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Hydrology and Earth System Sciences
Discussions

HESSD

Interactive comment

Interactive comment on "Drought monitoring and prediction in climate vulnerable Pakistan: Integrating hydrologic and meteorologic perspectives" *by* Taimoor Akhtar et al.

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General Comment: Th paper explores the relationship between meteorological and hydrological droughts in snow-dominated catchments of Pakistan in West Asia. The study aims to provide research findings that can be used in regional operational drought monitoring and early warning based on Standard Precipitation and Evaporation Index (SPEI) and Standard Streamflow Index (SSI). The two indices are calculated as meteorological and hydro- logical drought during identified drought events between 1961 and 2018. Seasonal and lagged cross-correlations between both indices is analyzed and drought characteristics in terms of drought duration and severity are investigated.

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Discussion paper

Five parametric distributions are fitted for calculating SSI.

I believe that the paper requires major revisions. Research assumptions and novel aspects of the study need to be added and highlighted. It is not surprising that a meteorological drought may develop and end rapidly, while the onset of hydrological/agricultural droughts responds to a meteorological drought with some time lag because of hydrological indicators such as soil moisture or reservoir effect. The paper has not addressed benefits/limitations of SPEI and SSI compared to other indices. Additional discussions are required for justifying selected drought indices among other meteorological, agriculture and hydrological drought indices which have not been mentioned in the manuscript but have been investigated in similar research studies in West Asia. Additional analysis and discussions should be addressed with respect to selection of an appropriate probability distribution function for SSI. It is suggested that authors indicate how different aspects of drought characteristics differs in one particular/selected extreme drought event(s) which have had different dynamics. Suggestions for future studies should be addressed based on aspects which have not been taken into consideration in the scope of current study (e.g. comprehensive drought analysis based on inter-comparison of more indices, aspects relevant to agricultural drought).

Response: We sincerely thank the referee for insightful comments that should surely help us in improving the quality of our manuscript. We agree that the assumptions used in the study, especially regarding the choice and aggregation of indices need further elaboration. Hence, we will i) compare three different meteorological drought indices (SPEI, SPI and RDI) to ascertain the most suitable index for the study area, and ii) investigate multiple strategies for grouping gridded SPEIs (e.g., elevation-based grouped averaging) to make better use of the gridded information before correlating with point streamflow deficits. We will also include nonparametric approaches in the comparison of distributions. Finally, we will include a multivariate regression analysis to better represent the spatiotemporal correlations (with lead time) between SPEI and SSI for the 4 catchments analyzed in this study.

Point-by-point Reply to Comments:

- I was not able to find any methodology or findings with regard to drought prediction in the paper. Therefore, I suggest omitting the world "prediction" from the title.

Response: We agree that the manuscript in its current form does not attempt to predict droughts in streamflow using climate data. However, we plan to include a multivariate regression analysis in the revised submission that will attempt to predict SSI-1 using lagged meteorological indices.

- Line 4: It is suggested to use both terms of "indicator" and "index" based on established definitions in the entire manuscript. For example, you might refer to definitions provided in:

World Meteorological Organization (WMO) and Global Water Partnership (GWP), 2016: Handbook of Drought Indicators and Indices (M. Svoboda and B.A. Fuchs). Inegrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva.

Response: We thank the referee for this comment, and we will revise the manuscript to ensure that the terms "indicator" and "index" are used, as defined in the above-mentioned Handbook.

- Lines 123-126: There are other observation-based gridded data available in the study region for precipitation, e.g. APHRODITE in Monsoon Asia domain (http://aphrodite.st.hirosaki-u.ac.jp/products.html). In addition, recent datasets have been developed based on several information and not solely based on reanalysis which their performance must be investigated compared to reanalysis or station-based dataset. For example:

Beck, H. E., Wood, E. F., Pan, M., Fisher, C. K., Miralles, D. M., van Dijk, A. I. J. M., McVicar, T. R., and Adler, R. F. 2019. MSWEP V2 global 3-hourly 0.1 precipitation: methodology and quantitative assessment, Bulletin of the American Meteorological Society 100(3), 473–500.

Response: We agree that numerous precipitation datasets are available for the study area, including but not limited to APHRODITE, GPM, GLDAS, WEI etc. Some prior studies show that observation-based datasets perform better than reanalysis-based datasets in the Asia Pacific region. We chose CRU for this study, since it is an observation-based dataset. Moreover, the data availability time period for CRU is more than other popular observation-based datasets (e.g., APHRODITE which is available from 1976-2015, and GPM which is available from 2000-now), and CRU data is available for the entire time period for which streamflow data is also available (1961-2018). However, we agree with the referee's comment on investigating other datasets. Thus, we will include a comparison of CRU and APHRODITE with station data in the revised submission, and consequently compute SPEI-based on the best performing dataset.

- Is there any particular reason why CRU TS4.03 is selected among other available dataset? Authors may provide additional arguments on this point.

Response: Kindly refer to our response to the previous comment.

- The time period of meteorological data used for SPEI calculation must be provided.

Response: SPEI was calculated for the same time period for which streamflow data is available, i.e., 1961-2018.

- Line 83: In order to claim and highlight that gridded climate datasets can be a reasonable alternative to station data for drought analysis in catchments under study, referring to other studies is not enough. At least, uncertainty of several grided data must be investigated and communicated and a comparison between existing station and gridded data be investigated based on existing literature.

Response: We agree that referring to other studies is not enough to ascertain the accuracy of a chose dataset. Thus, we have computed correlations between CRU TS4.3 and observed precipitation (mm) of six stations within the study area (4 catchments), and results are provided in the attached Figure 1. The stations analyzed and corresponding catchments (mentioned within brackets) to which they belong to are: Jhelum (Jhelum), Peshawar (Kabul), Chitral (Kabul), Gilgit (Indus), Kotli (Jhelum) and Muzaffarabad (Jhelum). These stations are maintained by Pakistan Meteorological Department (PMD). In Figure 1, observed precipitation (mm) are compared to corresponding values of nearest grid point available in the CRU data sets, with R squared values ranging from 0.5-0.75. We will include these comparisons in the revised manuscript as well, and will also include more stations, if available. Moreover, we will also include APHRODITE precipitation in the comparative analysis, and use the precipitation product for SPEI calculations, that better correlates with station observations.

- Line 96 – Figure 1: Please use the same map projection as figure 2. A map which shows the location of four western river catchments together with upper and lower Indus can be significantly informative.

Response: Agreed. We will revise the figures to use the same map projections, and will also include boundaries of the four western river catchments.

- Line 96 – Figure 1: Why the period of 1901 to 2018 is considered for drawing the map? It is very likely that homogeneity of data in the early century is influenced by number of stations which has been used in CRU dataset.

Response: Our purpose was to maximize the value of available data. However, we agree with the referee's comment regarding the influence of stations and thus will revise Figure 1 to include climate data for 1961-2018 only, i.e., the streamflow time period.

- Please provide maps for the similar period used for the streamflow (1968-2018).

Response: We agree on this, and we will revise Figure 1 to include data for 1961-2018 only.

- Method which is used to calculate PET must be explained.

Response: PET values are directly taken from the CRU dataset, which computes it via the Penman-Monteith method. Further details are provided in:

Harris, I., Osborn, T.J., Jones, P. et al. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci Data 7, 109 (2020). https://doi.org/10.1038/s41597-020-0453-3

- Providing the extent of Indus Basin Irrigation System (IBIS) in either Figure 1 or 2, can significantly help to understand area under study and for mechanisms of drought management.

Response: The Indus Basin Irrigation System (IBIS) is not part of the study area and is downstream of the 4 streamflow stations analyzed in this study. However, a major proportion of water withdrawals within IBIS originate from these 4 streamflow stations, and are also planned based on the streamflows of these stations as well. We allude to this in lines 99-102 and 117-120 of the manuscript. Consequently, streamflows at these stations are critical for agricultural water supply, groundwater recharge, and overall water balance of the Lower Indus Basin. This is why we chose to investigate streamflow droughts at these stations, via the Standard Streamflow Index (SSI). Given the importance of IBIS for the motivation behind this study, we agree with the referee that it is important to visualize IBIS and its extents to better understand the study area and its possible drought mechanisms. Figures 1 and 2 will be revised in the resubmission to include extents of the area covered by IBIS.

- Is there any significant agricultural activities upstream of selected streamflow gauge stations?

Response: There are no significant agricultural activities upstream of the selected streamflow gauge stations in the Upper Indus, Chenab and Jhelum catchments. The Kabul basin has some agricultural activity upstream of Nowshera (the streamflow gauge analyzed in this study). However, river withdrawals from Kabul, upstream of Nowshera, are a small proportion of its flows. For this study, we assume that they are negligible. We will state this assumption clearly in the revised manuscript, since agricultural activities are rapidly increasing in the Kabul basin (upstream of Nowshera). Some details regarding land-use changes in the Kabul basin are discussed in:

Khan, H.F, Yang, Y.C.E, Wi, S. Case Study on Hydropolitics in Afghanistan and Pakistan: Energy and Water Impacts of Kunar River Development. Journal of Water Resources Planning and Management, 146(9) (2020).

- The role of reservoirs in water resources and drought management needs to be highlighted.

Response: We agree that reservoirs play a critical role in drought management. The two major surface reservoirs of IBIS, i.e., Mangla and Tarbela, are immediately downstream of two streamflow gages of this study. Hence, we do not include them in the current analysis. We feel that their planning and operations can be indirectly linked with streamflow droughts at these gages. We will include some discussion on this in the revised submission.

- Line 130: Providing monthly time series of streamflow records of four selected gauges can help understanding hydrological regime in the region.

Response: Daily streamflow records of the selected gages are recorded by the Water and Power Development Authority (WAPDA) of Pakistan and are available at: https://www.wapda.gov.pk/index.php/river-flow-in-pakistan

- Section 3.1. The performance evaluation and inter-comparison of different drought indices is necessary for identifying and selecting appropriate drought indices which has been addressed by authors. However, it is not conclusive why SPEI and SSI are selected specifically for representing meteorological and hydrological droughts in the study region? For example, several studies have shown the high performance of Effective Drought Index (EDI) which is also a standardized index. Discussions on criteria for selection of suitable drought indices in the research must be explained based on evaluation of several indices (more than two) and in the context of their performance in early warning of drought's onset, severity, persistence, and spatial extent within region under study. At minimum, the performance of other drought indices which was assessed for basins with similar climate in West Asia must be addressed. For example:

Wable, P.S., Jha, M.K. and Shekhar, A. 2019. Comparison of Drought Indices in a Semi-Arid River Basin of India. Water Resources Management, 33, 75–102. https://doi.org/10.1007/s11269-018-2089-z

Response: The rationale behind choosing SPEI as the preferred meteorological drought index is its ability to incorporate both precipitation and evapotranspiration, which is important in the snow-dominant catchments analyzed in this study. We discuss this rationale in lines 152-157 of the manuscript. Another reason for using SPEI, specifically is that its computation methodology and interpretation are similar to SPI, which as per our knowledge is the preferred meteorological drought used by Pakistan's National Drought Monitoring Centre (NDMC) (see line 38 of manuscript). One of the desired outcomes of this study is to illustrate that a drought index that incorporates both precipitation and evapotranspiration is more informative for the study area. Hence, we do agree with the referee's comment that multiple indicators should be compared. We will thus include a comparison of SPI, SPEI and RDI in the revised manuscript. We intend to include RDI in the mix, since, as aptly noted by the referee, RDI may be computed without fitting a distribution since it only requires log-transformation.

- Section 3.1. With respect to general information provided in lines 49-56, why authors did not explore agricultural drought based on soil moisture which is relevant for Indus Basin Irrigation System (IBIS) planning?

Response: As mentioned in an earlier response, the lower Indus basin's agricultural demands (supplied via the Indus Basin Irrigation System (IBIS)) heavily rely on the unregulated streamflows of the 4 station analyzed in this study (see lines 109-112 of the manuscript). A major proportion of water withdrawals within IBIS originate from these 4 streamflow stations, and all seasonal plans and daily IBIS operations are also based on the streamflows of these stations. IBIS is not a demand-driven system, since surface storage capacities within the system are insufficient for ensuring on-demand water supplies. Agricultural withdrawal plans are thus primarily based on streamflow availability at these stations. This is why we chose to investigate streamflow droughts at these stations, which will also be indicative of deficit water agricultural water availability.

- Line 159: There are other meteorological indices which are based on both precipitation and potential evapotranspiration and do not have complexity of fitting probability distribution (e.g. Reconnaissance Drought Index (RDI)). Please provide argument on selection of SPEI over same indices.

Response: As mentioned in an earlier response, we will compare SPEI with RDI in the revised manuscript. However, our initial premise for using SPEI was that its interpretation is similar to SPI, which is already used for drought monitoring in Pakistan.

- Line 166: It looks like that the basis of all analysis to evaluate the coherence between the two drought indices is SPEI calculated based on areal-average (at catchment level) and its comparison to the gauge point at the outlet of the corresponding catchments. However, Figure 11 suggests that spatial variability of SPEI can be high for a particular drought event at least for Indus sub-basin. Authors require to provide convincing arguments to support any assumptions made on the subject.

Response: We will investigate an appropriate strategy for grouping gridded SPEI values (e.g., via elevation bands) before correlating them with SSI values at the gauge points. We agree that gridded SPEI values can be utilized better in this analysis.

- Line 176: Standard Streamflow Index (SSI) should not be confused with the Standardized Runoff Index (SRI), see e.g. Shukla and Wood (2008).

Response: We thank the referee for correcting us on this. We will modify line 176 of the manuscript accordingly.

- Averaging meteorological fields over a spatial domain can have a smoothing effect of extreme values especially in complex topographies. In addition, comparison of two indices which are calculated in the same spatial domain (grid to grid/ areal-average to areal-average/pointwise) is more reasonable than comparing an index which is calculated by areal-averaging (SPEI in this case) with another index which is calculated on its outlet (SSI in this case).

Response: This is a very interesting point. In-fact, in our initial experiments, we computed grid-based SPEIs and averaged them over the catchment before comparing against SSI. The results seemed similar. We will investigate this further before resubmission and report our findings. We thank the referee for this insight.

- Since SRI can be calculated and provided based on the same resolution as SPEI, authors are requested to argue why they SSI is selected over SRI.

Response: As mentioned in earlier responses, the 4 streamflow gages analyzed in this study are critical points of interests to Pakistan's water managers, we are motivated to investigate how meteorological drought indices can allude to droughts at these critical points. Thus, we chose SSI over SRI for this study. These 4 streamflow gages, also called system 'rim stations' are critical indicators of water availability for IBIS, and also dictate how water is allocated to the stakeholders of IBIS. While some discussion on this is provided on lines 109-116, we will elaborate further on this in the revised manuscript.

- Section 3.1.2. To avoid the computational burden in fitting parametric distributions, it is a common practice to use an empirical cumulative probability distribution. Authors are suggested to provide additional discussion on comparison between parametric and nonparametric approaches for calculating SSI to fulfil the purpose mentioned in lines 358-359.

Response: Agreed. We will also include nonparametric approaches in the comparison of distributions.

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Discussion paper

- Section 3.3 The title section might not well represent the contents of this section. Cross-correlations and lagged cross-correlations between meteorological and hydrological drought indices is introduced in this section as methods to investigate drought characterization and the use of term “integrating” for this case might be misleading.

Response: Agreed. We will revise the title of this section to adequately and accurately represent its contents.

- Figure 7: It is not clear if streamflow gauges record reservoir inflow or outflow? With regard to that point, please provide reasoning why Jhelum and Kabul have higher drought durations based on SSI? Authors might argue with respect to how hydrologic memory plays role in those sub-basins in terms of groundwater storage, reservoir, snowpack, and soil moisture.

Response: The streamflow gauges record reservoir inflows. We believe that the higher drought durations in Jhelum are indeed be due to storage effects, specifically storage in snowpack. The Jhelum has a higher dependence on snowmelt, in comparison to other catchments. This trend is discussed in:

Charles, S.P, Wang, Q.J, Ahmad, M. et. al. Seasonal streamflow forecasting in the upper Indus Basin of Pakistan: an assessment of methods. Hydrology and Earth System Sciences, 22, 3533–3549, (2018). https://doi.org/10.5194/hess-22-3533-2018

The reasoning is similar for Kabul. We will include a discussion on this in the revised submission.

- Figure 8: Please specify if the figure is based on areal-average of all four catchments and provide the same heat-map based on SSI-3 and SSI-6.

Response: The figure is based on computation of SPEI on the entire catchment after aggregating of climate variables across all grid cells. A figure that includes SSI-3 and SSI-6 is attached as Figure 2 of this response.

- Line 299: Readers might expect results based on statistical methodologies which are applied to identify possible trend components in any hydro-meteorological time series whereas monthly cross correlations are investigated in this section. It is recommended to modify title accordingly.

Response: We will change the title of this section to “Monthly Cross-Correlations” in our revision.

- Line 314-315: Attributing weak cross-correlations for summer and fall to CRU error needs to be verified with other datasets.

Response: Agreed. As mentioned earlier, the revised manuscript will include a comparison of CRU against APHORDITE as well. We will also analyze cross-correlations computed with APHRODITE to see if there are any differences in summer and fall cross-correlations.

- Figure S3: Representing a flood event based on monthly evaluation of SPEI-12 needs to be reconsidered.

Response: We agree with the referee. Figure S3 will be removed from the supplement.

- Lines 375-380: The title suggests integrating hydrologic and meteorologic perspectives is the one aim of the study based on analysis of SPEI and SSI. Cross-correlation and lagged cross-correlations are calculated to evaluate the relation between two indices. Authors finally conclude that SPEI could be used in operational drought forecasting and warning system based on strong correlations. However, I believe that this conclusion is highly controversial as a drought index which is going to be used for operational regional drought monitoring and prediction system must be robust for different hydroclimate conditions and in areas where spatiotemporal variability of hydroclimate variables is high, for all months. In addition, the uncertainty of gridded data has not been thoroughly investigated in this study and many of the findings reported in the manuscript are based on analysis of indices calculated in different spatial domains (areal-average against point measurements). Authors should provide strong arguments on the concerns mentioned above.

Response: We agree with the referee on this. In order to improve our investigation and related arguments, we will i) incorporate comparison of CRU with Aphrodite and Station observations to ascertain the best possible precipitation dataset to be used in the analysis, ii) compare three different meteorological drought indices (SPEI, SPI and RDI) to ascertain the most suitable index for the study area, and iii) include a multi-variate regression analysis between SPEI and SSI to better understand the correlations between streamflow deficits and gridded SPEI calculations. Multiple strategies for grouping gridded SPEIs will also be explored (e.g., elevation-based grouped averaging) to make better use of the gridded information before correlating with point streamflow deficits.

Technical Comments

- Please Check punctuations in entire manuscript for period and comma (e.g., in lines 28, 104, 296)

Response: We will correct these in the revised submission.

- Line 140: Use appropriate way for citations at the end of the sentence. - Line 158: A paragraph contains more than one sentence.

Response: Noted. We will make these corrections.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-297, 2020.

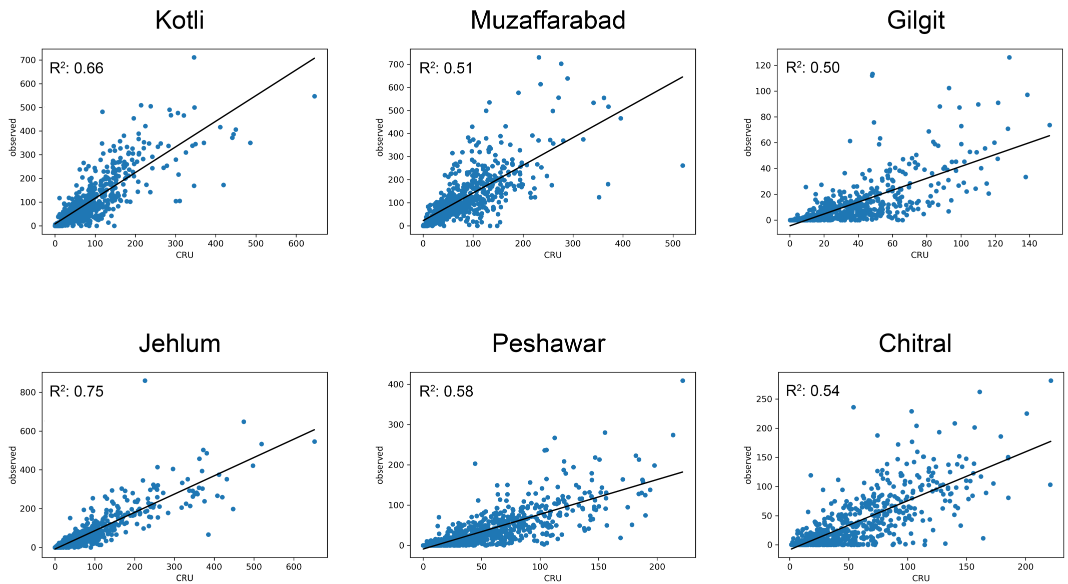

Fig. 1. Comparison of monthly CRU precipitation with station observations.

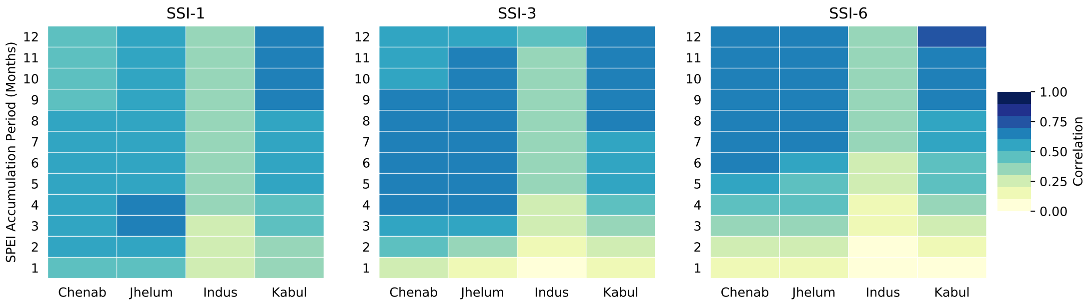

Fig. 2. Heatmap of cross-correlations between SSI-1 and SPEI (for different accumulation periods) for the four Upper Indus catchments, i.e., Chenab, Jhelum, Indus and Kabul.