Dated: December 28, 2015

The Editorial Board,

Earth System Dynamics Journal

Revised submission of ESDD-6-579-2015

Dear Editor,

We are pleased to submit the revised version of our paper "Prevailing climatic trends and runoff response from Hindukush-Karakoram-Himalaya, upper Indus basin". We have addressed all the referees' comments and revised the paper for the agreed changes. Our point-by-point response (in black) to the referees' comments (in grey), along with changes made to the manuscript (in red), is attached below.

We hope that the revised paper is now in the form acceptable for publication in ESD and that it may contribute to the understanding of prevailing hydroclimatic state over the upper Indus basin.

With kind regards,

Shabeh ul Hasson

Response to the Referee # 1

We thank the referee for his comments. However, we respectfully disagree on most of the referee's comments and thus his/her recommendation. Following is the point by point response (in black) to his/her comments (in grey) and the agreed changes in the revised manuscript (in red).

Major comments

1. The paper is too long. Lot of information, already known through earlier publications of different researchers, are repeated or falsely presented as new materials (and this is a severe problem with this paper). The unnecessary wordy sentences and redundancy of various statements have contributed to the length of the paper to become annoyingly long.

It is to clarify that the paper is seen for a broader audience and submitted to an inter-disciplinary and multi-disciplinary journal of the Earth System Dynamics where articles ranging from the Geoengineering to the thermodynamics to the socio-economic issues are published. In view of the broader audience, it is indispensable to present basics about the study area and its hydroclimatology, the present status of research etc.

The length of the manuscript is reduced substantially (by 25%). Sentences have been made short, and redundancy is removed. Studies as per referees comments are properly cited.

2. The English of the paper is not free flowing. Sentence constructions in many places are awkward. In places, certain phrases or words are used strangely. There are grammatical errors. There are excessively long and loquacious sentences which make the readability of the paper very poor. The paper should be copy edited by someone with a better command on the English language. [To give some examples, look at Lines 7 – 9 on page 585 – Does it carry any substance or is it just a gibberish to create a place for self-citation?; or .look at Lines 14 – 18 on page 581 or read Lines 14 – 16 on page 585; Lines 7 – 12 on page 586; there are plenty of such examples throughout the paper].

It is not agreed that readability of the paper became poor due to long sentences and (strange) phrases, as noted from the examples given by the referee. For instance, on Page 585, lines 7-9 introduce the diversity of the UIB in terms of its contrasting hydrometeorology and abode cryosphere, and that, such diversity is defined by the interactions between two large-scale circulation modes and their modulation by the complex HKH terrain. In order to introduce the field significance analysis, which the referee liked the most, given information on the diversity of the UIB and sparse meteorological network was thought necessary to be reported first. For further details the reader is directed to the recent work from the authors as suggested by the referee under point #1. Further, it is to clarify that since the cited authors' publications are further cited at relevant places in the article, there was no need to create a place here for self-citation.

For Page 581, lines 14-18, Page 585 Line 14-16 and page 586 line 7-13, it is very much clear what has been said.

The manuscript is corrected for grammatical errors. The readability of the manuscript has been further improved.

3. The tenor of the language used in the paper is repelling to workers interested in this area of research. The underlying tone of the paper is that the authors are the ones who for the first time have done a thorough comprehensive job in everything presented in this paper and with the exception of a few, they either give a little credit to previous works that are also

repeated in this work or give no credit to some earlier works by not referencing those. This is tantamount to academic dishonesty. For example, the authors "reinvent" delineation of UIB and provide a lengthy discussion on how their delineation is by far the best and give a cursory mention of the work of Khan et al. (2014) [Line 17, p. 587]. But the fact of the matter is that Khan et al. (2014) have already resolved the issue of proper delineation of UIB and their estimate of the area of UIB up to Besham Qila is as good as that is presented in this paper. This sort of self-crediting, self-gratifying, and self-congratulatory writing easily alienates other researchers in this area and does not help the authors to achieve the very objective of theirs in writing so – i.e. to establish credibility and earn respect for their work. On the other hand if the authors review all relevant previous work and give due credit to those then they would easily earn the trust and respect of the peers familiar with the topics presented in this paper. In that process, if the authors disagree with any of the earlier studies that is fine. However, the reasons for such disagreements must be backed up with sufficient analysis and convincing arguments and must be presented respectfully without trying to just trash those out simply because the authors have conducted a "reanalysis of the same data" used by some of the previous workers.

The use of the word "repelling" has no place in a scientific debate. We kindly urge the reviewer to take it back. We continue the review putting this major issue of academic respect aside.

The referee first raises a serious allegation of academic dishonesty in a dramatized way for giving a little or no credit to the previous work, and in last, asks for whether there is a disagreement. It is to clarify that some publications have appeared during the preparation of the manuscript and since its submission (from second half of 2014 till now), and the authors already intend to refer such lately published articles in the revised version in order to comprehensively summarize the previous findings, regardless of the fact that the manuscript is not a review paper.

For citing previous work, it is to clarify that in the specific Comments # 7, referee asked to replace the Archer, 2003 and Fowler and Archer, 2006 with Mukhopadhyay and Khan (2015). Since the suggested study came up during or after the submission of the manuscript, how could the authors cite such a study? Note similar case for the specific comments # 1.

Interestingly, in the specific comments # 2, the referee seeks citation for the Mukhyopadhyay and Khan (2014a) considering it a better and more recent reference. However, the study does not present any concrete supportive analysis, as desired by the referee himself in case of his specific comments # 1 and #7. On the other hand, disagreement with the Mukhopadhyay and Khan (2014b) is already given in the manuscript on Page 601, lines 9-19 and reinforced in the response to specific comments # 25.

For Khan et al. (2014), it is to clarify that authors have delineated the UIB for their own work, as anybody else will do it for his own work. Thus, the authors have reported their work in a way it has been carried out, as anybody else will report their work as they would have done it. During the UIB delineation, the Pangong Tso and small internal drainages have been eliminated based upon the conclusion reported by Khan et al. (2014), for which due credit has been given by citing the study. Against this background, it is beyond understanding that what kind of credit the referee wants for Khan et al. (2014) from the authors and what leads him to be highly obsessed with this study. The referee might think that after Khan et al. (2014), nobody else is allowed to delineate the UIB. It is also to clarify that in fact, Khan et al. (2014) are not the first ones who said the Pangong Tso drainage is a closed basin. Such fact is already well established over more than a century by the published geological studies and field surveys and recently by others (e.g. from Hungtington, 1906 and earlier to Alford, 2011, as cited by Khan et al., 2014 themselves). It is also depicted by around half-century old UIB drainage area estimates from the SWHP WAPDA reports.

The Khan et al. (2014) has been cited in the manuscript as they have lately investigated the relationship of the Pangong Tso with the Indus basin and discussed based on the SRTM 90 and ASTER GDEM V2 30m DEMs that the lake is roughly 24-28 meters lower than the critical lake drainage barriers. Being curious to the referee's obsession, it is learnt that such additional evidence is however highly uncertain in view of the reported vertical accuracy of the employed DEMs and their precision required for this specific analysis.

For instance, it is implicitly assumed that the vertical accuracy of the ASTER GDEM V2 estimated over the US (i.e. ±17.01 meters at 95% confidence interval with full range interval of -137.37 to 64.80 meters) is equally applicable in a highly complex terrain of the Karakoram. Even though it is assumed to be true, such vertical accuracy is not precise enough to be certain to accurately identify the real height difference between lake level and critical points. Similarly for the SRTM, Farr et al. (2007) have been cited for linear absolute height error of less than 16m at 90% confidence interval but unfortunately not for their statement that "*… the greatest errors are associated with steep terrain (Himalayas…*", which implies that the rest of 10% confidence interval should equally applies to this region of high relief and not to another planet. Further, the reported accuracy is based upon 1/8^{o} resolution and mainly contaminated by a random error, thus it is not equally applicable on a specific 90meters grid cell. In view of different vertical datum and intrinsic problems of the instruments for heterogeneous surfaces in a high relief area, the reported vertical accuracy feature high uncertainty for such a precise analysis.

The inter-dataset differences further reinforce the uncertainty issue. For instance, height of the critical point 3b in SRTM and GDEM v2 is offset by 7 meters, which is roughly an order of magnitude difference between height of critical point 3b and lake level in SRTM. In fact lake surfaces were very 'noisy' in the original DEMs and set to constant heights afterwards. Even then, the most reliable lake level height derived from ICESat altimetry data is 4219.68 m on 08/10/2004 (Srivastava et al., 2013), suggesting that SRTM and GDEM overestimate lake level by 22 and 10 m, respectively. When considered over the complex terrain and heterogeneous surfaces, the inter-dataset difference is expected to be even large.

Against this background, investigation of the critical points being few meters higher or lower than the lake level is an application the employed DEMs are not yet tested to be suitable for, in the study region. In view of such uncertainty associated with the additional evidence, it is more convincing to believe earlier studies stating that the Pangong Tso is a closed basin, and subsequently, not excluding the small internal drainages. In view of "reanalysis of the same data" comments, recently available 30-meter version of the SRTM DEM is considered as a more appropriate choice for re-delineation (Kindly see the discussion Figure 1 in response to the referee # 2).

Moreover, though the limitation in finding and filling sinks in the DEMs is already explained in the ArcGIS online help and in the respective publications, Khan et al. (2014) have shown how such limitation applies to the UIB delineation case, for which of course the study will be cited. In this regard, the text on page 587, Lines 8-20 will be revised (Kindly see the response to the major comment # 2 of the referee # 2. Since the present manuscript is not a right forum to discuss the UIB drainage issues and DEM accuracies, the above discussion will not be included in the manuscript and deemed as distracting from the main subject of the manuscript.

4. The authors' claim that they are using, "for the first time observations from high altitude automated weather station" [Abstract, Line 8, p. 580; Introduction, Line 24, p. 585;

Discussion, Line 16, p. 615) is a false claim. Mukhopadhyay and Khan (2014b) and Mukhopadhyay et al. (2014) have already used those data and noted that no trends could be established from those data due to the very short period of record and the scatters present in those observations.

Since this issue of 'for the first time' has also been raised by the referee # 2, kindly see the combined response to his/her specific comments # 5.

It is to clarify that based upon a 12-year time series from only four stations Mukhopadyay et al. (2014) have stated that no trend can be established. If it is assumed true, how results from a 12 year time series can be generalized to 18-year time series (with 50% increase in length) from the same stations? Further, how can the results of no trend from four stations with shorter period of record be generalized for the rest of 8 stations not analyzed by Mukhopadyay et al. (2014)? Further, Mukhopadyay et al. (2014) have stated that "*Because the stochastic component is often large, simple regression often results in trends that are statistically insignificant and thereby can be erroneous."* and implemented a non-parametric trend test procedure with a benchmark smoothing technique to analyze river flow trends. However, surprisingly, they still used a simple regression analysis for ascertaining a trend from four high-altitude stations, ?. It is to clarify that any conclusion based upon their findings cannot be generalized or equally applicable to this study, which in contrast applies a non-parametric trend test with a sophisticated pre-whitening procedure over relatively longer period of record for a larger set of stations.

5. The climatic data used from the automated meteorological stations cannot be used to establish any" credible long-term climatic trends". The period of record for those 12 stations is very short. In most cases the period is 1995 – 2012 (18 years, i.e. not even two recent decades) and in some cases it is even shorter (e.g., 17 Aug 1998 – 31 Dec 2011 at Deosai, 15 Jan 1997 – 31 Jul 2012 at Dainyor; and 27 Aug 1996 – 31 Dec 2012 at Shigar). The authors use this period of record for the low altitude stations also [Page 596 (Line 20)]. The actual success of the statistical method implemented here, regardless of its level of sophistication, in establishing meaningful trends in the climatic variables extracted from those station records, is very much apocryphal.

Since the data from high-altitude stations is maximum of 18-years length, neither is it claimed nor any effort has been made to establish "… long-term climatic trends" as said by the referee. The title already makes this very clear. The effort is to present the prevailing climatic trends during the analysis period, based on the maximum available and accessible observational record, and applying sophisticated method in a systematic way. This period of record (1995-2012) has been used for low altitude stations, first in order to furnish a complete picture from all stations for the same time period, and secondly to present a comparison of the prevailing observed climatic changes between the high-altitude and low altitude stations.

Is data being exactly of two decades ensures that the trends will be significant? Or it guarantees that the 18-years data will not feature any significant result? In any of these cases, reference is solicited. The data presented here for most of stations is 18-years, which is beyond the minimum time series length requirement for the Mann-Kendall trend test for detecting a trend.

The TPPW method, applied here, uses lag-1 autoregressive process and hence it is particularly suitable for a long time series. Therefore, most of the results of the trend analyses presented in this study are highly doubtful. This is partially evident from the results presented in Tables 4 3 and 5 where most of the trends have no statistical significance. So the authors should state that fact and should only concentrate on those trends that are statistically significant.

Exactly opposite is true. The pre-whitening is particularly required for the shorter time series, for instance, of sample size n<=50 (Bayazit and Önöz, 2007; Yue and Wang, 2002). The cited studies noted that the effect of short memory process either becomes negligible or diminishes away for the longer time series. It is also to clarify that if the AR(1) in a time series is statistically significantly different from zero, it has to be removed for the reasons well explained in the manuscript and in the cited literature. Moreover, the pre-whitening procedure is mainly used to force the falsely high rate of rejecting the null hypothesis of no trend to nominal rate when trend in fact does not exists in a time series.

It is true that most of the trends are statistically insignificant. However, authors emphasize that a wider agreement amid statistically insignificant tendencies that is further highly consistent with the significant trends (Discussion Table 1) is almost as valuable as the statistically significant trends themselves, particularly in view of the data scarcity in the region. Both, the statistically significant and insignificant tendencies consistently suggest a general pattern of change over the study region.

Based on the above given discussion, particularly on the suitability of pre-whitening application, the authors have serious concerns about the doubts the referee has on the presented trend analysis. A careful consultation of the relevant literature cited in the manuscript and elsewhere is solicited in this regard, as amid series of publications; issues pointed out by one are resolved by others. Thus, only partly reviewing can lead to further confusions. A nice brief summary is therefore presented in the introduction and method sections of the manuscript for the multi-disciplinary readership.

6. The way authors have done flow analysis of certain discharge data clearly shows that the authors have ignored some fundamental rules of hydrologic flow balance and therefore there are serious errors in their hydrologic calculations.
7. The authors should understand that the additive (subtractive) method of flow balance in deriving flows at an upstream gauging station from the flow data from one downstream and couple of upstream gauges is fraught with errors (explained in details in the specific comments below). On the other hand the multiplicative (ratio and proportion) method is a much more robust method.

Since comments #6 and #7 are repeated in the specific comment section, kindly find the response to these comments in the respective section under specific comment # 25 and # 26.

8. The authors have attempted to explain the trends in discharge in the light of trends in temperature only. However, temperature is an inappropriate proxy to the energy input that causes snow and glacial melting in the elevation range of 3500 – 5500 m in UIB. Not temperature, but insolation is the prime source of energy for the cryospheric melting process in this terrain. So the explanations they offer are too simplistic and do not explain both rising and falling trends of river flows at various locations of UIB.

It is to clarify that though the insolation is a prime source of energy however it is not solely responsible for the cryospheric melt processes, understanding of which in fact requires a precise estimation of available energy budget. For instance, regardless of changes in the insolation, energy budget can be perturbed by the albedo in case of fresh snow events and that such events are inversely proportional to melt water availability as explained in the manuscript on Page 624, lines 15-23. Moreover, wind speed/air mass stability is another factor, which can considerably perturb the cryospheric melt processes. Thus, any conclusion drawn on solely the insolation will also be too simplistic. Moreover, availability or accessibility of the relevant variables that are required for the computation of fully resolved energy balance is much more difficult in such a data-sparse study region as compared to temperatures. Thus, in order to fully explain the melt processes and their relationship with the climatic and flow variables, authors should change their approach and use hydrological and radiative transfer models, which is beyond the scope of this study. However, authors take this suggestion as a possible input to the future work, more oriented on the modelling of melt-runoff from the region.

9. The main contributions of this work are actually given in pages 604 – 629. However, by the time a reader arrives here he/she is already tired of reading pages 580 -604 (half of the paper with no new substance). So the authors are strongly advised to write the background, data, and method very succinctly and then condense the result and discussion section so that the reader can remain focused on the key findings and does not get lost in the maze of longwinded discussion.

Since this comment is not different from the major comment # 1, here response is the same. The manuscript will be shortened to the extent possible, but without considerable loss of information in view of targeting the multi-disciplinary readership.

10. The authors find the trends of the climatic variables for the period 1995 – 2005 different form the trends for the period 1961 – 2012. As noted above this is perhaps an artifact of the short period (for the high-altitude climatic stations) which does not really allow to detect any long term climatic trends

It is reiterated that no 'long-term climatic trends' are intended from the 1995-2012 period. Instead, focus is on the prevailing patterns of change during this period as depicted by high altitude stations, which are relatively more representative of the high altitude climatic patterns. Trend analysis over 52 year period suggests prevailing pattern of trend changes over that period and trend analysis over recent 18-years suggests findings for that period. How it comes that the trends over the short period only from the high-altitude stations are subject to an artifact? Kindly see details in response to major comment # 5.

Specific Comments

1. Page 581 (Lines 25 – 27) – Page 582 (Line 1): First of all, snowmelt and glacial melt contributions to river flows do not remain constant. They vary with location as well as season. Second, none of these references you cite here provides the quantitative estimates of snowmelt and glacial melt contributions to river flows in UIB. None of these works has seriously made any attempt to estimate these proportions. On the other hand there is a recent study that is exclusively devoted to this problem (Mukhopadhyay and Khan, 2015, Journal of Hydrology, 527, 119 - 132). Consult this reference and rewrite this section.

   This is not true. The SIHP, 1997 states the fact based on extensive field work over several years, while Immerzeel et al. (2009) state quantitative estimates based on a multi-year modelling study that incorporates inter-annual variation of and compensation between the snow and glacier melt. The comment is however only true for Archer and Fowler (2004) who state this fact without supportive analysis. Since lately available 'exclusively devoted' study of Mukhopadyay and Khan (2015) has presented similar fact based upon distinct analysis of hydrograph separation, the study has been cited in place of Archer and Fowler (2004) at line 60 in the revised manuscript. The results from all these studies consistently support what has been said on Page 581, line 25-27.

2. Page 583 (Lines 13 – 14). There are better and more recent references than SIHP (1997), e.g. see Mukhopadhyay and Khan (2014a, Journal of Hydrology, 509, 549 - 572). Also see Archer (2004 in Nordic Hydrology) for altitudinal shift of thawing temperatures.

   Since the SIHP report is based on multi-year extensive field work covering wider area of the study region, this seems to be more relevant reference suggesting active hydrologic altitudinal range as given in the manuscript. None of the mentioned studies present this fact backed by a concrete analysis, as desired by the referee in the specific comment # 1 and # 7.

3. Page 584 (Line 4). The stochastic component of a time series is called "white noise" NOT "red noise". Do not use wrong terms.

   In an AR(p) process the signal is indeed a red noise. The "forcing" term on the rhs of the equation describing the process is a white noise process. The AR(p) process is the stochastic component on top of the deterministic, slow trend or time modulation. So it is a red noise. These terms are well known and already explained briefly on page 599, lines 3-10 and thus need not to be explained further.

4. Page 585 (Lines 13 -14). Explain here what is meant by "field significance". I know you have explained it later on page 600 (Linea 11 – 13).

   "field significance" has been briefly explained on lines 155-157 of the revised manuscript.

5. Page 586 (Line 12 -13). There is no diverse hydrologic regime within UIB. The hydrologic regimes throughout the UIB are uniform as evidenced from the uniform characteristics of annual hydrographs from various parts of the basin [see the discussion on hydrologic regimes in UIB as given in Mukhopadhyay and Khan (2014a)]. It appears that you are making the same mistake as Archer (2003) did in calling hydrologic regimes for different genetic sources of river water. See Krasovskia (1995) for the correct definition of hydrologic regime (reference given in Mukhopadhyay and Khan, 2014a).

   Instead of Krasovskia (1995) the flow regimes are in fact originally defined in Krasovskia (1994) mainly for the study area of the FRIENDS (Flow Regimes from International Experimental and Network Data) project. The following extract and the Table 2 from the Krasovskia (1994) clearly suggest the sub-types of high flow regime as the Mountain nival and Mountain glacial flow regimes as quoted below:

   "Mountain regime types have in general the same character as the NorthScandinavian type, with a distinct maximum in late spring/summer and low flow in winter. They occur at altitudes higher than 500 m. The nival sub-types are characterized by earlier maxima compared to the glacial-fed sub-types which have their maximal flow later in summer."

   In Table 2, Krasovskia (1994) clearly name these types of flow regime as Mountain Nival and Mountain Glacial. These sub-types of high flow regime can easily be differentiated based on peak flow timings as stated in the manuscript on Page 589, lines 232-26. Since the sub-regions within the UIB exactly feature Mountain nival and Mountain Glacial flow regimes, the statement given in the manuscript is correct. Thus, neither the Archer (2003) is mistaken nor the authors blindly followed him.

Moreover, in view of the multi-disciplinary nature of the manuscript and the targeted audience, it seems strange to codename these sub-types of high flow regimes as H1 and H2 only as done by the Mukhopadyay and Khan (2014a). Instead, it is more convenient to name them as have done by Krasovskia (1994) himself.

6. Page 586 (Line 23). So you are now giving us the "right direction" and all previous workers were so stupid that they provided wrong directions, ha? Stop such self-patting. It does not help your cause.

   It is to clarify that "right direction" for the climate community here particularly emphasizes on the water availability assessment from the region additionally under the prevailing climatic trends, since neither any of the study so far (to the best of authors' knowledge) has considered summer cooling nor the climate models are able to reproduce or project such phenomenon. As a result, the climate impact studies suggest signs of change, even for the near future water availability, exactly opposite to what is expected under the prevailing climatic patterns. Kindly see detail on Page 626, lines 13-22 and in Hasson et al. (2014b).

7. Page 587 – Page 592: Section 2. All of the information given in this section are well known and have been described by various previous workers. You need to condense this section to couple of paragraphs

   It is realized that explanation of the sub-basins of the UIB is to-some-extent already summarized in Table 1. Thus, (03 pages of) text between the Page 590, line 6 and Page 592, line 20 of the discussion paper have been removed in the revised manuscript. For the text between page 587 and 589, as stated in response to comment # 1 above, the multi-disciplinary audience does not necessarily know the region and its physio-geographical and hydro-climatic characteristics and related peculiarities. Thus, it is not convincing to shorten this introduction of the study area.

   giving proper reference to previous works [e.g. refer to Mukhopadhyay and Khan, 2015 in relation to Lines 14 – 21 on page 589; Archer (2003) and Fowler and Archer (2006) are not the relevant references in this case since in those work this particular issue has not been addressed].

   Based upon correlation analysis with valley-based stations and discharge, Archer (2003) has presented the distinct hydrological regimes, which have been reiterated in Fowler and Archer study. Lately, Mukhopadyay and Khan, 2015 have concluded similar facts through hydrograph separation analysis. The Fowler and Archer reference has been replaced with Mukhyopadyay and Khan, 2015 on lines 246-247 of the revised manuscript.

   This is not your Ph. D. thesis where you need to write all background information to satisfy you supervisory committee. Readers familiar with UIB know all of these very well and they get irritated when they see that you are presenting this material as if for the first time someone is describing this river basin and providing all those details.

   What about the readers not familiar with the UIB? The response to such repeated comment is already given in major comment # 1 and # 9.

8. Page 592 (Line 25). Delete "data collection". Just "three different organizations" [they are not just data collection organization; also phrasing of the words is wrong].

Regardless of what else these agencies do, here have been introduced particularly in the context of data collection. However, “data collection” has been removed as it does not affect the clarity of the sentence.

9. Page 593 (Lines 9 -10). Repeated from Section 2. Do not repeat statements or information. Also in this regard (“active hydrological altitudinal range” – strange phrase) – see Fig. 8 in Mukhopadhyay and Khan (2014a).

   The expression “active hydrologic altitudinal range” has been replaced with “active hydrologic zone” on lines 100-101 and lines 291-292 of the revised manuscript, exactly as stated by the SIHP, (1997). Repetition will be removed.

10. Page 593 (Line 15). Instead of “solid moisture input (another awkward phrase) simply say “snow” or “snowfall”. Also hydrology is NOT dominated only by snows (seasonal snow to be more precise), but also by glacial melts. So your statement here is not correct.

    It is to clarify that regardless of the fact that it is ephemeral, intermediate or perennial snow, firn, clean-ice or debris-covered ice etc., the hydrology of the region dominates with the solid moisture melt. For general clarity, “input” has been replaced with “melt” on lines 279 of the revised manuscript.

11. Page 593 (Lines 28 -29). No; they do not cover “most of the vertical extent of …..altitudinal range”. Most of the frozen water reserves are above 3500 m and extends all the way up to 8000 m. There are only couple of DCP stations above 3500 m (e.g. Deosai and Khujerab) and only a few above 3000 m.

    On Page 593, line 29, ‘the vertical extent of UIB frozen water resources and’ has been deleted as statement is only appropriate for the active hydrologic zone which extends up to roughly 5300-5500 m asl only.

12. Page 594 (Lines 19 – 20) – Delete – It is a nonsense sentence (gauge stations are not based on “distinct hydrologic regimes and magnitude of runoff contributions” they are carefully placed to gauge river flows of all major tributaries and main stem of the Upper Indus).

    It has been deleted.

13. Page 594 (Lines 21 -22) and Table 3. Shigar gauging station does not have continuous data from 1985 – 2011. The continuous data are only from 1985 – 1998 and then there are data for one year that is 2011. Get your facts straights.

    It is to clarify that on Page 594, lines 21-22 authors are talking about the availability of sub-basin gauges, and not the data availability from these gauges. However, thanks for pointing out this overlooked piece of information, which has been explicitly stated in the table 3.

14. Page 595 (Line 12). “limited skill” – another strange use.

    Authors don’t see any problem with this expression. A few ready references are Liu et al., (2015), Maurer and Hidalgo, (2008), Jiang et al., (2009), and elsewhere, many more …

15. Page 595 (Line 25). Another wordy sentence with little weight.

The sentence indicates reasons to justify why the relative homogeneity was performed instead of using a reference time series. It has been shortened on lines 337-339 of the revised manuscript.

16. Page 596 (Line 20). This period of record (1995 – 2012) is too short to detect any meaningful trend.

    Since this comments is repeated, kindly see the response to major comment # 5.

17. Page 598 (Line 2). Should be S NOT Z.

    Why not *Z.* It can particularly be S when n <= 10 and directly compared to probabilities table without calculating its variance and standardized normal variable, Z.

18. P 598 (Line 10). Say white noise, not "noise process".

    No. It is not necessarily the white noise only but can additionally be an autoregressive process, indicating sequential dependence of the time series. Kindly see response to specific comment # 3 and the relevant literature cited in the article.

19. Page 599 (Line 6, Eq 8). The yt in this equation is not the same yt in Equation 6. Change symbol. Also, add □t in this equation.

    In fact equation 6 showing a linear trend approximation can directly be referred here. So, the equation 8 has been removed. The ε_t refers to the white noise and it is shown in Eqn. 9.

20. Page 599 (Lines 10 – 25) and Page 600 (Lines 1 – 9). This procedure is valid for a long time series. For such a short time series (1995 – 2012) this is an overkill and the results are doubtful.

    No. This procedure is particularly required for shorter time series and not necessarily needed for n >= 50 (Bayazit and Önöz, 2007; Yue and Wang, 2002), as the effect of short memory diminishes or becomes negligible for longer time series. Since this comment is repeated, kindly see detailed response to major comment # 5.

21. Page 600 (Lines 11 – 13). Rewrite this sentence with correct grammar.

    The sentence has been corrected on lines 155-157 and on lines 428-430 of the revised manuscript.

22. Page 600 (Line 15). You cannot divide UIB into smaller units based on hydrological regime. Obviously you don't now what is meant by "hydrological regime" and are using the term completely ignorantly. There are two hydrological regimes throughout UIB. One is the high flow regime (May to September) and the other is low flow regime (October of a year to April of the following year). What you mean here is actually predominance of different genetic sources of river water (e.g. snowmelt dominant over glacial melt and vice-versa). Read Mukhopadhyay and Khan (2014a) for a better understanding of the distinction between hydrologic regimes and genetic sources of river flows. You have fallen as a victim of the misconception introduced by Archer in his 2003 Journal of Hydrology paper.

Since the comment is repeated, kindly see the detailed response to specific comment # 5, where definitions of the hydrological regimes are clarified and relevant literature is referred.

23. Page 600 (Line 24). Same problem as noted above.

Kindly see the detailed response to specific comment # 5, as stated above.

24. Page 601 (Line 8). Wrong information as noted above. Shigar gauging station does not have continuous data from 1985 – 2011. The continuous data are only from 1985 – 1998 and then there are data for one year that is 2011. Get your facts straights.

It is to clarify that nowhere in the manuscript it is suggested that the Shigar gauge has continuous data for 1985-2011. May be the referee means 1985-2001 period instead of 1985-2011 period. Any case, here purpose is to state that the Shigar gauge went non-operational after 2001. The continuous data availability for the 1985-1998 period and then for the year 2001 will be stated in the Table 3, as mentioned in the response to specific comment # 13.

25. Page 601 (Lines 10 – 24). The method used here for the calculation of derived flows at Shigar is wrong. It is because the reach lengths between the upstream gauges and a downstream gauge are significantly long. Throughout those long reaches flows from numerous other tributaries join the main stem and contribute to a downstream gauge. So subtraction of the sum of two upstream gauge flows from a downstream gauge flow gives substantial overestimation of the derived flows at a third upstream gauge. For example, excepting Shigar gauge, the only other two gauges upstream of Kachura are at Kharmong and at Yogo. So if you subtract sum of Kharmong and Yogo flows from Kachura flows to derive flows at Shigar then you are completely ignoring other flows that originate and contribute to Kachura from the points of gauging at Kharmong and Yogo and are assuming that only flows from Kharmong, Yogo, and Shigar contribute to Kachura. This process gives wrong flows at Shigar. In other words, the additive (subtractive) method of flow derivation is not a valid method. On the other hand the method of using flow ratios (as implemented in Mukhopadhyay and Khan, 2014b) is much more robust even if time-averaged ratios of flows at upstream and downstream gauges are used since the ratio of flows at two points is independent of contributions of other flows between these two points (assuming if there is any increase or decrease in flows then it affects all contributing streams in the same way).

It is to clarify that no attempt has been made to derive the flows right at the Shigar gauging site. The expression given in the Table 1, serial no.11 and explanation given in the text on page 601 lines 19-24 clearly suggest that flows are derived for the region comprising the Shigar sub-basin itself and all the extraneous area not represented by two upstream gauges of Kharmong and Yogo (shown without color in the manuscript Figure 2). Such area is already named as derived-Shigar in Table 1, serial no.11.

To avoid confusion, first the equations 11-13 has been removed and only Table 1 is referred. Second, the region has been renamed as Shigar-region in the Table 1 and lines 19-24 of the discussion paper has been revised as following on lines 444-449 of the revised manuscript:

"On the other hand, instead of estimating post-1998 discharge at the Shigar gauge, we have derived the discharge for the Shigar-region, comprising Shigar sub-basin itself plus the adjacent region shown blank in the Figure 2. This was achieved by subtracting the mean discharge rates of all gauges upstream Shigar gauge from its immediate downstream Kachura gauge at each time step of every time scale analyzed."

The reason for estimating the Shigar-region discharge is well explained on Page 601, lines 15-20 that coefficients identified from the pre-1998 period cannot be assumed time-invariant for the post-1998 period, in view of large drainage area upstream and also due to the distinct discharge trends present for the upstream gauges. This reason is further supported by Mukhopadyay and Khan, (2014b) themselves, who stated that since the correlation between the Shigar and Kachura gauges during the pre-1998 period was not constant in time, the generated post-1998 flows for the Shigar gauge have greater uncertainties than its pre-1998 flows. The variable snow and glacier melt contributions as stated by the referee in the specific comment # 1 also reinforce this fact. Given that the found relationship between two time series is variable in time over the known period, what guarantees that it will be time-invariant for the unknown period, and particularly when upstream flow series are non-stationary? Against this background, no attempt has been made to generate the missing flow records for any gauge. Instead, flows from the Shigar-Region and from the other ungauged regions are derived from the upstream-downstream gauges. For this, the additive approach is applied at each and every time step of the considered time scale (monthly to annual), which ensures application of time-variant relationship/factor. It is to clarify that both the additive or multiplicative approaches in the context of time-variant relationships for each time step, yield exactly the same results.

The time-variant relationships between the Shigar and Kachura gauges as found by Mukhopadyay and Khan, (2014b) are mainly due to the active memory processes that occur at various temporal scales. Thus, the derived flow series obtained through either additive (expressions given in Table 1) or multiplicative approach are only an approximation of the measured flow series. In Table 1, 'Expression of Derived discharge' has been replaced by 'Expression for deriving approximated discharge'

26. Page 601 (Lines 24 – 29) – Page 602 (Lines 1 – 6). Strictly speaking, Equations (11) – (13) are not correct because they do not obey the fundamental principle of flow balance of hydrology. However, this limitation can be partially removed by using an approximation sign (≈) instead of equal sign in the equations.

The equations 11-13 will be removed as stated above. However, in Table 1, 'Expression of Derived discharge' will be replaced by 'Expression for deriving approximated discharge' as stated in above.

27. Pages 602 (Lines 7 – 24) to Page 604 (Line 10). This is the only original contribution of this work. This part is relatively well written. However, based on the mathematics presented to illustrate the method of "field significance", it appears to me that this method is most reliable when there are several local stations in a region. In the sub-regions of UIB, defined in this work, there are two to three local stations and the areal extents of these sub-regions are too large (e.g. UIB East). I am not sure how good this analysis is, in spite of the fact this is the first time someone has attempted this (in sharp contrast to Archer and Fowler or Fowler and Archer who made big conclusions

about climate change in the entire UIB based on a few local observations at valley floors). This is the part of your paper I like most.

Authors are thankful to the referee for the appreciation that leads towards encouragement. As indicated by the referee, the problem of uneven distribution for the method is briefly discussed on Page 625, lines 3-10. Also, this is one of the main reasons that the field significance is further qualitatively compared with the discharge trends from the corresponding regions.

28. Page 614 – 616. Section 6. This whole section should be abridged. Everything stated here is superfluous. If your objective is to have an interested reader to read your paper then you need to capture his/her attention by making things short and succinct. Develop respect for a reader's time.

First, all the text between Page 614, line 17 and Page 616, 7 has been removed. further, the Section 6 has been substantially shortened in the revised manuscript.

29. Page 622 (Line 25). Mukhopadhyay et al. (2014) is not in the reference list. Discussion should also include the trends for Yogo (eastern Karakoram) and Hunza (west Karakoram) as given in Mukhopadhyay et al. (2014; Hydrological Sciences Journal, http://dx.doi.org/10.1080/02626667.2014.947291).

The trends for Yogo and Hunza from Mukhopadyay et al. (2014) has been discussed on lines 872-873 of the revised manuscript. The reference list is corrected.

30. Page 622 (Lines 26 – 26) – Your calculation of Shigar flows is in error due to the reason explained above.

Since this comment is repeated, kindly see response to the specific comment # 25.

31. In general from Page 605 – 629 – Shorten the discussion. Discuss to the point otherwise it is hard to remember the key points (trends) in the maze of lengthy and verbose discussions. Your main contribution has been establishing field significance of the trends whereby you can draw some generalization for a region from point observations. So focus on that aspect and then your paper will receive the derived attention of a reader. Currently, the way materials have been presented and discussed, no one will have the time to go through all these details and then get lost to figure out the key points than be taken from this study.

The discussion has been shortened, and now focus on the field significance results. Kindly see response to major comment # 1.

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Table 1.Hydroclimatic trends (1995-2012)

Variable	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Tavg	Khunrab	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
	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
P	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
	Gilgit	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**
	Bunji	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
	Chilas	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**	-37.17	-9.48	0.60	***8.97***	***5.97***	***1.65***	0.11	-24.43	5.64	-3.90
	Hindukush	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
	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
	Astore	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
	Partab_Bridge	1.00	-0.13	3.60	8.80	63.22	-34.86	-39.86	-67.33	29.65	0.69	8.89	15.12	8.40	36.29	-67.00	9.81	-12.40
	UIB-WL	1.88	0.41	6.39	-0.52	41.58	**59.50**	28.19	***81.58***	**30.99**	16.18	5.17	2.33	1.92	19.90	***65.53***	***16.02***	***25.44***
	UIB-WL-Partab	-3.00	0.80	-4.38	-0.82	***87.89***	51.53	9.00	17.67	2.71	-12.24	1.40	-6.00	-3.74	28.32	47.93	-3.00	18.94
	UIB_West	2.45	1.37	5.43	2.42	**61.35**	54.89	0.21	42.93	***28.24***	**13.68**	***5.87***	1.38	2.00	**23.43**	44.18	***17.71***	***22.17***
	Himalaya	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***
	UIB	1.82	***5.09***	5.37	-2.50	11.35	14.67	-46.60	41.71	35.22	10.17	5.29	0.75	1.91	15.72	-1.40	19.35	4.25

Response to Anonymous Reviewer #2

We are thankful to the Referee # 2 for his/her comments, however, we respectfully disagree with most of them and thus with his/her recommendations. Following is our point by point response (in black) to his/her comments (in grey) along with the suggested changes in the revised manuscript (in red).

Major comments

#1. The quoted precipitation data sets for low altitude valley based stations are far different from already available other published papers' data sets for the same stations, obtained from the same sources, although there is slight difference in time periods (and can be ignored for long term averages). For example for the Gilgit station long term average annual quoted precipitation is below 50mm (see Line 30 page 588, Line 18) as opposed to long term average annual precipitation for the same station ~130 mm (see for example in Archer and Fowler, 2004; Tahir 2011; Mukhopadhyay and Khan, 2014a). Similarly, for the Skardu station the quoted annual precipitation is more than 1000mm (see Line 3 page 589 and Line 4 page 591), whereas for this station the long term annual precipitation is about 223 mm (about 1/5th of the present study) in various published studies (such as in Archer and Fowler, 2004; Tahir 2011; Mukhopadhyay and Khan, 2014a). Interestingly, all previous studies' long term average annual precipitation estimates for their studied stations are in good agreement, besides there are also slight differences in study time periods. Due to difference in time periods, the difference among current study's estimates and previous studies' data cannot be too large (~ 1/3rd to 1/5th). This, indicates that there are some serious accuracy issues for datasets used in current study, at least in low altitude valley based stations' precipitation data (or wherever data is shown/provided). The temperature and high altitude stations' data could have not been compared due to either limited available published data or due to non-provision of estimates in the current study. Use of inaccurate data and their trends cannot provide true representation of the Hydro-Climatology of the study area, therefore the results of the current study are doubtful, else otherwise all above previous studies' results and trends are inaccurate and biased. In sum, the authors need to check the accuracy of their collected and estimated data sets, and a Tabulated comparison (in re-submitted version) with previous studies could/will be useful.

The presented analysis is based on a correct dataset, received after problem with the earlier dataset was communicated to the PMD. The following table shows a comparison of the long term annual precipitation with earlier studies. The figures given in the text has been corrected accordingly on lines 236-237 of the revised manuscript.

	Archer and Fowler (2004)	Sheikh et al (2009)	Tahir, 2011 and Tahir et al. 2011	Hasson et a., 2015
		1951-2000		
Astore	516.7 (1954-97)	512.8	501 (1954-2007)	454.7 (1962-2012)
Bunji	126.3 (1952-97)	151.1	-	163.8(1961-2012)
Chillas	-	192.7	-	184.3 (1962-2012)
Gilgit	131.2 (1894-1999)	133.8	132 (50-year record)	137.3(1960-2012)
Gupis	-	166.8	-	204.4(1961-2010)
Skardu	222.3 (1894-1999)	218.5	-	239.2(1961-2012)

#2 The authors argue that the UIB boundary has long been overestimated by various researchers, and they have estimated it precisely/accurately. There are two major drawbacks in their statements in Line 8-20 page 587. a) The cited reference studies (03 out of 04 cited studies) have not overestimated/over-quoted basin areas (except 01: Hasson et al 2014a). According to WAPDA the UIB at Besham Qila is about 162,393 km2, while the cited studies have provided nearly the same estimates, such as Alford (2011) has quoted an area ~ 166,069 km2 (see his section 1.1, page 7), Sharif et al. (2013) have provided an area ~ 168,000 km2 (see their section 2, page 1505), and Young and Hewitt have used an area of WAPDA (i.e 162,393 km2, see their Table 2). The maximum difference (overestimation) is < 3.5% (for Sharif et al. 2013), however, such slight differences can be ignored due to difference in projection systems, difference in delineation methods and use of different Digital Elevation Models (DEMs) (Also see specific comment (x), where some examples of various area estimates are provided and are plausibly due to use of different projection). Although Hasson et al. (2014a) significantly overestimated the UIB boundary but this study is for the entire Indus Basin, and no separate estimate (numerical estimate) of the UIB has provided, therefore such an example is also not easy to follow. Another study, Hasson et al. (2014b), should have been cited, instead. In this study the estimated area for the UIB is ~ 271,359 km2 (~ 67% greater than WAPDA's basin). There are many other studies, which overestimated the UIB boundary, and their areas are > 23% than the WAPDA's estimate (see for example Immerzeel et al., 2009; Tahir et al. 2011; Bookhagen and Burbank, 2010). Such detailed examples of overestimation can be found in Khan et al. (2014) and Reggianni and Rientjes (2014) studies. Therefore, the authors need to avoid biased citation of previous studies, and have to revisit the available literature. b) The argument that the authors have precisely and accurately estimated the basin boundary is an example of self-praise and not crediting previous researcher's work, and should be strictly avoided. Besides some other available precise estimates for the UIB, a first comprehensive study was presented by Khan et al. (2014), where reasons of such overestimations have been discussed in detail. This study was followed by Reggiani and Rientjes (2014), where the studies with overestimation and precise estimate have been provided. The authors should duly consult/cite these studies. The authors also need to provide details about delineation method and source of the SRTM DEM.

Lines 8-20 page 587 has been revised on lines of the revised manuscript given as follows. Since the issue is also raised by the referee # 1, kindly refer to the detailed response to his/her major comments # 3.

"As summarized in Reggianni and Rientjes (2014) and Khan et al. (2014), the total drainage area of the UIB has long been overestimated by various studies (e.g. Immerzeel et al., 2009; Tahir, 2011; Bookhagen and Burbank, 2010). Such overestimation is caused by limitations of the GIS-based automated watershed-delineation procedure that results in erroneous inclusion of the Pangong Tso watershed (Khan et al., 2014), which instead is a closed basin (Huntington, 1906; Brown et al., 2003, Alford, 2011). Khan et al. (2014) have provided details about the delineation of the UIB based upon ASTER GDEM 30m and SRTM 90m DEMs. For this study, the UIB drainage area is estimated from the lately available 30 meter version of the SRTM DEM, which was forced to exclude the area connecting the UIB to the

Pangong Tso watershed in order to avoid its erroneous inclusion by the applied automated delineation procedure. Details of the delineation procedure will be provided elsewhere. Our estimated area of the UIB at Besham Qila is around 165515 km2, which is to a good approximation consistent with the actual estimates of 162393 km2 as reported by the SWHP, WAPDA."

#3 During delineation of a watershed boundary the stream network (particularly the start point of a stream) is generated based on either flow area (or number of cells draining to a downstream cell). This provides a stream network, well within the basin's boundaries. This provides nearly a uniform distance of stream network from the basin's boundary. However, the stream network provided in Figure-2, page 648 does not provide nearly uniform distance from the exterior basin's boundary. In no case a stream should cross the basin's boundary (except at the basin's outlet), whereas near to the eastern part of the Shyok basin the stream 2 in following Figure B (zoomed part of Figure 2, page 648) crosses the outer basin's boundary. Similarly, stream 3 also nearly touches the boundary. The distance between boundary and streams is significantly variable (see streams 1-4, following Figure B). All this makes the delineation of the UIB doubtful. The authors need to address this issue, and have to carry out a re-delineation, together with a revision of the Figure.

In view of the new delineation of the UIB using SRTM 30 m DEM (Discussion Figure 1 below), this major comment is not relevant any more. However, it is to clarify that previously, ArcGIS basin tool was applied on the DEM, forced to an automated delineated UIB boundary that was buffered out to a certain threshold. The resultant small basins were combined together excluding the internal drainages identified by Khan et al. (2014); and, the river network was manually forced within the newly achieved boundary. Similar approach can apparently be noted from the Figures # 2 in the Mukhopadhyay et al. (2015) for the Shyok basin and from the Figure # 2 in the Mukhopadhyay and Khan (2014) for Zinskar river, featuring no uniform distance from the exterior boundaries instead rivers touching the watershed boundary. Also, kindly see response to Referee #1, major comment #3.

#4 The authors have adopted an additive method for estimation of missing flow values for the Shigar basin (in addition to some other parts of the UIB). This is provided at S.No 11 in Table 1, page 638, where flows of the Yogo and Kharmong stations have been subtracted from Kachura station's flows. During flow estimation the area between the downstream station (Kachura station) and upstream stations (Shigar, Yogo, and Kharmong stations) has been ignored. Ignoring such upstream areas can generate significant biases, particularly near to the highly glacierized basins. According to the areas in Table 1, page 638, there is about 3,649 km2 (>50% of the Shigar basin's area) ungauged area, which contribute to the flows of Kachura station in addition to upstream gauging stations' flows. Furthermore, sum of the Shigar, Yogo and Kharmong stations (for the available overlapping period of record) is not equal to the Kachura stations' flows. This confirms that a simple additive approach (at least as authors applied herein) may not be suitable for the Shigar's flow estimation. Therefore, the current study's additive approach may contain significant biases in Shigar's estimated flows, and require a re-visit. In addition, other parts of the UIB, where additive approach has been used, needs revisit.

Since this issue is raised by the Referee # 1 as well, kindly see our detailed response to Referee # 1, specific comment # 25, where it is clarified that no attempt has been made to derive flows at the Shigar gauge and how the additive or multiplicative approaches are insensitive to the way discharge is derived for the Shigar-region.

#5 Most of the discussion and conclusions are based on statistically-insignificant trends. The authors should only focus on statistically significant trends.

We agree with the reviewer that most of the trends are statistically insignificant. However, we note that such insignificant tendencies feature a better agreement for the similar pattern/direction of change, which is interestingly further consistent to what has been suggested by the significant trends (discussion Table 1 in color scale in response to Referee # 1). We believe that such an agreement amid statistically insignificant trends, which are further consistent with the statistically significant trends, provide as valuable information as the statistically significant trends do. Thus, in view a shorter length of the analyzed dataset and sparse location of the analyzed observations, both the insignificant and significant trends collectively exhibit a consistent and detailed picture of prevailing changes over the regions and need to be discussed.

#**6** Short time period hydro-climatic trends may not be true representative of climate. The long term trends' results are not in good agreement with short term trends' results (Table 4-6), and could be an artifact of the selected short time period's data (1995-2012) for trend analysis. Such unexplained trends can be seen in the Astore basin (for example), where precipitation is rising for the Rattu station and declining for Rama station (see Table 5, page 643). Most of the monthly trends are statistically significant for both stations. This results in questions: such as which trends should be taken for discussion and which should be discarded and why?

It is to clarify that stations at the valley bottom should not necessarily be in agreement with the high-altitude stations that are more representative of the topoclimate; however, still their better qualitative agreement with the valley bottom stations for spring (summer) months warming (cooling) suggests that the region is more-or-less under the influence of similar phenomenon. The period of 1995-2012 is considered not by choice but due to the limited accessibility of the high-altitude stations data. Moreover, trends over the period of 1995-2012 truly tell about the prevailing climatic state during such a period. Stations at the valley bottoms are also analyzed for the same period for sake of their comparison with the high-altitude stations over the same length of record.

For the Ramma and Rattu stations, it has already been explained on Page 588, lines 23-25, that the hydrology of the region is influenced by two large scale circulations, where such influence is further modulated by the complex terrain present in the region. The opposite change depicted by two stations may be a best example of such topographic modulation. Provided the abode stations in a particular region exhibit opposite responses, field significance is a best indicator to yield a dominant signal over that region, which can further be verified against the integrated signal of change from the stream flow record, as have been done in the manuscript. Recently published study of Immerzeel et al. (2015) have addressed in detail the precipitation uncertainty over the whole UIB, motivating the analysis of direct high altitude observations alike the presented analysis does in the manuscript.

#7. The manuscript is very long with un-necessary descriptions, such as details about sub-basins. Such details can /should be presented in a Table rather than long descriptions. The authors should also avoid discussion about statistically insignificant trends.

Since this issue is also raised by the Referee # 1, kindly see our response to his specific comment # 7, in which we agreed to remove the description of the sub-basins as most of the information is already summarized in Table 1. For statistically insignificant trends, kindly see our response given above to the major comment # 6.

#8 There are many confusing/false/biased/without reference statements/arguments/estimates in the current study. Such as in Line 28, page 587 the glacierized area of the UIB has been estimated to be 18,500 km2 (∼ 11.3% of total basin's area). Just on the next page, same paragraph (Line 3-4, page 588), the snow cover is estimated/quoted to be in the range of 3 to 67%, although no reference for the statement is provided (therefore can be assumed an analysis of the current study). Minimum snow cover area can be regarded as perennial snow and glacier cover area (Painter et al., 2012). Assuming the same, one will get a glacier area of about 4,905 km2 as opposed to a total of ∼ 18,500 km2 (mentioned above). Such statements need further explanation, and or should be avoided.

It is not true that the minimum snow cover area can be regarded as glacier cover area for the study region where substantial portion of the glaciers are under debris cover. Kindly again consult Painter et al., 2012 and also Rittger et al., 2013, who state inability of the employed MODIS MODSCAG product (which is based on spectral mixture analysis and is superior to the MODIS standard products) in detecting the debris covered ice and dirty snow. Second, the snow cover estimates given in the manuscript are based on Hasson et al. (2014b), who used the MODIS standard daily snow products, which too are unable to detect the debris covered glacier ice and dirty snow/ice. In addition to these, there are several other reasons that lead towards substantial differences between the minimum snow cover and the actual glacier cover, emphasizing not to regard the both as a proxy of each other, as explained in Hasson et al. (2014b) for the study region. Since the issue is not the focus of the study, such discussion will not be included in the revised manuscript.

#9 The authors have conducted homogeneity analysis, and found that some of the datasets are non-homogeneous. How good/bad are these datasets for further trend analysis? Some of the stations' data (e.g Bunji stations' temperature data) have already been evaluated and argued to be non-homogeneous (as mentioned in the paper), then how realistic could be the trend results of such data? The authors ignored homogeneity results due to non-availability of additional record/data, and used the stations' raw data. This arises a question that what is the significance of such an incomplete analysis or should this be included in this paper?

It is to clarify that the statistically identified change points in the data (particularly when found only in the minimum temperature) may not necessarily be considered as an inhomogeneity until there is a documentary evidence stating the reason for such shifts in the data. Otherwise, in view of the high altitude topoclimate, role of topography in modulating the climatic effects, and also presence of substantial internal variability, shifts in the data may be present for real. Thus, it is not a pragmatic idea to dispose off the stations with statistically identified data shifts in view of lacking inhomogeneity evidence. Rather, it is more convincing to present the analysis from such stations raising caution to the reader and hoping any better explanation of such behavior in future. Moreover, the scarcity of stations within the region, and more importantly, the large consistency amid suggested changes by the stations featuring data shifts and those of homogeneous stations reinforces the idea to present the analysis from all stations, as have been done in the manuscript.

Specific Comments

1. Line 14-18, page 581, where it is mentioned that around half of the surface water of Pakistan is derived from the UIB. What is the source or background of this information?

   The authors have estimated it from the long term (1961/62-2005/06) mean inflows of Indus at Tarbela against the long term mean inflows at the River Inflow Measurement (RIM) stations of the Indus river system (IRS), including Ravi at Balloki, Sutlej at Sulemanki, Chenab at Marala, Indus at Tarbela, Jhelum at Mangla and Kabul at Nowshera. According to the WAPDA data, Indus at Tarbela constitutes on the average 43.2% of the total IRS inflows with a range between 38.2 and 51.7 % as minimum and maximum contributions during the maximum and minimum water availability years, respectively.

2. Line 20, page 582, similar period should be replaced by same period.
   ‘similar’ has been replaced with ‘same’ on line 78 of the revised manuscript

3. Line 21-23, page 582, which period’s data have been analyzed by Sheikh et al. (2009)?
   The analysis period of 1951-2000 has been mentioned on line 81 of the revised manuscript.

4. Line 5-7, page 583, what is the time period of data analysis by Rio et al. (2013)?
   The analysis period of 1952-2009 has been mentioned on line 92 of the revised manuscript.

5. Line 24-27, page 585, is this really the first study? I believe there are also some other recent studies, where high altitude data have been analyzed (see e.g Mukhopadhyay and Khan, 2014b; Farhan et al., 2014; Tahir et al., 2015; Mukhopadhyay et al., 2015).
   It is agreed that few studies, appeared online in late 2014 or in 2015, have presented only the subset of the data from few of the automated stations analyzed in the manuscript, for a relatively shorter period and mainly as a supported/side analysis. For instance:

   - Farhan et al. (2014) have used the Burzil station, which is in fact outside the UIB and located in the Jhelum basin. Thus, it is not relevant here.
   - Mukhopadhyay and Khan, 2014b have used mean temperature and precipitation from the Shigar station only for the 1999-2010 period.
   - Mukhopadhyay et al., (2015) have used mean temperature and precipitation from only four stations of Naltar, Ziarat, Khunjrab and Hushe for the 1999-2010 period.

- Tahir et al., 2015 have used mean temperature and precipitation from the Ramma and Rattu stations for 1995-2008.
- Mukhopadhyay and Khan (2014b) have graphically shown the annual cycle of precipitation for the unknown period.

None of the above studies has presented the mean temperature and precipitation from five high altitude stations of Deosai, Yasin, Ushkore, Dainyor and Shendoor. More importantly, none of the above mentioned studies has presented the minimum and maximum temperature datasets from any of the high altitude stations.

Nevertheless, 'for the first time' has been removed from line 168 of the revised manuscript.

6. Line 13-16, page 586, needs a supporting Figure or Figure No (of the existing Figures).
   the Figure (2) has been referred on line 181 of the revised manuscript

7. Line 2-4, page 587, the statement needs a reference, as this sounds to be taken from an available literature.
   Archer (2003), Fowler and Archer, (2006) and Hasson et al (2013) have been cited on line 195 of the revised manuscript.

8. Line 13, page 587, calculated should be replaced by estimated.
   "calculated" is generally used in a GIS environment for areas and geometry calculations.

9. Line 14-15, page 587, what is the source of void filled SRTM DEM?
   Instead of void filled SRTM 90m DEM, the 30 meter version of SRTM DEM available from the U.S. Geological Survey will be used in the revised manuscript. Kindly see response to Referee # 1 major comment # 3.

10. Line 18, page 587, what projection system has been used for current study? There are also difference in current study's glacier cover estimates (besides using same glacier data) with available published papers, and could mainly be due to use of a different projection system. This can be noticed by comparing the glacier cover values with other available studies, for example the estimated glacier area for the Astore and Hunza basins in Table 1, page 638 are 527 km2 and 3815 km2, respectively, while for the same basins (and data) the areas are ~543 (Farhan et al., 2015; Tahir et al., 2015; Khan et al., 2015) and 3860 km2 (Tahir et al., 2015; Khan et al., 2015; Mukhopadhyay and Khan, 2014a). Basin areas of Alford (2011), Sharif et al. (2013), and Young and Hewitt (1988) are also within the same uncertainty level, hence are not examples of overestimated basin boundary. Therefore, limitation of use of different projection system should also be properly explained.
    The WG84 and UTM projected system for the North 43 zone has been used for areal estimates. Given that the projection is equal area, it should not be the reason of small differences in the areal estimates. Kindly note that for the same basins, estimated drainage areas amid above studies are not the same, for instance, it ranges between 3903 and 3990 for the Astore basin. In fact, small differences in the drainage areas may arise due to slight along-stream shifts while snapping the outlet to the

accumulated raster for delineation. Thus, small differences in the basin shapefile can create small differences in the glacier estimates.

11. Line 3-4, page 588, what is the reference of snow cover estimate?
    All snow cover estimates are based on Hasson et al. (2014b), which has been added on line 216 of the revised manuscript.

12. Line 1-3, page 590, it is argued that around 45% of total available surface water comes from the UIB. What is its source or how this has been estimated?
    Since it is repeated, kindly see answer to specific comments (i).

13. Line 10-13, page 592, glacier cover of the Astore basin is around 14%, while minimum snow cover 2-4%. How? Needs further explanation.
    Hasson et al. (2014b) have explained that the minimum snow cover does not necessarily corresponds to the glacier area due to debris covered portion of the glaciers as well as due to skill (though limited) of the MODIS snow products in differentiating between the snow and the glacier ice. Anyhow, this text will be removed in response to specific comment # 7 from the referee #1.

14. Line 8-11, page 593, is repetition of Line 13-15, page 583. Other such repetitions should also be discarded.
    The repetitions has been removed

15. Line 13, page 613, select should be replaced by selected.
    It is to clarify that here, ‘select’ has been used as an adjective not as a verb

16. Line 1-14, page 618, the authors should also consult Forsythe et al. (2015), which is about cloud cover variation in the UIB. In addition, warming influence varies with respect to altitude, therefore the authors should consult some relevant articles (such as Mountain Research Initiative, 2015), and should caution readers about their results.
    Forsythe et al., (2015) is cited on line 794-796 of the revised manuscript. The signal of elevation-dependent warming is briefly mentioned on lines 931-935 of the revised manuscript.

17. Line 10-14, page 621, trends of different seasons and months are compared. How these are comparable?
    The text has been removed.

18. Line 24-27, page 623, decline in July flows have been argued to be a sign of positive mass balance. However, this can also be due to negative mass balance, where available ice volume may has reduced, together with a reduction in July precipitation. Therefore, needs further explanation and elaboration.
    In view of the overall stable areal extent of the regional glaciers (Bolch et al., 2012) and typical surface melting property of the cryosphere, it is not the case that a negative mass balance of few centimeters (Kaab et al., 2015) can explain reduction in the discharge, until the available energy for the melt is reduced, as already explained. Further, kindly see on Page 626, line 13-24, explaining how reduction in the solid precipitation has ironically an opposite effect on the melt discharge. The

reduction in rainfall however may reduce the discharge, but meager amounts of rainfall received in summer months do not yield perceptible river runoff, particularly when the evaporation is considered (Mukhopadhyay and Khan, 2014). Thus, the case presented above is highly less likely.

19. Line 10-11, page 624, flow trends have been argued to be mainly driven by temperature trends. This could be wrong. For example July flows and stations' precipitation are declining, and could be a main cause of flows decline (provided trends are true).
    The July discharge is largely generated from cyrospheric melt and only little contribution comes from the rain (typically true for even whole high flow period - Archer and Fowler, 2004; Mukhopadhyay and Khan, 2014). Thus, changes in the available energy for melt are mainly responsible for the discharge perturbation. Further, the influence of precipitation on discharge is already explained on Page 626, lines 13-24. Kindly also see response to the specific comment # 18.

20. Line 10-15, page 625; positive mass balance in the Karakoram. . . .. . . Gardelle et al. (2013) study only covers part of the Shyok basin (eastern Karakoram). A negative mass balance has been estimated by Kaab et al. (2012; 2015). Kaab et al. (2012) shows slightly negative mass balance in the western Karakoram and significantly negative in the eastern Karakoram. The latest study (Kaab et al., 2015) provide a significant negative mass balance in the eastern Karakoram (Shyok basin). Mukhopadhyay et al. (2015) also provide details about trends of the western and eastern Karakoram, and is good agreement with the mass balance studies. It is therefore, suggested to consult and include these studies.
    The above referred contradictory findings has been mentioned on lines 927 and lines 873-874 of the revised manuscript.

21. Line 3-9, page 626, is an example of very long sentence. Necessary editing should be carried out for such sentences in the entire paper.
    Long sentences have been shortened throughout the revised manuscript.

22. Use of article "the" is haphazard, for example in some places the authors write the UIB whereas at other places only UIB. Such minor English writing corrections should also be considered in the revised version, if any.
    The use of article has been given a proper care and have been revised throughout the revised manuscript.

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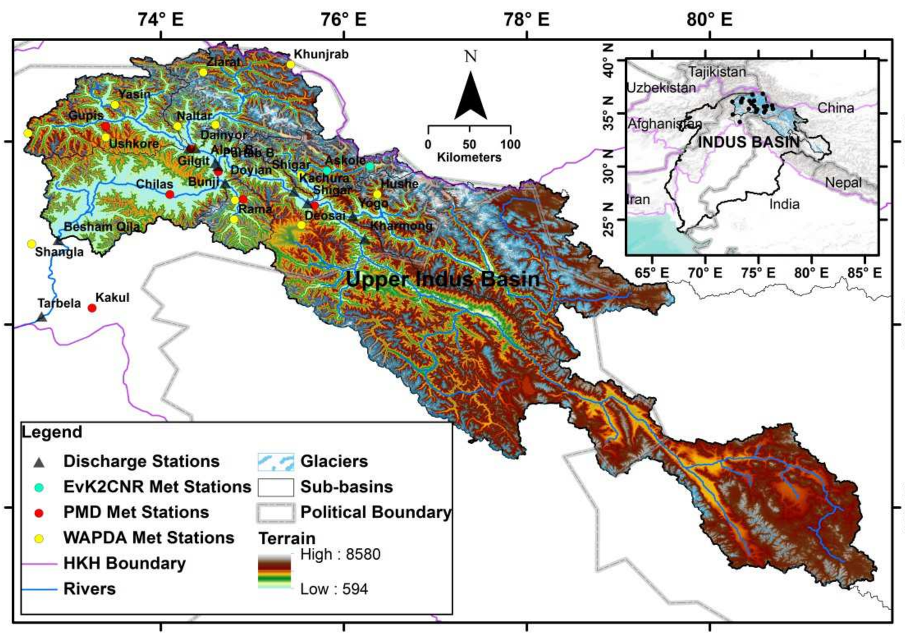

Discussion Figure 1: The UIB delineated from the SRTM 30meter DEM.

Prevailing climatic trends and runoff response from Hindukush-Karakoram-Himalaya, upper Indus basin

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Abstract

Largely depending on meltwater from the Hindukush-Karakoram-Himalaya, withdrawals from the upper Indus basin (UIB) contribute to half of the surface water availability in Pakistan, indispensable for agricultural production systems, industrial and domestic use and hydropower generation. Despite such importance, a comprehensive assessment of prevailing state of relevant climatic variables determining the water availability is largely missing. Against this background, we present a comprehensive ~~hydro-climatic~~hydroclimatic trend analysis over the UIB~~, including for the first time observations from high-altitude automated weather stations~~. We analyze trends in maximum, minimum and mean temperatures (Tx, Tn, and Tavg, respectively), diurnal temperature range (DTR) and precipitation from 18 stations (1250-4500 m asl) for their overlapping period of record (1995-2012), and separately, from six stations of their long term record (1961-2012). We apply Mann-Kendall test on serially independent time series to assess existence of a trend while true slope is estimated using Sen's slope method. Further, we statistically assess the spatial scale (field) significance of local climatic trends within ten identified sub-regions of the UIB and analyze whether~~ the~~ spatially significant (field significant) climatic trends qualitatively agree with a trend in discharge out of corresponding sub-~~region~~regions. Over the recent period (1995-2012), we find a well agreed and mostly field significant cooling (warming) during monsoon season i.e. July-October (March-May and November), which is higher in magnitude relative to long term trends (1961-2012). We also find a general cooling in Tx and a mixed response ~~in~~of Tavg during ~~the~~ winter season ~~and~~as well as a year round decrease in DTR, which ~~are in~~

~~direct contrast to their long term trends. The observed decrease in DTR~~ is stronger and more significant at high altitude stations (above 2200 m asl), and mostly due to higher cooling in Tx than in Tn. Moreover, we find a field significant decrease (increase) in late-monsoonal precipitation for lower (higher) latitudinal regions of Himalayas (Karakoram and Hindukush), whereas an increase in winter precipitation for Hindukush, western- and whole Karakoram, UIB-Central, UIB-West, UIB-West-upper and whole UIB regions. We find a spring warming (field significant in March) and drying (except for Karakoram and its sub-regions), and subsequent rise in early-melt season flows. Such early melt response together with effective cooling during monsoon period subsequently resulted in a substantial drop (weaker increase) in discharge out of higher (lower) latitudinal regions (Himalaya and UIB-West-lower) during late-melt season, particularly during July. ~~These discharge tendencies qualitatively differ to their long term trends for all regions, except for UIB-West-upper, western Karakorum and Astore.~~ The observed hydroclimatic trends, being driven by certain changes in the monsoonal system and westerly disturbances, indicate dominance (suppression) of nival (glacial) runoff regime, altering substantially the overall hydrology of the UIB in future. These findings largely contribute to address the hydroclimatic explanation of the 'Karakoram Anomaly'.

1 Introduction

The hydropower generation has key importance in minimizing the on-going energy crisis in Pakistan and meeting country's burgeoning future energy demands. In this regard, seasonal water availability from the upper Indus basin (UIB) that contributes to around half of the annual average surface water availability in Pakistan is indispensable for exploiting 3500 MW of installed hydropower potential at country's largest Tarbela reservoir immediate downstream. This further contributes to the country's agrarian economy 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-July), the extent of which largely depends upon the accumulated snow amount and concurrent temperatures (Fowler and Archer, 2005; Hasson et al., ~~2015~~2014b). Snowmelt runoff is then overlapped by ~~the~~ glacier melt runoff (late-June to late-August), ~~the magnitude of which~~ primarily ~~depends~~depending upon the melt season temperatures (Archer, 2003). ~~The~~ Snow and glacier melt ~~runoff~~runoffs, originating from the Hindukush-Karakoram-Himalaya (HKH) Ranges, together constitute around 70-80% of the mean annual water available from the UIB (SIHP, 1997; ~~Archer~~Mukhopadhyay and ~~Fowler 2004~~Khan, 2015; Immerzeel et al., 2009). ~~Contrary~~As opposed to large river basins of ~~the~~ South and Southeast Asia ~~that~~, which feature extensive summer monsoonal wet regimes downstream, the lower Indus basin is mostly arid and hyper-arid and much relies upon the meltwater from the UIB (Hasson et al~~.~~., 2014b).

Climate change is unequivocal and increasingly serious concern due to its apparent recent acceleration. For instance, ~~previous~~the last three decades ~~were consecutively warmer~~have been the warmest at a global scale since 1850, while ~~a~~the period of 1983-2012 in the Northern Hemisphere has been estimated as the warmest since last 1400 years (IPCC, 2013). ~~Such globally averaged~~The global warming signal, however, is spatially heterogeneous and not necessarily ~~synchronous among~~equally significant across different regions (Yue and Hashino, 2003; Falvey and Garreaud, 2009). Similarly, local impacts of the regionally varying climate change can differ substantially, depending upon the local adaptive capacity, exposure and resilience (Salik et al., 2015), particularly for the sectors of water, food and energy security. In view of high sensitivity of mountainous environments to climate change and the role of meltwater as an important control for the UIB runoff dynamics, it is crucial to assess the prevailing climatic state over the UIB and subsequent water availability ~~from the UIB~~. Several studies have been performed in this regard. For example, Archer and Fowler (2004) have analyzed ~~trend~~trends in precipitation from four stations within the UIB and found a significant increase in winter, summer and annual precipitation during the period 1961-1999. By analyzing ~~the~~ temperature ~~trend~~trends for the ~~similar~~same period, Fowler and Archer (2006) have found a significant cooling in summer and ~~a~~ warming in winter~~, within the UIB~~. Sheikh et al. (2009) documented a significant cooling of mean temperatures during the monsoon period (July-September), and consistent warming during the pre-monsoonal ~~period~~months (April-May~~).~~) for the period 1951-2000. They have found a significant increase in monsoonal precipitation while non-significant changes for the rest of year. Khattak et al. (2011) have found winter warming, summer cooling (1967-2005), but no definite pattern for precipitation. It is noteworthy that reports from the above mentioned studies are based upon at least a decade old data records. Analyzing updated data for the last three decades (1980-2009), Bocchiola and Diolaiuti (2013) have suggested that winter warming and summer cooling trends are less general than previously thought, and can be clearly assessed only for Gilgit and Bunji stations, respectively. For precipitation, they found an increase ~~in precipitation~~ over the Chitral-Hindukush and northwest Karakoram regions and decrease ~~in precipitation~~ over the Greater Himalayas within the UIB, though most of such precipitation changes are statistically insignificant. By analyzing temperature record ~~only~~for the period 1952-2009, Río et al. (2013) also reported dominant warming during March and pre-monsoonal period~~ instead during the winter season~~, consistent with findings of Sheikh et al. (2009).

~~The analysis from~~ The above mentioned studies ~~are mostly based upon~~have analyzed observations from only a sub-set of half dozen manual, valley-bottom, low-altitude stations being maintained by Pakistan Meteorological Department (PMD~~—~~) within the UIB (Hasson et al., ~~2015~~2014b). Contrary to these low-altitude stations, ~~stations at~~ observations from high altitude stations in South Asia mostly feature opposite ~~signs~~sign of climatic ~~change~~changes and extremes, possibly influenced by the local factors (Revadekar et al., 2013). Moreover, the bulk of the UIB ~~stream flow is contributed~~streamflow originates from the active hydrologic ~~altitudinal range~~zone (2500-5500 m asl~~)~~), when thawing temperatures migrate over and above 2500 m asl (SIHP, 1997). In view of such a large altitudinal dependency of the ~~climate~~climatic signals, data from low-altitude stations, though extending back into the first half of 20th century, are not optimally representative of the hydro-meteorological conditions prevailing over the UIB frozen water resources (SIHP, 1997). Thus, ~~the~~an assessment of ~~the~~ climatic trends over the UIB has been much restricted by ~~the~~ limited availability of~~ the~~ high-altitude and most representative observations as well as their accessibility, so far.

Amid above mentioned studies, Archer and Fowler (2004), Fowler and Archer (2006) and Sheikh et al. (2009) have used linear least square method for trend analysis. Though such parametric tests more robustly assess the existence of a trend as compared to ~~the~~ non-parametric trend tests (Zhai et al., 2005), they need the sample data to be normally distributed, which is not always the case for ~~the~~ hydro-meteorological observations (Hess et al., 2001; Khattak et al., 2011). In this regard a non-parametric test, such as, Mann Kendall (MK - Mann, 1945; Kendall, 1975) ~~test~~ is a pragmatic choice, which has been extensively adopted for the hydro-climatic trend analysis (Kumar et al., 2009 and 2013). The above mentioned studies of Khattak et al. (2011), Río et al. (2013) and Bocchiola and Diolaiuti (2013) have used ~~the non-parametric~~ MK test in order to confirm the existence of a trend along with Theil-Sen (TS - Theil, 1950; Sen, 1968) slope method to estimate true slope of a trend.

Most of the hydro-climatic time series contain ~~a~~ red noise because of the characteristics of~~ the~~ natural climate variability, and thus, are not serially independent (Zhang et al., 2000; Yue et al., 2002 & 2003; Wang et al., 2008). On the other hand, ~~the~~ MK ~~statistic~~statistics is highly sensitive to serial dependence of a time series (Yue and Wang, 2002; Yue et al., 2002 & 2003; Khattak et al., 2011). For instance, the variance of ~~the~~ MK statistic *S* increases (decreases) with the magnitude of ~~a~~ significant positive (negative) auto-correlation of ~~the~~a time series, which leads to an overestimation (underestimation) of ~~a~~ trend detection probability (Douglas et al., 2000; Yue et al., 2002 and 2003; Wu et al., ~~2007~~2008; Rivard and Vigneault, 2009). To eliminate such ~~affect~~an effect, von Storch (1995) and Kulkarni and von Storch (1995) proposed a pre-whitening procedure that suggests the removal of a lag-1 auto-correlation prior to applying the MK-test. Río et al. (2013) have analyzed ~~the~~ trends using ~~a~~ pre-whitened (serially independent) time series. This procedure, however, is particularly inefficient when a time series features a trend or it is serially dependent negatively (Rivard and Vigneault, 2009). In fact, presence of a trend can lead to ~~the~~ false detection of ~~a~~ significant positive (negative) auto-correlation in a time series (Rivard and Vigneault, 2009), removing which through ~~the~~ pre-whitening procedure may remove (inflate) the portion of a trend, leading to an underestimation (overestimation) of ~~the~~ trend detection probability and ~~the~~ trend magnitude (Yue and Wang, 2002; Yue et al., 2003). In order to address this problem, Yue et al. (2002) have proposed a modified pre-whitening procedure, which is called trend free pre-whitening (TFPW). In ~~this method~~TFPW, a trend component is separated before the pre-whitening procedure is applied, and after the pre-whitening procedure, the resultant time series is blended together with the pre-identified trend component for further application of the MK ~~-~~test. Khattak et al. (2011) have applied TFPW ~~procedure~~ to make time series serially independent before trends analysis. The TFPW method takes an advantage of the fact that estimating auto-correlation coefficient from a detrended time series yields its more accurate magnitude for the pre-whitening procedure (Yue et al., 2002). However, prior estimation of a trend may also be influenced by the presence of a serial correlation in a time series in a similar way the presence of a trend contaminates ~~the~~ estimates of an auto-correlation coefficient (Zhang et al., 2000). It is, therefore, desirable to estimate most accurate magnitudes of both, trend and auto-correlation coefficient, in order to avoid the influence of one on the other.

The UIB observes contrasting hydro-meteo-cryospheric regimes mainly because of the complex ~~terrain of the~~ HKH ~~ranges~~terrain and sophisticated interaction of prevailing regional circulations (Hasson et al., 2014a and ~~2015~~2015a). The sparse (high and low altitude) meteorological network in such a difficult area neither covers fully its vertical nor its horizontal ~~extents~~extent - it may also be highly influenced by ~~the~~ complex terrain features and variability of ~~the~~ meteorological events. Under such scenario, tendencies ascertained from the observations at local sites further need to be assessed for their field significance. ~~This will yield~~The field significance indicates whether the stations within a particular region collectively exhibit a significant trend or not, irrespective of the significance of 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 conflicting climate change will have on the overall hydrology of the UIB and of its sub-regions. However, similar to ~~the~~ sequentially dependent local time series, ~~the~~ spatial-/cross-correlation amid ~~the~~ station network within 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 ~~significance of local~~significant trends (Yue et al., 2003; Lacombe and McCarteny, 2014). Such effect of cross/spatial correlation ~~of a~~amid station network should be eliminated while testing the field significance ~~of local trends~~ as proposed by several studies (Douglas et al., 2000; Yue and Wang, 2002; Yue et al., 2003)

In this study, we present a first comprehensive and systematic hydro-climatic trend analysis for the UIB based upon ~~updated dataset from~~ ten stream flow ~~and~~, six low altitude ~~meteorological stations studied earlier, and by including for the first time, observations from~~ manual and 12 high-altitude automatic weather stations ~~from the HKH ranges within the UIB.~~. We apply a widely used non-parametric MK trend test over ~~the~~ serially independent time series, obtained through a pre-whitening procedure, for ensuring the existence of a trend ~~where~~. The true slope of an existing trend is estimated by the Sen's slope method. In pre-whitening, we remove ~~the~~ negative/positive lag-1 autocorrelation that is optimally estimated through an iterative procedure, ~~thus, the~~so that, pre-whitened time series ~~features~~feature the same trend as of ~~the~~ original time series. Here, we investigate ~~the~~ climatic trends on monthly time scale in addition to seasonal and annual time scales, first in order to present a more comprehensive picture and secondly to circumvent the loss of intra-seasonal tendencies due to an averaging effect. ~~In view of the contrasting hydrological regimes of UIB due to its complex terrain, highly concentrated cryosphere and the form, magnitude and seasonality of moisture input associated with two distinct modes of prevailing large scale circulation; westerly disturbances and summer monsoon, we decided to investigate in detail~~For assessing the field significance of ~~the~~ local ~~scale~~ climatic trends~~. In such regards~~, we divide the ~~whole~~

UIB into ten regions, considering its diverse hydrologic regimes, HKH topographic divides and installed hydrometric station network. Such regions are Astore, Hindukush (Gilgit), western-Karakoram (Hunza), Himalaya, Karakoram, UIB-Central, UIB-West, UIB-West-lower, UIB-West-upper and the UIB itself~~.~~ (Figs. 1-2). Provided particular region abodes more than one meteorological station, individual climatic trends within ~~the~~that region were tested for their field significance based upon the number of positive/negative significant trends (Yue et al., 2003). Field significant trends are in turn compared qualitatively with ~~the~~ trends of outlet discharge from the corresponding regions, in order to furnish physical attribution to statistically identified regional signal of change. Our results, presenting prevailing state of the hydro-climatic trends over the HKH region within the UIB, contribute to the hydroclimatic explanation of the ‘Karakoram Anomaly’, provide right direction for the impact assessment and modelling studies, and serve as an important knowledge base for the water resource managers and policy makers in the region.

2 Upper Indus basin ~~and its sub-basins~~

The UIB is a unique region featuring ~~a~~ complex HKH terrain, distinct physio-geographical features, conflicting signals of climate change and subsequently contrasting hydrological regimes~~.~~ (Archer, 2003; Fowler and Archer, 2006; Hasson et al., 2013). The basin extending from the western Tibetan Plateau in the east to the eastern Hindu Kush Range in the west~~,~~ hosts mainly the Karakoram Range in the north, and western Himalayan massif (Greater Himalaya) in the south (Fig. ~~1). It is a transboundary basin, sharing borders with Afghanistan~~1). As summarized in ~~the west, China in the north and India in the east.~~ Reggianni and Rientjes (2014) and Khan et al. (2014), the total drainage area of the UIB has long been overestimated by various studies (e.g. Immerzeel et al., ~~Young and Hewitt, 1988; Alford, 2011; Sharif et al., 2013; Hasson et al., 2014a) - owing to an automated basin~~ 2009; Tahir, 2011; Bookhagen and Burbank, 2010). Such overestimation is caused by limitations of the GIS-based automated watershed-delineation procedure ~~based on remotely sensed elevation datasets - featuring a large offset~~ that results in erroneous inclusion of the Pangong Tso watershed (Khan et al., 2014), which instead is a closed basin (Huntington, 1906; Brown et al., 2003, Alford, 2011). Khan et al. (2014) have provided details about the delineation of the UIB based upon ASTER GDEM 30m and SRTM 90m DEMs. For this study, the UIB drainage area is estimated from the ~~original estimates reported by the Surface Water~~

~~Hydrology Project (SWHP) of the Water and Power Development Authority (WAPDA), Pakistan, that maintains the basin. Here, we have precisely calculated the area of UIB at Besham Qila from the gap-filled 90~~ lately available 30 meter ~~shuttle radar topographic mission (SRTM) digital elevation model (DEM). For this we have first calculated~~ version of the ~~basin~~ SRTM DEM, which was forced to exclude the area ~~using an~~connecting the UIB to the Pangong Tso watershed in order to avoid its erroneous inclusion by the applied automated ~~watershed~~ delineation procedure. ~~We have then excluded the adjoining closed-basin areas, for instance, Pangong Tso basin (Khan et al., 2014).~~Details of the delineation procedure will be provided elsewhere. Our estimated area of the UIB at Besham Qila is around ~~163,528~~165515 km^2, which is~~, so far, in best agreement~~ to a good approximation consistent with the actual ~~area surveyed and~~estimates of 162393 km^2 as reported by the SWHP, WAPDA ~~i.e. 162,393 km2.~~. According to the newly delineated basin boundary, the UIB is located within the geographical range of 31-37^o E and 72-82^o N~~, hosting three gigantic massifs, such as, the Karakoram (trans-Himalaya), eastern part of the Hindukush and western part of the Greater Himalaya. A remarkable diversity of the hydro-climatic configurations in UIB is predominantly determined by complex orography of these HKH ranges and the geophysical features, such as presence of frozen water reservoirs. Based on the Randolph Glacier Inventory version 4.0 (RGI4.0 - Pfeffer et al., 2014), these ranges collectively host around 11,000 glaciers, with the Karakoram Range hosting the largest portion. The total area under glaciers and permanent ice cover is around 18,500 km^2, which is more than 11% of the total surface area of the basin.~~. Around 46 % of the UIB falls within the political boundary of Pakistan, containing around 60 % of the permanent cryospheric extent. ~~The~~Based on the Randolph Glacier Inventory version 5.0 (RGI5.0 - Arendt et al., 2015), around 12% of the UIB area (19,370 km^2) is under the glacier cover. While snow ~~coverage within the UIB~~cover ranges from 3 to 67% of the ~~total~~basin area (Hasson et al., 2014b). ~~.~~

The hydrology of the UIB is dominated by ~~the~~ precipitation regime associated with the mid-latitude western disturbances. These western disturbances are ~~the~~ lower-tropospheric extra-tropical cyclones, which are originated and/or reinforced over the Atlantic Ocean or the Mediterranean and Caspian Seas and transported over the UIB by the southern flank of the Atlantic and Mediterranean storm tracks (Hodges et al., 2003; Bengtsson et al., 2006). The western disturbances intermittently transport moisture over the UIB mainly in solid form throughout the year, though their main contribution comes during winter and spring (Wake, 1989; Rees and Collins, 2006; Ali et al., 2009; Hewitt, 2011; Ridley et al., 2013; Hasson et al., 2013 & ~~2015~~2015a). Such contributions are anomalously higher during~~ the~~ positive phase of the north Atlantic oscillation (NAO), when southern flank of the western disturbances intensifies over Iran and Afghanistan because of ~~the ~~heat low there, causing additional moisture input to the region from the Arabian Sea (Syed et al., 2006). Similar positive precipitation anomaly is evident during ~~the ~~warm phase of the El Niño–Southern Oscillation (ENSO - Shaman and Tziperman, 2005; Syed et al., 2006). In addition to westerly precipitation, the UIB also receives contribution from the summer monsoonal offshoots, which crossing ~~the ~~main barrier of the Greater Himalayas (Wake, 1989; Ali et al., 2009; Hasson et al., ~~2015~~2015a), precipitate moisture over higher (lower) altitudes in~~ the~~ solid (liquid) form (Archer and Fowler, 2004). Such occasional incursions of the monsoonal system and the dominating westerly disturbances, largely controlled by the complex HKH terrain, define ~~the ~~contrasting hydro-climatic regimes within the UIB. ~~For the mean annual precipitation, Hasson et al. (2014b) has recently provided a most comprehensive picture of the moisture input to the HKH region within the northern Indus Basin from 36 low-/high-altitude stations, up to an elevation of 4500 m asl. According to their estimates, ~~Mean annual precipitation within the UIB ranges from less than ~~50~~150 mm at Gilgit station to ~~above 1000 mm at Skardu station. Within the Karakoram Range, mean annual precipitation ranges between 200 to~~around 700 mm at ~~Khunjrab and ~~Naltar ~~stations; within the western Himalayas it ranges from 150 to above 1000 mm at Astore and Skardu stations; and within the Hindukush from less~~station. Lately, addressing precipitation uncertainty over the whole UIB, Immerzeel et al. (2015) have suggested the amount of precipitation more than ~~50 to 400 mm at Gilgit and Ushkore stations, respectively.~~twice as previously thought. The glaciological studies ~~however~~also suggest substantially large amount of snow accumulation that account for 1200-1800 mm (Winiger et al., 2005) in Bagrot valley and above 1000 mm over the Batura Glacier (Batura Investigation Group, 1979) within the western Karakoram, and more than 1000 mm and, at few sites above 2000 mm over the Biafo and Hispar glaciers (Wake, 1987) within the central Karakoram.

~~Within the UIB, ~~The Indus River and its tributaries are gauged at ten key locations~~, rationally~~ within the UIB, dividing it into ~~various sub-basins namely ~~Astore, Gilgit, Hunza, Shigar and Shyok sub-basins (Fig. 2). These basins feature distinct hydrological regimes~~, which are linked with the main source~~ (snow- and glacier~~) of their melt-water generation and can be differentiated by its strong correlation with the climatic variables. For instance,~~-fed). Previous studies (Archer 2003; ~~Fowler~~Mukhopadhyay and ~~Archer, 2006~~Khan, 2015) have separated the snow-fed (glacier-fed) sub-basins of the UIB on the basis of their; 1) smaller (larger) glacier coverage and, 2) strong runoff correlation with previous winter precipitation (concurrent temperatures) from low altitude stations., and, 3) using hydrograph separation technique. Based on such division, Astore (within the western Himalayan Range) and Gilgit (within the eastern Hindukush Range) basins are considered as mainly the snow-fed basins while the Hunza, Shigar and Shyok (within the Karakoram Range) are considered as mainly glacier-fed basins. Since the low-altitude stations do not measure snowfall, such correlation analysis is actually based on winter rainfall, which is not a dominant source of moisture input to the UIB. In fact, unravelling the contrasting hydrological regimes that feature distinct source of melt-water is quite straight forward based on the timing of maximum runoff production (Sharif et al., 2013). Nevertheless,sub-basins. The strong influence of the climatic variables on the generated runoff within and from the UIB suggests vulnerability of spatio-temporal water availability to climate change.climatic changes. This is why the UIB discharge features high variability -– the maximum mean annual discharge is around an order of magnitude higher than its minimum mean annual discharge, in extreme cases. The Mean annual discharge from the UIB is around 2400 m^3s^{-1}, which contributes to around 45 % of the total surface water availability within Pakistan. Since the UIB discharge contribution mainly comes from the is dominated by snow and glacier melt thus, it concentrates mainly within the melt season (April – September). During the rest of year, melting temperatures remain mostly below the active hydrologic elevation range, resulting in minute melt runoff (Archer, 2004). The characteristics of the UIB and its sub-basins are summarized in Table 1. Here, we briefly discuss the sub-basins of UIB.

The Shyok sub-basin located between 33.5-35.7° E and 75.8-79.8° N in eastern part of the Karakoram Range constitutes the eastern UIB. The drainage area of Shyok basin has long been overestimated by number of studies, which in fact lead to overestimation of UIB drainage area. This has serious implications for studies, particularly those modelling impacts of climate change on water availability in absolute terms (Immerzeel et al., 2009). According to our updated estimates, which are in best agreement with the SWHP, WAPDA, its drainage area is around 33,000 km^2. Based on such drainage estimate, the basin elevation range, derived from gap-filled 90 meter SRTM DEM, is 2389-7673 m asl. Based on RGI4.0 (Pfeffer et al., 2014), approximately 24% of the basin area is under the glacier and permanent ice cover, hosting around 42 % of the total glacier cover within the UIB. Westerly disturbances are mainly responsible for moisture input to the Shyok basin; however one third of the solid moisture input comes from the summer monsoon system (Wake, 1989). Mean annual precipitation from the only available high-altitude station Hushe is around 500 mm. The mean annual discharge contribution of 360 m^3s^{-1} is mainly constituted from the snow and glacier melt, which contributes around 15 % to the UIB discharge.

The Shigar sub-basin lies within the central Karakoram Range, coordinated between 74.8-76.8◦ E and 35.2-36.2◦ N. Its elevation range is 2189-8448 m asl. Around one third of the basin area lies above 5000 m asl. The basin area is around 7000 km^2, of which around one third is covered by glaciers, including some of those among the largest in the world. The basin receives its main moisture from the westerly disturbances during the winter and spring season in solid form, however, occasional summer monsoonal incursions drop moisture to the upper reaches and influence the overall hydroclimatology of the basin. The mean annual precipitation input ranges between 450 mm at Shigar high-altitude station to above 1000 mm at nearby low-altitude Skardu station. Representing only the basin below 2400 m asl, these precipitation amounts are quite small compared to those reported by the glaciological studies. The snow cover ranges between 25±8 and 90±3% (Hasson et al., 2014b). The discharge from the Shigar basin mainly comprises of slow runoff (snow and glacier melt runoff) and is estimated to be around 200 m^3s^{-1}, which is around 9 % of the mean annual discharge at UIB Besham Qila.

The Gilgit sub-basin (between 35.8-37^o E and 72.5-74.4^o N) encompasses eastern part of the Hindukush Range and drains southeastward into the Indus River. Gilgit River is measured at Gilgit hydrometric station, right after which the Hunza River confluence with the Gilgit River at Alam Bridge. The drainage area of the basin corresponds to more than 12000 km^2 with an elevation range of 1481-7134 m asl. Around 7 % of the basin area is under glacier and permanent ice cover, accounting for 4% of the UIB cryospheric extent. The Gilgit basin receives its precipitation from both westerly disturbances and summer monsoon system, which amounts less than 50 mm at Gilgit station to more than 350 mm at Ushkore station (Hasson et al., 2014b). Snow cover in the basin ranges between 3±1 and 90±4% (Hasson et al., 2014b). Discharge mainly depends upon the snowmelt, followed by the glacier melt and rainfall. Mean annual discharge out of Gilgit basin is around 300 m^3s^{-1}, which contributes around 12% to the UIB mean annual discharge.

The Hunza sub-basin abodes mainly the western part of the Karakoram Range and covers an area of 13734 km^2. It also includes area of east and southeastward draining Hindukush massifs. It is located within the coordinates 35.9-37.2° E and 74-75.8° N. The elevation range of basin is 1420-7809 m asl where one third of the basin lies above 5000 m asl, alike Shigar basin. Around 28 % of its total surface area is covered by glacier and permanent ice (Pfeffer et al., 2014), which is almost 21% of the permanent cryospheric extent of UIB. Mean snow cover ranges from *17*±6 to 83±4 % of the total basin area during the period 2001-2012 (Hasson et al., 2014b). Mean annual moisture input ranges from 200 at Khunjrab station to 700 mm at Naltar station during the period 1995-2012 (Hasson et al., 2014b). The mean annual discharge for the period 1966-2010 is 330 m^3s^{-1}, which contributes approximately 14% to the mean annual discharge of UIB at Besham Qila.

The Astore sub-basin, lying within the southern foothills of western Himalayan extremity, is the only north-facing gauged basin within the UIB, located between 34.7-35.6° E and 74.3-75.3° N. It has a drainage area of around 3900 km^2 with an elevation range of 1504-8069 m asl, where only a small area lies above 5000 m asl. Almost 14% of the total basin area is covered by permanent ice and glaciers, aboding only 3% of the total within the UIB. Snow cover within the basin ranges from 2±1 to 98±1% (Hasson et al., 2014b). The hydrology of Astore basin is mainly influenced by the westerly solid moisture input, however the basin receives one third of its annual precipitation under the summer monsoon system (Farhan et al., 2014). Mean annual precipitation within the Astore basin ranges from around 140 mm at the rainfall-only low-altitude Astore station to above 800 mm at high altitude Ramma station (Hasson et al., 2014b). The mean annual runoff from Astore basin measured at Dainyor site is around 140 m^3s^{-1}, which contributes around 6% of the mean annual discharge at UIB Besham Qila.

3 Data

3.1 Meteorological data

The network of meteorological stations within the UIB is very sparse and mainly limited to within Pakistan's political boundaryboundaries, where around 20 meteorological stations are being operated by three different data collection organizations. The first network, being operated by PMD, consists of six manual valley-based stations that provide the only long-term data series, generally starting from first half of the 20th century. However, data before 1960 are scarce and feature large data gaps (Sheikh et al., 2009). Such dataset covers a north-south extent of around 100 km from Gupis to Astore station and east-west extent of around 200 km from Skardu to Gupis station. The altitudinal range of These stations is limited to 1200-2200 m asl only and merelylie within the western Himalaya and Hindu KushHindukush ranges. and between the altitudinal range of 1200-2200 m asl, whereas most of the ice reserves of the Indus Basin lie within the Karakoram range (Hewitt, 2011) and above 2200 m asl (Fig. 1). In view of the fact that bulk contribution to the UIB stream flow occurs from the active hydrologic altitudinal range of 2500-5500 m asl when thawing temperatures migrate above 2500 m asl (SIHP, 1997), the low altitude stations are not optimally representative of the hydro-meteorological conditions prevailing over the UIB cryosphere. The EvK2-CNR has installed two meteorological stations in the central Karakoram1). In the central Karakoram, EvK2-CNR has installed two meteorological stations at higher elevations, which however, provide time series only since 2005. Moreover, the precipitation gauges within PMD and EvK2CNREvK2-CNR networks measure only liquid precipitation, while the hydrology of the region is dominated by solid moisture inputmelt. The third meteorological network within the UIB consists of 12 high altitude automatic weather stations, called Data Collection Platforms (DCPs), which are being maintained by the Snow and Ice Hydrology Project (SIHP) of WAPDA. The DCP data is being observed at hourly intervals and is transferred onto the central SIHP office in Lahore on a real time basis through a Meteor-Burst communication system to the central SIHP office in Lahore. The data is subject to missing values due to rare technical problems, such as ‘sensor not working’ and/or ‘data not received from broadcasting system’. Featuring higher altitude range of 1479-4440 m asl, these DCP stations provide medium-length time series of meteorological observations since 1994/95. Contrary to lower altitude stationsPMD and EvK2-CNR, precipitation gauges at DCPs measure both liquid and solid precipitation in mm water equivalent (Hasson et al., 2014b). Moreover, DCPs cover relatively larger spatial extent, such as, north-south extent of 200 km from Deosai to Khunjrab stationstations and east-west extent of around 350 km from Hushe to Shendure stations. Thus, spreading well across the HKH ranges and covering most of the vertical extent of UIB frozen water resources and the active hydrologic altitudinal rangezone, DCPs seem to be well representative of the prevailing hydro-meteorological conditions over the UIB cryosphere, so far. We have collected the daily data for the temperature maximum, temperature and minimum temperatures (Tx and Tn, respectively) and precipitation of 12

~~DCP stations~~DCPs for the period 1995-2012 from SIHP, WAPDA~~.~~ (Table 2). We have also collected the updated record of six low altitude stations from PMD for same set of variables within the period 1961-2012. ~~Details of the collected meteorological observations are listed in Table 2.~~

3.2 Discharge data

The discharge data, being highly sensitive to variations in precipitation, evaporation, basin storage and prevailing thermal regime, ~~describes~~describe the overall hydrology and ~~the~~an integrated signal of hydrologic change for a particular watershed. In order to provide physical attribution to our statistically based field significant trend analysis, we have collected the discharge data from SWHP, WAPDA. The project maintains a network of hydrometric stations within ~~the~~ Pakistan ~~region~~. The upper Indus river flows are being measured first at Kharmong site where the Indus river enters into Pakistan ~~Territory~~ and then at various locations until it enters into the Tarbela reservoir. The river inflows measuring stations at Tarbela reservoir, and few kilometers above it, at the Besham Qila are usually considered to separate the upper part ~~of the Indus~~ (i.e. UIB) from the rest of Indus basin. ~~The hydrometric station network rationally apportions UIB into smaller units based upon distinct hydrological regimes and magnitude of runoff contributions. Almost~~ Five sub-basins are being gauged, ~~from~~among which Shigar gauge ~~is~~has not been operational ~~after~~since 2001. Since we take the UIB extent up to the Besham Qila site, we have collected full length of discharge data up to 2012 for all ten hydrometric stations within the UIB~~. Details of the collected discharge data are given in Table 3 in downstream order.~~ (Table 3). It is pertinent to mention here that discharge data from central and eastern parts of the UIB are hardly influenced by the anthropogenic perturbations. The western UIB is relatively populous and ~~stream flow~~streamflow is used for solo-seasoned crops and domestic use, however, the overall ~~contribution to~~water diversion for such a use is ~~still~~indeed negligible (Khattak et al., 2011).

4 Methods

Inhomogeneity in ~~climate~~a climatic time series is due to variations ~~in the record that can be~~ ascribed ~~to~~ purely to non-climatic factors (Conrad and Pollak, 1950), such as, changes in the station site, station exposure, observational ~~method~~methods, and measuring ~~instrument~~instruments (Heino, 1994; Peterson et al., 1998). Archer and Fowler (2004) and

Fowler and Archer (2005 and 2006) have documented that PMD and WAPDA follow standard meteorological measurement practice established in 1891 by the Indian Meteorological Department. Using double mass curve approach, they have found inhomogeneity in the winter minimum temperature around 1977 only at Bunji station among four low altitude stations analyzed. Since climatic patterns are highly influenced by orographic variations and local events within the study region of complex terrain, double mass curve techniques may yield limited skill. Forsythe et al. (2014) have reported~~ the~~ homogeneity of Gilgit, Skardu and Astore stations for annual mean temperature during the period 1961-1990 while Río et al. (2013) have reported ~~the ~~homogeneity for ~~the ~~temperature ~~record~~records from~~ the~~ Gilgit, Gupis, Chillas, Astore and Skardu stations during 1952-2009. Some studies (Khattak et al., 2011; Bocchiola and Diolaiuti, 2013) do not report ~~the ~~quality control or homogeneity of the data used for their analysis.

We have first investigated~~ the~~ internal consistency of the data by closely following Klein Tank et al. (2009) such as situations of below zero precipitation and when maximum temperature was lower than minimum temperature, which found in few were then corrected. Afterwards, we have performed homogeneity ~~test~~tests using a standardized toolkit RH-TestV3 (Wang and Feng, 2009) that uses a penalized maximal F-test (Wang et al., 2008) to identify any number of change points in a time series. As no station has yet been reported homogenous at monthly time scale for all variables, ~~and that stations observe large Euclidean distance in a highly complex terrain, we were restricted to perform only a relative homogeneity test, without using a reference time series. We have tested the homogeneity for the monthly mean maximum and minimum temperatures and monthly total precipitation~~only a relative homogeneity test is performed by adopting a most conservative threshold level of 99% for statistical significance. We have found mostly one inhomogeneity in only Tn for the low altitude PMD stations during the period of record, except for ~~the ~~Skardu station (Table 2). ~~Within~~For the 1995-2012 period, such ~~homogeneity~~inhomogeneity in Tn is only valid for Gilgit and Gupis stations. On the other hand, data from DCP stations were found of high quality and homogenous. Only Naltar station has experienced inhomogeneity in Tn during September 2010, which was most probably caused by heavy precipitation event resulted in a mega flood in Pakistan (Houze et al., 2011; Ahmad et al., 2012; Hasson et al., 2013) followed by similar events during 2011 and 2012. Since the history files were not available, we were not sure that any statistically found inhomogeneity ~~in ~~only in Tn is real. Therefore, we did not apply any correction to ~~the data~~inhomogeneous time series and caution the careful interpretation of results based on such time series.

4.1 Hydroclimatic trend analysis

We have analyzed ~~trend~~trends in~~ the~~ minimum, maximum and mean temperatures (Tn, Tx and Tavg, respectively), diurnal temperature range (DTR – Tx - Tn), precipitation and discharge on monthly to annual time scales. ~~For this, we used a widely applied nonparametric~~The MK ~~statistical ~~test (Mann, 1945; Kendall, 1975) is applied to assess the existence of a trend ~~along with~~while the Theil-Sen (TS - Theil, 1950; Sen, 1968) slope method is applied to estimate true slope of ~~an existing~~a trend. For sake of intercomparison between low and high altitude stations, we mainly analyze overlapping length of record ~~from the two datasets (i.e. (~~1995-2012~~). However, we~~) from high and low altitude stations, and additionally~~ analyze~~, the full length of record (1961-2012) from low altitude stations.

Mann-Kendall test

The MK is a ranked based method that tests the significance of an existing trend irrespective of the type of ~~the ~~sample data distribution and whether such trend is linear or not (Yue et al., 2002; Wu et al., ~~2007~~2008; Tabari, H., and Talaee, 2011). Such test is also insensitive to the data outliers and missing values (Khattak et al., 2011; Bocchiola and Diolaiuti, 2013) and less sensitive to the breaks caused by inhomogeneous time series (Jaagus, 2006). The null hypothesis of the MK test states that ~~a~~the sample data $\{X_i, i = 1,2,3 \ldots n\}$ is independent and identically distributed, while ~~the ~~alternative hypothesis suggests the existence of a monotonic trend. The MK statistics *S* are estimated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \qquad (1)$$

Where X_j denotes the sequential data, n denotes the data length, and

$$sgn(\theta) = \begin{cases} 1 & if\ \theta > 0 \\ 0 & if\ \theta = 0 \\ -1 & if\ \theta < 0 \end{cases} \qquad (2)$$

provided n ≥ 10, *S* statistics are approximately normally distributed with the mean, *E*, and variance, *V*, (Mann, 1945; Kendall, 1975) as follows:

$$E(S) = 0 \qquad (3)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{m=1}^{n} t_m m(m-1)(2m+5)}{18} \qquad (4)$$

Here, t_m denotes the number of ties of extent *m*, where tie refers to $\mathrm{X_j} = \mathrm{X_i}$. The standardized MK statistics, Z_s, can be computed as follows:

$$Z_s = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & S < 0 \end{cases} \qquad (5)$$

The null hypothesis of no trend is rejected at a specified significance level, α, if $|Z_s| \geq Z_{\alpha/2}$, where $Z_{\alpha/2}$ refers to a critical value of standard normal distribution with a probability of exceedance $\alpha/2$. The positive sign of Z shows an increasing while its negative sign shows a decreasing trend. We have reported the statistical significance of identified trends at ~~10, 5~~90, 95 and ~~1~~99% levels by taking α as 0.1, 0.05 and 0.01, respectively.

Theil-Sen's slope estimation

Provided ~~the~~that a time series features a trend, ~~such trend~~it can be roughly approximated by a linear regression as

$$Y_t = a + \beta t + \gamma_t \qquad (6)$$

Where a is the intercept, β is ~~a~~the slope and γ_t is a noise process. Such estimates of β obtained through ~~a~~ least square method are prone to gross errors and ~~the~~ respective confidence intervals are sensitive to the type of parent distribution (Sen, 1968). We, therefore, have used ~~the~~ Theil–Sen approach (TS - Theil, 1950; Sen, 1968) for estimating the true slope of ~~the~~ existing trend as follows

$$\beta = Median\left(\frac{X_j - X_i}{j-i}\right), \forall\, i < j \qquad (7)$$

The magnitude of β refers to ~~a~~ mean change ~~in~~of a ~~considered~~ variable over the investigated time period, while a positive (negative) sign implies an increasing (decreasing) trend.

Trend-perceptive pre-whitening (TPPW)

~~In order~~ To pre-whiten the time series ~~for serial dependence~~, we have used an approach of von Storch (1995) as modified by Zhang et al (2000). ~~In~~ This approach~~, one~~ iteratively computes ~~the~~ trend and lag-1 auto-correlation ~~of a time series~~ until the solution converges to their most accurate estimates ~~of a trend magnitude and autocorrelation – an absolute difference between the estimates from two consecutive iterations becomes negligible.~~. This approach assumes that the trend ~~(T_t) in Eqn. 8~~ can be approximated as linear (~~$T_t = \beta.t$).~~ ~~Moreover, one assumes that~~Eqn. 6) and the noise, γ_t, can be represented as a pth order auto-regressive process, AR(p) of the signal itself, plus the white noise, ε_t.

~~$Y_t = a + T_t + \gamma_t$ (8)~~

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, yields Eqn. ~~8~~6 into:

$$Y_t = a + \beta t + rY_{t-1} + \varepsilon_t \qquad (~~9~~8)$$

The iterative pre-whitening procedure consists of the following steps:

1. In ~~the~~ first iteration, estimate of lag-1 autocorrelation, r_1 is computed on the original time series, Y_t.
2. Using r_1 as $(Y_t - r.Y_{t-1})\,/(1-r)$, an intermediately pre-whitened time series, $\acute{Y}_t$, is obtained on which first estimate of a trend, β_1 along with its significance is computed using TS (Theil, 1950; Sen, 1968) and MK (Mann, 1945; Kendall, 1975) methods.
3. The original time series, Y_t, is detrended using $\beta_1$as $(\widehat{Y}_t = Y_t - \beta_1 t)$.
4. In ~~the~~ second iteration, more accurate estimate of lag-1 autocorrelation r_2 is estimated on ~~a~~ detrended time series, $\widehat{Y}_t$, obtained ~~in a~~from previous iteration.
5. The original time series Y_t, is again intermediately pre-whitened and $\acute{Y}_t$ is obtained.
6. The trend estimate β_2 is then computed on $\acute{Y}_t$ and the original time series, Y_t is detrended again, yielding $\hat{Y}_t$.

The procedure has to be reiterated until r is no longer significantly different from zero or the absolute difference between the estimates of r, β obtained from the two consecutive iterations becomes less than one percent. If any of the condition is met, let's suppose at the iteration n, estimates from the previous iteration (i.e. $r = r_{n-1}, \beta = \beta_{n-1}$) are taken as final. Using these final estimates, Eqn. ~~10~~9 yields a ~~final~~ pre-whitened time series, Y_t^w, which is serially independent and features ~~a~~the same trend as of ~~the~~ original time series, Y_t (Zhang et al., 2000; Wang and Swail, 2001). Finally, the MK-test is applied over the pre-whitened time series, Y_t^w, to identify existence of a trend.

$$Y_t^w = \frac{(Y_t - r.Y_{t-1})}{(1-r)} = \hat{a} + \beta t + \epsilon_t \text{, where } \hat{a} = a + \frac{r.\beta}{(1-r)} \text{, and } \epsilon_t = \frac{\varepsilon_t}{(1-r)} \qquad (~~10~~9)$$

4.2 Field significance ~~of local trends~~and physical attribution

~~The~~ Field significance indicates ~~that whether the~~when stations within a particular region collectively exhibit a ~~regional~~ significant trend, irrespective of ~~either their~~ the significance of individual trends ~~were significant or not~~ (Vogel and Kroll, 1989; Lacombe ~~et al., 2013).~~and McCarteny, 2014). For assessing the field significance of local trends, we have divided the whole UIB into further smaller units/regions based on: 1) distinct hydrological regimes identified within the UIB~~; 2~~, 2) mountain massifs, and, 3) available installed stream flow network~~, and; 3) hosted mountain massifs. We have considered the whole Karakoram Range as an area within the natural boundaries of the Hunza, Shigar and Shyok basins, which we then considered as western, central and eastern Karakoram regions, respectively (Fig. 2). Similarly, we have considered the basin area up to Indus at Kharmong as UIB-East, area of Shigar and Shyok basins jointly as UIB-Central, and rest of the UIB area as UIB-West (Fig. 2). We have further divided the UIB-West region into its upper and lower parts, keeping in view relatively large number of stations and distinct hydrological regimes, which have been identified, based on timings of their maximum runoff production, by comparing median hydrographs from each steam flow gauging station. According to such division~~. ~~UIB-West-lower and Gilgit are mainly snow-fed basins while Hunza is mainly glacier-fed basin (Fig. 3). Since most of the Gilgit basin area lies at Hindukush massifs, we call it Hindukush region. Additionally, combined area of lower part of UIB-West and UIB-east is mainly the northward slope of the Greater Himalaya, so we call this combined region as Himalaya. Thus, apart from the gauged basins of Astore, Gilgit, Hunza, Shigar and Shyok, Indus at Kharmong (UIB-East), and UIB itself, we have obtained the regions of Karakoram, Himalaya, UIB-Central, UIB-West, UIB-West-lower and UIB-West-upper, for which discharge was derived from installed gauges.~~

As mentioned earlier, Shigar discharge time series ~~was~~is limited to 1985-2001 period since afterwards the gauge went non-operational. In order to analyze discharge trend from such an important region, Mukhopadhyay ~~et al.~~and Khan (2014) have first correlated the Shigar discharge with discharge from its immediate downstream Kachura gauge for the overlapping period of record (1985-1998). Then, they have applied the estimated monthly correlation coefficients to the post-1998 discharge at Indus at Kachura. This particular method can yield the estimated Shigar discharge, of course assuming that the applied coefficients remain valid after the year 1998. However, in view of ~~the~~ large surface area of more than 113,000 km^2 for

Indus at Kachura and substantial changes expected in the hydroclimatic trends upstream Shigar gauge, the discharge estimated by Mukhopadhyay ~~et al.~~and Khan (2014)~~ merely~~ seems to be a constant fraction of the Kachura discharge, rather than the derived Shigar discharge. On the other hand, instead of estimating post-1998 discharge at the Shigar gauge, we have derived the ~~Shigar discharge by excluding~~discharge for the Shigar-region, comprising Shigar sub-basin itself plus the adjacent region shown blank in the Figure 2. This was achieved by subtracting the mean discharge rates of all gauges upstream Shigar gauge~~, which do not represent the Shigar basin,~~ from its immediate downstream Kachura gauge~~. Such subtraction of all upstream gauges from immediate downstream gauge was performed for~~ at each time step of every time scale analyzed~~ during the period of discharge estimation. Similar methodology has been adopted to derive discharge out of identified ungauged regions, based upon the installed stream flow gauges (Eqn. 11-13, Table 1). In this~~. The procedure~~, however, we assume~~ assumes that ~~regions~~the gauges far from each other ~~(UIB-east and UIB-West-lower)~~ have negligible routing time delay at a mean monthly time scale ~~– our shortest time scale analyzed –~~ and that such an approximation does not further influence the ascertained trends. ~~In other words, we derived the discharge for considered ungauged regions by assuming them in place, since our focus was to assess changes in the discharge contribution out of such regions rather than their influence on the UIB outlet discharge at certain time.~~Similar methodology has been adopted to derive discharge out of identified ungauged regions, such as, Karakoram, Himalaya, UIB-Central, UIB-West, UIB-West-lower and UIB-West-upper (Table 1).

We have considered the Karakoram region as the area of Hunza and Shyok sub-basins and Shigar-region, which are named as western, eastern and central Karakoram, respectively (Fig. 2). Similarly, we have considered drainage area of Indus at Kharmong as UIB-East while Shyok and Shigar-region together constitute UIB-Central. The rest of the UIB is considered as UIB-West (Fig. 2), which is further divided into upper and lower regions, keeping in view relatively large number of stations and distinct hydrological regimes. Such distinct regimes have been identified from the median hydrographs of each steam flow gauging station based on maximum runoff production timings. According to such division, UIB-West-lower and Gilgit are mainly snow-fed basins while Hunza is mainly glacier-fed basin (Fig. 3). Since most of the Gilgit basin area lies at Hindukush massifs, we call it Hindukush region. ~~$Q_{(Central-UIB)} = Q_{(Indus\ at\ Kachura)} - Q_{(Indus\ at\ Kharmong)}$ (11)~~

~~$Q_{(Western\text{-}UIB\text{-}L)} = Q_{(UIB)} - Q_{(Indus\ at\ Kachura)} - Q_{(Gilgit\ at\ Alam\ Bridge)}$ (12)~~

~~$Q_{(Western\text{-}UIB)} = Q_{(UIB)} - Q_{(Indus\ at\ Kachura)}$ (13)~~

The combined area of lower part of UIB-West and UIB-east is mainly the northward slope of the Greater Himalaya, so we call this region as Himalaya.

We have analysed the field significance for those regions that contain at least two or more stations. ~~In order~~ To eliminate the effect of cross/spatial correlation ~~of a~~amid station network on assessing the field significance of a particular region, Douglas et al. (2000) have proposed a bootstrap method. This method preserves the spatial correlation ~~within a~~amid station network but eliminates its influence on testing the field significance ~~of a trend~~ based on ~~the~~ MK ~~statistic~~statistics *S*. Similarly, Yue and Wang (2002) have proposed a regional average MK test in which they altered the variance of MK statistic by serial and cross correlations. Lately, Yue et al. (2003) proposed a variant of method proposed by Douglas et al. (2000), in which - instead of *S* - they considered counts of ~~the~~ significant ~~positive and negative~~ trends ~~- instead of the MK statistic *S* -~~ as representative variables for testing the field significance ~~of both positive and negative trends separately~~. This method favourably provides a measure of dominant field significant trend when local positive or negative significant trends are equal in number. Therefore, we have employed the method of Yue et al. (2003) for assessing the field significance. We have used a bootstrap approach (Efron, 1979) to resample the original network 1000 times in a way that the spatial correlation structure was preserved as described by Yue et al. (2003). We have counted both the number of local significant positive and number of significant negative trends, separately for each resampled network dataset using Eqn. ~~14~~10:

$$C_f = \sum_{i=1}^{n} C_i \qquad (~~14~~10)$$

Where n denotes total number of stations within a region and C_i denotes a count for statistically significant trend (at ~~10~~90% level) at station, i. Then, we have obtained the empirical cumulative distributions C_f for both counts of significant positive and counts of significant negative trends, by ranking their corresponding 1000 values in an ascending order using Eqn.~~15~~11:

$$P\left(C_f \leq C_f^r\right) = \frac{r}{N+1} \qquad (~~15~~11)$$

Where r is the rank of C_f^r and N denotes the total number of resampled network datasets. We have estimated probability of the number 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. 1612).

$$P_{obs} = P\left(C_{f,obs} \leq C_f^r\right), \ where \ P_f = \begin{cases} P_{obs} & for \ P_{obs} \leq 0.5 \\ 1 - P_{obs} & for \ P_{obs} > 0.5 \end{cases}$$

$$(16 \begin{cases} P_{obs} & for \ P_{obs} \leq 0.5 \\ 1 - P_{obs} & for \ P_{obs} > 0.5 \end{cases} \quad (12)$$

At the significance level of 10 %, If expression, $P_f \leq 0.1$, is satisfied the trend over a region is considered asto be field significant. at the 90 % level.

In addition to investigatingThe statistically theassessed field significance of tendencies in meteorological variables, we have provided is further validated against the physically-based evidence from the stream flow record. We have ascertained the trends in stream flow data (from installed and derived gauges) and For this, we have compared them with the field significant climatic signal, particularly the(mainly temperature) trend from the corresponding regions.of a region with its stream flow trends (from installed and derived gauges). The qualitative agreement between the two can serve better in understanding the ongoing state of climateclimatic changes over the UIB. Since the most downstream gauge of UIB at Besham Qila integrates the variability of all upstream gauges, it represents the dominant signal of change. Thus, an assessment of statistically based field significance was not required for the stream flow dataset.

We also assess the dependency of local hydroclimatic trends on their latitudinal, longitudinal and altitudinal distribution. Here we mention that We have intentionally avoided the interpolation of data and results in view of limitations of the interpolation techniques in a complex terrain of HKH region (Palazzi et al., 2013; Hasson et al., 20152015a). Large offset of glaciological reports from the station based estimates of precipitation (Hasson et al., 2014b) further suggests that hydro-climatic patterns are highly variable in space and that the interpolation of data will further add to uncertainty, resulting in misleading conclusions.

5 Results

~~First, ~~We present ~~the results of ~~our trend analysis ~~based upon a common length of record (i.e.~~ results for the 1995-2012~~) from PMD and DCP stations (Table~~ period in Tabular Figures 4 ~~and ~~-5~~, ~~(and for the select time scales, in Fig. ~~4). Then, we compare~~4) while for the ~~trends at low altitude stations over the period 1995-2012 with their long-term trends (~~1961-2012~~), in order to investigate any recent development of rate or sign of change in the climatic trends. Here we remind that, we call mainly six PMD stations (1200-2200 m asl) as low altitude stations and all the trends estimated over full length record as long-term trends (Table 6). Similarly, we call DCP stations from SIHP, WAPDA as high altitude stations (2200-4500 m asl). Within the 1995-2012~~ period~~, we also compare the results from low altitude stations against the findings from high altitude stations, in order to present their consistencies and variations. We show in Table 7,~~ in Tabular Figure 6. The field significant trends in climatic variables and trends in discharge from the corresponding regions are presented in Tabular Figure 7.

5.1 Hydroclimatic trends

Mean maximum temperature

For Tx, we find that certain set of months exhibit a common response of cooling and warming within the annual course of time. Set of these months interestingly are different than those typically considered for seasons, such as, DJF, MAM, JJA, SON for winter, spring, summer and autumn, respectively (Fowler and Archer, 2005 and 2006~~,~~; Khattak et al~~,~~., 2011; Bocchiola and Diolaiuti, 2013). For the months of December, January, February and April, stations show a mixed response of cooling and warming tendencies by roughly equal numbers where cooling trend for Rattu in January, for Shendure in February and for Ramma in April are statistically significant (~~Table~~Tabular Fig. 4 and Fig. ~~4~~8). Though no warming trend has been found to be statistically significant, all low altitude stations, except Gupis, exhibit a warming trend in the month of January. During months of March, May and November, most of the stations exhibit a warming trend, which is statistically significant at five stations (Gilgit, Yasin, Astore, Chillas and Gupis) and relatively higher in magnitude during March. Interestingly, warming tendencies during March are relatively higher in magnitude at low altitude stations as compared to high altitude stations. Most of the stations feature cooling tendencies during July-October (mainly the monsoon period). During such period, we find a statistically significant cooling at five stations (Dainyor, Shendure, Chillas, Gilgit and Skardu) in July, at two stations (Shendure and Gilgit) in August and at twelve stations (Hushe, Naltar, Ramma, Shendure, Ushkore, Yasin, Ziarat, Astore, Bunji, Chillas, Gilgit and Skardu) in September, while there is no significant cooling tendency in October (~~Table~~Tabular Fig. 4 and Fig. ~~4~~8). Such cooling is almost similar in magnitude from low and high altitude stations and dominates during month of September followed by July because of higher magnitude and statistical significance agreed among large number of stations. Overall, we note that cooling trends dominate over the warming trends. On a typical seasonal scale, ~~insignificant but intra-station agreed cooling in February is averaged out for the~~ winter season~~, which then~~ generally ~~show~~shows a mixed behavior (cooling/warming) where only two stations (Dainyor and Rattu) ~~show a~~suggest significant cooling. For the spring season, there is a high agreement for warming tendencies among the stations, which are significant only at Astore station. Again such warming tendencies during spring are relatively higher in magnitude than those at higher altitude stations. For summer and autumn~~ seasons~~, most of the stations feature cooling tendencies, which are significant for three stations (Ramma, Shendure and Shigar) in summer and for two stations (Gilgit and Skardu) in autumn. On annual time scale, high altitude stations within Astore basin (Ramma and Rattu) feature significant cooling trend.

While looking only at long term trends (~~Table~~Tabular Fig. 6), we note that summer cooling (warming outside summer) in Tx is less (more) prominent and insignificant (significant) at stations of relatively high (low) elevation, such as, Skardu, Gupis, Gilgit and Astore (Bunji and Chillas). The absence of a strong long-term winter warming contrasts with what found for the shorter period 1995-2012. In fact, strong warming is restricted to spring season mainly during March and May months. Similarly, long-term summer cooling period of June-October has been shortened to July-October.

Mean minimum temperature

The dominant feature of Tn is the robust winter warming in Tn during November-June, which is found for most of the stations (~~Table~~Tabular Fig. 4 and Fig. ~~4~~8). Contrary to warming in Tx, warming trend in Tn is higher in magnitude among the high altitude stations than among the low altitude stations. During the period of July-October, we found a significant cooling of Tn at four stations (Gilgit, Naltar, Shendure and Ziarat) in July, at eight stations (Hushe, Naltar, Ushkore, Yasin, Ziarat, Astore, Chillas and Gilgit) in September and only at Skardu in October. In August, stations show warming tendencies, which are relatively small in magnitude and only significant at Gilgit station. Similar to Tx, cooling in Tn during

July-October dominates during the month of September suggesting a relatively higher magnitude and larger number of significant trends (Fig. ~~4~~8). Also, such cooling features more or less similar magnitude of a trend among high and low altitude stations as for Tx. Similarly, cooling trends in Tn mostly dominate over the warming trends as in case of Tx. On a typical seasonal scale, winter and spring seasons feature warming trends, while summer season exhibit cooling trend and there is a mixed response for the autumn season. Warming trend dominates during the spring season. Here, we emphasize that a clear signal of significant cooling in September has been lost while averaging it into October and November months for autumn season. This is further notable from the annual time scale, on which a warming trend is generally dominated that is statistically significant at five stations (Deosai, Khunjrab, Yasin, Ziarat and Gilgit). The only significant cooling trend on annual time scale is observed at Skardu station.

While looking only at low altitude stations (~~Table~~Tabular Fig. 6), we note that long term non-summer warming (summer cooling) in Tn is less (more) prominent and insignificant (significant) at stations of relatively high (low) elevation, such as, Skardu, Gupis, Gilgit and Astore (Bunji and Chillas).

Mean temperature

Trends in Tavg are dominated by trends in Tx during July-October while these are dominated by Tn, during the rest of year (~~Table~~Tabular Figs. 4-5). Similar to Tx, the Tavg features a significant cooling in July at four stations (Dainyor, Naltar, Chillas and Skardu), in September at ten stations (Hushe, Naltar, Rama, Shendure, Ushkore, Yasin, Ziarat, Astore, Chillas and Skardu) and in October only at Skardu station (~~Table~~Tabular Fig. 5 and Fig. ~~4~~8). In contrast, we have observed a significant warming at Ziarat station in February, at five stations (Deosai, Dainyor, Yasin, Astore and Gupis) in March and at three stations (Khunjrab, Gilgit and Skardu) in November. However, the trend analysis on typical seasonal averages ~~suggest~~suggests warming of winter and spring seasons, which is higher in magnitude as compared to the observed cooling in summer and autumn seasons. This ~~particular~~specific fact has led to a dominant warming trend by most of the station at annual time scale, which is higher in magnitude at high altitude stations, mainly due to their dominated winter warming as compared to low altitude stations (Shrestha et al., 1999; Liu and Chen, 2000).

The long term trends generally suggest cooling tendencies during the July-October while warming for the rest of year. On seasonal scale, low altitude stations unanimously exhibit summer cooling over the long term record, which is mostly significant. A mixed response is shown for other time scales.

Diurnal temperature range

For the DTR, most of the stations show its drop throughout a year except during months of March and May, where particularly low altitude stations show its increase mainly due to higher warming in Tx than in Tn or higher cooling in Tn than in Tx (~~Table~~Tabular Fig. 4 and Fig. ~~4~~8). Two stations (Chillas and Skardu) show a significant widening of DTR in May, followed by Chillas station in March, Deosai in August and Gupis in October months. Conversely, we observe high inter-station agreement of significant DTR decrease in September followed by in February. Such a trend is associated with the higher magnitude of cooling in Tx than in Tn (e.g. in September), cooling in Tx but warming in Tn or higher warming in Tn than in Tx (e.g. in February). We note that long term trends of increasing DTR throughout a year from low altitude stations (~~Table~~Tabular Fig. 6) are now mainly restricted to the period March-May, and within the months of October and December over the period 1995-2012. Within the rest of year, DTR has been decreasing since last two decades. Overall, high altitude stations exhibit though less strong but a robust pattern of year round significant decrease in DTR as compared to low altitude stations.

Total precipitation

We find that most of the stations show a clear signal of dryness during the period March-June, which is either relatively higher or similar at high altitude station than at low altitude stations (Table 5 and Fig. 4). During such period, significant drying is revealed by seven stations (Deosai, Dainyor, Yasin, Astore, Chillas, Gupis and Khunjrab) in March, by five stations (Dainyor, Rattu, Astore, Bunji and Chillas) in April, by two stations (Dainyor and Rattu) in May and by four stations (Dainyor, Rama, Rattu and Shigar) in June. We have observed similar significant drying during August by three stations (Rattu, Shigar and Gupis) and during October by three stations (Rattu, Shendure and Yasin). The Rattu station features a consistent ~~drop in precipitation~~drying trend throughout a year except during the months of January and February where basically a neutral behavior is observed. Stations feature high agreement for an ~~increase in precipitation~~increasing trend during winter season (December to February) and during the month of September, where such increase is higher in magnitude at high altitude stations as compared to low altitude stations. We note that most of the stations within the UIB-West-upper region (monsoon dominated region) exhibit an ~~increase in~~

~~precipitation.~~increasing trend. Shendure, Yasin, Ziarat, Rattu, Shigar and Chillas are stations featuring significant ~~increase in precipitation~~increasing trend in either all or at least in one of the monsoon months. Such precise response of ~~increase~~increasing or ~~decrease in precipitation~~decreasing trend at monthly scale is averaged out on a seasonal time scale, on which autumn and winter seasons show an increase while spring and summer seasons show a decrease. Annual trends in precipitation show a mixed response by roughly equal number of stations.

From our comparison of medium term trends at low altitude stations with their long term trends (See Table 5 and 6), we note that trends over the recent decades exhibit much higher magnitude of dryness during spring months, particularly for March and April, and of wetness particularly within the month of September – the last monsoonal month. Interestingly, shifts in the ~~trend~~trends have been noticed during the summer months (June-August) where trends over recent decades exhibit drying but the long-term trends suggest wetter conditions. ~~This may attribute to multi-decadal variability that is associated with the global indices, such as, NAO and ENSO, influencing the climatic processes over the region (Shaman and Tziperman, 2005; Syed et al., 2006).~~ Only increase in September precipitation is consistent between the long-term trend and trend obtained over 1995-2012 at low altitude stations.

Discharge

Based on the median hydrograph of each stream flow gauge for the UIB (Fig. 3), we clearly show that both snow and glacier fed/melt regimes can be differentiated based on their runoff production time. Figure 3 suggests that Indus at Kharmong (Eastern UIB), Gilgit at Gilgit (Hindukush) and Astore at Doyian are primarily snow fed basins, generally featuring their peak runoff in July. The rest of the basins are mainly glacier fed basins that feature their peak runoff in August.

Based on 1995-2012 period, our trend analysis suggests an ~~increase in discharge~~increasing trend from most of the hydrometric stations ~~within the UIB~~ during October-June, ~~which is higher in magnitude during~~ with highest magnitudes in May-June (~~Table~~Tabular Fig. 5). A discharge increase pattern seems to be more consistent with tendencies in the temperature record than in precipitation record. In contrast, most of the hydrometric stations experience a decreasing trend of discharge during the month of July, which is statistically significant out of five (Karakoram, Shigar, Shyok, UIB-Central and Indus at Kachura) regions, owing to drop in July temperatures. These regions, showing significant drop in discharge, are mainly high-altitude/latitude glacier-fed regions within the UIB. For August and September months, there is a mixed response, however, statistically significant trends suggest an increase in discharge out of two (Hindukush and UIB-West-lower) regions in August and out of four (Hindukush, western-Karakoram, UIB-West-lower and UIB-west) regions during September. We note that despite of the dominant cooling during September, discharge mainly drops during July, suggesting a strong impact of the cooling during such a month. ~~Moreover, regions showing an increase in discharge during September are mainly the western region of UIB. Such an increase in discharge can mainly be attributed to increasing precipitation trends over such regions. Overall, discharge from~~Discharge from the whole UIB also decreases during the month of July, however, such a drop is not statistically significant. Possibly, the lack of statistical significance in the ~~decrease of~~ UIB discharge trend may ~~possibly be due to integrating~~have been caused by the integrated response from ~~its~~ sub-regions, and ~~a statistically~~that significant signal might ~~become apparent~~appear when looking at higher temporal resolution data, such as 10-day or 5-day ~~average discharge.~~averages. During winter, spring and autumn seasons, discharge at most sites ~~increases~~feature increasing trend while during summer season and on an annual time scale there is a mixed response.

Our long-term analysis reveals a ~~rising~~positive trend of stream flow during the period (November to May) from most of the sites/regions (~~Table~~Tabular Fig. 6). Such ~~rising~~a positive trend is particularly higher in magnitude in May and also significant at relatively large number of gauging sites (14 among 16). In contrast to November-May period, there is a mixed signal of rising and falling stream flow trend among sites during June-October. The ~~rising~~increasing and ~~falling~~decreasing stream flow trends at monthly time scale exhibit similar response when aggregated on a typical seasonal or annual time scales. Winter discharge features an increasing trend while for the rest of seasons and on an annual time scale, sites mostly exhibit a mixed response.

While comparing the long-term trends with the trends assessed from recent two decades, we note most prominent shifts in the sign of trends during the seasonal transitional month of June and within the high flow months July-September~~, which~~. This may attribute to higher summer cooling together with the enhanced precipitation under the influence of monsoonal precipitation regime in recent decades. For instance, long term trend suggests that discharge out of eastern-, central- and whole Karakoram, UIB-Central, Indus at Kachura, Indus at Partab Bridge and Astore regions is increasing while rest of regions feature a decreasing trend. However, trend from the recent two decades suggests the opposite sign of discharge coming out of such regions, except the regions of Astore, Hindukush, UIB-West-upper and its sub-regions, which consistently show similar sign of change. ~~Such response may attribute to a multi-decadal variability of climatic processes over the region, which is driven by NAO and ENSO (Shaman and Tziperman, 2005; Syed et al., 2006).~~

5.2 Field significance ~~of local trends~~ and physical attribution

Based on number of local significant trends, we analyze their field significance for both positive and negative trends, separately (~~Table~~Tabular Fig. 7). We present ~~the~~ mean slope of the field significant ~~local~~ trends in order to present the dominant signal from the region. Our results show a unanimous field significant warming for most of the regions in March followed by in August. Similarly, we generally find a field significant ~~decrease~~decreasing trend in March precipitation ~~during month of March~~ over all regions, except Karakoram and UIB-Central regions. We find a field significant cooling over all regions during the months of July, September and October, which on a seasonal scale, dominates during autumn season followed by summer season. Interestingly, we note that most of the climatic trends are not field-significant during the transitional (or pre-monsoon) period of April-June. We found a general trend of narrowing DTR, which is associated with either warming of Tn against cooling of Tx or relatively lower cooling in Tn than in Tx. Field significant drying of the lower latitudinal regions (Astore, Himalaya, UIB-West-lower - generally snow-fed regions) is also observed particularly during the period March-September, thus for the spring and summer and for the annual time scale. On the other hand, we found an increasing (decreasing) trend in precipitation during winter and autumn (spring and summer) seasons for the Hindukush, UIB-West, UIB-West-upper and whole UIB while for the western Karakoram such increase in precipitation is observed during winter season only. For the whole Karakoram and UIB-central regions, field significant ~~increase~~increasing trend in precipitation is observed throughout a year except during the spring season where no signal is evident.

We have noted that for most of the regions the field significant cooling and warming trends are in good agreement against the trends in discharge from the corresponding regions. Such an agreement is high for summer months, particularly for July, and~~,~~ during winter season, for the month of March. Few exceptions to such ~~a~~ consistency are the regions of Himalaya, UIB-West and UIB-West-lower, for which, in spite of the field significant cooling in ~~month of~~ July, discharge still features a positive trend. However, we note that the magnitude of the increase in July discharge has substantially dropped when compared to ~~the increase~~increases in previous (June) and following (August) months. Such a substantial drop in~~ the~~ July discharge increase rate is again consistent with the prevailing field significant cooling during July for the UIB-West and UIB-West-lower regions. Thus, the identified field significant climatic signals for the considered regions are further confirmed by their observed discharge tendencies. ~~In case climatic trends are not field significant for a particular region, still trend in discharge out of that region represents its prevailing climatic state, since discharge is an integrated signal of controlling climatic variables.~~

Interestingly, we note that generally magnitude of cooling during September dominates the magnitude of cooling during July while magnitude of warming during March dominates the magnitude of warming during May. However, subsequent runoff response from the considered regions does not correspond with the magnitude of cooling and warming trends. In fact, most prominent increase in discharge is observed in May while decrease in July, suggesting them months of effective warming and cooling, respectively. Generally, periods of runoff decrease (in a sequence) span from May to September for the Karakoram, June to September for the UIB-Central, July to August for the western-Karakoram and UIB-West-upper, July to November for the Astore and only over July for the Hindukush and UIB regions. Regions of UIB-West-lower and Himalaya suggest decrease in discharge during months of April and February, respectively.

5.3 Tendencies versus latitude, longitude and altitude

In order to explore the geographical dependence of the climatic tendencies, we plot tendencies from the individual stations against their longitudinal, latitudinal and altitudinal coordinates (Figs. ~~5-7~~9-11). We note that summer cooling is observed ~~by~~in all stations; however the stations between 75-76^{o} E additionally show~~ such~~ cooling during the month of May in Tx, Tn and Tavg. Within 74-75^{o} E, stations generally show a positive gradient towards west in terms of warming and cooling, particularly for Tn. DTR generally features a narrowing trend where magnitude of such a trend tends to be higher west of 75^{o} longitude (Astore basin). Precipitation generally increases slightly but decreases substantially at 75^{o} longitude. Discharge decreases at highest (UIB-east) and lowest (UIB-west) gauges in downstream order, while increases elsewhere.

Cooling or warming trends are~~ much~~ prominent at higher latitudinal stations, particularly for cooling in Tx and warming in Tn. Highest cooling and warming in Tavg is noted around

36°N. Similarly, we have observed a highest cooling in Tx and warming in Tn, while Tx cooling dominates in magnitude as evident from Tavg. DTR generally tends to decrease towards higher latitudes where magnitude of decrease in a particular season/month is larger than increase in it for any other season/month. Highest increasing or decreasing trend in precipitation is observed below 36°N~~ where~~. Whereas station below 35.5°N show substantial decrease in annual precipitation mainly due to decrease in spring season~~ and~~. The stations between 35.5-36°N show increase in annual precipitation mainly due to increase in winter precipitation.

The magnitude of cooling (warming) in Tn decreases (increases) at higher elevations. Stations below 3500 m asl feature relatively higher magnitude of cooling in Tx, which is also higher than warming trends in Tx as well as in Tn. Such signals are clear from tendencies in Tavg. ~~Stations between the elevation range 2000-4000 m asl clearly show pronounced Tavg cooling than Tavg warming in certain months/seasons. For~~The low-altitude stations and the stations at highest elevation show the opposite response, featuring a pronounced warming in Tavg than its cooling in respective months/seasons. We note that precipitation trends from higher altitude stations are far more pronounced than in low altitude station, and clearly suggest drying of spring but wetting of winter seasons. Tendencies in DTR in high altitude stations are consistent qualitatively and quantitatively as compared to tendencies in low altitude stations.

6 Discussions

~~The hydrology of UIB dominates with the melt water runoff, which ensures the crucial water supply to the largest reservoir in Pakistan for reducing the ongoing electric shortfall by its use for hydro-power generation, and contributing to the economy through its use for mostly irrigated agricultural production downstream. The water availability from the UIB depends upon a highly seasonal moisture input from the distinct mode of large scale circulations; the summer monsoon system transporting moisture from the Bay of Bengal and Arabian Sea, and the westerly disturbances bringing moisture from the Mediterranean and Caspian Seas, to their far extremities over the region. An interaction among these large-scale circulations over the highly complex terrain of HKH within the UIB largely influences substantially its thermal regime, which in turn, is primarily responsible for the melt runoff generation. The extent of the existing permanent cryosphere within the UIB additionally influences the timings of melt~~

runoff production and ensures to a certain extent the compensation for variability in the moisture input in a running or previous accumulation season. In view of the fact that reduction in snow amount is somewhat compensated by the glacier melt, one can expect little changes in the overall meltwater availability from the UIB during subsequent melt season. The reduction of snow, however, may affect the timing of water availability due to certain time delays associated with the migration of melting temperature up to the glaciated region. In contrast, cooling tendencies during the melt season, even in the presence of abundant snow, may lead to both an overall decrease and delay in the melt runoff. Nevertheless, persistent changes in both can have strong impact on the long-term water balance of the study basin and subsequently the future water availability. Therefore, knowledge about the climatic regime prevailing over the UIB is utmost necessary for better management and use of available water resources in Pakistan at present and for the immediate revision of the near term future planning such as Water Vision 2025.

Earlier investigations of the UIB climatic regime have been mainly restricted to only a subset of six available low altitude, manual, valley-bottom stations, not fully representative of the active hydrologic regime of the UIB. For the first time, we present a comprehensive and systematic assessment of the climatic tendencies for two recent decades from the updated record of twelve high altitude automated weather stations from HKH ranges together with a full set of six low altitude stations, all covering the altitudinal range roughly between 1000 and 4500 m asl. First, we perform a quality control and homogeneity test, and then we correct the time series for its sequential dependence by removing the optimally identified lag-1 autocorrelation through an iterative procedure. We employed a widely used MK test for ensuring existence of a trend while true slope of a trend was estimated by the Sen's slope method on monthly to annual time scale. We have divided the UIB into pragmatic region of Astore, Gilgit, Hunza, Himalaya, Karakoram, UIB-Central, UIB-West, UIB-West-lower, UIB-West-upper and UIB itself depending upon available hydrometric station network, identified/known distinct hydrological regimes and in view of the existing topographic barriers of HKH massifs. Provided a particular region features more than one meteorological station, individual climatic trends within the region were tested for their field significance based upon number of positive/negative significant trends, which in turn compared with the trends of outlet discharge from the region in order to furnish physical attribution to statistically identified signal of change. We also compare results of our trend analysis, performed over the updated full length record from six low altitude stations (onward called as long term trend), with the reports from earlier studies analyzing only subset of these stations relatively over a shorter period.

Cooling trends

Our long term updated analysis suggests that summer and autumn cooling trends are mostly consistent with previously reported trends (Fowler and Archer, 2005 and 2006; Khattak et al., 2011), and with reports of increasing summer snow cover extent over the UIB (Hasson et al., 2014b). Our long term trend in Tavg suggests summer cooling at all stations which is mostly significant, while for autumn season and on an annual time scale we found a mixed response. Comparing results of our updated analysis with Fowler and Archer (2005 and 2006), who have analyzed subset of low altitude stations for the period (1961-1999/2000), we found a qualitative agreement for summer cooling tendencies at Astore, Bunji, Gilgit and Skardu stations, and during autumn, only at Bunji station. Sheikh et al. (2009) have also reported cooling in the mean annual temperatures at Gilgit, Gupis and Bunji stations during the monsoon period (June-September). In contrast, autumn cooling at Gilgit station, winter cooling at two stations (Astore and Bunji) and spring and annual cooling at three stations (Astore, Bunji and Gilgit), reported in Fowler and Archer (2005 and 2006) are not consistent with our results, which suggest instead warming or no change. Such inconsistency is not assured at Bunji station as its winter cooling reported in Fowler and Archer (2005) is inconsistently reported as a warming trend in Fowler and Archer (2006), over the same period of record investigated. Sheikh et al. (2009) have reported cooling in mean annual temperatures over Gilgit, Gupis and Bunji stations. Our results of cooling in Tavg during the monsoon months are consistently observed 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) for the respective investigated periods. For Tx, summer cooling tendencies at Astore, Bunji and Gilgit and autumn cooling at Bunji station are consistent with Fowler and Archer (2006). For Tn, our results are in high agreement for a significant summer and autumn cooling with Fowler and Archer (2006) and Khattak et al. (2011), and with the findings of an increasing snow cover extent for summer season as reported by Hasson et al. (2014b) over the region. Whereas, cooling tendencies during winter and spring seasons and on an annual time scale in all temperature variables (Fowler and Archer, 2005 and 2006; Khattak et al., 2011) instead have been inconsistently suggested either warming or no trend at all in our updated analysis. More surprisingly, Río et al. (2013) have reported overall warming trend over Pakistan (and UIB), at all timescales, which is in direct contrast with the cooling tendencies reported here and by the above mentioned studies regardless of the seasons.

We note that a robust pattern of long-term summer cooling in Tn, Tx and Tavg during June-October is weak over 1995-2012 period and has been restricted mainly to the monsoonal period of July-October, where cooling during months of July and September dominates in terms of magnitude. Cooling tendencies observed mostly during the monsoon season are The overall warming over Pakistan (and UIB) reported by Río et al. (2013) is however in direct contrast to the cooling tendencies reported here and by the above mentioned studies, regardless of the seasons. Our findings of long term cooling trends during the monsoon period are also in high agreement with reports of Sheikh et al. (2009) for the study region, which is consistently reported 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) for the investigated periods.

More importantly, the station-based cooling trends are found field significant for all identified sub-regions of the UIB mostly in July, September and October, coinciding with the months of monsoonal onset and retreat, and also with the glacier melt season. Thus, field significant cooling is further depicted from the trends in discharge out of respective regions, specifically during July, when discharge either exhibit falling or weaker rising trends relative to contiguous months due to declining glacial melt. The field significant cooling and subsequent discharge behaviour is attributed to coincidentthe incursions of south Asian summer monsoonmonsoonal system and its precipitation (Cook et al., 2003) into the Karakoram, through crossing Himalayas, and withininto the UIB-West region, for which the Himalayan barrier does not exist. Such phenomenon seems to be accelerated at present under the observed increasing trend in the cloud cover and, in the number of wet days, - particularly over the UIB-West region (Bocchiola and Diolaiuti, 2013) - and subsequently in the total amount of precipitation during the monsoon season. The enhanced monsoonal influence in the far north-west over the UIB-West region, and within the Karakoram, is consistent with the extension of the monsoonal domain northward and westward under the global warming scenario as projected by the multi-model mean from climate models participating in the

Climate Model Intercomparison Project Phase 5 (CMIP5) (- Hasson et al., 20152015a). Such hypothesis further needs a detailed investigation and it is beyond the scope of present study. Nevertheless, increasing cloud cover due to enhanced influence and frequent incursions of the monsoonal system leads to reduction of incident downward radiations and results in cooling (or less warming) of Tx. Forsythe et al. (2015) have consistently observed influence of the cloud radiative effect on the near surface air temperature over the UIB. The enhanced cloudy conditions most probably are mainly responsible for initially higher warming in Tn through longwave cloud radiative effect. Given that such cloudy conditions persist longer in time, Tx and Tn are more likely tend to cool. , which then under the clear sky conditions,Under the clear sky conditions, cooling in Tx further continues as a result of evaporative cooling of the moisture-surplus surface under precipitation event (Wang et al., 2014) or due to irrigation (Kueppers et al., 2007). Han and Yang (2013) found irrigation expansion over Xinjiang, China as a major cause of observed cooling in Tavg, Tx and Tn during May-September over the period 1959-2006. Similar cloudy conditions most probably are mainly responsible for initiallyFurther, higher warming in Tn through blocking outgoing longwave radiations and creating a greenhouse effect, depending on the relative humidity conditions. Given that such cloudy conditions persist longer in time, Tx and Tn are more likely tend to cool. Yadav et al. (2004) have related the higher drop in minimum temperatureobserved over UIB-West-lower region during winter months can be attributed to intense night time cooling of the deforested, thus moisture deficit, bare soil surface, exposed to direct day time solar heating. Such an explanation is valid here only for the areas under deforestation and below the tree line. as explained by Yadav et al. (2004).

Due to cooling trends, the UIB though features some responses consistent with the neighboring region and as observed worldwide but reason for such common responses may still be contradictory. For instance, field significant decreasing trend in DTR during July-October period is attributed to stronger cooling in Tx than in Tn, which is contrary to the reason of decreasing DTR observed worldwide and over the northeast China (Jones et al., 1999; Wang et al., 2014).

Warming trends

Long term warming during November-May is generally found consistent with previously reported warming trends (Fowler and Archer, 2005 and 2006; Sheikh et al., 2009; Khattak et al., 2011; Río et al., 2013) as well as with decreasing snow cover extent during spring (1967-

2012) in the Northern Hemisphere and worldwide (IPCC, 2013) and during winter (2001-2012) over the study region (Hasson et al., 2014b). Our findings of robust long term increasing trends in Tx and Tavg during November-May are consistent with the results from Khattak et al. (2011), who have analyzed data for the period 1967-2005. However, they have found highest rate of warming during winter season, instead we have found it during the spring season, which is consistent with findings of Sheikh et al. (2009) and Río et al. (2013). Our results of spring warming also agree well with the observation of a decreasing extent of spring snow cover worldwide and in the Northern Hemisphere over the period 1967 to 2012 (IPCC, 2013). Similarly, warming tendencies during winter at most of the stations are in good agreement with a decreasing snow cover extent over the study region during the period 2001-2012 (Hasson et al., 2014b). The long term warming tendencies (November to May) observed in the present study largely agree qualitatively with the findings of Fowler and Archer (2005 and 2006) for all temperature variables.

We have found the long term trend of winter warming in Tx at low altitude stations less significant during 1995-2012 accompanied by most of cooling tendencies during the months of February and December. Interestingly, well-agreed long-term cooling in Tx during June and warming during October are now featuring opposite signs of change by most of the low altitude stations. Similarly, long term warming trend in Tavg within November-May period has recently been restricted to mainly March-June period and within August and November months at low altitude stations, where most of these stations exhibit cooling tendencies during the winter months over the period 1995-2012. This suggests that a long-term trend of winterHowever, warming generally dominates in spring months, consistent with findings of Sheikh et al. (2009) and Río et al. (2013). Being consistent with recent acceleration of global climatic changes (IPCC, 2013), such spring warming is observed higher over the 1995-2012 period, particularly in March and May, respectively. Further, warming in Tx (Tn) is more pronounced at low (high) altitude stations. More importantly, the station-based spring warming is found field significant in March over almost all identified sub-regions of the UIB. Under the drying spring scenario, less cloudy conditions associated with increasing number of dry days for the westerly precipitation regime (Hasson et al., 2015a) together with snow-albedo feedback can partly explain such warming during spring months.

Contrary to spring warming since 1961 (Fowler and Archer, 2006) is no more valid over 1995-2012 period.

~~Within the 1995-2012 period~~, our analysis suggests ~~either~~generally a field significant cooling ~~(or weaker warming) during the~~in winter~~ season both at low and high altitude stations~~, which is in direct contrast to ~~the ~~long term warming trends ~~observed over the full length record~~analyzed here and those previously reported (Fowler and Archer, 2005 and 2006; Sheikh et al., 2009; Khattak et al., 2011~~) at low altitude stations and particularly surprising given the observed winter warming worldwide.~~). Such a recent shift of winter warming to cooling is ~~however ~~consistently observed over eastern United States, southern Canada and much of the northern Eurasia (Cohen et al., 2012). ~~Such~~The recent winter cooling is a result of falling tendency of winter time Arctic Oscillation, which partly driven dynamically by the anomalous increase in autumnal Eurasian snow cover (Cohen and Entekhabi, 1999), can solely explain largely the weakening (strengthening) of the westerlies (maridional flow) and ~~favor~~favors anomalously cold winter temperatures and their falling trends (Thompson and Wallace, 1998 and 2001; Cohen et al., 2012). Weakening of the westerlies during winter may explain an aspect of well agreed drying during subsequent spring season, and may further be ~~associated with conditions ~~related to more favorable conditions for the southerly monsoonal incursions~~ from south~~ into the UIB.

~~During the period 1995-2012, largely agreed warming in Tx dominates at low altitude stations as compared to high altitude stations, in contrast to warming in Tn, which is higher in magnitude among high altitude stations. Under the drying spring scenario, a less cloudy conditions associated with increasing number of dry days for the westerly precipitation regime (Hasson et al., 2015) are most probably responsible for warming in Tx, consistent with global warming signal. Trends in Tavg are dominated by trends in Tx during July-October while these are dominated by Tn, during rest of the year. Overall, trends based on recent two decades suggest higher magnitude of warming than the long term trends, which is consistent with the recent acceleration pattern of climatic changes (IPCC, 2013). Moreover, such warming tendencies (1995-2012), being restricted to months of March, May and November, relatively dominate in March at low altitude stations in terms of magnitude and significance but in May at high altitude stations in terms of magnitude only. Interestingly, a pronounced summer warming at higher elevations as reported in Tien Shan, central Asia (Aizen et al., 1997), over the Tibetan Plateau (Liu and Chen, 2000) and Nepal Himalayas (Shrestha et al., 1999), and as speculated for the UIB by Fowler and Archer (2006) by analyzing low altitude stations, is generally found invalid here. Instead of the summer~~

warming, we have found higher rate of spring warming at higher altitude stations, which is again only valid for Tn.

Our results of long term increase in DTR at low altitude stations within the UIB are consistent with Fowler and Archer (2006), and over the India, with Kumar et al. (1994) and Yadav et al. (2004) but in direct contrast to decrease worldwide (Jones et al., 1999) and over northeast China (Wang et al., 2014). Contrary to the long term trends in DTR, trends over 1995-2012 period at low altitude stations show a decrease. Similarly, contrary to the reason of decrease in DTR worldwide and over **Wetting and drying trends**

Enhanced influence of the late-monsoonal precipitation increase at high altitude stations suggests field significant increasing trend in precipitation for the regions at relatively higher latitudes, such as, Hindukush and UIB-Central, and thus, for the UIB-West-upper, Karakoram and the whole UIB.northeast China (Jones et al., 1999; Wang et al., 2014), summer DTR decrease during 1995-2012 is attributed to stronger cooling in Tx than in Tn. The observed DTR increase during spring is attributed to stronger warming in Tx than in Tn, which is again contrary to the reason for DTR increase from the full length record over UIB and India (Fowler and Archer, 2006; Kumar et al., 1994; Yadav et al., 2004). It implies that though UIB features some common responses of trends in DTR when compared worldwide or to the neighbouring regions, however reasons of such common responses are still contradictory.

Wetting and drying trends

Khattak et al. (2011) have found no definite pattern of change in precipitation from the low altitude stations analyzed for the period 1967-2005. Similarly, Bocchiola and Diolaiuti (2013) report mostly not statistically significant changes in precipitation. From our long term precipitation analysis, we have found, a coherent (but again lacking statistical significance) pattern of change in precipitation, which indicates an increasing tendency during winter, summer and autumn seasons and on annual time scale, while a decreasing tendency during the spring months at most of the low altitude stations. Significant drying found at Bunji station during spring season is consistent with decreasing precipitation trend from Archer and Fowler (2004) during January-March period, while for Astore station such spring drying is consistent with their result of slight decrease in precipitation during April-June period. Our results of long term increasing trend in precipitation at Astore station for the winter, summer and autumn seasons is also consistent with Farhan et al. (2014).

~~We note that stations at high altitude suggest relatively enhanced monsoonal influence since six stations (Shendure, Yasin, Ziarat, Rattu and Chillas and Shigar) within the UIB-West and Central Karakoram regions feature significant increase in precipitation in either all or at least one of the monsoon months.~~ This is in good agreement with the projected intensification of south Asian summer monsoonal precipitation regime under enhanced greenhouse gas emission scenarios (Hasson et al., 2013, 2014a & ~~2015~~2015a). At the low altitude stations, shifts of the long-term trends of increasing summer precipitation (June-August) to drying over the period 1995-2012 indicate a transition towards weaker monsoonal influence at lower levels. ~~This may relate to the fact that the monsoonal currents crossing the western Himalayan barriers reach the central and western UIB at higher levels.~~This may attribute to multi-decadal variability that is associated with the global indices, such as, NAO and ENSO, influencing the distribution of large scale precipitation over the region (Shaman and Tziperman, 2005; Syed et al., 2006).

~~The~~The field significant trends of precipitation increase during winter but decrease during spring season is associated with certain changes in the westerly precipitation regime under changing climate. For instance, field significant drying in spring ~~drying~~(except for Karakoram) is mainly consistent with the weakening and northward shift of the mid-latitude storm track (Bengtsson et al., 2006) and increase in the number of dry days within spring season for the westerly precipitation regime (Hasson et al., ~~2015~~2015a). On the other hand, observed increase in the winter precipitation for relatively high latitudinal regions is consistent with the observations as well as with the future projections of more frequent incursions of the westerly disturbances into the region (Ridley et al., 2013; Cannon et al., 2015; Madhura et al., ~~2015), which together with drying of spring season, indicate less intermittent westerly precipitation regime in future, as reported by Hasson et al. (2015) based on CMIP5 climate models.~~2015). In view of more frequent incursions of the monsoonal system and westerly disturbances expected in the future and certain changes projected for the overall seasonality/intermittency of their precipitation regimes by the climate models (Hasson et al., ~~2015), one expects~~2015a), significant changes in the ~~time~~timings of ~~the~~ melt water availability from the UIB are speculated. Such hypothesis can be tested by assessing changes in the seasonality of precipitation and runoff based on observations analyzed here and also through modelling melt water runoff from the region under prevailing climatic conditions.

Water availability

~~Consistent with Khattak et al. (2011), our long term trend in summer season discharge suggests its increase for Indus at Kachura region while its decrease for UIB-West-upper and whole UIB regions, and also, an increase in the winter and spring discharges for all three regions. Observed increases in annual mean discharge from Astore basin for the full length of record and for the period 1995-2012 are consistent with findings from Farhan et al. (2014) for the period 1985-1995 and 1996-2010, respectively. Our long term trend in Shigar discharge suggests partially consistent results with Mukhopadhyay et al. (2014) exhibiting its increase for June and August, however, in contrast, its slight decrease during July and September, though no trend was statistically significant. Moreover, Mukhopadhyay et al. (2014) have reported a downward trend of only June and July discharge after 2000. However, during the period 1995-2012, we have found a prominent drop in Shigar discharge for all four months June-September, which is higher in magnitude and statistically significant during July. We also found a change of sign in the long term discharge out of UIB-East over the period 1995-2012. Mukhopadhyay et al. (2014) related the drop in June and July months with drop in winter snow fall, which may only be partially true in view of relatively higher magnitude of drying in spring as observed in our analysis. Moreover, our analysis suggests that a recent drop in Shigar discharge is due to less snow amount available because of spring drying, an early snow melt under higher spring warming and concurrently less melting due to wide spread cooling during June-October, particularly at relevant (Shigar and Skardu) stations.~~

~~We note prominent shifts of long term trends of rising stream flow into falling during June-September~~The long term discharge tendencies are consistent with earlier reports from Khattak et al. (2011) for Indus at Kachura, and UIB regions and from Farhan et al. (2014) for Astore. Similarly, rising and falling discharge trends from Shyok and Hunza sub-basins, respectively, are consistent with Mukhopadhyay et al. (2015). The discharge trends from Shigar-region, though statistically insignificant, are only partially consistent with Mukhopadhyay and Khan (2014), exhibiting agreement for an increasing trend in June and August but a decreasing trend in July and September.

We note prominent shifts of the long term trends of rising melt-season discharge into falling over the period 1995-2012 for mostly the glacier-fed regions (Indus at Kachura, Indus at Partab Bridge, Eastern-, Central- and whole-Karakoram and UIB-Central~~), which~~). Such shifts may attribute to higher summer cooling together with certain changes in the precipitation regime~~ during such period.~~. Change in sign of discharge trend for~~ the~~ eastern-

Karakoram (Shyok) is expected to substantially alter discharge at Kachura site, thus deriving a Shigar discharge by applying previously identified constant monthly fractions to the downstream Kachura gauge (Mukhopadhyay ~~et al.,~~and Khan, 2014) would less likely yield a valid Shigar discharge for its period of missing record (1999-2010). Some regions, such as, UIB-West-upper and its sub-regions together with Astore ~~basin~~ and whole UIB are the regions consistently showing same sign of change in their long term trend when compared to the trends derived over the period 1995-2012.

~~During~~Over the 1995-2012~~, the~~ period, decreasing stream flow trend observed for mainly the glacier-fed regions is mostly significant ~~mostly during month of~~in July. ~~Despite the fact that~~Though cooling in July is less prominent than cooling in September~~ over the period 1995-2012~~, it is much effective ~~due to the fact that~~as it coincides with the main glacial melt season. Such drop in July discharge, owing to decreased melting, results in reduced melt water availability, but~~,~~ at the same time, indicates positive basin storage, in view of enhanced moisture input. Similarly, increase in discharge during May and June is due to the observed warming, which though less prominent ~~in magnitude~~ than warming in March, is much effective since it coincides with the snow melt season. This suggests an early melt of snow and ~~subsequently increased~~subsequent increase in the melt water availability, but concurrently, a lesser amount of snow available for the subsequent melt season. Such distinct changes in snow melt and glacier melt regimes are mainly due to the non-uniform ~~signs of change and magnitudes of trends in~~ climatic ~~variables at~~changes on a sub-seasonal scale. This further emphasizes on a separate assessment of changes in both snow and glacier melt regimes, for which an adequate choice is the hydrological models that are able to distinctly simulate snow and glacier melt processes. Nevertheless, changes in both snow and glacier melt regimes all together can result in a sophisticated alteration of the hydrological regimes of the UIB, requiring certain change in the operating curve of the Tarbela reservoir in future.

The discharge change pattern seems to be more consistent with ~~tendencies in the~~field significant temperature ~~record~~trends than ~~tendencies in the~~with precipitation ~~record~~trends. This points to the fact that the cryosphere melting processes are the dominating factor in determining the variability of the rivers discharge in the study region. However, changes in precipitation regime can still influence substantially the melt processes and subsequent meltwater availability. For instance, monsoon offshoots intruding into the region ironically result in declining river discharge (Archer, 2004), since crossing the Himalaya such monsoonal incursions~~, crossing the Himalaya,~~ mainly drop moisture over the high altitude regions and in the form of snow (Wake, 1989; Böhner, 2006). In that case, fresh snow and clouds firstly reduce the incident energy due to high albedo that results in immediate drop in the melt~~, and secondly, the~~. Secondly, fresh snow insulates the underlying glacier/ice, slowing down the whole melt process till earlier albedo rates are achieved. Thus, melting of ~~the~~ snow and glaciers and subsequent overall ~~resultant~~ meltwater availability is inversely correlated to the number of snowfall events/days during the melt season (Wendler and Weller, 1974; Ohlendorf et al., 1997).

~~We note that certain combinations of months exhibit common responses, and that such combinations are different from those typically considered for averaging seasons such as MAM, JJA, SON and DJF. We, therefore, suggest that analysis must be performed using the highest available temporal resolution, because time averaging can mask important effects. We also emphasize that analysis merely based upon the typical seasons averages out the pivotal signal of change, which can only be clearly visible at fine temporal resolution. Trends for typical seasons are analyzed in the study merely for sake of comparing results with earlier studies.~~

In view of the sparse network of meteorological observations analyzed here, we need to clarify that the observed cooling and warming is only an aspect of the wide spread changes prevailing over the wide-extent UIB basin. This is much relevant for the UIB-Central region where we have only one station each from the eastern- and central- Karakoram (UIB-Central), ~~which might~~ not ~~be~~exclusively representative ~~exclusively for the~~of their hydro-climatic state ~~over respective regions~~. Thus, field significant results for the whole Karakoram region are mainly dominated by contribution of relatively large number of stations within the western-Karakoram. Nevertheless, glaciological studies, reporting and supporting the Karakoram anomaly (Hewitt, 2005; Scherler et al., 2011; Bhambri et al., 2013) and possibly a non-negative mass balance of the aboded glaciers within eastern- and central-Karakoram (Gardelle et al., 2013 - contrary at shorter period – Kääb et al., 2015), further reinforce our ~~results~~findings. Moreover, our results agree remarkably well with the local narratives of climate change as reported by Gioli et al. (2013). ~~Since the resultant aspect has been confirmed for the UIB and for its sub-regions to be significant statistically, and are further evident from the~~ In view of such consistent ~~runoff response and~~ findings ~~from the existing studies~~, we are confident that the observed signal of hydroclimatic ~~change~~changes dominates at the present, at least qualitatively. Furthermore, climatic change signal observed within the mountainous environments can vary with respect to altitude (MRI, 2015; Hasson et al., 2015b). Such elevation dependent signal of climatic change is somewhat depicted by the sparse observations analysed here. However, the robust assessment of such an aspect requires spatially complete observational database.

The hydro-climatic regime of the UIB is substantially controlled by the interaction of large scale circulation modes and their associated precipitation regimes, which are in turn controlled by the global indices, such as, NAO and ENSO etc. The time period covered by our presented analysis is not long enough to disintegrate such natural variability signals from the transient climate change. Such phenomena need to be better investigated based upon longer period of observational record for in depth understanding of the present variability in the hydrological regime of the UIB and for forecasting future changes in it. For future projections, global climate models at a broader scale and their downscaled experiments at regional to sub-regional scales are most vital datasets available, so far. However, a reliable future change assessment over the UIB from these climate models will largely depend upon their satisfactory representation of the prevailing climatic patterns and explanation of their teleconnections with the global indices, which are yet to be (fully) explored. The recent generations of the global climate models (CMIP5) feature various systematic biases (Hasson et al., 2013, 2014a and 20152015a) and exhibit diverse skill in adequately simulating prevailing climatic regimes over the region (Palazzi et al., 2014; Hasson et al., 20152015a). We deduce that realism of these climate models about the observed winter cooling over the UIB much depends upon the reasonable explanation of autumnal Eurasian snow cover variability and its linkages with the large scale circulations (Cohen et al., 2012), while). On the other hand, their ability to reproduce summer cooling signal is mainly restricted by substantial underestimation of the real extent of the south Asian summer monsoon owing to underrepresentation of High-Asian topographic features and absence of irrigation waters (Hasson et al., 20152015a). However, it is worth investigating data from high resolution Coordinated Downscaled Experiments (CORDEX) for South Asia for representation of the observed thermal and moisture regimes over the study region and whether such dynamically fine scale simulations feature an added value in their realism as compared to their forced CMIP5 models. Given these models do not adequately represent the summer and winter cooling and spring warming phenomena, we argue that modelling melt runoff under the future climate change scenarios as projected by these climate models is still not relevant for the UIB as stated by Hasson et al. (2014b). Moreover, it is not evident when the summer cooling phenomenon will end. Therefore, we encourage the impact assessment communities to model the melt runoff processes from the UIB, taking into account more broader spectrum of future climate change uncertainty, thus under both prevailing climatic regime as observed here and as projected by the climate models, ~~considering them~~ relevant for ~~the~~ short ~~term~~ and ~~the~~ long term future water availability, respectively.

7 Conclusions

~~The time period covered by our presented analysis is not long enough to disintegrate the natural variability such as ENSO signals from the transient climate change. Nevertheless, we assume that~~ Our findings supplement the ongoing research on addressing the question of ~~dynamics of the existing~~ water resources dynamics in the region, such as, 'Karakoram ~~Anomaly~~Anomaly' and the future water availability. In view of recently observed shifts and acceleration of the hydroclimatic trends over HKH ranges ~~and~~ within the UIB, we speculate an enhanced influence of the monsoonal system and its precipitation regime during the late-melt season. On the other hand, changes in the westerly disturbances and in the associated precipitation regime are expected to drive changes observed during winter, spring and early-melt season. The observed hydroclimatic trends, suggesting distinct changes within the period of mainly snow and glacier melt, indicate at present strengthening of the nival while suppression of the glacial melt regime, which all together will substantially alter the hydrology of the UIB. However, such aspects need to be further investigated in detail by use of hydrological modelling, updated ~~observations~~observational record and ~~relevant~~suitable proxy datasets. ~~The~~Nevertheless, changes presented in the study earn vital importance when we consider the socio-economic effects of the environmental pressures. ~~Reduction in~~The melt water reduction will result in limited water availability for the agricultural and power production downstream and may results in a shift in solo-season cropping pattern upstream. This emphasizes the necessary revision of WAPDA's near future plan i.e. Water Vision 2025 and recently released first climate change policy by the Government of Pakistan, in order to address adequate water resources management and future planning in relevant direction. ~~We summarize main findings of our study below:~~

- ~~The common patterns of change ascertained are cooling during monsoon season and warming during pre-monsoonal or spring season. Pattern of tendencies derived for~~

Tavg are more robust throughout a year as it is dominated by a relatively more robust pattern of cooling in Tx than in Tn, and similarly by a relatively more robust pattern of warming in Tn than in Tx. Such signal is averaged out in typical seasons and on annual time scale.

- The long term summer cooling period of June-October has been shortened to July-October over the period 1995-2012 during which cooling becomes stronger, which further dominates during month of September followed by month of July in terms of higher magnitude and its statistical significance agreed among number of stations. Low and high altitude stations feature roughly similar magnitude of cooling during 1995-2012, which is however higher than the observed magnitude of warming in respective temperature variables during spring months.
- A strong long term winter warming in Tx is either invalid or weaker over the period 1995-2012, which being restricted to March, May and November months, dominates during March and particularly higher at low altitude stations. Whereas long term warming in Tn is restricted during February-May and month of November, which dominates during March and February and prominent at higher altitude stations than low altitude stations.
- The long term trends of increasing DTR throughout a year at low altitude stations have been restricted mainly to March and May while for the rest of year, DTR has been decreasing over the period 1995-2012. Overall, high altitude stations exhibit though less strong but a robust pattern of significant decrease in DTR throughout a year as compared to low altitude stations.
- Long term summer precipitation increase shifts to drying over 1995-2012 period at low altitude stations, indicating a transition of the precipitation regime to weaker monsoonal influence at low altitudes. Over 1995-2012 period, well agreed increase (decrease) in precipitation for winter season and for month of September (March-June period) has been observed, which is higher in magnitude than the long term trends and also at high altitude stations as compared to low altitude stations. Six stations suggest a significant increase in monsoonal precipitation during all or at least one month.
- Long term discharge trends exhibit rising (falling) melt season runoff from regions of eastern-, central- and whole Karakoram, UIB-Central, Indus at Kachura, Indus at Partab Bridge and Astore (for rest of the regions). However, over the period 1995-2012 rising and falling discharge trends from respective regions show opposite

~~behavior except for the Astore, Hindukush, UIB-West-upper and its sub-regions, which consistently show similar sign of change.~~

- ~~Hydroclimatic trends are prominently distinct among certain time periods within a year rather than against their geographical distributions. However, high altitude data suggest more pronounced and updated signal of ongoing change.~~
- ~~We have noted that for most of the regions the field significant cooling and warming trends are in good agreement against the trends in discharge from the region. Such agreement is high for summer months, particularly for July and, during winter season, for the month of March.~~
- ~~Magnitude of subsequent runoff response from the considered regions does not correspond with the magnitude of climatic trends. In fact, most prominent increase is observed in May while decrease in July, suggesting them months of effective warming and cooling.~~

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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 gauge times series are limited to common length of time series of the employed gauges, thus their statistics.

S. No.	Watershed/ Tributary	Designated Discharge sites	Expression ~~of Derived~~ for deriving approximated Discharge	Designated Name of the Region	Area (km^2)	Glacier Cover (km^2)	% Glacier Cover	% of UIB Glacier Aboded	Elevation Range (m)	Mean Discharge (m^3s^{-1})	% of UIB Discharge	No of Met Stations
1	Indus	Kharmong		UIB-East	69,355	2,643	4	14	2250-7027	451	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**	**18,340**	**11**	**100**	**569-8448**	**2405**	**100.0**	**18**
11			4 – 2 – 1	~~derived~~ Shigar-						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 2: List of Meteorological Stations and their attributes. Inhomogeneity is found only in Tn over full period of record. Note: (*) represent inhomogeneity for 1995-2012 period only.

S.	Station Name	Period From	Period To	Agency	Longitude	Latitude	Altitude	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. List of ~~SHP~~SWHP WAPDA Stream flow gauging stations in a downstream order along with their characteristics and period of record used. ***Gauge is not operational after 2001.

S. No.	Gauged River	Discharge Gauging Site	Period From	Period To	Degree Latitude	Degree Longitude	Height meters
1	Indus	Kharmong	May-82	Dec-11	34.9333333	76.2166667	2542
2	Shyok	Yogo	Jan-74	Dec-11	35.1833333	76.1000000	2469
3	Shigar	Shigar*	Jan-85	Dec-~~01~~98	35.3333333	75.7500000	2438
4	Indus	Kachura	Jan-70	Dec-11	35.4500000	75.4166667	2341
5	Hunza	Dainyor	Jan-66	Dec-11	35.9277778	74.3763889	1370
6	Gilgit	Gilgit	Jan-70	Dec-11	35.9263889	74.3069444	1430
7	Gilgit	Alam Bridge	Jan-74	Dec-12	35.7675000	74.5972222	1280
8	Indus	Partab Bridge	Jan-62	Dec-07	35.7305556	74.6222222	1250
9	Astore	Doyian	Jan-74	Aug-11	35.5450000	74.7041667	1583
10	UIB	Besham Qila	Jan-69	Dec-12	34.9241667	72.8819444	580

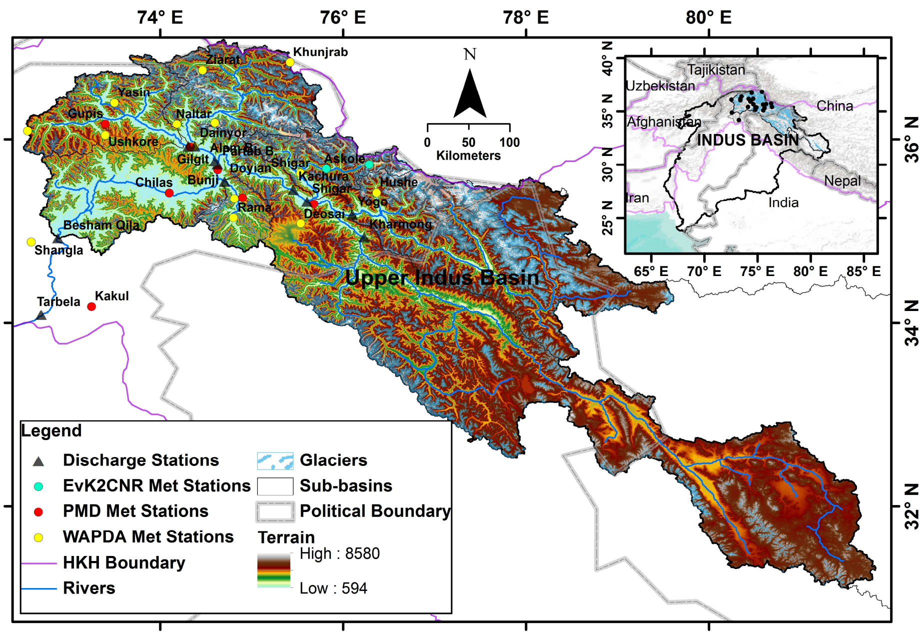

Figure 1: Study Area, Upper Indus Basin (UIB) and meteorological station networks

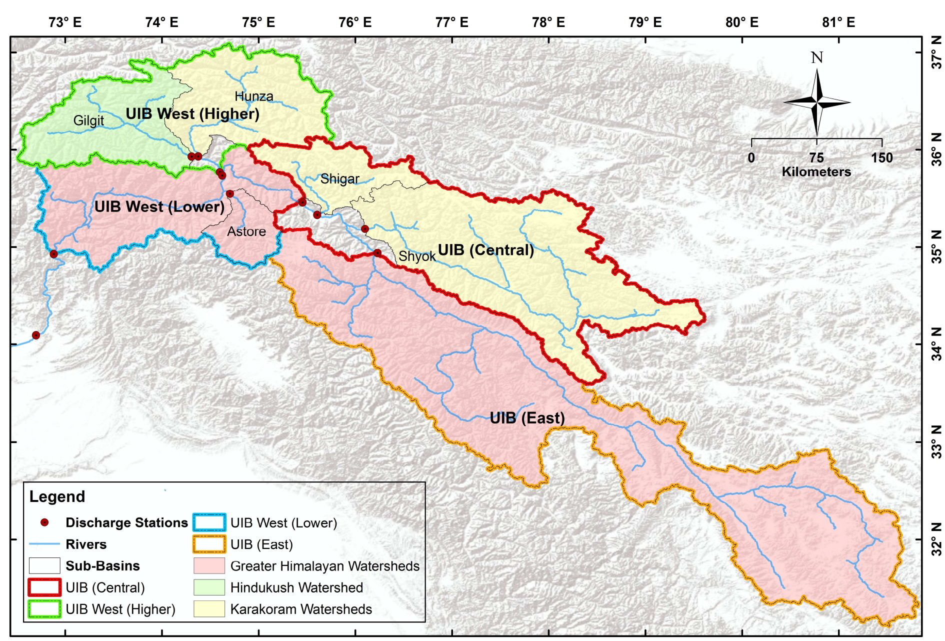

Figure 2: Gauged basins, gauges and regions considered for field significance

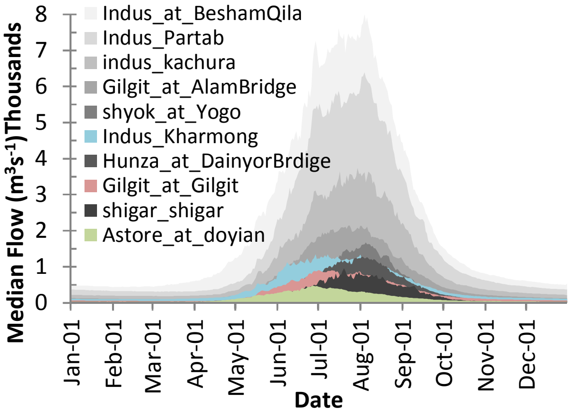

Figure 3: Long-term median hydrograph for ten key gauging stations separating the sub-basins of UIB having either mainly snow-fed (shown in color) or mainly glacier-fed hydrological regimes (shown in grey shades).

<u>Tabular Figure</u> 4: Trend for Tx, Tn and DTR in $^{o}C\ yr^{-1}$ (per unit time) at monthly to annual time scale over the period 1995-2012. Note: meteorological stations are ordered from top to bottom as highest to lowest altitude while hydrometric stations as upstream to downstream. Slopes significant at 90% level are given in bold while at 95% are given in bold and Italic. Color scale is distinct for each time scale where blue (red) refers to increasing (decreasing) trend

Variable	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Tx	Khunrab	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
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

Tabular Figure 5: Same as Table 4 but trend slopes are for Tavg in $^{o}C\ yr^{-1}$, for total P in $mm\ yr^{-1}$ and for mean Q in $m^3s^{-1}yr^{-1}$. Color scale is distinct for each time scale where blue, yellow and orange (red, green and cyan) colors refer to decrease (increase) 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	Khunrab	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
	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
P	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
	Gilgit	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**
	Bunji	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
	Chilas	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**	-37.17	-9.48	0.60	***8.97***	***5.97***	***1.65***	0.11	-24.43	5.64	-3.90
	Hindukush	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
	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
	Astore	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
	Partab_Bridge	1.00	-0.13	3.60	8.80	63.22	-34.86	-39.86	-67.33	29.65	0.69	8.89	15.12	8.40	36.29	-67.00	9.81	-12.40
	UIB-WL	1.88	0.41	6.39	-0.52	41.58	**59.50**	28.19	***81.58***	**30.99**	16.18	5.17	2.33	1.92	19.90	***65.53***	***16.02***	***25.44***
	UIB-WL-Partab	-3.00	0.80	-4.38	-0.82	***87.89***	51.53	9.00	17.67	2.71	-12.24	1.40	-6.00	-3.74	28.32	47.93	-3.00	18.94
	UIB_West	2.45	1.37	5.43	2.42	**61.35**	54.89	0.21	42.93	***28.24***	**13.68**	***5.87***	1.38	2.00	**23.43**	44.18	***17.71***	***22.17***
	Himalaya	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***
	UIB	1.82	***5.09***	5.37	-2.50	11.35	14.67	-46.60	41.71	35.22	10.17	5.29	0.75	1.91	15.72	-1.40	19.35	4.25

Tabular Figure 6: Results from low altitude stations for the full length of available record (as given in Table 2 and 3) for Tx, Tn, Tavg, DTR and P (rainfall) at monthly to annual time scales in respective units as per ~~Table~~Tabular Figures 4 and 5.

Variable	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Tx	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
P	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

Tabular Figure 7: Field significance of the climatic trends for all regions considered along with trend in their Q at monthly to annual time scales over the period 1995-2012. Color scale as in Tabular Figure 5.

Regions	Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Ann.
Astore	Tx	-0.17									-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
	P			-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
	P	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
	P			-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
	P		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			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
	DTR	0.13										0.09						
	P		2.95	1.97			2.35		1.58	2.15	1.43	2.40	1.57	5.99		5.39	5.76	45.07
	Q	**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	-0.14	-0.11	0.40				-0.20		-0.22	-0.20		-0.25			-0.09	-0.12	-0.09
	Tn		0.49	0.38				-0.13	0.31				-0.17			0.37	-0.14	0.27
	Tavg			0.37				-0.15	0.13	-0.18	-0.16		-0.11			-0.10	-0.12	-0.08
	DTR		-0.19		-0.14			-0.17	-0.24	-0.25	-0.38			0.11	-0.13	-0.10	-0.17	-0.09
	P			-2.17		1.17	-1.42		-2.40	1.65	1.10		1.97	5.98	-11.49	-7.91	3.68	
	Q	1.82	***5.09***	5.37	-2.50	11.35	14.67	-46.60	41.71	35.22	10.17	5.29	0.75	1.91	15.72	-1.40	19.35	4.25
UIB West	Tx	-0.14	-0.11	0.23				-0.18		-0.22	-0.21		-0.25	-0.11		-0.09	-0.12	-0.10
	Tn							-0.12	0.22				-0.18				-0.13	
	Tavg	-0.15		0.20				-0.13	0.13	-0.19	-0.19		-0.11				-0.11	-0.07
	DTR	-0.18	-0.20	-0.10	-0.16			-0.17	-0.24	-0.27	-0.38			-0.10	-0.13	-0.10	-0.19	-0.10
	P			-2.17	-5.71	1.17			-2.40	1.40			1.71	6.90	-11.49	-7.91	2.63	
	Q	2.45	1.37	5.43	2.42	**61.35**	54.89	0.21	42.93	***28.24***	**13.68**	***5.87***	1.38	2.00	**23.43**	44.18	***17.71***	***22.17***
UIB West Lower	Tx	-0.17	-0.10					-0.16		-0.21	-0.20		-0.28	-0.16		-0.07	-0.13	-0.06
	Tn		-0.23					-0.10	0.18				-0.12	-0.18		-0.08	-0.12	
	Tavg	-0.15						-0.13	0.17		-0.19		-0.07	-0.11		-0.06	-0.11	-0.07
	DTR	-0.15	-0.20	0.18	-0.18			-0.13	-0.18	-0.36	-0.25			-0.12		-0.08	-0.19	-0.09
	P			-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	1.88	0.41	6.39	-0.52	41.58	**59.50**	28.19	***81.58***	**30.99**	16.18	5.17	2.33	1.92	19.90	***65.53***	***16.02***	***25.44***
UIB West Upper	Tx	-0.14	-0.11	0.23				-0.18		-0.22	-0.21		-0.25	-0.11		-0.09	-0.12	-0.10
	Tn		0.22	0.13				-0.13	0.25	0.24		-0.18	-0.24	0.17		0.09	0.10	0.05
	Tavg	-0.15		0.20	-0.09			-0.13	0.08	-0.20			-0.13				-0.10	
	DTR	-0.21	-0.22	-0.11	-0.18	-0.25	-0.28	-0.19	-0.36	-0.28	-0.52	-0.38	-0.17	0.06	-0.16	-0.11	-0.19	-0.11
	P	1.30		-1.94		1.17	1.09	1.00		1.40	0.31		2.14	6.90	-10.19	-9.80	2.63	
	Q	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

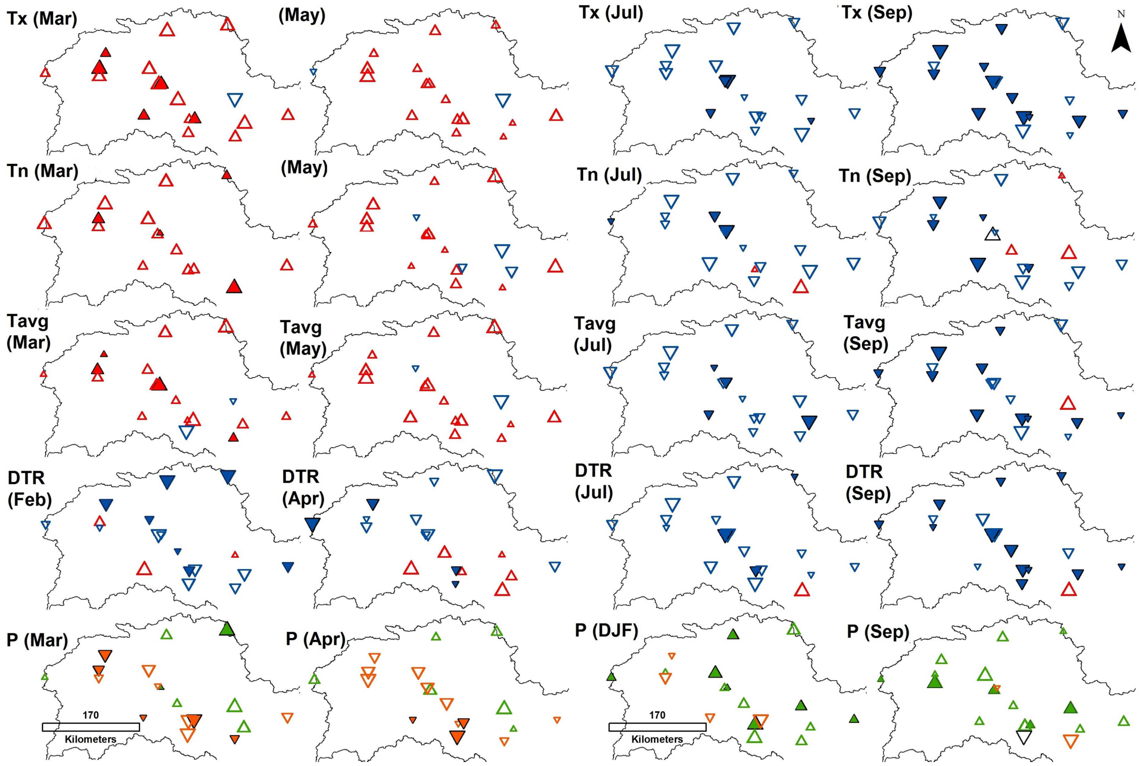

Figure 8: Trend per time step of cooling (downward) and warming (upward) in Tx, Tn and Tavg, and increase (upward) and decrease (downward) in DTR and in P for select months and seasons. Statistically significant trends at ≥ 90% level are shown in solid triangle, the rest in hollow triangles.

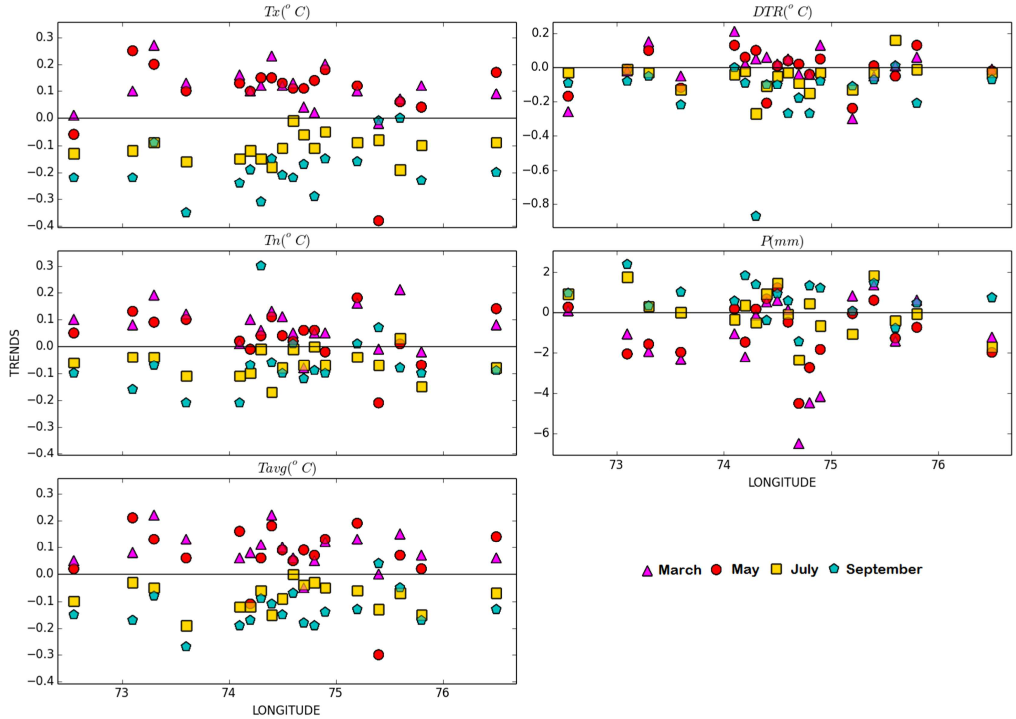

Figure ~~5~~9: Hydroclimatic trends per unit time for the period 1995-2012 against longitude.

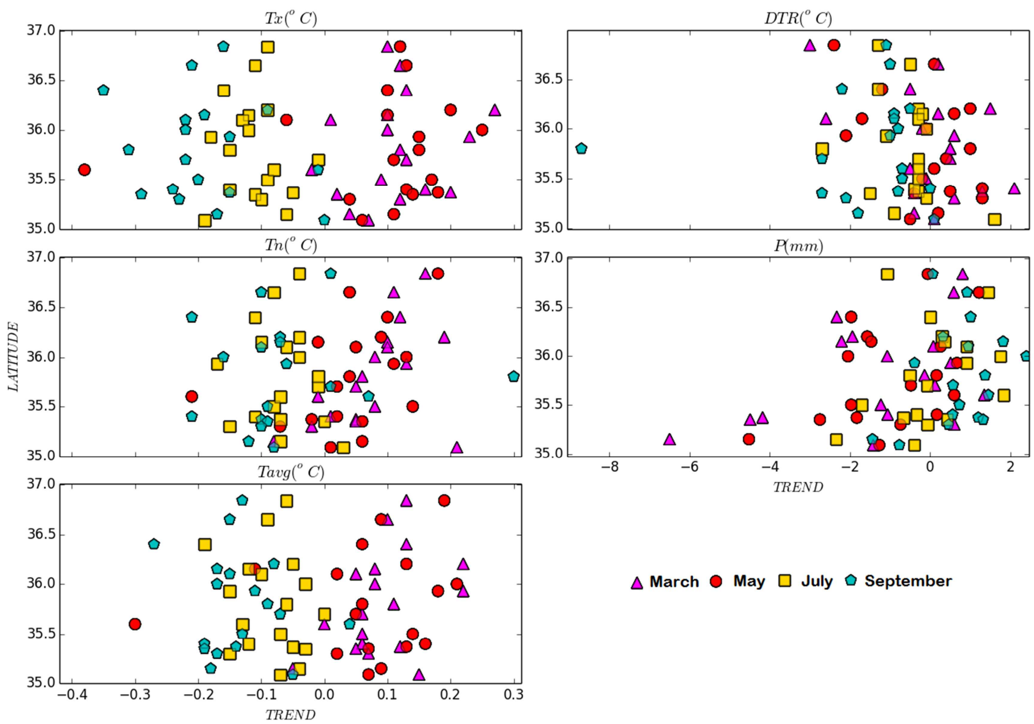

Figure ~~6~~10: Hydroclimatic trends per unit time for the period 1995-2012 against latitude. Here for DTR only overall trend changes over the whole 1995-2012 period are shown.

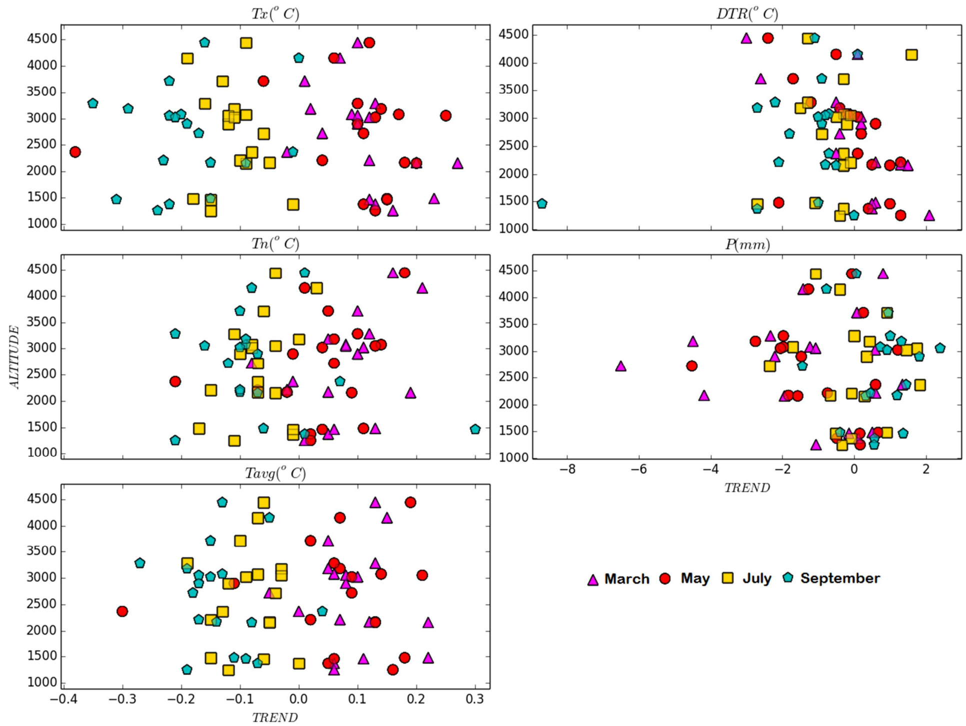

Figure ~~7~~11: Same as Figure 6 but against altitude.