Increasing footprint of climate warming on flash droughts occurrence in Europe

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Abstract

Flash droughts are caused by a rapid depletion of soil moisture, and they severely affect vegetation growth and agricultural production. Notwithstanding the growing importance of flash droughts under the warming climate, drivers of flash droughts across the Europe are not well understood. Here we estimate the changes in flash droughts characteristics across Europe using the ERA5 reanalysis dataset for 1950–2019 period. We find a substantial increase in the frequency and spatial extent of flash droughts across Europe (with 79% of the total area) during the growing season with at-least one fourth of domain showing two-fold increase in the recent decades. Increased occurrence of flash drought is largely attributed to frequent occurrence of warmer and drier compound extremes, with a sharp gradient of changes being noticed in Mediterranean and Central European regions. Compound meteorological extremes causing the flash drought events across Europe are pre-dominantly driven by the recent climate warming. With unabated greenhouse gas emissions and current pace of climate warming, Europe is likely to face an increased occurrence of flash droughts, requiring prompt response for effective drought adaptation and management strategies.

1. Introduction

Drought—perhaps the most complex and least-understood of all the climate extremes (Pulwarty and Sivakumar 2014)—poses an immediate threat to people (e.g. drinking water shortages), agriculture (e.g. crop losses), ecological states (e.g. forest fires), and infrastructure (Vogel et al 2019). Drought is traditionally regarded as a slowly evolving climate phenomenon that would take several months or years to peak its intensity. However, a particular type of drought events, namely ‘flash droughts’, can develop rapidly and last for a few weeks only (Otkin et al 2018) and can lead to apparent societal/economic impacts (Otkin et al 2016, Yuan et al 2019). Short duration droughts are typically triggered by precipitation deficit (Koster et al 2019) often combined with high potential evapotranspiration (PET), being a driving mechanism between the land and atmosphere (Pendergrass et al 2020). On the other hand, persistent high-pressure systems play a significant role in the generation of heatwaves, soil moisture deficit and mid-term droughts at both global and regional scale (Ionita et al 2020). While the short-term droughts are related to a decrease in root-zone soil moisture, more sustained droughts lead to a decline in surface water flows (Pendergrass et al 2020), and the long-term (multi-year) droughts could lead to aquifer depletion due to deficit in groundwater recharge and increased groundwater pumping (Wu et al 2020).

Much of the efforts have been put forward to understand the mechanisms of seasonal and multi-year European droughts and their associated socioeconomic and environmental impacts
(Fischer et al 2007b), Van Lanen et al 2016, Flach et al 2018, Samaniego et al 2018, Hari et al 2020, Moravec et al 2021). However, a comprehensive assessment of the flash droughts over Europe is substantially lacking. Flash droughts are those which intensify rapidly increase after onset, and their short-term yet devastating impacts on the ecosystem and agriculture have been noticed in many regions worldwide (Otkin et al 2016, Zhang et al 2017, Yuan et al 2018, Christian et al 2020, Mishra et al 2021). There are substantial evidences that anthropogenic warming exacerbates the occurrence and severity of such events (Wang et al 2016, Yuan et al 2019, Liu et al 2020). Additionally, current annual monetary losses across Europe due to droughts have been estimated at around 9 billion EUR every year (Naumann et al 2021); and the topic has sparked political debates on climate change adaptation and mitigation strategies (Daugbjerg and Feindt 2017). However, estimates of these economic losses, particularly considering the impacts of flash droughts which are imposing enormous challenges to climate change adaptation (in the agriculture sector), is largely unexplored.

It remains largely unknown how the characteristics of relevant hydrometeorological variables during the evolution of flash drought have contributed to spatio-temporal developments of flash droughts across Europe over the last decades. So far, only few studies have investigated flash droughts in Europe at a country level (e.g. Russia and Spain, Christian et al 2020, Noguera et al 2020). To address these gaps, we provide a comprehensive assessment of changes in flash drought characteristics across Europe over the last seven decades (1950–2019). We focus on the rapid changes in the spatio-temporal anomalies of root zone soil moisture as it integrates the crucial components of the water and energy coupling (Seneviratne et al 2010). We use the recently released ERA5 reanalysis dataset, which takes into account land-atmosphere feedback (https://cds.climate.copernicus.eu; Hersbach et al 2020), to systematically investigate short-term (pentad) changes in soil moisture anomalies, characterising the flash drought events. We then examine the role of driving meteorological conditions (e.g. precipitation and temperature anomalies) promoting and sustaining the flash drought events, including the co-occurrence of ‘warmer and drier’ and ‘colder and drier’ conditions. By analysing the changes over the last 70 years, our goal is to scrutinize the possible footprint of contemporary climate warming on the flash drought occurrence and its spatial extent across Europe.

2. Data and methods

Flash-drought characteristics (i.e. frequency and spatial extent) are derived from the soil moisture of the ERA5 global reanalysis product (Hersbach et al 2020). ERA5 is the fifth generation reanalysis product provided by the European Center for Medium-Range Weather Forecasts (ECMWF). Reanalysis blends various observation and remote sensing data in the coupled model, and with the use of the latest data assimilation techniques, without any gap in space and time generates the archived state of atmosphere and land (Li et al 2020). ERA5 uses the land-surface model HTESSEL coupled with the ECMWF IFS global climate model, which takes land-atmospheric-ocean feedback into account (Balsamo et al 2009). Compared to other reanalysis products (MERRA, GLDAS, JRA-55, among others), the ERA5 is available at a higher spatial resolution of 0.25° × 0.25° for the period 1950 to near real-time. Furthermore, recent studies have demonstrated the reasonable skill of ERA5 soil moisture simulation compared to observations across different locations (Li et al 2020, Yang et al 2020). We analyse the soil moisture dynamics of the top 30 cm soil, for the flash drought evaluation, since it represents near surface root-zone; and flash drought often causes rapid depletion of soil moisture and deteriorating the vegetation health and its productivity (e.g. Ford and Labosier 2017, Otkin et al 2018, Mishra et al 2021). We also perform complementary analysis of 1 m soil moisture simulations to evaluate flash drought characteristics for deeper soil column. Unless otherwise mentioned, we present the analysis of 30 cm soil moisture droughts in the main text; and the corresponding analysis of flash droughts using 1 m soil moisture is presented in supplementary information (available online at stacks.iop.org/ERL/17/064017/mmedia). To investigate the role of driving meteorological factors affecting flash drought developments, the ERA5-based total precipitation and average air temperature at 2-m height were also aggregated to corresponding pentad values used to describe the meteorological conditions. Good performance of precipitation and temperature data of ERA5 against observations was previously reported e.g. by Tarek et al (2020).

The most notable feature of flash drought is its ability to intensify rapidly from its onset (Otkin et al 2018). In this study, flash drought events are defined according to Ford and Labosier (2017) and Mishra et al (2021), and they are based on the rapid changes in soil moisture anomalies that integrate land surface and atmospheric coupling features. Hourly soil moisture data are converted to pentad (5-day) average to reduce the impact of day to day variability, resulting in a total of 73 pentad SM values per year (Christian et al 2019, Mahto and Mishra 2020). The pentad-average SM values are further converted to percentiles (also referred to as Soil Moisture Index; SMI) with the help of non-parametric Gringorten plotting position approach (Gringorten 1963). These percentile values range from 0 to 1, where values above 0.5 represent wetter than median conditions and below
0.5 represent drier than median conditions. Finally, we have adopted following conditions for defining a flash drought event:

(a) Flash drought starts when SMI above 40th percentile (i.e. near or above normal) falls below 20 percentile (i.e. drought) in less than three following pentads.

(b) In each following pentad, SMI should consistently decline. The mean intensification rate should be at least 0.1 of SMI per pentad, which follows a rapid intensification of SMI decline for the occurrence of flash drought events (Otkin et al 2018).

(c) The drought event terminates when the SMI rises above the 20th percentile threshold, and stays above this threshold for at-least two pentads. The latter condition ensures that a single abnormal pentad (with SMI > 0.2) does not terminate the flash drought event.

(d) The duration of a flash drought event is considered between 6 and 18 pentads, to remove short term abnormality and to distinguish it with long duration (conventional) drought (Yuan et al 2019, Mahto and Mishra 2020, Pendergrass et al 2020, Mishra et al 2021).

This study analyses the flash droughts occurring during the (vegetation) growing season, as the previous studies demonstrated a significant impact of flash droughts on vegetation health and productivity (e.g. Otkin et al 2016, 2018, Mahto and Mishra 2020, Mishra et al 2021). To summarise our analysis results, we consider three main climatic regions, prevailing across Europe following the IPCC climate reference regions (Iturbide et al 2020), namely: Northern Europe (NEU), Central Europe (CEU) and Mediterranean (MED) as depicted in supplementary figure S1(a). Mediterranean (MED) growing season usually starts from March while in Central Europe (CEU) and Northern Europe (NEU) it starts from April and May respectively (Rötzler and Chmielewski 2001); hence we use a common period from April to September as growing season for all three regions (i.e. from 19th to 55th pentads in a given calendar year). To analyse the driving meteorological conditions, similar to soil moisture, hourly temperature and precipitation from ERA5 are first averaged to the corresponding pentad time-scale; and subsequently, their anomalies are estimated considering the long-term mean of each (calendar) pentad values. For each soil moisture based flash drought event, we then estimate the composite of respective precipitation and temperature anomalies ($\Delta P$ and $\Delta T$) and group them into their respective four distinct classes of driving meteorological conditions: Class 1 signifies the ‘drier and warmer’ conditions ($\Delta P < 0 \& \Delta T > 0$); Class 2 represents the ‘wetter and warmer’ conditions ($\Delta P > 0 \& \Delta T > 0$); Class 3 the ‘wetter and colder’ conditions ($\Delta P > 0 \& \Delta T < 0$); and Class 4 depicts the ‘drier and colder’ conditions ($\Delta P < 0 \& \Delta T < 0$). A schematic representation of these classes for few grid cells is presented in supplementary figure S1(b). In supplementary, we also provide the analysis for more stringent meteorological conditions by considering varying thresholds for example for precipitation anomaly as 5% and temperature anomaly as 0.25 °C and 0.5 °C (see supplementary figures S7, S8, S13 and S14).

3. Results and discussion

3.1. Changes in flash drought frequency

Primarily, we analyse the flash drought characteristics focusing on their frequency and changes in recent times. For this purpose, we divide the data into two periods (i.e. 1950–1984 and 1985–2019). Figure 1(a) depicts the frequency of flash droughts experienced during the growing season for the period 1950–1984. In general, we notice a relatively higher number of flash drought events in the Northern European (NEU) region. Though this spatial pattern remains the same in the recent period (1985–2019), we notice a widespread increase in the occurrence of flash droughts throughout Europe (figures 1(b) and (c)). Nearly 79% of the total grids over the study domain exhibit an increased occurrence of the flash drought in the last 35-year period (figure 1(c)). In particular, in all the three regions, at least 25% of the grids cells experienced more than 80% increase in flash droughts frequency—a nearly two-fold increase in overall drought occurrence over the recent period (figure 1(d)). The more frequent precipitation events over NEU and CEU regions occur because of higher synoptic variability that can then lead to quick drop and recovery of soil moisture droughts (e.g. Manning et al 2019). This change in soil moisture variability can increase the frequency of flash drought events. On the other hand, when soil moisture drops in the MED region, it stays there for a long time, since the lower synoptic variability leads to lower variability of rainfall (and resulting soil moisture) that eventually lead fewer flash droughts in this region.

On the decadal scale, we notice a swift rise in the number of flash drought events during the growing season in all three climate regions (figures 1(e)–(g)). An increase in median frequency of one to two events during the 1950–1959 decade to almost four to six events during the recent decade (2010–2019). This systematic increase in the decadal occurrence of flash droughts is coinciding with a consistent trend of increasing global mean temperature, as depicted in figures 1(e)–(g) through the shading of corresponding decadal probability distribution density functions following global mean temperature anomalies (Lenssen et al 2019). We also analyse the flash drought frequencies based on the 1 m soil moisture simulations (supplementary figure S2). While the frequency of flash droughts events has been lower, the overall
pattern of increased occurrence of flash drought in the recent period is consistent as that observed in case of the 30 cm soil moisture drought.

Due to its drier climate regime, the MED region compared to other two regions, on average, has a lower number of flash drought events as once a drought is established in this region, it stays for a relatively longer time. This is in contrast to the other two regions (CEU and NEU) characterised by a relatively wetter and humid climate with more frequent precipitation events (see supplementary figure S3(c)). This leads to higher variability in soil moisture dynamics and resulting in more frequent drier and wetter anomalous conditions in such regions (see supplementary figure S3(d)). These findings are in line with a previous study (Chen et al 2021) reporting on flash drought identified using soil moisture definition that occur more frequently in regions with higher soil moisture variability.

We also analyse changes in other drought characteristics (e.g. drought duration and severity) between the two periods (see supplementary figures S4(a) and (b)). We observe an overall increase in total duration and total mean severity of flash droughts in the recent time period (1985–2019) compared to the pre-1984 period. The spatial patterns of the changes in these drought characteristics are consistent with the increased occurrence of flash drought events (see figure 1 and supplementary figure S4).

We separately discuss the analysis of changes in the spatial extent of flash droughts below in section 3.3.

### 3.2. Meteorological drivers of soil-moisture flash droughts

The flash droughts can be initiated by two main types of meteorological conditions: precipitation deficit (precipitation deficit flash drought) and abnormal increase in temperature (heatwave flash drought). Often, it is noted that the co-occurrence of precipitation deficit along with high-temperature anomaly is responsible for the occurrence of flash drought (Otkin et al 2018). The recent increase in the frequency of the flash drought over different regions of Europe points towards the prominent role of contemporary climate warming in exacerbating the flash drought events (figure 1). To understand these aspects in detail, we disentangle the role of precipitation and temperature on the occurrence of flash droughts across Europe, based on four overlying meteorological conditions, namely, ‘class 1: drier and warmer’, ‘class 2: wetter and warmer’, ‘class 3: wetter and colder’ and ‘class 4: drier and colder’ (see section 2 for these class definitions). All four classes are defined with respect to the long-term climatology.

We notice that collectively nearly more than 90% of the total flash drought events during the study period falls under the class 1 (‘drier and warmer’) and the class 4 (‘drier and colder’) categories (see...
Figure 2. Frequency of driving meteorological conditions associated with the occurrence of flash droughts during the period 1950–1984 (left) and 1985–2019 (middle); along with the respective changes in post-1985 relative to pre-1985 (right) for two dominant conditions: (a) ‘drier and warmer’ ($\Delta P < 0$ & $\Delta T > 0$) and (b) ‘drier and colder’ ($\Delta P < 0$ & $\Delta T < 0$). Scatter plots between the frequency of flash droughts and the respective driving conditions: (c) ‘drier and warmer’ and (d) ‘drier and colder’ across three European regions viz., NEU (left), CEU (middle) and MED (right), depicted as the density plots for both time-periods. R in the scatter plots stands for the respective correlation coefficient values.

Common to both of these categories is precipitation deficits that reflect their contribution as a necessary condition for the propagation of flash droughts. Therefore, we focus here more on analysing changes in flash drought occurrence within these two categories (See supplementary figure S6 for the minor contribution of other two categories i.e. classes 2 and 3). Within the two time periods, we observe a spatially coherent increase in ‘drier and warmer’ meteorological conditions during the flash droughts in the recent time period (post-1985), with nearly 87% of the total grids over Europe exhibited a positive change (figure 2(a)). On the contrary, we notice a widespread decline in the ‘drier and colder’ category related to flash drought events (figure 2(b)). Similarly, based on the regional analysis, we notice a significant and robust relationship between the frequencies of soil moisture flash drought events and the coinciding ‘drier and warmer’ conditions for all three regions (see figure 2(c)). The noticeable aspect, in this case, is that this relationship appears even stronger during the recent period (1985–2019) compared to that of the earlier one (1950–1984), specifically in the CEU and MED regions ($R$ values increases from 0.86–0.90 to 0.87–0.95; figure 2(c)). In the case of the ‘drier and colder’ category (class 4 in figure 2(d), corresponding to figure 2(b)), we notice a systematic weakening of this relationship over the recent period, specifically over MED, which is in contrast to the ‘drier and warmer’ conditions (class 1). The relative changes of events between two time periods as well as their
relationships to soil-moisture based flash droughts performed using precipitation anomaly threshold as 5% and temperature anomaly threshold as 0.25 °C and 0.5 °C exhibited similar patterns as that noticed for the 0% and 0 °C thresholds (see supplementary figures S7 and S8). Furthermore, above presented results appear to be robust also with flash drought analysis corresponding to 1 m soil moisture simulations (see supplementary figure S9).

Overall these analyses reveal that the changes in the flash drought events are overwhelmed by the positive temperature changes during the recent period (figure 2), indicating that the current climate warming have played a crucial role in increased flash drought occurrence across Europe. While the drier conditions (precipitation deficit; \( \Delta P \)) are prerequisite for flash drought events, the increase in air temperature during the recent period has amplified the occurrence of flash drought events across Europe. Overall, we find a moderate increase in precipitation deficits of around 10%–20% during the flash drought events in the recent period, however, associated with a robust and widespread increase in temperature anomalies of up to 1 °C–2 °C (supplementary figure S10).

While previous analysis (figure 2) quantified the changes in frequency based on a fixed threshold for precipitation and temperature at zero (i.e. warmer/colder and drier/wetter than average), figure 3 further substantiate the role of recent warming on flash droughts occurrence. These bi-variate heatmaps depict the total number of flash droughts which are categorised for varying thresholds of driving meteorological conditions of precipitation (\( \Delta P \)) and temperature (\( \Delta T \)) anomalies. Even though the precipitation deficit approximately remains the same during a flash drought event, the temperature anomaly has increased substantially in the recent time period. It again reinforces the notion of an expanded footprint of recent climate warming on the increased occurrence of flash drought events. A significant increase in flash droughts frequency during which temperature anomalies are more extreme has occurred during the latter period (1985–2019) compared with the pre-1985 period in all three climate regions. In particular, we notice nearly two-fold (more than 80%) increase in flash drought frequency in bins having the temperature anomalies 2 °C and above for all three regions in the recent period. Furthermore, given that the overall rise in flash drought frequency in recent period (1), the proportion (not given) of flash drought with the temperature anomaly of more than 2 °C increased from 17% to 27%, 16% to 34% and 6% to 25% in NEU, CEU and MED respectively between period 1950–1984 and 1985–2019.

The precipitation deficit, which is a common meteorological condition in both classes (1 and 4) of flash droughts, is an essential and necessary driving factor for flash drought occurrence (Koster et al 2019, Pendergrass et al 2020). On the other side, increased surface ET driven by positive temperature anomalies also play a significant role in the initiation and propagation of flash droughts, and this, in turn, often causes the feedbacks between the land and atmosphere (Pendergrass et al 2020). The evaporative demand represented as the amount of water evaporated under an unlimited supply of moisture (Pendergrass et al 2020) increases and with no replenishment of moisture through precipitation, eventually drives soil moisture regime to a water limiting condition as the surface moisture can no longer supply water for evaporation. Under such water limiting conditions, instead of evaporation, the sensible heat flux will be increased, thereby increasing the surface temperature, and thus also the evaporative demand, exacerbating further the land-atmospheric feedback resulting in a rapid decline in soil moisture (Seneviratne et al 2006, 2010, Fischer et al 2007a, Su et al 2014). These processes, in general, have a significant influence over the European region (Seneviratne et al 2006, Fischer et al 2007a). Moreover, Manning et al (2018) demonstrated that, while precipitation deficit is always a prominent factor for a drought in Europe, the concurrence of low precipitation with high temperature and resulting evaporative demands is found to be most relevant in a transitional climatic region, where the land-atmosphere interactions play a crucial role in the development of soil moisture drought. Our findings are in line with these previous studies wherein we also notice a stronger co-occurrence of flash droughts with the ‘drier and warmer’ conditions, specifically in the recent period over the CEU and MED regions (figures 2 and 3).

Our definition of the flash drought is based on the soil moisture percentiles, which are location specific and relative to site-specific climatological values and accounting for the seasonality aspect. In this respect, we do not consider for the changes in absolute soil moisture values but in their relative values (w.r.t. climatological values) —which means flash droughts can occur in every climatic regions (e.g. in very wet or very dry areas) as long as the criteria for the drop in SMIs are met (see section 2). We note that other hydroclimatic criteria can be included to further refine the identification of flash drought regions—e.g. pre-filtering of areas with a very low/high mean state of soil moisture or precipitation wherein perceived impacts of flash droughts are minimal.

3.3. Changes in the spatial extent of flash droughts

The frequencies of the flash droughts have shown an evident increase during recent times over Europe, amid the recent warming condition. Next, we focus on a spatial aspect of the flash drought, i.e. the temporal evolution of flash drought-affected areas and how this has changed over the study period across the three distinct European regions. To this end, we estimate the annual mean of the spatial extent of flash droughts.
Figure 3. Bi-variate heatmaps depicting the total number of flash drought events, categorized based on the varying levels of respective driving meteorological conditions i.e. composite of precipitation ($\Delta P$) and temperature ($\Delta T$) anomalies, plotted for the period 1950–1984 (left) and 1985–2019 (middle); and their respective percentage changes (right) summarized for three European regions: (a) NEU, (b) CEU, and (c) MED.

Figure 4. (a)–(c); left panels. As with the frequencies of the flash droughts, here also we notice a substantial increase in the spatial extent of flash droughts in the recent time period. This is more evident in the case of the CEU and MED, which exhibit an increasing trend in drought affected areas during the recent decades (from approximately 5%–8% of the total area in the 1980s to almost 12%–25% in the 2010s; figures 4(b)–(c)). In the NEU region, though the spatial extent of the drought-affected areas increased till 2000, this trend has rather stagnated at around 15% of the drought-affected area in the post-2000 period (figure 4(a)). We find a relatively larger interannual variability in the annual evolution of drought-affected areas for the NEU and CEU regions than that for the MED region. This primarily reflects the diversity in hydro-climatic conditions across these regions—NEU and CEU being characterised by a relatively wetter and humid climate with more frequent precipitation events, in contrast to the drier and (semi-)-arid MED region. Annual spatial mean severity also increased in recent period especially in CEU and MED (see supplementary figure S11).

Next, similar to the frequency analysis, we investigate the spatial co-occurrence of soil-moisture flash droughts and the driving meteorological conditions (classes 1 and 4; see section 2). Figure 4 (right panels) shows that the class 1 (‘drier and warmer’) conditions are the main contributor to the recent increasing trend of flash droughts affected areas in all three regions, while the class 4 (‘drier and colder’) contribution is found to be lower over the recent period.
Figure 4. Left panels: annual evolution of mean spatial extent of flash droughts during the growing season for three European regions: (a) NEU, (b) CEU, and (c) MED. Right panels: similar to left panels, but for areas depicting the spatial co-occurrence of meteorological drivers in each of the three regions, depicted here in orange for the ‘drier and warmer’ (\(\Delta P < 0 \& \Delta T > 0\)) conditions and violet for the ‘drier and colder’ (\(\Delta P < 0 \& \Delta T < 0\)) conditions. Additionally, the thick line represents mean trend estimated using the locally weighted scatterplot smoothing approach (LOWESS; Cleveland 1979), and the shaded areas show the corresponding 95% confidence interval. Since the spatially gridded data are provided at the regular latitude-longitude grid, the latitude weight is considered in area estimation when calculating the regional average value.

(post-1985). We notice a strong and significant relationship between the spatial extent of flash droughts and co-occurring ‘drier and warmer’ conditions (\(R \geq 0.95\)) in both time periods and over all three regions (supplementary figure S12; left panels). On the contrary, in the case of the ‘drier and colder’ driving conditions, such relationships are weaker and even deteriorate further for the recent period, irrespective of the regions (figure 4 and supplementary figure S12; right panels). Similar increasing spatial drought extent in the recent period and strong relationship with spatial extent of flash drought has been observed for other meteorological threshold conditions (\(\Delta P < -5 \& \Delta T > 0.25\)) and (\(\Delta P < -5 \& \Delta T > 0.5\)) (see supplementary figures S13 and S14) point towards robustness of results. Furthermore, similar patterns are also noticed for the temporal evolution of spatial drought extents for the 1 m soil moisture analysis (see supplementary figure S15).

Overall, our analysis suggests a prominent role of air temperature on both the increased occurrence and the spatial extent of soil-moisture flash droughts in Europe. Our findings agree with recent studies reporting on a stronger role of climate warming on droughts occurrences and spatial extents in different hydroclimatic regions. For example, Brunner et al (2021) in their study demonstrated the importance of temperature as the main contributor for the increased extent of hydrologic drought across the conterminous United States over recent time periods. Similarly, others have reported on the large contribution of anthropogenic warming on increased drought risks using combinations of observations and modelling studies (e.g. Dai 2013, Diffenbaugh et al 2015, Ault 2020, Williams et al 2020, Mishra et al 2021).

We also test the robustness of our findings with a GLEAM-based soil moisture dataset that incorporates the latest remote sensing observations and
data assimilation techniques to provide high-quality soil moisture and evaporation datasets (Martens et al. 2017). We observe a high degree of temporal correspondence between GLEAM and ERA5 soil moisture simulations with a median correlation of more than 0.7 across Europe over a common period of 1980–2019 (supplementary figure S16, top panel). This is in line with the recent findings of Beck et al. (2021)—who also demonstrated nearly similar skills of these two soil moisture products when compared against observations. Furthermore, we notice a consistent pattern of an increased occurrence of flash droughts in NEU compared to the other two regions (supplementary figure S16). The two databases of the soil moisture derived flash droughts differ in the Mediterranean region; wherein ERA5 exhibits a higher occurrence of flash droughts than GLEAM. These differences may be attributed to different aspects of underlying model components including parameterization of soil moisture dynamics, specification of soil depths and forcing datasets, among others. Despite these differences—which deserves in its own a separate analysis—the main finding of our study that the flash droughts in the post-1980 period is more tightly linked to the co-occurrence of drier and warmer meteorological conditions holds quite well in both datasets across all three European regions (see supplementary figure S16).

4. Conclusions

Europe experienced a series of droughts in the recent period, which were unprecedented compared to the past century (Hari et al. 2020, Büntgen et al. 2021, Rakovec et al. 2022). Although recent efforts were invested in understanding the characteristics of conventional droughts (Ciais et al. 2005, Hanel et al. 2018, Moravec et al. 2021), as well as their physical mechanisms (Ionita et al. 2020), an assessment of changes in flash drought events—that sets-up rapidly in a short time—over Europe has been lacking. In this study, we analyse and document the changes in growing season flash drought occurrence and its spatial extent across continental Europe, based on the recent release of the ERA5 (soil moisture) data-set for 1950–2019. Our analysis show that the frequency of growing season soil moisture flash droughts has substantially increased in the recent period (1985–2019), compared to their occurrence in the earlier period (1950–1984). Our analysis on disentangling the driving meteorological conditions show that the more frequent occurrence of drier and warmer conditions ($\Delta P < 0$ & $\Delta T > 0$) during the recent period have led to these higher frequencies of flash drought across Europe. These dry conditions ($\Delta P < 0$) co-occurring with hot conditions ($\Delta T > 0$) rapidly intensify the soil moisture drought by increasing evaporative demands through enhanced land-atmospheric feedbacks (Seneviratne et al. 2006, Zscheischler and Seneviratne 2017, Manning et al. 2019). Such conditions that are more prominent in the Central and Mediterranean regions of Europe exhibited rapid changes in the soil moisture flash droughts (e.g. spatial extent) post-1980.

Our analysis, therefore, highlights the role of changing meteorological conditions, promoting soil-moisture flash drought events—specifically of the rising temperature and the precipitation deficit—both being crucial in driving soil moisture dryness (Weiss et al. 2009, Diffenbaugh et al. 2015, Williams et al. 2020), through their direct influence on the evaporative demand (Dai et al. 2018). Under a current climate scenario, as the greenhouse gas concentration is likely to continue increasing in the (near-) future, a direct impact of which will be on the increasing temperature in the coming decades (IPCC 2021). This could not only intensifies the flash drought events but also amplify their spatial propagation through land-atmosphere interactions (Miralles et al. 2019). Due to its nature of being spatially more coherent, changes in temperature, compared to precipitation are likely to impact more contiguous areas under droughts (Brunner et al. 2021). With unabated greenhouse gas emission and current pace of climate warming, an increased occurrence of the flash drought across Europe can be expected, requiring prompt response for effective drought adaptation and management strategies. Future studies can look at a detailed assessment of possible changes in flash drought characteristics under different emission scenarios.

Although we deploy ERA5, one of the best available reanalysis products which considers coupled land-surface-ocean interactions and provides seamless soil moisture simulations, there remains a conceptual limitation in the use of a single model parameterization for soil moisture processes (Samaniego et al. 2018). Thus, we encourage future works to consider multi-model evaluations to account for inherent model uncertainty. Furthermore, significant adverse impacts of flash droughts are felt in the agricultural sector—a prominent example of this is the widespread flash drought event of 2012 that occurred across the central United States, with reported losses of more than 30 billion USD (Otkin et al. 2018). To this end, our study has been limited to an assessment and documenting of the changes in flash drought characteristics across Europe. We nevertheless provide a showcase example on the potential exposure of crop- and pasture-lands to flash droughts across Europe (supplementary figure S17) which clearly depict an increasing trend of drought exposed areas in all three regions by almost two to three folds. However a full scale impact assessment considering the losses in crop growth and productivity is beyond the scope of the current work, and it remains crucial to further extend this study with a comprehensive impact analysis (e.g. on plant productivity, crop losses, and other vegetation activity, among others).
Data availability statement

ERA5 data used in the analysis can be obtained from the Copernicus Climate Change Service (C3S) Climate Data Store (www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). GLEAM data can be requested from www.gleam.eu.

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Author contributions

R K conceived and designed the study experiments; J S conducted the analysis with inputs from R K and O R; J S, V H and R K wrote the initial draft with inputs from O R; all co-authors commented and edited the manuscript.

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