1 Prevailing climatic trends and runoff response from Hindukush-Karakoram-Himalaya,

2 upper Indus basin

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10 Abstract

11 Largely depending on the meltwater from the Hindukush-Karakoram-Himalaya, withdrawals 12 from the upper Indus basin (UIB) contribute half of the surface water availability in Pakistan, indispensable for agricultural production systems, industrial and domestic use and 13 14 hydropower generation. Despite such importance, a comprehensive assessment of prevailing 15 state of relevant climatic variables determining the water availability is largely missing. 16 Against this background, this study assesses the trends in maximum, minimum and mean 17 temperatures, diurnal temperature range and precipitation from 18 stations (1250-4500 masl) for their overlapping period of record (1995-2012), and separately, from six stations of their 18 19 long-term record (1961-2012). For this, Mann-Kendall test on serially independent time 20 series is applied to detect the existence of a trend while its true slope is estimated using the 21 Sen's slope method. Further, locally identified climatic trends are statistically assessed for 22 their spatial scale significance within ten identified sub-regions of the UIB, and the spatially 23 (field) significant climatic trends are then qualitatively compared with the trends in discharge 24 out of corresponding sub-regions. Over the recent period (1995-2012), we find a well agreed 25 warming and drying of spring season (field significant in March) and a rising early-melt 26 season discharge from most of the sub-regions, likely due to a rapid snowmelt. In stark 27 contrast, most of the sub-regions feature a field significant cooling within the monsoon period 28 (particularly in July and September), which coincides well with the main glacier melt season. 29 Hence, a falling or weakly rising discharge is observed from the corresponding sub-regions 30 during mid-to-late melt season (particularly in July). Such tendencies, being largely 31 consistent with the long-term trends (1961-2012), most likely indicate dominance of the nival

but suppression of the glacial melt regime, altering overall hydrology of the UIB in future.
These findings, though constrained by sparse and short observations, largely contribute in
understanding the UIB melt runoff dynamics and address the hydroclimatic explanation of
the 'Karakoram Anomaly'.

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37 **1 Introduction**

38 The hydropower generation has key importance in minimizing the on-going energy crisis in 39 Pakistan and meeting the country's burgeoning future energy demands. For this, seasonal 40 water availability from the upper Indus basin (UIB) that contributes to around half of the 41 annual average surface water availability in Pakistan is indispensable for exploiting 3500 42 MW of installed hydropower potential at country's largest Tarbela reservoir immediate 43 downstream. Withdrawals from the UIB further contribute to the country's agrarian economy 44 by meeting extensive irrigation water demands. The earliest water supply from the UIB after a long dry period (October to March) is obtained from melting of snow (late-May to late-45 46 July), the extent of which largely depends upon the accumulated snow amount and the concurrent temperatures (Fowler and Archer, 2005; Hasson et al., 2014b). Snowmelt runoff is 47 then overlapped by the glacier melt runoff (late-June to late-August) that primarily depends 48 upon the melt season temperatures (Archer, 2003). Snow and glacier melt runoffs, originating 49 50 from the Hindukush-Karakoram-Himalaya (HKH) Ranges, together constitute around 70-51 80% of the mean annual water available from the UIB (SIHP, 1997; Immerzeel et al., 2009). Unlike major river basins of the South and Southeast Asia that feature extensive summer 52 monsoonal wet regimes downstream, the lower Indus basin is mostly arid and hyper-arid and 53 54 much relies upon the meltwater from the UIB (Hasson et al., 2014b).

55 In view of high sensitivity of the mountainous environments to climate change (MRI, 2015; 56 Hasson et al., 2016d) and the role of meltwater as an important control for the UIB runoff dynamics, it is crucial to assess the prevailing climatic state of the UIB and the subsequent 57 water availability. Several studies have been performed in this regard. For instance, Archer 58 59 and Fowler (2004) have found a significant increase in winter, summer and annual 60 precipitation over the period 1961-1999. For the same period, Fowler and Archer (2006) have found a significant cooling during summer but warming during winter. Sheikh et al. (2009) 61 62 have documented significant cooling and wetting of the monsoon (July-September) but 63 warming of the pre-monsoon season (April-May) over the 1951-2000 period. Khattak et al.

64 (2011) have found winter warming, summer cooling (1967-2005), but no definite pattern for 65 precipitation. It is noteworthy that these findings are based upon at least a decade old data 66 records. Analyzing updated data for the last three decades (1980-2009), Bocchiola and 67 Diolaiuti (2013) have suggested that winter warming and summer cooling are less general than previously thought, and can be clearly assessed only for Gilgit and Bunji stations. They 68 69 have found mostly insignificant precipitation increase over the Chitral-Hindukush and 70 northwest Karakoram while decrease over the Greater Himalayas. Analyzing temperature 71 record for recent six decades (1952-2009), Río et al. (2013) have also reported dominant 72 warming during March and pre-monsoon season.

73 The above mentioned studies have analyzed observations from only a sub-set of half dozen 74 manual, valley-bottom, low-altitude UIB stations, being maintained by the Pakistan Meteorological Department (PMD). Contrary to low-altitude stations, observations from 75 76 high-altitude stations in the South Asia mostly feature opposite sign of climatic changes and extremes, possibly influenced by the local factors (Revadekar et al., 2013). Moreover, the 77 78 bulk of the UIB stream flow originates from the active hydrologic zone (2500-5500 masl), 79 when thawing temperatures migrate over and above 2500 masl (SIHP, 1997). Given such a 80 large altitudinal dependency of the climatic signals, data from the low-altitude stations, though extending back into the first half of 20th century, are not optimally representative of 81 82 the hydro-meteorological conditions prevailing over the UIB frozen water resources (SIHP, 83 1997). Thus, the assessment of climatic trends over the UIB has been much restricted by the 84 limited availability of high-altitude and most representative observations as well as their 85 accessibility, so far.

Above mentioned studies of Archer and Fowler (2004), Fowler and Archer (2006) and Sheikh et al. (2009) have used linear least square method for trend analysis. Such parametric tests though robustly assess the trend relative to non-parametric tests (Zhai et al., 2005), but need the sample data to be normally distributed, which is not always the case for hydrometeorological observations (Hess et al., 2001). Hence, a widely adopted non-parametric test, such as, Mann Kendall (MK - Mann, 1945; Kendall, 1975) is more pragmatic choice, as employed by Khattak et al. (2011), Río et al. (2013) and Bocchiola and Diolaiuti (2013).

93 Most of the hydro-climatic time series contain red noise because of the characteristics of 94 natural climate variability, and thus, are not serially independent (Zhang et al., 2000; Wang et 95 al., 2008). However, MK statistic is highly sensitive to the serial dependence of a time series

96 (Yue and Wang, 2002; Yue et al., 2002 & 2003). For instance, the variance of MK statistic S 97 increases (decreases) with the magnitude of significant positive (negative) auto-correlation of 98 a time series, which leads to an overestimation (underestimation) of the trend detection 99 probability (Douglas et al., 2000; Wu et al., 2008; Rivard and Vigneault, 2009). To eliminate 100 such affect, von Storch (1995) and Kulkarni and von Storch (1995) proposed a pre-whitening 101 procedure that removes the lag-1 auto-correlation prior to applying the MK test, as employed 102 by Río et al. (2013) amid the above cited studies. However, such procedure is particularly inefficient when a time series either features a trend or is serially dependent negatively 103 104 (Rivard and Vigneault, 2009). In fact, presence of a trend can lead to false detection of 105 significant positive (negative) auto-correlation in a time series (Rivard and Vigneault, 2009), 106 removing which through a pre-whitening may remove (inflate) the portion of a trend, leading 107 to the underestimation (overestimation) of trend detection probability and trend magnitude 108 (Yue and Wang, 2002; Yue et al., 2003). To avoid this, Yue et al. (2002) proposed a trend 109 free pre-whitening (TFPW) in which the trend component of a time series is separated prior 110 to pre-whitening and then blended back to the resultant time series, as adopted by Khattak et 111 al. (2011). However, prior estimation of the trend may also be influenced by the presence of 112 serial correlation in a time series in a similar way the presence of trend contaminates the 113 estimates of auto-correlation (Zhang et al., 2000). It is, therefore, desirable to estimate the 114 most accurate magnitudes of both, trend and auto-correlation, in order to avoid the influence 115 of one on the other.

116 The UIB observes contrasting hydro-meteo-cryospheric regimes mainly because of the 117 complex HKH terrain and sophisticated interaction of prevailing regional circulations 118 (Hasson et al., 2014a and 2016a). The sparse meteorological network in such difficult area 119 neither covers fully its vertical nor its horizontal extent - it may also be highly influenced by 120 complex terrain features and variability of meteorological events. Under such scenario, 121 tendencies ascertained from the observations at local sites further need to be assessed for their 122 field significance. The field significance indicates whether the stations within a particular 123 region collectively exhibit a significant trend or not, irrespective of the significance of 124 individual trends (Vogel and Kroll, 1989; Lacombe and McCarteny, 2014). This yields a dominant signal of change and much clear understanding of what impacts the observed 125 126 conflicting climate change will have on the overall hydrology of the UIB and of its sub-127 regions. However, alike sequentially dependent local time series, spatial-/cross-correlation 128 amid the station network of a region, possibly present due to the influence of a common

climatic phenomenon and/or of similar physio-geographical features (Yue and Wang, 2002),
anomalously increases the probability of detecting the field significant trends (Yue et al.,
2003; Lacombe and McCarteny, 2014). Therefore, the effect of cross correlation amid the
station network needs to be eliminated while testing the field significance (Douglas et al.,
2000; Yue and Wang, 2002; Yue et al., 2003). Further, statistically identified field significant
climatic trends should be verified against the physical evidence.

135 In this study, we present a first comprehensive and systematic hydroclimatic trend analysis 136 for the UIB based on ten stream flow, six low-altitude manual and 12 high-altitude automatic 137 weather stations. We apply the MK trend test over serially independent hydroclimatic time 138 series for ensuring the existence of a trend while its true slope is estimated by the Sen's slope 139 method. The monthly to annual scale individual trends are further assessed for their field 140 significance within the ten identified sub-regions of the UIB, and in order to furnish the 141 physical attribution to statistically identified regional signal of change, the field significant 142 trends are in turn compared qualitatively with the trends in discharge out of the corresponding 143 regions.

144

145 2 Upper Indus basin

146 Spanning over the geographical range of 31-37°E and 72-82°N, the basin extends from the 147 western Tibetan Plateau in the east to the eastern Hindu Kush Range in the west, hosting the 148 Karakoram Range in the north and the western Himalayan massif (Greater Himalaya) in the 149 south (Fig. 1). Around 46 % of the UIB falls within the political boundary of Pakistan, 150 containing around 60% of the permanent cryospheric extent. Based on the Randolph Glacier 151 Inventory version 5.0 (Arendt et al., 2015), around 12% of the UIB area (19,370 km²) is 152 under the glacier cover. The snow cover varies from 3 to 67% of the basin area (Hasson et al., 153 2014b).

The hydrology of the UIB is dominated by the precipitation regime associated with the yearround mid-latitude western disturbances that intermittently transport moisture mainly during winter and spring and mostly in the solid form (Wake, 1989; Ali et al., 2009; Hewitt, 2011; Hasson et al., 2016a & 2016b). Such moisture contribution is anomalously higher during the positive phase of the north Atlantic oscillation (NAO), when the southern flank of the western disturbances intensifies over Iran and Afghanistan because of heat low there, causing additional moisture input from the Arabian Sea (Syed et al., 2006). The basin further receives
moisture from the summer monsoonal offshoots, which crossing the main barrier of the
Greater Himalayas (Wake, 1989; Ali et al., 2009), precipitate over higher (lower) altitudes in
solid (liquid) form (Archer and Fowler, 2004). Such occasional incursions of the monsoonal
system and the dominating westerly disturbances -- further controlled by the complex HKH
terrain -- define the contrasting hydroclimatic regimes within the UIB.

Mean annual precipitation within the basin ranges from less than 150 mm at Gilgit station to around 700 mm at Naltar station. However, the glaciological studies suggest substantially large amounts of snow accumulations that account for 1200-1800 mm (Winiger et al., 2005) in the Bagrot valley and above 1000 mm over the Batura Glacier (Batura Investigation Group, 1979) within the western Karakoram. Within the central karakoram, such amounts account for more than 1000 mm, and at few sites, above 2000 mm over the Biafo and Hispar glaciers (Wake, 1987).

173 The Indus River and its tributaries are gauged at ten key locations within the UIB, dividing it 174 into Astore, Gilgit, Hunza, Shigar and Shyok sub-basins that feature distinct hydrological 175 regimes (snow- and glacier-fed). Archer (2003) and Mukhopadhyay and Khan (2015) have 176 identified snow-fed (glacier-fed) sub-basins based on their: 1) smaller (larger) glacier cover; 177 2) strong runoff correlation with previous winter precipitation (concurrent temperatures) from 178 low-altitude stations, and; 3) hydrograph separation. Their findings suggest that Astore and 179 Gilgit are mainly snow-fed while Hunza, Shigar and Shyok are mainly glacier-fed sub-basins. 180 The strong influence of climatic variables on the generated melt runoff suggests high 181 vulnerability of spatio-temporal water availability to climatic changes. This is why the UIB 182 discharge features high variability – the maximum mean annual discharge is around an order 183 of magnitude higher than its minimum mean annual discharge, in extreme cases. Mean annual UIB discharge is around 2400 m³s⁻¹, which contributing around 45% of the total 184 185 surface water availability in Pakistan, mainly confines to the melt season (April-September). 186 For the rest of year, melting temperatures remain mostly below the active hydrologic 187 elevation range, resulting in minute melt runoff (Archer, 2004). The characteristics of the 188 UIB and its sub-basins are summarized in Table 1.

189

190 **3 Data**

191 **3.1 Meteorological data**

192 The network of meteorological stations within the UIB is very sparse and mainly limited to 193 within the Pakistan's political boundary, where 20 meteorological stations are being operated 194 by three different organizations. The PMD operates six manual valley-bottom (1200-2200 masl) stations that provide the only long-term record since the first half of 20th century, 195 196 however, the data before 1960 are scarce and feature large data gaps (Sheikh et al., 2009). 197 EvK2-CNR maintains two high-altitude stations within the central Karakoram, which provide 198 data only since 2005. The third meteorological network being maintained by the Snow and 199 Ice Hydrology Project (SIHP) of the Water and Power Development Authority (WAPDA), 200 Pakistan consists of twelve high-altitude (1479-4440 masl) automated weather stations, called 201 Data Collection Platforms (DCPs), which provide observations since 1994. Contrary to PMD 202 and EvK2-CNR precipitation gauges, DCPs measure snow in mm water equivalent as solid 203 moisture is the main source of melt dominated hydrology of the UIB (Hasson et al., 2014b). 204 Moreover, extending to the Karakoram Range that hosts most of the Indus basin ice reserves 205 (Fig. 1) and covering most of the active hydrologic zone of the UIB (2500-5500) -- unlike 206 PMD stations -- DCPs are well representative of the hydro-meteorological conditions 207 prevailing over the UIB cryosphere, so far. We have collected the daily data of maximum and 208 minimum temperatures (Tx and Tn, respectively) and precipitation from 12 DCPs for the 209 period 1995-2012 and from six PMD stations for the period 1961-2012 (Table 2).

210 **3.2 Discharge data**

The daily discharge data of all ten hydrometric stations within the UIB have been collected 211 212 from the Surface Water Hydrology Project of WAPDA, Pakistan for their full length of 213 available record up to 2012 (Table 3). Among the installed hydrometric stations, Shigar 214 gauge has not been operational since 2001. It is to mention that discharge observations from 215 the central and eastern UIB are hardly influenced by the anthropogenic perturbations. Though 216 the western UIB is relatively populous and the stream flow is used for the solo-seasoned 217 crops and domestic use, the overall water diversion for such use is negligible (Khattak et al., 218 2011).

219

220 4 Methods

221 We have checked the internal consistency of the data by closely following Klein Tank et al. 222 (2009) such as the situations of below zero precipitation and when maximum temperature 223 was lower than minimum temperature, which found in few were corrected. Then, we have 224 performed homogeneity tests using a standardized toolkit RH-TestV3 (Wang and Feng, 2009) 225 that uses a penalized maximal F-test (Wang et al., 2008) to identify any number of change 226 points in a time series. As no station has yet been reported homogenous at monthly time scale 227 for all variables, only relative homogeneity test was performed by adopting the most conservative threshold level of 99% for the statistical significance. Except Skardu, PMD 228 229 stations mostly feature one inhomogeneity in only Tn, which over the 1995-2012 period is 230 valid only for Gilgit and Gupis stations (Table 2). The DCP data were found of high quality 231 and homogenous. Only Naltar station has experienced inhomogeneity in Tn during 232 September 2010, which was most probably caused by heavy precipitation event resulted in a 233 mega flood in Pakistan (Houze et al., 2011; Ahmad et al., 2012) followed by similar events in 234 2011 and 2012. Since history files were not available, it was not sure that any statistically 235 found inhomogeneity only in Tn is real. Thus, we did not apply corrections to 236 inhomogeneous time series and caution the careful interpretation of results based on them.

237 4.1 Hydroclimatic trend analysis

238 We have analyzed trends in minimum, maximum and mean temperatures (Tn, Tx and Tavg, 239 respectively), diurnal temperature range (DTR = Tx - Tn), precipitation and discharge on 240 monthly to annual time scales. For this, the MK test (Mann, 1945; Kendall, 1975) is applied 241 to assess the existence of a trend while the Theil-Sen (TS - Theil, 1950; Sen, 1968) slope 242 method is applied to estimate its true slope. The MK is a ranked based method that tests the 243 existence of a trend irrespective of the type of sample data distribution and whether such 244 trend is linear or not (Wu et al., 2008; Tabari and Talaee, 2011). MK is also insensitive to the 245 data outliers and missing values (Bocchiola and Diolaiuti, 2013) and less sensitive to the 246 breaks caused by inhomogeneous time series (Jaagus, 2006). For comparison between low-247 and high-altitude stations, we have mainly analyzed their overlapping period of record (1995-248 2012) but additionally the full period of record (1961-2012) for the low-altitude stations.

249 **4.2 Trend-perceptive pre-whitening**

The used approach of Zhang et al (2000) assumes that the trend can be approximated as linear (Eqn. 1) and the noise, γ_t , can be represented as *p*th order auto-regressive process, AR(*p*) of the signal itself, plus the white noise, ε_t . Since the partial auto-correlations for lags larger than one are generally found insignificant (Zhang et al., 2000; Wang and Swail, 2001),
considering only lag-1 auto-regressive processes, *r*, transforms Eqn. 1 into Eqn. 2:

- $255 \quad Y_t = a + \beta t + \gamma_t \tag{1}$
- 256 $Y_t = a + \beta t + rY_{t-1} + \varepsilon_t$ (2)

Then the most accurate magnitudes of lag-1 auto-correlation and trend are iteratively found using the following steps:

- 1. In first iteration, lag-1 autocorrelation, r_1 is computed on the original time series, Y_t
- 260 2. Using r_1 as $(Y_t r, Y_{t-1})/(1 r)$, intermediate time series, Y_t , is obtained and its 261 trend, β_1 is computed using TS and MK methods
- 262 3. Original time series, Y_t is detrended using β_1 as $(\hat{Y}_t = Y_t \beta_1 t)$
- 4. In second iteration, lag-1 autocorrelation, r_2 is estimated on detrended time series, \hat{Y}_t
- 264 5. Original time series, Y_t is again pre-whitened using r_2 and Y_t is obtained

265 6. Trend, β_2 is then computed on \dot{Y}_t and Y_t is detrended again, yielding \hat{Y}_t

The steps have to be reiterated until r is no longer significantly different from zero or the absolute difference between the estimates of r,β obtained from two consecutive iterations becomes less than one percent. If any of the condition is met, let's suppose at the iteration n, the estimates from previous iteration (i.e. $r = r_{n-1}, \beta = \beta_{n-1}$) are used in Eqn. 3 to obtain a pre-whitened time series, Y_t^w which features the same trend as of the original time series, Y_t (Zhang et al., 2000; Wang and Swail, 2001).

272
$$Y_t^w = \frac{(Y_t - r \cdot Y_{t-1})}{(1-r)} = \hat{a} + \beta t + \epsilon_t \text{, where } \hat{a} = a + \frac{r \cdot \beta}{(1-r)} \text{, and } \epsilon_t = \frac{\epsilon_t}{(1-r)}$$
(3)

4.3 Field significance and physical attribution

274 Field significance implies whether two or more stations within a particular region collectively 275 exhibit a significant trend, irrespective of the significance of their individual trends (Vogel and Kroll, 1989; Lacombe and McCarteny, 2014). The field significance of climatic variables 276 277 has been assessed for the ten sub-regions of the UIB identified based on: 1) distinct hydrological regimes; 2) mountain divides, and; 3) installed hydrometric stations. Further, 278 279 statistically identified field significant climatic trends were qualitatively compared to the physically-based evidence of trend in discharge out of corresponding region, in order to 280 281 establish more confidence. As outlet discharges describe the integrated signal of hydrologic 282 change within the basin, testing their field significance was not required.

283 The Shigar has continuous discharge only till 1998 where its post-1998 discharge needs to be 284 derived. For this, Mukhopadhyay and Khan (2014) have estimated the pre-1998 monthly 285 correlation coefficients between Shigar and its immediate downstream Kachura gauge and 286 applied these coefficients to the post-1998 Kachura discharge. However, such approach 287 yields merely a constant fraction of the Kachura discharge as the applied coefficients are less 288 likely to remain invariant after 1998, in view of the large drainage area of Indus at Kachura 289 (113,000 km²) and the hydroclimatic changes expected upstream Shigar gauge. Here, instead 290 of estimating the post-1998 discharge at the Shigar gauge, we have derived the discharge for 291 the Shigar-region that comprises the Shigar sub-basin itself plus the adjacent region shown in 292 blank in Figure 2. This was achieved by subtracting the discharge rates of all gauges 293 upstream Shigar gauge from its immediate downstream gauge of Kachura, for each time step 294 of every time scale analyzed. The procedure assumes that the gauges far from each other have 295 negligible routing time delay at the analyzed mean monthly time scale and that such 296 approximation does not further influence the ascertained trends. Similar approach was 297 adopted to derive discharges out of ungauged identified sub-regions (Table 1).

298 We have considered the combined drainage area of Shyok and Shigar-region as UIB-Central 299 and the drainage area of Indus at Kharmong as UIB-East (Fig. 2). The rest of the UIB is 300 named as UIB-West (Fig. 2), which is further divided into upper and lower parts due to their 301 distinct hydrological regimes. Here, these regimes are identified based on the timings of 302 maximum runoff production from the median hydrographs of each hydrometric station. 303 According to such division, UIB-West-lower and Gilgit are mainly the snow-fed while Hunza 304 is mainly the glacier-fed (Fig. 3). Since the most of Gilgit basin area lies at the Hindukush 305 massifs, we call it Hindukush region. The combined area of UIB-West-lower and UIB-east 306 mainly contains the northward slopes of the Greater Himalaya, so we call it Himalaya. 307 Similarly, drainage areas of Hunza, Shyok and Shigar-region are named as western, eastern 308 and central Karakoram, respectively, that collectively constitute the Karakoram region.

For assessing the field significance, we have used the method of Yue et al. (2003), which preserves the cross correlation amid the stations network but eliminates its effect on testing the filed significance through resampling the original network using bootstrapping approach (Efron, 1979), in our case 1000 times. The method considers the counts of significant trends as the representative variables. Unlike MK statistics, *S* or its regional average (Douglas et al., 2000; Yue and Wang, 2002) 'counts' variable favourably provides a measure of dominant field significant trend when both positive and negative significant trends are present. The method counts both the number of local significant positive trends and the number of significant negative trends separately for each of 1000 resampled networks using Eqn. 10:

318
$$C_f = \sum_{i=1}^n C_i$$
 (10)

Where *n* denotes total number of stations within a region and C_i denotes a count for statistically significant trend (at 90% level) at station, *i*. Then, the empirical cumulative distributions C_f were obtained for both counts of significant positive trends and counts of significant negative trends, by ranking their 1000 values in an ascending order using Eqn.11:

323
$$P(\mathcal{C}_f \le \mathcal{C}_f^r) = \frac{r}{N+1}$$
(11)

Where *r* is the rank of C_f^r and *N* denotes the total number of resampled network datasets. We have estimated the probability of counts of significant positive (negative) trends in actual network by comparing the number with C_f for counts of significant positive (negative) trends obtained from resampled networks (Eqn. 12).

328
$$P_{obs} = P(C_{f,obs} \le C_f^r), \text{ where } P_f = \begin{cases} P_{obs} & \text{for } P_{obs} \le 0.5\\ 1 - P_{obs} & \text{for } P_{obs} > 0.5 \end{cases}$$
(12)

329 If $P_f \le 0.1$ is satisfied the trend for a region is considered to be field significant at 90% level.

We have intentionally avoided the interpolation of data and results in view of the limitations of interpolation techniques in HKH complex terrain. Large offset of glaciological estimates from the station-based precipitation amounts (Hasson et al., 2014b) further suggests that the hydroclimatic patterns are highly variable in space and that the interpolation will add to uncertainty, resulting in misleading conclusions.

335

336 5 Results

Results for the 1995-2012 period are presented in Tabular Figures 4-5 (and for select months,

- in Fig. 4) while Tabular Figure 6 presents results for the 1961-2012 period. Field significant
- climatic and discharge trends of corresponding regions are given in Tabular Figure 7.
- 340 5.1 Hydroclimatic trends

341 Mean maximum temperature

342 During months of March, May and November, most of the stations suggest mostly 343 insignificant warming, which in terms of magnitude and significance, dominates during 344 March and at the low-altitude stations (Tabular Fig. 4 and Fig. 8). In contrast, during the 345 monsoon (July-October) and in February, most of the stations suggest cooling, which being 346 similar in magnitude amid low- and high-altitude stations, dominates in September followed 347 by in July in terms of both magnitude and statistical significance (at 12 and 5 stations, 348 respectively). Moreover, the observed cooling dominates the observed warming. For the rest 349 of the months, there is a mixed response of mostly insignificant cooling and warming trends. 350 On a typical seasonal scale, there is a high agreement on spring warming, summer and 351 autumn cooling but a mixed response for winter and annual timescales.

While looking only at long-term trends (Tabular Fig. 6), we note that summer cooling (warming outside summer) in Tx is less (more) prominent and insignificant (significant) at relatively high-altitude stations, such as, Skardu, Gupis, Gilgit and Astore. When compared with trends over the shorter period of 1995-2012, strong long-term warming is restricted to spring months mainly during March and May. Similarly, long-term summer cooling period of June-September has been shifted to July-October.

358 Mean minimum temperature

359 The dominant feature of Tn is November-June insignificant warming, which contrary to 360 warming in Tx, is observed higher at the high-altitude stations than at the low-altitude 361 stations (Tabular Fig. 4 and Fig. 8). In contrast to August cooling in Tx, stations suggest a 362 minute and mostly insignificant warming in Tn. In contrast to mostly insignificant warming, 363 we have also found cooling in Tn during months of July, September and October, which 364 though similar in magnitude amid low- and high-altitude stations, dominates in September followed by in July (significant at 8 and 4 stations, respectively) as well as over the general 365 366 Tn warming, alike Tx.

On a typical seasonal scale, our results suggest warming during winter and spring, cooling during summer and a mixed response for the autumn season. The observed warming dominates during spring. It is noted that a clear signal of significant September cooling has been lost when trend has been assessed on seasonally averaged observations for autumn (combining October and November months). This is further notable from the annual time scale, on which warming trends (significant at 5 stations) dominate instead of cooling trends. While looking only at low-altitude stations (Tabular Fig. 6), we note that long-term nonsummer warming (summer cooling) in Tn is less (more) prominent and insignificant (significant) at stations of relatively high-altitude, such as, Skardu, Gupis, Gilgit and Astore. The long-term warming of winter months is mostly absent over the period 1995-2012.

377 Mean temperature

Trends in Tavg are dominated by trends in Tx during the July-October period and by Tn 378 379 during the rest of year (Tabular Figs. 4-5). Similar to Tx, Tavg features dominant cooling in 380 September, followed by in July and October (significant at 10, 4 and 1 stations, respectively). 381 In contrast, warming dominates in March, which is significant at five stations. Additionally, 382 insignificant warming tendencies observed in May and November are well agreed amid most 383 of the stations (Tabular Fig. 5, Fig. 8). On a typical seasonal timescale, the magnitude of 384 winter and spring warming is observed higher than that of summer and autumn cooling, 385 leading to dominant though mostly insignificant warming on annual timescale. The long-term 386 trends generally suggest cooling tendencies for the Jun-October period but warming for the 387 rest of year. On a seasonal timescale, low-altitude stations unanimously agree on long-term 388 and mostly significant summer cooling. For the annual timescale, a mixed response is found.

389 Diurnal temperature range

390 DTR is generally found narrowing throughout the year except for March and May, where 391 particularly low-altitude stations suggest its widening either owing to higher Tx warming or 392 higher Tn cooling (Tabular Fig. 4, Fig. 8). With high inter-station agreement, narrowing of 393 DTR is particularly significant in September followed by in February and associated with 394 higher cooling in Tx than in Tn, higher warming in Tn than in Tx or cooling in Tx but 395 warming in Tn. Narrowing DTR is more prominent at high-altitude stations and during 396 winter, autumn and annual timescales. We note that the long-term (1961-2012) year-round 397 DTR widening observed at low-altitude stations (Tabular Fig. 6) is mainly restricted to March and May, and to some extent, October and December over the period 1995-2012 (Tabular 398 399 Fig. 4).

400 **Total precipitation**

Generally, March-June months are featuring decreasing precipitation trends, which are
significant at 7, 5, 2 and 4 stations, respectively (Tabular Fig. 5 and Fig. 8). Similarly,
significant drying is observed during August and October at three stations while Rattu station

404 suggests year-round drying except in January and February. High inter-stations agreement is 405 observed for rising September and winter precipitation, which is higher at high-altitude than 406 at low-altitude stations. Most of the stations within the UIB-West-upper (monsoon dominated 407 region) exhibit an increasing trend. Six stations (Shendure, Yasin, Ziarat, Rattu, Shigar and 408 Chillas) feature significant precipitation increase in either all or at least one of the monsoon 409 months. Such precise response of monthly wetting and drying has been averaged out on 410 seasonal to annual timescales, suggesting increase (decrease) for autumn and winter (spring 411 and summer) but a mixed response for annual precipitation.

412 Comparison of long-term trends at low-altitude stations (1961-2012) with their trends over 413 recent period (1995-2012) suggests that the long-term spring drying particularly of March 414 and April months and wetting of September (the last monsoonal) month has recently been 415 intensified while the long-term increasing summer precipitation has been changed to 416 decreasing (See Tables 5 and 6).

417 Discharge

From Figure 3, we clearly show that snow and glacier melt regimes of the UIB can be differentiated from the maximum runoff production timing based on the median hydrographs of available gauges. Figure 3 suggests that Indus at Kharmong (UIB-East), Gilgit at Gilgit (Hindukush) and Astore at Doyian basins that generally feature their peak runoffs in June/July are primarily snow fed while the rest that feature peak runoff in August are mainly glacier fed.

424 Over the 1995-2012 period, discharge change pattern seems to be more consistent with 425 tendencies in temperature than in precipitation record. Most of the hydrometric stations 426 feature increasing discharge during October-June (dominant during May-June) but decreasing 427 discharge during July, which is significant for five high-altitude/latitude glacier-fed sub-428 regions (Karakoram, Shigar, Shyok, UIB-Central and Indus at Kachura), mainly owing to 429 drop in July temperatures (Tabular Fig. 5). There is a mixed response for August and 430 September months, however, significant trends suggest an increasing discharge from two 431 regions (Hindukush and UIB-West-lower) in August and from four sub-regions (Hindukush, 432 western-Karakoram, UIB-West-lower and UIB-west) in September.

Despite dominant September cooling, discharge drops mainly during July, suggesting it as
month of effective cooling. Discharge of July is also decreasing for the whole UIB though

such trend is not significant. During winter, spring and autumn seasons, discharge at most
sites feature increasing trend while during summer season and on an annual time scale there
is a mixed response.

438 Long-term discharge is generally rising from November to May (Tabular Fig. 6), where such 439 rise is higher in magnitude and mostly significant in May. There is a mixed response for 440 June-October. Consistently on coarser temporal scale, winter discharge is rising while a 441 mixed response is observed for other seasons and on annual timescale. While comparing the 442 long-term trends with those assessed over 1995-2012 period, we note prominent shifts in the 443 sign of trends for the seasonal transitional month of June and within the high flow period of 444 July-September. Such shifts may attribute to recent higher summer cooling accompanied by 445 the enhanced monsoonal precipitation. For instance, long-term July discharge is rising for 446 eastern-, central- and whole Karakoram, UIB-Central, Indus at Kachura, Indus at Partab 447 Bridge and Astore but falling for other sub-regions. In contrast, trends over recent two 448 decades feature opposite signs, except for Astore, UIB-West-upper and its sub-regions.

449 **5.2 Field significance and physical attribution**

450 We present the mean of positive and negative field significant trends from each region (if 451 both exist) in order to present the dominant signal (Tabular Fig. 7). Results show unanimous 452 field significant warming for most of the regions in March followed by in August. Similarly, 453 field significant drying is found in March over all regions, except Karakoram and UIB-454 Central. Alike local trends, we find field significant cooling over all regions in July, 455 September and October, which on a seasonal timescale, dominates in autumn followed by in 456 summer. Note that most of the climatic trends are not field-significant for the transitional (or 457 pre-monsoonal) period of April-June.

458 We find a general trend of narrowing DTR, which is associated with either warming of Tn 459 against cooling of Tx or relatively lower cooling in Tn than in Tx. Field significant drying of 460 the lower latitudinal generally snow-fed sub-regions (Astore, Himalaya, UIB-West-lower) is 461 also observed particularly during March-September, thus for spring and summer and on 462 annual timescale. On the other hand, wetting (drying) of winter and autumn (spring and 463 summer) is observed for the Hindukush, UIB-West, UIB-West-upper and whole UIB. For the 464 western Karakoram, increasing precipitation is observed only for winter. For the whole Karakoram and UIB-central, field-significant rising precipitation trend is found throughout a 465 466 year, except for spring where no signal is evident.

467 Moreover, field significant climatic trends are mostly in qualitative agreement with the trends 468 in discharge from the corresponding regions. Such an agreement is high during summer, 469 particularly for July, and during winter, for March. Few exceptions to such consistency are 470 the sub-regions of Himalaya, UIB-West and UIB-West-lower, for which, in spite of the field 471 significant cooling in July, discharge is still rising. However, the magnitude of rise in July 472 discharge has substantially dropped when compared to previous (June) and following 473 (August) months. Such substantial drop in July discharge increase rate is again consistent 474 with the field significant cooling in July for the UIB-West and UIB-West-lower. Further, 475 besides substantial cooling (warming) in September (March), most prominent decrease in 476 discharge is observed in July while its decrease in May, suggesting them months of effective 477 cooling and warming, respectively. Generally, periods of runoff decrease (in a sequence) 478 span from May to September for the Karakoram, June to September for the UIB-Central, July 479 to August for the western-Karakoram and UIB-West-upper, July to November for the Astore 480 and only over July for the Hindukush and UIB. UIB-West-lower and Himalaya suggest 481 decrease in discharge during months of April and February, respectively.

482

483 6 Discussions

484 **6.1 Cooling trends**

Observed long-term summer and autumn (or monsoon) cooling is mostly consistent with the
earlier reports for the study basin (Fowler and Archer, 2005 and 2006; Khattak et al., 2011;
Sheikh et al., 2009), as well as those, for the neighboring regions, such as, Nepal, Himalayas
(Sharma et al., 2000; Cook et al., 2003), northwest India (Kumar et al., 1994), Tibetan
Plateau (Liu and Chen, 2000), central China (Hu et al., 2003), and central Asia (Briffa et al.,
2001).

Over the 1995-2012 period, field significant cooling observed mostly in July, September and October for all UIB sub-regions coincides with the monsoonal onset and retreat months, and most importantly, with the main glacier melt season, thus anticipated to negatively affect the glacier melt runoff. The observed cooling phenomenon is generally attributed to the incursions of the south Asian summer monsoonal system and its precipitation (Cook et al., 2003) into the Karakoram and the UIB-West that presently seems to be accelerated in view of the observed increase in cloud cover, precipitation and number of wet days (Bocchiola and 498 Diolaiuti, 2013). Since summer precipitation over the UIB is partly received from the 499 westerly disturbances (Wake 1987), the observed cooling may also be attributed to the 500 enhanced influence of the westerly disturbances during summer months, alike during winter 501 and spring (Madhura et al., 2015). Nevertheless, observed increase in cloud cover leads to 502 reduction of incident downward radiations and results in cooling (or less warming) of Tx. 503 Forsythe et al. (2015) have consistently observed the influence of cloud radiative effect on 504 the near surface air temperature over the UIB. The enhanced cloudy conditions most probably 505 are responsible for initial warming in Tn through longwave cloud radiative effect, and when 506 such conditions persist longer in time, Tx and Tn more likely tend to cool. Under the clear 507 sky conditions, cooling in Tx further continues as a result of evaporative cooling of the 508 moisture-surplus surface under precipitation event (Wang et al., 2014) or due to irrigation 509 (Kueppers et al., 2007). Han and Yang (2013) found irrigation expansion over Xinjiang, 510 China as a major cause of observed cooling in Tavg, Tx and Tn during May-September over 511 the period 1959-2006. Further, higher drop in Tn observed over UIB-West-lower during 512 winter may be attributed to intense nighttime cooling of the deforested, thus moisture deficit, 513 bare soil surface, exposed to direct day time solar heating as explained by Yadav et al. 514 (2004). The relevance of such hypotheses for the UIB further needs a detailed investigation 515 of the land-atmosphere processes and feedbacks using high-resolution climate model 516 simulations with explicitly resolved convections, which is beyond the scope of our analysis.

517 **6.2 Warming trends**

518 Long-term warming during November-May is generally found consistent with earlier reports 519 of warming (Fowler and Archer, 2005 and 2006; Sheikh et al., 2009; Khattak et al., 2011; Río 520 et al., 2013) as well as with decreasing snow cover in spring (1967-2012) over the Northern 521 Hemisphere and worldwide (IPCC, 2013) and in winter (2001-2012) over the study region 522 (Hasson et al., 2014b). Consistent with the findings of Sheikh et al. (2009) and Río et al. 523 (2013), warming dominates in spring months where it is field significant in March over 524 almost all identified sub-regions of the UIB. Under the drying spring scenario, less cloudy 525 conditions associated with increasing number of dry days for the westerly precipitation 526 regime (Hasson et al., 2016a & 2016b) together with the snow-albedo feedback can partly 527 explain spring warming. Contrary to long-term warming trends analyzed here or to those 528 previously reported, a field significant cooling is found for winter, which is consistently

529 observed over the eastern United States, southern Canada and much of the northern Eurasia

530 (Cohen et al., 2012).

531 **6.3 Wetting and drying trends**

Field significant rising precipitation for the sub-regions of relatively higher latitudes (Hindukush and UIB-Central, and thus, for the UIB-West-upper, Karakoram and the whole UIB) may be attributed to the enhanced late-monsoonal or westerly precipitation regimes at high-altitude stations. Whereas, shift of the long-term summer (June-August) wetting to drying at the low-altitude stations over the period 1995-2012 indicates a recent transition towards weaker monsoonal influence therein.

538 The field significant precipitation increase during winter but decrease during spring 539 anticipates certain changes within the westerly precipitation regime. The field significant 540 spring drying (except for Karakoram) is mainly consistent with the weakening and northward 541 shift of the mid-latitude storm track (Bengtsson et al., 2006) and also with increasing number of spring dry days (Hasson et al., 2016a & 2016b). On the other hand, observed winter 542 543 precipitation increase for relatively high latitudinal sub-regions is more consistent with the 544 observed more frequent incursions of the westerly disturbances therein (Cannon et al., 2015; 545 Madhura et al., 2015). Nevertheless, in view of the enhanced influence of prevailing weather 546 systems and certain changes expected in their seasonality/intermittency under changing 547 climate (Hasson et al., 2016a & 2016b), we speculate significant changes in the timings of the 548 melt water availability from the UIB. Such hypothesis can be tested by assessing changes in 549 the seasonality of observed precipitation and runoff.

550 **6.4 Water availability**

551 The long-term discharge tendencies are consistent with earlier reports from Khattak et al. 552 (2011) for Indus at Kachura, and UIB and from Farhan et al. (2014) for Astore. Similarly, 553 rising and falling discharge trends from Shyok and Hunza sub-basins, respectively, are 554 consistent with Mukhopadhyay et al. (2015). The discharge trends from Shigar-region, 555 though statistically insignificant, are only partially consistent with Mukhopadhyay and Khan 556 (2014), exhibiting agreement for an increasing trend in June and August but a decreasing 557 trend in July and September. Further, prominent shifts of the long-term trends of rising melt-558 season discharge into falling over the period 1995-2012 for mostly the glacier-fed sub-559 regions (Indus at Kachura, Indus at Partab Bridge, Eastern-, Central- and whole-Karakoram

and UIB-Central) may attribute to higher summer cooling together with certain changes inprevailing precipitation regimes.

562 Over the 1995-2012 period, significant decreasing trend in July discharge is most probably 563 attributed to observed July cooling, which though less prominent than cooling in September, 564 is much effective as it coincides with the main glacier melt season. A drop in July discharge 565 further indicates reduced melt water availability but at the same time positive basin storage, 566 particularly under prevailing wetter conditions. Similarly, rising discharge during May and 567 June most likely is due to the observed warming, which though less prominent than warming 568 in March, is much effective since it coincides with the snowmelt season. This suggests an 569 early melt of snow and subsequent increase in the melt water availability, but concurrently, a 570 lesser amount of snow available for the subsequent melt season. These seasonally distinct 571 changes emphasize on the separate assessments of snow and glacier melt regimes, for which 572 an adequate choice is the hydrological models, which are able to independently simulate 573 snow and glacier melt processes, e.g. University of British Columbia (UBC) watershed 574 model. Based on the UBC model, Hasson et al. (2016c) has recently confirmed our findings 575 that the continuation of prevailing early-melt season warming will yield an increased and 576 early snowmelt runoff, but in stark contrast, mid-to-late melt season cooling will result in a 577 decreased and delayed glacier melt runoff in near future. Such changes in both snow and 578 glacier melt regimes all together can result in a sophisticated alteration of the hydrological 579 regimes of the UIB, and subsequently, the timings of the downstream water availability.

580 Although discharge change pattern seems to be more consistent with the field significant 581 temperature trends, indicating cryospheric melt as a dominating factor in determining the 582 UIB discharge variability, it can also be substantially influenced by changes in the 583 precipitation regimes. For instance, monsoonal offshoots intruding into the study region 584 ironically result in declining river discharge (Archer, 2004). In fact, high albedo of fresh 585 snow reduces the incident energy that results in immediate drop in the melt. The fresh snow 586 also insulates the underlying glacier/ice, slowing down the whole melt process till earlier 587 albedo rates are achieved. Thus, melting of cryosphere and subsequent water availability is 588 also inversely correlated to the number of snowfall events/days during the melt season 589 (Wendler and Weller, 1974; Ohlendorf et al., 1997).

590 In view of the sparse observational network analyzed here, we need to clarify that the 591 observed cooling and warming is only an aspect of the wide spread changes prevailing over 592 the wide-extent UIB basin. This is much relevant for the UIB-Central where we have only 593 one station each from the eastern- and central-Karakoram (UIB-Central) that is not 594 exclusively representative of the hydro-climatic state of corresponding sub-region. Thus, field 595 significant results for the whole Karakoram are mainly dominated by the contribution of relatively large number of stations from the western-Karakoram. Nevertheless, reports of 596 597 increasing end-of-summer snow covers and falling regional snow line altitudes (Minora et al., 598 2013; Hasson et al., 2014b; Tahir et al., 2016), increasing or stable glacial extents (Hewitt, 2005; Scherler et al., 2011; Bhambri et al., 2013; Minora et al., 2013), and possibly a non-599 600 negative glaciers' mass balance within eastern- and central-Karakoram (Gardelle et al., 2013 601 - contrary at shorter period – Kääb et al., 2015), local climate change narratives (Gioli et al., 602 2013) and overall simulated reduced near-future water availability for the UIB (Hasson et al., 603 2016c), reinforce our presented findings.

We find a common response of hydroclimatic changes from a certain set of months, which are different than those (DJF, MAM, JJA, SON) typically considered for winter, spring, summer and autumn seasons, respectively. This emphasizes on analyzing the hydroclimatic observations on higher temporal resolution to robustly assess the delicate signals of change.

608 It is to mention that the hydro-climatic regime of the UIB is substantially controlled by the 609 interaction of large scale circulation modes and their associated precipitation regimes, which 610 are in turn controlled by the global indices, such as, NAO and ENSO etc. However, time 611 period covered by our presented analysis is not long enough to disintegrate the natural 612 variability signals from the transient climate change. These phenomena need to be better 613 investigated over the longer and spatially complete observational record, thus preferably 614 including the extensive database of validated proxy observations since the challenges of short 615 and sparse robust in-situ observations are most likely to remain invariant for the UIB.

616

617 7 Conclusions

618 We present a first comprehensive and systematic hydroclimatic trend analysis for the UIB 619 based on ten stream flow, six low-altitude manual and 12 high-altitude automatic weather 620 stations. Results suggest general narrowing of DTR throughout the year except for March and 621 May, which is significant in September followed by in February. Such year-round narrowing of DTR is further found field significant for almost all sub-regions, and is mainly associatedwith either higher cooling in Tx than in Tn or cooling in Tx but warming in Tn.

624 Cooling at most of the stations is observed during the monsoon and the main glacier melt 625 season (July-October), which is significant in September followed by in July. Further, locally 626 observed cooling is found field significant for almost all sub-regions in July, September and 627 October, and on a seasonal timescale, for autumn and summer. In contrast, well agreed local 628 warming though mostly insignificantly observed in March, May and November is field 629 significant in March for most of the sub-regions. For precipitation, March, spring and 630 summer feature field significant drying for all the sub-regions except those within the 631 karakoram while winter, autumn and September mostly feature wetting of high (drying of 632 low) altitudinal sub-regions. Change pattern in discharge out of corresponding sub-regions 633 seems more consistent with the field significant tendencies in temperature than in 634 precipitation, where discharge is either falling or weakly rising (rising) in response to cooling 635 (warming), particularly in the month of July (May). These findings though constrained by 636 short and sparse observational dataset suggest distinct changes for the snow and glacier melt seasons, indicating at present strengthening of the nival but suppression of the glacial melt 637 regime, altering the overall hydrology of the UIB. The presented findings largely contribute 638 639 to the ongoing research on understanding the melt runoff dynamics within the UIB and in 640 addressing the hydroclimatic explanation of the 'Karakoram Anomaly'.

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S.	Watershed/	Designated	Expression	Designated Name	Area	Glacier	%	% of UIB	Elevation	Mean	% of UIB	No of
No.	Tributary	Discharge sites	for deriving	of the Region	(km^2)	Cover	Glacier	Glacier	Range (m)	Discharge	Discharge	Met
			approximated			(km ²)	Cover	Aboded		$(m^{3}s^{-1})$		Stations
1	Induc	Vhormona	Discharge	LIID East	60.255	2 6 4 2	4	14	2250 7027	451	10.0	1
1	maus	Knarmong		UIB-East	09,333	2,043	4	14	2230-7027	431	18.8	1
2	Shyok	Yogo		Eastern-Karakoram	33,041	7,783	24	42	2389-7673	360	15.0	1
3	Shigar	Shigar		Central-Karakoram	6,990	2,107	30	11	2189-8448	206	8.6	1
4	Indus	Kachura		Indus at Kachura	113,035	12,397	11	68	2149-8448	1078	44.8	
5	Hunza	Dainyor Bridge		Western-Karakoram	13,734	3,815	28	21	1420-7809	328	13.6	4
6	Gilgit	Gilgit		Hindukush	12,078	818	7	4	1481-7134	289	12.0	5
7	Gilgit	Alam Bridge		UIB-West-upper	27,035	4,676	21	25	1265-7809	631	27.0	9
8	Indus	Partab Bridge		Indus at Partab	143,130	17,543	12	96	1246-8448	1788	74.3	
9	Astore	Doyian		Astore at Doyian	3,903	527	14	3	1504-8069	139	5.8	3
10	UIB	Besham Qila		UIB	163,528	19,370	12	100	569-8448	2405	100.0	18
11			4 - 2 - 1	Shigar-region						305	12.7	
12			2 + 3 + 5	Karakoram	53,765	13,705	25	75	1420-8448	894	37.2	*8
13			2 + 11 + 5	derived Karakoram						993	41.3	
14			4 - 1	UIB-Central	43,680	9,890	23	54	2189-8448	627	26.1	*4
15			10 - 4	UIB-West	50,500	5,817	13	32	569-7809	1327	55.2	14
16			10 - 4 - 7	UIB-West-lower	23,422	1,130	7	6	569-8069	696	28.9	5
17			1 + 16	Himalaya	92,777	3,773	5	20	569-8069	1147	47.7	7

Table 1: Characteristics of the gauged and derived regions of UIB. Note: *Including nearby Skardu and Gilgit stations for the Karakoram and
 Deosai station for the UIB-Central regions. Derived time series are limited to a common length of used gauges' record, thus their statistics.

887 Table 2: Meteorological stations and their attributes. Inhomogeneity is found only in Tn over

full period of record. Note: (*) represents inhomogeneity only over the 1995-2012 period.

S. No.	Station Name	Period From	Period To	Agency	Latitude (degrees)	Longitude (degrees)	Altitude (meters)	Inhomogeneity at
1	Chillas	01/01/1962	12/31/2012	PMD	35.42	74.10	1251	2009/03
2	Bunji	01/01/1961	12/31/2012	PMD	35.67	74.63	1372	1977/11
3	Skardu	01/01/1961	12/31/2012	PMD	35.30	75.68	2210	
4	Astore	01/01/1962	12/31/2012	PMD	35.37	74.90	2168	1981/08
5	Gilgit	01/01/1960	12/31/2012	PMD	35.92	74.33	1460	2003/10*
6	Gupis	01/01/1961	12/31/2010	PMD	36.17	73.40	2156	1988/12
								1996/07*
7	Khunjrab	01/01/1995	12/31/2012	WAPDA	36.84	75.42	4440	
8	Naltar	01/01/1995	12/31/2012	WAPDA	36.17	74.18	2898	2010/09*
9	Ramma	01/01/1995	09/30/2012	WAPDA	35.36	74.81	3179	
10	Rattu	03/29/1995	03/16/2012	WAPDA	35.15	74.80	2718	
11	Hushe	01/01/1995	12/31/2012	WAPDA	35.42	76.37	3075	
12	Ushkore	01/01/1995	12/31/2012	WAPDA	36.05	73.39	3051	
13	Yasin	01/01/1995	10/06/2010	WAPDA	36.40	73.50	3280	
14	Ziarat	01/01/1995	12/31/2012	WAPDA	36.77	74.46	3020	
15	Dainyor	01/15/1997	07/31/2012	WAPDA	35.93	74.37	1479	
16	Shendoor	01/01/1995	12/28/2012	WAPDA	36.09	72.55	3712	
17	Deosai	08/17/1998	12/31/2011	WAPDA	35.09	75.54	4149	
18	Shigar	08/27/1996	12/31/2012	WAPDA	35.63	75.53	2367	

Table 3. SWHP WAPDA stream flow gauges given in the downstream order along with their characteristics and their periods of record analyzed. *Gauge is not operational after 2001.

S. No.	Gauged River	Discharge Gauging Site	Period From	Period To	Latitude (degrees)	Longitude (degrees)	Height (meters)
1	Indus	Kharmong	May-82	Dec-11	34.93	76.21	2542
2	Shyok	Yogo	Jan-74	Dec-11	35.18	76.10	2469
3	Shigar	Shigar*	Jan-85	Dec-98 & 2001	35.33	75.75	2438
4	Indus	Kachura	Jan-70	Dec-11	35.45	75.41	2341
5	Hunza	Dainyor	Jan-66	Dec-11	35.92	74.37	1370
6	Gilgit	Gilgit	Jan-70	Dec-11	35.92	74.30	1430
7	Gilgit	Alam Bridge	Jan-74	Dec-12	35.76	74.59	1280
8	Indus	Partab Bridge	Jan-62	Dec-07	35.73	74.62	1250
9	Astore	Doyian	Jan-74	Aug-11	35.54	74.70	1583
10	UIB	Besham Qila	Jan-69	Dec-12	34.92	72.88	580





Figure 1: The upper Indus basin (UIB) and meteorological station networks



Figure 2: Hydometric stations and the sub-regions considered for field significance



Figure 3: Long-term median hydrograph for ten gauges separating the sub-basins of the UIB

featuring either mainly snow-fed (in color) or glacier-fed hydrological regimes (in greyscale).



915 Tabular Figure 4: Trend for Tx, Tn and DTR in °C (per unit time) at monthly to annual

timescales over the period 1995-2012. Note: stations are given in top to bottom altitude order.

917 Slopes significant at 90% level are given in **bold**. Color scale is distinct for each timescale.

Blue (red) refers to decreasing (increasing) trend.

Variab	le Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Тх	Khunjrab	0.01	-0.01	0.10	0.03	0.12	-0.01	-0.09	0.06	-0.16	0.01	0.12	0.07	0.05	0.07	-0.05	0.04	0.04
	Deosai	0.02	-0.05	0.07	-0.01	0.06	0.01	-0.19	-0.01	0.00	0.02	0.06	0.05	0.08	0.06	0.03	0.02	0.06
	Shendure	-0.17	-0.09	0.01	-0.03	-0.06	-0.10	-0.13	-0.07	-0.22	-0.06	0.04	-0.11	-0.08	-0.06	-0.11	-0.05	-0.05
	Yasin	0.00	-0.03	0.13	-0.02	0.10	0.03	-0.16	-0.08	-0.35	0.12	-0.02	-0.10	0.03	0.08	-0.06	-0.01	0.05
	Rama	-0.06	-0.07	0.02	-0.11	0.14	0.04	-0.11	-0.09	-0.29	-0.10	0.01	0.00	-0.04	-0.04	-0.07	-0.07	-0.08
	Hushe	-0.05	-0.01	0.09	0.00	0.17	-0.06	-0.09	0.02	-0.20	-0.09	0.01	0.03	0.02	0.03	-0.02	-0.03	-0.03
	Ushkore	-0.04	-0.02	0.10	0.03	0.25	-0.01	-0.12	-0.06	-0.22	-0.05	0.06	-0.01	0.02	0.08	-0.05	-0.02	-0.01
	Ziarat	0.00	-0.01	0.12	-0.02	0.13	0.09	-0.11	-0.03	-0.21	-0.04	0.09	0.04	0.06	0.06	-0.02	-0.04	0.01
	Naltar	-0.04	-0.04	0.10	-0.03	0.10	0.03	-0.12	-0.03	-0.19	0.03	-0.01	0.01	-0.02	0.07	-0.03	-0.05	0.00
	Rattu	-0.16	-0.10	0.04	-0.03	0.11	0.14	-0.06	-0.05	-0.17	-0.23	0.04	-0.15	-0.12	-0.03	0.01	-0.03	-0.07
	Shigar	-0.04	-0.08	-0.02	-0.08	-0.38	-0.15	-0.08	0.03	-0.01	-0.09	0.11	0.01	-0.02	-0.09	-0.09	-0.02	-0.02
	Skardu	0.10	0.08	0.12	0.04	0.04	-0.08	-0.10	0.06	-0.23	-0.10	-0.04	-0.05	-0.02	0.13	-0.07	-0.09	-0.02
	Astore	0.09	0.00	0.20	0.03	0.18	0.06	-0.05	-0.03	-0.15	-0.11	0.05	0.04	0.08	0.15	-0.01	-0.05	0.02
	Gupis	-0.05	0.03	0.27	0.11	0.20	0.01	-0.09	-0.13	-0.09	0.12	0.12	0.03	0.11	0.20	0.03	0.03	0.07
	Dainyor	-0.04	-0.08	0.23	-0.02	0.15	-0.19	-0.18	0.01	-0.15	-0.04	0.10	-0.07	-0.06	0.14	-0.08	-0.01	-0.02
	Gilgit	0.09	-0.07	0.12	0.03	0.15	0.02	-0.15	-0.08	-0.31	-0.07	0.07	-0.05	-0.04	0.06	-0.05	-0.08	-0.05
	Bunji	0.09	-0.08	0.13	0.04	0.11	0.07	-0.01	0.04	-0.22	-0.12	-0.01	-0.08	0.00	0.11	0.02	-0.07	-0.02
	Chilas	0.09	-0.03	0.16	0.01	0.13	0.01	-0.15	-0.06	-0.24	0.00	0.03	-0.06	-0.05	0.08	-0.07	-0.05	-0.06
_	ennus 	0.05	0.00	0.10	0.01	0.15	0.01	0.10	0.00	•=-	0.00	0.00	0.00	0.05	0.00	0.07	0.05	0.00
Tn	Khunrab	0.15	0.26	0.16	0.03	0.18	-0.02	-0.04	0.00	0.01	0.05	0.17	0.10	0.21	0.08	-0.01	0.06	0.09
	Deosai	0.02	0.09	0.21	0.00	0.01	0.00	0.03	-0.02	-0.08	0.03	0.09	0.00	0.06	0.10	-0.02	0.05	0.10
	Shendure	0.04	-0.03	0.10	0.06	0.05	0.00	-0.06	0.00	-0.10	-0.01	0.10	0.08	0.09	0.07	-0.03	0.01	0.05
	Yasin	0.09	0.07	0.12	0.02	0.10	0.01	-0.11	-0.05	-0.21	0.10	0.04	-0.08	0.06	0.11	-0.04	0.03	0.08
	Rama	-0.08	0.10	0.05	0.02	0.06	0.01	0.00	0.01	-0.09	0.00	0.11	0.07	-0.02	0.03	0.03	0.02	0.02
	Hushe	0.00	0.14	0.08	0.02	0.14	-0.04	-0.08	0.04	-0.09	-0.04	0.04	0.01	0.06	0.06	-0.01	0.01	0.01
	Ushkore	-0.06	0.05	0.08	0.09	0.13	0.00	-0.04	-0.02	-0.16	-0.09	0.08	0.01	0.00	0.08	0.01	-0.01	0.00
	Ziarat	0.12	0.23	0.11	0.04	0.04	0.04	-0.08	0.01	-0.10	-0.01	0.09	0.09	0.17	0.07	0.00	0.01	0.06
	Naltar	-0.01	0.08	0.10	0.02	-0.01	-0.03	-0.10	-0.01	-0.07	0.00	-0.03	0.00	-0.07	0.10	-0.03	-0.01	0.04
	Rattu	-0.05	0.10	-0.08	-0.02	0.06	0.05	-0.07	0.01	-0.12	-0.02	0.07	0.01	0.04	-0.03	0.01	-0.08	-0.04
	Shigar	0.03	0.02	-0.01	-0.03	-0.21	-0.09	-0.07	0.05	0.07	-0.11	0.05	0.04	0.01	-0.02	-0.06	-0.01	0.01
	Skardu	-0.03	0.08	-0.02	-0.02	-0.07	-0.11	-0.15	-0.08	-0.10	-0.12	-0.14	-0.11	-0.18	-0.01	-0.12	-0.16	-0.08
	Astore	0.01	0.09	0.05	0.03	-0.02	0.02	-0.07	0.01	-0.10	-0.05	0.05	-0.08	0.06	0.11	-0.01	-0.03	-0.02
	Gupis	-0.15	-0.03	0.19	0.11	0.09	0.03	-0.04	0.04	-0.07	-0.03	-0.12	-0.14	-0.11	0.14	-0.04	-0.09	0.01
	Dainyor	-0.13	0.01	0.13	0.01	0.11	-0.04	-0.17	0.03	-0.06	-0.02	-0.06	-0.05	0.01	0.07	-0.03	-0.04	0.01
	Gilgit	0.03	0.10	0.06	0.04	0.04	0.05	-0.01	0.26	0.30	0.05	0.09	-0.01	0.08	0.07	0.06	0.19	0.08
	Bunji	0.01	0.03	0.05	0.03	0.02	0.04	-0.01	0.17	0.01	0.03	0.13	0.00	0.02	0.05	0.06	0.04	0.03
	Chilas	-0.09	-0.18	0.01	-0.07	0.02	-0.05	-0.11	-0.08	-0.21	-0.10	0.00	-0.06	-0.15	-0.05	-0.07	-0.11	-0.07
DTR	Khunrab	-0.10	-0.25	-0.30	-0.19	-0.24	-0.08	-0.13	-0.11	-0.11	-0.04	-0.03	-0.05	-0.17	-0.18	-0.04	-0.04	-0.08
	Deosai	0.07	-0.09	0.01	0.11	-0.05	0.05	0.16	0.19	0.01	0.02	-0.01	0.03	0.01	0.00	0.13	0.01	0.13
	Shendure	-0.06	-0.09	-0.26	-0.29	-0.17	-0.08	-0.03	-0.05	-0.09	-0.07	-0.05	-0.24	-0.12	-0.20	-0.10	-0.06	-0.15
	Yasin	-0.13	-0.23	-0.05	-0.15	-0.12	-0.20	-0.13	-0.11	-0.22	-0.58	-0.24	-0.19	-0.08	-0.07	-0.14	-0.25	-0.12
	Rama	-0.05	-0.16	-0.04	-0.11	-0.04	-0.02	-0.15	-0.13	-0.27	-0.20	-0.08	-0.07	-0.09	-0.07	-0.07	-0.13	-0.08
	Hushe	-0.08	-0.17	-0.01	-0.05	-0.02	0.00	-0.03	-0.02	-0.07	0.00	-0.03	-0.01	-0.10	-0.01	-0.02	-0.03	-0.04
	Ushkore	0.00	-0.06	-0.02	-0.08	-0.01	-0.05	-0.01	-0.02	-0.08	-0.01	-0.02	-0.03	-0.03	-0.02	-0.03	-0.03	-0.03
	Ziarat	-0.09	-0.26	0.02	-0.02	0.01	-0.01	-0.05	-0.01	-0.10	-0.03	-0.03	-0.12	-0.13	0.03	-0.02	-0.05	-0.06
	Naltar	-0.06	-0.15	0.02	-0.06	0.06	-0.02	-0.02	-0.02	-0.09	-0.03	-0.03	-0.13	-0.08	0.00	-0.01	-0.06	-0.05
	Rattu	-0.10	-0.16	-0.04	-0.10	0.02	-0.04	-0.09	-0.11	-0.18	-0.16	-0.18	-0.15	-0.12	-0.01	-0.04	-0.10	-0.05
	Shigar	0.08	0.00	-0.05	0.00	0.01	0.03	-0.03	-0.01	-0.07	0.01	0.08	0.07	0.07	0.03	-0.06	0.00	-0.07
	Skardu	-0.04	-0.14	0.06	0.01	0.13	0.06	-0.01	-0.02	-0.21	0.04	0.03	0.14	-0.07	0.07	-0.01	-0.01	0.00
	Astore	-0.02	-0.13	0.13	0.00	0.05	0.00	-0.03	-0.07	-0.08	0.03	-0.03	0.04	-0.09	0.06	-0.02	-0.05	-0.01
	Gupis	0.04	0.00	0.15	-0.01	0.10	-0.01	-0.03	-0.10	-0.05	0.16	0.16	0.15	0.13	0.07	-0.06	0.09	0.09
	Dainyor	-0.05	-0.09	0.06	-0.11	-0.21	-0.19	-0.11	-0.07	-0.10	-0.44	-0.01	-0.07	-0.09	-0.07	-0.23	-0.12	-0.19
	Gilgit	-0.13	-0.19	0.05	-0.02	0.10	-0.13	-0.27	-0.26	-0.87	-0.18	-0.09	-0.02	-0.11	-0.03	-0.15	-0.25	-0.18
	Bunji	-0.04	-0.14	0.05	0.03	0.04	-0.01	-0.03	-0.04	-0.27	-0.03	-0.16	-0.10	-0.07	0.06	-0.01	-0.14	-0.05
	Chilas	0.07	0.09	0.21	0.11	0.13	0.03	-0.04	0.04	0.00	0.08	0.01	0.04	0.10	0.14	0.02	0.02	0.02

919

- 921 Tabular Figure 5: Same as Tabular Figure 4. Here, slopes for P are in mm and for Q in m^3s^{-1} .
- 922 Hydrometric gauges are given in the downstream order. Blue, yellow and orange (red, green

and cyan) colors refer to decreasing (increasing) trends in Tavg, P and Q, respectively.

Variable	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Tavg	Khunirab	0.13	0.09	0.13	0.05	0.19	0.00	-0.06	0.06	-0.13	0.05	0.17	0.10	0.15	0.09	-0.03	0.06	0.06
Ū	Deosai	0.06	0.01	0.15	0.00	0.07	0.01	-0.07	0.03	-0.05	0.02	0.08	0.01	0.10	0.06	0.03	0.04	0.07
	Shendure	-0.05	-0.05	0.05	0.02	0.02	-0.05	-0.10	-0.05	-0.15	-0.04	0.06	-0.03	0.01	-0.04	-0.05	-0.02	0.01
	Yasin	0.02	0.01	0.13	0.01	0.06	0.04	-0.19	-0.07	-0.27	0.11	0.01	-0.08	0.04	0.13	-0.05	0.02	0.06
	Rama	-0.12	0.02	0.05	-0.06	0.07	0.01	-0.03	-0.03	-0.19	-0.09	0.05	0.02	0.02	0.00	0.00	-0.01	-0.04
	Hushe	-0.03	0.05	0.06	0.02	0.14	-0.05	-0.07	0.02	-0.13	-0.07	0.03	0.04	0.01	0.06	-0.01	0.00	-0.01
	Ushkore	-0.07	0.00	0.08	0.05	0.21	0.00	-0.03	-0.03	-0.17	-0.09	0.06	0.01	0.04	0.09	-0.01	-0.02	0.01
	Ziarat	0.04	0.11	0.10	0.00	0.09	0.06	-0.09	-0.03	-0.15	-0.03	0.09	0.03	0.08	0.07	-0.02	0.00	0.05
	Naltar	-0.03	0.01	0.08	-0.05	-0.11	-0.07	-0.12	-0.06	-0.17	0.00	-0.03	0.01	-0.13	0.07	-0.04	-0.04	0.01
	Rattu	-0.11	-0.01	-0.05	-0.04	0.09	0.10	-0.04	0.00	-0.18	-0.07	0.04	-0.10	-0.06	0.03	0.00	-0.05	-0.05
	Shigar	0.05	-0.02	0.00	-0.06	-0.30	-0.13	-0.13	0.04	0.04	-0.14	0.07	0.03	0.01	-0.04	-0.07	-0.01	0.00
	Skardu	0.02	0.11	0.07	0.01	0.02	-0.10	-0.15	0.04	-0.17	-0.11	-0.06	-0.07	-0.11	0.06	-0.12	-0.12	-0.07
	Astore	0.10	0.03	0.12	0.01	0.13	0.03	-0.05	0.00	-0.14	-0.09	0.03	-0.01	0.05	0.13	-0.02	-0.03	0.01
	Gupis	-0.08	-0.06	0.22	0.09	0.13	0.00	-0.05	-0.05	-0.08	0.06	0.04	-0.07	0.02	0.14	0.02	-0.01	0.03
	Dainyor	-0.06	-0.02	0.22	-0.01	0.18	-0.08	-0.15	0.02	-0.11	-0.04	0.04	-0.09	-0.05	0.11	-0.04	-0.04	0.00
	Gilgit	0.02	0.01	0.11	0.03	0.06	0.04	-0.06	0.05	-0.09	0.00	0.08	0.05	0.03	0.08	-0.02	0.00	0.03
	Bunji	0.06	-0.02	0.06	0.02	0.05	0.02	0.00	0.09	-0.07	0.03	0.06	-0.06	0.03	0.08	0.06	0.00	0.01
	Chilas	-0.02	-0.14	0.06	-0.02	0.16	-0.03	-0.12	-0.07	-0.19	-0.07	0.01	-0.06	-0.09	0.03	-0.06	-0.08	-0.07
Р	Khunrab	3.64	2.59	-2.21	-1.55	-1.47	0.10	0.35	0.80	1.82	-1.04	0.93	2.34	8.86	-9.09	-1.74	1.65	6.14
	Deosai	0.07	1.28	-1.42	-0.66	-1.27	-0.89	-0.40	-1.00	-0.77	-0.42	-0.81	-0.32	1.40	-4.50	0.00	-1.99	-7.87
	Shendure	1.54	2.75	1.35	2.13	0.60	2.12	1.83	1.38	1.45	1.24	1.40	1.20	5.71	4.50	4.82	3.58	29.53
	Yasin	1.33	1.86	0.59	0.25	1.22	-0.50	1.45	0.02	0.92	-0.21	0.06	2.74	6.09	0.60	1.32	0.26	11.70
	Rama	0.77	0.00	-6.50	-8.55	-4.52	-2.16	-2.35	-1.89	-1.44	-2.05	-3.74	-2.03	7.00	-25.44	-8.41	-14.60	-43.92
	Hushe	0.65	0.24	-1.23	-0.30	-1.97	-1.21	-1.71	-0.60	0.73	-0.64	0.11	0.72	3.47	-4.51	-4.28	0.70	-5.54
	Ushkore	0.56	-0.59	-2.33	-1.02	-1.97	-0.93	0.00	-0.09	1.01	-0.61	-0.48	0.09	-0.13	-4.57	-1.54	-0.42	-3.83
	Ziarat	-0.91	-0.56	-4.18	-5.28	-1.83	0.25	-0.67	-0.18	1.20	-0.58	-0.43	-0.61	-3.59	-9.10	-1.71	-0.21	-16.32
	Naltar	3.75	8.41	-4.49	-0.36	-2.75	-2.17	0.43	-2.33	1.32	-0.36	-0.70	1.35	19.43	-8.39	-0.99	2.42	-0.28
	Rattu	1.36	2.13	0.08	0.36	0.26	0.53	0.91	0.75	0.95	0.84	0.69	1.53	4.43	1.23	1.81	2.36	10.64
	Shigar	-0.24	-0.89	-1.07	-2.62	-2.05	-0.33	1.75	0.80	2.40	1.13	0.18	1.49	-1.67	-8.36	0.78	3.08	-7.04
	Skardu	-0.64	1.62	0.60	0.19	-0.74	-0.47	-0.07	-0.44	0.46	0.00	0.00	0.20	0.41	0.89	-1.26	0.49	1.29
	Astore	0.00	0.41	0.12	-1.41	-0.48	-0.16	-0.08	-0.29	0.57	0.00	0.00	0.29	1.50	-1.36	-1.63	0.34	-0.16
	Gupis	0.65	0.97	0.81	0.38	-0.06	-1.33	-1.07	-0.49	0.06	0.35	0.26	0.89	2.81	0.29	-3.49	0.43	4.46
	Dainyor	-0.21	0.42	0.51	0.55	0.67	1.24	0.91	-0.71	-0.39	0.00	0.00	0.00	1.68	1.81	3.09	-0.34	6.69
	Gligit Bunii	0.98	0.45	-1.94	-1.34	-1.57	-0.73	0.29	-3.99	0.32	0.00	0.00	0.30	0.00	-9.39	-9.60	-0.92	-20.31
	Chilas	0.01	-0.10	-1.06	-2.34	0.17	0.20	-0.34	-0.22	0.56	-0.01	0.00	0.11	-0.47	-2.68	-0.51	0.06	0.09
	Clillds	0.00	0.13	-0.14	-1.56	0.16	0.29	-0.51	0.13	1.37	-0.10	0.00	0.07	0.22	-0.81	-0.80	1.86	0.53
Q	UIB-East	-0.80	0.00	0.04	0.11	-4.19	2.00	-1.65	6.70	-4.74	-5.45	-2.46	-1.37	-0.75	-2.64	-2.62	-0.86	-1.73
	Eastern-Karakoram	0.06	0.08	-0.10	0.00	1.96	0.96	-22.97	0.92	-8.84	-1.06	0.50	-0.09	0.29	0.67	0.30	-4.41	-0.95
	Central-Karakoram	0.96	1.28	1.56	-0.84	3.74	-8.94	-37.93	-9.08	-5.98	0.71	2.50	2.76	1.13	1.13	-21.61	1.10	-1.56
	Kachura	0.33	1.39	1.06	-0.33	-2.08	-22.50	-50.04	-16.74	-4.25	-2.18	0.59	2.64	0.46	-0.81	-18.90	-2.63	-4.97
	UIB-Central	2.19	1.81	2.02	-0.84	6.89	-18.08	-43.79	-20.20	-4.88	1.05	4.38	2.34	2.00	1.79	-18.34	2.01	-2.47
	Western-Karakoram	1.20	1.00	1.50	2.00	0.59	12.09	-4.53	-4.09	6.40	3.50	3.82	2.03	1.88	1.00	-1.64	5.43	2.50
	Karakoram	1.88	2.00	1.33	1.00	-5.82	-7.80	-64.97	-3/.1/	-9.48	0.60	8.97	5.97	1.65	0.11	-24.43	5.64	-3.90
	HINDUKUSN	0.87	0.26	0.15	1.2/	2.05	3.49	-6.61	14.02	7.03	2.1/	1.82	1.06	0.75	1.00	3.94	4.44	4.00
	UIB-WU	1.24	1.02	1.39	2.38	16.85	12.38	-25.48	-15.50	-1.28	0.69	0.98	0.52	0.55	7.76	-3.68	0.45	-1.25
	ASIOR Dartab Bridge	0.05	0.00	0.22	0.50	7.65	4.26	-3.01	5.00	-1.00	-1.11	-0.6/	0.00	0.00	2.20	1.9/	-0.89	2.16
	Partab_Bridge	1.00	-0.13	3.60	8.80	03.22	-34.80	-39.80	-07.33	29.65	0.69	8.89	15.12	8.40	30.29	-67.00	9.81	-12.40
	UID-WL	2.00	0.41	0.39	-0.52	41.58	59.50	28.19	17.67	30.99	10.18	5.1/	2.33	2.92	19.90	47.02	2 00	12 04
	UID-WL-PdildU	-3.00	1 27	-4.38	-0.62	61.09	51.55	9.00	17.07	2./1	12.24	1.40	1 20	-3.74	20.52	47.93	- 3.00	10.94
	UID_WESL Himalaya	2.45	1.3/	5.45 A 10	2.42	12 00	62.22	12.42	42.93	20.24	13.08	3.0/	1.38	2.00	25.43	44.18	7 75	22.17
	i i i i i i di di y d I II D	1 97	-0.32	4.10	-2.50	45.99	14 67	-46.60	05.55 //1 71	25.25	5.9/	2.3Z	0.23	1.1/	20.04	-1 /0	10.25	24.00 // 25
	UD	1.02	5.09	5.57	-2.50	11.33	14.07	-40.00	41.71	35.22	10.17	5.29	0.75	1.71	13.72	-1.40	13.32	4.23

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Tabular Figure 6: Long-term trends (1961-2012) in Tx, Tn, Tavg, DTR and P at monthly to annual timescales. The units and color scale are described in the Tabular Figures 4 and 5.

Variable	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Тх	Skardu	0.07	0.06	0.06	0.05	0.07	0.02	0.01	0.00	0.02	0.03	0.06	0.06	0.05	0.07	0.01	0.04	0.04
	Astore	0.02	0.01	0.06	0.04	0.05	-0.01	-0.01	-0.02	0.00	0.02	0.03	0.04	0.02	0.06	-0.01	0.02	0.02
	Gupis	0.02	0.02	0.03	0.04	0.06	-0.02	-0.02	-0.03	-0.01	0.04	0.04	0.06	0.04	0.04	-0.02	0.03	0.02
	Gilgit	0.04	0.03	0.04	0.05	0.06	-0.01	-0.01	-0.02	-0.01	0.02	0.05	0.05	0.04	0.04	-0.01	0.02	0.02
	Bunji	0.02	0.01	0.04	0.00	0.01	-0.06	-0.05	-0.05	-0.04	-0.04	0.03	0.02	0.02	0.02	-0.05	-0.02	0.00
	Chilas	-0.01	-0.01	0.03	0.01	0.02	-0.05	-0.02	-0.02	-0.02	0.00	0.00	0.01	0.00	0.02	-0.03	0.00	0.00
Tn	Skardu	0.00	0.02	0.00	-0.01	-0.01	-0.04	-0.04	-0.04	-0.04	-0.05	-0.02	0.01	0.01	0.00	-0.04	-0.04	-0.02
	Astore	0.02	0.01	0.03	0.03	0.04	0.00	-0.02	-0.02	-0.01	0.00	0.02	0.01	0.01	0.04	-0.01	0.01	0.01
	Gupis	-0.04	-0.02	-0.01	-0.03	-0.01	-0.07	-0.06	-0.07	-0.05	-0.03	-0.03	-0.01	-0.03	-0.02	-0.07	-0.05	-0.04
	Gilgit	0.00	0.03	0.00	-0.01	0.01	-0.02	-0.05	-0.03	-0.01	-0.02	-0.01	0.01	0.01	0.00	-0.03	-0.02	-0.01
	Bunji	0.01	0.01	0.03	0.00	0.00	-0.03	-0.04	-0.03	-0.03	-0.03	0.00	0.01	-0.01	0.01	-0.04	-0.04	0.00
	Chilas	0.04	0.02	0.01	0.01	0.03	-0.02	-0.01	-0.03	-0.02	0.00	0.03	0.04	0.03	0.02	-0.02	0.00	0.01
Tavg	Skardu	0.03	0.04	0.03	0.02	0.03	-0.01	-0.02	-0.02	-0.01	0.00	0.02	0.03	0.03	0.03	-0.02	0.00	0.01
	Astore	0.02	0.01	0.04	0.04	0.05	0.00	-0.01	-0.02	0.00	0.01	0.03	0.02	0.01	0.05	-0.01	0.02	0.01
	Gupis	0.00	0.00	0.00	0.01	0.03	-0.04	-0.05	-0.05	-0.03	0.00	0.01	0.02	0.00	0.01	-0.04	-0.01	-0.01
	Gilgit	0.02	0.03	0.02	0.02	0.04	-0.02	-0.03	-0.03	-0.02	-0.01	0.03	0.03	0.03	0.02	-0.03	0.00	0.00
	Bunji	0.00	0.01	0.02	-0.01	-0.01	-0.04	-0.05	-0.04	-0.05	-0.04	0.00	0.01	0.01	0.01	-0.04	-0.03	0.00
	Chilas	0.02	0.00	0.01	0.01	0.03	-0.03	-0.02	-0.02	-0.02	0.00	0.02	0.02	0.01	0.02	-0.03	0.00	0.00
DTR	Skardu	0.06	0.02	0.05	0.07	0.09	0.05	0.06	0.03	0.06	0.09	0.09	0.05	0.05	0.07	0.05	0.09	0.06
	Astore	0.04	0.00	0.01	0.02	0.02	-0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.00	0.02	0.02
	Gupis	0.08	0.06	0.05	0.07	0.09	0.06	0.06	0.04	0.07	0.10	0.09	0.08	0.09	0.06	0.05	0.08	0.07
	Gilgit	0.04	0.02	0.04	0.07	0.06	0.00	0.05	0.04	0.05	0.05	0.07	0.05	0.04	0.04	0.03	0.06	0.04
	Bunji	0.04	0.01	0.03	0.01	0.03	0.00	0.00	-0.01	0.03	0.02	0.06	0.04	0.04	0.02	0.00	0.03	0.02
	Chilas	-0.04	-0.02	0.00	0.00	0.00	-0.03	-0.01	0.01	0.01	-0.01	-0.02	-0.03	-0.03	0.00	-0.01	-0.01	-0.02
Р	Skardu	0.30	0.32	0.16	0.16	-0.02	0.08	0.06	0.19	0.07	0.00	0.00	0.15	0.98	0.45	0.29	0.12	1.76
	Astore	0.00	-0.28	-0.78	-0.51	-0.25	0.27	0.19	0.06	0.02	-0.05	0.02	-0.08	0.24	-1.31	0.45	0.06	-1.33
	Gupis	0.08	0.04	0.28	0.30	-0.08	0.00	0.24	0.18	0.00	0.00	0.00	0.00	0.11	0.20	0.32	-0.09	2.00
	Gilgit	0.00	0.00	-0.02	0.05	-0.05	0.23	0.01	0.01	0.03	0.00	0.00	0.00	0.02	-0.44	0.28	0.10	0.38
	Bunji	0.00	-0.06	-0.14	0.02	-0.17	0.09	0.05	0.12	0.11	-0.03	0.00	0.00	0.13	-0.59	0.36	0.09	0.21
	Chilas	0.00	0.03	-0.12	0.00	-0.01	0.10	0.07	0.07	0.07	-0.02	0.00	0.00	0.25	-0.12	0.51	0.03	0.70
Q	UIB-East	0.58	0.89	1.18	0.80	0.08	-12.94	-21.37	-10.53	-1.42	-0.18	0.06	0.16	0.55	1.10	-14.86	-0.57	-1.59
	Eastern-Karakoram	0.00	0.00	-0.04	-0.08	1.79	6.46	5.17	6.81	4.34	1.31	0.24	0.00	0.07	0.41	7.08	2.05	2.43
	Central-Karakoram	0.32	-0.07	-0.51	-0.67	6.13	3.85	-1.22	6.30	-7.40	-4.08	-1.36	-0.29	-0.35	1.75	6.22	-2.80	0.31
	Kachura	1.04	1.40	1.19	0.43	6.06	12.88	14.75	19.45	14.27	3.69	1.14	1.13	1.12	2.67	19.20	6.12	7.19
	UIB-Central	0.35	0.21	-0.19	-0.43	9.99	20.49	13.74	20.73	-4.95	-2.15	-0.80	-0.29	-0.30	2.76	17.69	-2.84	3.30
	Western-Karakoram	0.04	0.00	0.00	0.00	0.29	-3.75	-12.69	-13.75	-2.14	-0.24	0.18	0.20	0.13	0.24	-10.23	-0.59	-2.55
	Karakoram	0.28	-0.20	-0.60	0.33	9.67	24.33	8.29	8.13	-7.57	-2.18	-0.59	0.63	-0.15	4.17	24.39	-4.36	6.44
	Hindukush	0.00	0.05	0.04	0.19	3.31	-1.00	-0.85	0.11	0.64	0.23	0.15	0.13	0.04	1.25	0.24	0.31	0.48
	UIB-WU	0.58	0.60	0.33	0.51	3.55	-1.86	-12.74	-12.50	0.68	1.48	1.02	0.71	0.48	1.30	-6.83	1.22	-0.95
	Astore	0.28	0.24	0.32	0.97	3.52	1.29	-0.62	0.54	0.16	0.28	0.32	0.23	0.31	1.63	0.43	0.28	0.76
	Partab_Bridge	1.01	0.49	0.44	1.93	18.03	13.07	12.89	-8.37	9.74	3.84	2.61	1.63	1.74	6.84	7.05	4.93	4.72
	UIB-WL	1.94	1.96	3.49	0.17	2.89	-12.90	-25.95	-12.06	-1.35	1.57	1.94	2.35	1.92	1.93	-13.82	0.48	-2.63
	UIB-WL-Partab	1.58	1.87	2.11	-0.82	-0.30	-22.26	-16.35	-17.07	0.02	-2.20	0.23	1.18	1.32	0.34	-22.10	-0.99	-5.40
	UIB_West	2.02	2.01	2.73	1.12	8.00	-19.88	-32.88	-23.24	-5.13	1.95	2.59	2.40	2.18	3.99	-25.21	0.93	-4.03
	Himalaya	3.23	3.91	4.73	2.33	-0.33	-32.29	-69.33	-17.55	-4.61	-0.05	3.40	2.05	3.37	6.86	-40.09	-0.72	-6.13
	UIB	3.00	3.33	3.53	0.62	12.97	-8.84	-13.31	-3.24	8.19	4.03	3.92	3.04	3.04	5.00	-6.15	5.14	2.23

933 Tabular Figure 7: Field significant climatic trends for ten sub-regions along with their

discharge (Q) trends at monthly to annual timescales over the period 1995-2012. Color scale
is same as in Tabular Figure 5. Bold Q values indicate significant trends at 90% level.

Regions	Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Astore	Tx	-0.17			•				Ū		-0.21		-0.42	-0.16				-0.06
	Tn							-0.10			-0.10		-0.12				-0.10	
	Tavg	-0.15						-0.13			-0.21							-0.05
	DTR		-0.22							-0.13			-0.17	-0.07			-0.06	-0.08
	Р			-3.73	-7.50	-4.60	-2.18	-1.90	-1.80	-2.11					-19.25	-6.02	-18.93	-38.01
	Q	0.05	0.00	0.22	0.50	7.65	4.26	-3.01	5.00	-1.00	-1.11	-0.67	0.00	0.00	2.20	1.97	-0.89	2.16
Hindukush	Tx		-0.11	0.23				-0.19		-0.29			-0.18				-0.12	-0.09
	Tn								0.25	0.24		-0.18	-0.24			0.09	0.10	
	Tavg			0.18				-0.11	0.08	-0.25			-0.13				-0.10	
	DTR	-0.21		-0.11	-0.18	-0.25	-0.28	-0.19	-0.36	-0.40	-0.52	-0.38		0.03	-0.16	-0.18	-0.33	-0.20
	Р	1.30		-1.94				1.00		1.05	0.31		1.31	4.73	-10.19	-9.80	2.39	
	Q	0.87	0.26	0.15	1.27	2.05	3.49	-6.61	14.02	7.03	2.17	1.82	1.06	0.75	1.00	3.94	4.44	4.00
Himalaya	Tx	-0.17	-0.10					-0.22		-0.21	-0.19		-0.28	-0.16		-0.07	-0.12	-0.06
	Tn		-0.23	0.26			-0.14	-0.15	0.18		-0.16	-0.18	-0.14	-0.18		-0.13	-0.14	0.02
	Tavg	-0.15		0.25				-0.18	0.17	-0.18	-0.18	-0.09	-0.08	-0.11		-0.10	-0.13	-0.07
	DTR	-0.02	-0.20	0.18	-0.18			-0.13	-0.18	-0.36	-0.25			-0.12		-0.08	-0.19	-0.09
	Р			-2.29	-5.71	-4.60	-2.18	-1.90	-1.80	-2.11			0.42		-12.15	-6.02	-18.93	-38.01
	Q	0.30	-0.32	4.10	0.91	43.99	62.23	12.43	83.33	22.43	9.97	2.32	0.23	1.17	26.64	57.88	7.75	24.66
West Karakoram	Tx			0.23				-0.18		-0.17	-0.16			-0.06				
	Tn		0.22	0.13				-0.13						0.17				0.05
	Tavg	-0.15		0.22	-0.09			-0.14		-0.15								
	DTR		-0.22							-0.13			-0.17	-0.07			-0.06	-0.08
	P					1.17	1.09						3.81	9.08				
	Q	1.20	1.00	1.50	2.00	0.59	12.09	-4.53	-4.09	6.40	3.50	3.82	2.03	1.88	1.00	-1.64	5.43	2.50
Karakoram	Tx		-0.11	0.23				-0.18		-0.22	-0.16			-0.06			-0.12	-0.06
	Tn		-0.11	0.23				-0.18		-0.22	-0.16			-0.06			-0.12	-0.06
	Tavg		0.22	0.13			-0.14	-0.14	0.25	0.46	-0.16	-0.18	-0.16	0.17		-0.08	0.06	-0.05
	DTR	-0.15		0.22	-0.09			-0.15	0.08	-0.16	-0.12	-0.09				-0.13	-0.14	-0.08
	Р		2.95	1.97		1.17	1.72		1.58	2.15	1.43	2.40	2.69	6.39		5.39	5.76	45.07
	Q	1.88	2.00	1.33	1.00	-5.82	-7.80	-64.97	-37.17	-9.48	0.60	8.97	5.97	1.65	0.11	-24.43	5.64	-3.90
UIB Central	TX							-0.26		-0.20	-0.16						-0.12	
	Tn T			0.26			-0.14	-0.20			-0.16	-0.18	-0.16			-0.17	-0.18	0.02
	Tavg			0.25				-0.20		-0.18	-0.15	-0.09				-0.13	-0.14	-0.08
	DIR	0.13	2.05	4 07					4 50			0.09						
	P		2.95	1.97		6.00	2.35	40.70	1.58	2.15	1.43	2.40	1.57	5.99	4 70	5.39	5.76	45.07
	ų Tu	2.19	1.81	2.02	-0.84	6.89	-18.08	-43.79	-20.20	-4.88	1.05	4.38	2.34	2.00	1.79	-18.34	2.01	-2.47
UIB	Tx Tr	-0.14	-0.11	0.40				-0.20	0.24	-0.22	-0.20		-0.25			-0.09	-0.12	-0.09
	In Teur		0.49	0.38				-0.13	0.31	0.10	0.10		-0.17			0.37	-0.14	0.27
	Tavg		0.10	0.37	0.14			-0.15	0.13	-0.18	-0.16		-0.11	0.11	0.12	-0.10	-0.12	-0.08
			-0.19	2 1 7	-0.14	1 1 7	1 4 7	-0.17	-0.24	-0.25	-0.56		1 07	0.11	-0.15	-0.10	-0.17	-0.09
	0	1 0 7	E 00	-2.17	2 50	11.17	-1.42	16.60	-2.40	25.22	10.17	E 20	1.97	1.01	-11.49	-7.91	3.00	1 25
	Q Tv	0.14	0.11	0.22	-2.30	11.55	14.07	-40.00	41.71	0.22	0.21	3.25	0.75	0.11	13.72	-1.40	0.12	4.23
OID West	Tn	-0.14	-0.11	0.25				-0.18	0.22	-0.22	-0.21		-0.23	-0.11		-0.09	-0.12	-0.10
	Tava	0.15		0.20				-0.12	0.22	0.10	0.10		-0.10				-0.13	0.07
	Idvg	-0.15	0.20	0.20	0.16			-0.15	0.15	-0.19	-0.19		-0.11	0 10	0.12	0.10	-0.11	-0.07
		-0.10	-0.20	-0.10	-0.10	1 1 7		-0.17	-0.24	-0.27	-0.56		1 71	-0.10	-0.15	-0.10	-0.19	-0.10
	r 0	2 45	1 27	=Z.17	-3.71	61.25	E / 90	0.21	-2.40	20 24	12 60	E 07	1.71	2.00	22 42	-7.91	17 71	22.17
	Q Tv	2.43	0.10	5.45	2.42	01.55	54.05	0.21	42.55	0.24	0.20	5.07	1.30	2.00	23.43	44.10	0.12	0.06
OID West Lower	Tn	-0.17	-0.10					-0.10	0.10	-0.21	-0.20		-0.20	-0.10		0.07	-0.13	-0.00
	Tour	0.15	-0.23					-0.10	0.10		0.10		-0.12	-0.10		-0.08	-0.12	0.07
	Idvg	-0.15	0.20	0 1 0	0.19			-0.13	0.17	0.26	-0.19		-0.07	-0.11		-0.06	-0.11	-0.07
	DIK	-0.15	-0.20	0.18	-0.18	_1 60	_2 10	-0.13	-0.18	-0.30	-0.25		0 47	-0.12	-1215	-0.08	-0.19	-0.09
	г О	1 00	0.41	-2.29	-5./1	-4.00	-2.18	-1.90	-1.60	-2.11	16 19	5 17	2 2 2 2	1 0 7	-12.15	-0.02	-10.93	-56.01
IIIR Wast Linear	u Tv	1.00	-0.11	0.39	-0.52	41.58	59.50	20.19	81.58	-0.33	10.18	5.1/	2.33	1.92	19.90	-0.00	-0.12	-0.10
ore west opper	1X Tn	-0.14	-0.11	0.23				-0.18	0.25	-0.22	-0.21	-0.10	-0.25	-0.11		-0.09	-0.12	-0.10
	Таус	-0.15	0.22	0.13	-0.00			-0.13	0.25	-0.24		-0.18	-0.24	0.17		0.09	_0.10	0.05
	DTP	-0.15	0 22	0.20	-0.09	0.25	0.20	-0.13	0.08	-0.20	0.53	0.20	-0.13	0.00	0.10	0.11	-0.10	0.11
	טוג ס	-0.21	-0.22	-0.11	-0.18	-0.25	-0.28	-0.19	-0.36	-0.28	-0.52	-0.38	-0.1/	0.06	-0.16	-0.11	-0.19	-0.11
	г О	1.30	1.03	-1.94	2 20	1.1/	12.09	1.00	15 50	1.40	0.31	0.00	2.14	0.90	-10.19	-9.80	2.03	1.25
	ų	1.24	1.02	1.59	2.38	10.05	12.38	-20.4ŏ	-12.20	-1.28	0.09	0.98	0.52	0.55	1.70	-5.08	0.45	-1.25



Figure 8: Trends per time step in Tx, Tn, Tavg, DTR (°C) and P (mm) for select months and seasons.
Triangles pointing upward (downward) or in green/red (blue/yellow) colors show increasing
(decreasing) trends. Solid (hollow) triangles indicate significant (insignificant) trends at 90% level.