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# How Severe Was the 2022 Flash Drought in the Yangtze River Basin?

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**Abstract:** Flash droughts, characterized by their rapid onset and severe impacts, have critical implications for the ecological environment and water resource security. However, inconsistent definitions of flash droughts have hindered scientific assessments of drought severity, limiting efforts in disaster prevention and mitigation. In this study, we propose a new method for explicitly characterizing flash drought events, with particular emphasis on the process of soil moisture recovery. The temporal and spatial evolution of flash droughts over the Yangtze River Basin was analyzed, and the severity of the extreme flash drought in 2022 was assessed by comparing its characteristics and impacts with those of three typical dry years. Additionally, the driving factors of the 2022 flash drought were evaluated from multiple perspectives. Results indicate that the new identification method for flash droughts is reasonable and reliable. In recent years, the frequency and duration of flash droughts have significantly increased, with the Dongting Lake and Poyang Lake basins being particularly affected. Spring and summer were identified as peak seasons for flash droughts, with the middle reaches most affected in spring, while summer droughts tend to impact the entire basin. Compared to 2006, 2011, and 2013, the flash drought in 2022 affected the largest area, with the highest number of grids experiencing two flash drought events and a development rate exceeding 15%. Moreover, the summer heat in 2022 was more extreme than in the other three years, extending from spring to fall, especially during July–August. Its evolution was driven by the Western Pacific Subtropical High, which suppressed precipitation and elevated temperatures. The divergence of water vapor flux intensified water shortages, while anomalies in latent and sensible heat fluxes increased surface evaporation and heat transfer, further disturbing the regional water cycle. This study provides valuable insights for flash drought monitoring and early warning in the context of a changing climate.

**Keywords:** soil moisture; flash drought; Yangtze River Basin; driving factors



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## 1. Introduction

The effects of global warming have led to an increase in the frequency and intensity of extreme climate events [1,2]. Notably, the responses of droughts and heatwaves to global warming are particularly pronounced, making them central and pressing topics in current climate change research [3,4]. In recent years, the flash drought, often occurring alongside heatwaves, has gradually established itself as a new norm in drought phenomena [5–7]. Flash droughts can develop within days to weeks, and their rapid progression amplifies their destructive impacts, potentially causing irreversible ecosystem damage [8,9]. This swift development presents significant challenges for forecasting, early warning, and risk management related to extreme natural disasters.

Unlike traditional droughts, flash droughts are more likely to occur in humid regions. In these areas, where water is abundant, evapotranspiration is primarily limited by energy supply. The increase in evapotranspiration, coinciding with high temperatures, leads to rapid soil moisture depletion, creating favorable conditions for flash droughts.

Additionally, dense vegetation further draws substantial amounts of water from deep soil layers, causing a sharp increase in evapotranspiration over a short period, which triggers flash droughts [10–12]. In the summer of 2013, 13 provinces in southern China suffered from a severe flash drought within a month, impacting over 2 million hectares of crops [13,14]. After ten years, in the summer of 2022, the Yangtze River Basin in southern China experienced the most severe extreme flash drought since complete meteorological records began in 1961 [15,16]. The rapid onset and widespread impact of this extreme drought in the Yangtze River Basin have triggered a range of social issues, including crop failures, wildfires, shortages in water and energy supplies, and heat-related health problems [17,18]. Annual statistics indicated that the drought affected 0.6 million hectares of cropland, with direct economic losses estimated at USD 7.5 billion. Additionally, large-scale drying of lakes and reservoirs has led to ecological degradation, which may take decades to recover [19,20]. Given the severe consequences, it is crucial to accurately identify flash drought events and clarify their development rules for better drought warning and disaster reduction, especially in ecologically and climatologically vulnerable areas such as the Yangtze River Basin.

Despite extensive research on flash droughts from various perspectives, there remains a lack of consensus on a definition suitable for identifying these events, particularly in the Yangtze River Basin. Previous studies have highlighted the utility of soil moisture anomalies in characterizing drought onset, especially for rapid-onset droughts [20–23]. The rapid decline in soil moisture could potentially serve as a precursor for flash droughts. Zhang et al. [24] examined flash drought characteristics across China, including the Yangtze River Basin, from 1979 to 2016 by focusing on the weekly depletion rate of surface soil moisture percentiles. Nevertheless, root zone water is highly sensitive to climatic factors such as rainfall and temperature and plays a crucial role in determining vegetation growth. Therefore, in the Yangtze River Basin, where vegetation and crops are abundant, flash droughts should be identified using root zone soil moisture. Similar to conventional drought events [25], flash droughts should encompass both the onset and recovery phases [26,27]. However, existing definitions mostly focus on the development stage of flash droughts, neglecting the complex hydrological processes involved in the recovery phase. Current definitions often consider flash droughts to end when soil moisture exceeds a fixed threshold. Yet, following a brief intense rainfall, soil moisture might return above the threshold, but under the influence of a heatwave, soil moisture could decline again. Such dynamic changes in soil moisture can continue to significantly impact vegetation's physiological condition, and a drought interrupted by a wet period might be classified as two separate drought events [28]. This misclassification can affect the assessment of flash drought frequency and complicate disaster prevention and mitigation efforts. Moreover, the drivers and severity of each flash drought event are different and need to be quantified from the perspectives of natural characteristics and affected areas. Under the influence of a strong high-pressure system in the Northern Hemisphere, the unique features of the 2022 flash drought in the Yangtze River Basin included significant precipitation deficits and temperatures markedly above normal [29,30]. The drought's development rate and intensity during the flash drought phase were unprecedented. Despite these insights, the physical mechanisms behind this rapid onset remain unclear and require multi-faceted analysis and research to illustrate how unusual the event is.

In summary, studying the characteristics of flash drought and understanding its driving factors are particularly important for the Yangtze River Basin, which has high vegetation cover and a humid climate. Here, we proposed a flash drought definition based on soil moisture that can capture both flash (rapid intensification of a drought condition, e.g., rapid decline in soil moisture) and drought (onset and recovery under a certain soil moisture threshold for a period of time) conditions. Subsequently, we analyzed the spatiotemporal evolution characteristics of these events, including their frequency, duration, development rate, and intensity. Then, the severity of the 2022 flash drought in the Yangtze River Basin was assessed by comparing it with the natural characteristics and actual impacts of typical drought years. Finally, we conducted a comprehensive and multidimensional analysis of the driving factors behind the extreme 2022 flash drought. This study not only provides a scientific basis for developing effective drought mitigation and adaptation strategies in the Yangtze River Basin but also contributes to the sustainable socio-economic development of the region.

## 2. Materials and Methods

### *2.1. Study Area*

The Yangtze River, China's longest and the world's third longest, originates from the Tanggula Mountains on the Qinghai-Tibet Plateau and empties into the East China Sea after flowing through 11 provinces. The Yangtze River Basin spans 90°−122°E and 24°−35°N (Figure 1a) and accounts for about one-fifth of China's land area [15]. The basin features a multi-tiered structure, rising in the west and falling in the east. The upper reaches include plateaus, mountains, valleys, and basins, while the middle and lower reaches are flatter, featuring plains like Dongting, Poyang, and Jianghan. Soil moisture also varies among these different geological units, with higher levels observed in the middle and lower reaches, whereas the western and northern regions are relatively drier (Figure 1b). To accurately capture the spatial heterogeneity of drought features, this study further divided the Yangtze River Basin into nine subbasins based on the natural divisions of secondary watersheds and river systems [31].

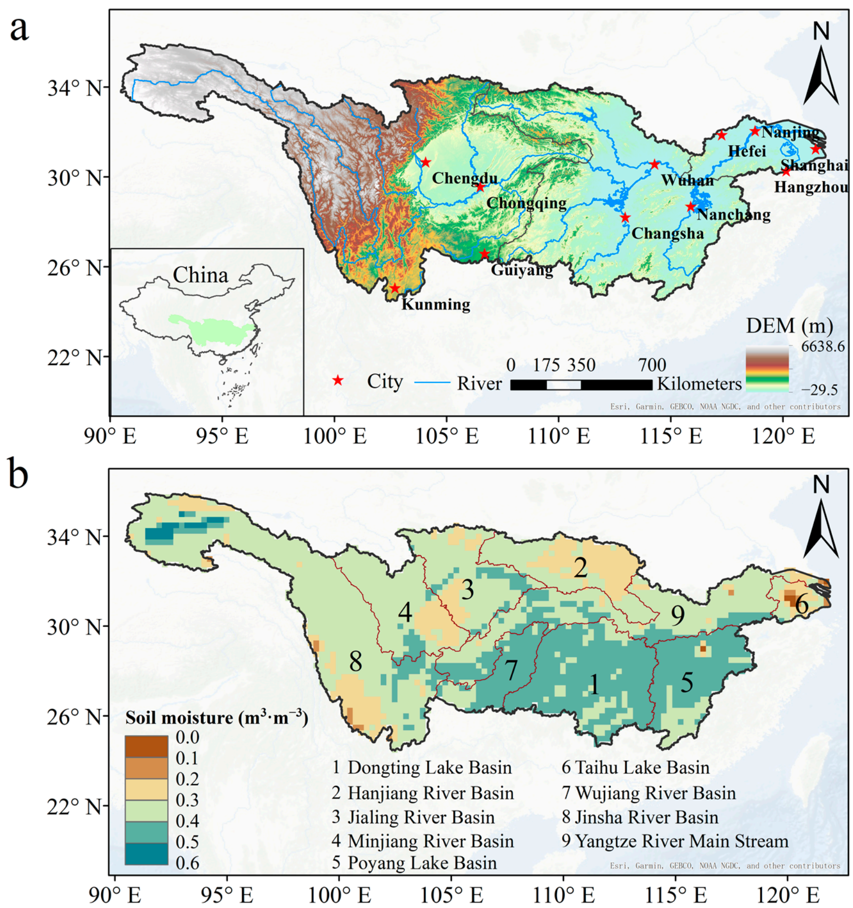


**Figure 1.** (**a**) The location and the elevation of the Yangtze River Basin. (**b**) The subbasins and average annual soil moisture of the Yangtze River Basin.

The Yangtze River Basin is influenced by both the East and South Asian monsoons, resulting in distinct seasonal precipitation patterns that predominantly occur during the summer and fall months [15]. On average, the basin receives approximately 1100 mm of precipitation annually and maintains an average temperature of 12.9 °C. The spatial distribution of both precipitation and temperature shows a consistent pattern, with higher values observed in the middle and lower reaches compared to the upper reaches [32]. In recent decades, the frequency of extreme climatic events has increased due to human activities and climate change, leading to a rising trend in both the frequency and intensity of droughts in the Yangtze River Basin. This poses a serious threat to local water resources, agriculture, ecosystems, and even human health [33].

### 2.2. Data

In vegetative ecosystems, soil moisture directly affects vegetation by regulating water availability, which in turn influences photosynthesis, carbon dioxide absorption, and overall plant growth. When soil moisture levels drop to drought thresholds, these processes can be significantly disrupted, leading to reduced crop yields and changes in regional agricultural production [34,35]. Given its direct impact on these crucial systems, soil moisture data serve as a scientifically sound and effective indicator for detecting and understanding the rapid development of flash droughts. The water stored in the root zone is highly sensitive to changes in other climatic factors, such as precipitation and temperature, and plays a critical role in determining agricultural productivity. Studies indicate that anomalies in root zone soil moisture are particularly effective for detecting the onset of flash droughts and assessing their impacts [36]. Therefore, this study employs the decay characteristics of root zone (0–100 cm) soil moisture during drought periods to model the dynamic progression of flash droughts.

The root-zone soil moisture data used in this study originate from the enhanced version of the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis known as ERA5-Land (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=download (accessed on 1 May 2023)) [37]. ERA5-Land is a reanalysis dataset with enhanced resolution compared to ERA5, providing consistent land variable data over decades. It combines model data with global observations based on physical laws, offering an accurate representation of past climate conditions. ERA5-Land provides soil moisture data from four layers, namely 0–7 cm, 7–28 cm, 28–100 cm, and 100–289 cm, with a temporal resolution of 1 h and a spatial resolution of 9 km. Its high temporal and spatial resolution make it useful for land surface applications such as flood or drought forecasting. Previous studies comparing ERA5-Land data with in situ observations have found that it effectively characterizes root-zone soil moisture (0–100 cm) in China, with particularly strong results in the Yangtze River Basin [17,38]. Therefore, in this study, soil moisture data of 0 to 100 cm from 1950 to 2022 in ERA5-Land were selected to estimate flash drought and resampled to 0.25° according to bilinear interpolation.

In addition, precipitation, temperature, moisture divergence, latent heat flux, sensible heat flux (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels-monthly-means?tab=download (accessed on 1 May 2023)) and 500 hPa geopotential height (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download (accessed on 1 May 2023)) were downloaded from ERA5 to analyze the synoptic conditions during the flash drought event [39]. The mean vertically integrated moisture divergence is the horizontal rate of flow of moisture (water vapor, cloud liquid, and cloud ice) per meter across the flow for a column of air extending from the Earth's surface to the top of the atmosphere. This parameter is positive for moisture that is diverging and negative for moisture that is converging, indicating whether atmospheric motions decrease (for divergence) or increase (for convergence) the vertical integral of moisture over time. Latent heat flux and sensible heat flux are essential components of the surface energy balance. Analyzing changes in these fluxes helps reveal shifts in the surface energy budget, offering insights into processes affecting surface temperature and humidity. Specifically, surface latent heat flux represents the transfer of latent heat between the Earth's surface and the atmosphere due to turbulent air motion, with evaporation acting as a transfer of energy from the surface to the atmosphere. Surface sensible heat flux, on the other hand, refers to the transfer of heat between the Earth's surface and the atmosphere, excluding heat transfer from condensation or evaporation. Geopotential is defined as the gravitational potential energy of a unit mass at a particular location relative to mean sea level, and it represents the work performed against gravity to lift a unit mass to that location. Geopotential height plays an important role in synoptic meteorology, particularly at the 500 hPa level, which is commonly used to analyze mid-tropospheric circulation characteristics. This layer balances the influences of temperature, humidity, and airflow, making it useful for identifying the distribution of ridges and troughs, thereby revealing potential weather changes and climate patterns.

### *2.3. Methods*

#### 2.3.1. Definition of Flash Drought

Flash droughts typically do not develop gradually like seasonal or long-term droughts but instead emerge rapidly within a short period, causing severe impacts on local ecosystems, economies, and societies. Soil moisture data with pentad-scale (5 days) averages help to mitigate short-term fluctuations in soil moisture caused by minor precipitation events minimize daily variability in noisy variables. In addition, it can capture the rapid onset of flash drought events, emphasizing their impact on agriculture and ecosystems. Given the prevalent use of pentad time scales in prior flash drought studies [5,40], we averaged root zone soil moisture data over a pentad scale (5 days) for analysis in this study.

Soil moisture exhibits significant regional and seasonal variability, focusing on current soil moisture conditions, which makes it challenging to use directly for long-term drought analysis. The soil moisture percentile is a simple and robust method that contextualizes current soil moisture conditions within the framework of average soil moisture and its variability at a specific location [41]. Therefore, this study employs soil moisture percentiles to identify flash droughts, enhancing the temporal and spatial comparability of the results. The formula for calculating soil moisture percentiles is as follows:

$$\mathrm{SM} = \frac{\mathrm{M}}{\mathrm{N}} \times 100 \quad (1)$$

where SM is the soil moisture percentile for the target date, M is the rank of the soil moisture for the target date, and N is the total number of soil moisture data points across all years. To maintain data sufficiency and smooth out short-term anomalies or noise, thereby better reflecting the overall trend in soil moisture and ensuring more stable and reliable results, this study calculates soil moisture percentiles using a sliding window of three pentads. Specifically, M is the rank position of soil moisture for the target pentad, the preceding pentad, and the following pentad, sorted from smallest to largest across all years, while N represents the total number of data points after applying the sliding window of three pentads across all years [27].

This study utilizes the attenuation characteristics of soil moisture during droughts to characterize the evolution of flash droughts. A framework has been developed that not only highlights the rate of soil moisture decline during the onset phase of flash droughts but also intricately depicts the dynamic recovery process of flash droughts [28]. The specific steps are as follows:

(1) Onset time: the onset time of a flash drought is defined as the last moment ($t_{start}$) in which the soil moisture percentile ($SM_{start}$) is above the 40th percentile. This criterion indicates that the soil is drier than normal, ensuring that the soil transitions from non-drought conditions to this phase [40]. Additionally, this condition helps differentiate flash drought events from situations where pre-existing drought conditions rapidly intensify into larger-scale events. As shown in Figure 2, pentad 7 was identified as the start of the flash drought, being the last time in which the soil moisture percentile was above the 40th percentile.

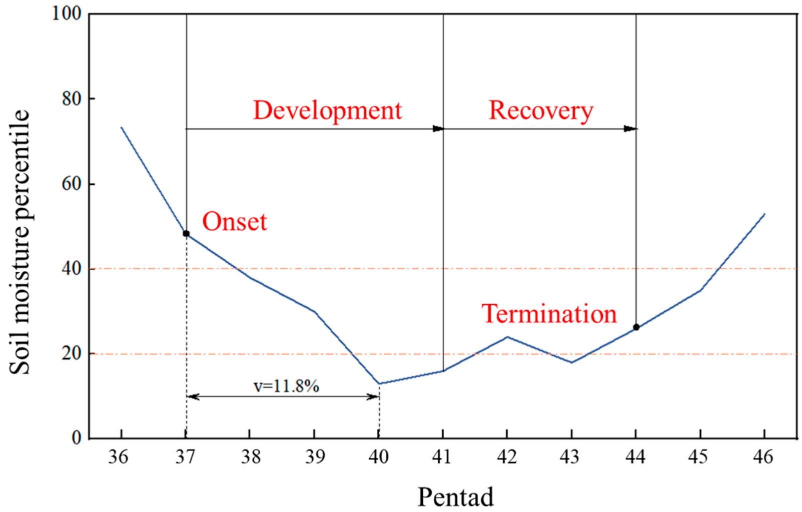


**Figure 2.** Schematic diagram of the definition of the onset, development and recovery stages in flash drought events used in this study. v is the development rate, defined as the average rate of decline in soil moisture percentiles.

(2) Rapid development phase: during this phase, the soil moisture percentile at any given time is below the 40th percentile, and at least one moment (t) must have a soil moisture percentile ($SM_t$) below the 20th percentile [42]. The development rate at which soil moisture percentiles decline below the 20th percentile (v) must be at least 5%. This threshold indicates that the flash drought has already caused significant impacts on vegetation within the ecosystem. The development rate is calculated using the following formula:

$$v = (SM_t - SM_{start})/(t - t_{start}) \quad (2)$$

where v is the average rate of decline in soil moisture percentiles, t is the moment when the soil moisture percentile drops below the 20th percentile, $SM_t$ is the soil moisture percentile at time t, $t_{start}$ is the last moment when the soil moisture percentile was above the 40th percentile, and $SM_{start}$ is the soil moisture percentile at $t_{start}$.

As shown in Figure 2, from pentad 37 to pentad 40, soil moisture rapidly declined over a short period, with a decline rate of 11.8%. The rapid decay phase ended when soil moisture remains at a relatively low level without significant downward or upward trends.

(3) Recovery phase: the flash drought event terminates when the pentad average soil moisture is above the 20th percentile for two consecutive pentads, with the first moment when the soil moisture exceeds the 20th percentile marking the end of the flash drought event.

Current definitions often consider flash droughts to end when soil moisture percentiles rise back to the 20th percentile. However, this definition oversimplifies the recovery phase of flash droughts, overlooking the complex hydrological processes during recovery and their profound impacts on vegetation structure, composition, and function. When soil moisture percentiles drop below the 20th percentile and remain there for some time, short and intense precipitation might quickly bring soil moisture back to the 20th percentile. Yet, under the influence of heatwaves, soil moisture may drop below the 20th percentile again. Such dynamic changes in soil moisture continue to significantly affect vegetation physiological conditions. Moreover, a prolonged drought interrupted by a wet period may be classified as two separate drought events, potentially impacting the assessment of flash drought frequency. The recovery conditions proposed in this study are designed to effectively address and mitigate this issue. As shown in Figure 2, the flash drought was alleviated on pentad 44.

(4) Total duration of flash drought: to account for the impact of flash droughts on vegetation and to ensure that the duration of a flash drought is on a seasonal timescale, this

study defines the duration of a flash drought event as lasting at least three pentads. As illustrated in Figure 2, the flash drought event in this example lasted for seven pentads.

(5) Flash drought characteristics: an event that meets all the aforementioned criteria is identified as a flash drought event. The characteristics of a flash drought include the frequency (in units: events), duration (in units: days), rate (in units: %), and intensity (in units: %). The intensity of a flash drought refers to the difference between the maximum and minimum soil moisture percentiles during the drought period, which represents the maximum change in soil moisture percentiles. This is because flash droughts develop rapidly, and the soil moisture change value can reflect the severity of drought conditions to some extent [42].

#### 2.3.2. Trend Test

Mann–Kendall (MK) analysis is a non-parametric statistical method developed by Mann and Kendall [43,44], widely used for detecting long-term trends in climate change, environmental quality, and hydrological data. A key advantage of the MK analysis is that it does not rely on assumptions about the data's distribution, making it suitable for non-normally distributed data. Additionally, it is robust to missing values and outliers. In this study, the MK test was applied to the frequency, duration, development speed, and intensity of flash droughts in the Yangtze River Basin to assess the trends in these drought indicators and analyze their temporal evolution characteristics.

## 3. Results

### *3.1. Spatio-Temporal Characteristics of Flash Droughts*

Figure 3 illustrates the characteristics (i.e., frequency, mean duration, mean development rate, and mean intensity) of flash droughts in the Yangtze River Basin from 1950 to 2022. As depicted in Figure 3a, flash droughts exhibit significant regional variation, with higher frequencies occurring at the boundary between the upper and middle reaches, as well as in the central and lower plains, particularly in the Dongting Lake Basin (sub-basin 1), Poyang Lake Basin (sub-basin 5), and Wujiang River Basin (sub-basin 7). On average, most grids experienced 1.3 flash drought events per year. This finding aligns with Lu et al. [45], who noted that the middle and lower reaches of the basin experience more than 12 drought events per decade. The central region is especially vulnerable, with many areas experiencing over two flash droughts annually. Although a few grids saw more than three flash drought events per year, these accounted for only 0.67% of the total area. Most areas had an average flash drought duration of 50 days, with durations ranging from a minimum of 25 days to a maximum of 110 days (Figure 3b). Approximately 59% of the regions experienced droughts lasting between 50 and 60 days, while only 6.38% of the regions saw droughts longer than 60 days. The longest and shortest events both occurred in the upstream areas, while the average duration in the middle and lower reaches exceeded 40 days. These results are consistent with those of Hu et al. [46], who reported an average flash drought duration of 58 days in the Yangtze River Basin. Longer drought durations in some areas may be attributed to slower soil moisture recovery, which can extend the period of drought and potentially evolve into seasonal droughts [21]. The development rates across the basin generally ranged between 5% and 10%, with about 13% of regions exceeding 10% (Figure 3c). Development rates were higher in the middle and lower reaches compared to upstream areas, underscoring the importance of timely monitoring and early warning systems in these regions. The spatial patterns of mean intensity were consistent with those of frequency, showing faster development and higher intensity in the eastern upstream regions and the central and lower reaches (Figure 3d). The average intensity of drought events across most areas was 36.76%.

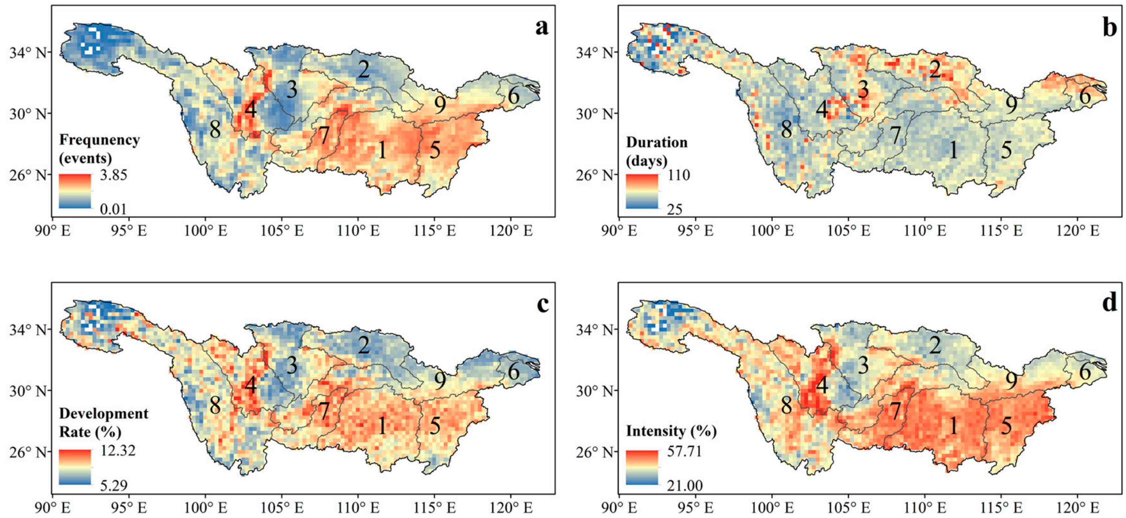


**Figure 3.** Spatial distribution of flash drought characteristics in the Yangtze River Basin from 1950 to 2022. (**a**) Frequency: the multi-year average number of flash drought events. (**b**) Mean duration: the average number of days each drought event lasted. (**c**) Mean development rate: the average speed at which each flash drought event developed. (**d**) Mean intensity: the average intensity of each drought event. The white grid points indicate that there was no flash drought. The numbers in the (**a**–**d**) represent the subbasins.

Figure 4 shows the changing trend in regional average fulminant drought characteristics from 1950 to 2022. The overall trends for the frequency, development rate, and intensity of flash droughts passed the Mann–Kendall (MK) trend test, with $p < 0.05$, while the duration also passed the MK test with $p < 0.1$. However, neither the pre-abrupt nor post-abrupt trends for all four characteristics passed the MK test (as can be seen in Supplementary Figure S1). As shown in Figure 4a, the time series of flash drought frequency exhibited a significant upward trend, with a sharp increase after 1993. The slope of the overall trend is 0.06. The average multi-year frequency before 1993 was 1.45 with a standard deviation of 0.3, while the average frequency after the mutation increased to 1.70 with a standard deviation of 0.2. The change in frequency is statistically significant, with a $p$-value of 0.0003 from the $t$-test. Over the past 20 years, the highest frequency was recorded in 2007, averaging 1.70 events per year, followed by 2017 and 2013. These findings are consistent with previous research and related reports, confirming that the flash drought definition used in this study effectively captures variations in flash drought occurrences. Figure 4b illustrates an increasing trend in the regional average duration of flash drought events, marked by an abrupt change in 1999. The slope of the overall trend for duration is 0.06. The multi-year average duration before 1999 was 50 days, with a standard deviation of 5, while the average duration after the abrupt change was approximately 55 days, with a standard deviation of 6. The change in duration was significant, with a $t$-test yielding a $p$-value of 0.003. Previous studies have indicated that the annual mean temperature in the Yangtze River Basin has followed an upward trend, with the most significant warming occurring in the 1990s, during which the average temperature increased by 0.3 °C compared to the 1961–1990 period [47]. This rise in temperature is likely to increase seasonal evapotranspiration and reduce soil moisture, thereby increasing the incidence of flash droughts in the Yangtze River Basin. In Figure 4c, the trend in the development rate of flash drought events shows a slight decline over the years, with the average rate decreasing from 9.72% before 1996 to 8.81% in subsequent years. As shown in Figure 4d, the intensity of flash drought events exhibited a modest decrease, with an overall trend slope of −0.05. The multi-year average intensity before 1997 was 48.26%, with a standard deviation of 2.72, while the average intensity after 1997 dropped to 46.14%, with a standard deviation of 1.88. The change in intensity before and after the mutation point was significant, with a $p$-value of 0.002 from the *t*-test. Intensity is defined as the difference between the maximum and minimum soil moisture percentiles during flash drought events. This mutation may be related to dynamic changes in soil moisture and the complex interactions of various climate factors. The nonlinear nature of climate change may have resulted in different impacts over time, thus causing the observed trends to differ from other drought characteristics.

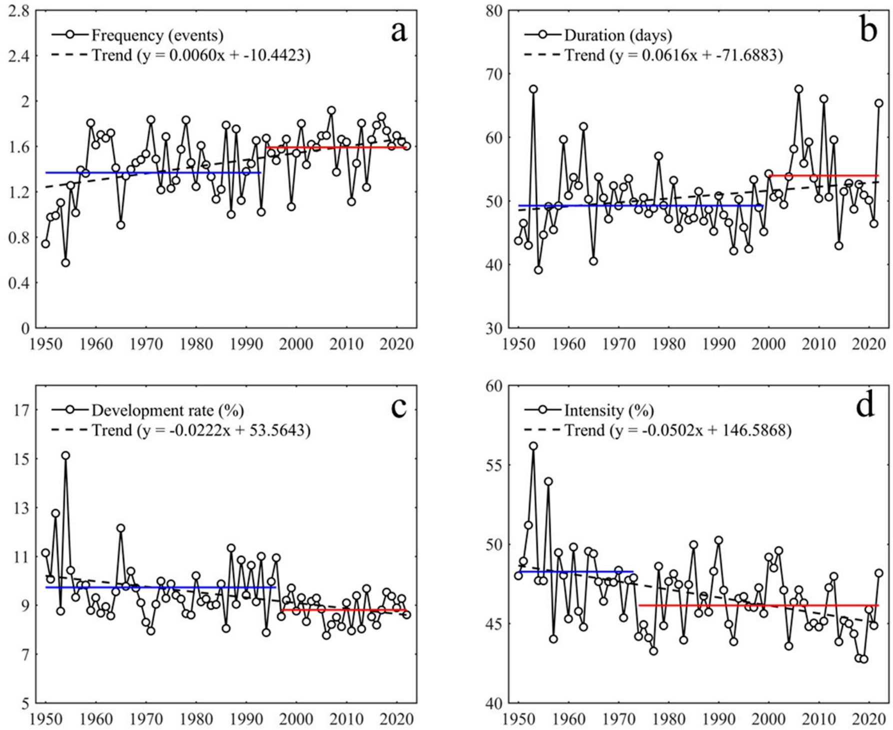


**Figure 4.** Trend changes in flash drought characteristics in the Yangtze River Basin from 1950 to 2022. (**a**) Regional average frequency of flash drought events. (**b**) Regional mean duration of flash drought events. (**c**) Regional average development rate of flash drought events. (**d**) Regional mean intensity of flash drought events. The black dotted line is the trend line. The solid blue line is the pre-abrupt mean. The solid red line is the post-abrupt mean. The overall trends passed the MK significance test with $p < 0.05$ in (**a**,**c**,**d**), and the overall trends passed the MK significance test with $p < 0.1$ in (**b**).

Figure 5 illustrates the characteristics of flash drought events across different seasons. Figure 5a depicts the average frequency of flash drought events initiating in the four seasons from 1950 to 2022. The analysis reveals that spring and summer exhibited a higher propensity for initiating flash droughts, with a median occurrence of approximately 0.6 events per season. Conversely, the frequency of flash droughts in fall and winter decreased markedly, to approximately 0.3 and 0.2 events per season, respectively. Notably, the frequency distribution for spring and summer droughts displayed larger whiskers, indicating greater variability in the occurrence of these droughts compared to fall and winter. Furthermore, the initiation of flash drought events was less frequent in fall and winter, potentially attributed to reduced evapotranspiration and soil moisture consumption due to lower temperatures. Figure 5b shows the distribution of total days affected by flash drought across different seasons. Spring, summer, and fall exhibited consistent ranges, with a median duration of approximately 60 days. In winter, the duration ranged from 45 to 65 days, demonstrating significant fluctuations. Despite the lower number of flash drought events initiating in winter (as shown in Figure 5a), some droughts persisted from fall into winter, leading to an increased number of drought-affected days during this season. Figure 5c represents the most frequent season for the occurrence of the first flash drought event in each region over a multi-year period (1950–2022). Specifically, a statistical analysis of the seasons in which the first flash drought event occurred at each grid point over the years was conducted, and the season with the highest frequency of occurrence was identified. The results indicate that spring was the most common season for the initial onset of flash droughts, particularly in the middle and lower reaches of the Yangtze River. In contrast, in the Jinsha River basin (sub-basin 8) in the upper Yangtze, most flash drought events first occurred during the summer.

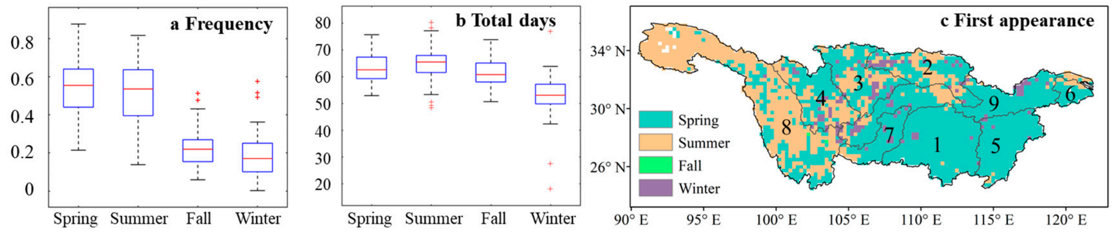


**Figure 5.** Seasonal characteristics of flash droughts in the Yangtze River Basin. (**a**) The multi-year average frequency of flash drought in different seasons. (**b**) The multi-year average total days of flash drought in different seasons. (**c**) Most frequent season of first flash drought event per grid, 1950–2022. The numbers in the figure represent the subbasins.

### *3.2. Severity of Flash Drought in the Yangtze River Basin in 2022*

The characteristics of the 2022 flash drought are presented in Figure 6. Figure 6a presents the percentage of grid points affected by flash droughts relative to the total number of grid points in the entire basin for each pentad. The results indicate that approximately 30% of the Yangtze River Basin was already experiencing flash droughts in the spring. However, from June onward, the number of grid points affected by droughts increased significantly, exceeding 50% of the basin in July and August, reaching a peak during these months. This period coincides with the critical stages of rice grain filling and milk maturity in the Yangtze River Basin, which are highly sensitive to hydrothermal conditions. The sustained high temperatures and drought during this time resulted in a significant reduction in rice yield.

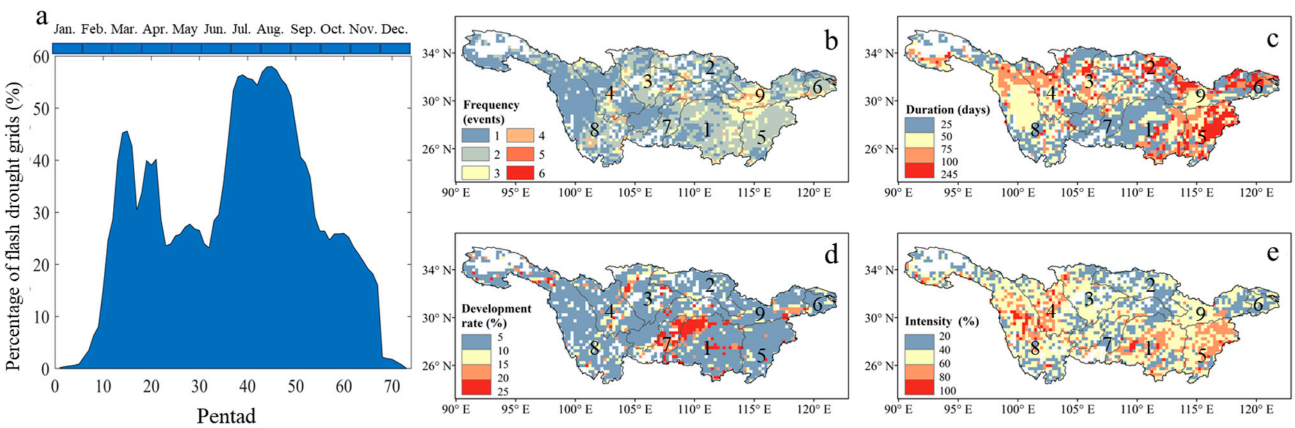


**Figure 6.** (**a**) The percentage of grid points affected by flash droughts relative to the total number of grid points in the entire basin for each pentad. (**b**) Spatial distribution of flash drought frequency in the Yangtze River Basin in 2022. (**c**) Spatial distribution of flash drought duration in the Yangtze River Basin in 2022. (**d**) Spatial distribution of flash drought development rate in the Yangtze River Basin in 2022. (**e**) Spatial distribution of flash drought intensity in the Yangtze River Basin in 2022. The numbers in the figure (**b**–**e**) represent the subbasins.

Figure 6b shows the spatial distribution of flash drought frequency across the Yangtze River Basin in 2022, revealing that flash drought events occurred across all subbasins, affecting 88.96% of the region. Notably, 57.31% of the grid cells experienced more than two flash drought events, with higher frequencies observed in the middle reaches. As depicted in Figure 6c, most areas experienced an average event duration of 70 days, with some regions extending up to 245 days, particularly through the summer and fall. Over 50% of the basin was impacted by flash droughts that persisted for more than 60 days, especially in the Dongting Lake Basin (sub-basin 1) and Poyang Lake Basin (sub-basin 5), which severely affected regional ecosystems. Figure 6d highlights that 78% of the regions had flash drought development rates between 5% and 10%. Approximately 5.39% of the regions, primarily in the Wujiang River Basin (sub-basin 7) and Dongting Lake Basin (sub-basin 1) at the junction of the upper and middle reaches, exhibited development rates exceeding 20%. In Figure 6e, the minimum drought intensity was recorded at 22%, with over 70% of the affected areas experiencing intensity levels above 40%, indicating substantial soil moisture depletion. Spatially, the middle and lower Yangtze River Basin faced more severe flash droughts compared to the upper regions, as evidenced by the longer drought durations (Figure 6c) and higher drought severity (Figure 6e). Prior to July, in preparation for the anticipated flooding season, reservoirs in the upper stream were emptied due to earlier-than-expected precipitation levels. However, this regulation worsened the impact when the unexpected drought occurred. According to local hydrological authorities, water levels in the basin's two largest lakes, the Dongting Lake Basin (sub-basin 1) and Poyang Lake Basin (sub-basin 5), reached historic lows by early August—three to four months earlier than usual [15]. In August, the water area of Poyang Lake sharply decreased by 67.58% from its July levels, shrinking by 58.4%, or 736.68 $km^2$, compared to the same period in historical records. This marked a new record low in nearly 20 years, causing significant damage to agriculture and power systems [15].

Figure 7a presents the standardized precipitation anomalies (SPAs) in the Yangtze River Basin over the past two decades, identifying 2006, 2011, and 2022 as notable years with precipitation-deficit-induced droughts. While the overall precipitation anomaly in 2013 did not meet the threshold for significant drought, the level of precipitation deficit was still relatively high, particularly in the middle and lower reaches of the basin, which experienced a severe episode of abrupt drought that year. These years were selected as reference dry periods due to the similarity of their precipitation anomalies to those observed in 2022. To assess the severity of the 2022 flash drought and explain its uniqueness, we compared regional average characteristics such as frequency, duration, development rate, intensity, and affected area during these drought years, as shown in Figure 7b. The results indicate that although the frequency and duration of flash droughts in 2022 were slightly lower than in 2006 and 2013, it exhibited the fastest development rate and the largest affected area.

Additionally, the area proportions for different drought characteristics were calculated, as shown in Figure 7c,d. In 2022, the percentage of grids experiencing two flash drought events exceeded that of the other typical drought years, as well as the multi-year average from 2003 to 2022. However, the percentage of grids with more than three flash drought events was minimal, accounting for only around 4% of the total, indicating that flash drought occurrences were tied to specific seasonal or temporary environmental conditions rather than being widespread throughout the year. In all four years analyzed, more than half of the basin experienced flash drought events lasting over 60 days, with 2022 having slightly fewer such events than 2006, though both years significantly exceeded the multi-year average. Moreover, the proportion of flash drought events with a development rate exceeding 15% in 2022 was considerably higher than in the other typical years, establishing it as a record-breaking event. Soil moisture in the Yangtze River Basin fluctuated dramatically in 2022, with areas experiencing drought intensity above 50% being substantially larger compared to other significant drought years.

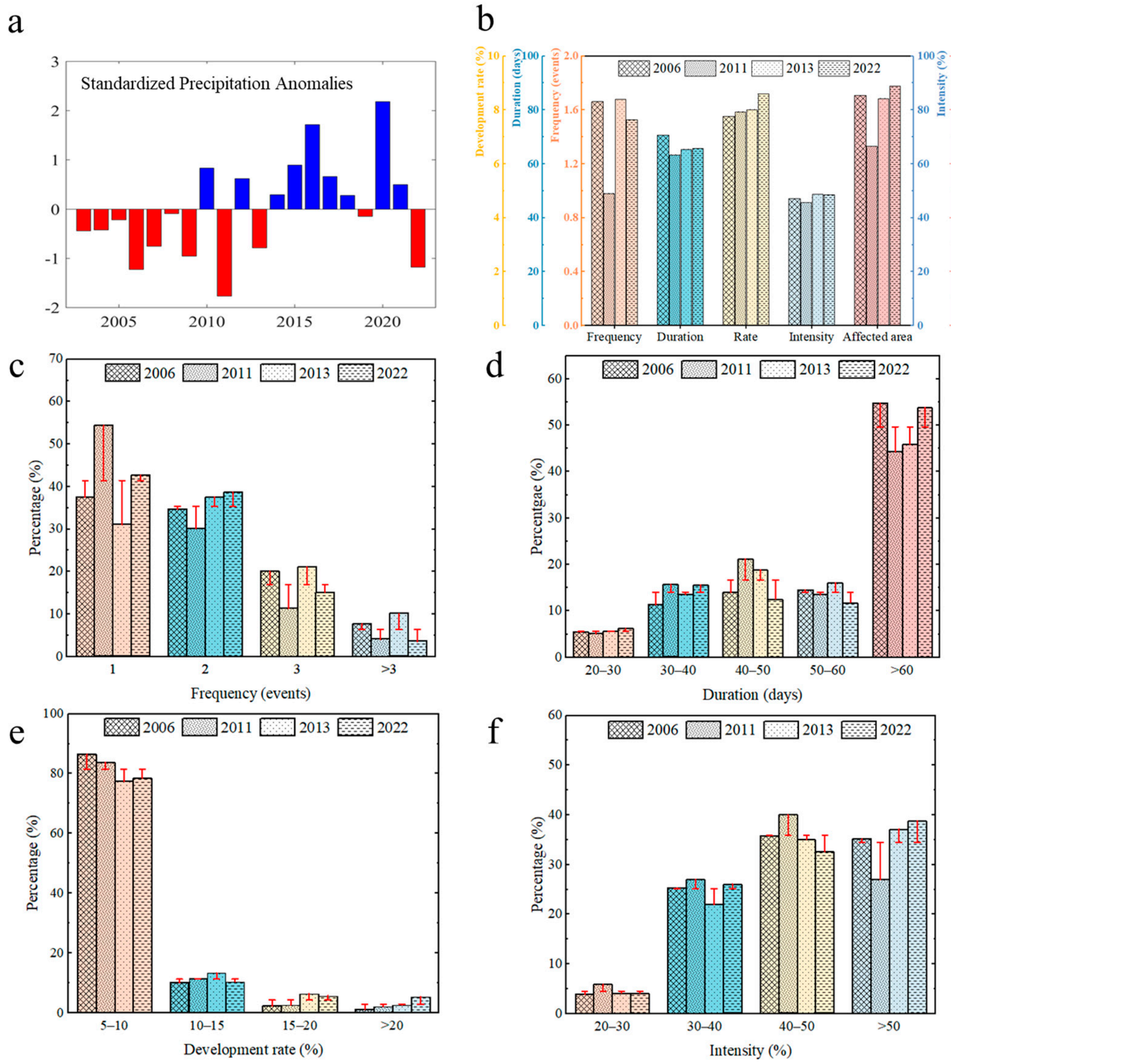


**Figure 7.** (**a**) Standardized precipitation anomalies from 2003 to 2022. (**b**) Comparison of regional average flash drought characteristics in typical drought years. (**c**) Percentage of different flash drought frequency in typical drought years. (**d**) Percentage of different flash drought durations in typical drought years. (**e**) Percentage of different flash drought development rates in typical drought years. (**f**) Percentage of different flash drought intensities in typical drought years. The red error bar in (**c**–**f**) indicates the difference from the multi-year average (2003–2022), and an upward trend indicates that the value is less than the multi-year average.

### *3.3. Driving Factors of the Flash Drought in 2022*

As previously mentioned, the 2022 flash drought in the Yangtze River Basin has been identified as the most severe drought in recent years. In this section, we investigate the driving mechanisms behind this record-breaking drought. Figure 8 displays the time series of accumulated precipitation and maximum temperature in 2022 and the other drought years (2006, 2011 and 2013). As shown in Figure 8a, cumulative precipitation prior to July 2022 was significantly higher than in other flash drought years as well as the multi-year average (black solid line). However, after that, there was a clear turning point, with the rise of accumulated precipitation slowing sharply and precipitation falling well below the multi-year average, leading to a rapid intensification of the summer flash drought in 2022. In addition to precipitation, temperature is another factor that significantly influenced the 2022 summer flash drought and presents a unique time pattern, as shown in Figure 8b.

Compared to the other three years of severe drought events, the summer heat of 2022 was more extreme, lasting from spring to fall, especially during the July-August period.

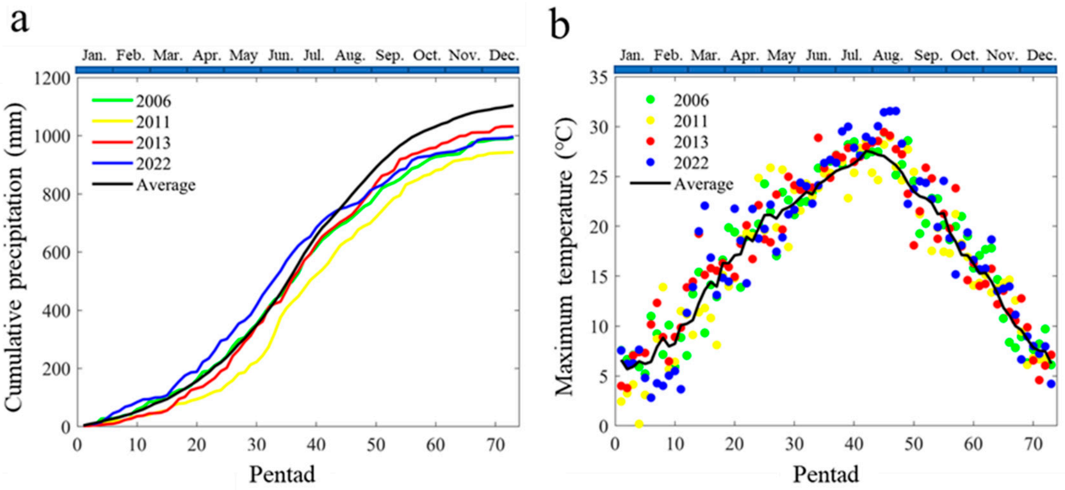


**Figure 8.** (**a**) Time series of accumulated precipitation in drought years. (**b**) Time series of maximum temperature in drought years. The horizontal axis represents the pentad of the year, and the black solid line indicates the multi-year average for the past twenty years (2003–2022) in (**a**,**b**).

To further analyze the driving mechanisms of the temporal and spatial evolution behind the 2022 summer flash drought event, we also examined the variations in key driving factors from June to August 2022, focusing on climate characteristics, circulation anomalies, and surface energy exchange. The primary variables considered include precipitation, temperature, moisture divergence, 500 hPa geopotential height, latent heat flux and sensible heat flux.

Figure 9 presents the precipitation and temperature conditions during the summer of 2022 flash drought event. Figure 9a–c illustrate a significant reduction in precipitation across the eastern and southern parts of the Yangtze River Basin from June to August 2022. Notably, in July and August, the precipitation deficit was almost widespread throughout the middle and lower reaches of the Yangtze River, highlighting a strong correlation between flash drought events and extreme precipitation shortages. Figure 9d–f indicate that temperatures were markedly higher than usual across the Yangtze River Basin during this period, with the most pronounced temperature anomalies in July and August, particularly in the eastern and southern regions. This high-temperature environment accelerated evaporation from soil and vegetation, further intensifying the propagation and severity of the drought.

Regional precipitation changes are closely linked to moisture convergence and divergence [48]. Figure 10a–c demonstrate that in July and August 2022, the moisture flux divergence in the central and eastern parts of the Yangtze River Basin exhibited predominantly positive values, indicating a trend toward moisture dispersion. This divergence reduced the moisture supply, subsequently decreasing precipitation and exacerbating the drought's severity. Changes in atmospheric circulation are closely associated with variations in atmospheric pressure. In May and June, moist air masses from the Indian Ocean and South Pacific Ocean had contributed to increased rainfall in the Yangtze River Basin. However, by early July, the Western Pacific Subtropical High (WPSH) intensified significantly, covering a much larger area after merging with a continental high-pressure system (Figure 10d–f). This led to westerly winds dominating northern China, blocking the southward movement of high-latitude moisture. Simultaneously, the WPSH induced an anticyclonic system over the Yangtze River Basin, further driving water vapor divergence and suppressing rainfall. This became the main driver of the record-breaking drought in the region.

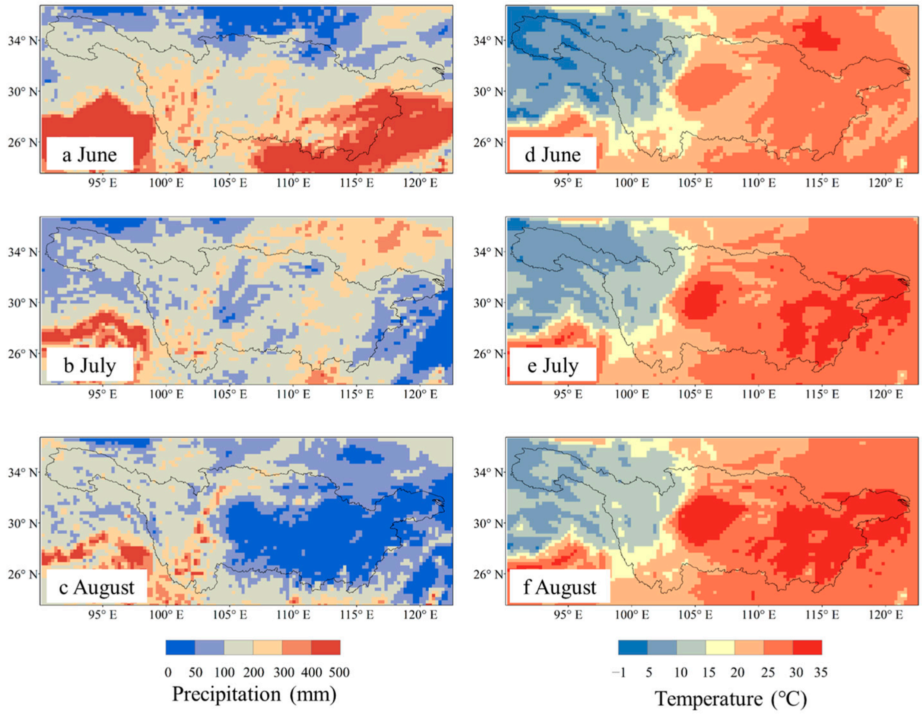


**Figure 9.** Spatial patterns of hydrometeorological variables over the Yangtze River Basin in 2022. (**a**) Precipitation in the Yangtze River Basin in June 2022. (**b**) Precipitation in the Yangtze River Basin in July 2022. (**c**) Precipitation in the Yangtze River Basin in August 2022. (**d**) Temperature in the Yangtze River Basin in June 2022. (**e**) Temperature in the Yangtze River Basin in July 2022. (**f**) Temperature in the Yangtze River Basin in August 2022.

In the ERA5 dataset, surface latent heat flux is defined as the transfer of energy from the surface to the atmosphere via evaporation or other phase changes in water. Typically, negative values indicate evaporation, where the surface transfers latent heat to the atmosphere. Sensible heat flux reflects surface temperature changes. Negative values generally indicate heat transfer from the surface to the atmosphere, while positive values suggest heat transfer from the atmosphere to the surface. As shown in Figure 11, since June, an increased amount of energy has been fluxed into the atmosphere as sensible heat. This led to an elevated lifting condensation level, causing the atmospheric boundary layer to become drier overall and a reduction in moist static energy, which effectively suppressed convective precipitation [49]. Additionally, the overall drying of the boundary layer increased the potential for land surface evaporation, leading to a rapid depletion of soil moisture and accelerating the onset of drought. However, as soil moisture diminished, evapotranspiration in August became increasingly limited by water availability and subsequently began to decline. While this slowed the further loss of soil moisture to some extent, it also indicated that the soil had approached or reached a critically dry state, coinciding with the most severe stage of the drought during the entire summer.

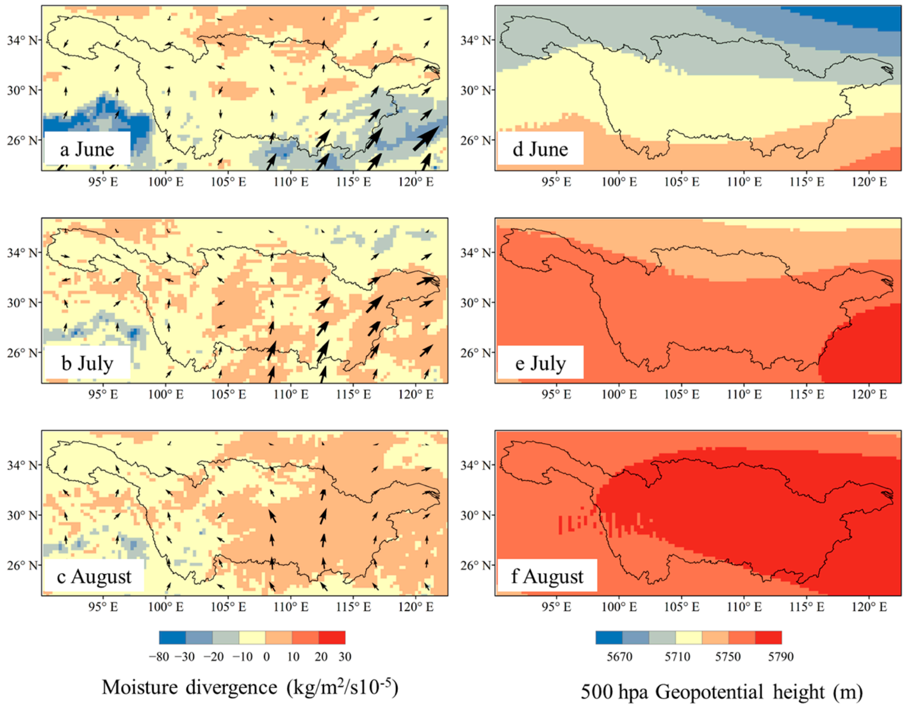


**Figure 10.** Spatial patterns of climatic variables over the Yangtze River Basin in 2022. (**a**) Moisture divergence in the Yangtze River Basin in June 2022. (**b**) Moisture divergence in the Yangtze River Basin in July 2022. (**c**) Moisture divergence in the Yangtze River Basin in August 2022. (**d**) Geopotential height of 500 hpa in the Yangtze River Basin in June 2022. (**e**) Geopotential height of 500 hpa in the Yangtze River Basin in July 2022. (**f**) Geopotential height of 500 hpa in the Yangtze River Basin in August 2022.

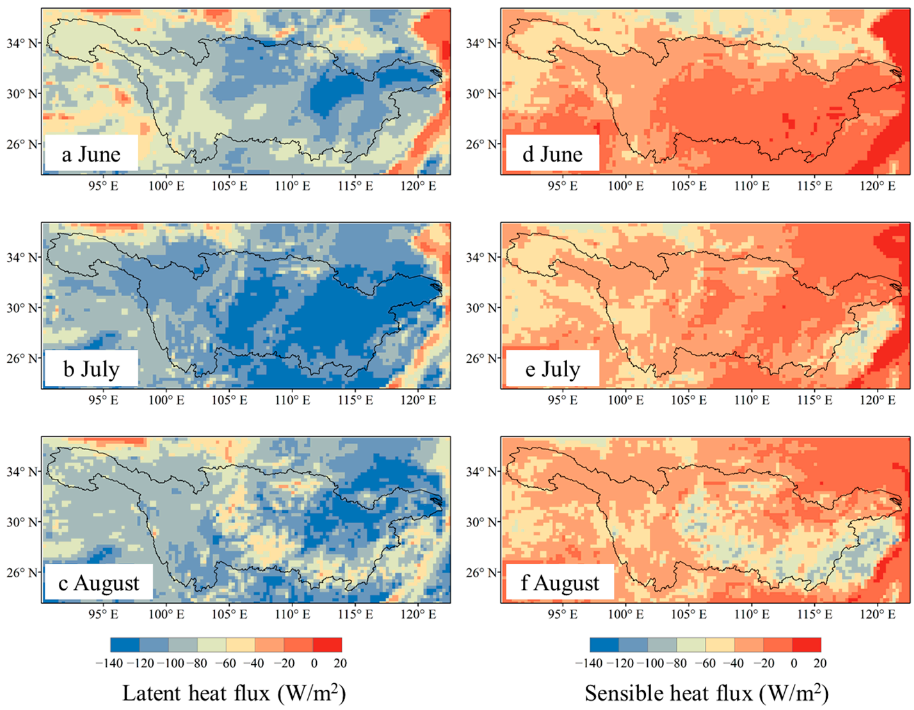


**Figure 11.** Spatial patterns of surface heat flux over the Yangtze River Basin in 2022. (**a**) Latent heat flux in the Yangtze River Basin in June 2022. (**b**) Latent heat flux in the Yangtze River Basin in July 2022.

(**c**) Latent heat flux in the Yangtze River Basin in August 2022. (**d**) Sensible heat flux in the Yangtze River Basin in June 2022. (**e**) Sensible heat flux in the Yangtze River Basin in July 2022. (**f**) Sensible heat flux in the Yangtze River Basin in August 2022. The ERA5 dataset convention for vertical fluxes is positive downwards. Negative surface latent heat flux indicates evaporation and negative surface sensible heat flux indicates heat transfer from the surface to the atmosphere.

## 4. Discussion

### *4.1. Development in Flash Drought Definition*

Both the development and recovery of drought affect the ecosystem to some extent. Therefore, it is very important to determine the recovery stage of flash drought. In this study, we suggested that the flash drought event terminates when the soil moisture is above the 20th percentile for two consecutive pentads. To verify whether there have been precedents of flash droughts that have not ended and then recurred, we employed the old definition to identify flash droughts in the Yangtze River basin. The results revealed that a significant proportion of grids experiencing flash droughts still had soil moisture percentiles below the 20th percentile, one pentad after the drought ended (seen in Table 1). This finding also underscores the necessity of refining this definition in the present study. According to the new identification framework, the hotspots of flash drought in the Yangtze River Basin and related characteristics were consistent with existing studies [21,45,46], which have been discussed in the Section 3.

**Table 1.** The proportion of grids with soil moisture percentiles below the 20th percentile, one pentad after the end of the flash drought in the old definition.

| Year | Percentage (%) | Year | Percentage (%) | Year | Percentage (%) | Year | Percentage (%) |
|---|---|---|---|---|---|---|---|
| 1950 | 11.19 | 1970 | 19.75 | 1990 | 21.34 | 2010 | 22.45 |
| 1951 | 6.66 | 1971 | 20.09 | 1991 | 20.28 | 2011 | 48.15 |
| 1952 | 14.33 | 1972 | 21.89 | 1992 | 21.16 | 2012 | 29.99 |
| 1953 | 19.23 | 1973 | 27.31 | 1993 | 37.36 | 2013 | 22.77 |
| 1954 | 33.00 | 1974 | 20.48 | 1994 | 18.67 | 2014 | 29.39 |
| 1955 | 9.12 | 1975 | 27.28 | 1995 | 17.95 | 2015 | 25.16 |
| 1956 | 26.33 | 1976 | 28.73 | 1996 | 16.15 | 2016 | 24.64 |
| 1957 | 11.27 | 1977 | 21.33 | 1997 | 23.11 | 2017 | 17.61 |
| 1958 | 13.81 | 1978 | 22.86 | 1998 | 23.40 | 2018 | 24.10 |
| 1959 | 20.08 | 1979 | 28.70 | 1999 | 38.90 | 2019 | 27.69 |
| 1960 | 16.02 | 1980 | 30.65 | 2000 | 19.65 | 2020 | 24.99 |
| 1961 | 14.75 | 1981 | 22.48 | 2001 | 17.68 | 2021 | 18.31 |
| 1962 | 20.72 | 1982 | 23.67 | 2002 | 18.23 | 2022 | 28.58 |
| 1963 | 18.52 | 1983 | 29.27 | 2003 | 22.24 | | |
| 1964 | 16.73 | 1984 | 25.60 | 2004 | 24.85 | | |
| 1965 | 23.17 | 1985 | 23.19 | 2005 | 27.08 | | |
| 1966 | 17.23 | 1986 | 22.24 | 2006 | 28.21 | | |
| 1967 | 20.34 | 1987 | 30.45 | 2007 | 21.41 | | |
| 1968 | 16.60 | 1988 | 17.16 | 2008 | 37.10 | | |
| 1969 | 16.58 | 1989 | 27.09 | 2009 | 25.97 | | |

### *4.2. Characteristics of Flash Drought in the Yangtze River Basin*

Previous studies have demonstrated that regions with dense vegetation and humid climates face a significantly higher risk of flash droughts [50,51]. The southern areas of the middle and lower Yangtze River Basin, known for their warm, humid climate and abundant vegetation, are particularly vulnerable compared to the drier northern regions, where high-density farmland dominates. Despite these regions being rich in water resources, such as rivers, lakes, and reservoirs, prolonged high temperatures and heat waves can exacerbate soil evaporation, leading to a rapid reduction in surface water and abnormal water vapor transport conditions over land, providing a favorable meteorological and hydrological background for flash droughts [52–54]. Furthermore, there are numerous ways in which humans modify land-use, water partitioning and hydrological regimes, which is especially crucial for the drought. Yuan et al. [15] attributed flash drought changes by optimal fingerprinting, which shows that anthropogenic climate change induced by the increased greenhouse gas concentrations accounts for 77% $\pm$ 26% of the upward trend in flash drought frequency in China, and population increase is also an important factor for enhancing the exposure risk of flash drought over southernmost humid regions. Due to the large population and developed economy in the middle and lower reaches of the Yangtze River Basin, human activity may enhance the risk of flash drought. Therefore, the monitoring and safeguarding of flash drought should be paid attention to by the management department.

Affected by both East and South Asian monsoon, precipitation in the Yangtze River Basin presents significant seasonality, with more than half of annual precipitation falling in summer and fall. Rice and wheat are commonly cultivated in the middle and lower reaches of the Yangtze River, with spring being a crucial growing season characterized by high water demand. During this period, insufficient precipitation or elevated temperatures can lead to rapid soil moisture depletion and increase the risk of drought. In contrast, in the upper reaches of the Yangtze River, most flash drought events initiate during the summer. This occurrence is likely attributed to significant seasonal climate variations, uneven precipitation distribution, or localized precipitation shortages. The region's complex terrain, including mountains and plateaus, contributes to rapid moisture evaporation and limited water storage capacity. Insufficient local precipitation exacerbates soil drought conditions, while terrain-induced rapid runoff further reduces moisture retention, accelerating drought development. In addition, we found a significantly lower incidence of flash droughts that began in the fall, possibly because many drought events that begin in spring or summer persist into the fall, resulting in fewer new occurrences during the fall season.

### *4.3. Uncertainty and Limitations*

Despite the growing attention to flash droughts and the associated challenges, research on the occurrence and drivers of flash droughts in the Yangtze River Basin remains limited. In this study, we analyzed the severity and driving factors of flash droughts in the Yangtze River Basin based on a new identification framework that emphasizes the rate of decline in soil moisture and fully accounts for repeated drying conditions during the recovery phase. However, several limitations should be acknowledged. First, while the ERA5 soil moisture dataset is generally considered to perform well in the Yangtze River Basin [15,26], the lack of long-term observed soil moisture data for validation introduces uncertainty in the accuracy of flash drought detection. Second, the formation of flash droughts is a highly complex process involving the interaction of multiple factors. Although this study investigates the role of meteorological conditions and atmospheric circulation in flash droughts from various perspectives, it does not examine the influence of large-scale climate modes as key drivers of heat forcing in flash drought formation. Under global warming, significant changes have occurred in the cycles, intensity, and phase transitions of major climate modes, which have, in turn, influenced their impact on Eurasian zonal circulation, the WPSH, the southern branch trough, and the East Asian monsoon system. Future research could focus on the effects of atmospheric circulation indices, such as the EI Niño–Southern Oscillation and the Indian Ocean Dipole, to explore their roles in the mechanisms driving flash droughts. This approach could offer deeper insights into the complex processes underlying flash drought formation.

## 5. Conclusions

In this study, the new soil moisture dynamic identification framework was employed to pinpoint flash drought events on a grid-by-grid basis. Four metrics—frequency, duration, development rate, and intensity—were calculated to assess the spatiotemporal evolution of flash drought events over multiple years in the Yangtze River Basin. Additionally, the proportion of affected areas and the seasonal characteristics of these events were analyzed. Finally, the severity of the extreme 2022 flash drought event was assessed by comparing it with the natural characteristics and actual impacts of typical drought years. Additionally, we analyzed the driving factors of this extreme flash drought from the perspectives of climatic characteristics, atmospheric circulation, and surface energy exchange.

The results revealed that flash droughts in the Yangtze River Basin exhibited significant regional disparities, with the middle reaches experiencing more severe drought conditions. Specifically, the Wujiang River Basin, Dongting Lake Basin, and Poyang Lake system faced flash droughts with higher frequency, faster onset, and greater intensity. Over the past 70 years, there has been a notable increase in the frequency and duration of flash drought events in the basin. Spring was identified as the season with the highest proportion of initial flash drought occurrences, particularly in the middle and lower reaches, while in the upper reaches, drought events predominantly began during the summer. Compared with droughts in 2006, 2011 and 2013, the Yangtze River Basin in 2022 was listed as the most severe flash drought event due to its fastest development rate and largest affected area. Unlike previous historical events, the 2022 extreme flash drought began in the flood season months. The spatiotemporal evolution of this severe flash drought was driven by a combination of factors: the influence of the WPSH reduced precipitation and caused temperatures to rise. The divergence of water vapor flux led to a regional shortage of water vapor, which further inhibited precipitation. The abnormal enhancement of surface latent heat flux and sensible heat flux led to intense surface evaporation and increased heat transfer to the atmosphere, which further destroyed the regional water cycle. Overall, the new framework can identify flash drought events more reasonably and accurately, and the results can provide scientific basis for the formulation of drought mitigation and adaptation strategies in the Yangtze River Basin.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs16224122/s1, Figure S1: Trend changes in flash drought characteristics in the Yangtze River Basin from 1950 to 2022. (a) Regional average frequency of flash drought events. (b) Regional mean duration of flash drought events. (c) Regional average development rate of flash drought events. (d) Regional mean intensity of flash drought events. The solid black line is the trend line. The solid blue line is the pre-abrupt mean. The solid red line is the post-abrupt mean. The blue dotted line is the pre-abrupt trend. The red dotted line is the pre-abrupt trend. The overall trends passed the MK significance test with $p < 0.05$ in (a,c,d), and the overall trends passed the MK significance test with $p < 0.1$ in (b). All of the pre-abrupt and post-abrupt trends fail the significance test.

**Author Contributions:** Conceptualization, L.Y. and J.W.; methodology, L.Y.; software, L.Y.; validation, L.Y. and J.W.; formal analysis, L.Y.; investigation, L.Y. and J.W.; resources, L.Y.; data curation, L.Y. and J.W.; writing—original draft preparation, L.Y.; writing—review and editing, J.W.; visualization, L.Y.; supervision, J.W.; project administration, J.W.; funding acquisition, J.W. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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