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Rapid Onset Droughts: Unraveling Flash Droughts and Ecosystem Resilience

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I hereby declare that the dissertation entitled *“Rapid Onset Droughts: Unraveling Flash Droughts and Ecosystem Response”* submitted for the Degree of Philosophy in Environmental Modelling is my original work guided by my supervisor. All sources of information, text, illustration, tables and images have been specifically cited. The dissertation was not published elsewhere.

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Ackowledgement

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Abstract

Compound extreme events, such as flash droughts, have garnered considerable attention in recent decades due to their rapid onset behavior and widespread effects on ecosystems. Consequently, the concept of flash droughts has gained global recognition within the scientific community and continues to evolve.

This thesis aims to investigate the temporal developments in flash drought research and to study the spatiotemporal characteristics of flash droughts, along with the ecosystem response to these events across Central Europe. Initially, a bibliometric approach was employed to evaluate quantitative developments in flash drought research globally between 2000 and 2021. Subsequently, the characteristics of flash droughts were examined on spatial and temporal scales. Finally, considering the impacts of flash droughts on ecosystems, we analyzed the ecosystem response to flash drought events.

The results reveal an exponential growth in flash drought research, with an average annual growth rate of 30%. Most studies on flash droughts have been conducted in the climates of the USA and China. Soil moisture and evapotranspiration emerged as the most useful indicators for identifying flash drought events. However, challenges persist in defining flash droughts, developing effective early warning systems, and addressing data scarcity issues..

Furthermore, a quantitative review of multiple studies indicated that Europe has experienced an increasing frequency of flash drought events over the past two decades, adversely affecting the region's ecosystems. Our investigation into the spatial and temporal characteristics of flash droughts confirmed a rapid increase in their occurrence over Central Europe. Additionally, the intensification rate and severity of flash droughts exhibited a positive correlation. The areal extent of flash drought events has expanded since 1970, with their centroid shifting from northern to southern Central Europe. Flash drought characteristics vary with soil moisture depth, with events most frequent at depths of 10-40 cm and higher intensification rates observed at higher altitudes.

The ecosystem response to flash drought events was assessed based on gross primary production, revealing a response time of 20-30 days on average across Central Europe. The mid-layer (10-40 cm) and root zone (0-100 cm) of ecosystems exhibited high sensitivity to flash droughts, with croplands demonstrating lower resistance compared to forests. Among forest types, evergreen needle leaf forests exhibited higher resistance to flash droughts.

Overall, this thesis contributes to a comprehensive understanding of flash drought dynamics and characteristics and provides valuable insights into their impacts on ecosystems. By enhancing scientific understanding, this study facilitates improved decision-making and mitigation of the societal impacts of flash drought events.

Thesis Preface

In embarking upon this thesis, I find myself standing at the culmination of an intellectual journey—a journey marked not only by academic pursuit but also by personal growth, perseverance, and the invaluable support of many individuals. As I reflect on the pages that follow, I am reminded of the countless hours spent in pursuit of knowledge, the challenges overcome, and the lessons learned along the way.

This thesis represents the culmination of years of dedication, curiosity, and passion for the impacts of flash drought on the ecosystem. From its inception to its completion, it has been a labor of love—a testament to my unwavering commitment to exploring and understanding the dynamics of flash drought.

Throughout this endeavor, I have had the privilege of receiving guidance, encouragement, and inspiration from a multitude of sources. I extend my deepest gratitude to my supervisor, whose expertise, support, and unwavering belief in my abilities have been instrumental in shaping this work. I am also indebted to my committee members for their invaluable insights, constructive feedback, and scholarly guidance.

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Lastly, to the readers who embark on this intellectual voyage with me, I hope that the pages that follow will inspire curiosity, spark dialogue, and contribute to the collective body of knowledge in flash drought.

As I pen these words, I am filled with a sense of accomplishment, gratitude, and anticipation for the future. May this thesis serve as a testament to the transformative power of inquiry, the pursuit of knowledge, and the unwavering human spirit

Chapter 1

Theoretical Background

Over the last two decades, the hydrological cycle has been drastically affected by the increase in global temperature (Saadi et al., 2023; Warburton et al., 2010). These changes have brought anomalies in temperature and rainfall rates, extent, and magnitude globally (Khan et al., 2019; Pour et al., 2020; Yaseen et al., 2021). According to the Intergovernmental Panel on Climate Change (IPCC), the global ecosystem is significantly sensitive to changes in climate characteristics (IPCC et al., 2014).

Climate change has further altered the natural pattern of droughts, making them more frequent, longer, and more severe. Drought events, often referred to as *the creeping disaster*, develop slowly and are often unnoticed, with diverse and indirect consequences. However, droughts can cover extensive areas and can last for months to years, with devastating impacts on the Earth system linked to many economic sectors (Ciais et al., 2005a).

1.1 Droughts

Drought is one of the most devastating natural disasters in almost all regions. It is a complex phenomenon, with various mechanisms or variables operating at different temporal or spatial levels, making it one of the least understood natural hazards (Kim, 2003). Drought is primarily attributed to precipitation loss, although in certain situations, variations in other factors such as temperature or evapotranspiration are likely contributors to drought (Cook et al., 2014; Livneh and Hoerling, 2016; Luo et al., 2017).

In particular, high temperatures can contribute to increased evaporation and reduced soil moisture, which can cause drought in the agricultural sector. Additionally, drought is not solely a natural disaster, as human activities such as land use changes and the construction of reservoirs can alter hydrological processes and influence the development of drought (Van Loon et al., 2016). In general, the development of drought is the result of complex interactions between climate variability, land surface processes, and human activities.

Drought can occur over a wide range of time scales, including sub-seasonal/weekly and seasonal durations, with numerous processes contributing to its origins, persistence, or recovery (Sheffield et al., 2012). Traditionally, drought has been defined on a seasonal time scale, but recent research has highlighted its occurrence on a sub-seasonal scale as well. For instance, the 2012 central U.S. drought in May is often referred to as a flash drought, characterized by rapid onset resulting from subsequent soil moisture deficits and anomalous high temperatures or increased evaporation (Hoerling et al., 2014; Mo, 2015; Wang et al., 2016). Furthermore, some regions experience drought on longer time scales spanning several years or even decades. For example, the droughts in South-East Australia from 2001 to 2009 were the most severe since 1900 and persisted with below-median rainfall for several years (Roundy and Santanello, 2017).

Drought prediction typically focuses on predicting drought severity. However, in certain cases, drought prediction may also encompass other characteristics, such as duration and frequency, or different phases like onset, severity, and recovery (Shabbar and Skinner, 2004), Numerous studies have been conducted to elucidate drought dynamics and establish relationships with large-scale climate indices. Shabbar and Skinner (2004)analyzed variations in the Canadian summer (June-August) Palmer Drought Severity Index (PDSI) and winter (December-February) global sea surface temperature (SST) anomalies over the period of 1940-2002. They found correlations between extremely wet or dry Canadian summers and anomalies in global SST trends during the previous winter season. Bordi and Sutera (2001) discovered interconnections between dry conditions in Europe, Eastern Asia, Central Africa, and the Caribbean region, influenced by tropical climate variability. Hoerling et al. (2014) investigated the droughts of 1998-2002 that affected the U.S., Southern Europe, and Southwestern Asia. They identified correlations between these prolonged and widespread droughts and particular oceanic influences.

This is why the scientific community focuses on climate extremes from various perspectives. It is crucial not only to describe parameters of drought such as duration, severity, and temporal location (initiation and termination time points), as well as areal coverage (Panu and Sharma, 2002), but also to consider various economic aspects of drought (Carroll et al., 2009; Pandey and Bhandari, 2009; Huynh et al., 2020; Smith, 2020). Some studies concentrate on specific types of drought, such as meteorological drought (Palmer, 1965; Patel et al., 2007), , hydrological drought (Tallaksen and Van Lanen, 2004; Van Loon and Van Lanen, 2012; Van Loon, 2015), agricultural drought (Liu et al., 2016; Moravec et al., 2019), socioeconomic drought (Mehran et al., 2015; Guo et al., 2019) or the newly categorized technological drought (Mondol et al., 2022). It is also important to consider the temporal scale of drought and examine its evolution compared to the past (Hanel et al., 2018), as well as to attempt to predict the future evolution of droughts (Sheffield and Wood, 2008; Spinoni et al., 2018).

The importance of drought research cannot be overstated. Understanding the mechanisms preceding the development of individual drought events, as well as the propagation of specific drought types and their termination, is essential. Drought research plays a crucial role in both adapting to climate change and mitigating its effects. It provides valuable guidance for policymakers and stakeholders in addressing drought-related challenges. In a dynamic climate where periods of drought are swiftly replaced by heavy rainfall and floods, it is imperative to consider both extremes. Research on both drought and flood dynamics should progress in tandem to maintain a balanced approach. Furthermore, it's notable that climatic extremes can fade surprisingly quickly from collective memory (Fanta et al., 2019). The better we understand individual drought types and their initiation, duration and possibly their termination (Markonis et al., 2021), the better we can predict their properties and also their effects. This is crucial, especially for adaptation to drought in the context of global climate change.

1.2 Droughts in Europe

Since the last two decades Europe has encountered a succession of exceptionally hot and arid summers. These extreme weather events have had far-reaching consequences across various sectors, including agriculture, hydrology and water resources, human health, and ecosystem servicesIn. For example,In 2003 European summer temperate season succeeded the former lengthened drought period, which promoted the immense agricultural loss in regions of Southern Europe of a compound cost of almost 15 billion euros (Kurnik et al., 2017). In the late 2008, the record breaking temperature and drought was observed in different parts of Northern and central Europe which was the consequence of the abnormal warm climate. Crop failure was being encountered by the farmers as one of the most intensified national droughts of the history , which was likewise to the 1976 great drought (Marsh et al., 2013) that badly influenced UK. Contemporarily, various drought incidences have been accustomed by European, not only dry area in the semi-arid regions of Iberian Peninsula and the Mediterranean regions, but also in almost everywhere geographically, from Western to East Europe, and to as high as Scandinavia depict the enormous drought episode from investigation of 1950 to 2012 (Spinoni et al., 2015). The results show that highest dryness frequency and harshness has been observed in Northern and Eastern Europe from the early 1950s to the mid-1970s, whereas highest drought frequency and severity has been noticed in the Southern and Western Europe from the early 1990s onwards.

1.3 Types of Drought

Subrahmanyam (1967) identified six types of drought: *meteorological, climatological, atmospheric, agricultural, hydrological*, and *water-management*. Some researchers have also incorporated economic or socio-economic factors into the concept of *socio-economic drought* (Gibbs et al., 1975). However, the scientific community now typically groups these types of drought into four main categories: *meteorological, hydrological, agricultural*, and *socioeconomic* (e.g., Wilhite and Glantz, 1985; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010; Sheffield and Wood, 2012). The following paragraphs elaborate on these four types of drought.

Meteorological Drought

One of the earliest definitions of meteorological drought was put forth by Palmer (1965), who described it as *"an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply"*. NOAA defines meteorological drought as occurring when dry weather patterns dominate an area. The National Drought Mitigation Center emphasizes the region-specific nature of meteorological drought, as the atmospheric conditions leading to precipitation deficits vary greatly from one region to another. The American Meteorological Society defines meteorological drought based on the magnitude and duration of a shortfall in precipitation. According to World Meteorological Organization (1992), meteorological drought involves (1) a prolonged absence or marked deficiency of precipitation, and (2) a period of abnormally dry weather lasting long enough to cause a serious hydrological imbalance. Wilhite and Glantz (1985) assert that meteorological drought can occur in both high and low rainfall areas and is relative to the long-term balance between rainfall and evapotranspiration. However, they note that average rainfall alone may not adequately characterize meteorological drought, especially in drier regions, as it does not account for the temporal distribution of rainfall throughout the year, which is crucial for understanding meteorological drought development. Various other definitions of meteorological drought exist. For instance, Dufour (1949) define it as a *"period of more than some particular number of days with precipitation less than some specified small amount"*. Tallaksen and Van Lanen (2004) describe meteorological drought as *"a precipitation deficiency, possibly combined with increased potential evapotranspiration, extending over a large area and spanning an extended period of time"*. Linsley and Kohler (1958) characterize meteorological drought as *"a sustained period of time without significant rainfall"*, while Yevjevich et al. (1967) define it as *"a deficit of water below a given reference value, with both deficit duration and deficit magnitude taken into account"*.

Some definitions of meteorological drought are tailored to specific regions. For instance, in the United States, meteorological drought is defined as receiving less than 2.5 mm of rainfall in 48 hours (Blumenstock, 1942), while in Britain, it is considered to occur when there are fifteen consecutive days, none of which received as much as 0.25 mm of rainfall (British Rainfall Organization, 1936). In Libya, meteorological drought is recognized when annual rainfall falls below 180 mm (Hudson and Hazen, 1964), and in India, it is defined as actual seasonal rainfall being deficient by more than twice the mean deviation (Ramdas, 1960). In Bali, meteorological drought is identified as a period of six consecutive days without rain (Hudson and Hazen, 1964). However, as Wilhite and Glantz (1985) noted, region-specific definitions can lead to problems due to the lack of comparability, as drought is perceived differently in each region. Some studies define meteorological drought by comparing the degree of dryness to a long-term average, often referred to as "normal". For example, McGuire and Palmer (1957) characterize meteorological drought as a period of monthly or annual precipitation less than a certain percentage of normal. Palmer (1957) describe drought as a temporary departure from the average climate towards drier conditions. Not only precipitation properties are used to define meteorological drought; for instance, Popov (1948) use wet-bulb depression, and Levitt (1958) express atmospheric drought as proportional to the vapor pressure deficit of the air. Condra (1944) refer to meteorological drought as "*a period of strong wind, low precipitation, high temperature and, usually, low relative humidity*". Upcoming sections will demonstrate that meteorological drought serves as a precondition for other types of drought because it establishes the water budget baseline for a given basin.

The most widely used drought indicators for meteorological drought are *Palmer Drought Severity Index* (PDSI) (Palmer, 1965; Alley, 1984), with temperature and precipitation as an input detecting rather prolonged drought conditions and its enhanced version *Self-Calibrating PDSI* (scPDSI) (Wells et al., 2004). The *Standardised Precipitation Index* (SPI) (McKee et al., 1993; Spinoni et al., 2017) using only precipitation which was later modified to serve also as a hydrological drought index (Nalbantis and Tsakiris, 2009). *The Standardised Precipitation Evapotranspiration Index* (SPEI) (Vicente-Serrano et al., 2010; Spinoni et al., 2017) facilitating both – the sensitivity of PDSI and the simplicity of the SPI calculation. And finally *The Reconnaissance Drought Index* (RDI) (Tsakiris and Vangelis, 2005; Myronidis et al., 2018) incorporating directly potential evapotranspiration. To emphasise snowmelt in snow-governed catchments where SPI does not give sufficient results, Staudinger et al. (2014) came up with the *Standardized Snow Melt and Rain Index* (SMRI).

Agricultural Drought

Wilhite and Glantz (1985) defined agricultural drought as *"a linkage of various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, reduced groundwater or reservoir levels"*. Because a plant's water demand depends on prevailing meteorological conditions, the biological characteristics of the specific plant, its growth stage, and the physical and biological properties of the soil, it's challenging to generalize the definition or indices for agricultural drought. The timing and severity of agricultural drought can vary greatly for each plant at a given stage of its life cycle. Adverse moisture conditions in a particular space and time may be harmful to certain plant species, while beneficial for others. Moreover, as a plant's water demand fluctuates throughout the growing season, deficient subsoil moisture in the early growth stage may have little impact on final crop yield (if topsoil moisture is adequate to meet early growth requirements). However, if subsoil moisture deficiency persists, it could lead to significant yield loss (Wilhite and Glantz, 1985).

At this juncture, it's crucial to differentiate between agricultural and agronomic drought. According to Bidwell (1973), agricultural drought pertains more to plant biology and plant well-being, resulting from soil moisture depletion when the plant's water consumptive use is not met. Conversely, agronomic drought is approached from the perspective of crop yield loss/gain, such as economic losses due to crop underproduction resulting from climatic conditions or failure of water management infrastructure, as highlighted by Mondol et al. (2022). Agronomic drought can also be linked to socioeconomic factors, as will be discussed in the following section. Agricultural drought, characterized by a lack of soil moisture storage, is influenced by various factors, including evaporation from bare soil, evapotranspiration through plants, drainage to groundwater, and runoff to streams. During dry spells, drainage and runoff are typically minimal, but potential evapotranspiration may increase due to factors like heightened radiation, wind speed, or vapor pressure deficit (Van Loon, 2015). The depletion of soil moisture is, to some extent, dependent on canopy type (Zeleke and Wade, 2012). Given that soil can store significant amounts of water, a deficit in soil moisture can affect climate interactions by impacting moisture returning to the atmosphere through evapotranspiration. Some studies suggest that soil moisture can influence a small-scale water cycle through soil moisture-precipitation feedbacks (D'Odorico and Porporato, 2004; Seneviratne et al., 2010).

In the context of agricultural drought, various drought indices have been developed and refined over time. The assessment of agricultural drought typically utilizes well-known meteorological drought indices but often with longer time frames. For example, while the Standardized Precipitation Index (SPI) with a 1-month time frame is commonly used for meteorological drought assessment, a 3-month SPI is often employed for agricultural drought evaluation (Rhee et al., 2010). One example of a meteorological drought index modified for agricultural drought assessment is the Crop Moisture Index (CMI), which is incorporated into the calculation procedure of the Palmer Drought Severity Index (PDSI). The CMI specifically targets short-term dry spells affecting agriculture. Similarly, the Soil Moisture Index (SMI) (Hunt et al., 2009) is utilized to assess soil moisture conditions and quantify soil drought intensity. This index is based on the premise that evapotranspiration becomes limited either below the midpoint between field capacity and wilting point or at 50% of total available water. The Crop Drought Index (CDI) (Boken et al., 2005) serves to quantify agricultural drought intensity by indicating the reduction of evapotranspiration relative to potential evapotranspiration due to soil water deficit. Additionally, Narasimhan and Srinivasan (2005) introduced the Soil Moisture Deficit Index (SMDI) and the Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. These indices offer a fine spatial and temporal resolution to better understand the development of agricultural drought.

Hydrological Drought

Hydrological drought encompasses the impacts of dry weather on surface and subsurface hydrology. Linsley Jr et al. (1975) described hydrological drought as *"a period during which streamflows are inadequate to supply established uses under a given water management system"*. It refers to a deficiency of water in the hydrological system, characterized by abnormally low streamflow in rivers and diminished levels in lakes, reservoirs, and groundwater (Tallaksen and Van Lanen, 2004). Nalbantis and Tsakiris (2009) further defined hydrological drought as *"a significant decrease in the availability of water in all its forms appearing in the land phase of the hydrological cycle"*. Hydrological drought may manifest as below-normal groundwater levels, diminished water levels in lakes, reduced wetland areas, and decreased river discharge (Tallaksen and Van Lanen, 2004). While meteorological drought can be delineated by specific precipitation thresholds based on the climatic conditions of a particular location, hydrological drought is often influenced by factors beyond precipitation, such as catchment properties. Consequently, thresholds for hydrological drought must be calculated for specific river points or groundwater storage locations, accounting for the impact of human activities, which can contribute significantly to water availability within a catchment.

Hydrological drought is frequently conflated with low flow, leading Beran and Rodier (1985) and Hisdal et al. (2004) to advocate for a clear distinction between low flow characteristics and hydrological drought characteristics. Accordingly, hydrological drought can be defined using low flow characteristics, which are typically derived from time series data and directly reflect aspects relevant to hydrological drought. Different low flow characteristics are calculated depending on the field of interest, such as those measured by water treatment plants (typically total deficit volume or timing of daily/monthly minimum) or shipping companies (usually water level thresholds), among others. The definition of hydrological drought relies more on the calculation of specific flow characteristics, termed indices, compared to precipitation, where a time frame below a certain threshold is typically considered. For instance, Hisdal et al. (2004) proposed several low flow indices, including the lowest flow in a specific time period, the lowest daily streamflow value each year, and the mean annual minimum flow. Due to various influencing factors, the peak minimum flow can be observed at different times throughout the year (Van Loon and Van Lanen, 2012).

Hydrological drought is commonly evaluated using the Standardized Runoff Index (SRI) with longer aggregation periods, typically ranging from 3 to 12 months (Nalbantis and Tsakiris, 2009; Salimi et al., 2021), reflecting its slower development process. The SRI, along with the Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012), employs a calculation procedure akin to the Standardized Precipitation Index (SPI), involving fitting a distribution to the data and transforming it to a normal distribution. It's important to note that the Soil Water Supply Index (SWSI) (Shafer and Dezman, 1982) was initially devised as a hydrological drought index, primarily influenced by snow storage, as highlighted by Hayes (2006). In addition to indices like SRI and SSI, the threshold method, also known as the deficit index, is frequently utilized for hydrological drought assessment. Unlike traditional drought indices, the threshold method captures more drought characteristics, facilitating further drought analysis and assessment.

Socioeconomic Drought

While meteorological, agricultural, and hydrological droughts are viewed as physical phenomena, socioeconomic drought is closely tied to local water supply and has a direct impact on the socioeconomic system (Tu et al., 2018). Socioeconomic drought essentially emerges from the repercussions of the aforementioned three types of drought, each affecting different segments of society. The degree of impact of a specific type of drought depends on the societal context and the level of vulnerability and resilience to that particular type of drought. Unlike meteorological, agricultural, and hydrological droughts, which are typically characterized by measures of duration, severity, and frequency, socioeconomic drought is assessed statistically in terms of the resilience, reliability, and vulnerability of the system (Hashimoto et al., 1982; Ward et al., 2013). The definition of socioeconomic drought incorporates elements of meteorological, agricultural, and hydrological droughts, focusing on whether the water supply can satisfy the demands of various water-use sectors and their associated economic benefits (Wilhite and Glantz, 1985; Orville, 1990). Essentially, any decline in the agricultural or industrial sectors that can be attributed to the effects of any of the aforementioned drought types can be considered socioeconomic drought. For example, while meteorological drought may occur over a season or a series of years, its impacts on society may persist for many years, illustrating the long-term implications of socioeconomic drought on communities and economies.

1.4 Response of Ecosystem to Droughts

Droughts wield significant impacts across diverse climates and ecosystems, ranging from regional to sub-continental scales. Over the past four decades, there has been a noticeable expansion in the geographic extent affected by droughts globally (Dai et al., 2004). Despite inherent uncertainties in climate model predictions, the majority of future climate projections outlined in the IPCC-AR4 suggest a likelihood of more frequent and severe droughts, particularly in midlatitude regions and across Africa, Australia, and Latin America (Bates et al., 2008; Meehl and Tebaldi, 2004). Periodic drought events affecting agriculturally productive regions have the potential to induce abnormally high atmospheric CO2 growth rates (Knorr et al., 2007), indicating an expected stronger impact of droughts on the carbon cycle in the future.

Drought significantly impacts the terrestrial carbon balance by altering both the rates of carbon uptake through photosynthesis based on Gross Primary Production (GPP) and the release via total ecosystem respiration (TER), as well as the interaction between them (Meir et al., 2008). Figure 1.1 represents how carbon uptake and release are influenced by various factors, including water availability and temperature, in a nonlinear manner. Several studies utilizing CO2 flux measurements collected from a global network have demonstrated that the majority of sites experience decreases in both GPP and TER during drought periods. (Baldocchi, 2008; Bonal et al., 2008; Ciais et al., 2005b; Reichstein et al., 2007).

Considering that autotrophic respiration (in foliage, stems, and roots) contributes to approximately 60% of TER (Janssens et al., 2001), and field experiments indicate a strong correlation between root respiration and recent carbon assimilation (Irvine et al., 2008), short-term variations in TER are predominantly determined by the availability of labile organic carbon compounds produced through photosynthesis, with the soil moisture effect on microbial activity likely playing a lesser role. This correlation explains the tendency for concurrent reductions in both GPP and TER (Law, 2005; Ryan and Law, 2005). Moreover, the absolute reduction in GPP during drought periods tends to be larger than that of TER. Consequently, droughts typically shift ecosystems toward acting as a source of CO2 to the atmosphere.

Changes in vegetation structure induced by drought can also lead to reductions in GPP. The extent of GPP reduction is influenced by both the physiological responses to limited plant-available water (Meir et al., 2009) and structural alterations in vegetation during drought periods. Physiological responses of vegetation to drought encompass reductions in enzymatic activities and the closure of stomata to mitigate water loss. Two contrasting strategies for water use have been proposed, although they likely represent points along a continuum (Tardieu and Simonneau, 1998): isohydric species decrease stomatal conductance to prevent leaf water potential from dropping below a critical threshold, while anisohydric species exert minimal or no stomatal control in response to drought. Since stomatal closure also reduces CO2 diffusion into the leaf (Leuning, 1990), isohydric species experience a more pronounced short-term reduction in GPP compared to anisohydric species. Certain tree species exhibit significant dynamic responses in fine roots, potentially increasing specific root length and area, thereby enhancing the capacity for water and nutrient uptake with minimal carbon investment (Kätterer et al., 1995; Metcalfe et al., 2008; Singh and Srivastava, 1985). However, not all species demonstrate such dynamic root responses (Mainiero and Kazda, 2006). Continuous depletion of soil moisture may eventually lead to mortality in vegetation.

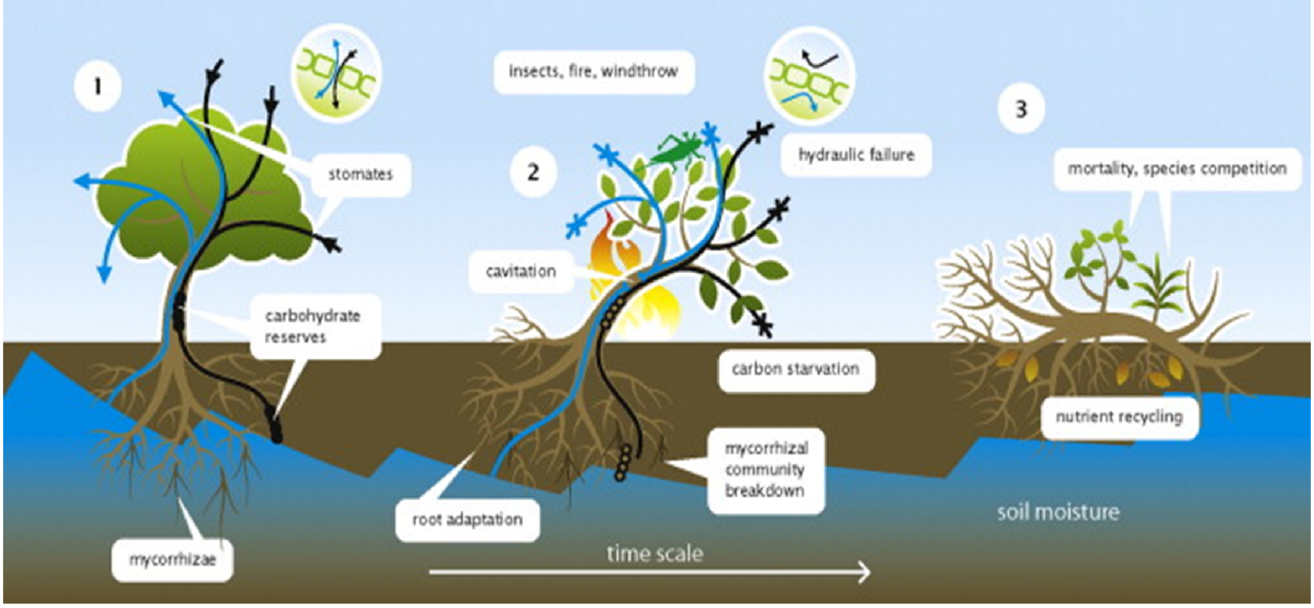

Figure 1.1: Drought and Carbon Cycle of Ecosystem (van der Molen et al. (2011))

1.5 Flash Drought

Flash droughts occur simultaneously with extreme heat waves that intensify drought conditions and vice versa (Wang et al., 2016). In addition, the effects of flash drought on crop yields and water sources are rapid, extraordinarily high, and catastrophic (Wang et al., 2016). For instance, the Central US drought in 2012 caused significant damage to crops amid high temperatures and soil humidity depletion, resulting in massive economic losses. From 1979 to 2010, the occurrence of flash droughts in China increased by 109%, primarily due to long-term warming, increased evapotranspiration, and decreased rainfall (Wang et al., 2016). Flash droughts exhibit specific properties relative to typical forms of droughts. Unlike typical droughts, flash droughts are characterized by strong evapotranspiration rates due to abnormally high temperatures, winds, and incoming radiation typically present prior to their development (Chan et al., 2018). Otkin et al. (2018) proposed that the pace of intensification should be given greater emphasis than duration, as flash droughts progress at an extremely fast rate of intensification relative to other forms of drought. In fact, flash droughts fall under the category of agricultural droughts since they are specifically related to soil moisture variations. Therefore, changes in soil moisture have been regularly used to identify the sudden occurrence of flash droughts (Ford et al., 2015)

Two types of flash drought exist with different nomenclatures (Mo, 2015; Wang et al., 2016; Zhang et al., 2017b; Tang et al., 2009). Wang et al. (2016) investigated high-temperature-driven (Type I) and precipitation-deficit-driven (Type II) forms of flash drought over China. Type I, characterized by extreme temperatures with rapidly decreasing soil moisture due to increased evapotranspiration, is akin to heat wave flashes (e.g., the 2012 US Central Flickering Drought). On the other hand, Type II flash droughts are caused by rainfall shortages, leading to a decrease in evapotranspiration and a rise in temperature (Mo, 2015). Flash droughts of Type I emerge as higher temperatures increase evapotranspiration and decrease soil moisture before their onset, while in Type II flash droughts, evapotranspiration and soil moisture decrease with rising temperatures before the drought begins (Wang et al., 2011). Type I events occur in Southern China where there is an adequate moisture supply, while in semi-arid northern China, Type II events occur due to deficiencies in soil moisture (Wada et al., 2017; Zhang et al., 2017b; Tang et al., 2009). In the US, heatwave flash drought events typically last just 1–2 pentads, while precipitation-deficit flash droughts can persist for over three pentads (Mo, 2015). In China, however, heatwave flash droughts range from 5 to 8 pentads, while precipitation-deficit flash droughts can extend up to 4 pentads (Wang et al., 2017).

In the context of climate change, the combined occurrence of high temperature and droughts has increased worldwide. This leads to an intensified drying pattern of soil moisture and increased evapotranspiration, resulting in more frequent flash droughts, particularly during hiatus warming (Wang et al., 2016). Moreover, anthropogenic warming raises the risk of combined warm or dry environments affecting human and natural habitats, as observed in the 2012–14 California drought (Diffenbaugh et al., 2015). Anthropogenic warming in China is expected to exacerbate potential flash drought conditions, particularly in humid and semi-humid regions such as southern and northeastern China (Wang et al., 2016; Zhang et al., 2017b). In South Africa, flash droughts have tripled over the past 60 years due to anthropogenic climate change and worsened during the 2015–2016 heatwaves (Yuan et al., 2019). These trends indicate that anthropogenic impacts may increase the likelihood of warm climates during reduced precipitation years (Diffenbaugh et al., 2015). To anticipate the rapid onset of flash droughts driven by anthropogenic activities, it is essential to develop drought intensification forecasts through advancements in prediction technologies and improvements in climate models (Otkin et al., 2018). In situ measurements of soil moisture are thus crucial sources of information for early warning systems tailored to the rapidly changing occurrence of flash droughts (Ford et al., 2015).

1.6 Characteristics of Flash Drought

The unique features of flash droughts, such as their high rate of intensification and rapid onset, distinguish them from conventional droughts. However, alongside these rapid developments, various factors such as climatology, pre-weather conditions, and land use can significantly impact the occurrence of flash droughts. Regional climatology is a crucial factor to understand when and where flash droughts are likely to occur. Understanding regional climatology can provide a solid foundation for improved monitoring and predictability of flash drought development. Research indicates consistent hotspots for flash drought occurrences, notably over regions such as the Sahel and India (Christian et al., 2021; Koster et al., 2019; Poonia et al., 2022; Yuan et al., 2020b). Flash droughts tend to peak in frequency during the middle of the warm season in equatorial latitudes (Christian et al., 2021; Koster et al., 2019; Mahto and Mishra, 2020), with significant warming and reduced precipitation contributing to increased flash drought occurrences in major global croplands between 1981 and 2020. Additionally, there is a notable seasonal cycle, with higher flash drought occurrences during the warm season in mid-latitudes, primarily due to heightened evaporative demand in the summer months. Furthermore, climate drivers such as La Nina and El Nino have been found to be relevant for a better understanding of flash droughts (Chan et al., 2021; Mahto and Mishra, 2020; Pendergrass et al., 2020).

The rapid development characteristics of flash droughts depend on pre-weather anomalies of precipitation and temperature. Flash droughts may either transition quickly back to normal conditions (Hunt et al., 2014; Mo, 2016) or persist for longer durations, extending into seasonal droughts (Li et al., 2020; Otkin et al., 2018; Noguera et al., 2020). In comparison, conventional droughts last for years and are governed by precipitation deficits. Flash droughts develop rapidly and are driven by a deficit of precipitation coupled with high temperatures, which induce evaporative stress and reduce soil moisture.

The occurrence of flash droughts is also influenced by the land cover and terrain of the region. Evaporative stress is the main driver of flash drought occurrence, but it further depends on vegetation and soil types. For example, the semi-arid regions of the Great Plains-Corn Belt in the United States are particularly vulnerable to flash drought conditions due to their shallow root zones and high evapotranspiration rates. These regions are sensitive to changes in soil moisture, which reduce evapotranspiration and affect atmospheric moisture availability, thereby reducing precipitation and leading to the rapid intensification of flash droughts (Pendergrass et al., 2020). This situation is even more pronounced in humid and sub-humid regions (Mukherjee et al., 2018). In contrast, high-elevation arid and forested mountainous regions appear to be less vulnerable to flash drought occurrence due to their deeper soil moisture profiles and root zones, which can mitigate the rapid increase of evaporative stress (Chen et al., 2020; Christian et al., 2021). A recent study by **?** on land-atmosphere-vegetation coupling suggests that high-elevation humid regions are most vulnerable to flash droughts because high solar radiation and vapor pressure deficit may increase transpiration in these areas (Oogathoo et al., 2020).

1.7 Components of Flash Drought

1.7.1 Precipitation, Temperature and Flash Droughts

Like other droughts, water deficits are crucial for determining the speed, intensity, and duration of flash drought events (Koster et al., 2019). However, in the context of flash droughts, it is widely believed that below-average rainfall levels are a necessary though insufficient condition (Otkin et al., 2013). Studies indicate that the role of precipitation in forming flash droughts varies by region, with a more significant effect observed in monsoon climates (Han et al., 2023; Mahto and Mishra, 2020). While the significance of rainfall in flash droughts is recognized, there remains a lack of precipitation-focused flash drought indicators. Researchers are exploring new precipitation-based indices that may better capture the rapid emergence of these extreme events.

Precipitation-based metrics such as the Standardized Precipitation Index (SPI) and Standardized Precipitation–Evapotranspiration Index (SPEI) are commonly utilized in drought monitoring and research owing to their simplicity of computation and the availability of precipitation data (McKee et al., 1993; Vicente-Serrano et al., 2010). While SPI and SPEI have shown some usefulness in tracking flash droughts, their effectiveness varies depending on the region and the specific case. In particular, SPEI has gained prominence as it accounts for both precipitation and evaporative demand.

The rising temperatures have underscored the necessity for improved integration of temperature and evapotranspiration aspects in evaluating drought conditions, as increasing heat is altering the characteristics of flash droughts in many regions (Noguera et al., 2022; Yuan et al., 2023). However, akin to indicators reliant on evapotranspiration, the Standardized Precipitation–Evapotranspiration Index (SPEI) risks inaccurately assessing drought severity and duration if the evapotranspiration component is improperly calibrated or unrealistic. Furthermore, SPEI's effectiveness in identifying flash droughts depends on the accuracy of potential evapotranspiration (PET) estimation. For instance, PET techniques that are highly sensitive to temperature, such as Thornthwaite, may exaggerate both the frequency and intensity of flash droughts. Utilizing Penman–Monteith and energy budget-based approaches for PET estimation can enhance SPEI's ability to accurately capture flash drought onset and severity. Additionally, these challenges are compounded when using temperature projections to assess future drought risks.

1.7.2 Soil Moisture and Flash Droughts

Understanding soil moisture fluctuations in the hydrological cycle and the impact of global warming is crucial for prediction. Soil moisture refers to the quantity of water contained in the unsaturated layer of soil. This water-holding component is a necessary and vital segment of the hydrological cycle (Seneviratne et al., 2010). Soil, as Earth's primary constituent, interacts with climatic phenomena by collecting precipitation and facilitating its transport to the underground or atmosphere through processes such as evaporation.

Soil moisture dynamics are governed by a non-linear interplay among diverse hydro-meteorological and biophysical processes, including precipitation, evapotranspiration, and drainage (Ghannam et al., 2016). Due to these interactions, soil is considered a crucial factor in regulating plant growth and water uptake (Daliakopoulos et al., 2016), as well as playing a role in energy transfer, biogeochemical cycles (Seneviratne et al., 2010), and mitigating natural hazard phenomena.

Plant growth and agricultural crop yields are significantly impacted by soil moisture depletion, which is a prominent issue during droughts (Ciais et al., 2005b). This condition is commonly referred to as agricultural drought. Evapotranspiration plays a major role in depleting soil moisture in the root zone, leading to deterioration of vegetation and the physical environment. Therefore, these consecutive conditions are recognized as agricultural drought (Otkin et al., 2018). When precipitation shortages persist over a substantial period of time, drought conditions accumulate gradually, exacerbating the severity of their impact on ecosystems, communities, and economic conditions

Flash droughts often occur when there is a rapid decline in moisture content accompanied by high temperatures (Otkin et al., 2018). Severe reductions in water levels in reservoirs, whether in groundwater or surface water, occur due to the depletion of soil moisture, ultimately leading to persistent drought conditions (Naumann et al., 2018). It is crucial to accurately assess the reduction in soil moisture conditions, as this parameter governs water utilization, land use practices, and the development of risk reduction plans.

Food safety inspection is a major concern in the context of drought (Mishra et al., 2017). Various techniques have been developed to measure soil moisture conditions. For example, the Soil Moisture Index (HuntED et al., 2009b; Carrão et al., 2016) is a simple formula that standardizes soil moisture deviation from the average, based on the soil moisture at field capacity and wilting point. The Modified Soil Water Deficit Moisture (Yuan et al., 2017a) is an analytical database refined as a drought index, computed using soil humidity data from crop growth models. The Root-Weighted Soil Moisture Index (Zhou et al., 2017) measures soil moisture status considering root-weighted soil moisture content, providing a more concise assessment of soil moisture state while also considering factors like irrigation schedules, plant growth, and crop water requirements.

Drought models based on climate variables are a common approach (Sims et al., 2002; DaiAG, 2004; Mika et al., 2005), while others utilize remote sensing analysis and modeling (Sivakumar et al., 2011). To address this, various tools and methods have been developed. For instance, the Soil Water Deficit Index and Evapotranspiration Deficit Index were developed by (Pendergrass et al., 2020) to monitor agricultural scarcity based on weekly soil moisture and evapotranspiration values obtained from the Soil and Water Assessment Tool (SWAT) hydrological model. Similarly, (Sheffield et al., 2012) utilized high-resolution land surface hydrology simulations from the Variable Infiltration Capacity (VIC) model to evaluate hydrologically based drought models. The Empirical Standardized Soil Moisture Index (Carrão et al., 2016) is based on a remote sensing model designed to classify soil moisture anomalies using satellite-derived surface moisture data into categories of agricultural drought intensity.

1.7.3 Evapotranspiration and Flash Droughts

Monitoring and modeling the surface and vegetation processes of terrestrial ecosystems are crucial for evaluating water and carbon dynamics. Accurate estimates of evapotranspiration (ET) and soil moisture content (SMC) are particularly important for food security, land management systems, and water balance modeling. ET information is essential for addressing management issues related to water supplies, such as irrigation, industrial water use, and water reserve management. ET is the process by which water from various sources is transferred from the soil and/or vegetation layer to the atmosphere. It encompasses the evaporation of surface water bodies, soil surfaces, snow and ice sublimation, as well as water captured by plants and canopy evaporation, representing both a mass and energy flux. ET typically includes plant transpiration, soil evaporation, and intercepted water evaporation fluxes (Schelde, 1996; Ladekarl, 1998).

Evaporation is the physical process of transferring water to the atmosphere from various surfaces such as soil, canopy surfaces, roots, branches, and paved areas. Transpiration, on the other hand, is the evaporation of water through leaf stomata in the vascular system of plants. Stomata are regulated by guard cells, which control their opening and closing. Transpiration is also a biophysical mechanism as it involves living organisms and their tissues. Thornthwaite proposed one of the earliest definitions of potential evapotranspiration (ET) (Thornthwaite, 1948). He defined ET as the maximum amount of water transferred from vegetation to the environment under conditions of full physiological functioning and unlimited water and nutrient availability. The FAO-24 method (Allen et al., 1998), and its extension, the FAO-56 procedure, are widely used approaches for estimating ET, based on ET and crop coefficients (Kc) (Allen et al., 1998). While most ET assessments focus indirectly on plant physiological knowledge, it's important to recognize that plant water transport involves active physiological processes that consume energy. Therefore, even though most ET assessments are only partially reliant on plant physiological information, it's crucial to acknowledge that plant water transport requires active, energy-consuming metabolic processes.

Due to the spatial variability of soils, vegetation types and cover, as well as soil moisture status and plant water supply, the spatial distribution of evapotranspiration (ET) varies significantly (Makkeasorn et al., 2006). Furthermore, the influence of meteorology and climate change on hydrological processes introduces spatial and temporal complexity to ET. The complex relationship between space and time in evaporation processes necessitates sophisticated ET evaluation methodologies (Bastiaanssen et al., 1998). Measurement of ET often requires consideration of mass and energy conservation principles. Therefore, the utilization of Earth observation (EO) data or models assimilating remote sensing information, particularly for geographic and continental scales, is crucial (Li and Islam, 1999; Verhoef and Bach, 2003). Numerous methods and modeling approaches have been proposed in this regard (Bastiaanssen et al., 1998). ET estimation methods should be tailored to the spatial scale of implementation and adhere to conservation principles. Various Earth observation approaches have been explored, as documented in studies such as (Jackson et al., 1977; PRiCE, 1990; Carlson et al., 1990,9; Carlson, 2007; Moran et al., 2000; Gellens-Meulenberghs, 2000; Su, 2002; Verstraeten et al., 2005).

1.8 Definitions of Flash Drought

There is no single definition agreed upon among the research community. In the past, flash drought has been defined differently based on its impacts, rate of intensification, duration, or a combination of both rate of intensification and duration. The temporal evolution in the definition of flash drought has been described by (Lisonbee et al., 2021). Here, we discuss some compiled definitions of flash drought.

Initially, definitions of flash drought described it based on its impact on agricultural production loss due to high temperature and soil moisture deficit. Early studies reported that flash droughts occurred during the growing season and had devastating impacts on the agricultural ecosystem (Hunt et al., 2014; Yuan et al., 2015,0). Recent studies also indicate that flash droughts not only impact agricultural ecosystems but also have devastating effects on terrestrial ecosystems, characterized by rapid onset and the lack of an early warning system (Zhang et al., 2017a,0).

The definition of flash drought based on the rate of intensification is the most definitive feature of flash drought (Woloszyn et al., 2021). In recent years, several studies have defined flash droughts using the rate of intensification along with indicators such as Soil Moisture (SM), Standardized Precipitation Evaporation Index (SPEI), Standardized Evaporative Stress Ratio (SESR), and Evaporative Demand Drought Index (Christian et al., 2019a; Ford et al., 2015; Koster et al., 2004; Liu et al., 2020b; Pendergrass et al., 2020; Noguera et al., 2022). They defined specific threshold limits for 15-30 days, such as a soil moisture decline from the 40th percentile to the 20th percentile (Ford and Labosier, 2017), or an increase in US Drought Monitor (USDM) drought severity by three or more categories within 8 weeks (Ford et al., 2015; Otkin et al., 2018).

In several studies, flash droughts are considered short-term events, typically lasting less than four weeks (HuntED et al., 2009a; Li et al., 2020; Mo, 2015,0). These studies often categorize flash droughts into two subcategories: (a) temperature-driven flash droughts, where high temperatures trigger the event by increasing evapotranspiration and decreasing soil moisture, and (b) precipitation-deficit-driven flash droughts, caused by a decrease in evapotranspiration and an increase in temperature (Liu et al., 2020b; Wang et al., 2020). While these two criteria are commonly used in research, they may underestimate the occurrence of flash droughts. Furthermore, definitions based solely on the onset duration of flash droughts overlook the intensification of key indicators and fail to capture the severity of flash drought events (Liu et al., 2020b).

A recent study has suggested that rapid onset and intensification should be the major defining factors for flash droughts (FD), regardless of the onset duration of the event (Woloszyn et al., 2021). Consequently, in recent years, there has been significant attention given to defining flash droughts based on both intensification rate and duration. For example, researchers have utilized pentad values of the evaporative stress ratio (SESR), applying specific criteria to ensure that identified flash droughts exhibit sudden onset intensification and are not simply the result of slow changes in precipitation, temperature, or cloud cover effects (Christian et al., 2019b; Guo et al., 2019). Similarly, Li et al. (2020) employed the Evapotranspiration Deficit Index (SEDI) to define flash droughts and track their propagation, setting criteria for duration ranging from a minimum of 25 days to a maximum of 60 days (Li et al., 2020). These studies have primarily focused on identifying sudden onset and the rate of intensification of flash droughts, but few definitions have incorporated severity. Otkin et al. (2021) introduced the Soil Moisture-based Flash Drought Intensity Index (FDII) to capture the severity of the 2012 flash drought event in the US, emphasizing the importance of including severity in flash drought definitions to accurately represent the evolution of these events (Otkin et al., 2021). The effectiveness of capturing flash droughts is sensitive to the choice of indicator used in their definition (Cook et al., 2020; Osman et al., 2021), underscoring the need to understand how different indicators may affect the detection of flash droughts.

1.9 Flash Drought Studies across the Globe

Numerous studies have been conducted worldwide since the inception of the concept of flash droughts. These studies offer comprehensive insights into the characteristics of flash droughts and their impacts on ecosystems

1.9.1 North & South America

In North American countries like the United States of America (USA), similar to China, a high number of studies have been conducted to understand the dynamics of flash droughts.

These studies show that flash droughts occur more frequently over central CONUS than in any other part of the country (Chen et al., 2019; Christian et al., 2019a; Lesinger and Tian, 2022; Osman et al., 2022). They usually occur at the beginning of warm seasons, mainly due to high rates of evapotranspiration demand (Chen et al., 2019; Christian et al., 2019b; Otkin et al., 2021).

Using rapid intensification data in the USDM from 2000 to 2019, it is estimated that flash droughts constitute 10% of all drought development in the United States (Leeper et al., 2022). Also, 37%–49% of flash droughts develop into long-term droughts in different parts of the United States (Christian et al., 2019a). Basara et al. (2021) revealed that the climate of the western region of the USA allows for relatively short and narrow dry-down periods, but at the same time, there are few instances counted as flash droughts because the rapid transitions of climate conditions are an innate aspect of the climate system here. On the other hand, Osman et al. (2022) classify flash droughts into three distinct types and find that (1) precipitation-deficit-driven flash droughts predominate on the Western High Plains of the United States, (2) evaporative-driven flash droughts are most prevalent in the upper Midwest, and (3) flash drought events characterized by dryness and demand are common in the southern High Plains.

Extensive study has been devoted to the flash drought that occurred in 2012 across central United States, examining its spatial and temporal evolution (Basara et al., 2019; Otkin et al., 2016), predictability (DeAngelis et al., 2020; Liang and Yuan, 2021), and impacts on agriculture and ecosystems (Jin et al., 2019). Similarly, the scientific literature closely follows the 2017 flash drought across the Northern Great Plains, which resulted in a significant decrease in crop production and an increased risk of wildfire development (He et al., 2019). Other flash drought events with dedicated studies include the flash drought-flash recovery sequence over the south-central United States in 2015 (Otkin et al., 2019), stakeholder response to flash drought during 2016 in the Northern Great Plains (Haigh et al., 2019; Otkin et al., 2019), and the 2019 flash drought in the southeast United States and its association with teleconnections (Schubert et al., 2021).

Across South America, Brazil is reported as a prominent hotspot of flash droughts (Christian et al., 2019a; Deng et al., 2022; Mukherjee and Mishra, 2022). Based on the Evaporative Stress Index (ESI), (Anderson et al., 2016a) identified notable flash drought events due to the rapid decline of ESI. Most of the flash drought events were observed in 2009 and 2012 across southern Brazil. The occurrence of flash drought is significantly associated with the reduction of crop production in Brazil.

1.9.2 Europe

Interest in flash drought research across Europe has surged in recent years. Two recent studies investigated flash droughts across the entire European continent (Shah et al., 2022; Sungmin and Park, 2023), utilizing rapid declines in soil moisture to detect flash drought occurrences. These studies revealed that flash droughts are most prevalent in central and eastern Europe (Shah et al., 2022; Sungmin and Park, 2023) and have become increasingly common across all of Europe, with many regions experiencing at least an 80% rise in flash drought frequency from 1950 to 1984 to 1985 to 2019 (Shah et al., 2022). Shah et al. (2023) further identified two distinct types of flash drought development across Europe: one associated with reduced precipitation coupled with heightened evaporative demand, and the other linked to preceding high precipitation followed by an immediate deficit.

In addition to continental flash drought studies, Spain has been the subject of two flash drought climatology investigations by Noguera et al. (2020). Utilizing the SPEI over a 4-week period, Noguera et al. (2020) observed that flash droughts are most frequent in summer, exhibiting substantial spatial variability across Spain, with the highest occurrence in the northwest region. They estimated that nearly 40% of drought events in Spain evolve into flash droughts. Mozny et al. (2012) examined case studies of flash drought events in the Czech Republic, while Noguera et al. (2022) investigated flash droughts across Spain. Furthermore, Noguera et al. (2022) demonstrated that employing different variables, even with the same identification methodology, can yield significantly different results regarding flash drought hotspots within Spain. Alencar and Paton (2022) utilized time series analysis to illustrate how various methods and indicators lead to considerable variability in flash drought timing and intensity.

Global climatological studies have not identified specific global hotspots of flash drought in Russia. However, a notable high-impact flash drought occurred in southwestern Russia during 2010 (Christian et al., 2019b). Rapid land surface desiccation in June exacerbated the development of an extreme heatwave by late July and early August across the region. This flash drought was associated with cascading agricultural and socioeconomic impacts, ultimately leading to global-scale effects on wheat prices.

1.9.3 China and India

Several studies have been conducted on the characteristics and development of flash droughts over China. These studies focused on climatological characteristics of flash droughts over various basins, plateaus, or subregions. For example, studies have investigated flash droughts in regions such as the Horqin Sandy Land (Hu et al., 2021), the Huaibei Plain (Gou et al., 2022), the Loess Plateau (Hu et al., 2021; Zhang et al., 2022; Liu et al., 2022), the Pearl River basin (Li et al., 2020; Yang et al., 2023; Zhong et al., 2022), provinces in southern China (**?**), Xilinguole (Liu et al., 2022), the Yellow River basin (Liu et al., 2020b), the province of Guangxi (Yang et al., 2023; Yun-chuan et al., 2023), the Hai River basin (Yao et al., 2022a), the Gan River basin (Zhang et al., 2017b), the Qilian Mountains (Yin et al., 2023), and the Yangtze River basin (Liang et al., 2023).

The majority of studies conducted in China have focused on examining flash drought events within individual basins or plateaus. Furthermore, in studies that encompass flash droughts across the entirety of China, illustrative years are commonly utilized to demonstrate methodological approaches, often lacking spatial context or detailed analysis of associated impacts from an event (Fu and Wang, 2022). One study highlighted widespread flash drought development across

China in 2006, attributed to negative precipitation and positive evaporative demand anomalies; however, the impacts of the event were not thoroughly investigated (Liu et al., 2020a). Moreover, smaller-scale studies have contributed notably through trajectory analysis, mapping the spatial evolution of flash drought development over time (Gou et al., 2022; Liang et al., 2023; Chen et al., 2020). In summary, there are ongoing opportunities to identify specific and high-impact flash drought events across China in the future.

These studies unveiled a gradient of flash drought frequency across China, with the highest incidence observed in the humid areas of southeast China and lower occurrence in the more arid and higher-elevation regions of northwest China. Similar findings were reported by (Xi and Yuan, 2023; Zhang et al., 2022). Additionally, it was discovered that flash droughts with the most rapid intensification rates tend to occur in southern China (Wang and Yuan, 2021). Liu et al. (2020b) identified a comparable spatial pattern, albeit with slight modifications, showing a higher frequency in central China and lower occurrences in southwest and far northeast China. Most of these studies employed similar variables and methodologies to identify flash droughts, leading to consistent conclusions (Fu and Wang, 2022; Wang and Yuan, 2021; Otkin et al., 2019). Gou et al. (2022) noted that even a minor adjustment to the identification method, such as altering the minimum duration of flash drought from 2.5 to 4 weeks, resulted in significant changes to the hotspot locations of flash drought occurrences across China.

India has been identified as a prominent global hotspot for flash droughts, according to various datasets and indicators (Christian et al., 2019a; Deng et al., 2022; Koster et al., 2019). Although limited studies have investigated regional flash drought characteristics across India, several key events have been identified. Among these, the most notable is the flash drought of 1979, recognized as the most severe occurrence since 1951 in terms of spatial coverage, duration, and intensity (Mishra et al., 2021). However, the climatological characteristics of these events at regional scales in India remain uncertain. Employing the same flash drought identification framework but utilizing different datasets, Mahto and Mishra (2020) observed that flash droughts occur most frequently in central and eastern regions of India during the summer monsoon season, whereas Poonia et al. (2022); Rakkasagi et al. (2023) identified the highest frequency in western India during the monsoon season. Moreover, Mahto and Mishra (2020) noted that over 80% of flash droughts occur during the summer monsoon season, whereas Poonia et al. (2022) reported twice as many flash droughts during the non-monsoon season compared to the monsoon season. While the utilization of different datasets may contribute to these discrepancies (Mukherjee and Mishra, 2022), further investigation is warranted to reconcile these differences, particularly concerning the climatological occurrence of flash droughts across India

1.9.4 Australia

The investigation of flash drought climatological characteristics surged in Australia over the last few years. The studies by (Parker et al., 2021; Nguyen et al., 2021) are the only two that have quantified a climatology of flash drought across the entire country. Their findings reveal the highest risk of flash drought occurrence in northern and eastern Australia. This regional analysis aligns with global flash drought analyses, which have also identified northern and eastern Australia as areas with elevated flash drought occurrence compared to the more arid central regions (Christian et al., 2021; DeAngelis et al., 2020). Additionally, flash droughts have been found to occur in about 25% of wet seasons on average across northern Australia (Lisonbee et al., 2021).

Flash drought case studies have mainly focused on eastern Australia, where elevated flash drought occurrence has been identified (Park et al., 2018). These events have primarily been examined using the Evaporative Stress Index (ESI) and include a flash drought event across eastern Australia between December 2017 and January 2018 (Nguyen et al., 2019), an event within the Central Slopes region in June 2019 (Nguyen et al., 2019), and a flash drought in eastern Australia in November 2019. Additionally, Dunne and Kuleshov (2023) found evidence of a likely flash drought event in southeastern Australia during March and April 2019 using a monthly drought risk index. There is also evidence of seasonality in flash drought occurrence, with the highest frequency observed during the Austral summer (December–February), particularly in northern Australia (Nguyen et al., 2021; Park et al., 2018). The timing of peak flash drought occurrence coincides with the onset of the monsoon in northern Australia; Christian et al. (2021) hypothesize that a delayed onset of the monsoon may contribute to flash drought development during the summer. Lisonbee et al. (2021) found that while a delayed monsoon onset occasionally contributes to regional flash droughts, prolonged breaks in the monsoon within the season can also play a role.

1.9.5 Africa

Limited studies have focused on flash droughts within specific regions of Africa, with most findings derived from global studies. For instance, Christian et al. (2021) observed that flash drought occurrence is highest across Africa compared to other continents, with notable hot spots identified over the Sahel and Great Rift Valley. In a case study examining a December 2015 flash drought in southern Africa and its relation to anthropogenic intensification, Yuan et al. (2018) revealed rapid drought development driven by significant rainfall deficits and above-average temperatures, leading to a swift decline in soil moisture. The study suggested that dry soils resulting from the flash drought may have exacerbated record heatwaves in the area. In a regional investigation within the Awash River basin of central Ethiopia, Getahun and Li (2024) found that flash droughts were primarily associated with agricultural crops and grasslands in the basin. Flash droughts predominantly occurred during the rainy seasons, exhibiting a strong sensitivity to the timing of the rainy season, particularly the short rains.

1.10 Aim of Thesis

The focus of this work is to explore the dynamics, characteristics, and impacts of flash drought events. The goal is to provide a comprehensive assessment of flash drought identification, characteristics, and their impact on the ecosystem.

The methods presented in this work are chosen with a clear focus on their applicability in real-world situations. By providing a thorough evaluation of these methods and their strengths and weaknesses, this work seeks to contribute to the ongoing efforts to improve our understanding of flash drought dynamics, characteristics, and their impacts, which are crucial for effective water resource management and planning.

The thesis also aims to evaluate the impacts and response of the ecosystem to the flash drought across central Europe. The focus of this work is on modifying existing methods to effectively deal with intermittent data, which can provide more accurate and reliable estimates of flash drought occurrence. Through literature review, the strengths and weaknesses of various approaches to identify flash droughts are discussed, and guidance is provided on selecting the most appropriate methods for flash drought identification. The ultimate goal is to provide the most reliable definition of flash drought identification, thereby contributing to a more accurate and reliable estimate of its impact on the ecosystem, which is crucial for effective drought risk assessment and management.

To summarise the aims of this thesis, they can be listed as follows:

- To perform the quantitative literature review on the development of flash drought concepts and challenges.
- To study the characteristics of flash drought on spatial and temporal scale across central Europe.
- To investigate the response of ecosystem to flash droughts.
- To identify the appropriate depth of soil moisture to study the impacts of flash drought on the ecosystem .

1.11 The Structure of the Thesis

The work is divided into four main parts: a systematic review of flash drought research (Chapter 2); Characteristics of flash drought (Chapter 3); Response of ecosystem to flash drought (Chapter 4); and Thesis summary (Chapter 5).

Chapter 2 provides a summary of the development and growth in flash drought research over the last few decades. A bibliometric approach has been used to investigate the global interest in the field of flash drought.

Chapter 3 investigates the characteristics of flash drought across Central Europe on both spatial and temporal scales.

Chapter 4 explores the response of the ecosystem to flash drought.

In the final part of the thesis - Chapter 5 - the findings of all chapters are discussed based on the literature review, and conclusions are drawn with recommendations.

Chapter 2

Systematic Analysis of the Flash Drought Research: Contribution, Collaboration and Challenges

2.1 Introduction

Flash droughts (FD) have only recently gained significant attention even though its effect on society and the environment is non-negligible (Yuan et al., 2019). The analysis of hydro-meteorological variables, such as soil moisture, precipitation, temperature, and evapotranspiration have been used to identify large-scale flash droughts (Mo, 2015; Wang et al., 2016). Rapidly evolving drought is usually associated with temperature and precipitation imbalance anomalies. Hence, two types of flash drought occur in nature: heatwave flash drought and precipitation-deficit flash drought Mo (2015). High-temperature anomalies drive the heatwave flash drought, while below-normal precipitation drives the precipitation-deficit flash drought (Mo, 2015,0). Evapotranspiration and soil moisture variations are observable during both forms of flash drought. Higher temperatures and lower precipitation rates reduce the soil moisture of the land and exert negative effects on plant growth (Yuan et al., 2017a). The sudden onset of drought can lead to significant decrease in agricultural production, and subsequently negative impact on society and economy. In 2012, for instance, a huge deficit in precipitation combined with record high temperatures caused very rapid drought in the United States. This event spanned more than two months and had a devastating effect on livestock, with 30 billion USD losses spread across the country (Otkin et al., 2016). Likewise, in the summer of 2013, a substantial flash drought hit the Guizhou and Hunan provinces in southern China and had dramatic effect on the crop growth rate on more than two million hectares of farmland (Yuan et al., 2017a).

In view of these catastrophic events, it is important to highlight the studies conducted in this field. Researchers have used various qualitative and quantitative literature review methods to explain and correlate previous results. Bibliometric analysis is an emerging tool used in literature analysis. The approach of the bibliometric process towards literature analysis effectively describes the stages of development (Wang et al., 2010) and guides the researcher through the body of knowledge. It also builds a reproducible workflow for the analysis. Bibliometric analysis further supports fair and constant research, relying on mathematical evaluation of science, scientists or scientific activity (Broadus, 1987; Aria, 2017). In their beginning, bibliometric examinations were applied to logarithmic and calculator procedures and several transmission publications (Pritchard et al., 1969). Nowadays, this method is applied to compile the results of a wide range of literature in different disciplines and to investigate the research trends in a particular field (Persson et al., 2009).

Very few quantitative literature reviews have been published in the field of environmental hazards and assessment. These studies vary according to the topics of investigation, time span and methods. For example, Li (2015) performed a keyword analysis on global Environmental Impact Assessment research, which transit towards studies focused on Strategic Environmental Assessment in 20 years. Wang et al. (2010) performed a keyword frequency analysis to investigate the changes in the research topics published in the "Journal of Water Research" from 1967 to 2008. Niu et al. (2014) conducted a statistical and bibliometric analysis to determine the growth in global groundwater research of the past two decades. Similarly, Barthel and Seidl (2017) conducted a bibliometric analysis to find how much collaboration has taken place in groundwater research. Wang et al. (2014) applied bibliometric analysis to climate change vulnerability research on 3004 published papers. In their study, they reveal that most literature in the field focuses on food security issues in the domain of agriculture, health issues in the field of socioeconomics, and water resources issues. These studies reveal the possible contributions and awareness-building that bibliometric analysis yields while portraying a body of knowledge.

The last decade saw rapid development of flash drought research because of increasing public understanding of water conservation and sustainable water management. The purpose of this study is to describe the evolution of the novel concept of flash drought and present the challenges in the identification of flash droughts. In this study, we performed a threefold analysis. First, a bibliometric approach to qualitatively and quantitatively asses the global research trends between 2000–2021. Second, we performed network analysis for bibliographic coupling, co-citation, co-occurrence and collaboration analyses. Third, we identified the challenges in the study of flash droughts. The study is organized as follows: in Section 2 we discuss the methods and data sources, in Section 3 we present the results of the analysis, and in Section 4 we conclude the research. The study improves our understanding of the evolution of the flash drought research, highlights the growth of flash drought related literature in the past decade, and reveals pressing research questions of the field as well as the network of scholars addressing them.

2.2 Material and Methods

It is essential to define the research questions or topic of interest before starting a bibliometric analysis. Three key elements are important in the phase of study design of a bibliometric study: the keyword of research topic, the geographical extent, and the time span (Aria, 2017). For this study, we selected Flash Drought as the keyword, global sources as geographical extent, and the time span from 2000 to 2021.

2.2.1 Data Collection and Screening

The Scopus search engine was used as a platform to obtain relevant peer-reviewed published articles based on title, keywords and abstract (TITLE-ABS-KEY). The full search code on the Scopus website (https://www.scopus.com/) relevant to flash drought followed as TITLE-ABS-KEY ("Flash Drought" OR "Sub seasonal Drought" OR "Rapid Drought") AND PUB YEAR 2000 and 2021 (till July). A total of 119 published articles were found between 2000 and 2021. The articles were further passed through the screening process adopted by (Hasan et al., 2019) for selection of the relevant ones. In the screening process, visual evaluation of the papers titles, abstracts and keywords was done. Only the articles related to the scope of the study were used for further analysis. Through the screening process, we selected 76 articles which were saved in Bibtex format for the subsequent bibliometric analysis. This Bibtex file was converted into a required data frame which consists of variable symbols, classes and their description for analysis (Table 2.1).

The workflow of the analysis involves contribution and collaboration network extraction (Figure 2.1). The analysis has been performed by using the bibliometrix R package (`https://www.bibliometrix.org`), which provides a set of tools for quantitative research.

The network and collaboration analysis has been performed using the software VOSviewer (`https://www.vosviewer.com`). The network analysis was performed for the author's documents, the author's keywords and global collaboration. VOSviewer builds network maps on a co-occurrence

Table 2.1: Data frame of bibliomatrix

Symbol	Class	Description
UT	CHR	Article Identifier
AU	CHR	Authors Name
TI	CHR	Title of Document
SO	CHR	Name of Publisher
DT	CHR	Type of Document
DE	CHR	Keywords use by Author's
AB	CHR	Abstract of Paper
CI	CHR	Address of Author
TC	NUM	Total Citations
PY	NUM	Year of Publish

matrix. In the co-occurrence matrix, the attributes of the document are linked with each other via the document itself (e.g., author(s) to the journal, keywords to the date of publication). Such links are represented by the matrix document attribute. We refer to (Perianes-Rodriguez et al., 2016; Van Eck, 2010) for an extensive discussion on the theory behind the workflow of VOSviewer.

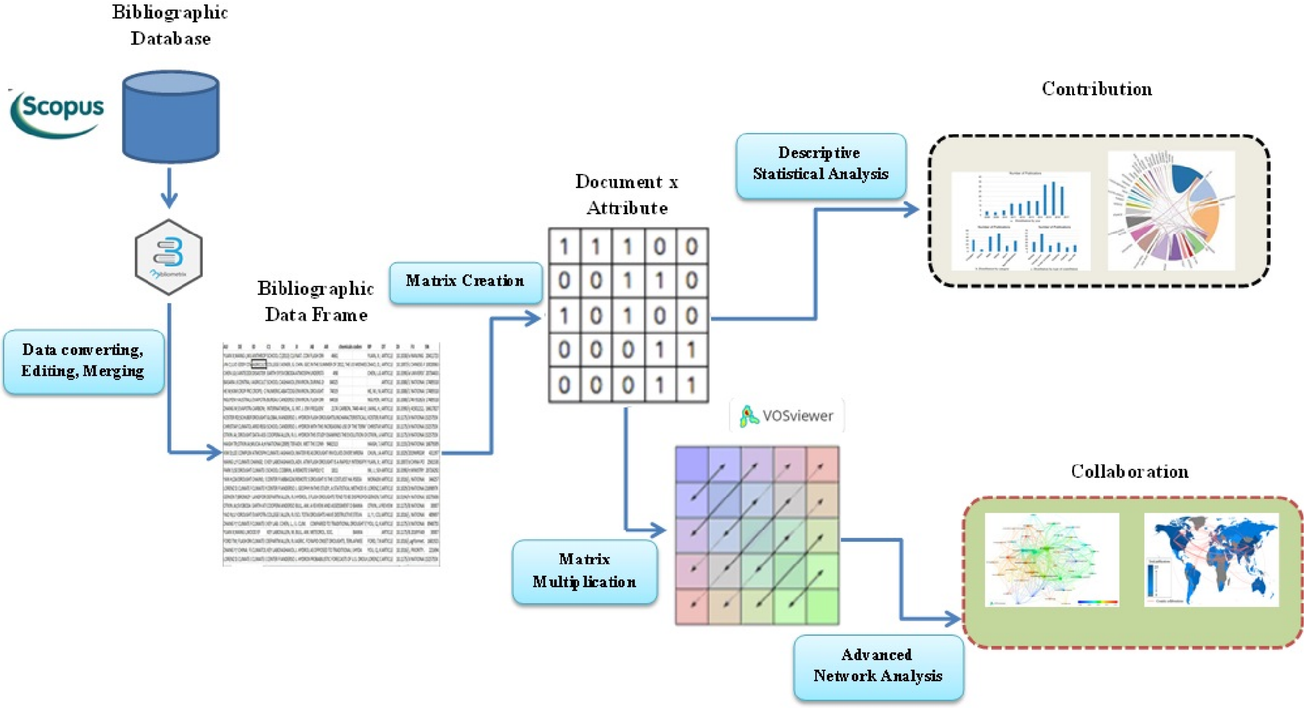

Figure 2.1: Workflow of biblimatrics analysis.

2.3 Results and Discussion

Out of the 76 documents published between 2000 and 2021, four were review articles and 72 were research articles (Table 2.2). A total of 158 authors contributed to the research. The number of authors per document was approximately four. The collaboration index, which is defined as "Total Authors of Multi-Authored Articles / Total Multi-Authored" was 3.45, and no single-authored document was reported.

Table 2.2: Basic data information of bibtex data frame

MAIN INFORMATION ABOUT DATA		AUTHORS	
Time Span	2000-2021	Authors	158
Sources (Journals)	25	single-authored documents	0
Documents	76	Authors of multi-authored documents	260
Average citations per documents	45.47	AUTHORS COLLABORATION	
Average citations per year per doc	6.99	Single-authored documents	1
References	2077	Documents per Author	0.278
DOCUMENT TYPES		Authors per Document	3.59
Article	72	Co-Authors per Documents	5.52
Review	4	Collaboration Index	3.45
DOCUMENT CONTENTS			
Keywords Plus (ID)	578		
Author's Keywords (DE)	183		

2.3.1 Contributions Analysis

The contribution analysis was done in four parts: a) Growth of flash drought literature since 2000, b) Chronological development of the flash drought concept, c) Temporal improvement in the indices and monitoring systems of flash drought, d) The most impactful articles on flash drought.

Growth and Trend of Literature

The number of published scholarly articles is a significant indicator of the growth of a certain scientific field. Literature research has demonstrated exponential growth of the literature on a single subject (Wang et al., 2014). Therefore, we analysed the growth of flash drought literature by using an exponential growth model (Figure 2.2). The growth model showed that annual number of publications grew substantially at an increasing rate after 2011. In Figure 2.2, the rapid increase in flash drought research in recent years can be seen. Based on the rate of increase, we fit two exponential models, one for the whole study period of 2000 to 2021, and the other for 2012 to 2021, to evaluate the growth rate in different time frames (2000–2021, 2012–2021). We simulated the growth trend based on the aggregate publications for each year from 2000 as the first year, which can be expressed as $N = 0.11 \times \exp(0.3 \times t)$ with (R2 = 0.99). Consequently, the formulation for providing growth of flash drought research from 2012 to 2021 can be shown as $N = 2 \times \exp(0.39 \times t)$ with (R2 = 0.98). Here N is the annual number of articles and "t" is the number of years since the beginning of analysed time period (for t = 0, 1, 2, . . .). The growth rate was 30% per year from 2000 to 2021 and 39% per year from 2012 to 2021, respectively. The growth rate for the whole study period (2000–2021) is smaller because the maximum number of articles were published after 2011 (Figure 2.2). Between 2000 and 2012, literature on the subject of flash drought was relatively quiet. It is possible that the researchers integrated the concept of flash drought into the studies on traditional drought. One reason for the increase after 2011 is the severe drought in Central US between 2011 and 2012. Since then, it seems that both the media and the scientific community around the world started adopting the term flash drought. Overall, flash drought literature follows the general rule of development in academic science (Jing and Kang, 2000).

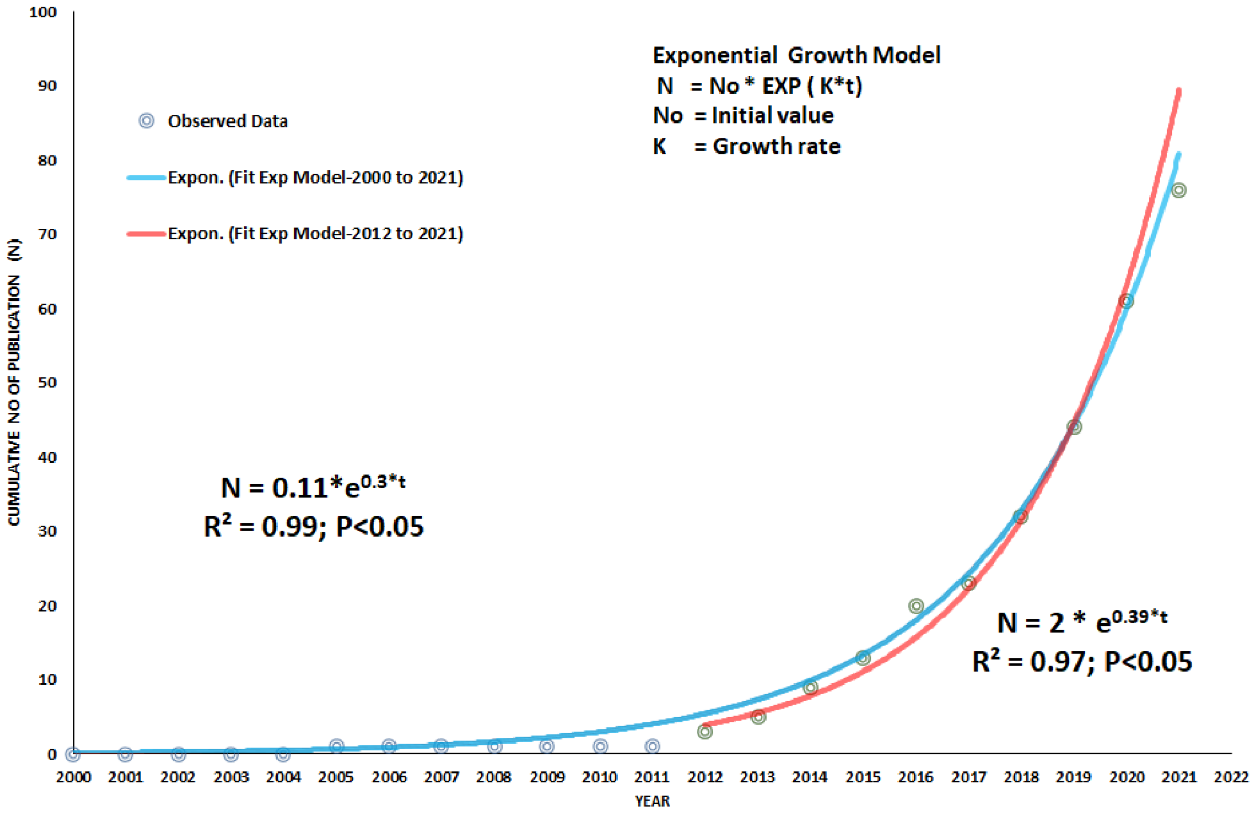

Figure 2.2: Literature growth trend from 2000 to 2021

The Evolution of Flash Drought Concept

In the past, the concept of flash drought was considered in the description of traditional slow-moving drought. At the 1999 EOS meeting, Showstack (1999) wrote a short note on drought, stating that not all droughts start with a slow phase. Three years later, both (Svoboda et al., 2002) and Peters et al. (2002) first used the term "flash drought". The concept of flash drought, its definition, and identification are debated among the research community to this day.

According to Lisonbee et al. (2021), the concept of flash drought has been explained in 49 different ways, even though all definitions are either closely related or build upon previous definitions by adding new indicators. For example, Svoboda et al. (2002) described flash droughts as the negative effects of heat waves which manifest over a short time period and lead to rapid droughts, whereas Peters et al. (2002) defined flash droughts as the combined effect of no precipitation with very high temperature. In 2009, HuntED et al. (2009a) referred to flash drought as a sudden onset of drought with high temperature and winds that cause a rapid decrease in soil moisture during a growing season. They introduced a new concept of flash drought by combining meteorological and soil characteristics (Soil moisture and Evapotranspiration). Anderson et al. (2011) believed that flash droughts are caused by hot and dry conditions, which can lead to severe water shortages and crop failure. In the beginning, the concept of flash drought definition revolved around the land atmospheric parameters (Precipitation, Temperature and Soil moisture), which could not completely describe the phenomenon of flash drought.

Between 2014—2018 a new concept of flash drought developed, incorporating numerical thresholds for various indices, duration and rate of intensification. Anderson et al. (2013) observed flash drought when the anomalies of evaporative stress index and soil moisture were strong over a four-week interval (> 1.5 deviations of the standard). In 2014, (Otkin et al., 2014) distinguished fast-onset drought events from those that developed more slowly (conventional drought). They introduced the distinctive feature of flash droughts, i.e., rapid rate of intensification. Yuan et al. (2015) designated 20th percentile (0.8 standardized value) of pentad (5 day) soil moisture as the threshold to define flash drought.Mo (2016) referred to flash drought as the phenomenon of a short period (up to three pentads) when warm surface temperature with rapid decrease in soil moisture has occurred. Ford and Labosier (2017) coupled the concept of threshold level and duration to define the flash drought. According to them when the pentad soil moisture declines from 40th percentile to 20th percentile or below in four or less pentads the event is considered a flash drought. Park et al. (2018) introduced the concept of a very short-term drought index (VSDI) for identifying flash droughts caused by a rapid rate of intensification. They recommended 0.4 value of VSDI as the threshold of single pentad to define flash drought.

Between 2019 – 2021 the research of flash drought revolved around its characteristics, response of ecosystems, climate drivers and the role of anthropogenic warming. The three major characteristics of flash drought (frequency, intensity and severity) were discussed by many researchers on various spatial and temporal scales (Christian et al., 2019b; Chen et al., 2019; Basara et al., 2019). In 2020, some studies focused on the design of frameworks for effective identification of flash drought through various data and methods (DeAngelis et al., 2020; Hoell et al., 2020; Liu et al., 2020a). Other works highlighted the response of ecosystems to flash droughts and revealed that the water use efficiency of an ecosystem increases during such events (Zhang and Yuan, 2020; Yuan et al., 2020a). Additionally, they concluded that, more effort should be devoted to the analysis of the impact of flash droughts on terrestrial ecosystem by using multiple observations (remote sensing and in-situ). Nguyen et al. (2021) investigated whether climatic drivers like

Indian Ocean Dipole mode (IOD) and the Central Pacific El Nino can aid in predictions of flash drought conditions. However, precise prediction of timing and magnitude of local events requires spatially and temporally finer information than such large-scale climate drivers provide. Mishra et al. (2021) investigated the linkage of flash drought as extreme climatic events to anthropogenic activities. Their study suggested that the risk of flash droughts will increase globally in the future due to the seasonal changes in summer monsoon rains and anthropogenic warming. This will in turn have adverse effects on crop production, irrigation demands, and groundwater abstraction.

Developments in Flash Drought Indices and Monitoring

Many indices have been created and used to evaluate flash drought events since the term flash drought became popular. The purpose of these indicators was to connect the flash drought meteorological drivers (rain, temperature and solar radiation) to better estimate the rate of change in the intensity of flash drought and to compare the severity of flash drought events.

U.S. Drought Monitor (USDM) was the first publicly available drought monitoring index used to quantify flash droughts (Ford et al., 2015). The USDM produced weekly maps of drought severity and spatial extent by integrating various hydro-meteorological indices. The USDM classified the severity of drought into five categories varying from abnormally dry to exceptionally dry (Svoboda et al., 2002). This monitoring index is widely used by many researchers (Otkin et al., 2013,0,0; Christian et al., 2019a) as a baseline to compare the effectiveness of flash drought prediction through different variables and indices. USDM was crucial in correctly identifying the flash drought of 2012.

Evaporative indices are another important metric used to study flash drought. The most common evaporative indices are evaporative stress index (ESI) (Anderson et al., 2013; Otkin et al., 2013,0), the Standardized Evaporative Stress Ratio(SESR) (Christian et al., 2019a), the Standardized Potential-Evapotranspiration Index(SPEI), the Evaporative Demand Drought Index(EDDI) (Pendergrass et al., 2020), and the Vegetation Drought Response Index (VegDRI) Otkin et al. (2016). These indices are useful for the stakeholders who rely on soil moisture alone because they reflect vegetation health.

The mentioned indices offer a satisfactory metric reflecting current state of vegetation health and soil moisture stress, but there is another indicator of “change in stress” which is also important in regards to the study of flash drought impacts. Otkin et al. (2013) introduced Rapid Change Index (RCI) by monitoring the rapid change in ESI over time. This index gathers weekly ESI change anomalies during the flash drought event (Otkin et al., 2015a). Otkin et al. (2013) argue that evaporative indices are not always suitable for the detection of flash drought because the complete picture of flash drought cannot be described through single variable. (Otkin et al., 2018) recommended the usage of a combined set of all land-atmospheric factors (precipitation, temperature, soil moisture and vapor pressure) to evaluate flash droughts.

Otkin et al. (2021) introduced the flash drought intensity index (FDII) by accounting for both the rapid rate of intensification as well as severity. In this index, he assumed that soil moisture is directly related to evaporative demand and evapotranspiration, which is a good indicator of flash drought. The FDII framework is useful to characterize flash droughts by combining the complete measure of the severity of flash droughts, unlike the current classification methods that only consider the intensity rates. The FDII was tested to analyse the 2012 US flash drought event and showed that FDII portraits severe drought condition more precisely in terms of crop condition and yield loss than the intensification rate alone.

Most Cited Articles

Number of citations is frequently used as an indicator of the impact of scientist's work (Cole and Cole, 1967; Martin and Irvine, 1983; Virgo, 1977). Thus, often cited papers can be considered more valuable than publications that are barely cited (Aksnes, 2005). The top ten (Table 2.3) most impactful papers are sorted by Total Citations (TC). The study of Breshears et al. (2005) got the highest number of citations at 1495. They focused on the die-off phenomenon of woody plants due to the evolution of rapid-onset drought and concluded that the risk for such die-off will be more severe and widespread for future drought events in warmer climates. After that, in 2012, Adams et al. (2012) linked the die-off phenomenon of wood plants to different hypothesis of rising temperature and severity of rapid droughts. This study earned a total of 167 citations and ranks second in the top ten. In 2013 Anderson et al. (2013) introduced the evaporative stress index (ESI) derived from North American Land Data Assimilation System (NLDAS), as an indicator for identification of flash drought. This study ranked third with a total of 149 citations. The study of Anderson et al. (2016b) with 149 citations again used ESI as an indicator of flash drought and demonstrated the impacts of flash drought in the terms of ESI anomalies on the crop yields. The ESI reported better effects of rapid cycling moisture conditions on crop yields. Otkin et al. (2016) studied the impacts of rapid soil moisture anomalies derived from satellite on the vegetation health during the flash drought event of 2012 in the USA. The study ranked fifth with 130 citations. In 2018 Otkin et al. (2018) reviewed the published literature on flash drought and introduced a framework to define a flash drought. This study also highlighted the challenges facing stakeholders when having less time for preparation for these events. This study had 130 citations. In the Otkin et al. (2013) study from the same year (2013) with 126 citations, ESI was used as an indicator in the early warning system of flash drought. The study shows that ESI anomalies reflect the substantial effects of flash drought on agricultural systems. The study of Wang et al. (2016) ranked eighth with total 117 citations. They examined long-term flash droughts patterns and variability across China by using the projected climate models. They found that the average number of flash droughts in China increased by 109% between 1979 and 2010, due to the rise in long-term temperatures. In the coming decades, anthropogenic heat could exacerbate severe drought conditions in China. Ninth ranked article with total citations of 97, Hobbins et al. (2016) introduced Evaporative Demand Drought Index (EDDI) as a flash and persistent droughts predictor. The study indicated EDDI's usefulness in real-time drought tracking and as a robust leading drought predictor. The Mo (2015) study ranked tenth with 94 citations. In this study, two kinds of flash drought events were investigated (Heatwaves and Precipitation deficit) over the conterminous U.S. (CONUS). They conclude that over the last century, the number of such events in the CONUS declined but rebounded after 2011.

Table 2.3: Top ten most cited articles

Rank	Title	Year of Publish	TC	Reference
1	Regional vegetation die-off in response to global-change-type drought.	2005	1495	Breshears et al. (2005)
2	Ecohydrological consequences of drought- and infestation- triggered tree die-off: insights and hypotheses.	2012	167	Adams et al. (2012)
3	An intercomparison of drought indicators based on thermal remote sensing and NLDAS-2 simulations with U.S. drought monitor classifications.	2013	149	Anderson et al. (2013)
4	The evaporative stress index as an indicator of agricultural drought in brazil: an assessment based on crop yield impacts.	2016	149	Anderson et al. (2016b)
5	Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought.	2016	130	Otkin et al. (2016)
6	Flash Droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States.	2018	130	Otkin et al. (2018)
7	Examining rapid onset drought development using the thermal infrared-based evaporative stress index.	2013	126	Otkin et al. (2013)
8	Increasing flash droughts over China during the recent global warming hiatus.	2016	117	Wang et al. (2016)
9	The evaporative demand drought index. part i: linking drought evolution to variations in evaporative demand.	2016	97	Hobbins et al. (2016)
10	Heatwave flash droughts in decline.	2015	94	Mo (2015)

2.3.2 Geographical Productivity and Collaboration

The number of papers from a given country reflects the research intensity in that country in a certain branch of study, 53 articles (66%) were single country-specific articles, and 23 articles (34%) were collaborative articles. Flash drought studies are mainly concentrated in the USA with a few studies published from China, Australia, South Korea, India, Spain and the Czech Republic. Among them, the researchers from USA have the largest number of publications (37 articles); out of which 33 are single-country articles (all authors from the same country), and four articles are collaborations with other countries. Researchers from China have published 14 single-country articles and seven articles with international collaborations. Scientists from South Korea and the Czech Republic have published one single-country article each. Two articles have been published from Australia in collaboration with the United States while two single country articles published from India. The highest number of published flash drought studies were conducted in the USA, and only a few in the rest of the world. Therefore, more studies are needed in other parts of the world in different climatic conditions. The collaboration network of scientific cooperation between countries helps us to understand the countries involved in the respective fields of science (Darko et al., 2019). Collaboration between countries on any topic also represents the flow of research ideas from one region to another (Figure 2.3). As we are still at the early stages of flash drought research, it is easy to see that it is a concept born in the USA and still being "exported" to the rest of the world through international collaborations. In their collaborations, the researchers from the USA have studied the impact of flash droughts on crop yield, early warning systems, and the reliability of remote sensing data for flash drought identification Adams et al. (2012); Anderson et al. (2013,0); Haigh et al. (2019). China follows the USA, having some collaborations with the USA and the UK. In their collaborations, Chinese researchers introduced the concept of an anthropogenic shift in the intensification of flash drought Yuan et al. (2018); Jin et al. (2019); Yuan et al. (2019). Australia and the USA have collaborated on the application of remote sensing data in the identification of flash drought Nguyen et al. (2019). There is still a gap in the collaboration among the remaining countries, especially in Europe, which could lead to a better understanding of the flash drought phenomenon.

Keywords Analysis and Hotspots

To identify hot-spot issues and research trends, a bibliometric approach by means of keyword analysis has been applied to the dataset. Authors' keywords and Keywords Plus are often used to expose the hot spots and patterns in a scientific investigation. In 76 publications, 578 Keywords Plus and 183 authors' keywords were found (Table 2.2). The top five most commonly published keywords for flash drought research from 2000 to 2021 were flash drought (25%), drought (10%), evapotranspiration (12%), soil moisture (11%) and land atmospheric interaction (4%). The occurrence of the top five keywords used by the authors indicates that the interaction of evapotranspiration and soil moisture is central in the study of flash droughts (Figure 2.4).

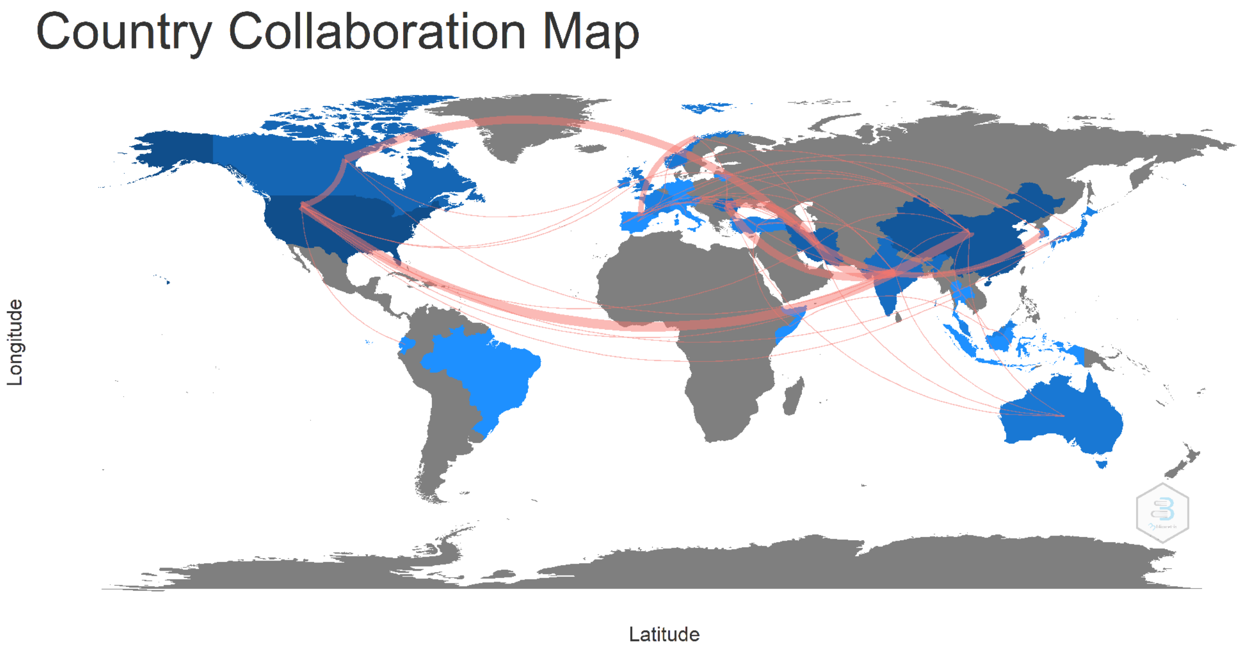

Figure 2.3: Global Collaboration Network on Flash Drought:The bold connecting lines represents two or more collaboration events, while the thin lines represents one collaboration event

Additionally, much concern was also devoted to "land atmospheric interaction" because the atmospheric evaporative demand and soil moisture anomalies tight coupling between moisture stress and the surface temperature.

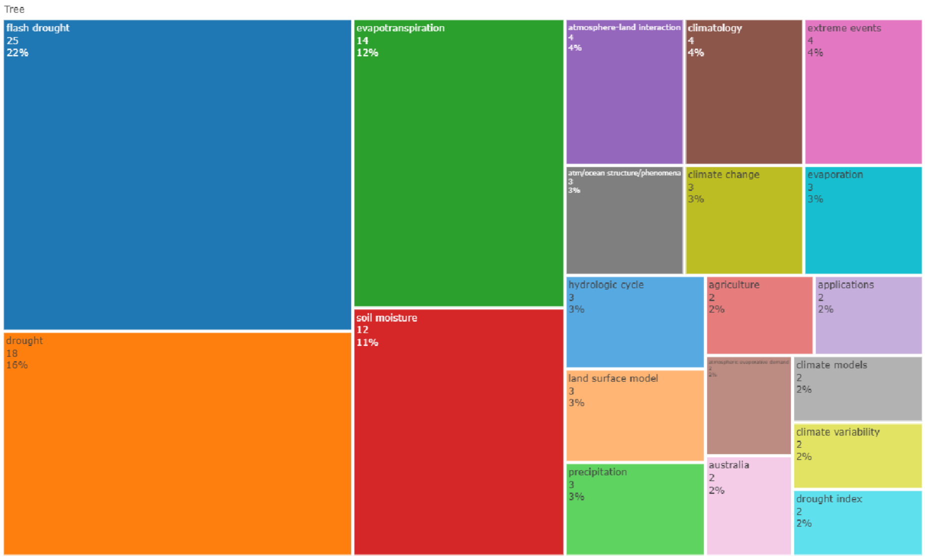

Figure 2.4: Ocurrance of top 20 Authors keywords

The VOSviewer was used to analyse the keyword network. The minimum threshold of two occurrences of a keyword was applied to the co-occurrence network (Figure 2.5). The node and word size in Figure 2.5 show the weight. The larger the node and word, the larger the weight. The distance between two nodes reflects the strength of the link between two nodes.

In general, a shorter distance shows a stronger relationship. The line between two keywords reveals that they appeared together. The thickness of the line represents a greater co-occurrence (Gu et al., 2017). The nodes of the same colour belong to a cluster. The author's keywords are divided into five clusters by using the cluster method of "association strength". The red cluster contains keywords of climate change impacts, adaptation and risk assessment of extreme events. This shows that the flash droughts are related to the study of climate change and the future agricultural production and water supply management. The green clusters contain keywords for remote sensing, satellite imagery, and vegetation dynamics and indicates the application of remote sensing data sets in the field of flash drought. The blue cluster contains mostly keywords related to hydroclimatic variables related to flash droughts, like evapotranspiration, soil moisture and precipitation deficit. This cluster highlights the indicators used to identify flash drought. The purple cluster is focused on monitoring and the development of an early warning system for flash drought in the growing season of agriculture production. Finally, the yellow cluster contains terms related to land atmospheric feedback mechanisms such as air temperature, the hydrological cycle and atmospheric-oceanic interaction. Overall, the hot spots of studies related to flash droughts are climate change impacts, suitable indicators for determining flash drought events, the interaction of flash drought with plant growth and the feedback mechanism of land atmospheric circulation. Some researchers are also focused on the development of effective early warning systems for flash drought monitoring (Wang et al., 2016; Yuan et al., 2019; Zhang et al., 2018).

2.3.3 Challenges and Future Perspectives

Despite the obvious significant improvement in flash drought prediction, the full aspects of flash drought onset, severity, development and recovery remain challenging. This might be because there is currently no consensus within the scientific community on identifying flash drought. There is an ongoing discussion about whether it should be dependent on how fast the onset of the drought is or dependent on its duration, as originally suggested by Svoboda et al. (2002). Otkin et al. (2018) argued, based on short duration criteria, that flash drought identification deviates from the basic characteristics of conventional drought. Here we discuss some of the key challenges in the study of flash drought.

A substantial number of studies show that the identification of flash drought depends on the selection of threshold levels (40th percentile or 30th percentile of used metric) and the duration for which those thresholds are exceeded (four to six pentads). Li et al. (2020) pointed out the sensitivity of choosing the threshold to address flash drought. They concluded that the choice

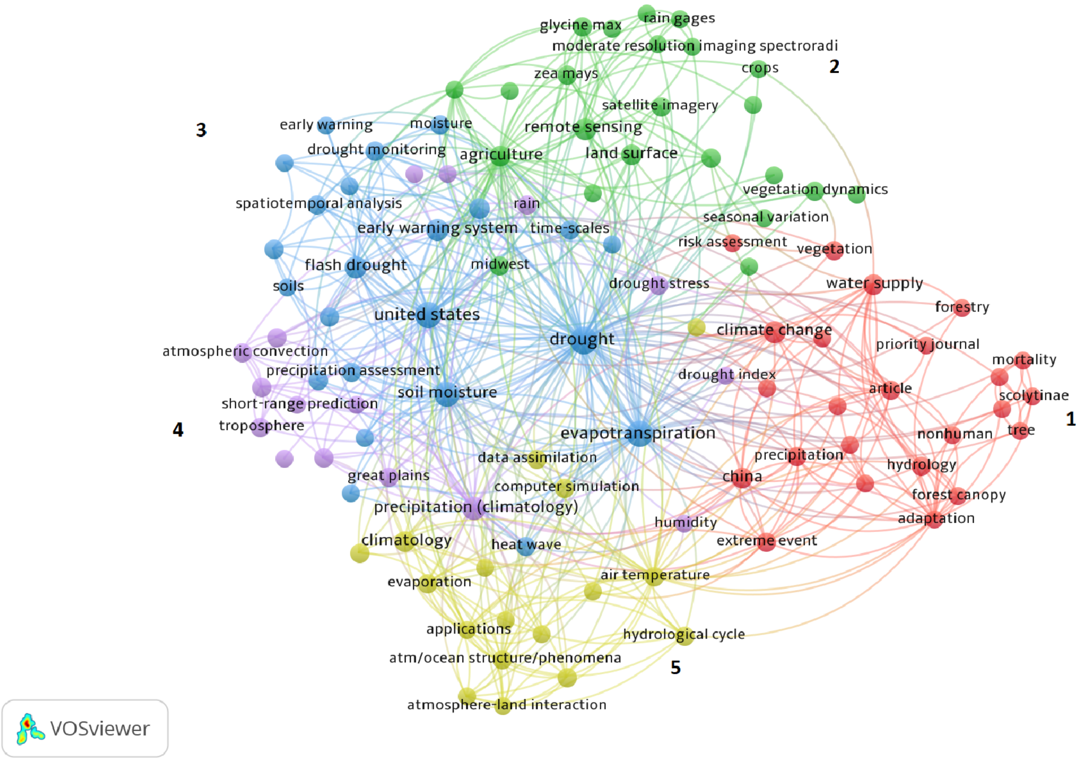

Figure 2.5: VOSviewer visualization of authors keywords clusters and their relations.

of threshold level could affect the characteristics of flash drought across different climatic zones. Changes in the threshold level and duration alter the frequency of occurrence (FOC) and the severity of the flash drought. Mo (2015) identified the heatwave flash drought by adopting the definition that: (a) Air temperature anomaly is greater than 1 standard deviation (SD) computed from the base period for a pentad, (b) ET anomaly is greater than 0, and (c) Soil moisture (SM) is lower than the 40th percentile. In their study, they did not consider the duration of the event, but instead assumed a single pentad duration for all flash drought events. Wang et al. (2016) also used the same definition over China by considering that if two or more consecutive pentads of flash drought happen one after another, they will be considered a single event. In some studies, only soil moisture percentile was used as an indicator to identify the flash drought. For instance, Ford and Labosier (2017) considered a flash drought event to occur when the soil moisture at a station falls from above the 40th percentile to the 20th percentile in up to four pentads. In addition, Yuan et al. (2019) identified a flash drought event by considering both the rapid rate of decline of soil moisture and the dry persistency. The flash drought is considered to begin when the pentad soil moisture decreases from above the 40th percentile to the 20th percentile within at least three pentads. They assumed that a short duration of flash drought does not lead to any impact; therefore, by keeping the dry persistency in their mind, they distinguished the flash drought events by considering that it should remain below 20% after 3 weeks of development stage. The rate of intensification of flash drought is also the point of concern for the researcher. Otkin et al. (2018) point out the method based on rapid rate of intensification for flash drought identification.

Each method comes with its own strengths and limitations. For instance, the rate of intensification flash drought (RIFD) method meets the condition of moisture limitation due to its secondary threshold, namely that the soil moisture should be lower than the 20th percentile for at least one week. In contrast, the heatwave flash drought (HWFD) and precipitation deficit flash drought (PDFD) make no such restrictions on soil moisture, which may lead to misjudgement of the results. It is reported in the study of Liu et al. (2020a) that the HWFD and PDFD overestimate the number flash drought events, detecting false positives. Therefore, it is suggested by Liu et al. (2020a) that HWFD and PDFD methods could not guarantee that all the identified events fall into the category of flash droughts. From the perspective of drought characteristics, flash droughts recognized by heatwave and precipitation deficit were mostly minor events (less than four weeks or five pentads) and had no impact on the health of crops. The flash droughts extracted by HWFD and PDFD (Mo, 2015,0) only focus on the threshold of related variables (e.g., precipitation and temperature), while neglecting the characteristics of the changes in soil moisture with time and its rapid intensification. The standardized evaporative index methods adopted by many researchers (Otkin et al., 2014; Anderson et al., 2013), coupled with a rapid intensification rate, are useful to identify the development phase of flash drought. For timely identification of flash drought, it is vital to understand the atmospheric-land feedback mechanism prior to the onset of flash drought development. There is a need to form and introduce a new definition of flash drought, which blends the atmospheric-land parameters with the rapid intensification of the event.

Flash droughts are space–time phenomenon of rapid intensification in nature (Li et al., 2020). Another challenge in flash drought research is the spatial and temporal resolution of selected indicators (soil moisture, evapotranspiration). Precise estimates of evapotranspiration (ET) and the soil moisture content (SMC) are very significant for correct identification of flash drought. Many researchers used ET and SMC data of the region as a fundamental indicator for the identification of flash drought (Otkin et al., 2018; Anderson et al., 2016a; Mo, 2015; Liu et al., 2020a). In situ soil moisture measurements with restricted spatial and temporal coverage are unable to represent a true image of flash drought for entire regions. In addition, soil moisture values derived from satellite images represent, at most, a few centimetres of the top soil (Albergel et al., 2012; Chan et al., 2018). Similarly, the quantification of (ET) is vulnerable to significant uncertainties as well as deficiencies in the structure and accuracy of the models, depending on the consistency of the inputs. Remote sensing data usually provides consistent spatial and temporal measurements of hydro-climatic variables on the regional and global scales (AghaKouchak et al., 2015; Tang et al., 2009). Despite the drawbacks of biases and limited records, a wide coverage of remote sensing products plays a vital role in the identification and monitoring of flash droughts, particularly in regions with scarce in-situ observations (Masih et al., 2014), and is also used for assessing land-atmosphere interactions (Roundy and Santanello, 2017). The spatial and temporal resolution of remote sensing products is one of the obstacles to the accurate identification of a flash drought. Data assimilation is expected to lead to a better initialization of climate and hydrological models and overall improvement in the predictability of flash droughts. As a result of the spatial variation of soils, as well as vegetation type and cover, soil moisture status and the supply of plant water vary spatially (Makkeasorn et al., 2006). In addition, the influence of meteorology and climate change on hydrological processes make ET spatially and temporally complex. The space and time relationship of evaporation processes leads to a complex ET evaluation methodology (Bastiaanssen et al., 1998). The measurement of ET often requires mass and energy conservation. The use of earth observation (EO) data or models that assimilate remote sensing data, for geographic and continental scales, is a significant requirement (Li and Islam, 1999; Verhoef and Bach, 2003). Many estimation methods and modelling approaches in this regard have been published (Bastiaanssen et al., 1998). ET methods should be grided in accordance with the spatial implementation scale and the rule on conservation applied.

Correct observations are also crucial for the performance of both numerical and statistical models (Hao and AghaKouchak, 2013; Vorobevskii and Kronenberg, 2022). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) proposed that it is difficult to project the human influence on climate change due to data scarcity (Sheffield et al., 2012; Wang et al., 2011), which results in considerable uncertainty surrounding future droughts (Stocker et al., 2013). The uncertainties in projected climatic data for extreme events make it challenging to achieve an accurate prediction of flash drought due to its rapid intensification over a few weeks or pentads. Recent studies have found that there is an incompatibility between original Coupled Model Intercomparison Project phase 5 (CMIP5) models and hydrological models (Wang et al., 2020; Kociuba and Power, 2015). There are still inconsistencies when CMIP5 projections are applied to regional hydro-meteorological studies, due to their coarser horizontal resolution (Zhang et al., 2018). In addition, short-term temperature variations can be underrated by the climate models, which can lead to an underestimation of heat wave flash droughts (Zhang et al., 2018).

Flash droughts have direct impact on the ecosystem due to their rapid intensification. On top of this, the vegetation response to flash droughts – reflecting the overall vegetation adaptability to changing climate conditions – is still a debated topic, currently under investigation (Berdugo et al., 2020). It has been showed that the increase in plant inherent water use efficiency could be partly attributed to inter annual fluctuations in plant functional traits (Mastrotheodoros et al., 2017). Indirect effects of elevated CO_2 are almost equal to the size of direct effects on evapotranspiration, which are far more challenging to understand and constrain (Fatichi et al., 2016). These are just few of the numerous studies on this increasingly investigated topic in eco-hydrological research, demonstrating that our understanding of the plant response to elevated CO_2 levels still remains inconclusive. Therefore, in order to predict the risk of a potential flash drought, many forms of uncertainties need to be quantified.

Recent studies on drought prediction concentrate mainly on natural, climatic or hydrological aspects. Studies on incorporating human aspects into drought prediction are uncommon but growing (Van Loon, 2015; Wada et al., 2017; Yuan et al., 2017b). In addition, the rapid onset of flash droughts poses a significant challenge for early warning. In 2012, the drought in Central America was so pernicious, because there was no time to prepare for it. It began with a flash drought, quickly started, worsened, and eventually evolved into a seasonal drought which lasted for eight weeks. In other words, at the start of a seasonal drought, a flash drought occurred. The transition of flash droughts to seasonal droughts is also a topic that needs further investigation, especially since seasonal droughts appear to be increasing in various regions over the world (Markonis et al., 2021). Another challenge to timely forecasting is the selection of suitable predictors. Generally, predictors that are already established prior to the prediction are obtained from historical observations. Multiple techniques like correlation analysis based on Pearson's correlation coefficient and composite analysis are commonly used to diagnose and choose the potential predictor. However, the recent advancements in machine learning offer new classification alternatives that have been recently applied in hydroclimatic research (Tyralis et al., 2019; Markonis, 2020; Papacharalampous et al., 2021).

The development of early warning systems for sub-seasonal to seasonal predictions is another one of the arising challenges (Pendergrass et al., 2020). To this end, DeAngelis et al. (2020) investigated the prediction skill of flash droughts in the Sub Seasonal Experiment (SubX) with a lead time of three weeks or more. Their study indicated that a robust prediction could be achieved by adjusting the accurate initial dry soil moisture conditions, along with quasi-stationary atmospheric anomalies. Similarly, Chen et al. (2020) addressed the interplay between precipitation and high temperature as a challenge in the prediction of flash droughts. The main findings suggest that in order to improve our ability to handle the risk of flash droughts, we need to enhance our understanding of climate-vegetation-drought interactions, as well as the human involvement to the hydrological systems.

2.4 Conclusion

The bibliometric approach and visualization software were used to assess the recent situation among the scientific community in the field of flash drought research from 2000 to 2021. Based on systematic literature review our study discusses the innovations in this recently-formed research topic from three main perspectives; contribution, collaboration and challenges. The scientific field has grown exponentially since 2012. The global growth rate of flash drought literature was 30% per year from 2000 to 2021. In global collaboration, China and the USA collaborate strongly with others. According to the keywords, the dominant areas of research are the identification of flash drought, the risks due to climate change, the impacts on agricultural production, and the role of land atmospheric feedback mechanisms on flash drought propagation. These four topic hot spots remained vigorous throughout 2000–2021, and are considered to remain the top research emphases in the near future. The main challenges in future flash drought research are the lack of a proper definition and framework to identify flash droughts, the scarcity of accurate, high-resolution data sets, biases in climate model projections, and the inability to develop robust early warning system for timely flash drought forecasting. All challenges that emerge from this newborn concept pose an opportunity for further research. There is no doubt that as the scientific community studying this extreme phenomenon will grow, even more questions will arise. To answer these questions is highly important due to the increasing amount of evidence linking flash droughts to global warming. We expect that this discourse will continue in future publications.

Chapter 3

The Space and Time Characteristics of Flash Droughts in Central Europe

3.1 Introduction

Over the past two decades, researchers have proposed many methods for flash drought identification based on their specific understanding of the phenomenon (Lisonbee et al., 2021; Rahim et al., 2023). A review by Lisonbee et al. (2021) revealed that 20 methods had been introduced for flash drought detection worldwide. Eleven of them include duration and rate of intensification as part of flash drought delineation, while nine considered only specific thresholds to define flash drought. Moreover, Osman et al. (2021) compared different definitions of flash drought based on temperature anomalies (Mo, 2015), evapotranspiration anomalies (Christian et al., 2019a; Pendergrass et al., 2020), rapid soil moisture depletion (Ford and Labosier, 2017; Yuan et al., 2019), and multi-criteria index (Otkin et al., 2018; Chen et al., 2019). Their study concludes that the use of different definitions might lead to different conclusions regarding flash drought frequency, predictability, and trends under changing climates. Similarly, Alencar and Paton (2022) also compared six flash drought identification methods across the cropland of central Europe. They suggested that an ensemble approach may capture flash drought events more efficiently than a single definition.

Every approach has its own set of strengths and limitations. For instance, the Rate of Intensification Flash Drought (RIFD) method addresses moisture limitation by imposing a secondary threshold: soil moisture must be below the 20th percentile for a minimum of one week. In contrast, the Heatwave Flash Drought (HWFD) and Precipitation Deficit Flash Drought (PDFD) methods lack such restrictions on soil moisture, potentially leading to result misinterpretation. Research by Liu et al. (2020a) indicates that HWFD and PDFD tend to overestimate the occurrence of flash drought events, resulting in false positives. Consequently, these methods cannot ensure the accurate categorization of all identified events as flash droughts. Examining drought characteristics, flash droughts identified through heatwaves and precipitation deficits are typically minor events (lasting fewer than four weeks or five pentads) with negligible impacts on crop health. The flash droughts identified by HWFD and PDFD concentrate solely on the thresholds of relevant variables (e.g., precipitation and temperature) while disregarding changes in soil moisture over time and its rapid intensification. Many researchers, incorporating standardized evaporative index methods alongside a rapid intensification rate, find it beneficial for recognizing the development phase of flash drought. To accurately identify impacted flash droughts, it is imperative to integrate the onset indicator of flash drought development (intensification rate) with its persistence (severity). Hence, there exists a necessity to introduce a new definition of flash drought that amalgamates rapid intensification with the event's persistence.

Although previous studies have provided some general methods of detecting and identifying flash droughts, very few studies have been conducted to study the space and time characteristics of flash droughts. As flash drought is a natural phenomenon that emerges in both space and time, with rapid intensities and expansion, investigating the space and time characteristics of flash drought is essential to understand the dynamic process of flash drought and to guide the development of early warning systems better. For example, Christian et al. (2019a) developed a statistical methodology to quantify the temporal evolution of flash droughts with rapid intensification and duration of flash droughts. Until more recently, Li et al. (2020) demonstrated a framework to investigate space and time characteristics of flash drought over the Pearl River basin of China. The results indicate that the defined framework captured the flash drought space-time structure very well, including severity and spatial extent. Various studies of conventional drought characteristics have been undertaken by many researchers in Europe. However, the characteristics of flash drought across central Europe have not been investigated. Moreover, most of the above-mentioned studies on flash drought have been conducted outside of Europe.

In this Chapter, our main aim is to investigate the space and time characteristics of flash drought events over Central Europe. We will explore the characteristics, including frequency, intensification rate, and severity of flash droughts from 1970 to 2020 across this region. Our major objectives include:

1.Designing conditions to identify the full impact of flash droughts by incorporating both rapid intensification rate and dry persistence, which have not been previously included together in one definition of flash drought.

2.Investigating the spatiotemporal characteristics of flash droughts, including areal extent and centroid analysis.

The findings from this study may help to deepen our understanding of flash drought mechanisms and improve detection capabilities. Additionally, the results will contribute to a general understanding of drought characteristics across Central Europe, which can assist in mitigating potential agricultural yield losses associated with flash droughts in this region.

3.2 Material and Methods

3.2.1 Study Area

The study area spans 16.2×10^5 km^2 and is situated in Central Europe, encompassing eight countries (see Figure 3.1). According to the Köppen-Geiger climate classification, the majority of the study area falls within the class of Dfb (warm summer) (Beck et al., 2018; Papacharalampous et al., 2022). The climate of the study area is characterized by cold winters, significant mountain snowfall, and hot summers, particularly in the lowlands. Several studies (van der Wiel et al., 2022; Samaniego et al., 2018; Massari et al., 2022) have indicated that rising temperatures in Europe may lead to a decrease in soil moisture. Markonis et al. (2021) reported a significant increase in short-term warm-seasonal droughts across Europe accompanied by an increase in potential evapotranspiration (PET). This rise in PET, coupled with a decrease in soil moisture, has contributed to an expanding footprint of flash droughts (Shah et al., 2022). The average topsoil moisture (1-10cm) in the study area varies from 15-40 kg/m^2 between April and October. Regions such as the Alps (Switzerland and Austria) in the south exhibit higher soil moisture levels compared to the northeastern areas (Poland) of the study area (see Figure 3.1).

3.2.2 Data

To detect and analyze flash droughts, we utilized the Global Land Data Assimilation System (GLDAS) data product. GLDAS is a globally integrated modeling dataset that provides near-real-time information about land surface conditions using both ground and satellite measurements. It integrates outputs from four Land Surface Models (LSMs): Community Land Model (CLM), Noah model, MOSAIC model, and Variable Infiltration Capacity (VIC) Model. Previous studies have shown a significant correlation between soil moisture derived from GLDAS and in-situ measurements of soil moisture across Europe (Zawadzki and Kedzior, 2014; Zawadzki and Kędzior,

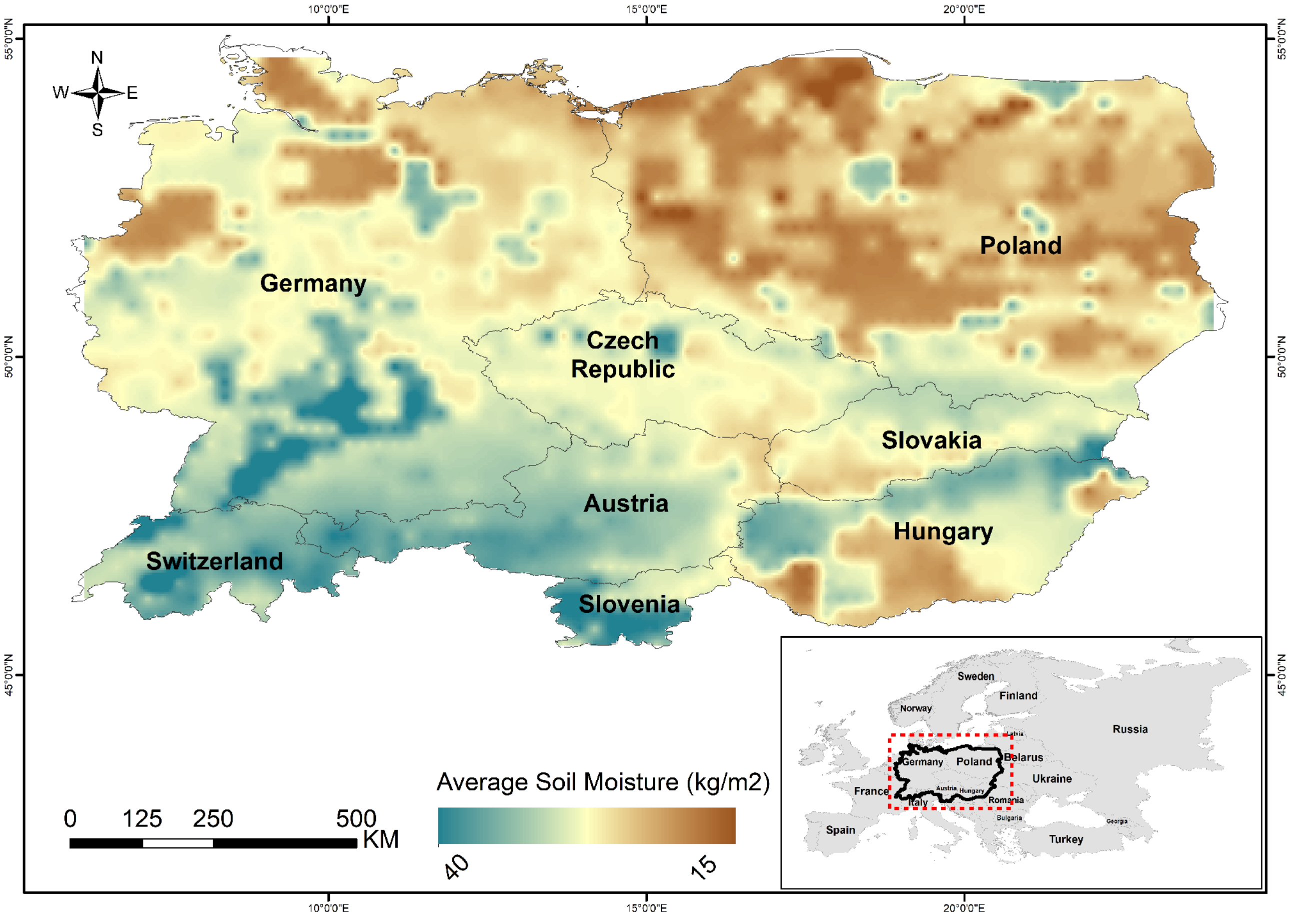

Figure 3.1: Study Area along with the averaged soil moisture (0-10 cm) of growing season(Apr-Oct) from 1970 to 2020

2016; Xu et al., 2021). In this study, we combined gridded soil moisture data from GLDAS version-1 (1970-2000) and version-2 (2001-2020) with a spatial resolution of 0.25° and a 3-hour time step. The 3-hourly soil moisture data were downloaded and processed into weekly average soil moisture using the Google Earth Engine platform (`https://developers.google.com`). Soil moisture percentiles were considered as the basic indicator to track drought conditions. The 3-hourly gridded soil moisture data (0-10 cm layer) were aggregated to weekly averages to avoid frequency variability. We constructed a cumulative distribution function (CDF) to determine the soil moisture percentile over 51 years (1970-2020) during the growing season (April-October) across each grid. This constructed CDF transformed the weekly soil moisture values into percentiles for the identification of flash droughts.

3.2.3 Identification of Flash Drought Events

In this study, we identified the flash drought by considering duration, rate of intensification and the dry persistence. The weekly average soil moisture of top root zone (1-10cm) layer has been used as an indicator to identify the flash drought. The following three criteria are used:

1. The soil moisture must decline from above the 40th percentile to the 20th percentile within the three weeks (e.g., June 1–June 21 in Fig 3.2).

2. The average decline rate of soil moisture must be no less than 5% in percentile per week (e.g., 8% from June 1–June 21 in Fig 3.2).

3. The average soil moisture must remain below the 20th percentile and last for at least 3 weeks. If the average soil moisture rises to the 20th percentile again, the drought terminates (e.g., July 15–19 in Fig 3.2).

The first two criteria describe the onset stage of a flash drought event. The average soil moisture percentile decline rate during the onset stage term as the onset speed. The third criterion is the minimal time regarding persistence or impact of drought after the onset phase. The consideration of averaged soil moisture, after the onset phase, remains below the 20th percentile for at least three weeks exclude the rapid recovered or non-impact drought (e.g., Apr 7 — May 7 in Fig 3.2).

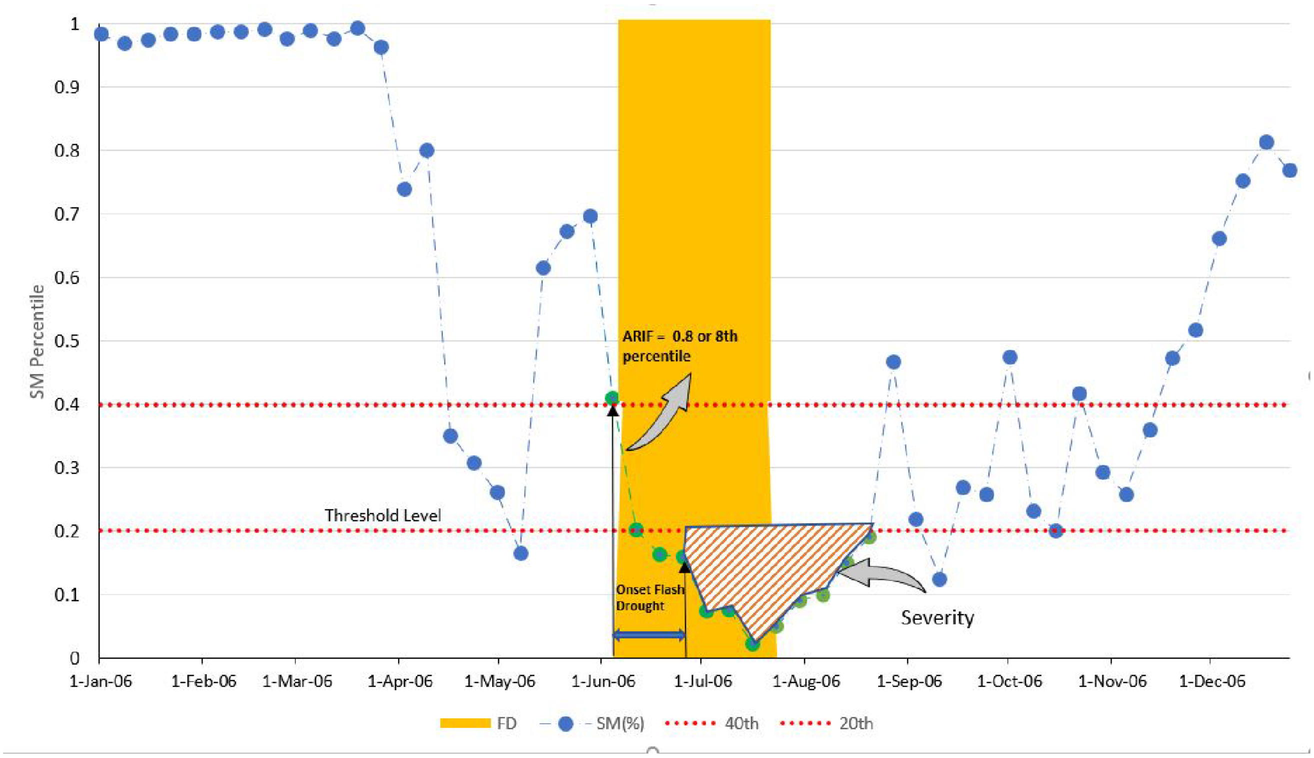

Figure 3.2: Identification of Flash Drought Event.

3.2.4 Characteristics of Flash Drought

With the definition mentioned above, three characteristics – frequency, intensification rate, and severity of flash drought events – have been investigated for each grid, similar to traditional drought events. To enhance our comprehension of when and where these events occur, we determined the relative frequency of occurrence during 1970 – 2020. The relative frequency is defined as the average number of flash drought events that occurred during the growing seasons (April to October) per year, calculated as follows:

$$RF_g = \frac{N_{FD}}{N_y}, \tag{3.1}$$

where RF_g is the relative frequency in a given grid, N_{FD} is the number of flash drought events in a specific grid during the study period [1979-2020], and N_y is the total number of years during the study period. Here, we also performed a decadal analysis on the occurrence of flash drought events. We formed five classes of ranges: [0-1], [1-2], [2-3], [3-4], [4-5], [5-6], [6-7], and [>8] events per decade. As intensification rate is an important characteristic of flash drought, we used a quantitative method to determine the rate of intensification by calculating the difference between two consecutive soil moisture percentiles (Otkin et al., 2018):

$$RI(t_i) = P_{SM}(t_{i-1}) - P_{SM}(t_i), \tag{3.2}$$

where RI is the rate of intensification at time t_i, and P_{SM} is the soil moisture percentile. The mean intensification rate ($\overline{RI}$) of a drought event during the onset phase n weeks is calculated as

$$\overline{RI} = \frac{1}{n} \sum_{i=t_{start}}^{t_{end}} RI(i), \tag{3.3}$$

where t_{start} is the time of the beginning of the onset of flash drought, and t_{end} is the time of the end of the onset. After calculating $\overline{RI}$, we determine the average rate of intensification for each grid cell

$$\overline{RI}_g = \frac{1}{n_g} \sum_{i=1}^{n_g} \overline{RI}(i), \tag{3.4}$$

where n_g is the total number of flash droughts occurred on the specific grid cell. To determine the flash drought severity (S_D) associated with the flash drought event we choose the average drought severity of n of 8 weeks following the end of the onset phase of flash drought as follows:

$$S_D = \frac{1}{n} \sum_{i=t_{end}}^{t_{Send}} [T_{SM}(i) - P_{SM}(i)], \tag{3.5}$$

where n is 8, t_{end} is the time of the end of the onset, t_{Send} is the end of the considered impact of the flash drought, T_{SM} is the soil moisture percentile threshold set to 20th percentile. If for any week $P_{SM} > T_{SM}$ then the $T_{SM} - P_{SM}$ of that week's is set to zero. Considering drought severity on a limited time scale (8 weeks), allows us to determine immediate rather than long-term effects.

3.2.5 Areal Extent and Flash Drought Centroid

The spatio-temporal analysis is conducted by extracting the area and centroids of flash drought events for each year. Before performing the spatio-temporal analysis, binary values are assigned to the grid cells of the study area to indicate the presence or absence of flash droughts. Specifically, when a grid cell is identified as experiencing a flash drought, its value is set to 1; otherwise, it is set to 0. The marked binary grids are then grouped into drought patches using the Contiguous Drought Area (CDA) analysis (Corzo Perez et al., 2011; Diaz et al., 2020). In the CDA analysis, a two-scan algorithm is employed. In the first scan, each grid cell is connected to its eight neighbors and assigned a preliminary label along with other contiguous grid cells. Subsequently, a second scan is conducted to re-label the connected labels listed in the equivalency table as a unique label. According to Xu et al. (2015), the area of a drought patch should exceed 1.6% of the study area to meet the required spatial extent criterion. Once the flash drought patches are identified, their centroids are calculated at each time step (year).

3.3 Results

In this study, our focus is on identifying and characterizing flash droughts in Central Europe since the 1970s. We utilized weekly averaged upper layer soil moisture (0–10cm) data to estimate flash droughts, consistent with previous studies (Nguyen et al., 2019; Yuan et al., 2019; Shah et al., 2022). Our analysis of flash drought characteristics centers on their frequency, intensification rate, severity, and areal extent during the growing season (April to October).

3.3.1 Frequency Analysis of Flash Drought

Figure 3.3a depicts the spatial distribution of flash drought occurrence across the study area during 1970–2020. The results reveal that flash droughts occurred more frequently over the southeast, northeast, and northwest of the study area. Despite differences in definition, data sources, and research periods, the spatial distribution of flash droughts in Figure 3.3a is quite similar to the results reported by (Shah et al., 2022). The relative change in the occurrence of flash drought is also investigated by dividing the study period into two periods, pre-1999 and post-2000. It is worth noting from Figure 3.3b that there is a significant decreasing trend of occurrence in the northern region. Moreover, it is also indicated that flash droughts occurred more frequently during 2000-2020 in the southern region. The finding of our study about the relative occurrence of flash droughts showing an increasing trend over the southern region is consistent with previous studies conducted across Central Europe such as those by Deng et al. (2022) and Shah et al. (2022).

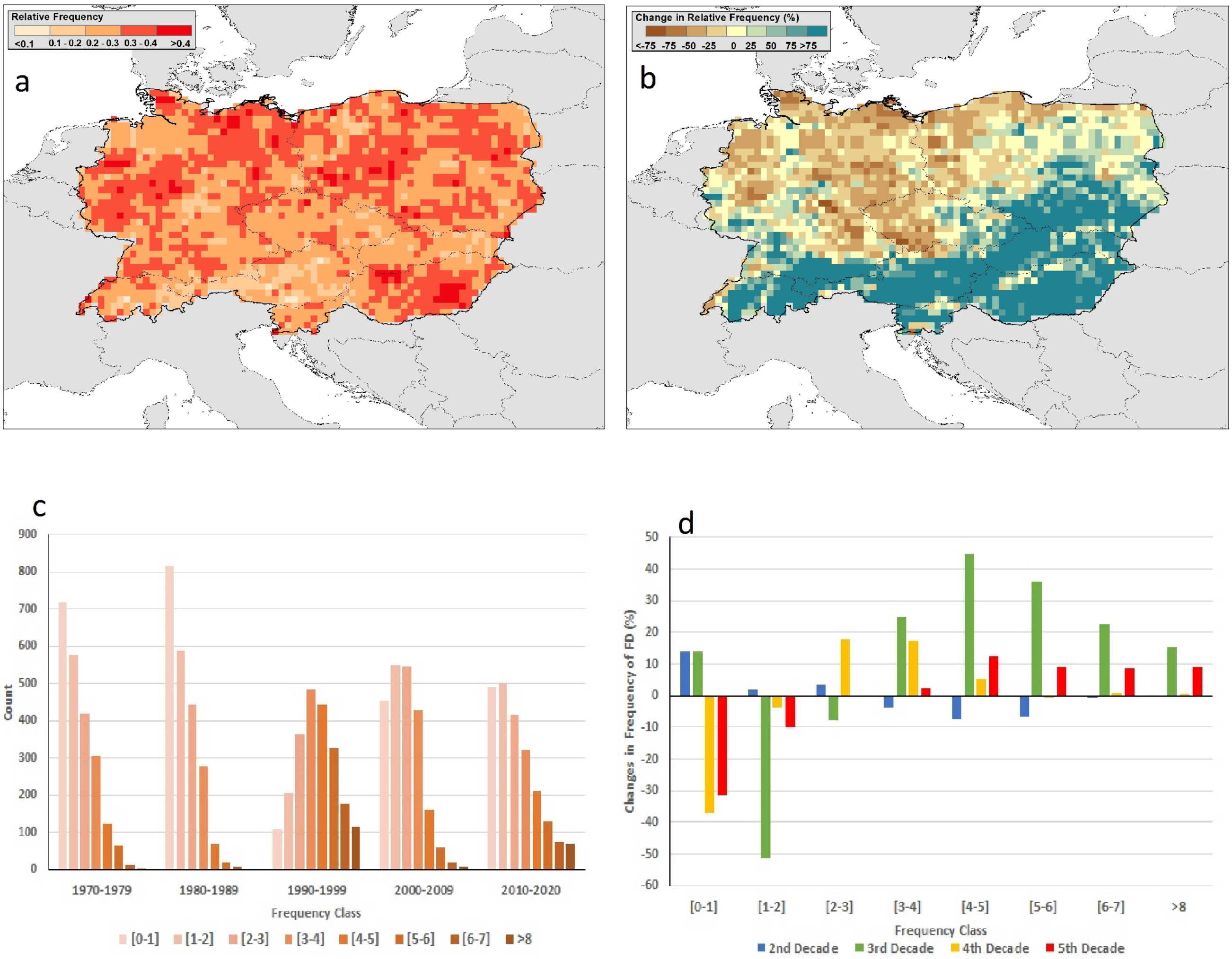

Figure 3.3: Frequency of flash drought events (a) Relative frequency (1970-2020); (b) relative changes in the frequencies of flash drought during the post-2000 relative to pre-1999, i.e., ((post-2000–pre-1999)/ pre-1999))∗100; (c) Spatial decadal flash drought frequency classes; and (d) Decadal changes in the frequencies classes of flash drought.

The decadal analysis in Figure 3.3c depicts that during the period (1970-1989), the frequency classes [1-3] appeared on a wide spatial scale (more than 60% area). From 1990-1999, Central Europe experienced a high frequency of occurrence of flash droughts, with more than 70% of the study area being affected. In the last two decades (2000-2020), the spatial extent of frequency class [>3] events per decade is approximately double that of the first two decades (1970-1989). In Figure 3.3d, the percentage change of extent in the occurrence of flash droughts with respect to the first decade (1970-1979) shows that frequency classes of [0-2] events per decade decreased by 10-15%, whereas the spatial extent of the frequency class of [3-5] events per decade increased by 3 to 15%, and for the frequency class of [>5] events per decade, it increased by 6 to 10%. Overall, the extent of flash drought frequency across Central Europe shows an increasing trend, particularly toward the southern part of Central Europe

3.3.2 Intensification and Severity of Flash Drought

The relationship between the intensification rate and severity of flash drought was studied by dividing Central Europe into four regions: northeast (NECE), northwest (NWCE), southeast (SECE), and southwest (SWCE) (see Figure 3.4a). These regions were chosen based on the differences in climate between the cooler northern areas and the warmer southern parts of Central Europe. The spatial distribution of flash drought intensification rates and severity can be seen in Figure 3.4a-b. In most regions with a high average intensification rate, there were fewer flash droughts and lower average severity. This relationship is prominent across the northwest and southeast of Central Europe. This reflects that flash drought intensification can be very rapid in these locations but does not occur frequently, with less long-term dry conditions after the period of intensification. A similar relationship between intensification and severity of flash droughts was also reported in the US by Otkin et al. (2021). The spatial distribution of average severity (Figure 3.4b) aligns with the occurrence of flash droughts (Figure 3.3a). It is also observed that where the occurrence of flash drought events is high, the severity of the flash drought is also high, such as in SECE.

Figure 3.5 depicts the total intensity and severity of flash drought events for each region. The data points on the plot represent the spatial sum of each grid cell within each region. A significant ($p < 0.05$) correlation between total intensity and total severity has been observed for each region. Overall, the intensity and severity of flash drought are positively correlated in the range of 0.58-0.69. This provides evidence that where flash droughts appear frequently, the severity of flash droughts is positively correlated with the intensification rate. This result also coincides with the findings of Otkin et al. (2014, 2015), who found that locations experiencing high onset of moisture stress may face severe drought. The linear regressions for regions NWCE and SECE are much steeper than in the other regions, which shows that a similar rate of intensification in those regions is more likely to lead to severe drought conditions. It may also indicate that more rapid soil moisture drying leads to a longer time to return to the threshold level (0.2). This may suggest that the physical process, such as land-atmospheric coupling in these regions, may produce more favorable conditions for drought severity to persist.

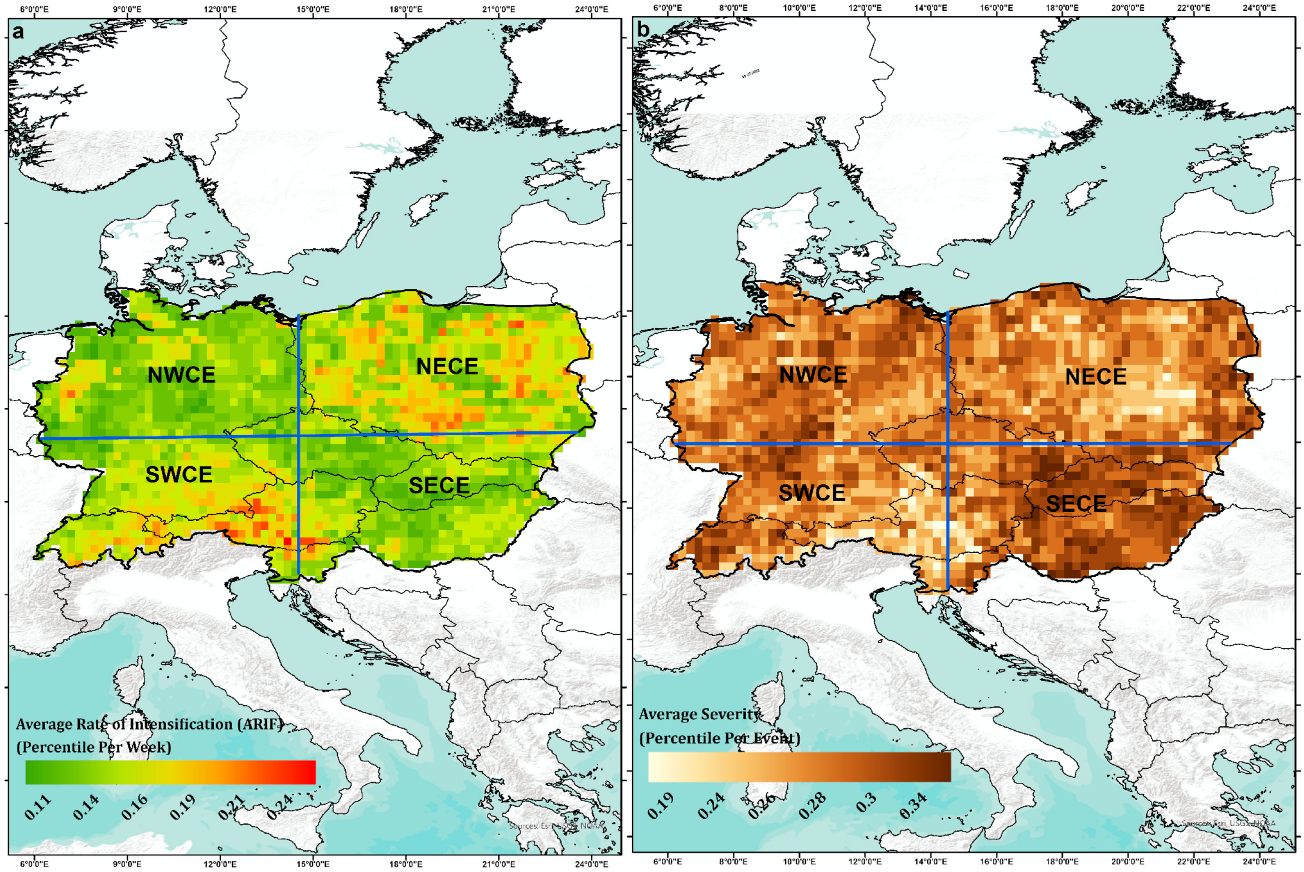

Figure 3.4: (a) Average rate of intensification (ARIF) of flash drought events (percentile/week) ; (b) Average Severity of flash drought events (percentile/event).

Figure 3.6a,b shows the density distribution for the average intensification rate and average severity of flash drought events in each region of Central Europe. A comparison of the distributions reveals large variations in flash drought characteristics (intensity and severity) across Central Europe. For example, the average rate of intensification in NWCE and SECE shows a peak of less than 0.15 (% per week) with higher probabilities (Figure 3.6a). Conversely, NECE and SWCE exhibit flatter distributions with peaks greater than 0.15 (% per week) and lower probabilities. Moreover, the density distribution of average severity (Figure 3.6b) shows an opposite pattern to the intensification rate. NWCE and SECE exhibit high severity with lower probabilities compared to the NECE region. Finally, the distributions for each variable in each region imply that their location within the climate transition zone results in a mix of severity and intensity characteristics.

3.3.3 Areal Extend and Centroid Analysis of Flash Drought

The annual spatial extent of flash drought along with the areal average rate of intensification (AARIF) were computed for the period of 1970-2020. The inter-annual average areal extent and intensification rate (% per week) of flash drought were 28% and 0.14 (% per week), respectively,

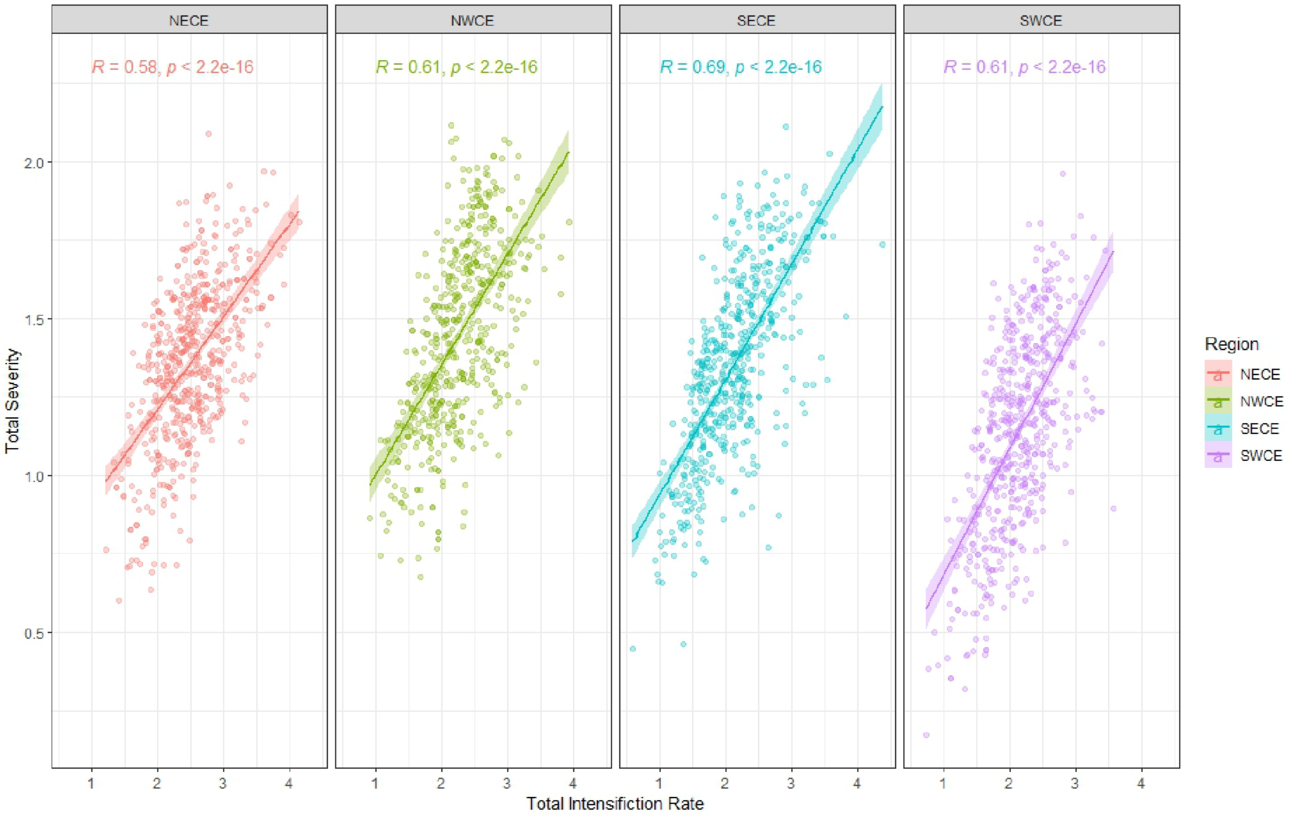

Figure 3.5: Relationship between the intensification rate and severity of flash droughts at regional scale.

in central Europe. Moreover, during 1990-1999, Central Europe experienced the maximum areal extent (>50%) (Figure 3.7a). AARIF increased significantly after 1990 (Figure 3.7b). In contrast, comparison of two periods (1970-1999, 2000-2020) shows that the inter-annual AARIF increased from 0.13 to 0.15 (% per week).

Figure 3.7 c represents the space and time distribution of flash drought centroids on a decadal basis. It is observed that during 1970-1979 most of the centroids were located across the northeast of Central Europe. While during 1980-1989 the centroids were observed across the northwest with a inter-annual average areal extent of 19%. Centroids calculated for the period of 1991-1999 were situated across the northwest. In 2000-2009, most of the centroids of flash drought were found in the eastern region of Central Europe. Whereas, during the last decade (2010-2020) the flash drought centroids were found in the southern part of Central Europe. Therefore, the centroid of flash drought events shifted from the northern to the southern region part of Central Europe from the begging to the end of the study period. Overall, the areal extent and AARIF of flash drought have increased since 1970. The fact that a larger extent of Central Europe is repeatedly exposed to the threat of flash drought may be associated with increased risk on agricultural production.

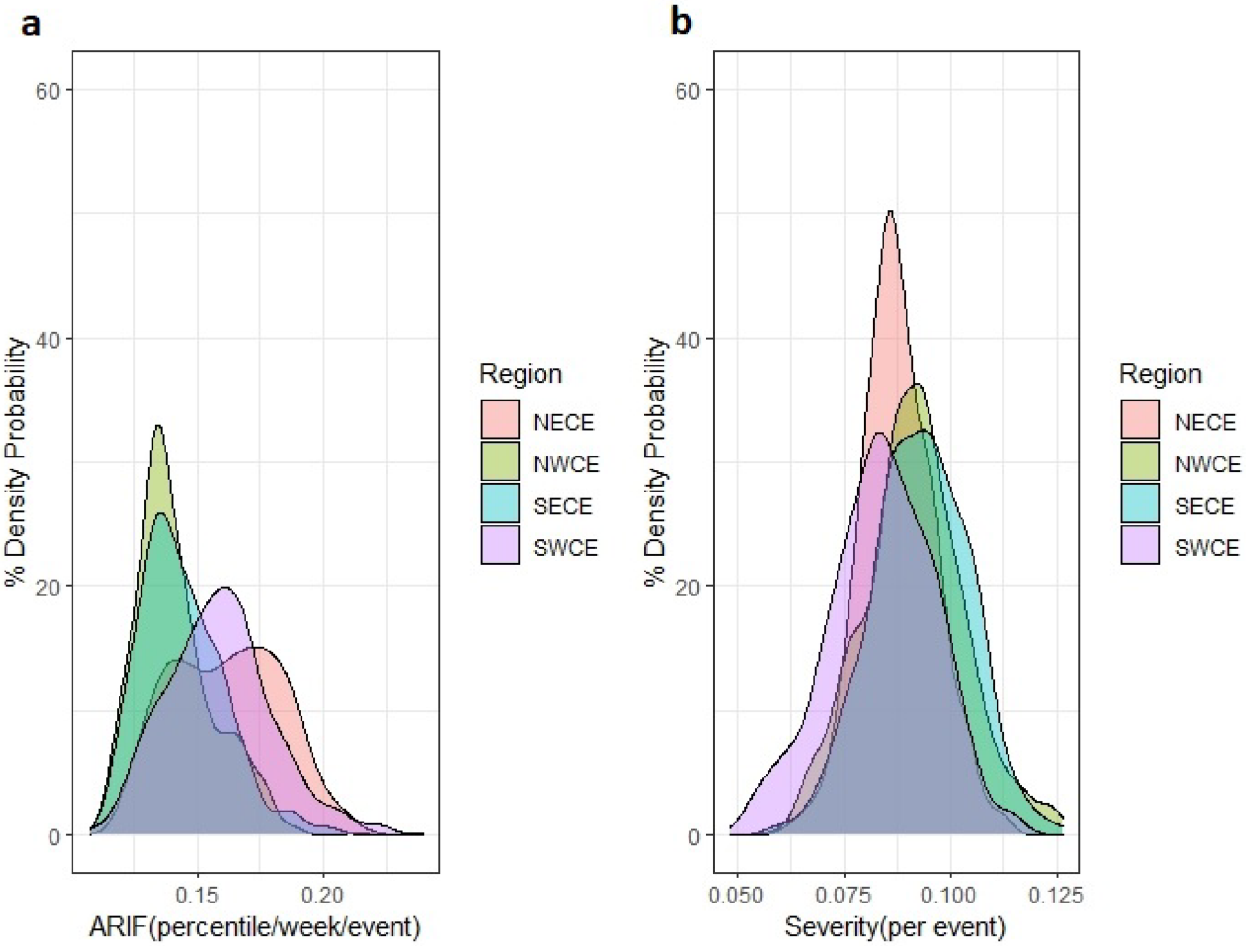

Figure 3.6: Regional average intensification rate and severity.

3.4 Discussion

An important feature of flash drought that distinguishes it from more traditional slowly developing droughts is the "flash" component of rapid intensity (Otkin et al., 2018). It is usually caused by extreme climate conditions and severe soil moisture deficits (Mo, 2015,0). Based on previous studies (Ford and Labosier, 2017; Liu et al., 2020a), we extended the definition of flash drought in this study by considering the onset intensification rate and dry persistence (severity) over the study area. We also investigated the spatial and temporal characteristics of flash drought in Central Europe.

The methodology for flash drought identification adopted here can be applied in other regions worldwide. The procedure for identifying the spatio-temporal variation of flash droughts is clear and straightforward, making it practical for reproduction. This study's method covers both the development and persistence of flash droughts. However, there is currently limited discussion on determining the threshold for the rapid intensification rate of flash droughts. In this research, most threshold values (such as 3 weeks, 40%, and 20%) are based on the soil properties of the

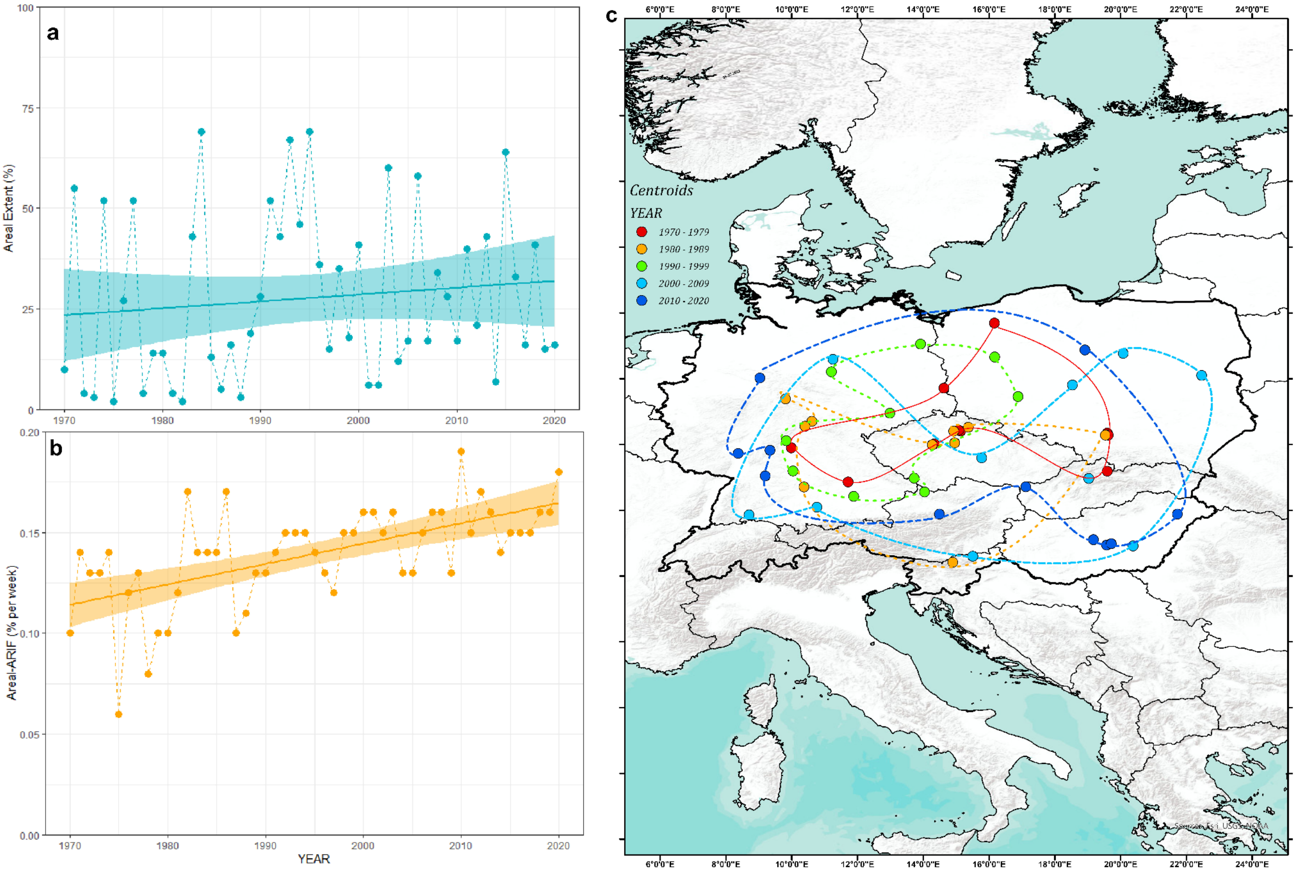

Figure 3.7: Temporal analysis of flash drought; (a) Areal Extent;(b) Average Areal Rate of Intensification (AARIF); (c) Decadal tracks of largest flash drought patch centroid

study area and empirical values derived from previous studies. It's essential to note that these threshold values can be adjusted based on the soil characteristics of different regions. Addressing this gap offers a path for further research into different methods for calculating threshold values for various regions and understanding their sensitivity in flash drought identification. Moreover, the current percentile-based methodology has limitations. For datasets with shorter time spans, applying this approach can be challenging as short time series may not provide enough data to establish a robust distribution According to the findings of Liu et al. (2020a), datasets with shorter records tend to yield higher frequency values for flash droughts compared to those calculated from longer time series. Notably, this methodology is likely to overestimate the number of flash droughts for datasets with shorter lengths (less than 30 years).

The frequency analysis of flash droughts revealed that the occurrence of flash drought events per year during the growing season increased with the intensification rate. There was a positive relative change in the frequency of flash drought occurrence in the southern part of Central Europe. This study's frequency analysis of flash droughts was consistent with the findings of Shah et al. (2022) , indicating increasing trends, especially during the last two decades of the study period across Central Europe. In this study, we observed a linear relationship between the total intensification rate and the total severity of flash droughts. However, weak relations were found across the western part of Central Europe. Overall, a higher intensification rate can trigger more severe impacts of flash droughts. An increase in the spatial extent of flash droughts has been observed since 1970, with the centroid of flash droughts shifting towards the southern part of Central Europe. Time series analysis of the extent and areal average intensification of flash droughts revealed that higher intensification rates of onset flash droughts are responsible for the wider extent. Overall, there has been a significant increase in the occurrence of flash droughts across Central Europe, especially in the last two decades (2000-2020). This increase may be attributed to the variability of extreme climate conditions, characterized by warm and dry conditions (Shah et al., 2022).

The characteristics of flash droughts can also be influenced by extreme climatic conditions. For instance, the co-occurrence of precipitation deficit along with high-temperature anomaly is responsible for the occurrence of flash droughts and controls their characteristics (Otkin et al., 2019). Recently Shah et al. (2022), found that flash droughts across Central Europe were caused by precipitation deficits under a warming climate, indicating a compound event. Therefore, dry-hot winds, also known as heat stress, could increase the intensification rate, leading to the development of flash droughts. Moreover, the severity of flash droughts was found to have a positive linear relationship with the intensification rate. However, not every rapid intensification leads to long-term drought conditions. This variability may be caused by diverse climate conditions, such as precipitation after the onset phase. For instance, Christian et al. (2019a)reported that over 50% of flash droughts did not transition to long-term droughts in the United States. Another finding of our study regarding the increased occurrence of flash droughts per year is closely linked to the findings of Shah et al. (2022), despite the use of different datasets (ERA-5, GLEAM) of soil moisture.

The development and intensification of flash droughts are significantly influenced by anomalies in both atmospheric and oceanic conditions. Atmospheric conditions and circulation patterns have been identified as contributors to drought occurrence in Europe (Sfîcă et al., 2021; Lhotka et al., 2020). The North Atlantic Oscillation (NAO) is recognized as a dominant mode of climate variability in Europe, impacting temperature and precipitation trends over recent decades (Kučerová et al., 2017). The association of heatwaves and precipitation deficits in central Europe with anthropogenic warming has allowed quasi-stationary high-pressure systems to persist, leading to drought conditions for prolonged periods (Huguenin et al., 2020). These multi-scale processes may also impact sub-seasonal climate variability, serving as triggers for flash droughts. The characteristics of flash droughts are impacted by these alterations, including changes in circulation patterns, given the connection between heatwaves and soil moisture conditions. Atmospheric dryness significantly reduces the probability of convective precipitation leading up to the initiation of flash droughts (Gerken et al., 2018; Basara et al., 2019). The role of circulation drivers in flash droughts in Central Europe was recently explored by Řehoř et al. (2023), who found that flash drought episodes were initiated when anticyclonic patterns prevailed and cyclonic patterns were absent, accompanied by higher temperatures and the presence of warm airflow. The changes in land-atmosphere coupling characteristics within flash drought hotspots and their subsequent impact on the onset of flash droughts are significant concerns for further study.

Overall, our study focused on soil moisture flash droughts in Central Europe, which are more apparent in their identification and spatiotemporal characteristics. As flash drought is characterized by the rapid depletion of soil moisture, the selection of soil moisture depth may affect the frequency of occurrence along with climatic variability. The characteristics of flash droughts based on the top layer (0-10 cm) surface soil moisture can differ from those based on the typical root zone soil moisture. Surface soil moisture in the top layer is strongly correlated with meteorological variability and fluctuates rapidly due to the strong coupling process of surface temperature and precipitation. Land cover or vegetation may also influence the characteristics of flash droughts (Christian et al., 2019a). Specifically, forested regions with deeper root zones may limit the rapid intensification of flash droughts (Christian et al., 2019a). As an extension of this study, future research should examine an appropriate absolute minimum value for the flash drought threshold and investigate the impact of land cover on flash drought characteristics.

3.4.1 Conclusions

The key findings of this study across Central Europe during the growing seasons are:

- Flash droughts occur most frequently in the northeastern and western parts of Central Europe. The frequency of flash droughts has substantially increased in the recent period (2000–2020) compared to their occurrence in the earlier period (1979–1999).

- On the decadal scale, the frequency of events with more than four occurrences per decade on average increased by 10% with respect to the first decade (1979-1989). During the period of 1990-1999 (3rd decade), the highest number of flash drought events was observed in the whole of Central Europe.

- The intensification rate of flash drought has been observed in the range of 0.1-0.23 percentile per week. The northeast region has experienced a high-intensity flash drought during the development phase.

- Severity analysis of flash drought revealed that the intensification rate and severity of flash drought are in a positive linear relation. But in some parts of the study area, the relationship between them was found to be negative. This may be due to climatic conditions after the onset phase.
- The annual areal extent of flash drought has also been increasing trend with the intensification rate. The average annual areal extent is 28% of the study area. The Contiguous Drought Area (CDA) analysis also revealed that the centroid of the flash drought is expanding across Central Europe.

Overall, our analysis suggests that the proposed methodology of flash drought identification can be applied in other regions with different climate zones. However, it is also notable that previous studies have not addressed how to estimate the flash drought's threshold for rapid intensification. The thresholds (20% and 40%) suggested in our study are empirical and may vary based on the spatiotemporal structures of the flash drought in various regions. Therefore, additional research should be carried out to examine the sensitivity of these criteria to flash drought identification using as many observations as practical from various locations throughout the world.

Chapter 4

Response of Ecosystem To Flash Droughts

4.1 Introduction

In the past, it has been reported that when a flash drought is combined with a heatwave, ecosystems suffer damages, and plant mortality increases (Hoell et al., 2020). For instance, in 2010, a flash drought in Russia, along with a heatwave, led to significant damage to wheat production, accompanied by wildfires and plant deaths (Barriopedro et al., 2011; Miralles et al., 2014). The flash drought event of 2012 across the Great Plains in the USA resulted in agricultural losses amounting to $30 billion (Basara et al., 2019). Another flash drought event in 2017 in the High Plains of the USA notably impacted wheat yields (Gerken et al., 2018). (He et al., 2019) reported that the flash drought event of 2017 in the US reduced crop production by 25% across the region from April to September, a figure relatively higher than the satellite record from 2008 to 2017. Similarly, during the summer of 2013, a severe flash drought affected the southern provinces of Guizhou and Hunan in China, impacting crop growth in over two million hectares. (Yuan et al., 2017b) also reported that the extraordinary flash drought of 1936 in the United States had a significant effect on human casualties and crop yields. Additionally, in December 2015 to January 2016, a severe heatwave with soil moisture deficit hit southern Africa, impacting plant growth (Yuan et al., 2018).

The discussion above regarding the impacts of a flash drought on ecosystems underscores the importance of timely monitoring of ecosystems on a large spatial scale (AghaKouchak et al., 2023). Integrating remote sensing measurements with environmental parameters can lead to strategies for estimating and monitoring ecosystem health. Therefore, remote sensing measurements can provide real-time and dynamic information for terrestrial ecosystems (Zhang et al., 2016b). The satellite-based Global Primary Productivity (GPP) of ecosystems is an important indicator for investigating the land-atmosphere carbon cycle, influencing the amount of carbon sequestration that can occur in different ecosystems (Li et al., 2021). As an extreme climatic event, flash droughts can significantly influence vegetation GPP and thus affect the land carbon cycle. Zhang (2020), elaborated on a large-scale flash drought that reduced 0.55 petagrams of terrestrial carbon during 2000–2009 in China. In 2009/2010, a flash drought in southwest China had serious adverse effects on vegetation dynamics and productivity (Li et al., 2019). While some studies from previous periods have contributed to understanding the impact of ordinary droughts on vegetation, few have addressed the impact of flash droughts on vegetation dynamics. Zhang et al. (2016a) discovered that savannas were relatively more sensitive and GPP was also much higher when it rained. Poonia et al. (2022) also demonstrated that GPP during flash droughts decreased by over 95%. Thus, flash droughts have a strongly negative influence on vegetated ecosystems. In the United States, crop yields fell by 26%, and losses of around $12 billion were noted in the central United States during a flash drought event in 2012 (Hoerling et al., 2014). The alpine ecosystems of arid and semi-arid northwest China were considered very sensitive to climate change and water deficit (Zhang et al., 2020).

The severity of flash droughts makes it challenging to mitigate their effects, exerting hazardous impacts on plant growth within a short period. The widespread agricultural damages observed globally serve as evidence of the devastating effects of flash droughts. Consequently, the balance of food supply and demand is severely affected by flash droughts at both regional and global levels. While numerous studies have reported a strong correlation between the severity of flash droughts and the health of agricultural ecosystems, none have specified how quickly agricultural ecosystems respond to flash droughts. In the past two decades, the literature on flash droughts has primarily focused on identification, challenges, and damages. However, a comprehensive examination of flash drought literature underscores the importance of understanding the response time of agricultural ecosystems. Therefore, knowing the resistance of agricultural ecosystems in terms of response time can play a vital role in preventing the damage caused by flash droughts.

The aim of this Section is to elucidate the response of ecosystems to flash drought events. Specifically, we investigated the response time of different types of land cover (crop, grass, forest) to flash droughts and explored the relationship between their response time and the intensification rate of flash drought events. The main objective of the study is to emphasize the response time of ecosystems to flash droughts. To achieve this objective, we have broken down the main objective into three sub-objectives. First, we identified flash drought events across different depths of soil moisture. Second, we examined the response of ecosystems to flash drought events across various depths. Third, we explored the relationship between response time and intensification rate of flash droughts with respect to elevation.

4.2 Study Area – Central Europe

The climatology of central Europe is characterized by a humid climate influenced by various geographical features and atmospheric patterns. Central Europe generally includes countries such as Germany, Austria, Switzerland, Czech Republic, Slovakia, Poland, Hungary, and parts of surrounding nations, where weather conditions differ markedly among its various regions. Central Europe experiences moderate temperatures throughout the year, with distinct seasons. Winters are generally cold, while summers are mild to warm. However, there can be significant variations depending on elevation, proximity to bodies of water, and geographical location. Precipitation in central Europe varies widely from west to east and from north to south. Western regions tend to receive more rainfall throughout the year due to the influence of Atlantic weather systems, while eastern regions experience drier conditions, particularly in areas sheltered by mountain ranges.

The elevation of central Europe varies from zero to 3500 meters above sea level (msl) (Figure 4.1 left top). The southwest part of the study area is a high-elevated region covered by forest land (Deciduous Broadleaf, Evergreen Needleleaf, and mixed forest) and grassland (Figure 4.1 left bottom). The study area is covered by 30% forest, 49% cropland, 17% grassland, while 4% is covered by other types of land cover. The average root zone soil moisture (SM) is observed to be high across the southern part of central Europe, and the average gross primary production (GPP) varies up to 800 (kg*C/m^2) (Figure 4.1).

4.3 Data & methods

4.3.1 Data

Although observation stations monitoring soil moisture across central Europe have been limited, reanalysis products such as GLDAS versions 2.1 and 2.0 have become a common choice owing to their high spatial resolution and extended temporal coverage. Here, we analyzed soil moisture data sets of GLDAS (2.1 & 2.0) in three layers (0-10 cm, 10-40 cm, and 0-100 cm). The 8-day averaged soil moisture data from 1979 to 2020 were used to identify flash droughts, while the period from 2000 to 2020, at a spatial resolution of 0.25 degrees, was considered to study ecosystem responses. To investigate the response of ecosystems to flash droughts, we used 8-day averaged Gross Primary Production (GPP) data (MOD17A2H) at a spatial resolution of 500 meters provided by the Terra MODIS sensor to assess ecosystem conditions across central Europe. All gridded GPP data were resampled through linear interpolation to a spatial resolution of 0.25 degrees.

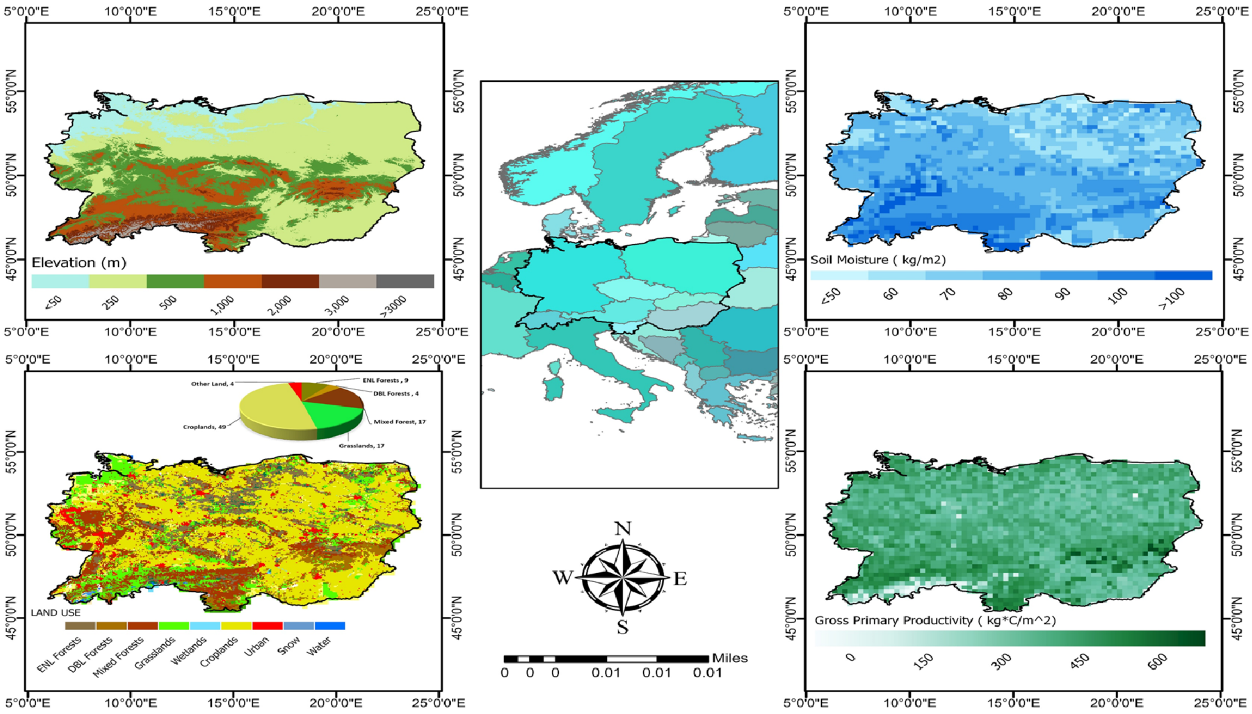

Figure 4.1: Top Left panel: Digital Elevation Model of Central Europe; Top Right panel: Average Root Zone Soil Moisture; Bottom Left panel: Land Cover classification; Bottom Right panel: Average Resample Modis Gross Primary Production (GPP).

4.3.2 Response time of Ecosystem to Soil Moisture flash Drought

Drought significantly impacts the productivity of ecosystems by altering plant photosynthesis and ecosystem respiration (Bee et al., 2007; Greenacre, 2006; Reichstein et al., 2007; Stocker et al., 2013). Gross Primary Production (GPP) determines the world's terrestrial carbon sink, and it is reduced by stomatal closure and various non-stomatal limitations, such as reduced carboxylation rate and active leaf area index due to water stress (De Faria et al., 2020). To the best of our knowledge, few studies have investigated the response time of ecosystems based on GPP to flash drought. However, many studies have identified normal drought recovery using GPP. Here, the response time of the ecosystem is defined as the lag time between the flash drought event in soil moisture and the first occurrence of a negative standardized GPP anomaly (SGPP) (Figure 4.2).

$$SGPP = \frac{X_{\text{GPP}} - \mu_{\text{GPP}}}{\sigma_{\text{GPP}}}, \tag{4.1}$$

Where μ_{GPP} and σ_{GPP} represent the mean and standard deviation, respectively, of the time series of GPP at the same dates as the target, which are 8 days for all years. For example, all 1-8 May periods during 2000-2020 would have one set of μ_{GPP} and σ_{GPP}, while 9-16 May would have another set, and so on. If the negative value of the SGPP occurred within 8 days of its mean, the ecosystem is considered unaffected by the specific flash drought event. Therefore, in this study,

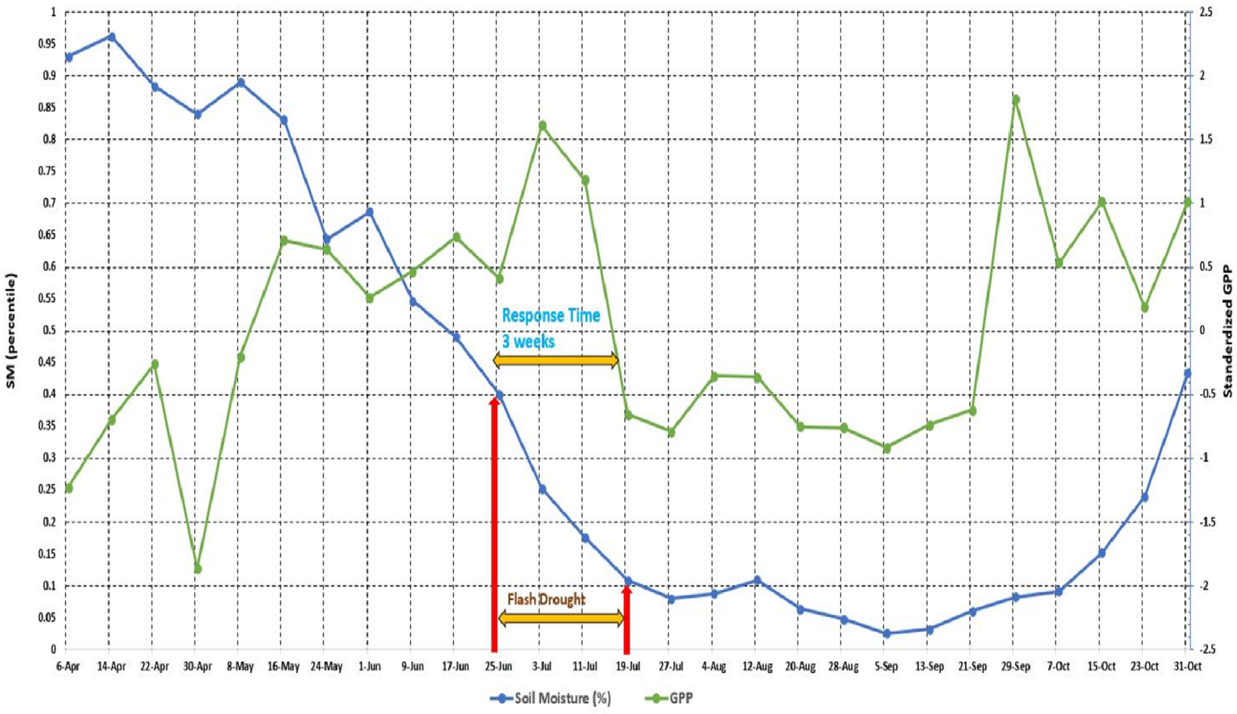

Figure 4.2: Estimation of Response Time of Ecosystem to Soil Moisture Flash Drought.

we also investigated the percentage of flash drought events responsible for impacting ecosystems.

4.4 Results

4.4.1 Frequency of Flash Drought Across the Different Layers of Soil Moisture

Figure 4.3(a-c), illustrates the frequency of flash drought occurrences spanning the past two decades, from 2000 to 2020. It becomes apparent that the southern region, encompassing areas such as the Alps (Austria and Switzerland), has been particularly susceptible to numerous flash drought events across all soil moisture depths. Notably, this region consistently experienced high incidences of flash droughts across each layer of soil moisture over the last two decades. Additionally, the southeast region, including countries like Hungary and Slovakia, witnessed a notable concentration of flash droughts, especially in the top layer of soil moisture. Overall, Figure 4.3(a-c) suggests a pronounced occurrence of flash droughts in the high altitude regions of central Europe.

Interestingly, fewer instances of flash droughts were observed in the top layer (0-10 cm) and root zone (0-100 cm) soil moisture compared to the mid layer (10-40 cm). This discrepancy can be attributed to variations in the development and persistence of drought conditions across different soil profiles. In the top layer, moisture depletion intensifies rapidly during onset but fails to sustain sub-threshold levels afterward. Conversely, the root zone moisture exhibits longer-term persistence below thresholds after onset, contrasting with the top layer's swift initial drawdown. Both rapid depletion and post-onset persistence below thresholds are more readily observed in the mid layer (10-40 cm).

Furthermore, the density plots (Figure 4.3 (d-f)) correlating flash drought occurrences with land use types (crops, grass, forest) reveal intriguing trends. Crop land experienced a median of five flash drought events for both the top and root zone layers and eight events for the mid layer soil moisture, as depicted in Figure 4.3(d). Similarly, grass and forest land demonstrated a higher incidence of flash drought events in the mid layer compared to other layers. These findings underscore the influence of land use practices and vegetation cover on flash drought vulnerability and emphasize the importance of considering soil moisture dynamics in drought risk assessments and management strategies.

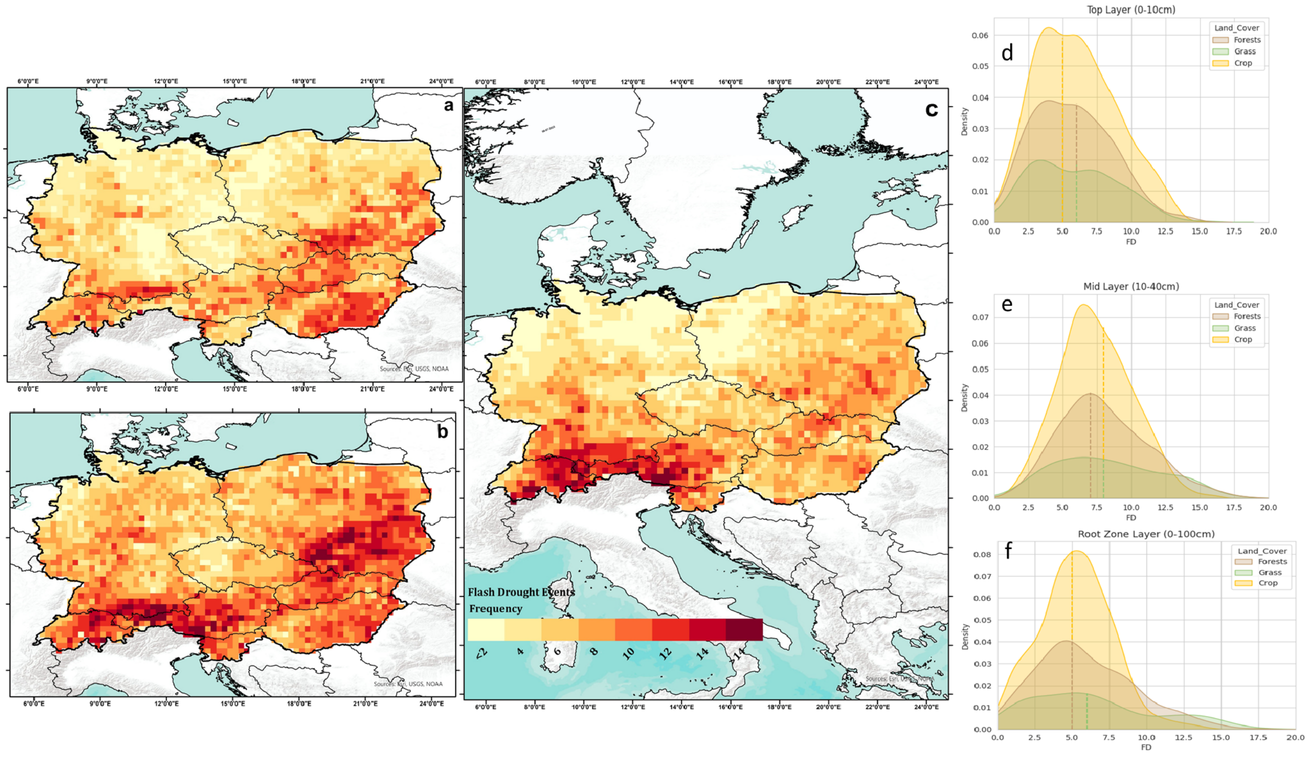

Figure 4.3: Frequency of flash drought occurrence across the different layers of soil moisture; a) Top Layer SM (0-10cm) b) Layer SM (10-40 cm), c) Root Zone (0-100 cm). Right side: Density Plot of flash drought frequency for different ecosystem types; d) Top Layer (0-10 cm), e) Mid Layer (10-40 cm), and f) Root Zone (0-100 cm)

4.4.2 Response of Ecosystem to Flash Droughts

Since the inception of the flash drought concept, there has been considerable debate in the research community concerning the layer of soil moisture at which ecosystems respond. The percentage response of ecosystems to flash drought events is shown in Figure 4.4 (a-f). For instance, if a grid cell experiences six events and only three results in GPP values falling under the threshold, it means that only 50% of the events in that grid cell was affected by flash droughts. The lowest response of ecosystem to flash droughts is particularly evident in the top layer of soil moisture, accounting for approximately 24% in central Europe. On the other hand, in the mid-layer and root zone, the identified flash droughts show a significant response from the ecosystems based on the GPP values.

Concerning the spatial scale ,it is clear (Figure 4.4 (a-c)) that the ecosystems' response to the flash droughts across central Europe is more pronounced in the northeast region (Poland) than the southeast region (Hungary). Overall, the ecosystem response across the top layer soil moisture shows that the response is below 30% . Therefore, to studying the impacts of flash drought events on the ecosystem through the use of top soil moisture is irrelevant. Moreover, the researcher should use the mid-layer soil moisture or the root zone in their studying.

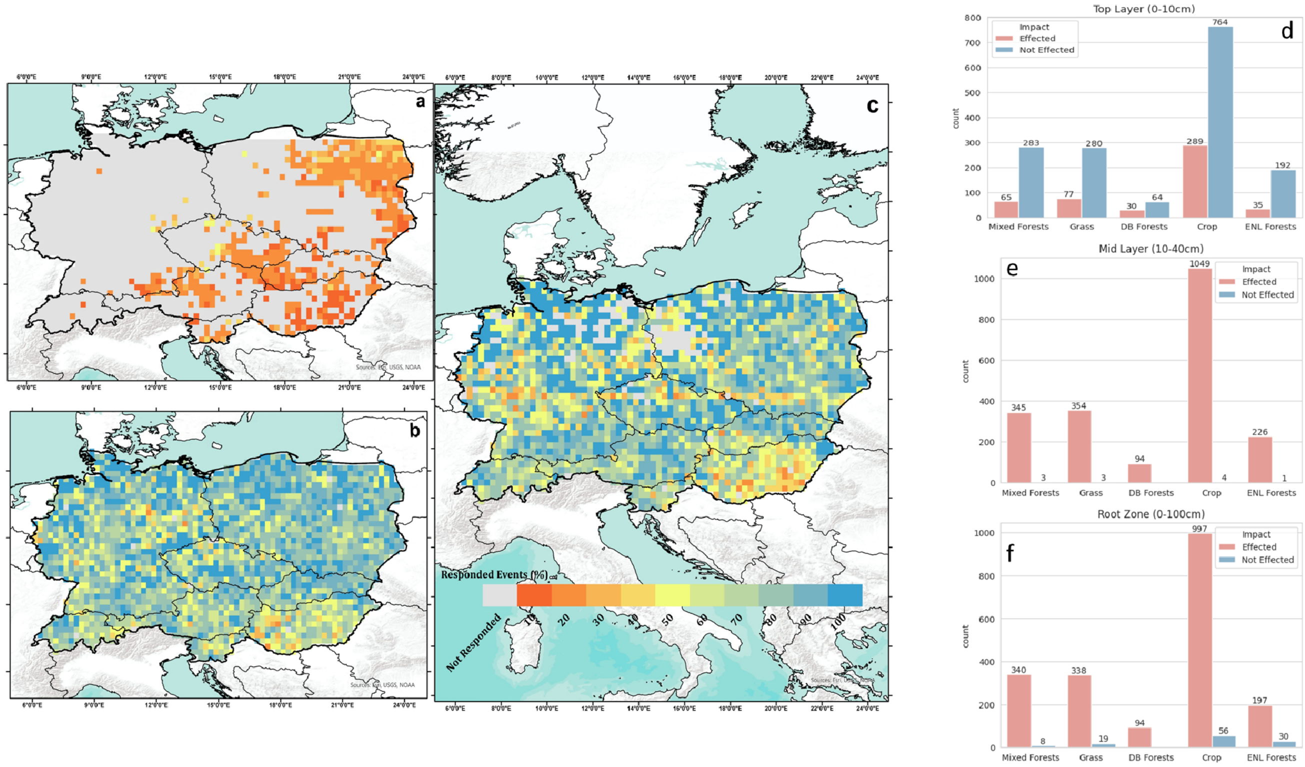

Figure 4.4: Response of Ecosystem to Flash Drought across the different depth of soil moisture. a) Top Layer SM (0-10 cm), b) Layer SM (10-40 cm), c) Root Zone (0-100 cm); Right side, Number of grids of different ecosystem effected by flash drought; d) Top Layer (0-10 cm), e) Mid Layer (10-40 cm), and f) Root zone (0-100 cm)

4.4.3 Intensification Rate of Responded Flash Drought Events

The intensification rate of flash drought events across different depths of soil moisture plays a crucial role in shaping ecosystem responses and vulnerabilities. The average intensification rate of flash drought events, to which the ecosystem responded, is depicted in Figure 4.5. It is evident that high intensification rates (up to the 25th percentile per week) are observed for flash drought events identified in the top layer. This suggests that the ecosystem only responds significantly to those flash drought events in the top layer characterized by high intensification rates. Additionally, for the mid and root zone layers, the ecosystem responds to an intensification rate of approximately the 15th percentile per week. As indicated in Figure 4.4, the ecosystem exhibits a strong response to flash drought events identified through mid-layer and root zone soil moisture. Consequently, it is plausible that the ecosystem in central Europe may be affected by flash drought events with intensification rates ranging from the 15th to the 20th percentile per week. Moreover, it also observed that the intensification rate is much higher to the southern Alps regions of high elevation. For mountainous areas where elevation varies, the percentile of soil moisture will vary with slope aspect, the slope angle as well as solar exposure. The southern facing parts have reduced soil moisture percentile because of higher rates of evaporation as well as high exposure to solar radiation. In addition, the southern facing parts are also associated with high temperature that could increase the rate of evaporation. More importantly, the evaporation rates increase with temperature and the southern slopes will have lower levels of soil moisture percentiles if it is experienced during flash drought.

4.4.4 Average Response Time of Ecosystem to Flash Droughts

The response time of various ecosystems to flash droughts can vary significantly, influenced by factors such as soil type, vegetation cover, land management practices, and climatic conditions. Figure 4.6 a, depicts the spatial extent of ecosystem response time to flash droughts, revealing that the response time of ecosystems to identified flash droughts through the top layer of soil moisture is higher (> 40 days) across the eastern (Poland) and central (south of Czech Republic) regions of the study area. Conversely, a shorter response time (<16 days) of ecosystems is observed in the rest of the affected ecosystem of central Europe. Additionally, Figure 4.6 b, illustrates a higher response time (>30 days) of ecosystems for the Alps region (Switzerland and Austria), indicating that the ecosystem of the Alps region exhibits high resistance to flash droughts despite higher intensification rates. A similar response time is shown by the ecosystem of the Alps across the root zone layer (Figure 4.6 c). Overall, the spatial variation in the response time of ecosystems

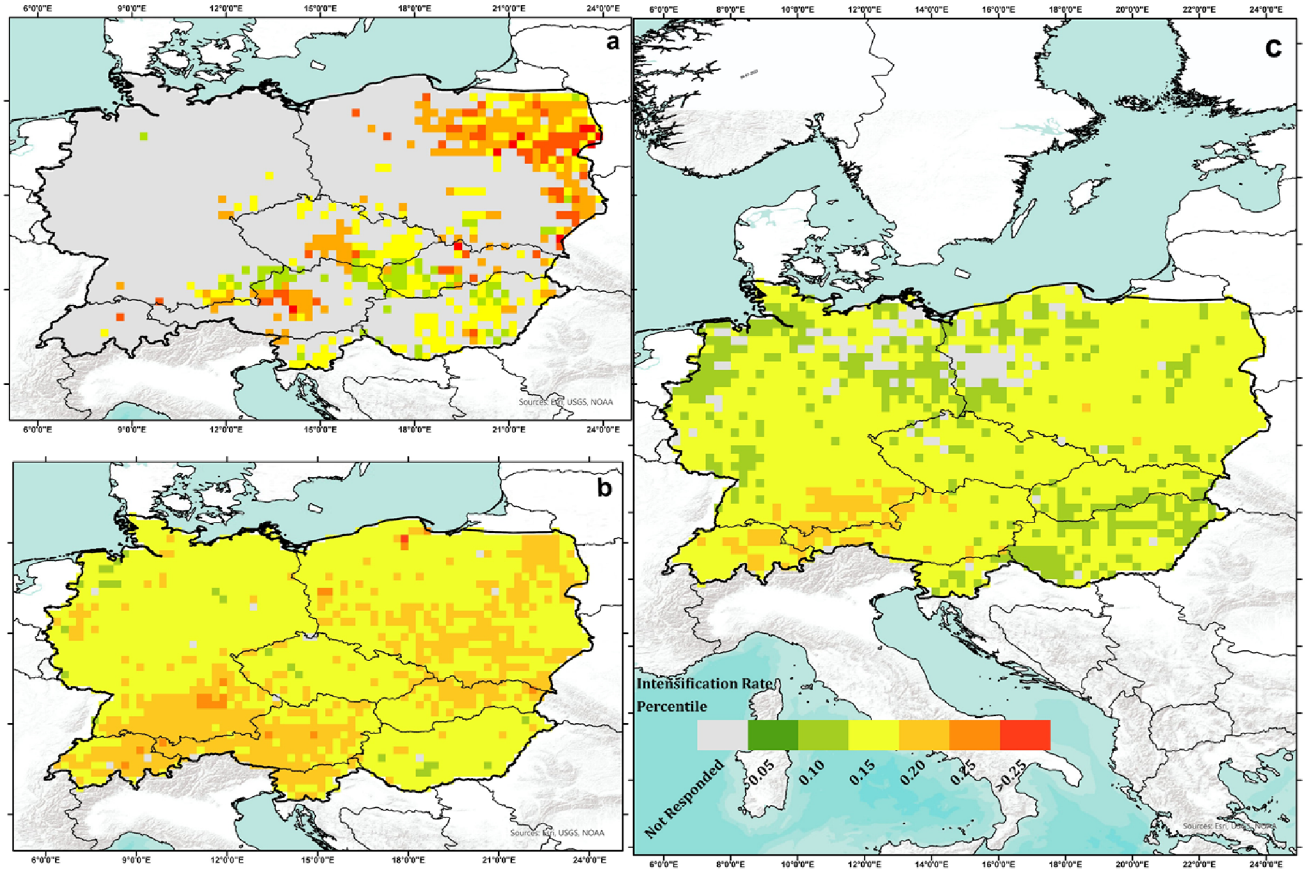

Figure 4.5: Intensification rate of Flash Drought events responded by the ecosystem across the different layers of Soil moisture; a) Top Layer SM (0-10cm), b) Layer SM (10-40 cm), c) Root Zone (0-100 cm).

across central Europe is not clearly distributed across each layer of soil moisture.

Therefore, to comprehend the average response time of each ecosystem (crop, grass, forest), a density curve of each land use class is plotted across every layer of soil moisture (Figure 4.5, d-f). which depicts, in the top layer, the average response time of all ecosystem types (crop, grass, and forest) to flash drought events is approximately 22 to 25 days. Conversely, for the mid and root zone layers, the average response time of ecosystems increases to around 30 days across the all kind of ecosystems. The changes in top layer soil moisture can swiftly impact surface vegetation and influence surface runoff and evapotranspiration rates. However, its shallow depth renders it more susceptible to rapid fluctuations, making it less reliable for sustaining vegetation during prolonged dry spells. In contrast, the mid-layer soil moisture, extending from 10 to 40 centimeters, acts as a buffer against short-term fluctuations, providing a more stable water supply to plants during moderate drought conditions. Deeper still, the root zone soil moisture, spanning from 0 to 100 centimeters or more, serves as a reservoir for plant roots to access water during extended periods of drought stress. These findings suggest that ecosystems respond more rapidly to flash droughts identified in the top layer of soil moisture compared to those in deeper layers.

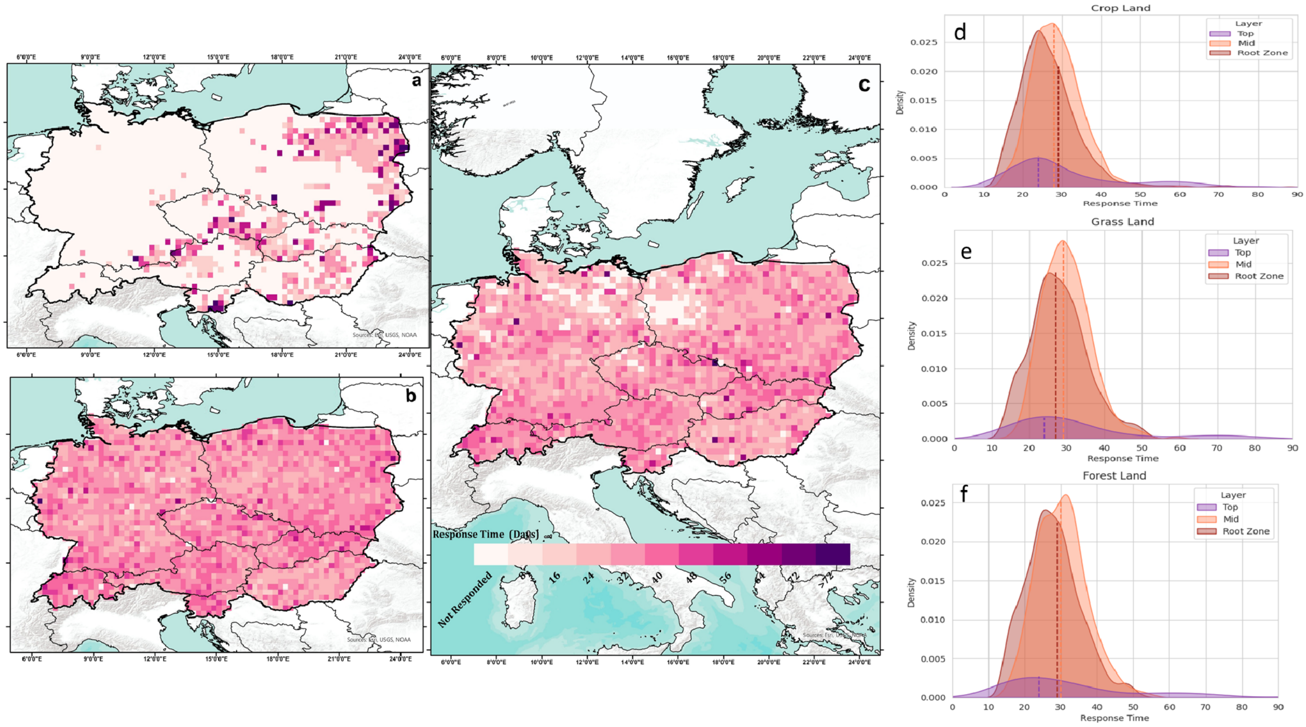

Figure 4.6: Average Response Time of ecosystem to flash drought events across the different layers of Soil moisture; a) Top Layer SM (0-10 cm), b)Layer SM (10-40 cm), c) Root zone (0-100 cm) Right side, Response time of ecosystem across the different depth of soil moisture; d) Crop land, e) Grass land, and f) Forest land

Flash droughts have significant impacts on forest ecosystems, depending on various factors such as the severity and duration of the drought, the tree species, soil conditions, and geographical location. To delve deeper into the response time of different forest types a density curve is plotted for each type of forest land Figure 4.7. The results reveal that the average response time of Evergreen Needle Leaf (ENL) forests is slightly shorter (26days) than that of Deciduous Broadleaf (DB) and Mixed Forest covers (30 days). Usually, deciduous forests (DB) and mixed forest can often tolerate short-term water stress by shedding leaves to conserve water and reducing metabolic activity. However, prolonged or severe flash droughts can lead to increased mortality rates among weaker or more susceptible tree species within these forests.

4.4.5 Relation between Intensification Rate and Response time of Ecosystem with respect to Elevation

The response time of ecosystems to flash drought varies significantly depending on the intensity of the flash drought and the elevation of the ecosystem. To address this, additional analyses were conducted to explore the relationship between the intensification rate of flash droughts and the response time of ecosystems relative to elevation. Figure 4.8 indicates that there is no significant correlation exists between the intensification rate of flash drought events and the response time

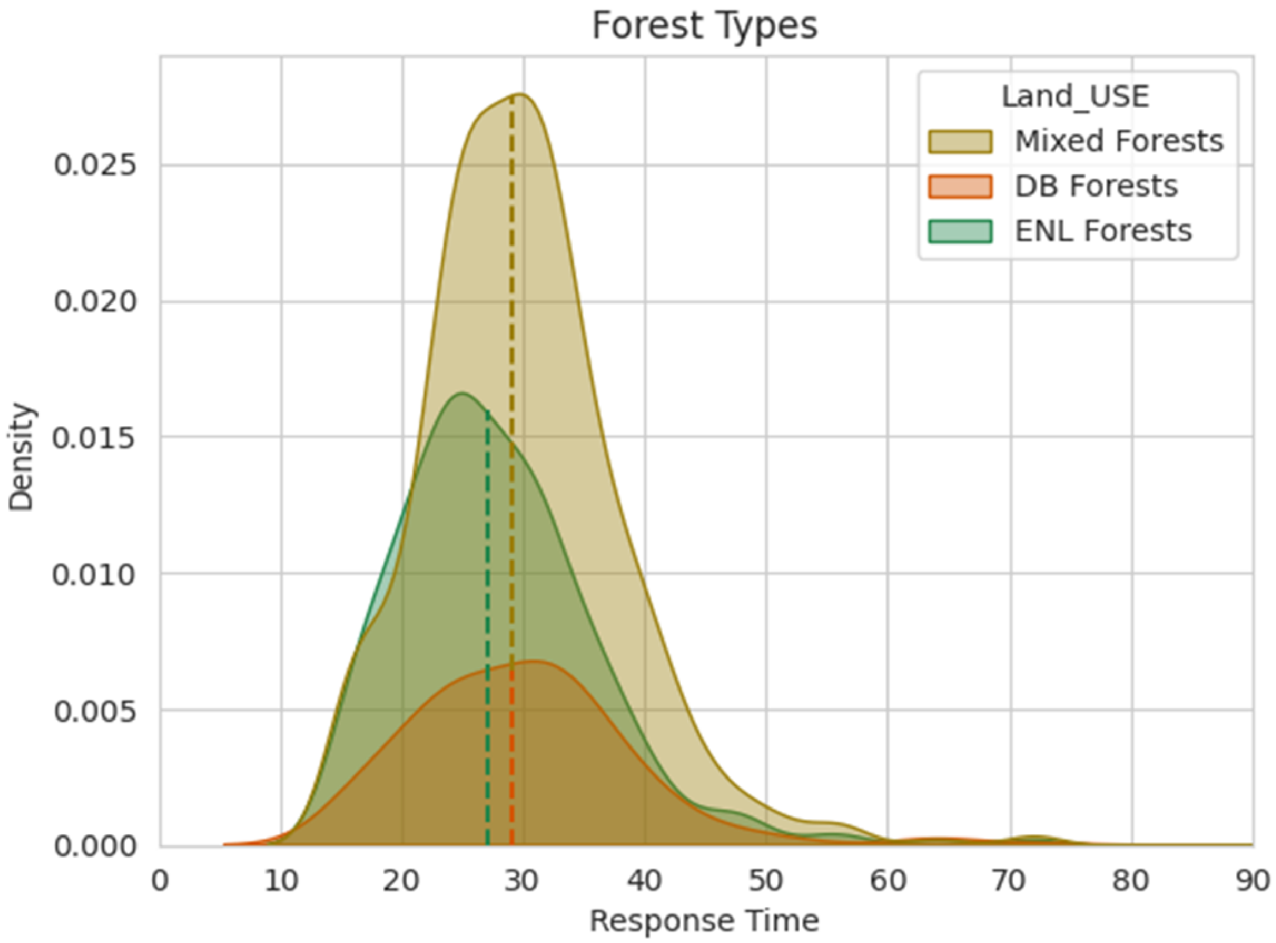

Figure 4.7: Density plot of response time for different kind of forest cover.

of each ecosystem across the top layer of soil moisture. This may be due to the less response of ecosystem is observed to the identified flash droughts.

However, a clear trend emerges regarding the intensification rate of flash drought events, across the mid and root zone, and response time (resistance) of ecosystem as elevation increases. For instant, in the region of elevation <1000 meters above sea level (msl), the response time of grassland ecosystems increases as intensification rates rise, suggesting a higher resistance to flash droughts. Conversely, grassland ecosystems at higher elevations (>1000 meters above sea level) demonstrate less resistance to flash droughts.

For crop land ecosystems, Figure 4.8 illustrates a negative correlation between the response time and the intensification rate of flash drought events in the mid and root zone layers. This suggests that crop land ecosystems are highly sensitive to intensively escalated flash droughts and exhibit low resistance to them. It is also notable that crop land below an elevation of 500 (msl) demonstrates higher resistance to flash droughts compared to crop cover at elevations above 500 msl.

Similarly, in forest land ecosystems (Mixed, Deciduous Broadleaf (DB), and Evergreen Needle

Leaf (ENL)), the response time decreases as the intensification rate of flash drought events in the mid and root zone layers increases with elevation. Its noticeable for mixed forest and ENL forest cover, the response time of ecosystems at higher elevations (>1500 msl) decreases with a decrease in intensification rate, as depicted in Figure 4.8.

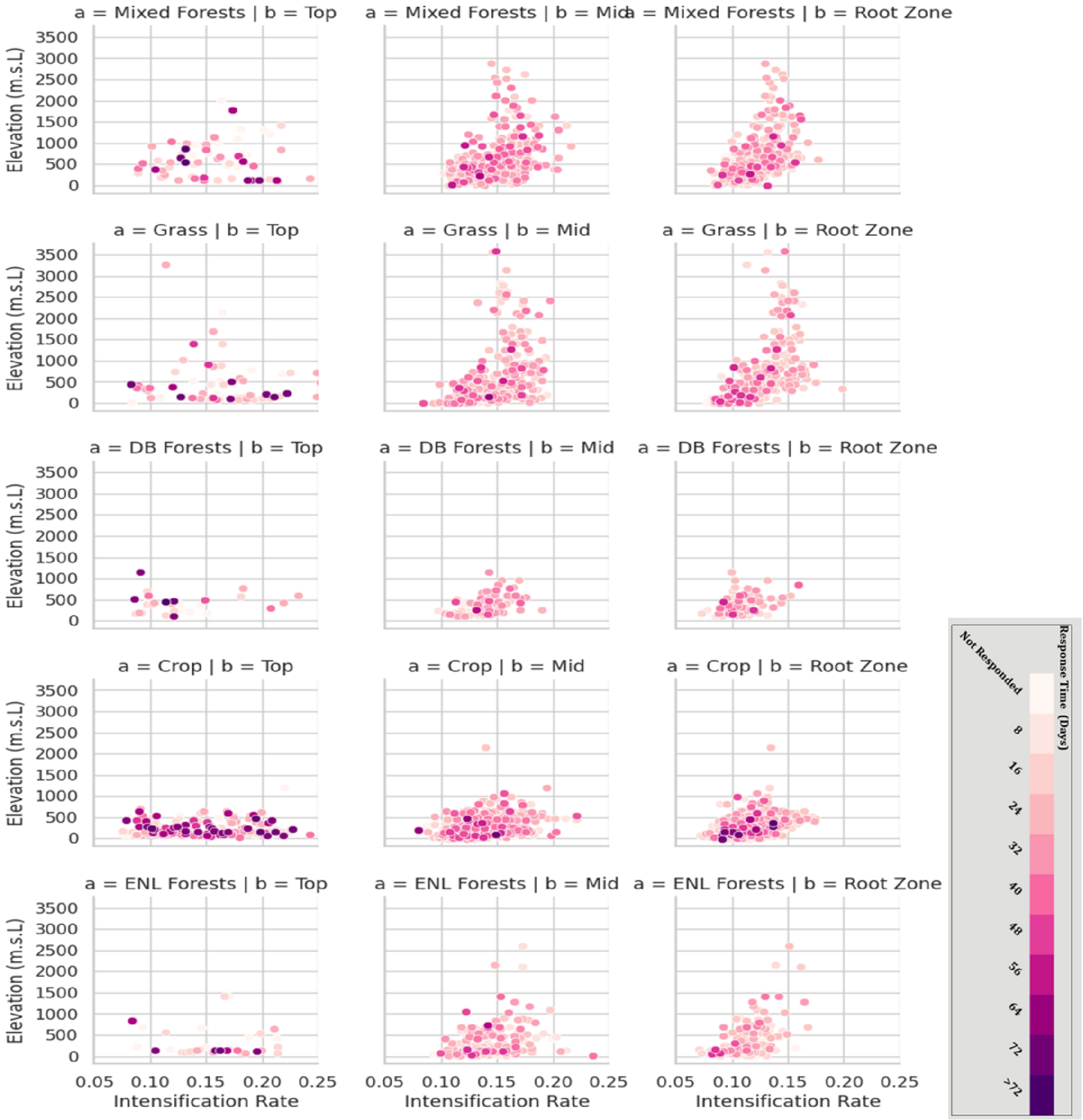

Figure 4.8: Relation between response time and intensification rate of flash drought with respect to elevation.

4.5 Discussion

The response of ecosystems to soil moisture at different depths varies depending on factors such as ecosystem type, climate, vegetation, and soil properties. Research suggests that Gross Primary Productivity is particularly sensitive to soil moisture during hot drought periods. Consequently, ecosystem responses based on GPP to flash droughts differ across soil moisture depths. For example, shallow-rooted ecosystems like grasslands primarily draw water for photosynthesis from the top layer (0-10cm) of soil, whereas deep-rooted ecosystems like forests access soil moisture from deeper layers. However, this study finds that ecosystem responses based on GPP are notably higher to mid-layer soil moisture (10-40cm). Additionally, the frequency of flash drought occurrence and the rate of soil moisture decline significantly influence ecosystem responses. This study reveals that in regions where flash droughts intensify rapidly and occur frequently, ecosystem response percentages are higher. Similar findings are reported by (Yao et al., 2022b), indicating a correlation between drought frequency and ecosystem response frequency. As global warming continues, the intensity and frequency of flash droughts are expected to increase, prolonging ecosystem recovery times and shortening response periods. Regions with shorter response times may face challenges in returning to their normal state, potentially leading to vegetation loss or transitioning to alternative states.

Currently, there is considerable debate surrounding how ecosystems respond to drought. For example, (Yao et al., 2022b) observed that tropical and high-latitude areas exhibited a rapid response, contrasting with the perspective of (Schwalm et al., 2017), who suggested that these regions experienced a more protracted reaction time. This discrepancy in findings could stem from variations in methods used for defining response levels and identifying flash droughts (Liu et al., 2019). Many studies have revealed that woody plants like forests generally require longer response times compared to herbaceous vegetation such as crops and grasses (Yao et al., 2022b; De Faria et al., 2020; Isbell et al., 2015). This may be because herbaceous vegetation tends to display a stronger capacity for growth and development than perennial woody species that persist for multiple years.

The resistance (response time) of ecosystems to drought refers to their ability to withstand drought conditions without significant change (Isbell et al., 2015). Our study revealed a higher resistance to drought in forested areas compared to grasslands (Fig. 4.6), consistent with previous research indicating that forested areas exhibit the strongest resistance, followed by croplands and grasslands (Xu et al., 2018). The contrast in resistance between forested areas and grasslands can be explained by several factors. Firstly, there is a difference in how soil water is utilized between these ecosystems during drought. Soil moisture plays a crucial role in mitigating drought impacts during periods of low or no rainfall (Song et al., 2019), with forests utilizing soil water at depths of 0-100 cm in semi-arid regions (Huang et al., 2021), significantly deeper than grasslands (Jobbágy and Jackson, 2004). This deeper access to soil water enables forested areas to alleviate drought effects, resulting in greater drought resistance compared to grasslands.Secondly, forest ecosystems tend to be more productive than grasslands. Ecosystems with higher productivity often have greater water and carbon storage capacities, essential for resisting drought.

Generally, resilience (recovery) has been viewed as inversely related to resistance (response), indicating that regions with low resilience often exhibit high resistance to withstand external stressors (Bee et al., 2007; Liang et al., 2021). Our study found that forested areas located at low altitudes (<1000 meters above sea level) demonstrated higher resistance to drought compared to grasslands (Fig. 4.6), even when facing the same intensification rate of flash droughts. This suggests that forested areas required less time to recover when experiencing flash droughts of similar intensity compared to grasslands. This finding aligns with research (STUART et al., 2018; Zhang et al., 2021) indicating that grassland ecosystems exhibit lower resistance, resulting in longer recovery times to mitigate stress impacts.

This difference in response time between forested areas and grasslands can be attributed to their ecosystem properties. Grasslands consist mainly of annual and biennial herbaceous plants capable of rapid re-establishment, reproduction, and growth (Hoover et al., 2014). In contrast, forested areas are dominated by perennial woody plants characterized by slower growth and reproduction rates and deeper root systems compared to grasslands (STUART et al., 2018). As a result, grasslands can respond more quickly than forested areas, demonstrating low resistance to drought.

Overall, the response of ecosystems to changes in soil moisture depth is complex and multifaceted, with implications for plant growth, water availability, nutrient cycling, soil stability, wildlife habitat, and fire risk. Understanding these responses is essential for effective ecosystem management and conservation in the face of changing environmental conditions.

4.5.1 Conclusion

Despite the increasing interest in the occurrence of flash droughts and their impacts on terrestrial ecosystems, they are least addressed in central Europe. It has been observed that the rapid decline of soil moisture is usually caused by rainfall deficits and high vapor pressure deficit (VPD). The rapid depletion of soil moisture allows limited time for early preparation and planning. Plants mainly extract water from the soil, which further regulates transpiration, stomatal control, and stem-water dynamics. During a flash drought event, stomatal conductance reduces to prevent extra water loss. Moreover, the decline in atmospheric moisture further reduces the stomatal conductance of plants, which affects the diffusion of carbon dioxide in plant leaves. In addition to flash droughts, the response of ecosystem respiration is also sensitive to high temperatures.

In this study, the dynamics of flash drought and its impacts on different types of ecosystems are investigated. Through this investigation, the main conclusions that can be drawn are:

- The frequency of flash events occurred more frequently across the mid-layer soil moisture compared to the top and root zone layer soil moisture.
- All types of ecosystems responded to the flash droughts identified across the mid and root zone layer soil moisture more than to flash drought events in the top layer soil moisture.
- The average response time of all types of ecosystems varies from 20 to 30 days to flash drought events.
- Cropland ecosystems are highly sensitive to flash drought events with high intensification rates and show low resistance to them, while grassland ecosystems show high resistance to flash drought events.
- Evergreen needle-leaf (ENL) forestland has a shorter response time to flash droughts than mixed and deciduous broadleaf (DB) forests. Therefore, ENL forestland has lower resistance compared to other types of forest ecosystems.

Overall, this study highlights significant disparities in the frequency and impact of flash drought events across different soil moisture layers and ecosystems. Flash events were observed to occur more frequently in the mid-layer soil moisture compared to the top and root zone layers. Furthermore, all types of ecosystems exhibited more pronounced responses to flash droughts occurring in the mid and root zone layers, indicating their heightened sensitivity to changes in deeper soil moisture levels. The average response time of ecosystems to flash drought events ranged from 20 to 30 days, underscoring the time it takes for ecosystems to exhibit noticeable changes in response to soil moisture deficits. Particularly, cropland ecosystems displayed high sensitivity and low resistance to flash drought events, contrasting with grassland ecosystems, which demonstrated greater resilience. Additionally, evergreen needle-leaf forests exhibited a shorter response time to flash droughts compared to mixed and deciduous broadleaf forests, suggesting their lower resistance to such events. These findings illuminate the diverse vulnerabilities of ecosystems to flash droughts, offering valuable insights for conservation and management efforts.

Chapter 5

Summary & Conclusions

5.1 Summary of Thesis

The thesis aims to contribute to a better understanding of flash drought characteristics and their impacts on the ecosystem of central Europe. Accordingly, the thesis conducts a quantitative review through bibliometric analysis on the development of the flash drought concept and associated challenges (Chapter 2). These analyses identify the temporal growth in the field of flash drought research and the geographical distribution of contributions to flash drought studies across the globe. In this study, the novel concept of keyword analysis has also been applied to identify the effective indicators used by researchers for flash drought research. Additionally, we explore the evolution of the flash drought concept and the temporal developments in the definitions of flash drought. Furthermore, based on the quantitative and qualitative review of flash drought research, we identify major challenges and provide recommendations for future studies that could seize opportunities to provide further insights into the flash drought concept.

Following a comprehensive review, encompassing both quantitative and qualitative analyses, of advancements in the field of flash drought presented in Chapter 2, we undertake the challenging task of studying the spatial and temporal characteristics of flash droughts over central Europe (Chapter 3). Considering various definitions based on onset duration and intensification rate for identifying flash droughts, we have developed and implemented a novel definition that incorporates onset duration, intensification, and persistency to identify flash droughts across central Europe. Furthermore, we examine the characteristics, intensification rate, and severity of flash droughts on spatial and temporal scales and discuss their interrelationship. Additionally, we apply Contiguous Drought Area (CDA) analysis to study the extent of flash drought events and the temporal movement of flash drought centroids across central Europe from 1979 to 2020.

After studying the characteristics of flash drought in Chapter 3, we conducted an analysis to investigate the resistance of ecosystems, in terms of response time, to flash drought events (Chapter 4). In this study, gross primary productivity (GPP) data were used as an indicator of ecosystem response, and soil moisture data from different layers—top layer (0-10 cm), mid layer (10-40 cm), and root zone layer (0-100 cm)—were utilized to identify flash drought events. The analysis was performed on three types of ecosystems (grassland, cropland, and forest land). Additionally, the analysis on the resistance of ecosystems was further investigated by linking it with the average intensification rate of flash drought events and the altitude of the study area. Considering the devastating impacts of flash droughts on ecosystems, this type of study provides a better understanding of flash droughts and a lead time for early warning systems.

5.2 Key Findings

Several conclusions are listed below regarding the objectives of the study defined in chapter-1.

Objective 1: Developments and Challenges in the Field of Flash Drought Research The concept of flash drought has experienced exponential growth on a global scale, particularly following the impact of the 2012 flash drought event in the USA. The characteristics and dynamics of flash droughts have been predominantly investigated in the USA and China. Researchers commonly utilize soil moisture and evapotranspiration as indicators to identify flash drought events. Major challenges reported by researchers in the field of flash drought include: the lack of a widely recognized definition of flash droughts, leading to confusion in recognizing and characterizing these events; the difficulty in studying flash droughts due to the requirement for high-quality and high-resolution data on parameters such as soil moisture, precipitation, temperature, and evapotranspiration, which are often lacking at the necessary spatial and temporal scales; the complexity in creating reliable prediction models and early warning systems for flash droughts due to the absence of clear precursors and the rapid development of these events; and the changing climate, which may alter the frequency, intensity, and spatial extent of flash droughts. Therefore, understanding the long-term, unbiased influence of climate change on the characteristics of flash droughts is crucial.

Objective-2: Investigate the Characteristics of Flash Drought across the central Europe

Flash droughts frequently occur in the northeast and southwest regions of central Europe. The relative frequency of flash drought events has increased in the last two decades (2000-2020). Observations show that the intensification rate of onset flash droughts is particularly high in the eastern region of central Europe, and the severity of flash droughts is positively correlated with the average rate of intensification in most of central Europe. Moreover, the intensification rate of flash droughts exhibits an increasing trend across the study area, indicating a growing propensity for rapid drought onset and escalation. Concurrently, the areal extent of flash droughts is expanding on both spatial and temporal scales, reflecting the broader impact and persistence of these events. Contiguous Drought Area (CDA) analysis further reveals that the centroid of flash drought events is shifting towards the southwest region of central Europe, highlighting spatial shifts in the distribution of these extreme drought phenomena. These findings underscore the evolving nature of flash droughts in central Europe and emphasize the need for enhanced monitoring, prediction, and adaptation efforts to mitigate their adverse impacts on water resources, agriculture, ecosystems, and society.

Objective-3: Investigate the Response of Ecosystem to Flash Droughts

It is observed that the ecosystem, as measured by the Gross Primary Productivity (GPP), responded significantly, around 95%, to flash drought events identified across the mid layer (10-40cm) and root zone (0-100cm). However, the southeast region of central Europe exhibited a lesser response to the identified flash droughts, potentially due to varying resilience capacities across different parts of central Europe. In contrast, the northeast region of central Europe displayed high resistance to flash droughts, likely attributed to its heightened tolerance to extreme deficits of soil moisture conditions.

Moreover, mixed forest land demonstrated higher resistance to flash drought compared to evergreen needle-leaf (ENL) forests. This finding is supported by Pardos et al. (2021), who reported that mixed forest ecosystems in Europe exhibit greater resistance to drought events than other types of ecosystems. The average response time of ecosystems to flash drought events ranged from 20 to 30 days, depending on the depth of the soil moisture layer.

Furthermore, ecosystems at lower altitudes ($<$ 1000 meters above mean sea level) displayed higher resistance to flash drought events with high onset intensification rates. Conversely, ecosystems at higher altitudes ($>$ 1000 meters above mean sea level) demonstrated lower resistance to flash events with high onset intensification rates. High resistance to flash droughts indicates a lower risk to GPP-based ecosystems, emphasizing the importance of considering altitude and ecosystem type in assessing vulnerability to flash drought impacts.

Objective-4: Investigate the Characteristics of Flash Droughts across the different Depths of Soil Moisture

It is observed that the identification of flash drought occurrences across the top layer (0-10cm) and root zone layer (0-100cm) is less frequent than the identified flash drought events across the mid layer (10-40cm). This discrepancy is attributed to the conditions of intensification rates during the onset phase and persistence after the onset phase. In the top layer, the intensification rate condition is quickly attained, but the soil moisture remaining below the threshold is not sustained. Conversely, this trend could be opposite for the root zone layer.

As discussed earlier, the Gross Primary Productivity (GPP)-based ecosystem responds maximally to flash drought events in the mid-layer soil moisture. Therefore, it can be concluded that soil moisture data up to the 40cm layer is suitable for studying the impact of flash droughts on ecosystems.

The average intensification rate of onset flash droughts is higher for the top layer of soil moisture. As we move deeper into the soil moisture layer, the intensification rate decreases. Additionally, there is no specific relation existing between the intensification rate and the altitude profile of central Europe for the top layer of soil moisture. However, the intensification rate of onset flash droughts increases with the increase of altitude for all types of ecosystems.

Moreover, it is usually considered that the resistance of ecosystems has an inverse relation to the intensification rate of flash droughts, meaning that for higher intensification rates, the ecosystem recovers quickly. However, here, no significant inverse relation is observed between the intensification rate and the resistance of ecosystems. This may be because the majority of central Europe lies in a humid region, and ecosystems in humid regions are highly resistant to droughts.

5.3 Limitations and Future Works

Limitations of any research usually define a constraint or failing within a research outcomes that might affect its credibility, generalization, or interpretation. Being able to tell about potential study limitations may help better understand the scope of a research or where to be rather skeptical about the drawn conclusions. Usually the limitations of the drought study, unsuitable methodologies, inability to collect adequate data, and low rates of external validity are quite common. These findings let others know what areas are not researched well and which should be considered more seriously by doing additional studies. Here, this study has also several limitations that point to further insights into the characteristics of flash droughts and their impacts on ecosystems.

Bibliometric analysis (Chapter-2) in flash droughts investigation faces limitations due to dependencies on indexed publications within databases. Drought research coverage might be incomplete because of divergences in indexing practices, language obstacles, and publication prejudices. This noncomprehensive representation can skew bibliometric results, potentially neglecting important contributions from non-listed sources or areas where drought is an pressing issue but scientific output is less prolific. Furthermore, bibliometric analyses regularly prioritize quantitative metrics for example citation counts or publication regularity, disregarding qualitative facets critical to thoroughly grasp drought dynamics. The examination of drought incorporates a extensive range of disciplines, such as meteorology, hydrology, agriculture, and social sciences. Encompassing weather patterns, water resources, crop yields, and communal impacts, drought research demands a multifaceted evaluation that bibliometric studies in their present form cannot satisfy on their own.

However, bibliometric analyses have difficulty grasping interdisciplinary collaborations and new research trends as illustrated in this way Of necessity, its contributions to drought science are piecemeal rather than comprehensive. Also, the time lag naturally present in bibliometric data brings its own set of challenges when trying to catch up with rapidly moving drought research: current though it may be by now nothing is set in stone. Next, bibliometric analyses often concentrate on the published literature, overlooking valuable contributions from grey literature, conference proceedings and unpublished data sets which can offer new angles on drought impacts, vulnerabilities and adaptation strategies. A further critical limitation lies in the reliance upon predefined keywords and search queries that may unwittingly exclude relevant studies which have employed different terminology or conceptual frameworks. Finally, bibliometric analyses frequently overlook the contextual forces that shape any research on drought such as socioeconomic conditions, policy priorities or environmental settings which profoundly affect both the direction and perspectives offered in scientific inquiry.

Despite these limitations, bibliometric analyses provide a useful overview of published drought research, solely relying on quantitative metrics risks overlooking important qualitative nuances. By cataloging topics and trends, these techniques help synthesize existing knowledge and uncover gaps needing exploration. However, their reduction of ideas into numbers abstracts away human understanding gained through deeper reading and contextualization. To inform strategic decisions around drought policy, planning, and management, researchers must look beyond metrics alone. Qualitative assessments that supplement bibliometric findings with qualitative assessments and contextual insights offer a more textured view of this multifaceted field. Proper consideration of both quantitative and qualitative data leads to wiser decision-making that recognizes not all aspects of science can be neatly quantified.

One limitation (chapter3) lies in the reliance on a single variable (soil moisture) dataset from GLDAS. Utilizing additional variables such as evapotranspiration (ET) could reveal different spatial and temporal patterns of flash droughts, potentially influencing the identification of flash droughts and the assessment of their duration, particularly in irrigated regions. Additionally, the analysis in this study was constrained by the small number of flash drought events studied, possibly leading to less robust results. To address these limitations, we intend to develop a multi-variable index for identifying flash droughts and assessing their severity. Furthermore, this study does not examine pre-weather conditions such as anomalies in precipitation, temperature, and atmospheric vapor pressure prior to the onset of flash droughts. Numerous studies conducted across Europe have highlighted the influence of these pre-weather conditions on the intensification rate of flash droughts. Addressing this gap is crucial as it allows for the incorporation of climatological factors in understanding the characteristics of flash droughts.

Despite these limitations, future research directions offer avenues for advancing the understanding of flash drought characteristics. Improving observational networks and data assimilation techniques can enhance the spatial and temporal resolution of drought monitoring systems, enabling more accurate detection and characterization of flash drought events. Integrating multi-disciplinary approaches, such as remote sensing, machine learning, and process-based modeling, can elucidate the underlying mechanisms driving flash drought development and propagation. Long-term monitoring efforts coupled with retrospective analyses can discern trends and patterns in flash drought occurrence, facilitating the development of early warning systems and risk assessment tools.

The inherent limitations during the study of ecosystem response to flash drought require some consideration and further research work. First of all, the complexity and variability of ecosystems present some challenges for the proper recognition of flash drought impact. Different types of vegetation, soils, topography, and climate variability factors determine the ways of ecosystem drought stress response. Consequently, the findings of chapter 4 results specific ecosystems to broader regions or across different climatic conditions may be limited by the lack of generalizability. Furthermore, the temporal and spatial scales of ecosystem response are also variable, and sometimes, it can be a challenge to capture the dynamic nature of flash drought impact on ecosystems.

Additionally, this study solely relies on the Gross Primary Production (GPP) dataset to investigate the ecosystem's response to flash droughts. However, it has been noted in various studies that relying on a single variable may not fully capture the phenology of ecosystems during water stress conditions. Therefore, it is imperative to incorporate multiple indicators of ecosystem response when studying the impacts of flash droughts. Such an investigation, considering the distinct characteristics of flash droughts compared to traditional droughts, could prove useful in developing effective adaptation strategies for the future.

5.4 Concluding Remarks

The study of flash droughts undeniably holds great value for researchers aiming to understand these rapid phenomena and mitigate their impacts. One of the key benefits of researching this topic lies in the opportunity for scientists to uncover the intricate mechanisms underlying such events. By investigating meteorological phenomena, soil moisture dynamics, and atmospheric circulation patterns, researchers can gain deeper insights into the combination of factors that precipitate the sudden onset and intensification of flash droughts. This research also holds promise for enhancing our understanding of flash drought dynamics in central Europe.

The utilization of bibliometric tools in Chapter 2 provides a quantitative review of flash drought research, shedding light on the breadth and depth of scholarly inquiry in this field. Moreover, studying the characteristics of flash droughts offers crucial insights into the dynamics, triggers, and impacts of these rapid-onset phenomena across central Europe. The proposed definition of flash drought encompasses its rapid onset characteristics and persistence, rendering it particularly impactful. In this study, the analysis of Contiguous Drought Areas (CDAs) offers a novel approach to understanding the movement of flash drought centroids on a temporal scale, thereby aiding in the identification of flash drought hotspots across the globe. By elucidating the spatial and temporal dynamics of flash droughts, researchers can better anticipate their occurrence, assess their impacts, and develop strategies to mitigate their effects.Overall, the exploration of flash droughts presents a valuable opportunity for researchers to deepen our understanding of these phenomena and develop effective strategies for managing their impacts, particularly in regions like central Europe where they pose significant challenges to water resources, ecosystems, and society at large.

Furthermore, this research provides essential knowledge and tools to ecologists for understanding, mitigating, and adaptations to the ecological impacts of these rapid-onset events. Flash drought can have profound effects on ecosystems, including changes in vegetation dynamics, species composition, and ecosystem processes. Ecologists study how different plant species and communities respond to water stress induced by flash droughts, allowing them to better understand the mechanisms driving these ecological changes. By elucidating these responses, ecologists can assess the vulnerability of ecosystems to flash droughts and develop strategies to enhance resilience. This research may also allow ecologists to evaluate how these ecosystem services are affected by drought stress, informing decision-making processes related to natural resource management and land-use planning. Moreover, identifying resilient species and habitats, ecologists can design restoration projects that enhance ecosystem stability and functionality, mitigating the impacts of future flash droughts. By quantifying the economic and societal benefits of ecosystem services, ecologists can advocate for their protection and restoration in the face of increasing flash drought risk.

In the light of the ongoing problems connected with drought, an increasingly essential and difficult phenomenon that needs to be addressed must be mentioned – flash droughts. Extremely rapid and intense, these negative phenomena pose a range of unusual challenges to every community, every ecosystem, and every economy around the globe. Thus, to respond to this phenomenon accordingly, one will have to explore the issue, prepare and develop the tools for managing it. Comprehending the many dimensions of flash droughts and related concerns – meteorological, hydrological, ecological, and socio-economic – Our interdisciplinary research helps to extricate the complex web of dynamics that cause flash drought, along with early warning signs and possible risk control strategies. Our interdisciplinary approach, which draws on the knowledge of climatologists, hydrologists, ecologists, satellite remote sensing specialists, and socio-economic experts, can improve our monitoring preconditions and response to flash drought.

In addition, community engagement and stakeholder participation are necessary components of developing flash drought resistance. Providing local communities with the information, resources , and tools they need to anticipate and react to flash droughts can help them minimise disaster risks and enhance readiness. Resilience can be created through education, communication, and capacity-building efforts that enable people to safeguard themselves against flash droughts. The endeavor to address the threat of flash drought will be driven by collaboration, innovation, and resilience. By establishing synergistic ties between scientists, policy-makers, practitioners, and communities, we might deepen our understanding of flash droughts and develop sustainable methods to protect against them. This is our chance to take charge of the calamity of flash drought and to safeguard the quality of life of current and future generations.

List of Figures

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Appendix A

List of selected publications

Systematic Analysis of the Flash Drought Research: Contribution, Collaboration and Challenges

Available at `https://doi.org/10.1007/s00704-023-04584-0`

Abstract

Compound extreme events, such as flash drought, have received wide attention in recent decades due to their far-reaching effects on the ecosystem. Thus, a new concept of flash drought has begun to spread globally in the scientific community and it is continuously being developed. This study offers for the first time an overview of the global trends in flash drought research from 2000-2021. The analysis was based on the Scopus database in order to investigate the publication trends, contributions, collaborations and challenges on a global scale. Furthermore, collaboration analysis was performed to detect collaboration networks within the flash drought research field. A total of 76 studies were published in the studied period. The research output grew exponentially with an average growth rate of 30% per year. The challenging issues in the field of flash drought research are the search for appropriate definition of flash drought, development of effective early warning systems and scarcity of high-resolution data. By presenting the details of the evolution of this new conceptualization in drought research, our study highlights the main pathways of scientific progress and stimulates future research.

The Space and Time Characteristics of Flash Droughts in Central Europe

Under Review
International Journal of Climatology

Abstract

Flash drought is a unique natural hazard due to its rapid rate of intensification. In previous studies, little work was done to investigate the space and time behaviour of flash drought across Central Europe. In this study, we examine the space and time characteristics (frequency, rate of intensification, severity, and extent) of flash drought events in Central Europe between 1970 and 2020. The anomalies in weekly averaged topsoil moisture (SM) data from the Global Land Data Assimilation System (GLDAS) was used for identifying flash drought events. Here, we adopted a new definition of flash drought that does not only consider intensity, and duration but also incorporates the persistence of flash drought. The results of this study revealed that the occurrence of flash droughts over Central Europe increased rapidly over the last decades. The intensification rate and severity of flash drought were positively correlated with each other. Moreover, the areal extent of flash drought events has increased since 1970, and their centroid shifted from the north to the southern part of Central Europe. Overall, the finding of this study contributes towards a better understanding of flash drought characteristics and their dynamics over Central Europe.

Rapid Onset Droughts: Unraveling Ecosystem Response to Flash Droughts

Under writing

Abstract

Flash drought is a rapid complex extreme climate disaster, causing adverse damages to the structure and functions of terrestrial ecosystem. The recent developments in the field of flash drought highlights the importance of understanding its characteristics and impacts on the terrestrial ecosystems. Here, in this study we identify the soil moisture flash drought by considering the intensification rate and persistency and investigate the resistance of ecosystem in the terms of response time to flash drought during onset stage. We use the Global Land Data Assimilation System (GLDAS) 8-daily averaged soil moisture data of three different layers (0-10cm, 10-40cm, 0-100cm) and investigate the characteristics of flash drought across each layer of soil moisture. The 8-daily Gross primary productivity (GPP) is used as indicator to investigate the response of crop, grass, and forest lands ecosystem to flash drought. The results of the study revealed that the ecosystem responded 95% to flash droughts events identified across mid (10-40cm) and root zone (0-100cm) layer of soil moisture. The average response time of ecosystem to flash drought events varies from 20 to 30 days depending upon the depth of soil moisture layer. The ecosystem of lower altitude ($<$ 1000 msl) shows high resistance to flash drought events having high onset intensification rate. Moreover, the ecosystem of the high altitude ($>$ 1000 msl) shows low resistance to the flash events having high onset intensification rate. Overall, the forest land is shows high resistance to the flash drought as compare to grass and crop land ecosystem of central Europe. These finding provide inside characteristics flash drought and the response of ecosystem to flash drought which could be helpful for timely mitigate the impacts of flash droughts on the terrestrial ecosystems.

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