

Dear Editor and Reviewer,

Thank you for your letter and the reviewer's comments concerning our manuscript entitled "Drought cascades across multiple systems in Central Asia identified based on the dynamic space-time motion approach" (hess-2023-140). These comments are valuable and helpful for revising and improving our paper and providing significance to our research. We have carefully considered the words and made corresponding responses. The responses to the reviewer's comments are listed below.

The reviewer's comments are in red text, while the responses are in black. We use the blue text to denote the content that will be added to the manuscript.

General comments

The present paper proposes a novel framework for tracking drought cascades across 10 multiple systems by utilizing dynamic space-time motion similarities. The method seems innovative and the topic interesting. However, due to problems in logic, I would recommend major revision before moving to the next step.

Response: Thanks very much for your positive comments on the innovation of this study and for pointing out the logical problems!

Major comments

1. The introduction of the method, which is the core of the study, is unclear. For example, are the drought pixels a function of (lat, lon) or (time, lat, lon). How are the drought cells clustered, using which criteria or method. What metric(s) is used to determine similarity? I see some in the paragraph, but the vague description using the text is insufficient in clarification.

Response:

Thank you for raising the issue of the study methodology. In order to improve the understanding of the methodology, we will act on the several aspects as below.

- First, the drought pixels were defined by the one-dimensional (1D) function. The drought index value within each pixel is calculated with the time series of precipitation, evapotranspiration, runoff, and soil moisture. We will add the Standardized Drought Analysis Toolbox (SDAT) equation for calculating four types of drought index in section 2.3.1, as below.

$$p(x_i) = \begin{cases} \frac{i-0.44}{n+0.12} & \text{for } x > 0 \\ \frac{n_0+1}{2(n+1)} & \text{for } x = 0 \end{cases} \quad (1)$$

i: the ranking position of accumulation value; n: the sample size of all accumulation values within each pixel.

Adjacent drought pixels with common sides were clustered each day to form spatially contiguous 2D drought clusters (latitude and longitude) for each day. Contiguous regions of 3D drought events are tracked over time by looking for overlapping areas between 2D clusters on two consecutive days. If there is an

overlapping area between 2D clusters on two consecutive days, the clusters are considered to be a single 3D drought event.

- Second, the schematic diagram of the methodology (Figure.2) will be updated as follow:

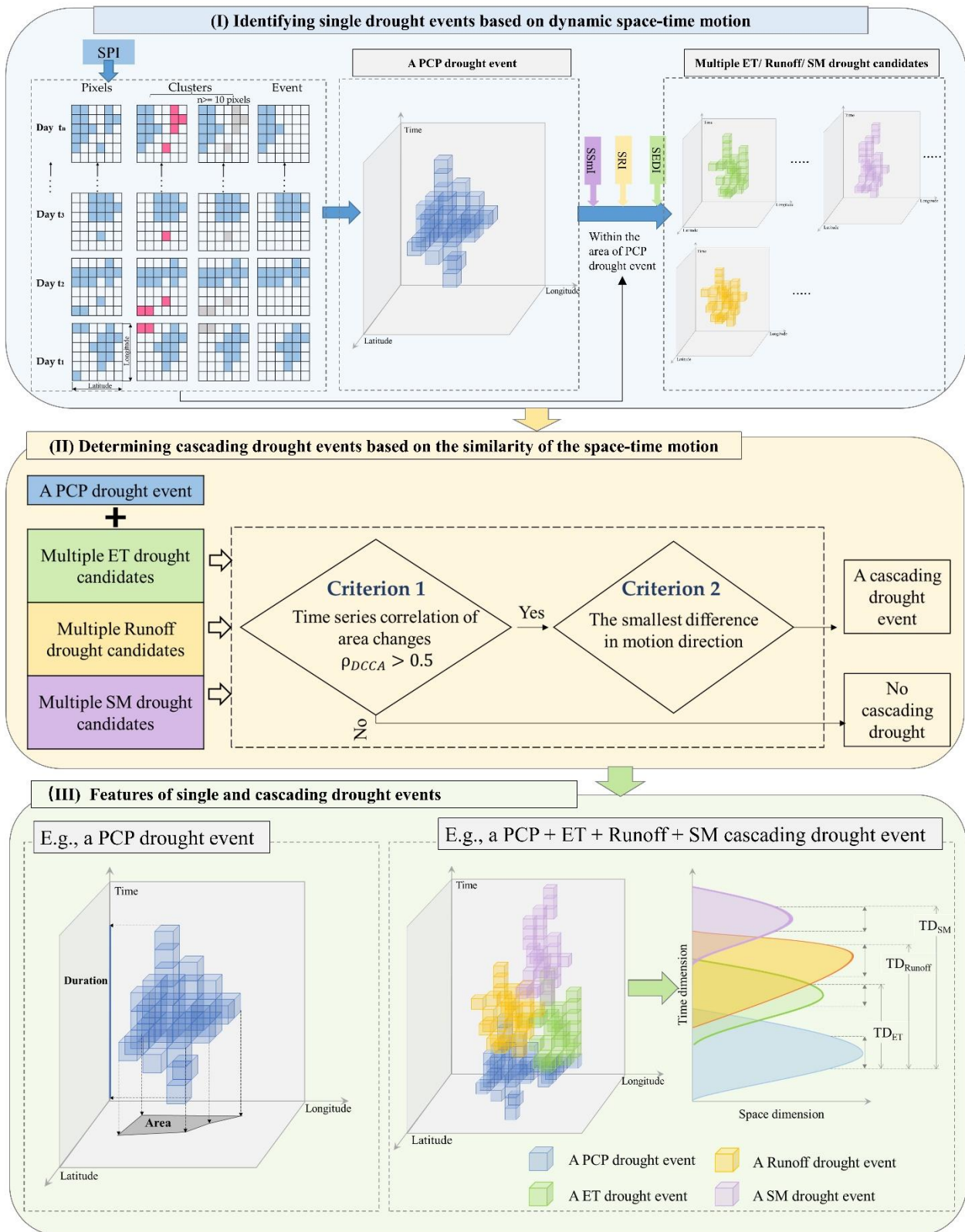


Figure.2. Schematic diagram of methodology detecting the multiple-system cascading event from the space-time dimension

- Third, there are two metrics adopted in this study. The first metric is the time series correlation of the area changes of a PCP drought event and its ET/Runoff/SM drought candidates, elaborated in Lines 185-210. The second metric is the difference in the direction of movement between the PCP drought event and its ET/Runoff/SM drought candidates, which was elaborated in Lines 211-218.

We will add Figure R1 in the manuscript to illustrate the second metric.

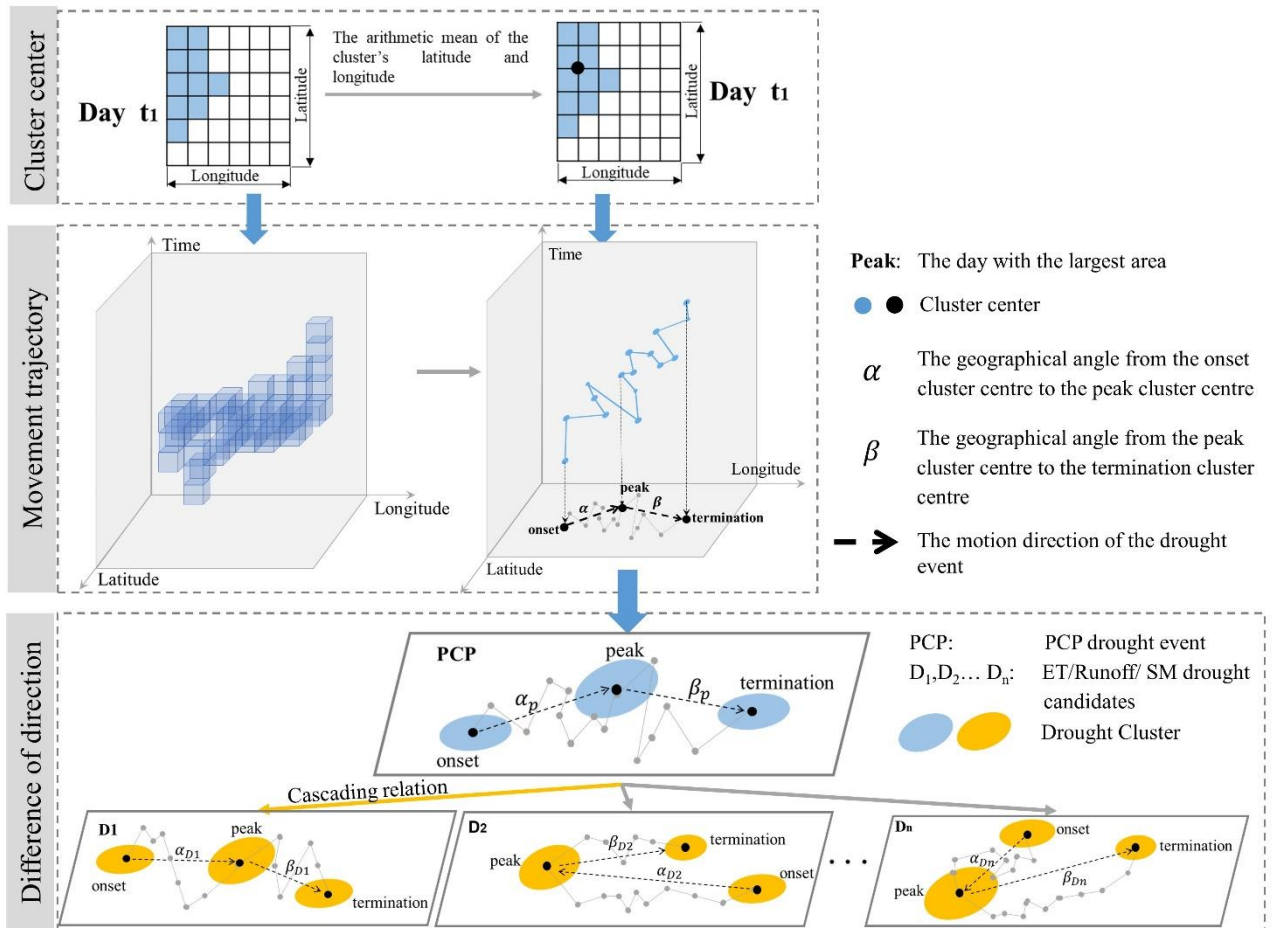


Figure R1: The schematic diagram for identifying the motion direction of a single drought event and a cascading event according to the metric of similarity in spatial motion

2. Loose logic problem. For example, in the method part (section 2.3), the introduction in section 2.3 seems too vague, and does not give you a general idea of the method. It does not give you an idea of the inner-connections between the sub-sections. Also, the section 2.3 has too much sub-sections that is un-necessary, consider combining the sub-sections to make the section more neatly.

Response:

Thank you for the comments on the structure of section 2.3. We will address several aspects below to make the section logic more compact and cleaner.

- First, I will generally describe the methodology structure at the beginning of section 2.3 to emphasize the connection between identifying single drought events in section 2.3.1 and cascading drought events in 2.3.2. The original content in the manuscript from Lines 132-139 will be replaced by the below text:

The approach proposed here is summarised in three parts (Fig.2). The three-dimensional (3D) single drought event is identified in section 2.3.1 based on the continuously dynamic space-time motion. In section 2.3.2, we integrated the different types of single drought events with similar space-time motion to form the cascading drought event. The features of single drought events and cascading drought events focusing on this study were introduced in 2.3.3. As precipitation deficits are generally considered as the initiation of droughts, PCP droughts are considered the commencement of a cascading drought event in this study.

We will add “single” to the title of section 2.3.1 and revise it to ‘2.3.1 Identifying single drought events based on the dynamic space-time motion’.

We will add “single drought event” to the title of 2.3.3 and revise it to ‘2.3.3 Features of single and cascading drought events.’

- Second, we will combine the sub-section 2.3.1.1 and 2.3.1.2 in section 2.3.1. The updated section 2.3.1 will be elaborated into three parts: 1) drought pixel, 2) drought cluster, and 3) drought event. We will add a description at the beginning of section 2.3.1 to give an overview of defining the 3D single drought event.

“Here, a single 3D drought event is defined by space-time continuum motion to account for the spatial variations in drought development, the approach including the definition of 1) drought pixels (1D, function of time), 2) drought clusters (2D, function of latitude and longitude), and 3) drought events (3D, function of time, latitude, and longitude). The PCP drought event was identified based on these three steps. Within the area of each PCP drought event, the above three steps were repeated to identify its ET/Runoff/SM drought candidates. The detailed detection approach is as follows.”

- Third, in section 2.3.2, the sub-section of 2.3.2.1 and 2.3.2.2 will be combined. Section 2.3.2 will describe corresponding two criteria determining the cascading drought event, namely:

Criteria 1: Correlation of time-series area changes of the PCP drought event and its ET/Runoff/SM drought candidates.

Criteria 2: Similarity in motion direction between the PCP drought event and its ET/Runoff/SM drought candidates.

3. Confusing subsection in discussion. There's no need to break into too many subsections. Also, it is not clearly to me what the discussions are for? In common discussions, it is usually to raise up an interesting issue with one or more paragraphs. But the discussion here seems to be more apt in the results. Other paragraphs about the issue can be put in discussion.

Response: Thanks for pointing out the problems in the discussion! We will combine sections 4.1 and 4.3 to form a new section and move the new section to the result part (Section 3.5) to make the discussion neater. The discussion will focus on two aspects: 1) the driving mechanism behind the cascading drought pattern and 2) the comparison between the approach proposed in this study and previous studies. We will revise and reorganise the discussion section as follows.

First, the title of the new section 3.5 will be revised to “Characteristics of PCP drought could signalize systematic drought risk of cascading events.” Section 3.5 emphasizes three following points. To make the structure of Section 3.5 clear, we will add the following three sentences at the beginning of the first, second, and third paragraphs of Section 3.5, respectively.

- 1) Cascading drought events, which present a systematic drought risk induced by drought evolution, deserve more attention than the traditional focus on individual droughts due to their higher severity (Fig. 7) and the more dynamic spatial and temporal scope.
- 2) Single droughts in terrestrial systems persist longer than atmosphere droughts (PCP droughts).
- 3) As the commencement of the cascading drought event, precipitation has the more readily available data compared to ET, Runoff, and SM. To examine if the PCP single drought events could signify the severity of systematic drought risk, features of PCP drought in the cascading events involving the different amounts of systems were investigated in Fig. 8.

Second, the purpose of the original Section 4.2 is to discuss the possible driving mechanism of the cascading drought phenomenon reflected by the different patterns in Central Asia. The title will be revised: “Integrated driving effects of energy-limited and water-limited regimes on cascading drought patterns in CA.” The response to the other reviewer's comments presents evidence proving this hypothesis (Figure R1). This section will be rewritten as below:

Multiple cascading drought patterns with mixed temporal order were identified in this study. The result likely reflects the integrated driving effect of the water-limited and energy-limited phases. When at the energy-limited phase, the soil moisture is sufficient and does not regulate the evaporation. During this period, the precipitation deficit might enhance the potential and actual evaporation demand. The cascading drought pattern might present the PCP+Runoff, PCP+Runoff+ET, or PCP+ET+SM. When the water-limited phase begins, PET could continue to increase. However, the increase in AET is no longer sustained and subsequently decreases as soil moisture is limited, during which the evaporative deficit gradually increases and evaporative droughts are

exacerbated (Pendergrass et al., 2020). During the water-limited phase, the cascading drought pattern possibly presented as the PCP+SM+ET.

The three most common cascading drought patterns identified in this study are PCP+ET+Runoff, PCP+Runoff+ET and PCP+ET+Runoff+SM. This result could be explained from two aspects. 1) The drought signal in soil moisture only sometimes are detected. 2) Given the more significant evaporative deficits in the water-limited phase, the significant ET droughts signal after PCP droughts shown in the cascading drought pattern indicates the occurrence of cascading droughts under the water-limited phase. This result could be due to three possible reasons. First, the SM data adopted in this study are from the soil layer of 40-100cm. The shrubland and grassland with short roots are the dominant vegetation in the study area (Klein et al., 2012), and their root density is typically concentrated on the 0-40 cm soil layer (Kurc and Small, 2007). It could result in lower vegetation water requirements and less fluctuation of the space-time signal of soil moisture in the deep layer.

Second, the coupling of SM and evaporation raw data might not be reflected by their drought index. The fluctuation in deep layer soil moisture is most stable relative to the precipitation and runoff (Van Loon, 2015). The SM drought index might not recognise declines in SM in the constantly dry region that fluctuates within a small magnitude. Moreover, the spatio-temporal progression of SM and ET droughts is different. The spatiotemporal progression of SM droughts is the slowest compared to the other three droughts, which is reflected by the fact that SM droughts are the longest in duration and the smallest in area (Fig.4).

Third, the effect of energy-limited regimes could be underestimated in Central Asia. Hsu and Dirmeyer (2023) recognized most of Central Asia as the transitional and energy-limit regime. Yuan et al. (2023) found that around 30%-50% of soil moisture drought events in CA are flash droughts possibly induced by the precipitation deficit and increased evapotranspiration at the energy-limited phase. This could be presented as the PCP+ET+SM or PCP+ET+Runoff+SM cascading drought pattern. Central Asia is typically characterized by significant warming in the past years than the average worldwide (Mirzabaev, 2013). Under significantly warming conditions, annual evapotranspiration (ET) significantly increased during low precipitation and sequentially amplified the runoff deficit in the alpine (Mastrotheodoros et al., 2020). Zhao et al. (2022) found that previous studies overestimate the reduction in evaporation from bare soil during droughts in arid climates under water-limited regimes. They found that ET increases during almost half of the drought months worldwide (drought was defined by the deficits in precipitation and total water storage) as a result of increased atmospheric water demand outweighing the limiting effect of soil moisture supply on ET. Possible reasons may be that conventional modelling of the ET response to soil moisture stress downplays the deep soil moisture supply to ET, could better constrain plant drought response traits and ignores the effects of soil structure on soil hydraulic conductivity.

The driving mechanism of large-scale drought evolution is highly complex involving modulators (atmospheric oscillations), climate drivers (precipitation and temperature), feedback of land surface phenology, and anthropogenic activities. All these factors and their interactions construct the initial condition and running situation for drought evolution and trigger the variation of cascading drought patterns. In this study, the diversity

of topography and land surfaces complicates the regional climate regimes of Central Asia. The introduction of spatiotemporal movement in the definition of cascading drought events has resulted in that a cascading drought event may be involved in multiple climatology-land-cover regimes, further adding to the complexity of identifying the driving mechanism. Therefore, the simple comparison or common correlation method with single factors, often applied at gauge/catchment scale, may not be appropriate for exploring the driving mechanism of the large-scale cascading phenomenon. More information and an appropriate attribution framework need to be explored in the next stage.

The purpose of section 4.4 is to compare and discuss the difference between the previous method and the method developed in this study. Because the reviewer also mentioned this in the fourth comment, this part will be explained in the response to the fourth comment.

4. Is there a comparison with the other drought identification methods/indices? It would be good if the authors are comparing this method to other similar methods or single indices to strengthen the core value of this method.

Response: Thanks a lot for the suggestion! We fully agree that it is crucial to compare the method of this study with other methods for similar purposes. To illustrate the difference clearly, section 4.4 (A new framework to detect high-dimensional drought cascades) will be reconstructed as four paragraphs corresponding to the four aspects.

First, we will compare this study with the common pointwise/catchment-wise correlation method. The content in Line 395-397 will be revised as follows:

Many studies are customized to link meteorological drought to hydrological drought by point-to-point time series correlation based on the drought index (Geyaert et al., 2018; Guo et al., 2020; Van Loon et al., 2012). These studies identified their lag, attenuation, prolongation, and pooling based on the time series between two drought types. However, these studies are often conducted at a fixed spatial scale, such as at a gauge station or in a catchment, and the spatial variation in drought progression is not considered.

Second, the difference between the method in this study and the temporal and spatial overlapping method has already been discussed in section 4.4 (Line 397-400). To further clarify this difference, we will add the following sentences at the beginning of this part (Line 397).

More recently, researchers have begun to define three-dimensional single drought events by introducing continuous spatial-temporal motion and, based on this, have adopted temporal and spatial overlap thresholds to determine whether there is a relationship between two drought events (Jiang et al., 2023; Liu et al., 2019). The method proposed in this study not only introduces spatiotemporal motion, but also integrates the time series correlation method. The daily time scale used in this study provides more detailed time series of drought area changes and more accurate spatial trajectories (Fig.7). The high-resolution time series at daily time scale provides more input data for analysing temporal and spatial movement correlations (Fig.6). Based on the above, the method can detect the relationship without temporal overlap (Table 2 and Fig.6), identify the linkage among more than two types of droughts, and address their temporal orders.

Third, since the above two previous approaches identify the relationship between two types of drought events, they do not involve the cascading phenomenon among more than two types of droughts. In the third part, we will compare this work with the previous cascading drought study with multiple types of droughts.

Farahmand et al. (2021) investigated the cascading drought phenomenon involving precipitation, runoff, soil moisture, and streamflow to explore their temporal structure. This study differs from our work in three aspects.

1) This work did not involve identifying the relationship between different drought events, as they directly linked the most significant drought events in a given region to form a cascading event. 2) Moderate and small drought events were also not considered (e.g., flash droughts). 3) They do not take into account area variations and spatial motions during drought progression.

Fourth, the limitation of this study and future work was already discussed in the manuscript (Line 416-424). This part will be kept as original.

Minor comments

1. Line 36, “arising from” -> “arise from”.

Response: We will correct it accordingly.

2. Line 53, “compared to defining the drought...” It is redundant.

Response: Thanks! We will delete it.

3. Line 72 “Based on above....” It seems weird to say “based on above” in here. The authors seem to have point out the situation in characterizing drought. The logic then is to “fill the gap” rather than to sum up. So it may be better to use “To fill gap..” or similar expression.

Response: We will correct it as “To fill the above-mentioned gaps.”

4. Line 76, “Central Asia (CA) is a typical arid and semi-arid region.....”. The sudden jump from discussion of method to introduction of Central Asia in the last paragraph seems weird. It may be better just to say something like “test this method in Central Asia which is a typical arid/semi-arid region”. It is better to put more info in the section 2.1 study area.

Response: We will correct it as “This method was applied in Central Asia which is a typical arid/semi-arid region.”

5. Line 82, “The findings of this study are anticipated to” The whole sentence may be better in the conclusion section rather than introduction.

Response: Thanks for the suggestion! We will delete this sentence.

6. Line 83, Please add a section introduction of the sections in the last of the paragraph.

Response: Thanks for the suggestion. The added text is as follows:

This paper is structured as follows: Section 2 provides a brief overview of the geographic information of CA and describes the datasets used in this work and the procedure for identifying the cascading drought events. The results of the proposed approach and the comprehensive analysis are presented in Sections 3 and 4, respectively. Finally, the conclusions are presented in Section 5.

7. Line 84 “Material & Methods”-> “Data and method”.

Response: We will correct it accordingly.

Again, we sincerely appreciate the opportunity to revise our work for consideration for publication in Hydrology and Earth System Sciences. Thank you once again for your valuable comments and suggestions. We sincerely hope that our response will meet with your approval.

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