## Responses to Referee (1)

The referee **comments** are highlighted in **black** and numbered with **C1-C12**, whereas the **responses** are in **red**.

**Update:**

Initially we did not provide any supplementary material along with submitted manuscript. However, considering the concerns of reviewers about the ERA5 precipitation bias correction, we added evidence of a few results, relevant to assess the reliability of ERA5 precipitation bias correction, as supplementary material. Here we present the results of four different bias correction approaches (LS-linear scaling, LOCI-local scaling intensity, PT-power transformation and DM-distribution mapping) in terms of some statistical terms. The detailed results of these bias correction approaches with respect to extreme precipitation indices are under review.

Kindly see figure S1 below as supplementary material.

### Mean (mm)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OBS** | 90.63 | 131.91 | 151.97 | 109.21 | 75.18 | 84.73 | 199.52 | 177.36 | 94.32 | 39.59 | 29.66 | 59.13 |
| **RAW** | 102.09 | 184.42 | 198.48 | 138.92 | 63.91 | 92.07 | 267.48 | 245.95 | 90.56 | 50.43 | 51.06 | 82.22 |
| **LS** | 90.63 | 131.91 | 151.97 | 109.22 | 75.18 | 84.73 | 199.52 | 177.35 | 94.32 | 39.59 | 29.66 | 59.13 |
| **LOCI** | 90.63 | 131.91 | 151.97 | 109.21 | 75.18 | 84.73 | 199.52 | 177.36 | 94.32 | 39.59 | 29.66 | 59.13 |
| **PT** | 90.63 | 131.91 | 151.97 | 109.21 | 75.18 | 84.73 | 199.52 | 177.36 | 94.32 | 39.59 | 29.66 | 59.13 |
| **DM** | 89.88 | 131.86 | 151.69 | 107.15 | 70.18 | 79.94 | 200.39 | 180.13 | 92.87 | 38.57 | 29.68 | 59.97 |

**<50**, **51-100**, **101-150**, **151-200**, **>200**

### Coefficient of Variation (-)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OBS** | 3.24 | 2.61 | 2.51 | 2.74 | 2.87 | 2.69 | 2.29 | 2.49 | 3.62 | 4.47 | 5.23 | 4.41 |
| **RAW** | 3.24 | 2.42 | 2.40 | 2.89 | 3.97 | 3.63 | 2.54 | 2.73 | 3.77 | 5.13 | 4.60 | 3.95 |
| **LS** | 3.24 | 2.42 | 2.40 | 2.89 | 3.97 | 3.63 | 2.54 | 2.73 | 3.77 | 5.13 | 4.60 | 3.95 |
| **LOCI** | 3.27 | 2.44 | 2.41 | 2.90 | 3.97 | 3.65 | 2.59 | 2.82 | 3.81 | 5.19 | 4.75 | 4.04 |
| **PT** | 3.24 | 2.61 | 2.51 | 2.74 | 2.87 | 2.69 | 2.29 | 2.49 | 3.62 | 4.47 | 5.23 | 4.41 |
| **DM** | 3.29 | 2.61 | 2.46 | 2.66 | 2.97 | 2.85 | 2.79 | 3.19 | 3.79 | 4.78 | 5.29 | 4.63 |

**<2.90**, **2.91-3.50**, **3.51-4.00**, **4.01-4.50**, **>4.50**

### Wet Day Probability (Rel.)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OBS** | 0.27 | 0.36 | 0.38 | 0.37 | 0.33 | 0.35 | 0.48 | 0.46 | 0.29 | 0.16 | 0.13 | 0.18 |
| **RAW** | 0.39 | 0.51 | 0.48 | 0.41 | 0.30 | 0.36 | 0.75 | 0.79 | 0.42 | 0.24 | 0.22 | 0.31 |
| **LS** | 0.39 | 0.50 | 0.48 | 0.41 | 0.30 | 0.36 | 0.75 | 0.78 | 0.42 | 0.23 | 0.22 | 0.31 |
| **LOCI** | 0.27 | 0.36 | 0.38 | 0.36 | 0.32 | 0.34 | 0.48 | 0.46 | 0.28 | 0.16 | 0.12 | 0.18 |
| **PT** | 0.37 | 0.48 | 0.47 | 0.40 | 0.30 | 0.36 | 0.74 | 0.76 | 0.41 | 0.23 | 0.19 | 0.28 |
| **DM** | 0.27 | 0.36 | 0.38 | 0.36 | 0.32 | 0.34 | 0.48 | 0.46 | 0.28 | 0.16 | 0.12 | 0.18 |

**<0.25**, **0.26-0.35**, **0.36-0.45**, **0.46-0.60**, **>0.60**

### Standard Deviation (mm)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OBS** | 8.76 | 11.55 | 11.44 | 8.91 | 6.30 | 7.46 | 14.28 | 13.62 | 11.30 | 5.50 | 4.77 | 7.81 |
| **RAW** | 10.02 | 15.17 | 14.80 | 12.56 | 7.27 | 11.36 | 20.48 | 20.09 | 10.80 | 8.03 | 7.38 | 9.67 |
| **LS** | 9.05 | 10.97 | 11.30 | 9.77 | 8.71 | 10.18 | 16.07 | 15.51 | 11.92 | 6.39 | 4.31 | 7.12 |
| **LOCI** | 9.13 | 11.06 | 11.37 | 9.79 | 8.71 | 10.21 | 16.33 | 15.94 | 12.04 | 6.46 | 4.44 | 7.29 |
| **PT** | 8.76 | 11.55 | 11.44 | 8.91 | 6.30 | 7.46 | 14.28 | 13.62 | 11.30 | 5.50 | 4.77 | 7.81 |
| **DM** | 9.14 | 11.79 | 11.51 | 8.73 | 6.13 | 7.44 | 17.50 | 18.61 | 11.74 | 5.73 | 4.97 | 8.59 |

**<7.00**, **7.01-10.00**, **10.01-13.00**, **13.01-17.00**, **>17.00**

### 90th Percentile

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OBS** | 8.53 | 15.22 | 15.67 | 11.28 | 7.49 | 8.94 | 20.15 | 18.34 | 8.40 | 1.94 | 1.05 | 3.57 |
| **RAW** | 9.50 | 21.60 | 21.37 | 13.55 | 5.03 | 7.34 | 24.09 | 19.85 | 7.45 | 1.95 | 2.49 | 6.30 |
| **LS** | 8.30 | 15.46 | 16.60 | 10.98 | 5.73 | 6.91 | 17.55 | 13.89 | 7.33 | 1.38 | 1.37 | 4.41 |
| **LOCI** | 8.38 | 15.58 | 16.68 | 11.00 | 5.73 | 6.92 | 17.79 | 14.23 | 7.40 | 1.37 | 1.33 | 4.53 |
| **PT** | 8.53 | 14.81 | 15.80 | 11.31 | 8.10 | 9.79 | 17.99 | 14.33 | 7.46 | 1.96 | 1.07 | 3.83 |
| **DM** | 8.32 | 15.16 | 16.22 | 11.14 | 7.05 | 8.54 | 17.77 | 13.81 | 7.34 | 1.64 | 0.79 | 3.24 |

**<5.00**, **5.01-9.00**, **9.01-13.00**, **13.01-18.00**, **>18.00**

### Precipitation Intensity (mm)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OBS** | 10.86 | 12.97 | 12.76 | 9.77 | 7.29 | 8.27 | 13.26 | 12.41 | 11.28 | 8.44 | 8.48 | 11.01 |
| **RAW** | 8.74 | 13.13 | 13.42 | 11.70 | 7.10 | 10.13 | 11.73 | 10.25 | 7.93 | 8.48 | 8.58 | 8.85 |
| **LS** | 10.892 | 12.8854 | 12.7433 | 9.8907 | 7.67 | 8.697 | 13.0793 | 12.2553 | 11.418 | 8.643 | 8.636 | 10.9 |
| **LOCI** | 10.99 | 13.07 | 12.83 | 9.90 | 7.58 | 8.52 | 13.31 | 12.45 | 11.46 | 8.54 | 8.69 | 11.12 |
| **PT** | 8.03 | 9.77 | 10.37 | 8.97 | 8.27 | 8.81 | 8.93 | 7.58 | 8.26 | 6.53 | 5.29 | 7.03 |
| **DM** | 10.92 | 13.07 | 12.81 | 9.73 | 7.04 | 8.06 | 13.36 | 12.64 | 11.31 | 8.36 | 8.65 | 11.30 |

**<7.00**, **7.01-8.50**, **8.51-10.00**, **10.01-11.50**, **>11.50**

**Figure S1:** Comparison of raw and bias corrected ERA5 precipitation statistics with observed data for the period 1981-2014

**General Comments**

In this paper authors investigate the evolution of wet and dry events collectively in space and time over Upper Jhelum Basin for a period of 1981-2014. They use SPEI index calculated from distribution mapping based corrected ERA5 precipitation estimates and observed temperature data, and locate the hotspot regions for wet, dry and both wet-dry rapid transit events. The idea of the analysis is interesting and the potential for the results is high, however the manuscript remains mostly descriptive.

The paper is well written, with a clear, fluent and concise language and a well-organized structure. I think that the manuscript can provide new insights into understanding the evolution of compound extreme events. Hence, my assessment of the manuscript is overall positive. However, some revision is needed before the work can be accepted for publication in the journal. Below detailed comments are listed:

**Response:** We would like to thank Dr. Muhammad Zaman for his fair and thorough review. Below, we give a comment-by-comment response, indicating the changes we plan to make to the manuscript.

**Specific comments:**

**C1**: Figure 1 is not well explained. I suggest that the authors should revise the figure by showing name or number of the gauging stations. I suggest presenting a detail figure of study area.

**Response:** Figure 1 was updated by incorporating names of each station.

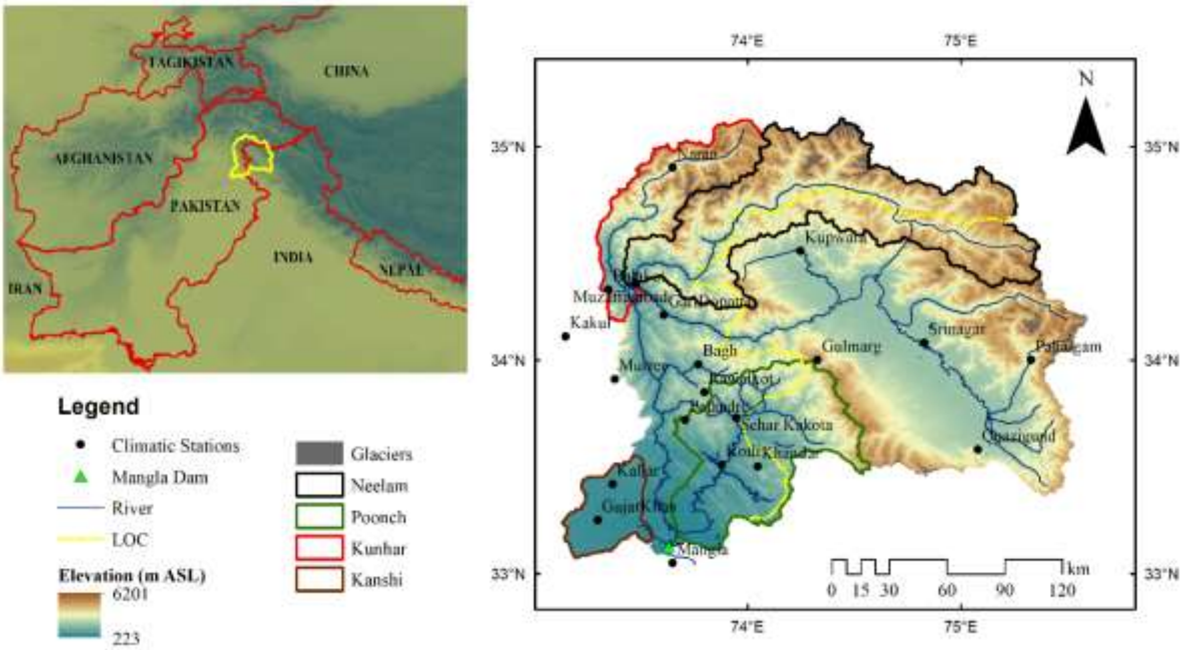

**Figure 1:** Location of the UJB and spatial distribution of climatic stations

**C2**: The writing and English need thorough polishing. Numerous grammatical and rhetorical issues too.

**Response:** The text of the paper was further checked to remove grammar errors and typos.

**C3**. I have some concerns about the introduction section. I think that if the authors wish this paper is well considered by experts, more attention should be devoted to discuss the extreme events in the area. Moreover, this section is lacking clarity and sufficient motivations. I suggest to improve it or better explain with realistic examples. Kindly go through the Zaman et al (2020) for extreme events in the UIB.

**Zaman, M.;** Ahmad, I.; Usman, M.; Saifullah, M.; Anjum, M.N.; Khan, M.I.; Uzair Qamar, M. Event-Based Time Distribution Patterns, Return Levels, and Their Trends of Extreme Precipitation across Indus Basin. Water **2020**, 12, 3373

**Response:** Introduction part was revised to improve clarity and paper motivation. Moreover, the mentioned study is indeed relevant and a reference to it was added in the Introduction chapter of the revised paper.

**C4:** As the data use to carry out a research work is the base of a research work and the most important ingredient. The authors have not provided any detail of the data they have used to carry out their work. I suggest that the authors must provide the complete detail of the data they have used in this research work. Moreover, the authors have applied any homogeneity test on the data to ensure the data quality? In data description section the authors did not mention from where they took observed data and what is the ethnicity of the data. I suggest the authors to go through the Zaman et al 2020 for the data quality and presentation.

**Zaman, M.;** Ahmad, I.; Usman, M.; Saifullah, M.; Anjum, M.N.; Khan, M.I.; Uzair Qamar, M. Event-Based Time Distribution Patterns, Return Levels, and Their Trends of Extreme Precipitation across Indus Basin. Water **2020**, 12, 3373

**Response:** Suggestions were accounted for in the text incorporated under the heading "**Data Description".** Kindly see the updated version of subchapter below:

**Data Description**

The daily observed precipitation and temperature data of 15 climatic stations located within the political boundary of Pakistan were collected from Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA). For the Indian side region, Indian Meteorological Department (IMD) daily gridded precipitation and temperature datasets, derived from a dense network of meteorological stations for the Indian mainland (Pai et al., 2015), were extracted at five stations and used for that region. The analysis was carried out for a period of 34 years (1981-2014), due to the availability of observed data.

In fact there are only a few climatic stations where data are available starting from 1971, but the number of stations would not be enough for the spatial analysis. The observed temperature data was used to calculate potential evapotranspiration (PET) using the Thornthwaite equation (Thornthwaite, 1948) due to data limitation. A study conducted by Beguería et al. (2014) compared the SPEI values calculated with three different methods (Penman-Manteith, Hargreaves, and Thornthwaite) and found small differences in humid regions. Mavromatis (2007) also reported similar outcomes of PET methods for drought indices calculation. Afterwards PET values were interpolated at 0.25$^{o}$ using Kriging with External Drift (KED), considering elevation as a predictor (Goovaerts, 2000). For the precipitation, contrasting reviews are reported in the literature about the performance of KED technique. For instance, (Masson et al., 2014) reported considerable improvement in interpolation accuracy with KED compared to other linear regressions not accounting for any predictor in high mountainous regions. On the other hand, (Berndt and Haberlandt, 2018, Ly et al., 2011) argue that topographical impact was indispensable for only temperature reconstruction at all temporal resolutions and station densities, but its influence was less clear for daily to monthly precipitation. Furthermore, all spatial interpolation techniques can perform poorly in regions with insufficient high-elevation data, due to inaccurate estimation of local lapse rates (Ruelland and Sciences, 2020). Therefore, the distribution mapping (DM)-corrected ERA5 precipitation estimates (0.25$^{o}$ horizontal resolution) were used in the present study. ERA5 is a relatively new reanalysis launched by European Centre for Medium-Range Weather Forecasts (ECMWF) (Saha et al., 2010). The data are developed by using advanced 4Dvar assimilation scheme and provide various atmospheric variables at 139 pressure levels for the period 1979-present time. The DM method adjusts the cumulative distribution function (CDF) of modelled precipitation to match with the observed precipitation CDF using a transfer function (Sennikovs and Bethers, 2009) and it is commonly used to correct the systematic distributional biases (Cannon et al., 2015). The Gamma distribution (Thom, 1958) with a shape and a scale parameter was found to be suitable for the precipitation distribution in the study region (Azmat et al., 2018). The suitability of ERA5 precipitation and bias correction method with respect to extreme precipitation analysis was checked against observed station data and a few results of the reliability check of DM-corrected ERA5 is provided in supplementary material.

**C5:** Line 138, I would strongly suggest adding 2-3 sentences why authors prefer to use distribution mapping method of bias correction of ERA5 precipitation and which frequency distribution was employed/fitted to the precipitation data.

**Response:** Suggestions were accounted for in the text incorporated under the heading "**Data Description".** Kindly see the updated version of subchapter "**Data Description"** in the response of C4.

**C6:** Authors used gridded ERA5 precipitation and observed temperature based potential evapotranspiration for the calculation of SPEI index. Would you please just clarify the reason why authors use gridded and observed data combination instead of use only gridded or observed datasets for both variables?

**Response:** Reviewer concern was accounted for in the text incorporated under the heading "**Data Description".** Kindly see the updated version of subchapter "**Data Description"** in the response of C4.

**C7:** From line 152 onward. Overall, the explanation of SPEI is very easy to understand and I think it should not be substituted by merely a reference to another publication. However, would it be possible to add basic equations to guide some type of readers?

**Response:** More explanation of SPEI with equations was added under the heading **"Wet and Dry Events Identification".** Kindly find the additional explanation of SPEI below:

**Wet and Dry Events Identification**

The calculation procedure of SPEI involves two steps: fitting a log-logistic distribution to the monthly climatic water balance (P-PET) time series and then transforming the cumulative probability of the fitted distribution to a standard normal distribution (with mean equal to 0 and variance equal to 1). Accordingly, in the first step the log-logistic probability distribution function, expressed as:

$$F(x) = [1 + (\frac{\alpha}{x-\gamma})^{\beta}]^{-1}$$

where α, β and γ are the shape, scale, and origin parameters respectively, was fit to the variable x (monthly climatic water balance). In the second step, SPEI was calculated as the standardized value of F(x) as follows:

$$SPEI = W - \frac{C_o + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3}$$

where

$$W = \sqrt{-2\ln(F(x))} \qquad \text{for } F(x) < 0.5$$

$$W = \sqrt{-2\ln(1 - F(x))} \qquad \text{for } F(x) > 0.5$$

The parameters C0, C1, C2, d1, d2, d3 are SPEI constants (Vicente-Serrano et al., 2010). The log-logistic distribution for SPEI calculation was used and recommended by many researchers (Ullah et al., 2021a, Akhtar et al., 2020, Himayoun and Roshni, 2019, Vicente-Serrano et al., 2010). The detailed description of the SPEI calculation procedure can be found in (Vicente-Serrano et al., 2010).

**C8:** The authors used monthly time scale to detect floods and flash droughts. What do you mean by flash drought? Please explicitly define somewhere in manuscript.

**Response:** The flash drought is a relatively new type of drought. Currently, there is not a universally accepted definition or criteria for flash drought, though there is a general consensus on the principle of rapid onset or intensification characterized by moisture deficits and abnormally high temperatures for a period lasting at least 3 weeks (Lisonbee et al. 2021, Otkin et al. 2018, Hunt et al. 2009).

We incorporated this definition in the manuscript.

**C9:** Figure 8, what are the units of transition time? Kindly mention it.

**Response:** Units were added in figure 8.

**C10:** Geographical coordinates are provided in figure 7 only. It would be better to add geographical coordinates to all figures or remove it from figure 7.

**Response:** Thank you for your suggestion. Figure 7 was updated/revised.

**C11:** Rapid transition of wet-to-dry or dry-to-wet event refers to the one extreme event is followed by the opposite event. It must not necessarily happen with similar severity level.

**Response:** Yes, the rapid transition refers to the consecutive events/months of different types (one type of event followed by another type of event), regardless of their severity level. These consecutive opposite events could be of the same or of different severity level.

**C12:** Line 261-263, rephrase the sentence.

**Response:** We rephrased the sentence to make it clearer**.**