A review on the identification methods of flash drought and its spatial dynamic propagation

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Abstract. Flash drought is a type of drought that develops rapidly, lasting for a short period of time, and is highly destructive. During its rapid intensification stage, it is usually accompanied by high temperature, high evapotranspiration, soil moisture decline, and precipitation deficit, thus causing significant damage to ecosystems and human society. Many attempts have been made to distinguish the phenomenon of flash drought from drought and to better understand the mechanisms of its generation. Since 2013, researchers have continued to refine and clarify the definition of flash drought in response to its characteristics, and have made many efforts to propose appropriate identification methods, classify the phenomenon of flash drought, identify the mechanism of flash drought generation, and improve the early warning capability of flash drought disasters. Despite this, researchers still do not have a clear and consistent system for identifying and classifying flash drought emergencies. In addition, some researchers have explored the spatial dynamics of flash drought propagation, hoping to better understand the spatial and temporal characteristics of flash drought.

1. Introduction

Unlike droughts which can last up to several months or several years, the flash drought, which was first proposed by Svoboda et al. (2002)[1-][2][3], is a special kind of drought event that is distinguished by its short duration, high intensity and rapid onset, with most flash droughts completing their development within about 15 days.[4-][5]Flash droughts are often accompanied by large precipitation deficits and high temperature anomalies, strong winds or changes in atmospheric radiation, while the coupling effect of these factors can suddenly increase evapotranspiration rates, which can more easily lead to a rapid deterioration of the water stressed conditions [3],[6].The simultaneous occurrence of flash droughts and high temperatures can have significant impacts on ecosystems and human production, such as the 2012 flash drought event in the central United States, which caused more than ten billion dollars in economic losses[7-][8][9][10].Researchers have used a variety of indices for the identification of flash drought, such as the evaporative stress index (ESI), rapid change index (RCI), standardized evaporative stress ratio (SESR), soil moisture (SM), land surface water index (LSWI), and they may have different effects on identification results.SESR and SM are relatively more used in current studies .

There are many studies within the field of flash drought research that speculate on the mechanism of flash drought generation based on environmental response factors, and the drivers of flash drought generation are often different when the climatic and geographical conditions of the event areas are different[3]. Wang et al.(2021)[11] believes that consolidating the tele-connected ocean-atmosphere and land-atmosphere coupling in the context of climate change will be useful for understanding the mechanism of flash drought onset.Zha et al.(2022)[12] believes that different vegetation types also affect the occurence of flash droughts. However, there is a general consensus among researchers that the development of flash drought is generally inseparable from precipitation deficit and high evapotranspiration, and that this process is often accompanied by positive temperature anomalies[13].

In the recent five years, the research on flash droughts has focused on describing the spatial and temporal characteristics of flash droughts, attributing the causes of flash droughts in different regions, and predicting their development trends. Although researchers have some knowledge of how flash drought generates, they are still exploring how to accurately predict the accelerating drought events[3].The research about the spatial and temporal characteristics of flash drought events[5],[14],[16] can help us better understand the dynamic propagation of flash drought, which can be useful for flash drought monitoring and water resources management.Further research is needed to establish a clear and unified physical model of the flash drought generation mechanism, and breakthroughs in this area will be of great help for flash drought forecasting and monitoring[16]-[17].

The purpose of this paper is to review the changes in researchers' definition of flash drought and methods proposed for identifying flash drought events since 2013 and to summarize the current research progress on its spatial propagation.

2. Definition and Identification of Flash Drought

2.1 Definition

When Svoboda et al.[1] first mentioned the concept of drought in 2002， He considers it a type of drought that causes a rapid deterioration in the state of crop growth due to causing severe heat waves and short-term dryness. Flash drought events are often accompanied by abnormal precipitation and high temperatures, and their adverse effects can greatly impact normal human production efforts such as agriculture and animal husbandry. For example, the catastrophic drought event in the Midwest Plains of the United States caused tens of billions of dollars in damage. Since then, flash droughts have received more attention from researchers as an intense natural disaster event[18].

Researchers have also gone through several iterations of the specific definition of drought,Otkin et al.(2013)[19] and Mo et al.(2015)[20] believe that a flash drought event should not only exhibit the characteristics of a traditional drought, such as water loss, but also the characteristics of rapid onset and high intensity development of the drought event.According to the main meteorological drivers of flash drought, Mo and Lettenmaier et al.(2015, 2016)[20],[22]divided it into heat-wave-driven flash drought dominated by high temperature anomalies and precipitation-deficit-driven flash drought dominated by precipitation deficit.They also noted that the two anomalies often occur together during flash droughts, resulting in a drop in soil moisture.Otkin et al.(2017)[2] summarized the existing definition and development process of flash drought and points out that there should be a rapid intensification and an intensification of water deficit similar to normal drought events. The paper suggests that researchers should mainly consider the rapid intensification characteristics of flash drought events rather than the duration when defining the events, which means flash droughts should be defined only during periods of rapid intensification. In addition, the paper summarized the characteristics of an ideal indicator for identifying flash droughts, such as it should have the ability to describe certain quantitative changes over a period of time, and it should be below the 20th percentile of recorded values of all years during the rapid development of flash drought events.Christian et al.(2019)[23]selected SESR as the index for identifying flash drought, and proposed three identification criteria based on Otkin et al. 's ideas to ensure that the identified flash drought has the characteristics of drought and rapid change. In addition, Christian requires that the duration of flash droughts be no less than 30 days to ensure that what is extracted is a truly severe impact on ecosystems and agriculture, which is a complement to Otkin et al. 's concept in 2017. Similarly to Christian et al., Yuan et al. (2019)[24] also emphasized the constraints of drought, rapid development and a long enough duration to ensure the identification of the damage to the ecosystem caused by the event. In addition, Yuan argued that flash drought events should be considered to have onset stage and recovery stage, and clearly distinguished the two stages in his study.

More recently, researchers have further discussed whether flash drought events should be divided into different categories.Vijay Sreeparvathy et al.(2022)[3] believes that a distinction should be made between meteorological flash droughts and agricultural flash droughts. The typical heat-wave-driven flash drought Mo and Lettenmaier et al.(2015)[20] identified is a kind of agricultural drought because it is caused by the depletion of soil moisture and can cause serious crop damage. The typical precipitation-deficit-driven flash drought belongs to the category of meteorological drought, because this type of drought is mainly caused by the negative precipitation anomalies which results from climate change, and it makes the evapotranspiration decrease and the positive temperature anomalies increase.The paper points out that most of the identification methods are applied to agricultural flash drought, but there are relatively few researches on meteorological flash drought.Osman et al.(2022)[25] thinks that most of the previous studies put forward the concept of flash drought focusing on how to capture flash drought events, but they did not evaluate whether it represented a coherent actual process of flash drought events. They used mathematical methods to divide captured flash drought events into three categories, “dry and demanding” events， “evaporative”events and “stealth” events.However, Osman et al. also pointed out that the occurence of flash drought may be caused by completely random meteorological factors, which could make it difficult for a flash drought event to correspond to a specific class.Yuan et al.(2023)[16] distinguished the flash drought from the slow drought on the subseasonal scale, and studied global trends of flash drought and slow drought. The research results showed that there was a global transition to more flash drought in most regions of the world.

At present, researchers have basically reached a consensus on the description of the characteristics of flash drought, but there is still no consistent description of flash drought phenomenon. The indicators and specific procedures used by different researchers to identify flash drought events are still different[25].

2.2 Methods for identifying flash drought events

Since 2013, new methods for identifying flash drought have been proposed almost every year. To identify the occurrence of flash drought events, Otkin et al.(2013)[19] first proposed the satellite-based evaporation index ESI, which is the standardized ratio of actual evaporation on a weekly time scale to the potential evaporation calculated by Penman-Monteith formula. Otkin et al.(2014)[26] considered the regional rapid change index (RCI), which represented the change rate of cumulative ESI variation in the whole flash drought event, and preliminatively proved that the fast-changing drought index could be used to identify flash drought. Otkin et al.(2015)[27] studied the recognition effect of RCI calculated using ESI and several traditional drought indices, and found that the RCI using ESI had good recognition effect in statistical sense. They also pointed out that while the study has demonstrated that rapid changes in the drought index can be used to identify drought-prone areas and to predict the probability of drought intensification on subseasonal time scales, it should not be taken as the final answer, and much additional research is needed to optimize these results.Mo and Lettenmaier et al.(2015, 2016)[20][22] classified flash drought according to the anomaly of precipitation, temperature, evapotranspiration and soil moisture, and designed a set of multivariate discrimination methods for heat-wave-driven flash drought and precipitation-deficit-driven flash drought respectively.Ford and Labosier et al.(2017)[28] found that temperature and precipitation themselves were not strongly correlated with conditions prior to rapid drought, and this weak correlation meant that the predictive ability of these two variables was limited. The variables that explain the surface water balance or the atmospheric water demand are more closely related to the conditions that lead to the transient drought. Therefore, they mainly chose soil moisture as the identification variable in the paper. They believed that if the five-day average surface soil moisture decreased from the 40th percentile to the 20th percentile within 20 days, it indicated the occurrence of flash drought events. It is found that this method is not very sensitive to the threshold value of the range of soil moisture change.

Taking into account the existing studies, Otkin et al.(2017)[2] gave a formal description of the characteristics of ideal indicators for identifying flash drought events. According to the requirements of Otkin, Christian et al.(2019)[23] and Yuan et al.(2019)[24] put forward a more perfect discrimination system than before. The index proposed by Christian is standardized evaporation stress ratio (SESR). He normalized the stress ratio of actual evaporation and potential evaporation at each cell point by time, and established four criteria for judging the process of flash drought events by using SESR: 1) the duration of the judged event should be at least 30 days; 2) The final SESR value at the end of the event is lower than the 20th percentile ; 3) The ΔSESR between each pentad must be equal to or below the 40th percentile of the sequence value of ΔSESR; After all ΔSESR satisfying the former, no more than one ΔSESR can be above the 40th percentile; 4) Over the course of the drought event, the mean change in SESR must be less than the 25th percentile of all changes in SESR historically at the same grid point and at the same period of a year.

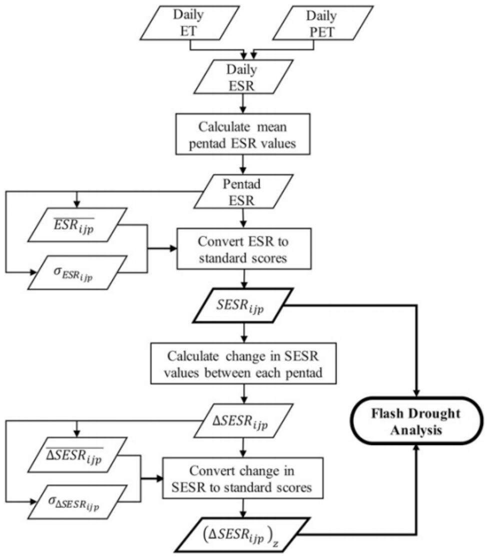

Figure 1(a) A flow chart for calculating SESR[23]

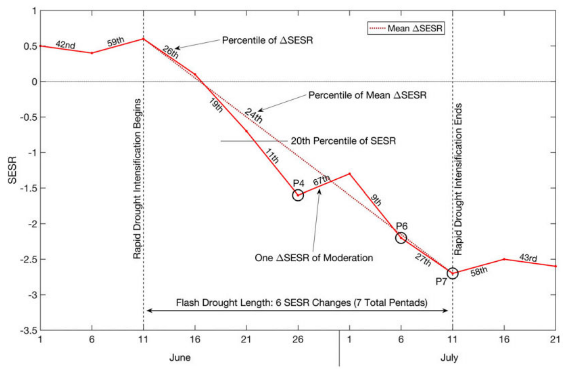

Figure 1(b) A time series schematic illustrating the four criteria used by Christian et al.[23]

This identification procedure takes into account the characteristics of "rapid" and "dry", emphasizing the impact of flash drought on vegetation and the rapid onset of flash drought. Christian et al. also found that the SESR calculated by using the data of the North American Regional Reanalysis(NARR) is similar to the ESI identification results that have been proved to be effective, which also indicates that this index is reasonable. Yuan et al., however, inherited the idea of Otkin and Ford et al.[28], and used the percentile of 5-day average soil moisture in the root zone (top 1m) as the identification index. They considered the rapid decline rate of soil moisture and the persistence of drying, paying more attention to the agricultural response nature of flash drought.They proposed three criteria for identifying flash drought. 1) On a 5-day(pentad) scale, the mean soil moisture in the root zone (top 1m) decreased from more than 40th to 20th percentile, and the average decrease rate was no less than 5% within each pentad; 2) If the decreased soil moisture rises to the 20th percentile again, the drought will end; 3) Drought (soil moisture below 40th percentile) should last for at least 3 pentad(15 days). The first two criteria describe the onset and recovery stages of a drought event. Although the recovery threshold can be increased from the 20th percentile to the 40th percentile, the 20th percentile was chosen here to exclude excessively long duration drought events.

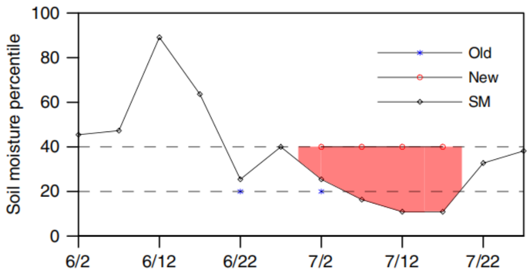

Figure 2 A time series schematic illustrating the three criteria used by Yuan et al.[24]

Later, some researchers have tried to explore the differences between these different identification methods, Liu et al.(2020)[29] studied the application effect of the multi-variable identification system proposed by Mo and Lettenmaier et al.(2015, 2016)[20],[22] and the intensification rate identification method developed by using soil moisture percentile.The paper concluded that the method based on rapid intensification can effectively track the sudden change of water state. However, because the multivariate identification method ignores the change of soil moisture over time and the threshold value is not reasonable, it cannot guarantee the rapid evolution of the flash drought determined by the method. Osman et al.(2021)[18] proposed another index, the soil moisture volatility index(SMVI), based on the rate of change of soil moisture volatility, and compared it with the application effect of six other identification indices of flash drought phenomenon. It is found that their spatial pattern distribution is not the same. In addition, it is proposed that flash drought is a complex and comprehensive event, and there are multiple possible ways to produce rapidly intensifying drought, while changeable meteorological variables such as temperature and abnormal rainfall noise may disturb the evaluation results of different definitions. Therefore, it can be seen from the identification results that flash drought may be divided into more than two categories, not just heat wave flash drought and precipitation deficit flash drought. The researchers therefore suggest that when assessing risk models, developing drought prediction systems, or quantifying and predicting the impacts of climate change, clearly defined options and reasons for making these choices are essential. They point out that flash drought is a kind of compound event, and the identification index to use should be determined according to the specific application purpose and regional characteristics.

In addition to the above indicators, there are still many new identification indicators are being proposed. For example, Otkin et al.(2021)[30] proposed the flash drought intensity index(FDII), which considers the ratio of the observed maximum soil water change rate to the actual change rate and the intensity of flash drought development in the subseasonal time scale. Vijay, Sreeparvathy et al.(2022)[3] developed a Standardized Antecedent Precipitation Evapotranspiration Index(SAPEI) by considering accumulated water, and hoped to distinguish the identification of meteorological flash drought ; Zhang et al.(2022)[31], to fully consider changes in possible driving factors of flash drought, used principal component analysis (PCA) to integrate the Temperature Condition Index(TCI), the Precipitation Condition Index(PCI) and soil moisture Condition Index(SMCI) and developed a PCA-based Meteorological Drought Index(PMDI) ; Christian et al.(2022)[32] proposed a vegetation index (LSWI) which used near infrared and short wave infrared bands to characterize the total water content of vegetation. In addition, there are also attempts and summaries to enhance the existing recognition ability of flash drought by using machine learning and deep learning methods. Tyagi et al.(2022)[17] summarized the application effects of traditional physical models, machine learning (ML) and deep learning (DL) methods in flash drought management and prediction. It is found that ML and DL methods have better effect on reducing the uncertainty of prediction than traditional methods, but these methods still have limited effect on the prediction of short duration drought events.

3. Spatial propagation

Rapid development in time dimension and dynamic structure in space dimension are two key characteristics of flash drought. Accurate tracking of flash drought in time and space is very important to enrich researchers' knowledge of dynamic process of flash drought and improve the design of early warning system.

Although previous studies have provided some general methods to detect and characterize flash drought, most researchers study the characteristics of flash drought events at fixed grid points, and rarely consider the spatial dynamic propagation of flash drought. For example, Christian et al.(2019)[23] developed a statistical method for identifying temporal and spatial characteristics of flash drought, which is based on SESR to determine flash drought at a specific spatial scale. It quantitatively considered the rapid development rate and the duration of flash drought and provided more details of the time evolution of flash drought. However, this study failed to capture the spatial dynamic propagation of flash drought because it only considered the index changes in the fixed grid area. Osman et al.(2021)[18] also mentioned that SESR does not have a good grasp of spatial propagation in typical flash drought events. In recent years, although there have been more researches on the spatial-temporal variation of flash drought, the work done is relatively few[5],[14]. Most researchers decided the temporal and spatial distribution of flash drought mainly by classifying and combining the flash drought events in the temporal and spatial structure of grid points, so as to study the characteristics of its temporal and spatial changes.

In the framework proposed by Li et al.(2020)[14], SEDI was first used to select the interrelated drought patches in time dimension and space dimension. Then they used the change rate of the cumulative SEDI (CSV) of patches during the flash drought development duration (FDDD), namely the instantaneous intensification/recovery rate (IIR/IRR) to screen out patches that were experiencing flash drought events. Considering the characteristics of rapid development and a certain duration of flash drought, Li et al. set three screening criteria. First, the duration is more than 25 days, but less than 60 days; Second, during the development stage of the flash drought event, that is, from the beginning of the flash drought to the time when the negative SEDI's absolute value reaches the maximum peak, there is one or more IIR at or below the 25% of cumulative distribution frequency of the average CSV change of the flash drought event during FDDD. Third, during the development period of the flash drought event, the average value of the average CSV change rate for all time periods, that is, the average instantaneous intensification rate(AIIR), should be equal to or less than 40% of the cumulative distribution frequency of the mean CSV change rate at the whole grid point during FDDD. Li et al. then studied the characteristics of meteorological variables including maximum air temperature(Tmax), wind speed(WS), relative humidity(RH), sunshine duration(SSD), vapor pressure deficit(VPD) and precipitation(P) during identified flash drought events, and found that Tmax and SSD have similar patterns of positive anomalies in most areas during the drought period, while P and RH have obvious negative anomalies, but WS and VPD do not show obvious monotone abnormal pattern. During the flash drought recovery duration (FDRD), P is mainly positive and the relative humidity RH is negative. Compared with FDDD, positive anomalies of Tmax and SSD were reduced to a certain extent, which is consistent with the results of other studies on flash drought.

Gou et al.(2021)[5] questioned the rationality of the identification procedures in Li et al.'s framework. They suggested that the method which selects dry patches first and then selects SEDI accumulation does not directly select patches reflecting rapid development conditions of flash drought, because the selected events may be mixed with common droughts that spread rapidly in space. Gou et al. used SESR as the identification index in the article, considering that SESR could reflect meteorological information and respond to surface water deficit conditions. In their framework, they used SESR to select and label the flash events on each grid, and then used a two-scan algorithm to link the flash events together in spatio-temporal dimensions before clustering them. Finally, they used three variables to characterize each event: duration, defined as the number of consecutive days of dry patches in a time series; the severity of the flash drought event was defined as the total SESR value within the patch during the flash drought event; drought area refers to areas affected by flash drought events. The paper used the framework to study the duration, frequency, centroid transfer path and meteorological conditions of flash drought in the Huaibei Plain. The results showed that the average duration of flash drought identified was in good agreement with the previous findings[24]. This framework has the advantages of simple operation process, easy calculation of SESR and applicability to a variety of climate conditions. However, Gou et al. pointed out that there was little discussion in the current research on how to determine the threshold of rapid intensification rate of flash drought. Most of the thresholds used in the identification criteria in this study were based on the soil properties of the study area and the empirical values of previous research conclusions, which were not universal. In addition, the method also has limitations in distinguishing the rapid intensification period and the dry period of flash drought events spatially.

In the voxel-based three-dimensional FD(V3DFD) method proposed by Li et al.[15], soil moisture was used as the discrimination basis to extract the connected flash drought events in three dimensions, latitude, longitude and time. Then they further combined, separated and deleted the drought events defined in the three dimensions according to the duration and the common coverage area of the drought events in the patch, and finally got relatively accurate results.The paper compared the drought characteristics identified by this method with the results of Yuan et al.'s one-dimensional flash drought identification method[24] and the results of the traditional severity-area-duration(SAD) method.The paper found that because V3DFD did not ignore the drought event whose impact area was less than 1.6% of the whole area, it has better performance in capturing the emergence and development of flash drought events. In addition, the characteristics of flash drought captured using this model were in good agreement with the previous results. However, Li et al. did not systematically discuss the influence of threshold selection on identification results mentioned by other researchers.

The main process of studying the spatial-temporal characteristics of flash drought in the above papers is basically the same, but there are still some deficiencies in the following two aspects of research: First, the method to select the threshold parameters of rapid intensification rate used in the research is mainly based on experience, and no researchers have studied the sensitivity of identification results in different climate regions to the threshold or proposed a strict threshold calculation method. Second, no one has studied the influence of the stationarity of hydrological variables, such as soil moisture, on the identification of temporal and spatial characteristics of flash drought, and the existing research results are mostly based on the stationarity hypothesis[12]. Current estimates of flash drought severity and rate of development are likely to be off by more than 10% if the non-stationarity of soil moisture is taken into account.

4. Conclusion and prospect

Flash drought has been proved to be a threatening natural disaster. Most studies on the mechanism of flash drought show that the mechanism of flash drought is not the same under different climatic conditions and different underlying surface conditions of river basin, and even the path of flash drought may be almost random. Complex changes of meteorological conditions before and after flash drought event make it difficult to strictly classify all flash drought events. Nevertheless, since the 2012 U.S. drought outbreak, researchers have made considerable attempts to define and better capture drought events. At present, researchers have basically reached a consensus on the description of the development characteristics of flash drought, especially the fast development rate and the severe drought effect, but they have not yet formed a consistent description of flash drought phenomenon[25]. Different researchers may have completely different views on whether flash drought events need to be distinguished from drought events, and until now, no conclusion has been reached.

In addition, the supervision and prediction of flash drought events are still difficult in the current field. The overall prediction effect of traditional physics-based prediction models and prediction models using machine learning and deep learning algorithms still needs to be improved. This challenge may be related to both the rapidly evolving nature of flash drought events and the poor forecasting processes they rely on in standard subseasonal scale systems. If we can improve the accuracy of data acquisition and deepen the understanding of the complex physical process of flash drought, the prediction effect of the current model can be further improved.

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