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ORIGINAL ARTICLE

Climate Extremes are Becoming More Frequent, Co-occurring, and Persistent in Europe

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Abstract

With global warming, many climate extremes are becoming more frequent, often co-occurring, or repeatedly occurring in consecutive years. However, only limited studies have investigated these changes of climate extremes together. We study these changes in Europe for the last seven decades (1950–2019) based on 39 climate indices to identify climate extreme hotspots and coldspots. These indices belong to the four climate index groups: cold, heat, drought, and precipitation. Compared to the first half of the study period (1950–1984), most of our study locations faced heat extremes that are more frequent and occurring in consecutive years in the second half (1985–2019). However, the number of cold extremes has decreased in most locations. Simultaneously, some locations, mainly the Mediterranean region, faced an increase in droughts while others, e.g., parts of Eastern Europe and Northern Europe, experienced more intense precipitation. Two or more of these cold, heat, drought, and precipitation extremes have also co-occurred in a few locations of our study area in the same year. Our study highlights that climate extremes are becoming more frequent, co-occurrent, and persistent in Europe. These changes in climate extremes are associated with climate change. Therefore, we could infer that climate change mitigation is crucial for limiting these extremes.

Keywords Climate extremes · Climate indices · Climate change · Compound extremes · Co-occurrence · Persistence

1 Introduction

Globally, climate extremes are changing with global warming, including their frequency, intensity, spatial extent, duration, and timing (Seneviratne et al. 2012). For example, climate extreme trends show a decrease in the number of cold nights, but an increase in the number of warm ones in most locations across the globe (Seneviratne et al. 2012; Alexander et al. 2006; Easterling et al. 2000). In recent decades, more locations are facing an increased number of heavy precipitation events, but with regional variations (Seneviratne et al. 2012; Alexander et al. 2006; Easterling et al. 2000). These changes in climate extremes are projected to become more pronounced in a warming world (Sillmann et al. 2013). The frequency of climate extremes increases with global warming (Seneviratne et al. 2012; Rahmstorf and Coumou 2011), e.g., droughts (Dai 2011, 2013), heat waves (Ga 2004; Kirtman et al. 2013), extreme precipitation events (Kirtman et al. 2013; Myhre et al. 2019). Social, economic, and environmental systems are and will be negatively impacted by these climate extremes (Easterling et al. 2000).

Climate extremes are becoming more frequent and increasingly co-occurring with global warming, resulting in compound hazards (AghaKouchak et al. 2020; Forzieri et al. 2016). For example, most locations in Canada have experienced the co-occurrence of temperature and precipitation extremes, showing positive relationships between warm days and heavy rainfall events (Tencer et al. 2014). Similarly, a few locations in Europe have faced droughts, heatwaves, and wildfires in the same year during the period 1990–2018 (Sutanto et al. 2020). These co-occurring extremes, i.e., occurrence of different types of climate extremes in the same location in the same year, are projected to increase in

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Europe with global warming (Forzieri et al. 2016). However, only limited studies have accounted for co-occurrences of climate extremes, resulting in underestimation of their impacts (Zscheischler et al. 2018). For example, Johnson et al. reported an increase in cold and heat extreme occurrences in recent decades (Johnson et al. 2018). However, it is unclear whether or not they are co-occurring, i.e, cold and heat extreme occurrences in the same year in the same location. A recent review highlights this gap in understanding and quantifying changes in climate extreme co-occurrences (Chen et al. 2018).

Similar to co-occurrences, a climate extreme event can occur in the exact location in consecutive years, here defined as *persistence of climate extremes* (Beniston and Goyette 2007). With global warming, an increase in the frequency of climate extremes leads to a decrease in return period (Lehner et al. 2006), resulting in more persistent climate extremes. For example, consecutive record-breaking high temperatures have been observed globally in recent years (Su et al. 2017). However, limited studies have investigated changes in such persistence of climate extremes. This research gap also holds to investigate aggregated changes of climate extremes, i.e., frequencies, co-occurrences, and persistence together.

We aim to fill the above-highlighted research gaps by investigating changes in climate extremes in Europe, considering the aggregated changes for the last seven decades. Our primary research objective is to estimate changes in cold, heat, drought, and precipitation extremes. Our next objective is to identify hotspots and coldspots for climate extremes in Europe based on these changes. We derive the climate extremes based on climate indices that are simple measures for climate variability (Hansen et al. 1998).

2 Data and Methods

2.1 Data

We obtain data on the European gridded observational (E-OBS) climate indices (version 22.0e) from the Copernicus Climate Change Service (C3S). These climate indices are derived from the E-OBS data on daily minimum temperature, daily maximum temperature, and daily precipitation for 1950.01.01–2020.06.30 (Cornes et al. 2018). The C3S provides the best estimate for the climate indices on a 0.1° regular grid, considering the median of the dataset based on the first 20 out of 100 members of the E-OBS ensemble. The data covers the area between the latitudes 25° N and 71.5° N and the longitudes 25° W and 45° E. These ensemble datasets consist of multiple equally probable interpolation of climate station data to gridded values.

We base our study on 39 climate indices belonging to four climate index groups that correspond to various aspects of climate change (Table S1). These groups are cold, heat, drought, and precipitation consisting of 11, 9, 4, and 15 climate indices, respectively. The C3S provides these different number of indices for the four groups following the definitions recommended by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices. Data for most indices are provided as annual, seasonal, and monthly values. However, indices on cold spell duration, warm spell duration, consecutive dry days, consecutive wet days, and growing season length are only available as annual values. Similarly, data on standardized precipitation index (SPI) are given only as monthly values. Therefore, we conduct our analysis based on annual values, besides SPIs, to use all indices. Our study uses the data for 1950–2019.

2.2 Methods

We define a climate extreme as a climate index value beyond two standard deviations of the mean for the baseline period 1961–1990 (Fig. 1) . The World Meteorological Organization recommends to use the 1961–1990 period as a baseline for the purposes of historical comparison and climate change monitoring (WMO 2017). We consider a location has a climate extreme for a particular climate index in the year if its value is greater or smaller than two standard deviations of its mean. This relative measure for "extremeness" has the advantage of identifying (generically) the range of events for which socio-ecological systems are not used to. Therefore, they would have a low adaptation potential for these events, resulting in considerable impacts. Studies addressing a broad range of potential climate extreme impacts employ these relative measures because absolute index thresholds are highly variable in space and impacted realm (Seneviratne et al. 2012). Therefore, we choose a two standard deviations threshold to obtain reasonable numbers of events, resulting in a near-Gaussian distribution in the 2.3 (97.7) percentile. Many studies used this approach to investigate climate extremes (Batibeniz et al. 2020; Rifai et al. 2019). Since SPI is a probability index with values ranging from − 3 to + 3, we consider the values greater than + 2 or smaller than − 2 as climate extremes. This consideration is similar to taking two standard deviations. The SPI data are also based on the reference period 1961–1990.

We start with analyzing the changes at an index level by identifying locations and years with climate extreme for each climate index. The analyses are carried out for the whole area covered by the data. Our climate extreme definition accounts for greater and smaller values than the two standard deviations of its mean. These values can have different meanings in the context of the severity of climate extremes, depending on the index. For example, a smaller value of "minimum value of daily maximum temperature" or a greater value of "frost days" will lead to a

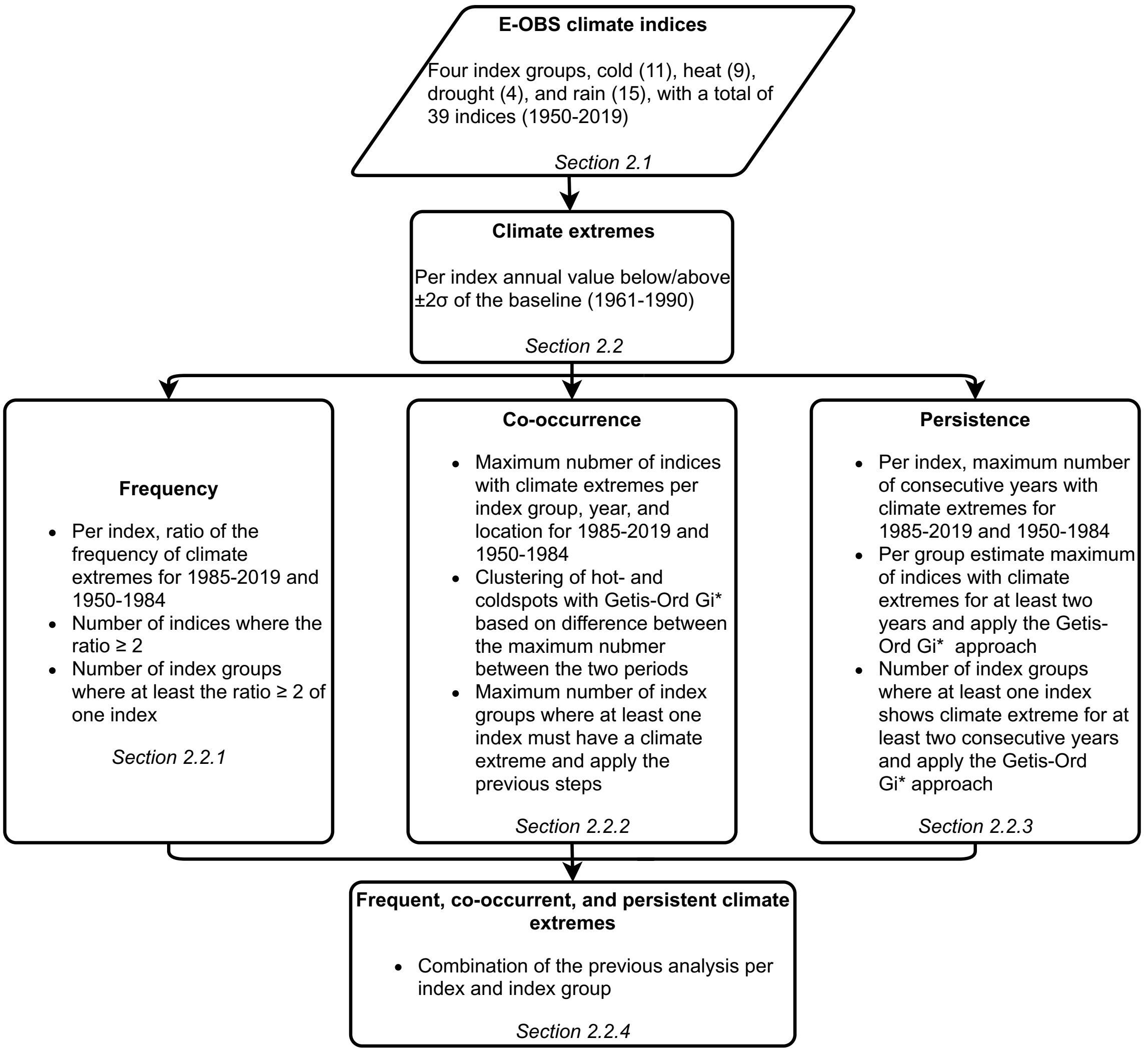

Fig. 1 Flowchart depicting the data and methodology applied in the study

cold extreme. We introduce a sign for each climate index, accounting for this different meaning (Table S1). A positive sign indicates the greater value than the two standard deviations of its mean as the upper end of the severity of climate extreme and vice versa. Similarly, a negative sign reflects the greater value as the lower end of severity and vice versa. We identify climate extreme hotspots accounting for changes in frequency, co-occurrence, and persistence of climate extremes between the first and the second half of the study period (i.e., 1950–1984 and 1985–2019, respectively), considering effects of climate change on climate extremes (Ren et al. 2018). These changes are identified for each grid, and the spatial analysis was conducted by counting the number of grid cells. Our analysis considers the upper and lower ends separately.

2.2.1 Frequency of Climate Extremes

We estimate the ratio of climate extreme frequency in the second half to that in the first one (Fig. 1). The ratio above one represents that climate extremes are more frequent in the second half. Some locations only have climate extremes in the second half, resulting in divergent ratios, with an undefined value. In such cases, we only consider the locations with the climate extreme frequency larger than two in the second half by omitting the division by zero cases and assuming the undefined value as greater than two. This consideration is an attempt to capture hotspots with increased climate extremes in the second half and avoid climate extremes that might be due to a chance. Afterward, we count the number of climate indices for each location with a ratio greater than or equal to two within each climate index group. For example, we identify the number of indices out of 11 cold indices with a ratio greater than or equal to two for each location. For characterizing the hotspots based on the four climate index groups, we count the number of climate index groups with at least one of its climate indices showing the ratios greater than or equal to two. In terms of frequency, that means our hotspots show the number of climate index groups consisting of at least one index with an increased frequency of climate extreme by two times or more in the second half compared to the first half of the study period.

2.2.2 Co-occurrence of Climate Extremes

To analyze changes in climate extreme co-occurrences, we count the maximum number of the indices exhibiting climate extremes within each climate index group for the same location and year (Fig. 1). We define co-occurrences as occurrences of different climate extremes in the same location within the same year. These extremes could, however, occur at different times in the year, e.g., heat extremes in summer and cold extremes in winter. The maximum of the annual maxima is calculated for each location for both halves of the study period. For each index group, the differences in the maximum value between the second and the first half define hotspots and coldspots. We perform the Getis-Ord Gi* analysis to identify hotspots and coldspots throughout the study (Ord and Getis 1995). The analysis returns a z score of each location accounting for its neighborhood, in our case, a search radius of 0.2°. A z score above 1.96 and below − 2.81 indicate hotspots and coldspots significantly at a confidence interval of 95%, respectively. Here, hotspots are spatial clusterings of locations with an increase in climate extreme co-occurrences in the second half of the study period. Similarly, coldspots depict clustering of decreased climate extremes in terms of the co-occurrence. Our study also characterizes the co-occurrence hotspots and coldspots, accounting for the four climate index groups. For this, we consider co-occurrence as climate indices from the different groups depicting climate extremes in the same location and year. Following this consideration, we count the number of the climate index groups having co-occurrences for each location for both halves of the study period. By applying the Getis-Ord Gi* analysis described above, we identify the co-occurrence hotspots and coldspots.

2.2.3 Persistence of Climate Extremes

To investigate climate extreme persistence changes, we derive the maximum number of consecutive years with climate extremes for each climate index for both halves of the study period for each location. Afterward, we estimate the maximum number of the indices exhibiting climate extremes for at least two consecutive years within each climate index group for each location. Applying the Getis-Ord Gi* analysis described in Sect. 2.2.2, hotspots and coldspots are identified as the differences in the maximum value between the second and the first half for each group. We also characterize the persistence hotspots and coldspots, accounting for the four climate index groups. For each location, we count the number of climate index groups with at least one of its climate indices showing climate extremes for at least two consecutive years. Following the Getis-Ord Gi* analysis, we identify the persistence hotspots and coldspots based on the differences between the number of climate index groups for the second and first halves of the study period.

2.2.4 Frequent, Co-occurrent, and Persistence Climate Extremes

In the above analyses, we investigate the three features of climate extremes, i.e., frequency, co-occurrence, and persistence, separately. However, these features can occur together for some climate indices. Thus, we analyze changes in the three features together between the first and the second half of the study period, following three steps. First, we estimate climate extreme frequency ratios between the second and the first half for each climate index. We also derive differences in the maximum number of consecutive years with climate extreme between the second and the first half for each climate index. Second, our analysis estimates the maximum number of the indices that depicts climate extreme within each climate index group for the same location and year. We also derive differences in the maximum number of indices showing climate extreme between the second and the first half for each group. Third, our study characterizes frequent, co-occurrent, and persistent climate extremes, accounting for the four climate index groups. For each location, we count the number of the groups with at least one of its climate indices having the ratios greater than or equal to two, the differences in the maximum number of consecutive years greater than or equal to one, and the differences in the maximum number of indices showing climate extreme greater than or equal to one.

3 Results

Climate extremes are more frequent, co-occurring, and persistent in the second than in the first half of the study period (Fig. 2). In this section, we highlight some locations with changes in climate extremes instead of describing the results presented in the figures. A larger share of locations has the frequent, co-occurring, and persistent climate extremes while considering the upper than the lower end of extremes. For around half of the study area (46%), climate

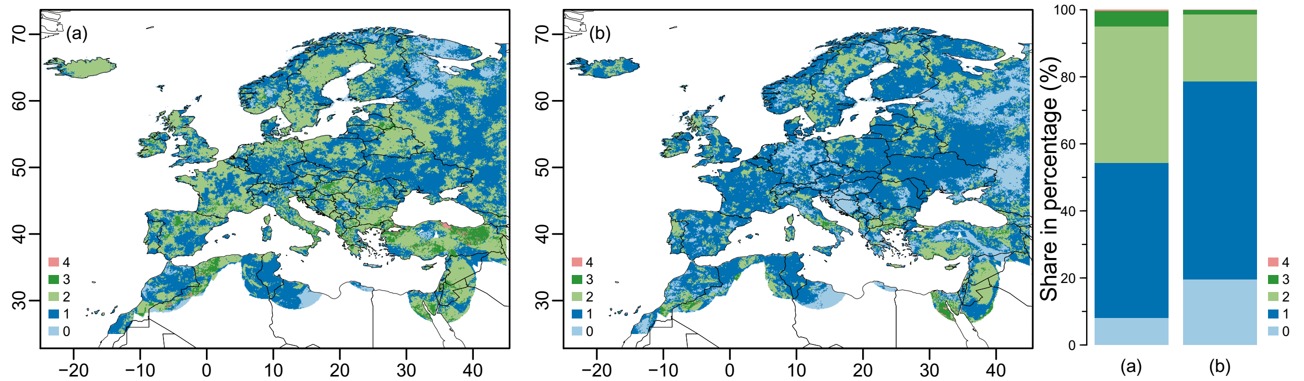

Fig. 2 The number of climate index groups showing more frequent, co-occurring, and persistent climate extremes in the second than in the first half of the study period (i.e., 1950–1984 and 1985–2019, respectively) for **a** upper and **b** lower ends of severity. The bars show the share of locations with the number of climate index groups with frequent, co-occurring, and persistent climate extremes

indices belonging to at least two climate index groups have shown these features of being more frequent, co-occurring, and persistent towards the upper end of climate extremes. These locations are widely distributed across our study area. Looking at the lower end of climate extremes, only around 21% of the locations has experienced these features for climate indices belonging to two or more climate index groups. Interestingly, these locations are concentrated in Northern Europe and the Mediterranean region. Below, we discuss the three features of climate extremes separately and in detail, highlighting locations and climate indices with extremes.

3.1 Changes in Climate Extreme Frequencies

Climate extremes become more frequent in the second than in the first half of the study period (Fig. 3). Looking at the upper end of severity, we observe an increased climate extreme frequency for at least two climate index groups for most locations (93%). Around half of the study area (49%) shows more frequent climate extremes for at least three climate index groups. These locations are distributed across Eastern Europe and the Mediterranean region. Considering the lower end of severity, frequencies of climate extreme have increased in 74% and 19% of the locations for indices belonging to at least two and three climate index groups, respectively.

Changes in climate extreme frequencies vary across climate index groups (Figs. S1, S2). Looking at the upper end, around 36% of the locations has faced an increased climate extreme frequency for at least one cold index, reflecting not so harsh winter in most locations in recent decades. For example, only less than 20% of the locations has similar or more extreme "frost days", "ice days", and "heating degree days" in the second half of the study period compared to the first one (Figs. S3 and S4). However, some parts of the Mediterranean region (mainly Turkey) have an increased number of cold extremes (i.e., for five or more indices, Figs. S1, S4). These parts have faced more frequent colder

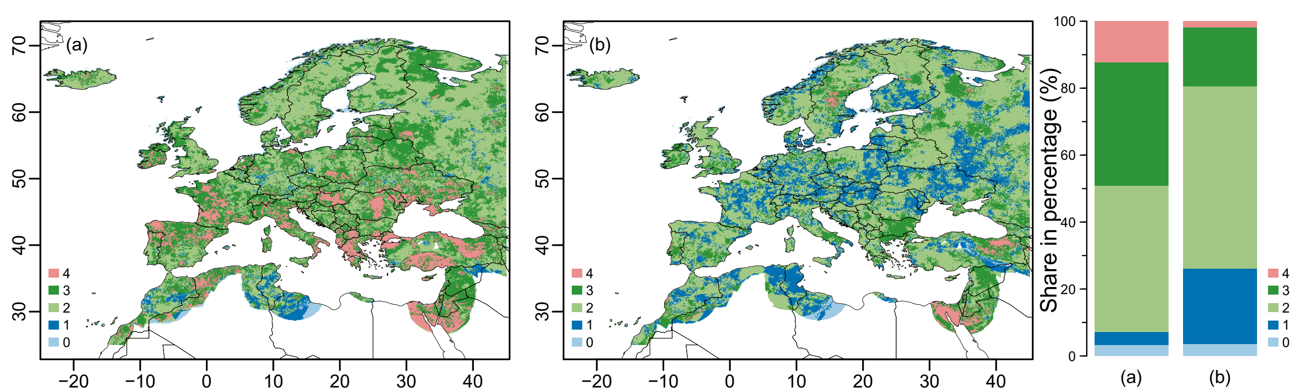

Fig. 3 The number of climate index groups showing more frequent climate extremes in the second than in the first half of the study period (i.e., 1985–2019 and 1950–1984, respectively) for **a** upper and **b** lower ends of climate extremes. The bars show the share of locations with the number of climate index groups with the frequent climate extremes

winter in the second half of the study period than the first one. These cold extremes could be attributed to an east–west dipole in sea level pressure over the Mediterranean region (Alpert et al. 2004; Hochman et al. 2020; De Luca et al. 2020). This east–west dipole favors cold-air advection from northern Europe to Cyprus, contributing most of the winter precipitation and cold spells over the Eastern Mediterranean in recent decades. Most of our study area (94%) faced a more frequent lower end of severity for cold extremes for at least one cold index, reflecting warmer winter in recent decades. For example, in the second half of the study period, more than 70% of locations has similar or more extreme "frost days" and "heating degree days" compared to the first half (Fig. S3).

Regarding heat extremes, five or more indices show more frequent climate extremes (upper end) for most locations (87%), indicating warmer summers across our study area in recent decades (Figs. S1, S2). Specifically, in the second half of the study period, more than 65% of locations faced similar or more extreme "summer days" and "tropical nights" compared to the first half (Figs. S3, S4). These findings highlight that heat extremes have become and will become more intense, frequent, and longer lasting with changing climate (Ga 2004; Kuglitsch et al. 2010). Similarly, less than 10% of the locations experienced more frequent heat extremes (lower end) for at least one index, mainly in parts of Northern Europe and the Mediterranean region. For all heat indices, only a few locations (less than 10%) has a similar or more number of extremes in the second half of the study period than the first one (Fig. S3). These results indicate that most of our study area has faced more frequent extreme summers in recent decades. However, summer has also become less extreme in a few locations as an exception. For example, in the second half of the study period, parts of Northern Europe and Eastern Europe experienced less frequent extreme "summer days" and "tropical nights" compared to the first half, respectively (Fig. S4). A reason for this observation might be due to an increased summer precipitation. Studies have reported further increased in precipitation in parts of Europe due to climate change (Kundzewicz et al. 2006).

Drought extremes (upper end) have increased in the second half of the study period for at least one index for around 33% of the locations, mainly in the Mediterranean region (Figs. S1, S2). For example, extreme "maximum number of consecutive dry days" has been more than doubled in 22% of the locations between the first and the second half of the study period (Figs. S3, S4). Similarly, 25% of the locations has the same or more years in the second half of the study period with the "3-month SPI" value less than − 2 compared to the first half. These results indicate that parts of our study area have suffered from an increased drought frequency in recent decades, particularly in southern Europe and the Middle East. This increased drought is due to decreased precipitation triggered by the multidecadal variations of tropical Atlantic sea surface temperatures (Dai 2011, 2013). Interestingly, drought extremes (lower end) have also increased in around half of the locations for at least one index, mainly in parts of Northern Europe. For example, years with the "3-month SPI" value greater than + 2 have been more than doubled in 37% of the locations (Fig. S3), reflecting wetter weather conditions in parts of our study area in recent decades.

Considering precipitation indices, a majority of our study area (52%) experienced more frequent climate extremes (upper end), i.e., for five or more indices, in the second half of the study period. These locations with increased wetter weather conditions are distributed across the study area to a lesser extent in the Mediterranean region. For example, the number of extreme "very heavy precipitation days" and "maximum number of consecutive wet days" has been more than doubled in 44% and 28% of the locations between the first and the second half of the study period, respectively (Figs. S3 and S4). However, the increased heavy precipitation is at the expense of light and moderate rainfall events (Trenberth et al. 2003; Sun et al. 2007). Therefore, parts of our study area have also faced more frequent drier weather conditions, mainly in the Mediterranean region. Two or more precipitation indices show climate extremes at the lower end of severity for around 21% of the locations. For example, extreme "wet days" has been the same or more for around 24% of the locations in the second half of the study period than the first one (Figs. S3, S4).

3.2 Climate Extreme Co-occurrences

The number of climate extremes that are co-occurring in the same year and location has increased in the majority of our study area (Figs. 4, 5). Looking at the upper end, the share of locations with co-occurrence of climate extremes belonging to three or more climate index groups has increased from 53 to 64% between the first and the second half of the study period. Cold, heat, drought, and precipitation extremes have occurred in the same year in an increased share of locations (5%) in the second half of the study period compared to the first one (i.e., 4%). Spatially, parts of Western Europe and the Mediterranean region have faced an increased number of multiple climate extremes in the same year in recent decades. Thus, they can also be called hotspots for climate extreme co-occurrences (Fig. 5). In contrast, the number of multiple climate extremes in the same year has decreased in parts of Eastern and Northern Europe, referring to these locations as coldspots. On the lower end, the share of locations with climate extreme occurrences has also increased from 63 to 87% between the first and the second half of

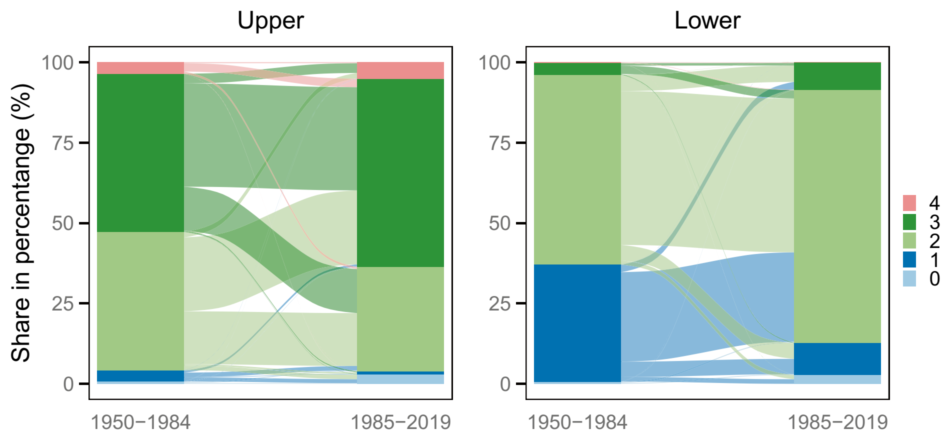

Fig. 4 The bars show changes in the share of locations with the number of climate index groups with the co-occurring climate extremes between the first and the second half of the study period (i.e., 1950–1984 and 1985–2019, respectively) for upper and lower ends of severity

the study period, considering climate indices belonging to two or more climate index groups. Parts of Eastern and Northern Europe are hotspots in terms of climate extreme co-occurrences at the lower end. These results show that some parts of our study areas have experienced multiple climate extremes in the same year, either in the upper or lower end of severity.

Co-occurrences of climate extremes within a climate index group vary across our study area (Figs. S5–S9). Looking at the upper end, the share of locations facing cold extreme co-occurrences for five or more indices has decreased from 57 to 21% between the first and the second half of the study period (Figs. S5, S6). This decrease has occurred mainly in Western and Eastern Europe, resulting in them as coldspots in terms of cold extreme co-occurrences. This finding is consistent with reported trends in temperature extremes from weather stations in Europe, where the extreme cold events experienced an average decrease by a factor of two to three during 1950–2018 (Lorenz et al. 2019). In terms of hotspots, the number of cold indices with extreme values has increased in the second half of the study period in parts of Northern Europe and the Mediterranean region. Considering the lower end, the share of locations with climate extremes for five or more cold indices has increased from 4 to 27% between these two periods, mainly in parts of Eastern and Western Europe. These results indicate less severe winters in these locations.

Regarding heat extreme upper end, five or more indices have extreme values in the same year for most locations (94%) in the second half of the study period (Figs. S5, S7). In the first half, only 39% of the locations has experienced this occurrence phenomenon. These results indicate that summer has become more severe with occurrences of different heat extremes across our study area. Similarly, the share of locations with no indices showing heat extremes (lower end) has increased from 15 to 71% between the two periods, indicating increasingly hotter summers.

The share of locations with drought extremes (upper end) for three or more indices has decreased from 64 to 43% between the first and the second half of the study period (Figs. S5, S8). These locations with decreased extreme co-occurrences are observed in parts of Western and Northern Europe. In the same period, the locations with extreme co-occurrences for two or more drought indices have decreased from 90 to 86%. These drought co-occurrence hotspots are mostly distributed across the Mediterranean region. Considering the lower end, drought extreme co-occurrences for two or more indices have increased from 78 to 85% of the locations between the two periods. These locations, experiencing less severe droughts or dry weather conditions in recent decades, are distributed across Northern Europe.

Considering precipitation indices, locations with co-occurring extremes (upper end) for five or more indices increased from 64 to 77% between the first and the second half of the study period (Figs. S5, S9). The locations with an increased number of precipitation indices depicting co-occurrence hotspots are distributed across parts of Eastern and Northern Europe. In some locations, the number of precipitation indices depicting co-occurrences has also decreased between the two periods. Parts of the Mediterranean region show this phenomenon, also considered as precipitation extreme co-occurrence coldspots. In other words, these locations have experienced drier weather conditions, which can also be interpreted by looking at the lower end of severity. In parts of the Mediterranean region, the number of indices depicting precipitation extreme co-occurrences at the lower end has increased in the second half of the study period compared to the first half. The patterns of co-occurrent hot- and coldspots of precipitation extremes in Europe are in line with previous studies based on different datasets, e.g. HadEX2—a global land-based climate extremes dataset (Donat et al. 2013).

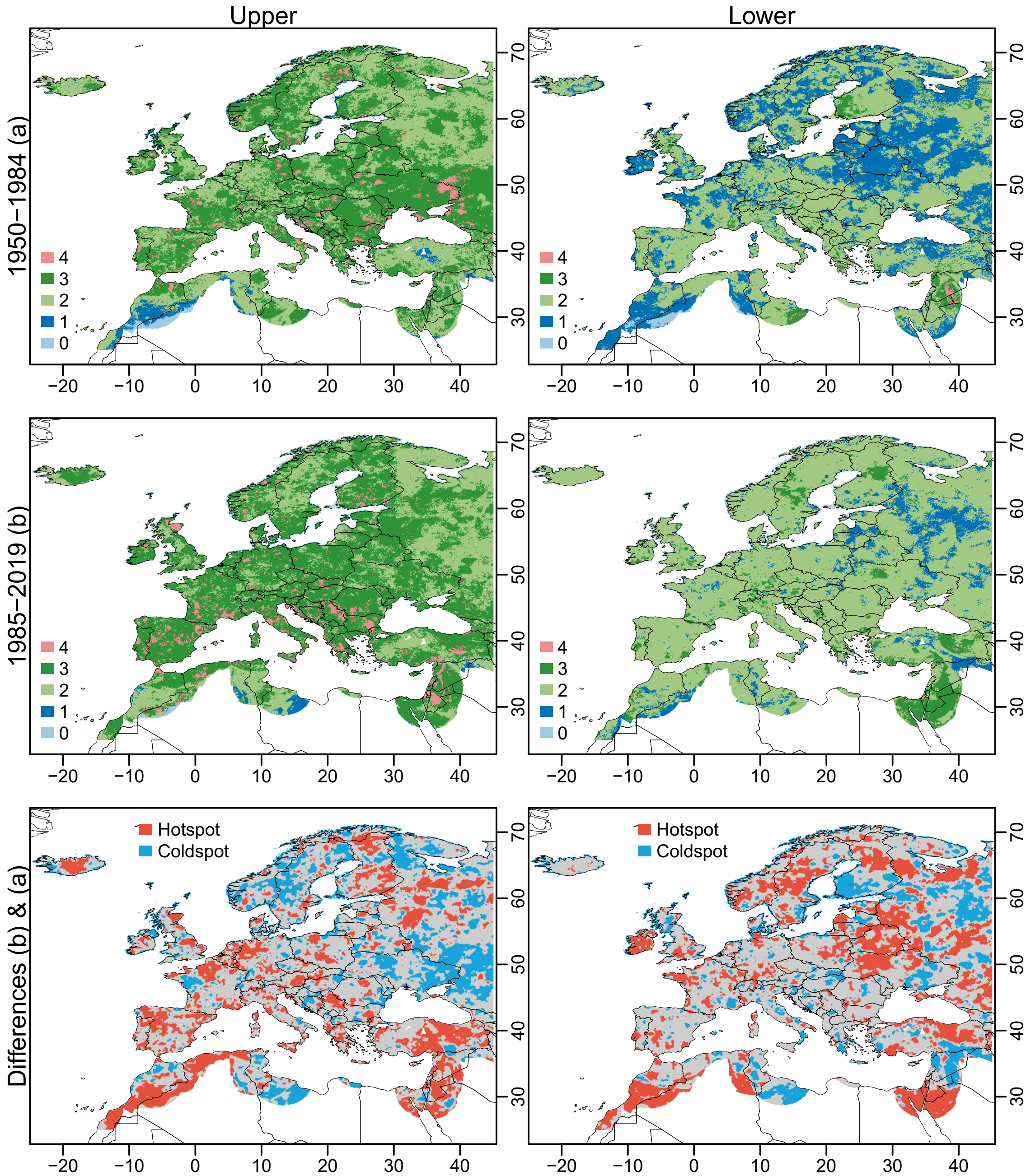

Fig. 5 The number of climate index groups showing co-occurring climate extremes in **a** the first and **b** the second half of the study period (i.e., 1950–1984 and 1985–2019, respectively) for upper and lower ends of climate extremes. The differences in the number of climate index groups between the second and the first half of the study period provide climate extreme hotspots and coldspots. Here, hotspots are spatial clusterings of locations with an increase in climate extreme co-occurrences in the second half of the study period. Similarly, coldspots depict clustering of decreased climate extremes in terms of the co-occurrence

3.3 Climate Extreme Persistence

Climate extremes have also become more persistent in the second half of the study period compared to the first one (Figs. 6, 7). Looking at the upper end, the share of locations with climate extreme persistence has almost doubled from 22 to 43% between the first and the second half of the study period, considering indices belonging to three or more climate index groups. In the same period, locations with consecutive cold, heat, drought, and precipitation extremes have also more than doubled from 3 to 7%. Spatially, parts of Eastern Europe and the Mediterranean region have experienced more consecutive climate extremes for different climate index groups in recent decades. Thus, they can also

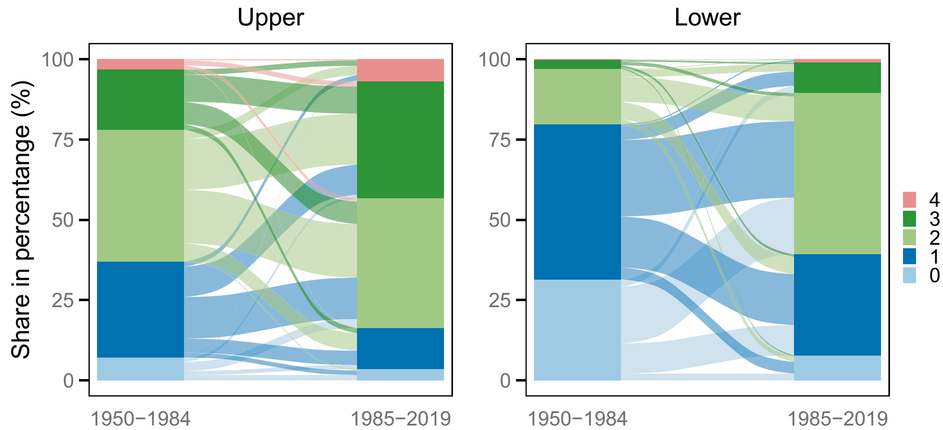

Fig. 6 The bars show changes in the share of locations with the number of climate index groups with persistent climate extremes between the first and the second half of the study period (i.e., 1950–1984 and 1985–2019, respectively) for upper and lower ends of climate extremes

be called hotspots for climate extreme persistence (Fig. 7). On the lower end, the share of locations with consecutive climate extremes, considering indices belonging to two or more groups, has also increased from 20 to 61% between the first and the second half of the study period. Parts of Eastern and Northern Europe are hotspots in terms of climate extreme persistence at the lower end. Similar to climate extreme occurrences, these results indicate that parts of our study area have experienced consecutive climate extremes at upper and lower ends of severity in recent decades.

Changes in consecutive extremes within a climate index group vary across our study area (Figs. S10–S17). Looking at the upper end, only 17% of the locations have experienced consecutive cold extremes for at least one index in the second half of the study period (Figs. S10, S11). In the first half, this share was 46%, indicating that winters are becoming not so harsh in most locations in recent decades consecutively. For example, the share of locations with consecutive extreme "frost days" has decreased from 6 to 3% between the first and the second half of the study period (Figs. S15–17). This decrease is associated with the downward trend of cold extremes in most parts of Europe (Lorenz et al. 2019). However, some parts of the Mediterranean region (mainly Turkey) have faced more consecutive cold extremes in the second half of the study period (Fig. S10). These parts can be considered hotspots for consecutive cold extremes. Most of our study area (84%) faced cold extreme persistence (lower end) for at least one cold index, reflecting consecutive warmer winter in recent decades. For example, in the second half of the study period, around 40% of locations faced consecutive extreme "frost days" (Figs. S16, S17). This share was around 3% in the first half (Figs. S15, S17).

Regarding heat extremes, four or more indices show climate extreme persistence (upper end) for most locations (87%) in the second half of the study period (Figs. S9, S11). In the first half, this share was only 5%, indicating consecutive hotter weather conditions across our study area in recent decades. Hotspots for consecutive heat extremes are well-distributed across our study area. For example, in the second half of the study period, more than 40% of the locations faced consecutive extreme "summer days" and "tropical nights" (Figs. S16, S17). This share was less than 6% in the first half (Figs. S15, S17). Similarly, the share of locations that experienced consecutive heat extremes (lower end) for at least one index has decreased from 10 to 6% between the first and second half of the study period. For all heat indices, only a few locations (less than 5%) has faced consecutive heat extremes in the first and the second half of the study period (Figs. S15–S17). These results indicate that an increasing share of our study area has faced consecutive hotter years in recent decades.

The share of locations with drought extreme persistence (upper end) has decreased from 54 to 33% between the first and the second half of the study period, considering two or more drought indices (Figs. S10, S13). For example, consecutive extreme "3-month SPI" has decreased from 67 to 47% of the locations between these periods (Figs. S15–S17). These locations with decreased drought persistence (i.e., coldspots) are observed in parts of Northern Europe. In the same period, the locations with drought extreme persistence for at least one index have decreased from 74 to 59%. These drought persistence hotspots are mostly distributed across Western Europe and the Mediterranean region (Fig. S12). Considering the lower end, drought extreme persistence for at least one index has increased from 48 to 59% of the locations between the two periods.

Considering precipitation indices, 27% and 59% of the locations faced consecutive extremes (upper end) for at least one precipitation index in the first and the second half of the study period, respectively (Figs. S10, S14). For example, consecutive extreme "very heavy precipitation days" has increased from 5 to 23% of the locations between these two periods (Figs. S15–S17). These locations, depicting persistence hotspots, are distributed across Eastern Europe,

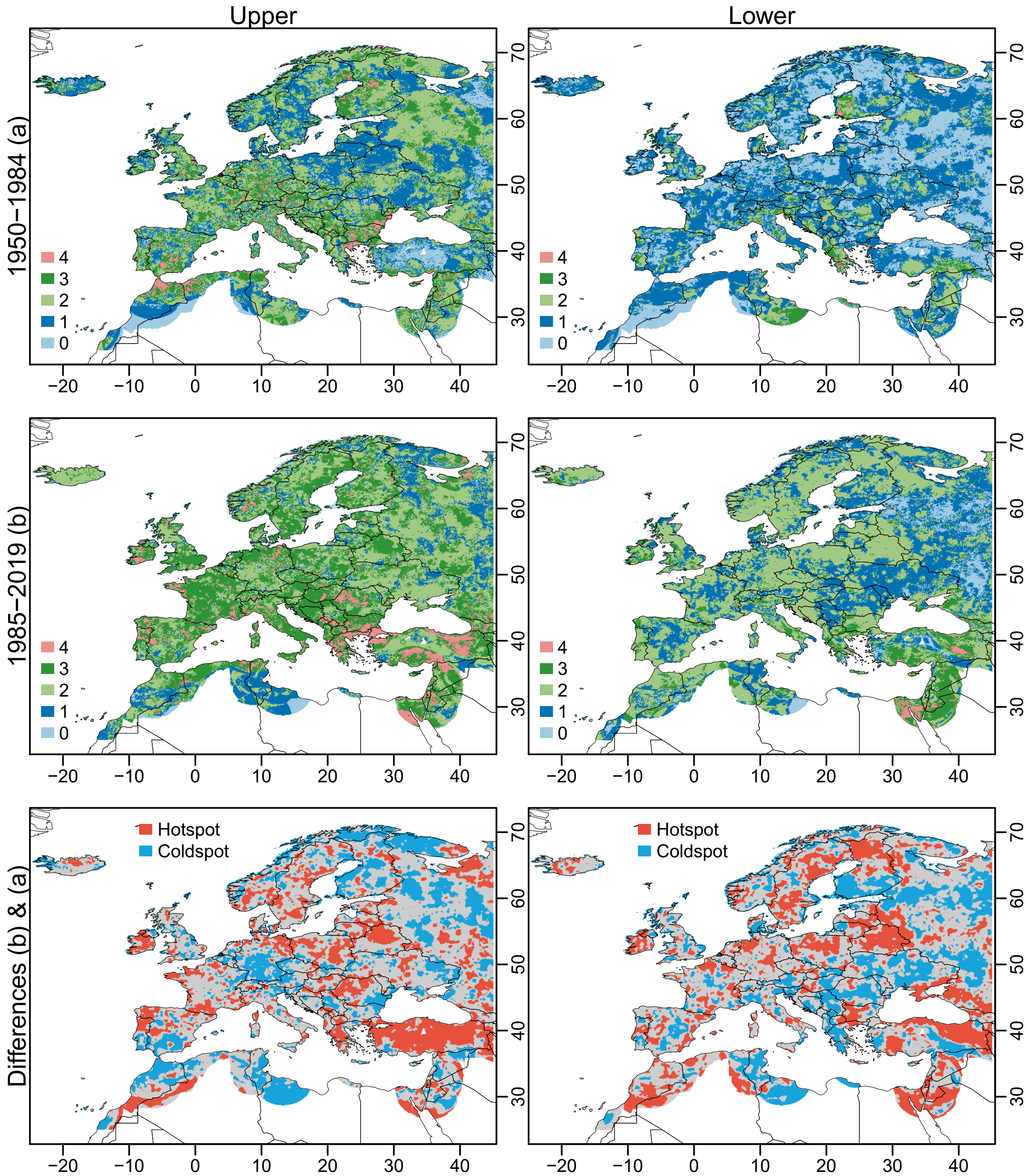

Fig. 7 The number of climate index groups showing persistent climate extremes in **a** the first and **b** the second half of the study period (i.e., 1950–1984 and 1985–2019, respectively) for upper and lower ends of climate extremes. The differences in the number of climate index groups between the second and the first half of the study period provide climate extreme hotspots and coldspots. Here, hotspots are spatial clusterings of locations with an increase in climate extreme persistent in the second half of the study period. Similarly, coldspots depict clustering of decreased climate extremes in terms of the persistency

Northern Europe, and the Mediterranean region. However, some locations have also experienced a decrease in the persistence of extreme precipitation. Parts of Western Europe and the Mediterranean region show this phenomenon also considered precipitation extreme persistence coldspots (Fig. S14). In other words, these locations have experienced less wet weather conditions in consecutive years, mainly in the second half of the study period. On the lower end, the share of locations with precipitation extreme persistence has decreased from 22 to 16% between the first and the second half of the study period, considering at least an index (Figs. S10, S14). This result indicates a reduced share of locations with consecutive drier weather conditions across our study area.

4 Discussion

In recent decades, climate extremes are becoming more frequent, co-occurrent, and persistent in our study area. Most parts experienced frequent and persistent heat extremes at the upper end of severity, indicating hotter summers. More often, winters are also becoming warmer in most parts, which is reflected by observed frequent and persistent cold extremes at the lower end. Simultaneously, some parts, mainly the Mediterranean region, faced an increase in droughts while others, e.g., parts of Eastern Europe and Northern Europe, experienced more intense precipitations. Few parts have also faced two or more of these cold, heat, drought, and precipitation extremes in the same year. Based on these findings, our study brings several novel understandings on climate extremes.

First, our study provides new insights into changes in climate extremes by investigating all climate indices belonging to the four climate index groups together. Similar to the existing studies (Easterling et al. 2000; Alexander et al. 2006), we highlight that various locations can face different types of climate extremes. Thus, investigating all climate indices is crucial to understand these differences in climate extremes across our study area. For example, this study reveals that a few parts of our study area have experienced colder winters and hotter summers in recent decades. However, both winter and summer have become warmer in most parts. In the same period, increased droughts and more intense precipitation events are observed in a few parts of the study area, although they are considered as opposite phenomena. We draw these insights by mapping climate extremes based on the 39 E-OBS climate indices. In contrast, most studies on climate extremes focus on some indices, i.e., one or more of the 27 core indices provided by Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al. 2005; Alexander et al. 2006; Brown et al. 2010). The E-OBS climate indices consist of a few additional indices to the 27 ETCCDI core indices.

Second, we bring new insights on climate extremes in terms of the aggregated features, i.e., frequency, co-occurrence, and persistence together. In line with existing studies (Scherrer et al. 2016; Łupikasza et al. 2011), our findings show that most of our study area is facing frequent hotter summers, intense precipitations, and warmer winters in recent decades. Besides an increase in frequency, parts of our study area have experienced that these extremes are happening more consecutively and are co-occurring. Climate indices belonging to an index group are related, and thus, multiple of these indices can depict extreme values in an extreme event, resulting in co-occurrences. However, these co-occurrences have changed in most of our study area in recent decades. For example, the number of heat indices with extreme values in the same year increased across the study area. Different climate extremes can be driven by the same process, resulting in increased extreme co-occurrences. For example, changes in North Atlantic atmospheric circulation due to global warming can result in winter flooding and summer drought over Europe (Rousi et al. 2020). Similarly, prolonged drought can increase heatwaves and forest fires in parts of our study area (Sutanto et al. 2020). Studies predict that climate extremes will be more frequent, co-occurrent, and persistent in a warmer world, e.g., an increase in compound drought and heatwaves (Mukherjee and Mishra 2020). These compound or co-occurring climate extremes can have more enormous impacts than a single extreme event, e.g., on agriculture (Potopová et al. 2021).

Third, our study identifies hotspots and coldspots of climate extremes considering cold, heat, drought, and precipitation extremes separately and together. The underlying Getis-Ord Gi* analysis enables a robust characterization of climate extremes' spatial patterns and prioritizes regional climate adaptation plans. Our hotspots represent locations with more frequent, co-occurrent, or persistent climate extremes in the second half of the study period than the first one and vice versa for coldspots. Similar to existing studies (Casanueva et al. 2014; Łupikasza 2017; Donat et al. 2013), we observe variation in hotspots and coldspots across our study area depending on the nature of climate extremes. For example, parts of the Mediterranean region are hotspots for drought, while precipitation hotspots are mostly observed in parts of Northern Europe. We also advance these existing studies limited to few extremes by identifying hotspots and coldspots for cold, heat, drought, and precipitation extremes.

Fourth, we observe a considerable small-scale spatial heterogeneity in climate extreme hotspots and coldspots. They are directly adjacent on a sub-national scale. These critical climate extreme phenomena drive climate change impacts in sectors (e.g., agriculture, traffic, and health) sensitive to extreme weather events. As these sensitivities are also spatially very heterogeneous, our study shows that we have to expect an even more patchy and small-scale pattern in the resulting impacts with severe consequences for adaptation strategies. These strategies have to be highly differentiated to the upcoming challenges, as "one size fits all" is an even less viable option than previously thought.

Our study also has a few limitations. First, identified climate extremes consider the period 1961–1990 as the baseline. Since the selection of the baseline can make differences on geographical patterns and trends of climate extremes (Sulikowska and Wypych 2020; Liersch et al. 2020), these results may vary when different baselines are chosen. However, we select the baseline following the World Meteorological Organization (WMO) guidelines to use the stable baseline period of 1961–1990 in studies investigating temporal variability of climate extremes (WMO 2017). In addition, our study's key finding, i.e., climate extremes are becoming more frequent, co-occurrent, and persistent, will be still valid while considering different baseline, as we identify hotspots based on differences of climate extremes between the second and the first half of the study period. Second, our study is limited to climate extremes and does not provide insights into these extremes' impacts on human and environmental systems. For example, our drought extremes refer to meteorological drought instead of hydrological or agricultural drought. Third, our analyses and conclusions are based on climate indices derived from the E-OBS gridded datasets. The choice of datasets could affect results drawn thereupon (Gross et al. 2018). However, it is beyond this study's scope to address the extent to which the results may change if climate indices based on other datasets are used, e.g. reanalysis data or modeled data included in the Coupled Model Intercomparison Projects (CMIPs). Nevertheless, the E-OBS gridded dataset is a high-resolution observed climate data available for our study area. In addition, the E-OBS climate indices are based on the median of the 20 members of the E-OBS ensemble instead of only one simulation. We might also have lost some details while aggregating the information based on climate index group. Our study concisely presented the results by highlighting the key findings, rather than discussing changes in each climate index. Nevertheless, we include the results for each climate index in the Supplementary Information.

In conclusion, climate extremes have and become more frequent, co-occurrent, and persistent with climate change. However, the nature of climate extremes can vary spatially across Europe, e.g., most parts with warm winters while a few experiencing cold ones. These climate extremes negatively impact social, economic, and environmental systems, e.g., agricultural yields (Shahzad and Abdulai 2020), critical infrastructures belonging to industry, transport, and energy sectors (Forzieri et al. 2018), and human health (Huber et al. 2020). With climate change, such impacts can be severe across multiple sectors (Piontek et al. 2014). Thus, future climate impact research needs to explore impacts of more frequent, co-occurrent, and persistent climate extremes across multiple sectors, accounting for spatial heterogeneity at a sub-national scale. In addition, our understandings of climate extremes need to be further enhanced by considering climate extremes at much finer temporal resolutions, e.g., day and month, capturing their intra-annual variation.

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Compliance with Ethical Standards

Data Availability The data produced by this study have been included as electronic Supporting Information.

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