermediate spatial correlation between model parameters. Panel A shows the average
 4 modelled precipitation field based on 10,000 simulations for the period 2003-2007, Panel B
 5 shows the ratio of corrected precipitation to the uncorrected APHRODITE precipitation for
 6 the same period, Panel C shows the standard deviation of the 10,000 simulations and panel D
 7 shows the average precipitation gradient.
 8



1
 2 Figure 6. Box plots of precipitation gradients for the entire UIB and for the three regions
 3 separately.
 4



1 All regions Himalaya Hindu Kush Karakoram

2 Figure 7. Normalized weights of multiple regression of the precipitation gradients by the

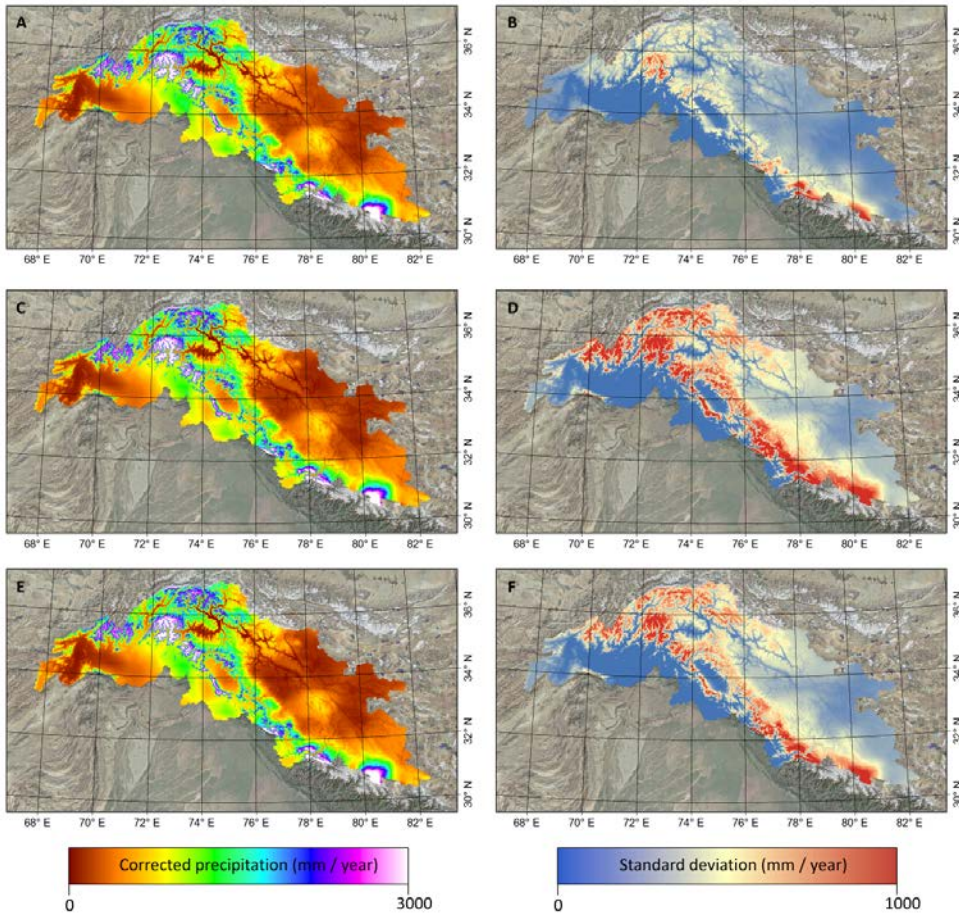
3 predictors slope (slope threshold for avalanching to contribute to accumulation), HREF (base

4 elevation from which lapsing starts), HMAX (elevation with peak precipitation), DDFd

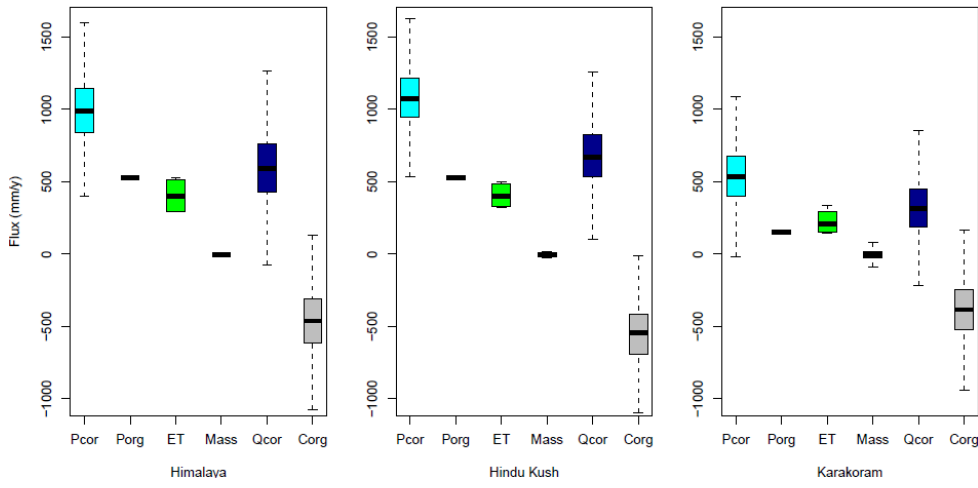
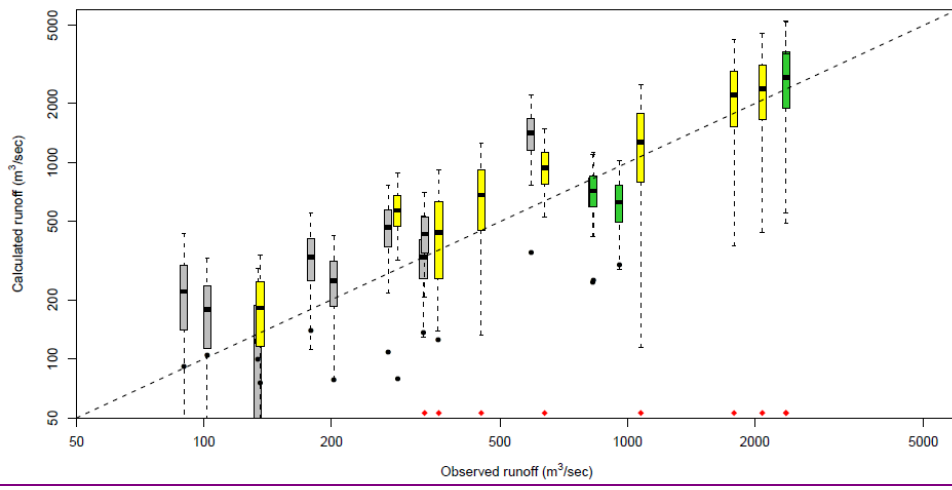
5 (degree day factor for debris covered glaciers), DDFdf (degree day factor for debris free

6 glaciers) and the MB (mass balance of the glacier).

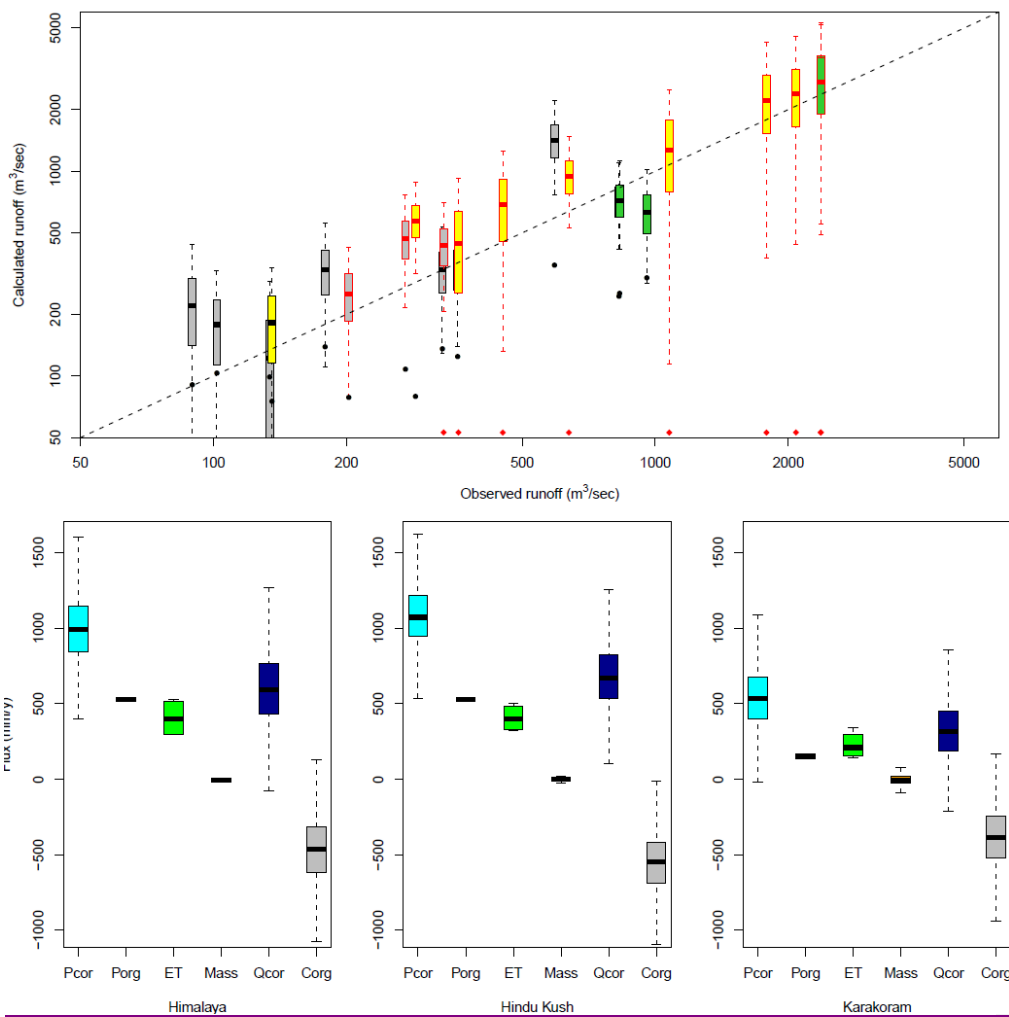
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 2 Figure 8. Impact of spatial correlation of parameters on the corrected precipitation field and
 3 associated uncertainty. The top panels show the corrected precipitation field (panel A) and
 4 uncertainty (panel B) for the fully uncorrelated case. The middle panels (D,E) for the fully
 5 correlated case and the bottom panels (E,F) for the intermediate case.
 6

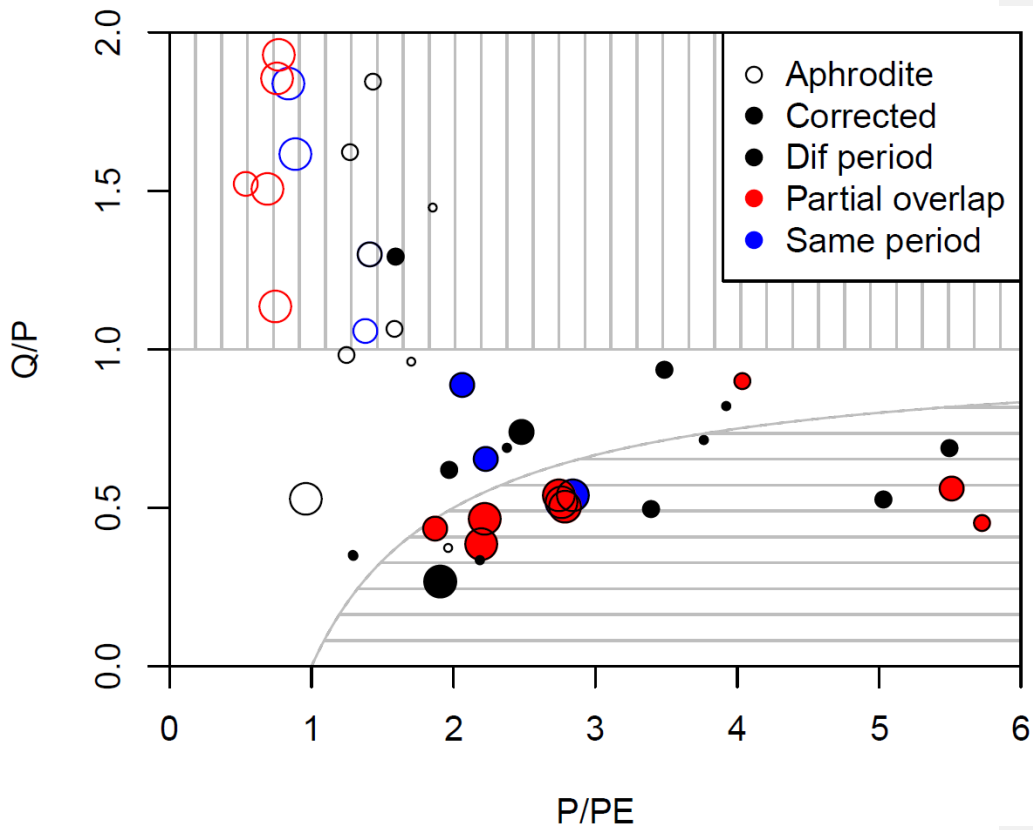


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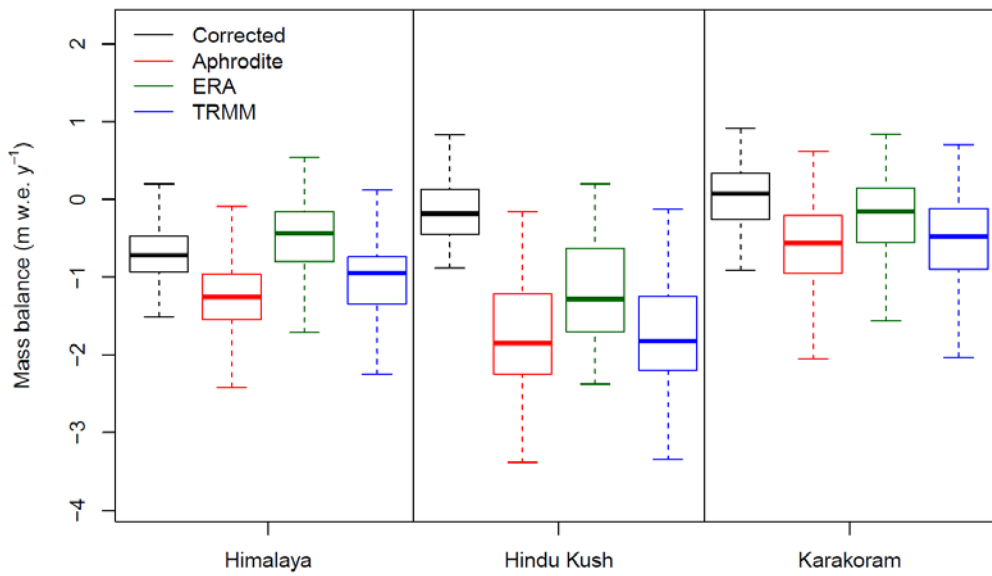


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 2 Figure 9. Validation of the precipitation correction using observed discharge (Table 2). Top
 3 panel: The box plots are based on the runoff estimate based on 10,000 corrected precipitation
 4 fields (grey: stations for which the observed record does not coincide with the 2003-2007
 5 period, yellow: stations for which the 2003 – 2007 period is part of the observational record,
 6 green: stations for which the observations are based precisely on the 2003 – 2007 period-).
 7 The black dots and red diamonds (estimated runoff below $50 \text{ m}^3 \text{ s}^{-1}$) show the estimated runoff
 8 based on the uncorrected precipitation. The box plots with a red outline have an average
 9 elevation higher than 4000 m. and the the box plots with a black outline have an elevation
 10 lower than 4000 m. Bottom panels: Water balance components of each zone (Pcor = corrected

1 precipitation, P_{org} = uncorrected APHRODITES precipitation, ET = actual
 2 evapotranspiration, $Mass$ = glacier mass balance, Q_{cor} = estimated runoff, C_{org} = water
 3 balance gap in case the P_{org} is used).



4
 5 Figure 10. Non-dimensional graphical representation of catchments using their mean runoff,
 6 Q , precipitation, P , and potential evapotranspiration, PE . The grey line in the empty centre
 7 area represents the theoretical Budyko relationship in the non-dimensional graph. The size of
 8 the dots is scaled to the catchment area.



1
 2 Figure 11. Reconstructed mass balances based on the corrected, APHRODITE, ERA-
 3 INTERIM and TRMM datasets. The black horizontal dotted line shows the observed mass
 4 balance for each zone.

5 |

