Responses to Reviewers' Comments on Manuscript ID Hess-2024-199

Article title: Accelerated soil moisture drought onset link to high temperatures and asymmetric responses associated with the hit timing

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Dear reviewers and editor:

Thank you so much for your valuable comments and kind suggestions on our paper. Your illuminating comments and suggestions give us the possibility to properly fix several questionable issues, and to improve the overall quality of the paper. We highly appreciate your time and effort. Please find our point-to-point responses to your comments below.

Responses to Reviewer 1's Comments:

Comment 1: The definitions of t_0 are different in the description and Figure 1. "The first day that SMP falls below the 40th percentile represents the initiation time (denoted as t_0) of the drought event" (Lines 98-99). "the duration of drought onset (*DDO*) is defined as the time interval between the initiation time of a drought (referred to as t_0) and the time when the moisture condition falls into moderate, severe, or extreme drought (referred to as t_d), denoted as DDO_m, DDO_s, and DDO_e for short, respectively" (Lines 113-115). In Figure 1, which one is t_0, the first blue square, the second blue square or the dot after the second blue square?

Response: Thank you for your valuable suggestion. We agree that Figure 1 makes it confused to distinguish the initiation time of a drought event. In the revised version, we updated Figure 1 with only t_0 marked in the format of blue square which may help readers to catch the initiation time of a drought easily. We also supplemented descriptions corresponding to Figure 1 in the main text as follow.

Lines 116-117 and 127: "*As shown in Fig. 1, the drought event initiated from t_0 (i.e.,* *the first blue square in the figure when SMP falls below 40% for the first time) and terminated at t_e (the second blue square in the figure)…… For example, Figure 1 shows the DDO_m, DDO_s, and DDO_e were of 5, 11, and 15 days, respectively.*"

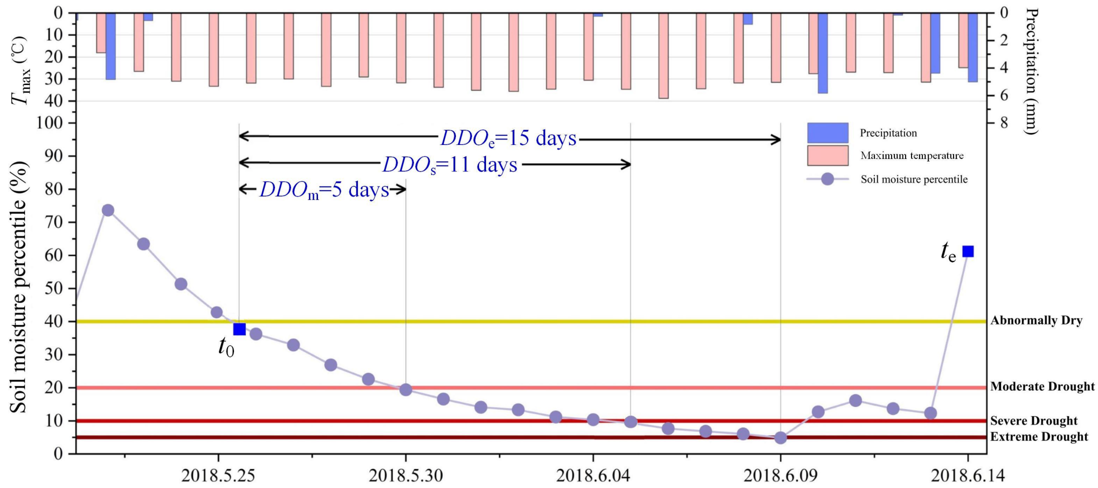

Figure 1. A schematic graph of the development process of drought. Data are from the grid cell (Beijing, 39.8°N 116.4°E). DDO_m, DDO_s, and DDO_e represent the time consumed for soil moisture percentile to reach categories of moderate, severe, and extreme drought, respectively.

Comment 2: The design of experimental scenario Ⅱ seems unreasonable. In experimental scenario Ⅱ, the high temperature occurred not only with the varied hitting times, but also with the different durations. Compared to the hitting time, the duration of high temperature may be more important. In addition, how did you conclude that the impacts of high temperatures were greatest during the week of drought onset (Line 20)?

Response: Thank you for your valuable suggestion. We agree that the duration of high temperatures is more important than the hitting time, and this is reason why we designed the experimental scenarios with duration considered. We also tested the influences of high temperatures occurring in each week from T_{0-7} to T_{0+7} (Figure R1). It shows that the influence of high temperatures in each week can be very limited. In this sense, we designed the experimental scenarios by considering the accumulated effects of high temperatures during pre-, and post-drought onset periods. The conclusion in Line 20 should be "*the impacts of high temperatures were greatest* *during the first four weeks (or one month) of drought onset stage*" according to the results of Figure 9. We have corrected corresponding descriptions in Line 20.

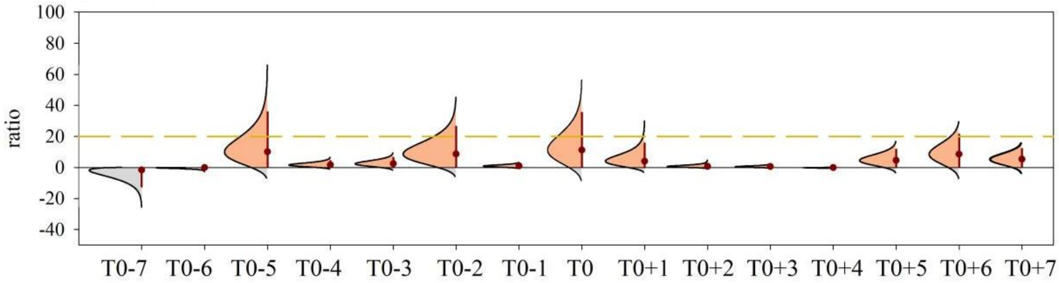

Figure R1. The change ratio of *DDO* caused by high temperatures occurring at different time intervals (from T_0 to T_i, and $i \neq 0$ and is an integer ranging from -7 to 7), which was averaged over all grid cells in China.

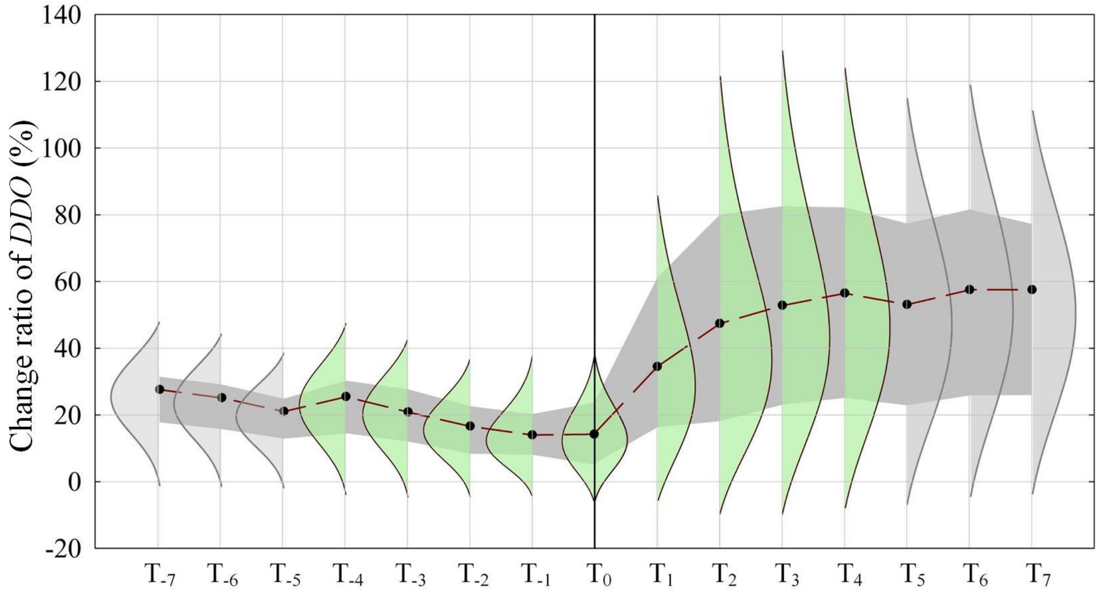

Figure 9. The change ratio of *DDO* caused by high temperatures occurring at different time intervals (from T_0 to T_i, and $i \neq 0$ and is an integer ranging from -7 to 7), which was averaged over all grid cells in China. The probability distribution curve for *i*-th time refers to the change rate of *DDO* caused by high temperatures randomly sampling within the range of 30~40°C during the period of T_0~T_i. The dark gray stripe represents the 25th to 75th percentiles of each probability distribution, and the black solid dots show the means of the probability distribution. The colored probability distributions show the effective time intervals of high temperatures on the formation process of drought.

Comment 3: Figure 3a: The precipitation was positively correlated with the *DDO* over most areas, why are the boxplots different from the spatial pattern? In addition, please modify the incorrect description in lines 182-184.

Response: Thank you for your reminding. We consider your questions carefully and checked the computation procedure and the statistical data, and redraw the boxplots. You are right the median and mean of the correlation coefficients between precipitation and *DDO* is positive, and Fig. 3 was revised. At the same time, we revised the corresponding descriptions in the main text to better match the information shown in Fig. 3.

Lines 194-200: "*As shown in Fig. 3a, the spatial map suggest in most areas, precipitation was positively correlated with* DDO_s*, especially for the northwestern region, the absolute values of CC were as high as 0.5. According to the boxplots, the absolute values of CC for* DDO_m*,* DDO_s*, and* DDO_e *were generally low indicating that the impacts of precipitation on DDO would be finite. For precedent soil moisture conditions, high correlation was found in the northwest China and the headwaters of the Yangtze and Yellow Rivers, and in majority regions, a weak correlation on DDO was found (Fig. 3b). Among three variables,* T_{max} *is closely correlated with DDO (Fig. 3c). The CC values were negative, with the strongest correlation in northeastern China, northern China, Qinghai-Tibet Plateau, and southern coastal areas of China.*"

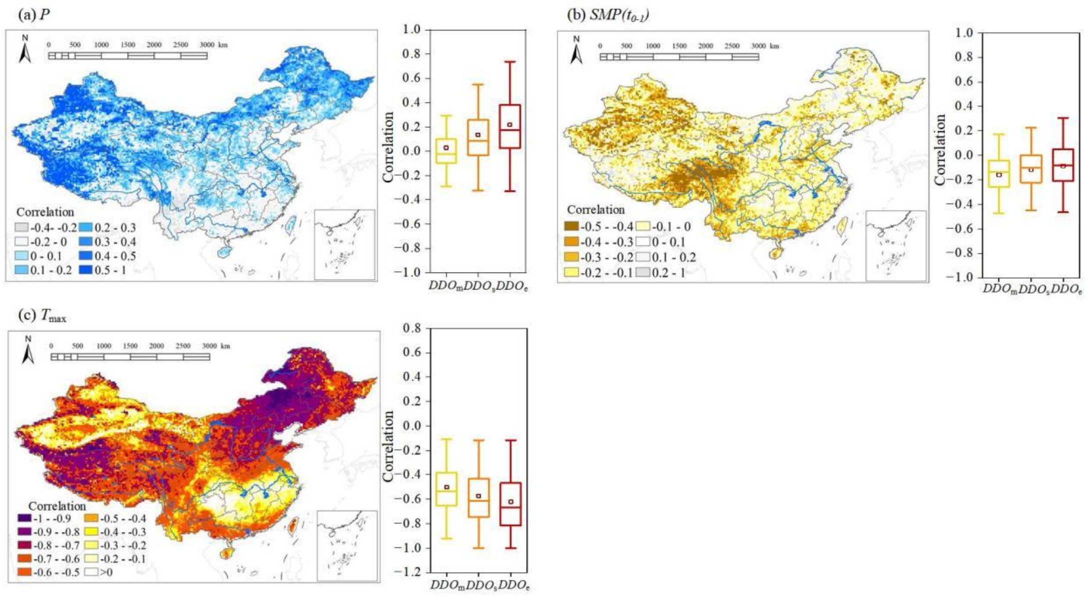

Figure 3. The spatial distribution of the CC between the DDO_s against (a) *P*, (b) *SMP*(t_{0-1}), and (c)

T_{max}, and the boxplots shows the CC between the DDO_m, DDO_s, and DDO_e against P, SMP(t_{0-1}), and T_{max}, respectively.

Comment 4: Figure 5: The frequency and duration of droughts are very unreasonable. How could there have been more than 500 drought events occurring in South China during the past 72 years? In addition, short-term drought events with duration less than one month were excluded given their limited effects on agricultural production and ecological system (Lines 101-102), why are most areas in South China still with a duration of less than 20 days? Please further review the definition and code of drought.

Response: Thank you for your valuable suggestions. The original figure presented is a drawing mistake that the calculation results without excluding short-term (with duration less than one month) drought events were used for drawing, and this is why the number of drought events were extraordinarily large and the drought duration were generally short. We deeply sorry for the mistakes. Following your suggestion, we carefully checked the coding procedure of drought, and corrected Figure 5 and corresponding descriptions.

Lines 220-228: "*Fig. 5 shows the spatial distribution of the number of drought events, mean duration, DDO_m, DDO_s, and DDO_e during 1950-2021 by using the ERA5-Land reanalysis data. As shown in Fig. 5a, the south region suffered more than 150 drought events during the past 72 years, which were two~three folds of the north region. For drought duration, drought persisted longer in the north than the south. Especially in the northeast and western regions, the drought duration were 60 days or longer. While drought duration in central and southern China (Yangtze River Basin) were less than 50 days (Fig. 5b). The duration of drought onset (Fig. 5c), i.e., the time period of moisture transition from normal to moderately dry (DDO_m), severely dry (DDO_s), and extremely dry (DDO_e), present a similar spatial pattern as in Fig. 5b. Overall, DDO_s were approximately 5~20 days longer than DDO_m, and DDO_e were 10~40 days longer than DDO_m. For example, in northeastern China, it took 18 days for the transition from a drought-free state to moderate drought (i.e., DDO_m), and the value of DDO_s almost doubled (more than 30 days), and DDO_e exceeded 42 days.*"

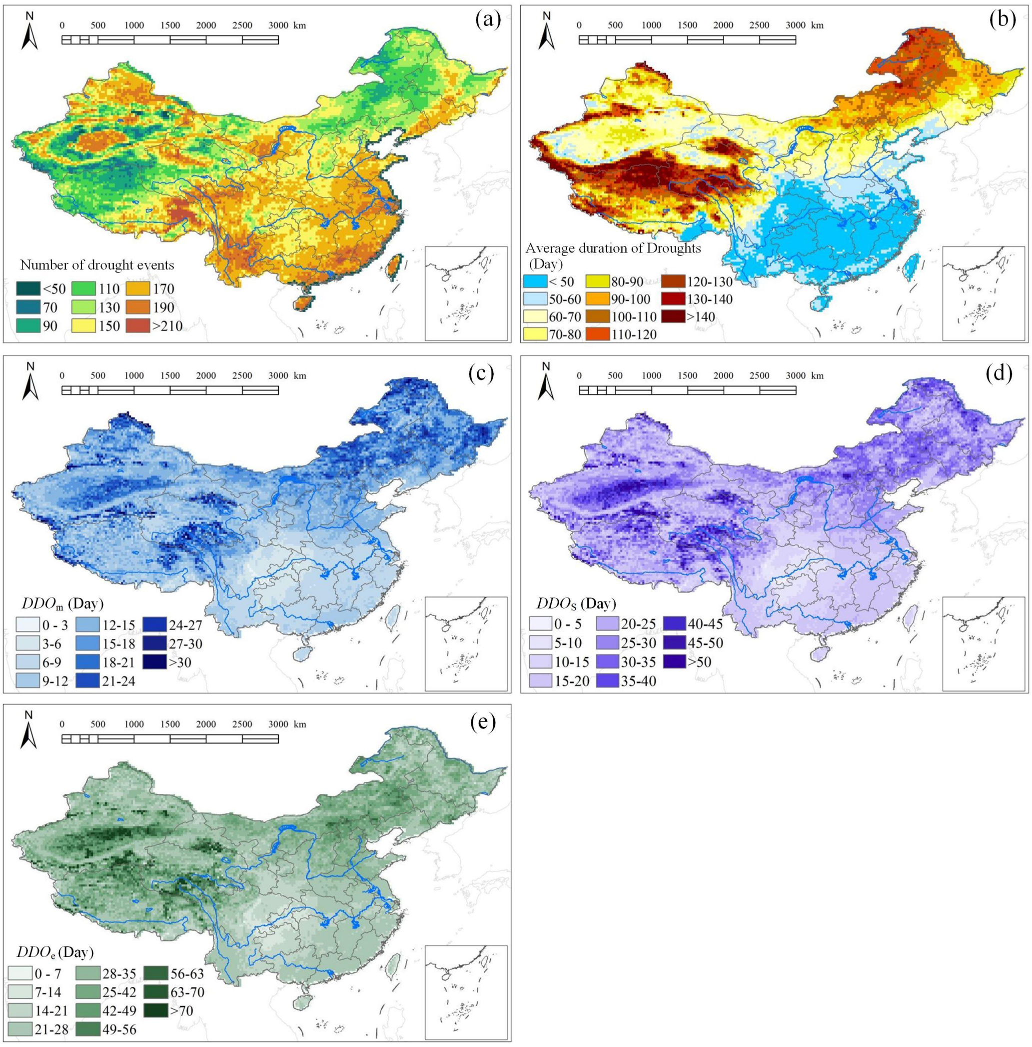

Figure 5. The spatial distribution of (a) the number of drought events, (b) the average duration of drought events, (c) the average days taken for reaching moderately dry (DDO_m), (d) severely dry (DDO_s), and (e) extremely dry (DDO_e) of all drought events during 1950-2021.

Comment 5: It seems that Figure 8 shows the *DDO* but not the change ratio of *DDO*. Please modify the y-axis labels and figure caption. The red (orange?) legend makes me confused. Please show the legends of all colors, or show the "25th~75th Percentile" in the suitable position. In addition, please provide the criteria for identifying the sensitive intervals.

Response: Thank you for your valuable suggestions. Yes, Figure 8 shows the *DDO* under different high temperature scenarios. The y-axis label and figure caption have been corrected and the legends of all colors have been added in the manuscript. The high temperature sensitive intervals are judged through the changes in the days of *DDO*, namely *DDO* significantly shortens along with increased T_{max} were recognized as high temperature sensitive intervals. The criteria for identifying the sensitive intervals have been added in the main text.

Lines 264-265: "*We further explored the sensitive intervals (where DDO significantly changes along with increased* T_{max}*) that temperature variation may lead to marked changes for the duration of drought onset.*"

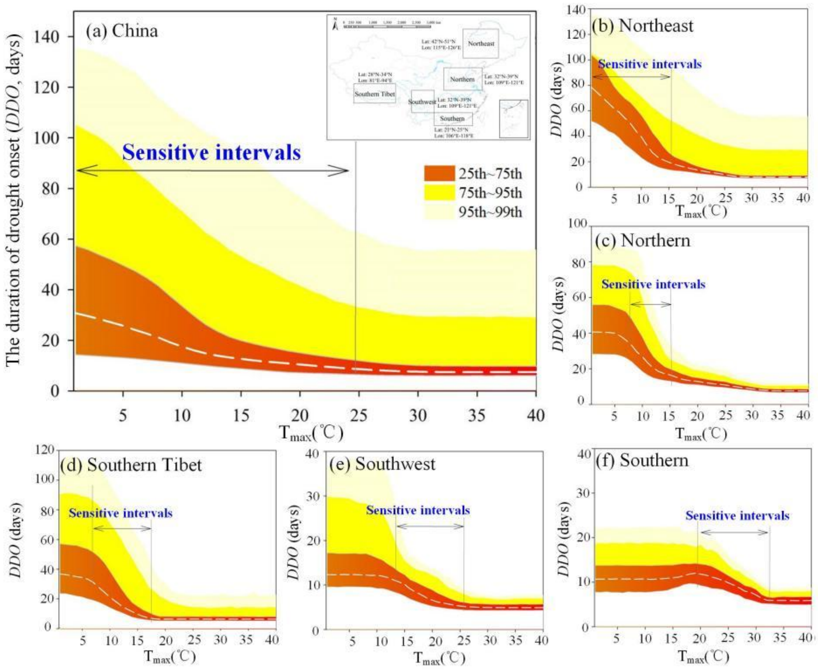

Figure 8. The days of drought onset under different temperature scenarios (a) over China and in (b) Northeast: 115°E-126°E, 42°N-51°N; (c) Northern: 109°E-121°E, 32°N-39°N; (d) Southern Tibet: 81°E-91°E, 28°N-34°N; (e) Southwest: 99°E-106°E, 25°N-32°N; (f) Southern: 106°E-118°E, 21°N-25°N China. The colored shades show the 25th, 75th, 95th, and 99th percentiles of the duration of drought onset under temperature scenarios for grid cells in each region, and the white dashed lines show the average values of the duration of drought onset.

Comment 6: Lines 284-285: Does Figure 9 show the change ratio of *DDO* according to equation (3)? It seems that the ratio is negative when the DDO_i decreases, why does a positive value of the ratio mean a decrease in *DDO*? In addition, please add the colorbar in Figures 9-10.

Response: Thank you for your valuable suggestions. The change ratio of *DDO* is employed to reveal the effects of high temperatures on the duration of drought onset. Following your suggestion, we revised the equation (3) as:

Line 183: $$Ratio = -\frac{DDO_i - DDO_{mean}}{DDO_{mean}} \times 100\%$$

Where DDO_i represents the duration of drought onset under a temperature scenario, and DDO_{mean} refers to the duration of drought onset under average temperature conditions. In this sense, positive change ratio indicates DDO_i is lower than DDO_{mean}, namely *DDO* shortens under high temperature conditions. In addition, we have also revised Fig. 9. We unified the color of each time period in the figure. Each probability distribution curve represents the distribution of the *DDO* change ratio within a time period, and the time period with a significant *DDO* change ratio (T_{-4} to T_4) is highlighted in green. We have corrected Fig. 10 as you suggest.

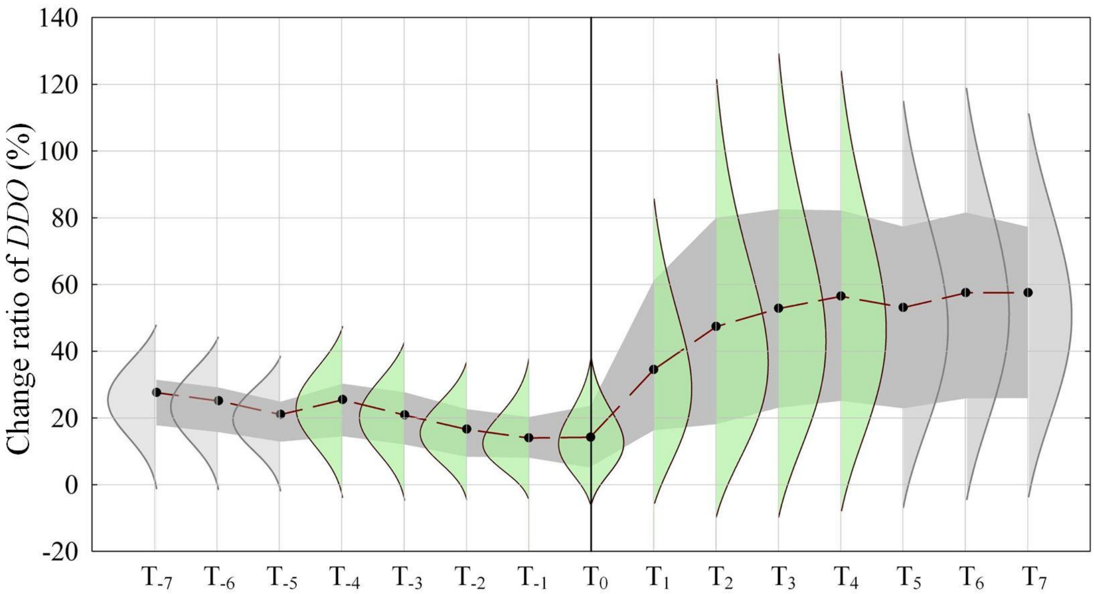

Figure 9. The change ratio of *DDO* caused by high temperatures occurring at different time intervals (from T_0 to T_i, and $i \neq 0$ and is an integer ranging from -7 to 7), which was averaged over all grid cells in China. The probability distribution curve for *i*-th time refers to the change rate of *DDO* caused by high temperatures randomly sampling within the range of 30~40°C during the period of $T_0 \sim T_i$. The dark gray stripe represents the 25th to 75th percentiles of each probability distribution, and the black solid dots show the means of the probability distribution. The colored probability distributions show the effective time intervals of high temperatures on the formation

process of drought.

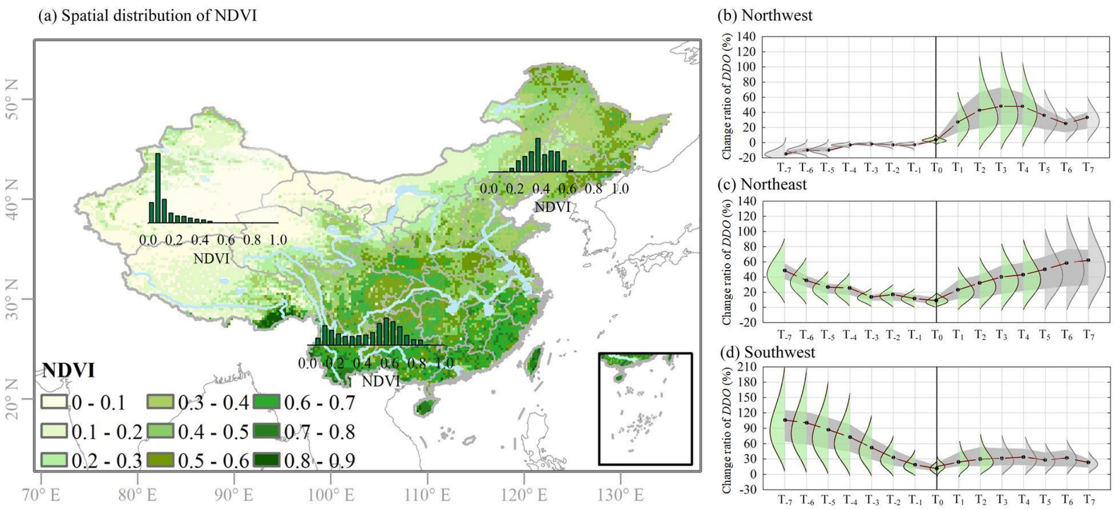

Figure 10. Spatial distribution of (a) NDVI over China and the change ratio of *DDO* as in Fig. 9 but for (b) northwest, (c) northeast, and (d) southwest regions. The histograms show the distribution of NDVI of all grid cells in Northwest, Northeast, and Southwest China.

Comment 7: Why is the dotted vertical line located at T_2 in Figure 11? Perhaps the dotted vertical line should be located at T_0, which means the drought initiation (Lines 285-286).

Response: Thank you for your remanding. We carefully checked the content in the figure, we found that there was an error when drawing the figure. You are right the dotted line in Fig. 11 should be located at the starting time of drought (T_0). We updated Fig. 11 in the revised manuscript and the content of the text.

Lines 331-333: "*Similar patterns were also found for the change ratio of DDO classified by NDVI values from 0 to 1 at an interval of 0.1 over China, where the positive effects of high temperatures during predrought periods tends to be weaker as the NDVI decreases (Fig. 11).*"

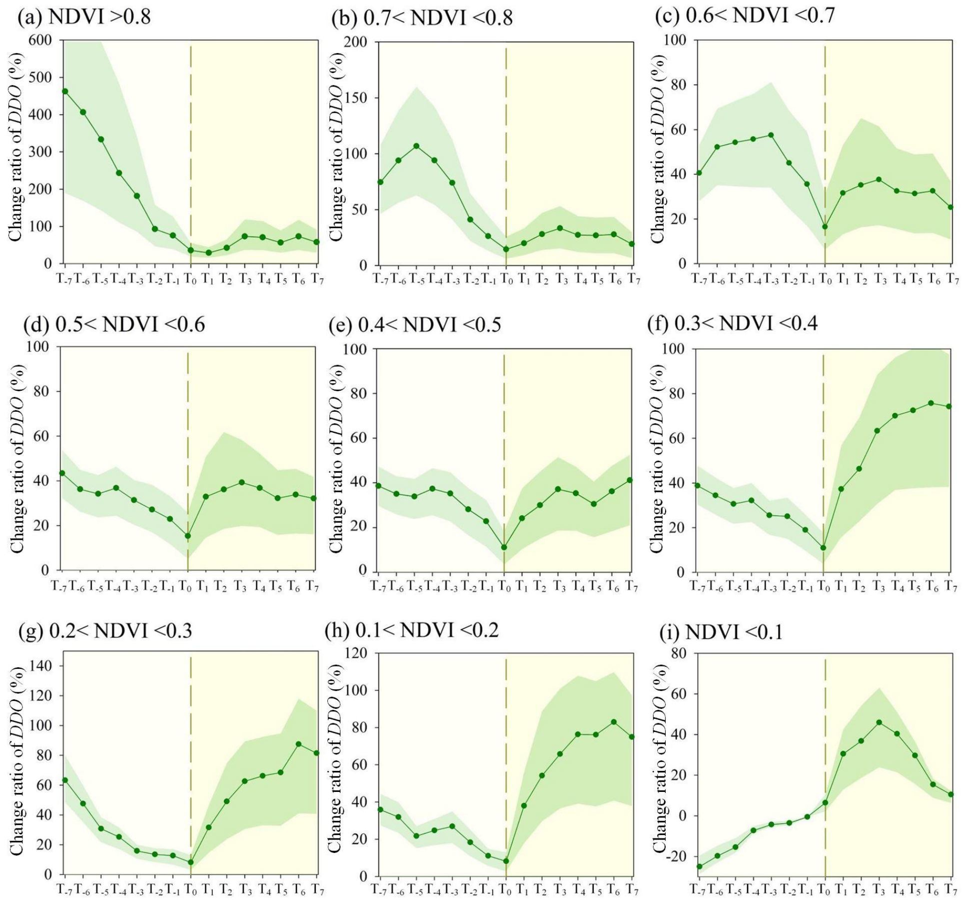

Figure 11. As in Fig. 9 but for the change rate of *DDO* under different NDVI values. The dotted vertical line in each panel shows the initiation time of a drought, the green dots are the mean change rate of *DDO* under high temperatures from T_0 to T_i, and the green shades show the range of 25th ~ 75th percentiles of the change rate of *DDO*.

Responses to Reviewer 2's Comments:

Comment 1: Introduction: this part seems too short, which does not clearly point out the gaps between existing studies and this study. The authors should further highlight their new contributions to this field.

Response: Thanks for your valuable suggestion. We supplemented descriptions on the gaps between existing studies and this study, and highlight the new contributions to this field in the third paragraph of the Introduction section.

Lines 49-56: "*Recent progresses of flash droughts include comparisons among different flash drought definitions, evaluations on the characteristics of flash drought* *in different regions of the world, unraveling the mechanism of flash drought based on causality analysis, incorporating multiple information for improving flash drought identification and monitoring strategies, and flash drought associated crop response (e.g., Osman et al., 2021; Shah et al., 2021; Ahmad et al., 2022; Ho et al., 2023; Zhou et al., 2023; Mahto and Mishra, 2024). These contribute a deep understanding on the accelerated drying process and its associated impacts. However, efforts for unraveling the formation process of drought under high temperatures, particularly for the changes during the onset stage of drought (e.g., the time consumed for moisture transition from a drought-free state to drought condition), are generally rare.* "

Lines 58-59: "*This calls for depicting drought development process at fine temporal resolutions (e.g., a daily time step).* "

Lines 67-70: "*The results are promising to improve our understanding on the driving mechanism of high temperatures on drought during the onset stage. Meanwhile, the modelling framework could also be an alternative for quantitative measurement on the changes of drought formation under future extreme high temperature scenarios.* "

References:

Ahmad, S. K., Kumar, S. V., and Lahmers, T. M.: Flash drought onset and development mechanisms captured with soil moisture and vegetation data assimilation, Water Resour. Res., 58, e2022WR032894, https://doi.org/10.1029/2022WR032894, 2022.

Ho, S., Buras, A., and Tuo, Y.: Comparing agriculture-related characteristics of flash and normal drought reveals heterogeneous crop response. Water Resour. Res., 59, e2023WR034994. https://doi.org/10.1029/2023WR034994, 2023.

Mahto S S, Mishra V.: Global evidence of rapid flash drought recovery by extreme precipitation, Environ. Res. Lett. 19 044031, 2024. DOI: org/10.1088/1748-9326/ad300c, 2024.

Osman, M., Zaitchik, B. F., and Badr, H. S.: Flash drought onset over the contiguous United States: sensitivity of inventories and trends to quantitative definitions, Hydrol. Earth Syst. Sci., 2021(2).DOI:10.5194/HESS-25-565-2021.

Shah J., Hari V., and Rakovec O.: Increasing footprint of climate warming on flash droughts occurrence in Europe, Environ. Res. Lett, 17 (2022) 064017. DOI:10.1088/1748-9326/ac6888, 2022.

Zhou Z.Q., Ding Y.B., and Zhao Y.Y.: A new perspective for assessing hydro-meteorological drought relationships at large scale based on causality analysis. Environ. Res. Lett., 18(10), 104046,2023. DOI: 10.1088/1748-9326/acfe1e, 2023.

Comment 2: How to determine the level of *DDO*? Why 8 days for moderate, 14 days for severe, and 18 days for extreme drought?

Response: Thank you for your comment. In this study, the *DDO* was proposed to measure how rapid the drought develops under varied warming scenarios. We think "8 days for moderate, 14 days for severe, and 18 days for extreme drought" do not represent the level of *DDO*, rather they show the average days consumed for moisture transition from a normal state to below-average condition over China during the past 72 years. We think you provide an interesting direction in future researches like finding a reasonable level of *DDO* to recognize flash drought, or for drought monitoring and management strategies. We also carefully checked the descriptions of *DDO* and Figure 1, and made some modifications to improve clarity. We also supplemented descriptions corresponding to Figure 1 in the main text as follow.

Lines 116-117 and 127: "*As shown in Fig. 1, the drought event initiated from* t_0 *(i.e., the first blue square in the figure when SMP falls below 40% for the first time) and terminated at* t_e *(the second blue square in the figure)…… For example, Figure 1 shows the* DDO_m*,* DDO_s*, and* DDO_e *were of 5, 11, and 15 days, respectively.* "

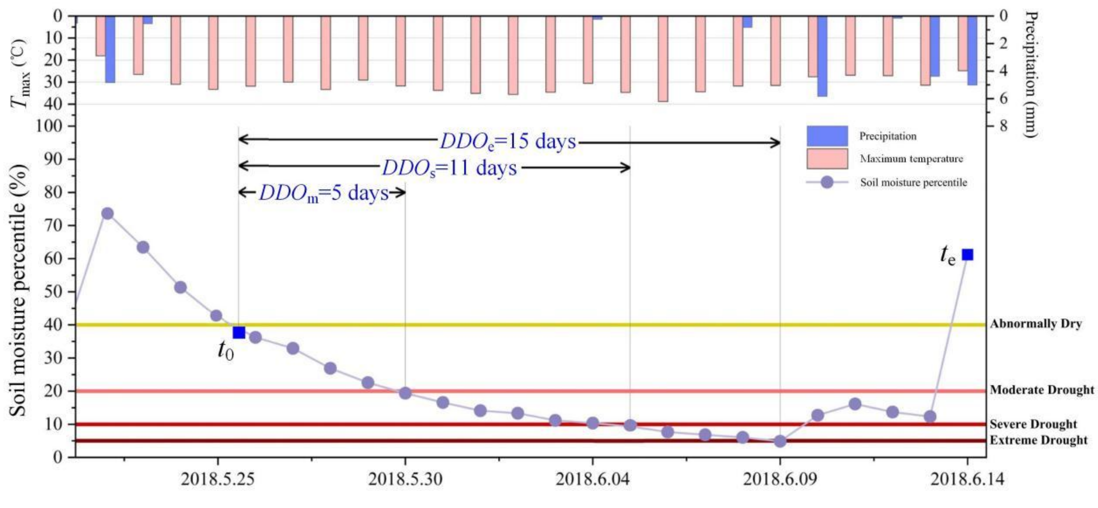

Figure 1. A schematic graph of the development process of drought. Data are from the grid cell

(Beijing, 39.8°N 116.4°E). *DDO_m*, *DDO_s*, and *DDO_e* represent the time consumed for soil moisture percentile to reach categories of moderate, severe, and extreme drought, respectively.

Comment 3: There are also many areas with estimation errors larger than 10 days in the northwest region (Line 204).

Response: Thanks for your comment. The estimation errors larger than 10 days were mostly in the Qinghai-Tibet Plateau and alpine regions. The areas climatically receive very little precipitation, and were in a state of drought all the year round. Droughts generally persist for a long time period, and the number of drought events is small. This resulted in small data samples for model training and is a primary reason for the calculation errors. The reason for the errors in the northwest region has been supplemented as follow.

Lines 213-214: "*Larger estimation errors (of 10 days) were found in the northwestern alpine regions, where droughts generally persist for a long time period, resulted in small data samples for model training.*"

Comment 4: Why not present the results for *DDO_e* (Lines 215-216)?

Response: Thank you for your valuable suggestion. The results for *DDO_e* have been supplemented, with corresponding descriptions of the figure corrected.

Lines 220-228: "*Fig. 5 shows the spatial distribution of the number of drought events, mean duration, DDO_m, DDO_s, and DDO_e during 1950-2021 by using the ERA5-Land reanalysis data. As shown in Fig. 5a, the south region suffered more than 150 drought events during the past 72 years, which were two~three folds of the north region. For drought duration, drought persisted longer in the north than the south. Especially in the northeast and western regions, the drought duration were 60 days or longer. While drought duration in central and southern China (Yangtze River Basin) were less than 50 days (Fig. 5b). The duration of drought onset (Fig. 5c), i.e., the time period of moisture transition from normal to moderately dry (DDO_m), severely dry (DDO_s), and extremely dry (DDO_e), present a similar spatial pattern as in Fig. 5b. Overall, DDO_s were approximately 5~20 days longer than DDO_m, and DDO_e were 10~40 days* *longer than DDO_m. For example, in northeastern China, it took 18 days for the transition from a drought-free state to moderate drought (i.e., DDO_m), and the value of DDO_s almost doubled (more than 30 days), and DDO_e exceeded 42 days.*"

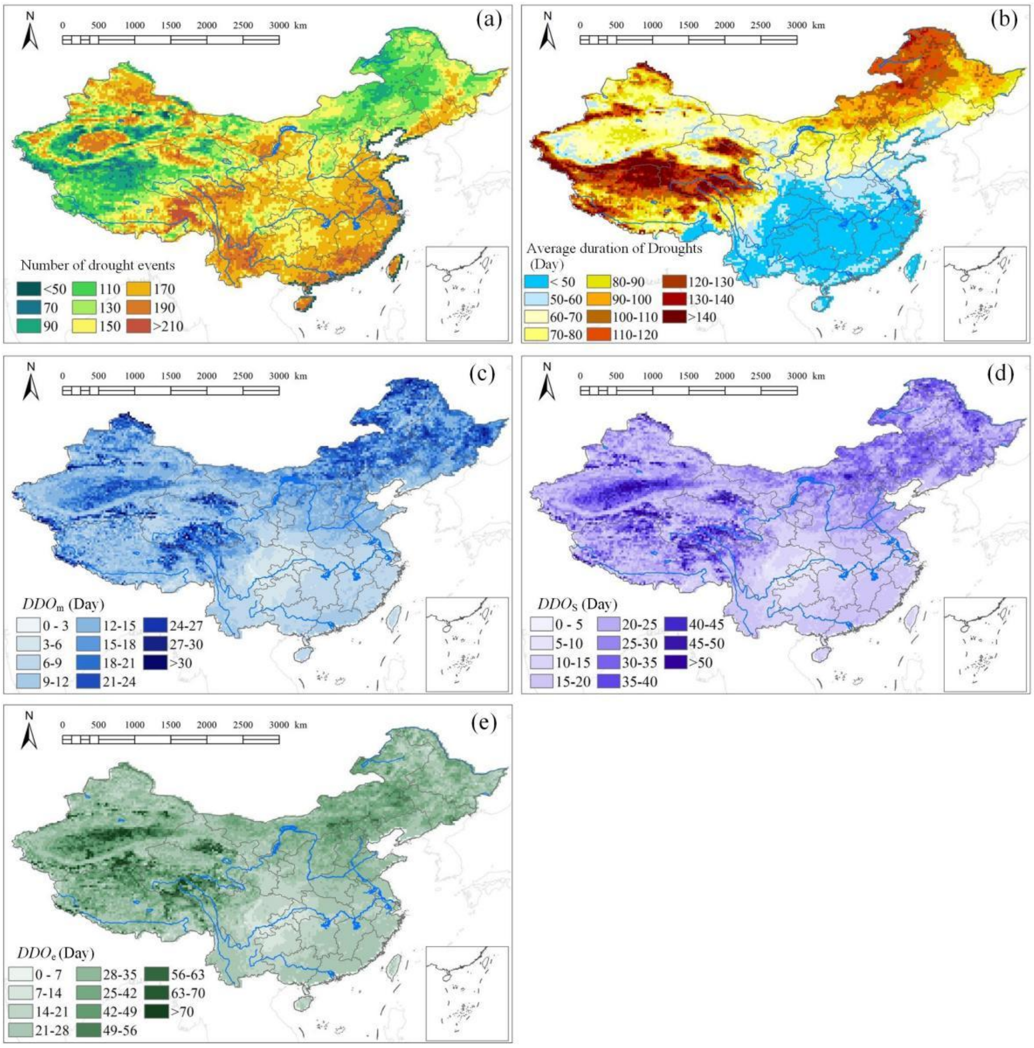

Figure 5. The spatial distribution of (a) the frequency of droughts, (b) the average duration of droughts, (c) the average time taken for reaching moderately dry (*DDO_m*), (d) the average time taken for reaching severely dry (*DDO_s*), and (e) for reaching extremely dry (*DDO_e*) of all drought events during 1950-2021.

Comment 5: Due to global warming, whether 35℃ can still be regarded as a threshold of high temperature days needs more discussion (Lines 242-243).

Response: Thank you for your valuable suggestion. We agree that in the context of climate warming, record-breaking high temperatures become more common, and it is

an interesting topic to reconsider the threshold of high temperature days. Considering 35℃ is currently a threshold of high temperatures employed by the China Meteorological Administration and also researches focused on heat waves, we chose 35℃ as an example of high temperature scenario to show how *DDO* will change comparing to the mean temperature state. We also extended the high temperature scenarios into a higher range, as shown in Fig. 8, the horizontal axis was extended to as high as 40 ℃. The sensitivity results show that for majority of China, *DDO* generally stays in a steady state between 35℃ and 40℃, indicating that the threshold of 35℃ would not influence the main conclusion a lot and the results derived were generally representative. The reason for choosing 35℃ has been supplemented in the revised manuscript. Discussion on the threshold of high temperature days provides us a direction and we will focus on this issue in the future.
Lines 250-254: "*Fig. 7 shows the spatial distributions of the DDO under scenarios of annual mean temperature and temperature of 35℃ (this value is employed as a threshold of high temperature days by the China Meteorological Administration and researches focused on heat waves, and in this study it was chosen as an example of high temperature scenarios to show how DDO will change comparing to the mean temperature state), respectively.*"

Comment 6: There are some track changes in the main text. Please check carefully.
Response: Thank you for your reminding. We carefully checked the whole manuscript and removed track changes in the clean version of the revised manuscript.

Comment 7: There are also some editing errors in the text. Some examples are as follows: Line 106: "phage"? Lines 269-270: wrong sentence. Lines 281 and 282: "change rate" or "change ratio"? Fig. 11: "ndvi" -> "NDVI". Line 342: the full name of *VPD* is not given. Line 343: "there virtually no changes"? Line 345: "were" -> "was".
Response: Thank you for your valuable suggestions.

Line 116: we have replaced the relevant expression: "*As shown in Fig. 1, the drought event initiated from t0 (i.e., the first blue square in the figure when SMP falls below 40% for the first time) and terminated at te (the second blue square in the figure).*"

Line 291: we have corrected "change rate" to "change ratio", and we also updated Figures 9, 10 , and 11 with the y-axis labels corrected.

We have changed "ndvi" into "NDVI" in Fig. 11.

Lines 349-350: The full name of *VPD*, i.e., vapor pressure deficit, has been added. "*Moreover, the coupling strength between vapor pressure deficit (VPD) and soil moisture also indicates the changing role of vegetation within a drying period.*"

Lines 354-356: we have reorganized the sentence as "there were virtually no changes within a drying period for low NDVI areas".

Line 355: we have corrected "were" to "was".

"*there were virtually no changes within a drying period for low NDVI areas. This to some extent explains why predrought high temperatures presented more prominent effects in high NDVI areas, while the role of vegetation in low NDVI areas was very limited.*"

We also carefully checked the entire manuscript to avoid such typos.