

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). The comments involve the driven mechanism of cascading drought, which is valuable and helpful for revising and improving our paper and providing significance to our research. We have taken care of the words carefully and made corresponding responses. The responses to the reviewer's comments are listed below.

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

General comments

This study presents a new framework to characterize and track drought events across multiple systems using the spatiotemporal evolution of deficits in precipitation followed by deficits in evapotranspiration, run-off and root-zone soil moisture.

I think this is an important study which will help to better understand the drought occurrence, its evolution and its associated impact on the ecosystem. I do however have some concerns/confusions that I would like to see clarified:

Response: Thanks very much for confirming the value of this work!

Major comments

1. The study identifies 503 drought cascading events with multiple combinations within 2-system, 3-system, and 4-system droughts. However, there is little discussion about the expected mechanism behind the occurrence of these drought cascading events mentioned in Table 1 and Figure 3.

Response: Thanks for the comment! We agree with the reviewer that the driving mechanism is essential to understanding the drought cascading pattern. In Section 4.2, we will explain the potential driving mechanism behind the cascading drought pattern from a water-limited and energy-limited perspective.

First, we will revise the title of section 4.2 to "The integrated driving effect of energy-limited and water-limited regimes on cascading drought patterns in CA." To clarify the perspective in this section, we will rewrite section 4.2. The following content will be added in section 4.2:

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 deficits are 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.

2. Given the strong coupling between soil-moisture and evaporation (under water-limited regime), why would we expect the two droughts to occur over different periods? The decrease in actual evaporation should be associated with an enhanced water stress so should not we expect the soil-moisture to reduce at the same time?

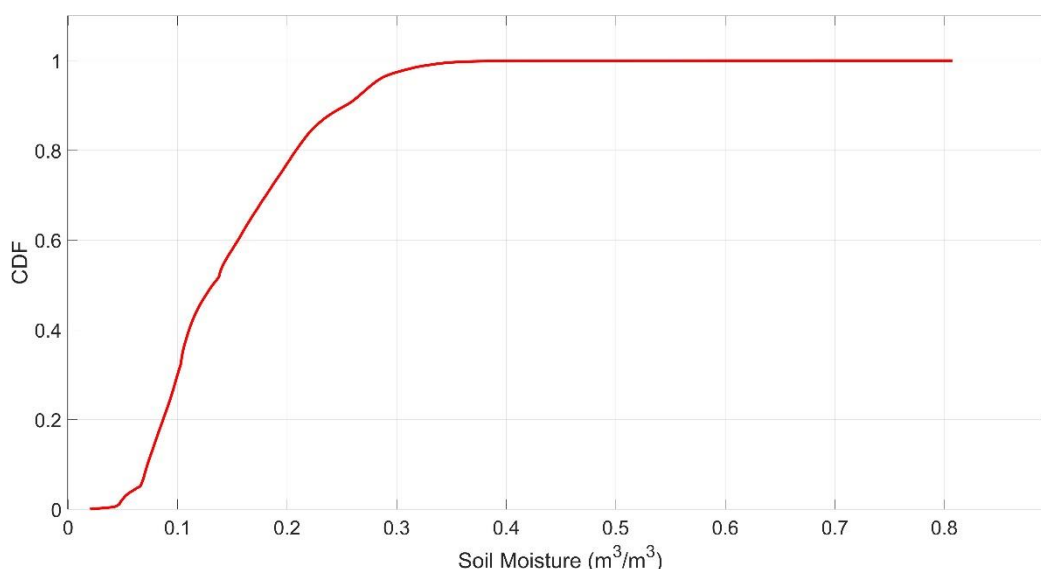


Figure R1: CDF plot of antecedent root-zone soil moisture 15 days before PCP drought onset

Response: Thanks for the comments! We will act on several aspects below to illustrate the reason why the ET and SM droughts could occur over different periods.

First, the water-limited regime are not the only controlling regime in Central Asia. Hsu and Dirmeyer (2023) recognized most of Central Asia as a transitional and energy-limited regime. In addition, an existing study proved that the soil moisture threshold separating water- and energy-limited regimes in nearly all of the diverse ecohydroclimate regions of Africa is around 0.14-0.18 m³/m³ (Feldman et al., 2019). Figure R1 shows the raw root zone soil moisture 15 days before PCP drought onset. We can see that, under SM drought conditions, over 45 % of the root-zone SM in Central Asia is still above 0.14 m³/m³.

Other reasons were discussed in the response to comment 1.

3. The study uses evaporative deficit as difference between actual and potential evaporation from GLEAM and the soil-moisture stress from GLDASv2.0-Noah model. How well the GLDAS and GLEAM dataset represent the soil moisture-evaporation coupling?

Response: Thanks for the comment! We draw the scatter plot of AET/PET and SM (Figure R2) in all pixels in Central Asia throughout the study period to illustrate this issue. As shown, the root-zone soil moisture does not present a significant linear relation with the actual and potential evaporation, according to the figures—most of the root-zone soil moisture presents stable with the increasing AET and PET.

Three possible reasons might be contributed to this result: 1) First, the SM data adopted in this study are from the soil layer of 40-100 cm. 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). The sparse vegetation cover results in lower vegetation water requirements and less fluctuation of the space-time signal of soil moisture in the deep layer. 2) The hybrid effect of water-limited regimes and energy-limited regimes in Central Asia. 3) The overestimation of the reduction in bare soil evaporation during droughts in drier climates (Zhao et al., 2022).

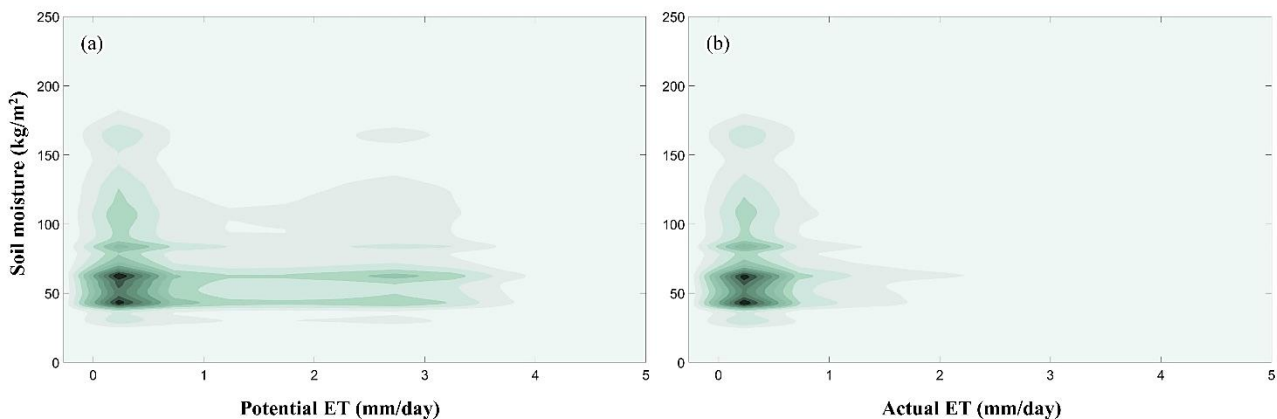


Figure R2: The density scatter plot of coupling soil moisture and potential/ actual ET, respectively. The x-axis of figure a/b is the potential/actual evaporation. The y-axis is the soil moisture. The colour denotes the point density, and the deeper color represents the higher point density.

4. The climatology of Central Asia is described in Figure 1 and section 2.1. But did authors also find any pattern between climatology/landcover-type and different kind of cascading events?

Response: Thanks a lot for the suggestion. The effect of climatology-land cover on cascading patterns is a very interesting research topic. The cascading drought patterns in different types of climatology-land cover is our ongoing work (Lu et al., 2022). In the ongoing work, we have categorised the climate regimes of Central Asia into five types: arid desert, arid steppe, temperate, cold, and alpine. We found that the possibility of the cascading phenomenon occurring in temperate is the highest among the five climate regimes. More details will be presented in the following work once published.

5. The study used PCP drought as a commencement for the event. Can the antecedent hydrologic conditions before the PCP event also govern the evolution? For instance, over a wet condition, I would expect Precipitation deficit (PCP) to be followed by energy limited evaporation with increased evaporative demand and that should lead to run-off deficit and eventually drying up the soil so an evaporation deficit i.e., PCP + Runoff + ET. Conversely over a dry surface, ET droughts may be triggered faster due to vegetation-water stress. Also, the precipitation deficits over dry regions could be lower so they may not directly translate into runoff droughts.

Response: Thanks for your comments! Antecedent hydrologic conditions are the factors that cannot be ignored in driving the cascading phenomenon. For example, the antecedent wet/dry condition (such as, antecedent soil moisture) could dominate the following response of other physical variables at the catchment/gauge station scale.

However, the wet/dry condition only defined by one parameter is too simple to explain the driving mechanism for the cascading pattern at the continent/global scale. First, the wet/dry condition is challenging to define in the regions containing the complicated climatology-land cover, like Central Asia. Second, one cascading drought event might involve different types of climatology-land cover, and these different kinds of climatology-land cover could interact with each other during the drought evolution. The figure presenting each drought-cascading pattern's antecedent root-zone soil moisture is as below, which does not show significant difference in 15 cascading drought patterns.

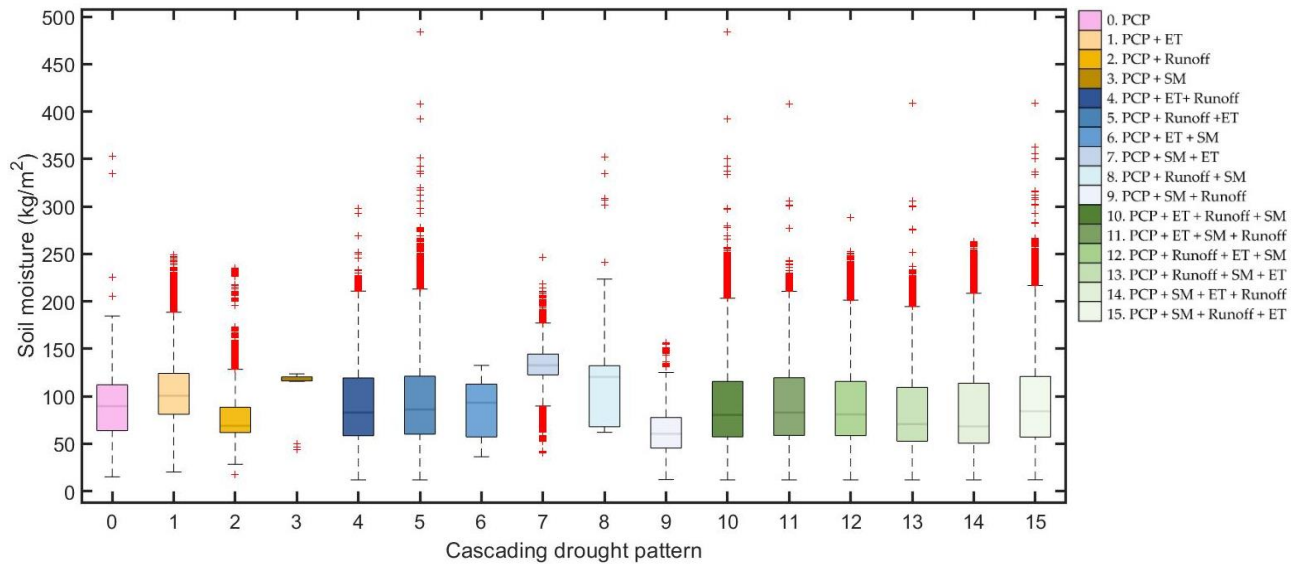


Figure R3: The antecedent root-zone soil moisture 15 days before PCP drought onset.

6. High intensity PCP droughts leads to increase in number of cascading system (Figure 8b). Can the intensity of PCP drought may also affect the type of cascading evolution?

Response: Thanks for the suggestion. We draw a new figure to compare the intensity of PCP in 15 cascading drought patterns. However, the intensity difference is not significant among different cascading pattern and the result is insufficient to draw a conclusion from this single factor, as it does not take into account other factors such as vegetation type, human activity and the modulator of atmospheric oscillation.

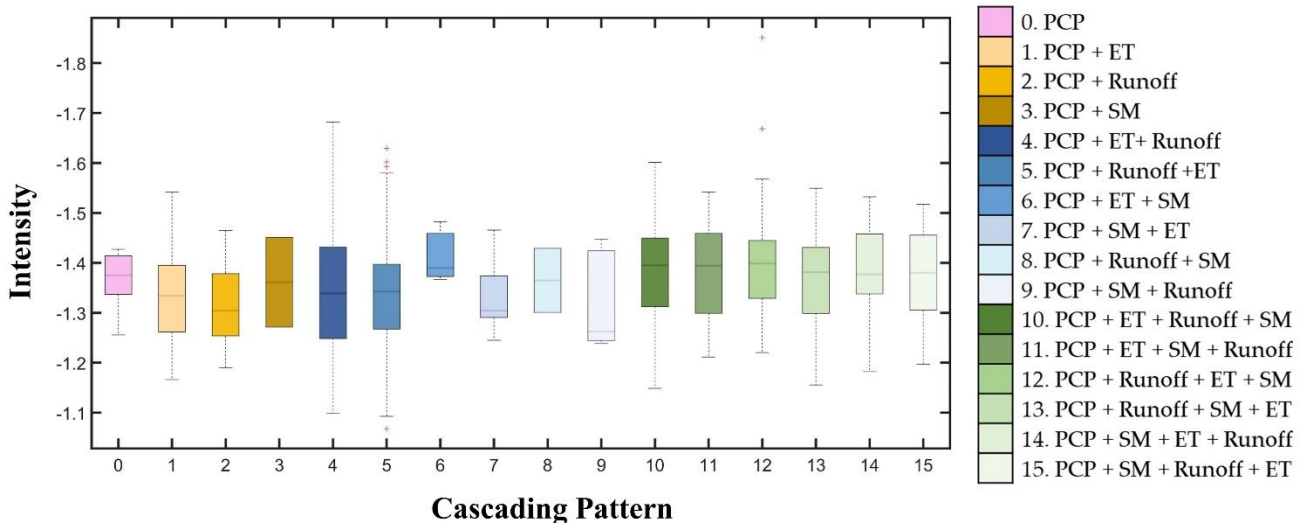


Figure R4: The intensity and severity of PCP drought event in 15 cascading drought patterns.

7. Does the presence of vegetation type over a region affect the pattern of drought cascades? For instance, over region where plants have deep-roots, they may still evaporate during dry periods and may only result in PCP + Runoff type droughts

Response: Thanks for the comments! Vegetation type is a critical element in determining cascading drought patterns. The vegetation of Central Asia is multiple and consists of the ‘bare area’ and ‘sparse vegetation’ irrigated grassland areas’, ‘ice and snow’, and ‘needle-leaved trees’. The class ‘needle-leaved trees’ in northeast Kazakhstan represents the beginning of the conifer forest of South Siberia (Klein et al., 2012). The vegetation effect on the cascading drought pattern needs to consider vegetation’s spatial and temporal variation. First, as the area of each cascading drought event is irregular and might be involved in multiple types of vegetation, spatial vegetation datasets are needed. Second, the cascading drought event often spans a long time across different seasons. The growing time of vegetation varies due to Central Asia's various vegetation types and climate regimes.

Therefore, the integrated effect of vegetation under different climate regimes on cascading drought patterns needs to be explored in detail, which is our ongoing work.

Minor Comment/Technical corrections:

- Line 435: “last” instead of “latest”?

Response: Thanks for the hint! We will revise it accordingly.

- Given that Violin plots are not very common, it may be helpful for the readers if authors could briefly describe the statistics of the plot before introducing them.

Response: Thanks for the hint! A violin plot is an easy-to-read substitute for a box plot that replaces the box shape with a kernel density estimate of the data and optionally overlays the data points. We will add the explanation of violin plot in the Fig.4: “The bandwidth denotes the density of the values quantified by the kernel density estimate. The black circle in the violin plot indicates the median value”.

The citation of the violin plot will be added to the manuscript: Bechtold, Bastian, 2016. Violin Plots for Matlab, Github Project <https://github.com/bastibe/Violinplot-Matlab>, DOI: 10.5281/zenodo.4559847

Thank a lot for all suggested hypothesis in the comment! The PCP characteristics, climatology/land cover type, antecedent hydrological conditions and vegetation type mentioned by the reviewer are essential for exploring the driving mechanism of the cascading drought pattern, which is very helpful for our ongoing work. However, given the spatial and temporal movement introduced in this paper and the complicated climate/terrestrial conditions in Central Asia, the simple comparison or conventional correlation method with single factors may not be appropriate for exploring the driving mechanism of the cascading phenomenon at the large scale. We will conduct a more appropriate framework in our ongoing work to elaborate it.

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