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Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale☆

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ABSTRACT

Compound and cascading natural hazards usually cause more severe impacts than any of the single hazard events alone. Despite the significant impacts of compound hazards, many studies have only focused on single hazards. The aim of this paper is to investigate spatio-temporal patterns of compound and cascading hazards using historical data for dry hazards, namely heatwaves, droughts, and fires across Europe. We streamlined a simple methodology to explore the occurrence of such events on a daily basis. Droughts in soil moisture were analyzed using time series of a threshold-based index, obtained from the LISFLOOD hydrological model forced with observations. Heatwave and fire events were analyzed using the ERA5-based temperature and Fire Weather Index datasets. The data used in this study relates to the summer seasons from 1990 to 2018. Our results show that joint dry hazard occurrences were identified in west, central, and east Europe, and with a lower frequency in southern Europe and eastern Scandinavia. Drought plays a substantial role in the occurrence of the compound and cascading events of dry hazards, especially in southern Europe as it drives duration of cascading events. Moreover, drought is the most frequent hazard-precursor in cascading events, followed by compound drought-fire events. Changing the definition of a cascading dry hazard by increasing the number of days without a hazard from 1 to 21 within the event (inter-event criterion), lowers as expected, the maximum number of cascading events from 94 to 42, and extends the maximum average duration of cascading events from 38 to 86 days. We had to use proxy observed data to determine the three selected dry hazards because long time series of reported dry hazards do not exist. A complete and specific database with reported hazards is a prerequisite to obtain a more comprehensive insight into compound and cascading dry hazards.

1. Introduction

The summers of 2003, 2010, and 2015 are considered, and already comprehensively described, as the most notable years of the 21st century in west-central Europe and west Russia in terms of drought but also witnessed numerous heat-related deaths (Stott et al., 2004; Ionita et al., 2015) and extensive forest fires (Grumm, 2011; Turco et al., 2017; Fink et al., 2004). These events developed from a precipitation deficit that led to drought conditions and record-breaking temperatures in the summer (Beniston, 2004; Fink et al., 2004; Russo et al., 1950). The relatively dry and hot conditions also contributed to widespread wildfires across Europe and Russia (Witte et al., 2011; European Commission, 2004). Heatwaves, droughts, and fires, called 'dry' hazards hereafter, are characterized by common precursors: persistent below normal precipitation and elevated temperature. These hazards can occur simultaneously (concurrent or compound hazards) or sequentially, i.e. one following the others (cascading events). Here we define compound hazards as two or more extreme events occurring simultaneously, i.e. on the same day and in the same region, following the definitions from Ref. (Leonard et al., 2014) and Ref. (Liu and Huang, 2015). We define cascading events as two or more extreme events (as single and/or as compound hazards) occurring successively or cumulatively over time without being interrupted by a zero-hazard day. Compounding or cascading dry hazards are expected to have more

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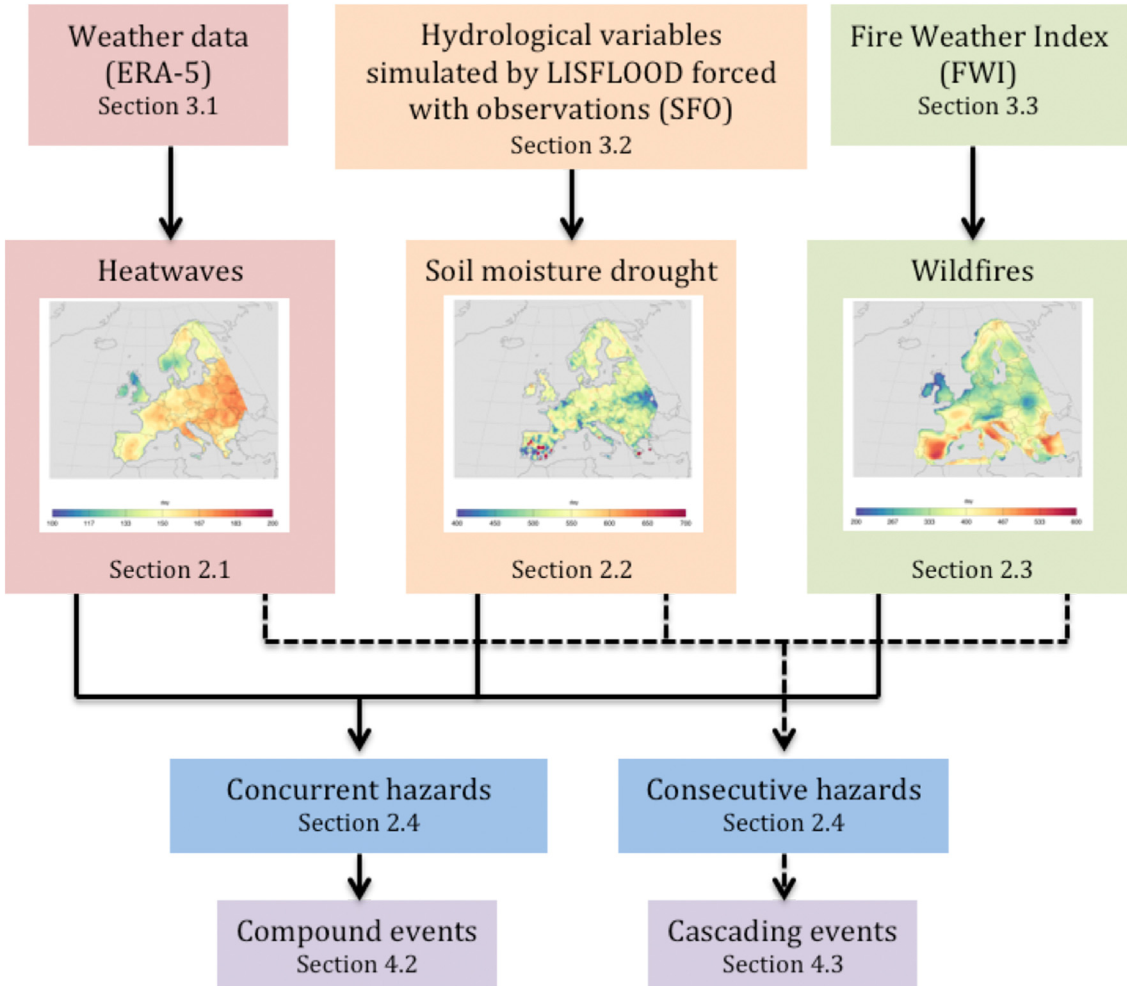

Fig. 1. Flowchart describing the methodology and data adopted in the study.

negative impacts (e.g. cumulative effects) than each of the hazards alone (Liu et al., 2016). For example, the drought that occurred in 2003 was not the most severe in Europe (Fink et al., 2004; Spinoni et al., 1950). However, in combination with extended heatwaves and fires, it is considered as the most fatal and costly. More than 70,000 people passed away as a result of extreme heat conditions (Robine et al., 2003; Di Napoli et al., 2018) and the economic damage exceeded 8.7 billion EUR (European Commission, 2007).

Despite the notable impacts of compound and cascading hazards, most studies have focused on single hazards due to the challenges of analyzing a multi-hazard framework (Kappes et al., 2012). A study by the World Bank shows that around 790 million people worldwide are highly exposed to two hazards and 105 million to three or more hazards (Dilley et al., 2005). Furthermore, the probability of dry hazards to simultaneously occur is expected to rise in the future due to an increase in global temperatures (AghaKouchak et al., 2014; Mazdiyasni and AghaKoucak, 2015; Forzieri et al., 2016; Zscheischler and Seneviratne, 2017). For the above reason, and in consideration of the Sendai Framework for Disaster Risk Reduction, highlighting the need for multi-hazard early warning systems for weather and climate extremes (Poljanšek et al., 2017), an urgent call has been broadcasted to researchers to assess compound disasters and the associated risks rather than focusing on single hazards (AghaKouchak et al., 2018). Ref. (Gill and Malamud, 2014) conducted the first comprehensive study to identify the interaction between 21 different natural hazards, including dry hazards. Their qualitative study was carried out based on disaster reports and literature reviews.

Some past studies on dry hazards mainly focused on two dry hazards only and its corresponding feedback mechanisms, i.e., between extreme high temperatures (or heatwaves) and drought, and between heatwaves and fires (AghaKouchak et al., 2014; Manning et al., 2018; Mazdiyasni and AghaKoucak, 2015; Miralles et al., 2018; Vautard et al., 2007; Vitolo et al., 2019; Miralles et al., 2012). Despite the clear importance of the topic, a pan-European study investigating the spatial distribution of dry hazards hotspots (i.e. areas prone to compound events, the probability of occurrence of compound hazards) and the propagation of single hazard into compound hazards and cascading events has not previously been undertaken. The definition of a practical approach to explore and assess the spatial distribution and the occurrence probability of compound and cascading dry hazards would be a step forward to prompt an efficient management of these events. One approach consists in providing mapping systems, in which users are able to explore multi-hazard interactions in a quantitative way. Ref. (Vitolo et al., 2019), for instance, propose a data-driven approach for analyzing historical and forecasted spatio-temporal concurrences of fires and heatwave-related stress. The study demonstrated that mapping concurrent heat-related events and fires can be instrumental to improve evidence-based decision making. The same study also highlights the need to analyze the patterns of dry hazards arising from historical occurrences. Here we aim to fill the gap and investigate the occurrence of the compound and cascading dry hazards across Europe through analyzing time series of historical data. The suggested analysis aims to give a better understanding of the occurrence and interactions of the dry hazards and contributes to fill the research gap on concurrent and cascading events (AghaKouchak et al., 2018; Zscheischler et al., 2018). A comprehensive approach assessing the occurrence and relation among the three dry hazards is barely explored and is the main focus and novelty of this work.

2. Methods

Dry hazard events occurring in the summer seasons (June, July, August; referred to as JJA hereafter) from 1990 to 2018 were analyzed at the pan-European level, with grid cells of 30 km by 30 km (35°N–72°N, 13°W–33°E, 164 lon x 131 lat). This is the period when high-impact heatwaves, droughts, and fires took place, which have led to high impact compound events.

The methodology to identify compound events can be summarized in two steps (modified from Ref. (Vitolo et al., 2019)):

(1) For each dry hazard, we independently analyze the spatial distribution and frequency of occurrences and create daily binary maps (details in Sections 2.1–2.3).
(2) For each day, we analyze the spatial overlap of the daily binary hazard maps to identify simultaneously occurrences of dry hazards (details in Section 2.4).
(3) Cascading events are then analyzed by looking at different combinations of hazard sequences (details in Section 2.5).

A flowchart describing the methodology, required data, and sections is presented in Fig. 1.

2.1. Heatwave occurrences

Although there is no commonly accepted definition for a heatwave, the exceedance of a climatological-based threshold for several consequent days is frequently used to distinguish heatwave days from non-heatwave days. In this study, a heatwave is defined as an event during which both daily maximum and minimum air temperatures at 2 m exceed the corresponding climatological 90th percentile for 3 days or longer. The choice of the mentioned percentile and minimum heatwave duration has been made in agreement with the current literature on the topic (e.g. (Lavaysse et al., 2018)). For each calendar day d, the climatological 90th percentile for maximum (resp. minimum) air temperatures at 2 m has been calculated from the daily air maximum temperatures at 2 m in a 9-day moving window centered on the day d. The moving window has been chosen in order to (a) account for the temporal variation of air temperature across the JJA season, and (b) remove possible artifacts due to the limited dataset (29 years). The result is a map of heatwave danger thresholds. If the reanalysis record of both daily maximum and minimum air temperatures at 2 m exceeds the threshold for a given location and day, that is considered as a heatwave occurrence.

2.2. Drought occurrences

Drought in soil moisture was calculated using the threshold-based approach (Yevjevich, 1967; Hisdal et al., 2004), which quantifies the magnitude of water deficits in different domains of the water cycle (e.g. soils). Based on this method, a drought event starts (ends) when the soil moisture falls (rises) below (above) a pre-defined threshold. We implemented the P80 as threshold value that is commonly used in drought studies (Hisdal et al., 2004; Van Loon and Van Lanen, 2012; Van Loon et al., 2012; Tallaksen and Stahl, 2013). The monthly P80 values are derived from the soil moisture values that are equal or exceeded in 80% of the time (80th percentile of the soil moisture duration curve). The 29 years time series of daily soil moisture was compared with the P80 thresholds to identify drought events. The result is a map of drought thresholds. If the soil moisture value exceeds the threshold for a given location and day, it is considered as a drought event. We applied a centered 30-days moving average to time series of soil moisture data to reduce the number of minor droughts.

2.3. Fire occurrences

The occurrence of dangerous fires depends on numerous factors, amongst which: dry weather conditions, availability of fuel (vegetation), and ignition agents. As the state of the vegetation changes very rapidly across seasons and ignition is considered a highly stochastic process (the majority of occurrences are caused by humans), many studies only refer to “fire weather” to quantify fire danger (Di Giuseppe et al., 2018; Field et al., 2015; Schroeder and Buck, 1970). Fire weather is a term used to identify conditions in which the combination of high temperature and wind speed, combined with a lack of precipitation and low relative humidity could cause a fire to spread beyond control. The Canadian Forestry Service (Van Wagner and Forest, 1987) developed the Fire Weather Index (FWI) system to rate fire weather. In this work, we will use the FWI index as a proxy for fire danger conditions. Admittedly, fire, drought, and heatwave danger indices (as used in this work) have common precursors (e.g. temperature) and are therefore expected to be correlated. However, FWI is not to be considered redundant because it is also designed to quantify other conditions, e.g. inflammability and ease-of-spread. For fire occurrences, we follow the same procedure as heatwave: we calculated the 90th percentile of the FWI reanalysis dataset for each day, taking into account 9 days centered on a given date. The result is a map of fire danger thresholds. If the reanalysis record exceeds the threshold for a given location and day, it is considered as a potential fire occurrence.

2.4. Analysis of compound events

As mentioned above, the first step is to identify the spatio-temporal occurrence of each hazard independently. We generated binary maps in which a cell contains the number 1, 2, or 4 (heatwaves, droughts, or fires, respectively) if the daily value of the hazard index is below a given threshold, and 0 (no hazard) otherwise. The second step consists of spatially overlapping the daily maps of individual hazards by summing up their values cell by cell. A compound event occurs in a cell if the sum is equal to 3, 5, 6 or 7. The value of 3 corresponds to a compound event in which a heatwave and drought occur simultaneously (1 + 2 = 3). A compound heatwave-fire event occurs when the value is equal to 5, and so forth. Table 1 summarizes all possible combinations of individual and compound hazards.

2.5. Analysis of cascading events

The evolution of dry hazards during a cascading event is analyzed by considering different combinations of hazard sequences. Any sequence made of at least two different numbers (or one number for compound hazard) and without being interrupted by a zero-hazard day is considered as a cascading event. Examples of cascading events and how we describe dry hazard patterns and evolution are presented in Table 2.

Table 1
Combinations of individual and compound hazards considered for analysis.

Value	Hazard	Abbreviation	Explanation
0	No hazard	–	No hazard occurred
1	Heatwave	H	Single hazard
2	Drought	D	Single hazard
4	Fire	F	Single hazard
3	Drought + Heatwave	DH	Compound of D-H
5	Heatwave + Fire	HF	Compound of H-F
6	Drought + Fire	DF	Compound of D-F
7	Drought + Heatwave + Fire	DHF	All concurrent dry hazards

Table 2
Examples of dry hazard combinations in cascading events. See Table 1 for hazard abbreviations

No	Example of cascading event	Hazard pattern	Hazard name
1	0, 1, 3, 3, 2,0	1, 3, 2	H-DH-D
2	0, 1, 1, 3, 3, 3, 2, 2, 2, 2, 0	1, 3, 2	H-DH-D
3	0, 2, 2, 2, 6, 6, 2, 0	2, 6, 2	D-DF-D
4	0, 1, 1, 2, 3, 3, 3, 7, 7, 3, 3, 2, 0	1, 2, 3, 7, 3, 2	H-D-DH-DHF-DH-D
5	0, 2, 2, 2, 2, 2, 2, 2, 4, 0	2, 4	D-F

Example number 1 and 2 indicate that different combinations of hazard values might result in the same hazard pattern, namely the combination of heatwave, compound drought-heatwave, and drought. The difference between Example 1 and 2 is that the latter occurs over a longer period of time compared to the former. Examples 3 and 4 show that drought (or other hazards) and the compound heatwave-drought (or other compounds) can appear twice in a cascading event, respectively. In Example 5, we show the case in which we identify a cascading event even if another single hazard (fire) only appeared once. Example number 5 also indicates that we counted a cascading event although it contains only at least two single hazards. In the present analysis, we did not control or pre-define the hazard pattern in cascading events, i.e. that ought to start with one of the hazards, but we focused on the most frequent hazard pattern on record.

3. Data

3.1. Weather data

Weather variables were used in this study as direct input to identify heatwaves. Data were obtained from a public dataset, ERA5 (Hersbach et al., 2019), generated and hosted by the European Centre for Medium-range Weather Forecasts (ECMWF). ERA5 is a reanalysis dataset (hereafter called proxy observed) that provides weather variables homogeneously distributed at the global scale (~30 km horizontal resolution), which are obtained from point-specific ground, ocean, atmosphere and satellite observations through the application of a data assimilation system based on the ECMWF Integrated Forecasting System and a 4-dimensional variational analysis (4D-Var). In this study, the following surface variables were retrieved for the European domain as a proxy for meteorological observations: the maximum temperature at 2 m (T_{max}) and the minimum temperature at 2 m (T_{min}). Both variables have a 3-h time resolution. Daily maximum (resp. minimum) temperatures at 2 m were obtained by finding the maximum (resp. minimum). This has been done for each summer day of the 1990–2018 period. The output is a dataset of 2668 pan-European maps of daily maximum (resp. minimum) temperature.

3.2. Hydrological data

The soil moisture data used in this study were obtained from the LISFLOOD model driven by Simulation Forcing with Observed (SFO). LISFLOOD is a state-of-the-art spatially-distributed rainfall-runoff hydrological model used within the European Flood Awareness System (EFAS) for flood monitoring and early warning system (De Roo et al., 2000; Thielen et al., 2009; der Knijff et al., 2010). More recently, LISFLOOD has also been used for drought monitoring and short-term forecasting under the European Drought Observatory (EDO (Sepulcre-Canto et al., 2012)) and seasonal hydro-meteorological drought forecasting under the EU funded ANYWHERE project (Van Hateren et al., 2019Sutanto et al., 2019). This model is run using interpolated raster information derived from meteorological observed data (>3,700 stations) and results in: (1) a proxy for European hydrological observed data (SFO), (2) hydrological initial condition (HIC) for the forecasts, and (3) the current state of the European hydrologic system. Model calibration was carried out using river discharge data in 717 catchments by tuning some model parameters. Calibration results on ~543 catchments show Kling-Gupta Efficiency (KGE) of more than 0.5 (Arnal et al., 2019).

The LISFLOOD-SFO system provides a wide-range of gridded hydrological variables, such as runoff, discharge, soil moisture, and groundwater storage, at 5 km by 5 km spatial resolution. In this study, we only used LISFLOOD-SFO soil moisture data from the top layer. Soil moisture from the top layer is highly influenced by atmospheric variability (Teuling, 2018). The LISFLOOD data were upscaled from 5 to 30 km to match ERA5 spatial resolution that is used for heatwaves and fires. The output is a dataset of 2668 pan-European soil moisture maps.

3.3. Fire danger

The European Centre for Medium-range Weather Forecasts (ECMWF) is the computational center for both the European Fire Forecasting System (EFFIS) and the Global Wildfire Information System (GWIS). As such, the center produces daily forecast and reanalysis products focused on fire danger (Di Giuseppe et al., 2018; Vitolo et al., 2019). Among these products, we selected the Fire Weather Index (FWI, based on the homonymous Canadian system(Van Wagner and Forest, 1987)) to quantify the occurrence of dangerous fire conditions. FWI is available with global coverage, although here we analyze a smaller extent (Europe). Daily FWI reanalysis data (hereafter called proxy observed) were collated for the period 1990–2018 (for consistency with the other datasets used in this study) then cropped over the region of interest (i.e. Europe). The output is a dataset of 2668 pan-European FWI maps.

4. Results

4.1. Hotspots of compound dry hazards

The total occurrence of single and compound hazards in the period 1990–2018 across Europe calculated as the number of days per hazard (or compound hazard) divided by the total number of JJA days (2668) is presented in Fig. 2. Fig. 2 shows that about a quarter of the cells in the European domain were affected by dry hazards at some point. Drought and fire are the most common single hazards (with 13.1% and 5.5% of the cells affected) followed by heatwave (1.2%). The compound of all three dry hazards accounts for not more than 0.6% of the cells over time. The total distribution suggests that, in Europe, dry hazards are expected predominantly to occur in isolation (19.8%) than in compound (5.1%).

In terms of spatial distribution, hotspot locations were calculated from the 90th percentile of the yearly number of days with concurrent hazards (P90) divided by the total number of summer days (92 days). We use the 90th percentile to show the extreme compound dry hazards in the period 1990–2018 for each grid cell. Fig. 3a shows that hotspot locations for compound drought-heatwave spread throughout Europe with a stronger signal in France, Italy, Spain, and east Europe. However, the occurrence of drought-heatwave is relatively small, ranging from 0 to 4%. An interesting result is found for compound heatwave-fire (Fig. 3b). Hotspots are clearly identified in the Scandinavian countries, and to some extent in Portugal and Sicily Italy. The number of heatwave-fire occurrences is twice as high compared to drought-heatwave, especially in northern Europe (up to 8%). The compound event with the highest occurrence in Europe is drought-fire (Fig. 3c). Large extents of concurrent drought-fire hotspots are clearly identified in central Ireland, southeastern UK, parts of Germany, southeast France, western Italy, and southeastern Europe. The Iberian Peninsula is not listed as a hotspots area although they also suffer from compound drought-fire events (Pausas and Fernández-Muñoz, 2012; Gudmundsson et al., 2014). In this region, the occurrence of drought-

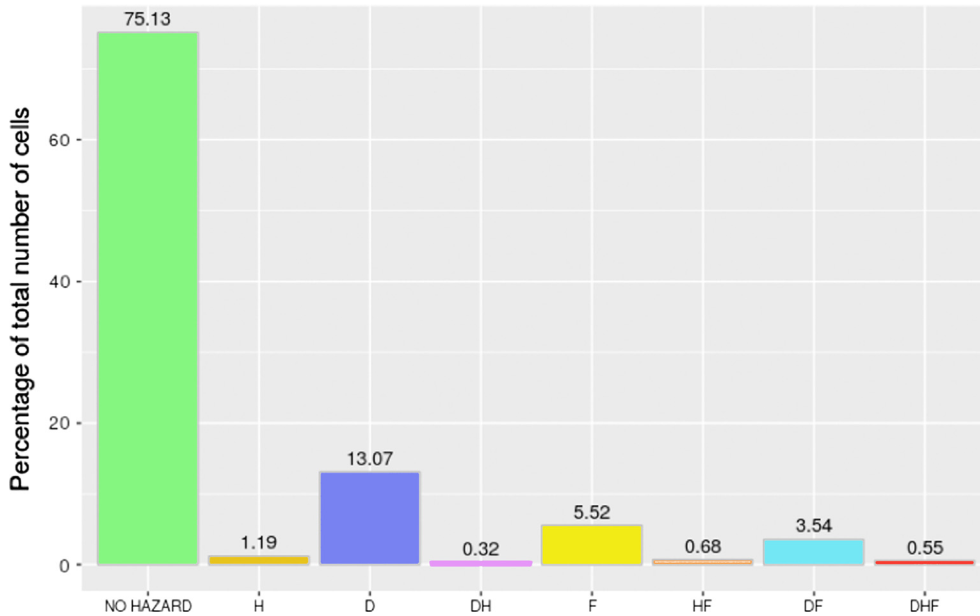

Fig. 2. Total occurrence of single and compound hazards, calculated as the number of days per hazard (or compound hazard) divided by the total number of JJA days (2668) over the period 1990–2018 across Europe. See Table 1 for hazard abbreviations.

fire is less than in central Europe.

Fig. 3d shows the hotspots of all three dry hazards concurring. Compound dry hazards mainly occurred in large parts of west, central, and east Europe, from southern UK, France, Germany, Italy, to Romania and Bulgaria, and less frequent in southern Europe, such as Spain, and eastern Scandinavia. Care is needed when interpreting the hotspots. Fig. 3 was plotted based on the occurrence of each type of (compound) hazard (1–7, Table 1) taken from overlapping the daily maps of individual hazards. By doing this, the occurrence of double hazards (e.g. drought-heatwave, number 3) in a specific cell is not counted if the third hazard occurs as well (in the example, a fire hazard) in the same grid cell. This cell will be counted under all dry hazards (number 7, Fig. 3d).

4.2. *Cascading events of dry hazards*

4.2.1. *Hotspots and frequency*

Besides investigating the hotspots of concurrent dry hazards (Section 4.1), the hotspots of cascading event occurrences were also determined. These were defined by calculating the total number of cascading events (Fig. 4a) and the mean of the average annual durations of cascading events in days (Fig. 4b) in each grid cell. Our analysis shows that around 70 to a maximum of 90 cascading events occurred in most parts of mid-Europe, from the UK to central and east Europe. In the Mediterranean countries, such as Spain, Italy, and southeastern Europe, only 40 to 50 events were identified during 1990–2018. Fig. 4 shows that regions characterized by a lower number of cascading events (Mediterranean countries compared to mid-Europe, Fig. 4a), experience longer-lasting cascading events (Fig. 4b). The average duration of cascading events in the regions with a low frequency of cascading events is 15–20 days, which is 10 days longer than the regions with a higher occurrence of cascading events. We anticipate that drought plays an important role in these frequencies and durations. Studies by Ref. (Van Loon et al., 2012) on drought propagation and characteristics demonstrated that regions experiencing few drought events have longer drought duration.

Fig. 5 shows the 90th percentile of the average frequency of heatwave, drought, and fire during cascading events in the period 1990–2018. Droughts have the highest frequency of occurrence in cascading events. Heatwaves did mostly occur during dry hazard cascading events in the Mediterranean countries, such as the south of Spain, Portugal, Sicily, and Greece (Fig. 5a). Interestingly, the north of Europe also has a high frequency of heatwaves during cascading events. Drought events, on the other hand, appeared most of the time during cascading dry hazards in the Mediterranean countries (Fig. 5b). Some mountainous areas in Norway (red spots) also present high drought frequency. Fires appear mostly in northern Europe, northern UK, and in some parts of central Europe (Fig. 5c).

In contrast to Fig. 5 that shows the 90th percentile of each of the three dry hazards during cascading events, Fig. 6 shows the frequency of concurrent dry hazards (⩾2 hazards on the same day) in cascading events. The compound drought-fire happened most frequently. Concurring drought-heatwave in cascading events occurred less frequently compared to others, with a frequency of 1–2 events spotted in some parts of Europe (Fig. 6a). The compound heatwave-fire hazard appeared 2 times higher than concurrent drought-heatwave and affected regions mainly in Spain, Portugal, Sicily, Greece, and in the Scandinavian countries (Fig. 6b). The frequency of concurrent drought-fire hazard and corresponding hotspots mainly occurred in the UK, western Spain, Italy, Belgium, northern Germany, and in southeastern Europe (Fig. 6c). The compound of all dry hazards in cascading events mostly occurred in northern Portugal, France, Germany, Italy, Bulgaria, and Romania, with a frequency of 3 events in the study period (Fig. 6d).

4.2.2. *Cascading event patterns*

Understandably, the high occurrence of concurrent drought-fire (DF) in cascading events (Fig. 6c) appears also in the cascading patterns of dry hazards, as obtained by summing up the number of cascading events in the JJA periods of 1990–2018 across Europe, i.e. at all grid cells (Table 3). DF can be found in 7 out of 10 of the most frequently occurring patterns of cascading events. Most cascading events in Europe are dominated by the occurrence of drought in the beginning, i.e. they start with drought, followed by the compound drought-fire (D-DF, Table 3 row 1). This cascading pattern occurred 5.9%, or 32,584 events out of 555,931 events multiplied by 100%, calculated from all land grid cells and from 2668 days. Cascading patterns starting with fire (F) and heatwave (H) are found at rank 3 and 5 with an occurrence of 4.5% and 4.05%, respectively. Interestingly, there is a high number of events that started with fire and ended up with drought (F-D, 4.5%). This cascading event occurred only for short periods as the frequency of fire occurring

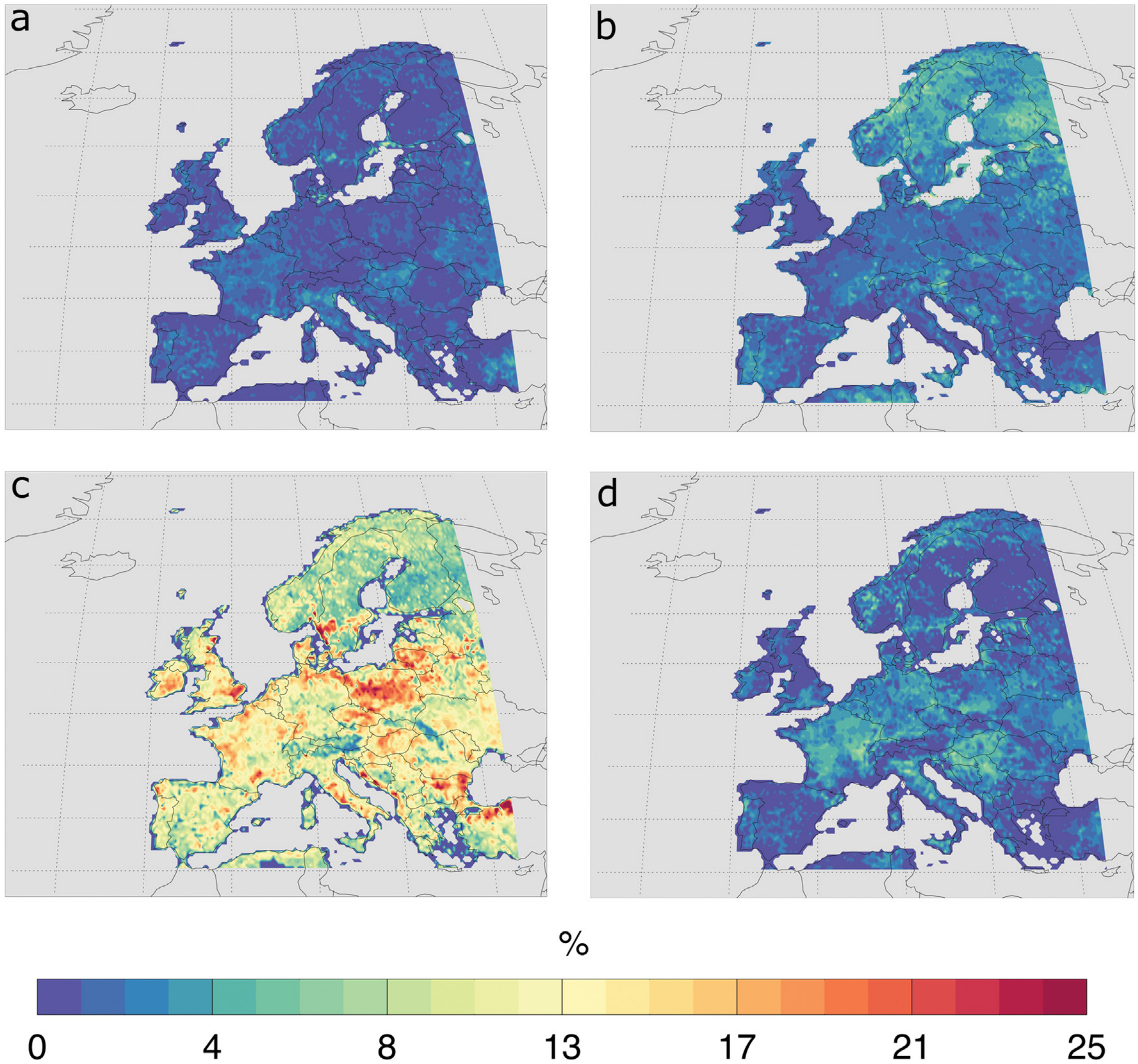

Fig. 3. Hotspots of compound dry hazards (P90, in %, of yearly number of compound days for each year/total number of summer days (92 days) × 100). (a) Hotspots of compound drought-heatwave, (b) hotspots of heatwave-fire (c) hotspots of drought-fire, and (d) hotspots of the three dry hazards all together in Europe obtained from daily proxy observed datasets (Section 3) covering the JJA periods of 1990–2018.

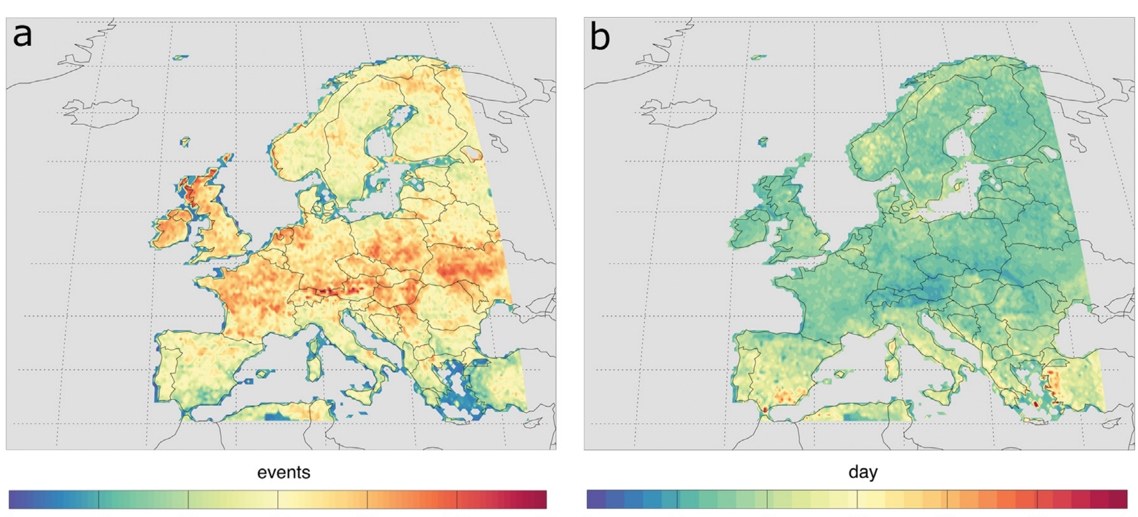

Fig. 4. (a) Total number of cascading dry hazards and (b) mean of the average annual durations of cascading events (in days) in Europe calculated from daily proxy observed datasets (Section 3) covering the JJA periods of 1990–2018. To compute the mean of the average annual duration of cascading events per grid cell, we calculated the average duration of cascading events for each year, and then averaged the result over 29 years.

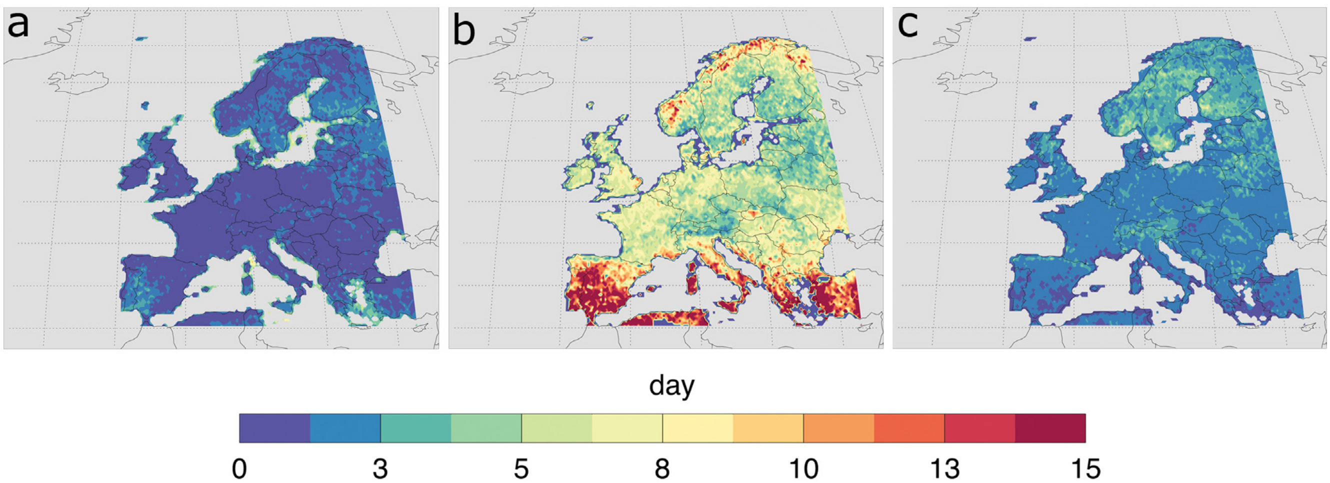

Fig. 5. The 90th percentile (P90) of occurrences during cascading dry hazards in Europe, (a) heatwave, (b) drought, and (c) fire, calculated from daily proxy observed datasets (Section 3) covering the JJA periods of 1990–2018. The P90 of the average frequency of dry hazards was determined by calculating the average number of dry hazard occurrences during cascading events for each year per cell, and then by computing the P90 from the yearly results.

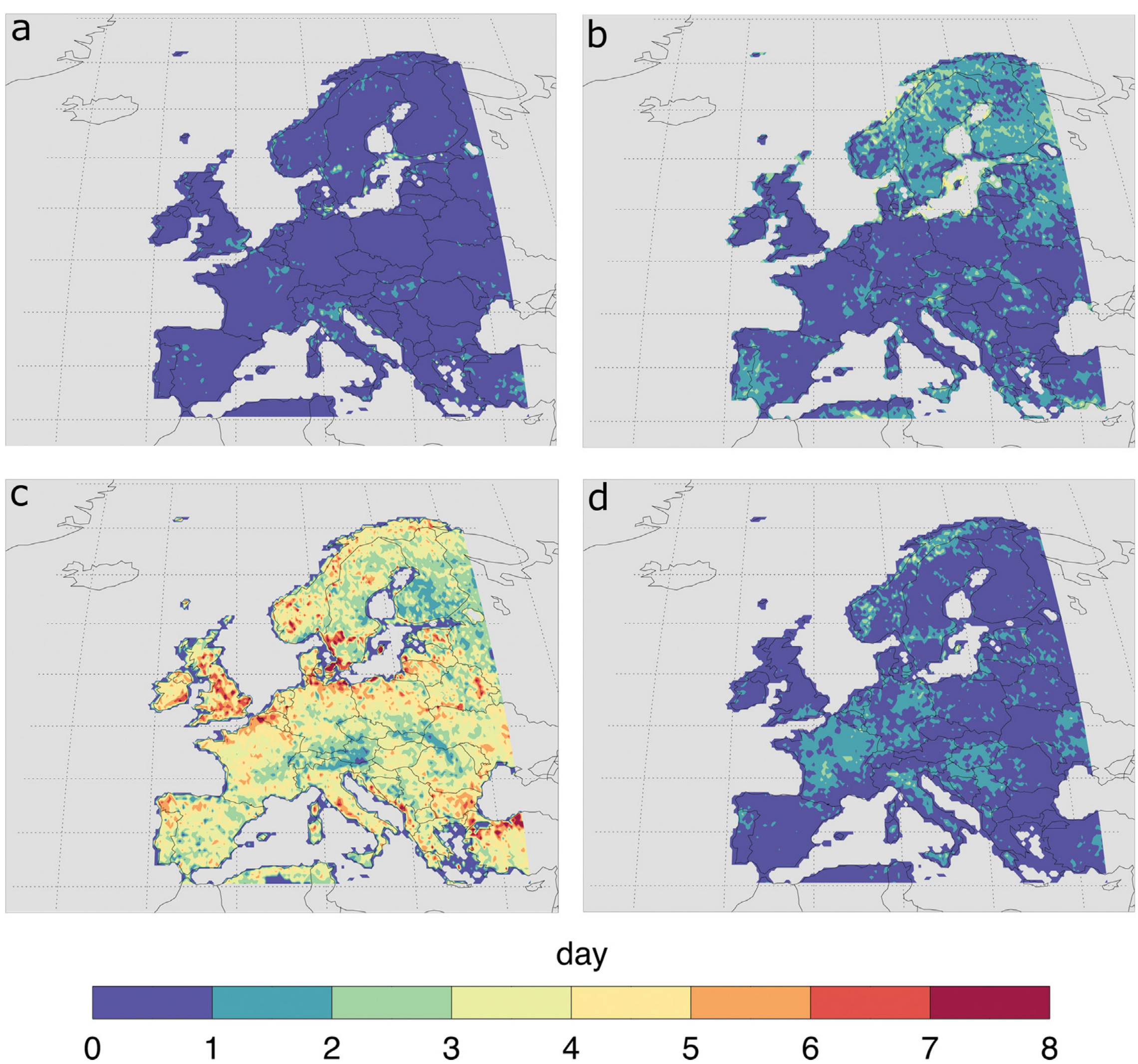

Fig. 6. The 90th percentile (P90) of compound dry hazards occurrences during cascading events in Europe, (a) drought-heatwave, (b) heatwave-fire, (c) drought-fire, and (d) all dry hazards, calculated from daily proxy observed datasets (Section 3) covering the JJA periods of 1990–2018. The P90 of the average frequency of dry hazards was determined by calculating the average number of dry hazard occurrences during cascading events for each year per cell and then by computing the P90 from the yearly results.

Table 3
The most frequent cascading patterns of dry hazards in Europe calculated from daily proxy observed datasets (Section 3) covering the JJA periods of 1990–2018. See Table 1 for hazard abbreviations.

No	Cascading pattern	Number of events (–)	Number of events (%)
1	D-DF	32584	5.9
2	D-DF-F	31247	5.6
3	F-D	24817	4.5
4	D-DF-D-DF	22877	4.1
5	H-HF	21989	4.0
6	F-DF	20501	3.7
7	DF-D	19213	3.5
8	DF-F	14860	2.7
9	F-DF-D	7589	1.4
10	HF-H	7257	1.3

in a cascading event is relatively low compared to drought (see Fig. 5b and c).

5. Discussion

5.1. The occurrence of compound and cascading dry hazards

The occurrence of concurrent dry hazards (heatwaves, droughts, and fires) is evident in west and east Europe. France, for instance, suffered from big losses in terms of total damage and deaths (4.4 billion USD damage and 19,495 fatalities, respectively; (EM-DAT, 2018)) in 2003 because of compound dry hazards. Fires hit across the country from 28th of July to 30th of July 2003, followed by a heatwave and a drought from 1st of August to the 20th of August 2003. This dry hazard cascading event in France demonstrates that fires may appear before drought and heatwave events (see Table 3 number 3, 6, and 9). This is in agreement with the findings here described that either drought or fire events tend to appear first in cascading events. We believe, however, that the probability of fire appearing first (4.5%, Table 3) as quantified in this study is too high, close to drought (5.9%), as fires rarely start without the triggers from both natural (e.g., temperature and moisture) and anthropogenic activities (non-intended and intended ignition). It should be noted that the appearance of concurrent dry hazards will most likely increase in the future. The increase in these compound events is linked with the increase in temperature associated with climate change (Mazdiyasni and AghaKoucak, 2015; Zscheischler and Seneviratne, 2017), which is a common driver for all dry hazards.

5.2. Drought as the main driver in cascading events

We also found that regions in mid-Europe, identified by a high number of cascading events, have short cascading event durations. On the other hand, Mediterranean regions have a low number of cascading events and longer durations (Fig. 4). These regions are characterized by a high number of heatwave and drought occurrences in cascading events (Fig. 5a,b). The number of heatwaves appearing in the cascading events, however, is relatively small compared to drought. Drought also takes the lead as the most frequently occurring hazard in a cascading event. Drought is also the first hazard appearing in cascading events, followed by concurrent drought-fire (DF, Table 3). Thus, we postulate that drought plays an important role in cascading dry events. Fire is placed at the top ranks as the most occurring last hazard in a cascading event (rank1 DF, rank 2 F, Table 3), which is plausible since fires are frequently categorized as an associated hazard to drought and heatwave (Xiao and Zhuang, 2007; Pausas and Fernández-Muñoz, 2012; Gudmundsson et al., 2014). In our analysis, the occurrence of drought followed by concurrent drought-heatwave is not listed as the most occurring cascading events (Table 3), However, the concurrence of drought-fire occurred in some places in Europe (Fig. 6a). Heatwaves can be enhanced by dry soils (less latent heat and more sensible heat) via land–atmosphere feedback mechanism (Alexander, 2011; Seneviratne et al., 2006; Teuling, 2018).

Our results support the argument that drought may accelerate a heatwave and not vice versa. High temperature accelerates soil drying and in turn warms the atmosphere by gaining less water from evaporation (Miralles et al., 2018; Teuling, 2018). Increase in the atmospheric demand for evaporation exacerbates high temperatures leading to a heatwave (Miralles et al., 2014). A study by Ref. (Rasmijn et al., 2010) shows how high temperatures can rise when droughts become even more severe.

5.3. Importance of disaster databases

Our study used proxy observed data to analyze the “potential” occurrences of dry hazards. This indicates that the hazards identified in our study presumably did not always happen in the past. The availability of observational data of hazard occurrences constraints studies on probabilities of single hazards and joint probabilities of compound natural hazards. One of the possible solutions is collecting (multi-) disaster occurrences as it has been done by the international disaster database (EM-DAT), that has collected the occurrence and effects of over 22,000 mass disasters in the world from 1900 to the present day, which were compiled from various sources (Jonkman, 2005). However, a disaster is only reported in EM-DAT if it fulfills at least one of the following criteria: (i) ten or more people were killed, (ii) one hundred or more people were reported affected, (iii) state of emergency was declared, or (iv) there was a call for international assistance. Based on these criteria, disaster occurrences, therefore, were not always reported or compiled in this database. The use of different languages in the local reports, newspapers, or media may represent another barrier in compiling a complete and spatially consistent disaster databases.

Another solution could be to combine separate dry hazard databases, reporting on individual hazard occurrences only. The European Drought Impact Inventory (EDII), for example, reports drought impacts in Europe for different categories, such as water-borne transportation, water quality, forestry, agriculture and livestock farming, and public water supply (Stahl et al., 2016). Another disaster-specific database is the European Forest Fire Information System (EFFIS), which provides insight into ongoing fires, as well as the fire history database (San-Miguel-Ayanz et al., 2013). However, there might be disparities on reported hazards in each database. Collaboration of European institutions to provide comprehensive information in the disasters database and to narrow the challenges in the trans-national data sharing on transboundary impacts of large-scale disasters in Europe, therefore, are at the utmost importance.

5.4. Limitations of the study

We defined a cascading event as an event between zero values in the series of dry hazard occurrences. The cascading event stops when there is one zero value (one day with no dry event). In reality, the cascading event may still develop further even after a short discontinuity, e.g. after one day with no hazard occurrence, which might be very relevant in terms of impacts on society. How many zero days without a dry hazard that are required to stop a cascading event (i.e. inter-event criterion), however, has never been documented in the literature. In this study we investigated this by changing the definition of a cascading event by assuming that a cascading event would not be interrupted when there are zero values from 1 day to 7 days (a week), 14 days (2 weeks), and 21 days (3 weeks). The results are presented as the 90th percentile (P90) and maximum (P100) of a number of cascading events and average duration of cascading events. The P90 and P100 of average durations of cascading events was determined by: 1) calculating the yearly average duration of cascading events (day) per year for each grid cell and then 2) calculating the P90 and P100 of these yearly average durations of cascading event from all grid cells. As expected, increasing

Table 4
The number of cascading events and average duration for a different number of zero hazard occurrences in between two cascading events (inter-event criterion) obtained for the period 1990–2018.

No	Number of zero days between events	Number of cascading events (–)		Average duration of cascading events (day)	
		Max	P90	Max	P90
1	1	94	60	38	11
2	7	69	44	86	33
3	14	52	36	86	50
4	21	42	32	86	64

the number of zero values from 1 to 21, i.e. more days without a dry hazard, lowers the number of cascading events and extends the average duration (Table 4).

We also used threshold-based values by employing methods and experiences that are most widely used in the scientific literature to derive the three selected dry hazards, which involve that the exceedance frequencies for drought differ (80th percentile) from those employed for heatwaves and fires (90th percentile). The use of a lower or higher threshold for a hazard may lead to different findings. For example, the use of a higher threshold value for drought might reduce the number of drought events and change the magnitude of drought characteristics (e.g. duration and severity) (Van Loon and Van Lanen, 2012). Similarly, the use of a different threshold value for heatwaves, such as the 95th percentile (e.g., Ref. (Guerreiro et al., 2018; Di Napoli et al., 2019)), will affect the occurrence of heatwaves.

It is also worth noting that high temperatures are not necessarily classified as heatwaves. In agreement with the methodology generally adopted in heatwave-related research (Perkins and Alexander, 2013), the percentiles used in this study to define a heatwave hazard are derived from climatology and are specified for each grid cell and each day (geographically and daily variable threshold). Because of this, the 90th percentile of air temperature in northern Europe is lower than the corresponding 90th percentile in southern Europe, and heatwaves in northern Europe might be associated with lower temperatures than southern Europe. This relative concept is also applied to drought and fires. The vulnerability in the north (wetter) is higher than in the south (drier), which seems to be reasonable because society in the south is better adapted to high temperatures and drier conditions than in the north. In addition, forests in the north are more vulnerable to fire than in the Mediterranean climate.

6. Conclusions

Compound and cascading hazards potentially trigger significant impacts relative to single hazards. This paper aims to explore the characteristics of the compound and cascading dry hazards, namely heatwaves, droughts, and fires, at the pan-European scale. Dry hazard hotspots were identified largely for an area stretching from west to east Europe, from southern UK, France, Germany, Italy, to Romania and Bulgaria, and with a lower frequency in southern Europe, such as Spain, and eastern Scandinavia. In the study period 1990–2018 (JJA), 0.55% of all cells had an occurrence of all dry hazards in the same day. Droughts dominate in the compound and cascading dry hazard events and mainly control the number and duration of cascading events, especially in the Mediterranean. In most cascading events drought appears first as a single hazard, followed by the concurrent drought-fire. This leads to a combination of drought, and drought-fire, as the most frequent cascading pattern of dry hazards in Europe (5.9%).

We had to use proxy observed data to determine the occurrence of the three selected dry hazards, as long and complete time series of observed/reported dry hazards do not currently exist. The use of different databases, with reports for each of the dry hazards as an alternative, may lead to disparities in the results. We suggest an international collaboration to collate data on hazards and to store these in a consistent and easily accessible database. Moreover, the use of real observations, such as from radars, satellites, and gridded at site observations, is encouraged.

This work is the first pan-European study that aims to provide a continental-wide view of the compound and cascading dry hazards. It presents a novel methodology for the identification of hotspots and the assessment of hazard patterns that can be useful to determine relationships among natural hazards. It also aims to support disaster risk reduction, as encouraged by the UN Sendai Framework. We anticipate that the methodology can also be applied to other hazard types, e.g. wet-related hazards (flash floods, floods, landslides, storm surges).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envint.2019.105276.

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