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Contrasting biophysical and societal impacts of hydro-meteorological extremes

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Abstract

Extreme hydrological and meteorological conditions can severely affect ecosystems, parts of the economy, and consequently society. These impacts are expected to be aggravated by climate change. Here we analyze and compare the impacts of multiple types of extreme events across several domains in Europe, to reveal corresponding impact signatures. We characterize the distinct impacts of droughts, floods, heat waves, frosts and storms on a variety of biophysical and social variables at national level and half-monthly time scale. We find strong biophysical impacts of droughts, floods, heat waves and frosts, while public attention and property damage are more affected by storms and floods. We show unexpected impact patterns such as reduced human mortality during floods and storms. Comparing public attention anomalies with impacts across all other considered domains we find that attention on droughts is comparatively low despite the significant overall impacts. Resolving these impact patterns highlights large-scale vulnerability and supports regional extreme event management to consequently reduce disaster risks.

1. Introduction

Extreme hydro-meteorological events are among the most important global risks as identified in a survey by the World Economic Forum [1]. Changes in extreme events are among the most relevant consequences of climate change [2, 3]. Increased future frequency and/or magnitude of such events [4] can stress natural and human systems beyond their limits. While there have been conceptual advances in understanding impacts from extreme events in recent years [5–8], there is a lack of empirical studies comparing characteristic impact signatures across event types and impact domains such as ecosystems, economy and society [9, 10]. Knowledge on such event type-impact signatures is key to build and enhance resilience to hydro-meteorological extremes.

Previous research on extreme event impacts has largely focused on individual processes such as reduction in primary production [11], excess human mortality [12], or yield losses in agriculture [13]. Studies considering multiple domains also exist, but are mostly based on projected or modelled impacts, as well as modelled climate (extremes) [14, 15], and/or more focused on vulnerability rather than observed impacts [16]. Studies analyzing observed impacts from empirical data, are often focused on individual events or countries only [17, 18].

In this study, we analyze impacts of extreme events using empirical evidence across extreme types, domains, and countries in Europe. In particular, we consider a broad selection of domains for which we could get consistently derived, empirical country-scale data; these include photosynthesis, crop yields, human mortality, public attention and property damage. As for the extreme event types, we consider and compare the impacts of droughts, floods, heat waves, frosts, and wind storms across 24 countries in Europe. These include the United Kingdom, Norway, and all member states of the European Union as of 2021 except Croatia, Cyprus, Luxemburg, Malta and Romania; the latter countries have not been considered due to relatively small spatial area or limited data availability.

2. Data and methods

2.1. Hydro-meteorological data

Hydro-meteorological data are obtained from the state-of-the-art ERA5 reanalysis [19] covering the time period 1979–2018 (table 1). This reanalysis is improved in many aspects over its predecessor, the widely used ERA-Interim reanalysis [20], including temporal and spatial resolution, data sources, and assimilation scheme [19]. Independent evaluation studies confirm the usefulness of ERA5 for hydro-meteorological applications [21–24]. We focus on country-scale spatial resolution and half-monthly temporal resolution in this study. This choice is made to enable the inclusion of multiple impact-related datasets (see below) which are typically available at national level and monthly-annual temporal resolution, while hydro-meteorological data is available at higher resolutions.

The spatial aggregation is done through averaging across the grid cells of each country. This averaging is done in different ways: (a) using equal weights for each grid cell, (b) weighting the grid cells with respect to their population in 2010 [25], and (c) weighting the grid cells with respect to the contained agricultural area [26]. The time series obtained through averaging with equal weights are used to detect extreme events for the analysis of impacts on photosynthesis by analyzing gross primary productivity. The time series obtained through population-weighting are employed to derive extreme events for the analysis of the impacts in terms of mortality, property damage, and Google searches. Finally, the time series calculated through agricultural area weighting are used to infer extreme events for the analysis of impacts on crop yields. Note that no detrending or removal of the seasonal cycle is performed for the hydro-meteorological data in order to detect the most extreme events in absolute terms.

2.2. Extreme event detection

While there is no commonly accepted definition of variables and time scales underlying these extreme event types [2], we consider half-monthly means of soil moisture and temperature to detect droughts and heat waves, respectively, and half-monthly extremes of runoff, wind speed and minimum temperature for floods, storms and frosts, respectively. Note that the choice of these definitions can affect the diagnosed impacts. Heat waves are defined here based on half-monthly periods based on previous literature [27, 28], while the IPCC special report on extreme events [2] does not indicate a specific time scale for these events. Further note that we chose to employ gridded runoff data here to detect flood events at the national level such that respective impacts can be compared with that of the other types of extremes, and evaluated with the impact datasets; however, this is not accounting for lateral flows and downstream transport of high flows. In this context we average the estimates of the hydro-meteorological mean and extreme values across the grid cells of each country. Only in the case of floods we use a different approach as these events can be very localized and potentially overshadowed by non-extreme runoff in other regions of the respective country; instead of country-wide mean runoff we consider for each half-monthly period the fraction of grid cells of a country where the daily runoff has exceeded the long-term 95th percentile on at least one day. This adaptive approach with considering specific temporal and spatial scales for each extreme event type we ensure to capture them at their typical spatial and temporal scales while enabling an comparative impact analysis across consistent half-monthly, national scales where impact-related data are available.

Table 1. List of employed hydro-meteorological variables to determine extreme event occurrences. All data is derived from the ERA5 reanalysis [19], and covers the period 1979–2018.

Extreme event type	Variable	Extreme event is half-monthly period with...
Drought	Top-meter soil moisture	Driest mean soil moisture
Flood	Total runoff	Largest country area fraction with daily runoff exceeding the 95th percentile
Storm	10 m wind speed	Strongest hourly maximum wind speed
Heat wave	2 m temperature	Hottest mean temperature
Frost	Minimum 2 m temperature	Coldest hourly minimum temperature

Extreme events are inferred from extreme hydro-meteorological values as characterized by long return periods. Inferring such return periods with extreme value theory [29], we ensure a consistent detection of extreme events and comparability in their rarity across variables and corresponding event types. For each variable and country, we fit a generalized extreme value distribution [29] to the 40 annual maxima or minima (depending on the variable) using the method of L-moments. This method has been shown to be applicable with similar amounts of data [30]. In addition, (a) we determine the corresponding goodness of each fit by computing the R^2 from respective quantile-quantile plots between the actual and fitted quantiles, confirming that >90% of all resulting R^2 values exceed 0.9, and (b) we test the match

Table 2. List of datasets to determine extreme event impacts. Access dates are specified in the list of references.

Domain (variable)	Spatial resolution	Temporal resolution	Time period	Source
Photosynthesis (gross primary productivity, GPP)	0.5° × 0.5°, aggregated to country level	8-daily (aggregated to half-monthly)	2001–2015	Fluxcom [31]
Crop yields (net primary productivity, NPP)	Countries	Yearly	2001–2015	Eurostat [32]
Mortality	Countries	Monthly	2001–2015	Eurostat [33]
Property damage (permille of gross domestic product, GDP)	Countries	Yearly	2001–2015	EM-DAT [34]
Public attention (Google searches)	Countries	Monthly	2004–2018	Google [35]

of each fitted generalized extreme value distribution with the actual data with a two-sided Kolmogorov–Smirnov test. At the 5% level this test indicates that the fitted distributions are plausible for all countries and all considered event types. The fitted distributions are used to infer return periods of the annual extremes in each country and for each variable. Finally, we select all extreme events with return periods exceeding 7 years for the impact analyses (except the analysis in figure 5), and respective events across event types and countries are listed in table S1 (available online at stacks.iop.org/ERL/17/014044/mmedia). This threshold was chosen to focus on the strongest extremes while ensuring to have a sufficient number of events to establish meaningful impact statistics (see supplementary material for details).

2.3. Impact data

Impacts are assessed and compared for all hydro-meteorological extreme events identified during 2001–2015. Thereby, we consider various domains as shown in table 2. In particular, we investigate photosynthesis (measured as gross primary productivity [31]), crop yields [32] (converted to net primary productivity, see supplementary material), excess human mortality [33], property damage [34], and public attention on respective extreme events as quantified through the number of corresponding Google searches (using Google trends data [35], different time period 2004–2018). Note that property damage includes insured and non-insured losses, and further comprises monetary damage on crops and livestock. Public attention data has been used in previous extreme event studies [36–38], but to our knowledge not yet in conjunction with empirical impact data from other domains. Unlike the hydro-meteorological time series, where extreme events are inferred based on absolute values, we use detrended and de-seasonalized values in the case of the impact time series. The detrending is done by fitting and subtracting a moving average from the data which is computed with a locally weighted scatterplot smoothing (lowess) filter with window size 20% of the entire 15 year time series. This allows us to some extent to isolate the impacts of extreme events from seasonal and long-term variations in the impact time series or confounding factors such as long-term changes in vulnerability and exposure. Event-related impacts are determined using the information on the timing of the half-monthly periods representing extreme events in each country. In impact datasets with yearly temporal resolution, the impacts of extreme events in each country are determined from the impact anomalies in the respective years. In impact datasets with sub-yearly temporal resolution, the extreme event impacts are computed by averaging impact anomalies over 3 months; this includes the respective identified half-monthly period, the two preceding half-monthly periods, and the three succeeding half-monthly periods. For example, the mortality data includes deaths by any cause, and by focsing on excess mortality (anomalies) at the time of extreme event occurrence, we can better infer actual event-related mortality impacts.

Most of the analyses in this study focus on European impacts derived by spatially aggregating the 24 considered European countries. As impacts are generally expressed per area or per capita, this aggregation is done by computing weighted averages of impacts across the countries, rather than cumulative sums (see supplementary material for additional information).

3. Results

In figure 1, we compare the relative roles of the extreme event types in each of the considered domains. The results show mostly reductions in photosynthesis and crop yields, and increases in property losses and public attention during the considered events, with some exceptions.

The figure allows to compare how different event types affect the considered variable of interest within each impact domain. We find that the relative importance of event types varies strongly across impact domains. For example storms cause more severe impacts than drought in terms of property damage, while the opposite is found in the case of

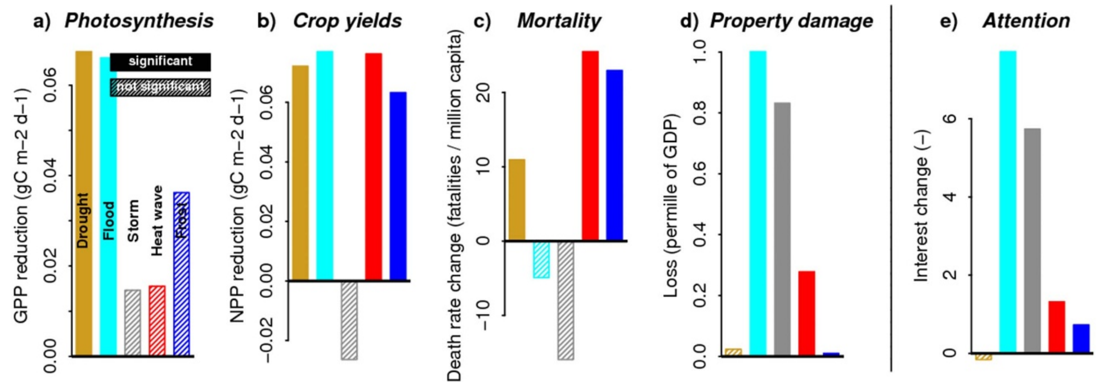

Figure 1. Contrasting impacts of hydro-meteorological extremes across domains. Bars show impacts of considered types of extremes, computed from all events across 24 European countries with return times exceeding 7 years. Results displayed for five considered impact domains. Full bars denote significant impacts at the 80%-level, while dashed bars show insignificant results.

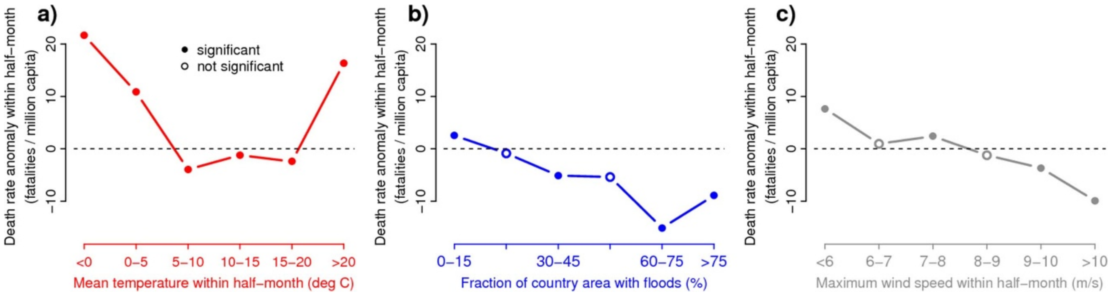

Figure 2. Decreased mortality during floods and storms. Mortality rate anomalies for particular (a) temperature, (b) runoff, and (c) wind speed, computed as averages across all half-monthly, country-based mortality rate anomalies within respective conditions. Note that mean temperature is used here in contrast to the heat wave and frost analyses to capture both maxima and minima.

photosynthesis and crop yields. Frost is more relevant than most other extremes for mortality, but less comparatively less important in terms of property damage. Overall, across all considered impact domains, water-related extremes (drought, flood) are slightly more impactful than temperature-related extremes (heat wave, frost). Despite of using fully independent underlying data sources, photosynthesis and crop yield results are broadly similar with strongest impacts from drought, flood, frost, and heat waves. The latter is more relevant for crops than for photosynthesis as the gross primary productivity dataset represents all vegetation, including e.g. forests, grasslands, and other vegetation types in addition to crops. Biophysical effects can allow forests to keep a lower canopy temperature (e.g. because of higher roughness) and avoid respective heat stress [39]. The fact that all vegetation types are reflected in our photosynthesis results can also explain the relatively low relevance of wind storms despite their particular impact on forests [40]. While the photosynthesis results shown above are based on gross primary productivity, similar results are found for net ecosystem exchange (figure S1). This confirms previous research showing that droughts and floods (or heavy precipitation) are of special importance for the land carbon sink [41, 42].

Human mortality is strongly increased during temperature-related extremes as also shown in figure 2; this is well known and is due to a temperature-dependent risk of death through several potential physiological effects [43, 44]. We also find increased mortality during droughts which, however, is likely related to the associated above-normal temperatures (figure S2). Interestingly, decreased mortality coincides with storms and floods, as previously reported for different spatial and temporal scales [45]. In fact, independent of extreme events we find linearly decreasing mortality towards conditions with more runoff and wind (figure 2). There are several possible explanations that all would require further analysis, for instance (a) people may potentially take more care in the case of extreme rain, (b) may perform less physical activity reducing their exposure to risks [46], or (c) the mortality caused by extreme events such as storm surges may have decreased due to improved early warning and disaster management [47, 48]. Further, indirect effects could be at play; more people seek shelter from wind and rain and thereby stay safe indoors. Inversely, in the case of heat waves and hot

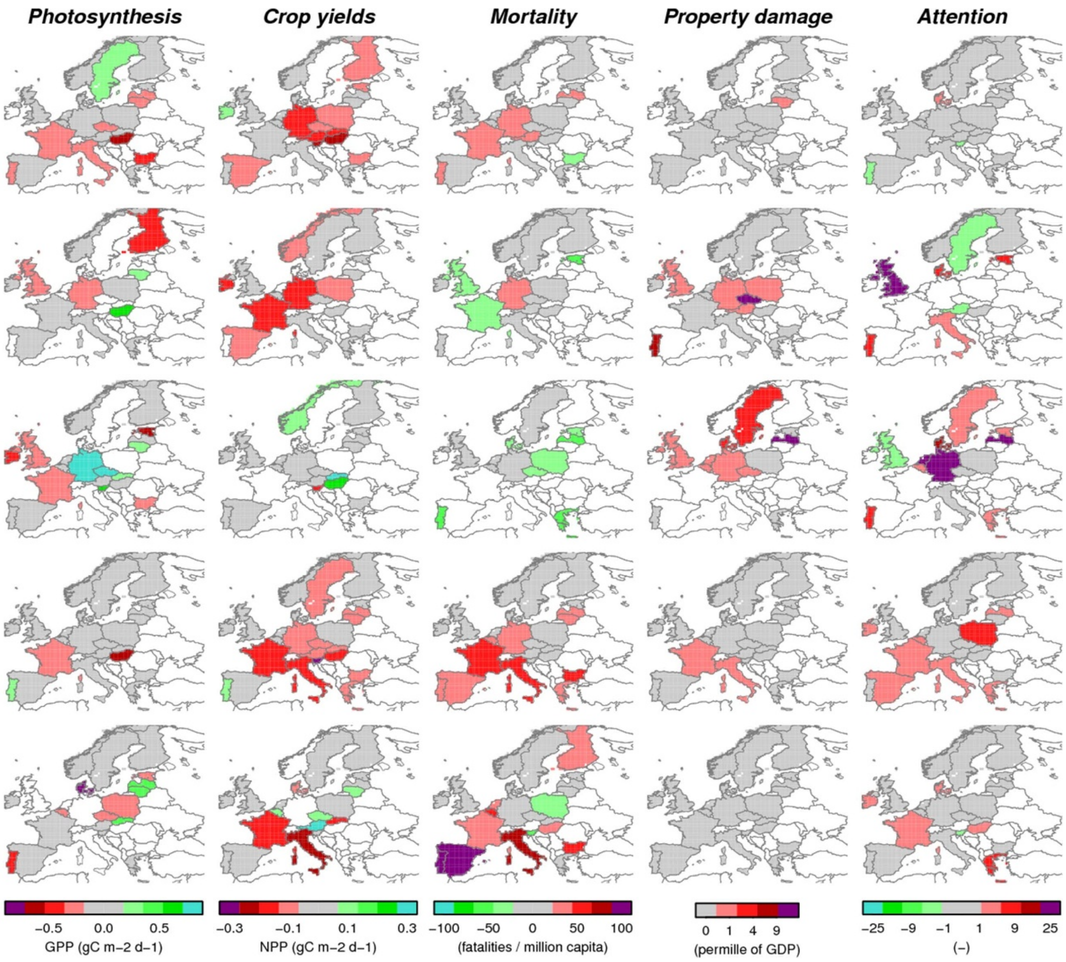

Figure 3. Spatial impacts of the considered extreme event types in Europe. Impacts of considered extreme event types in the 24 considered countries. Impacts are computed as averages across all events with return times exceeding 7 years in each country for each considered extreme event type. Countries shown in white did not experience respective events with such return periods during the study period, or are not considered in this study.

indoor temperatures people might be more prone to move outside where they are more exposed.

For most extreme event types and impact domains, impacts intensify with event magnitude, expressed as return period (figure S3). Interesting threshold behavior is found in the case of frost coincidences with crop yield reductions, where strongest impacts are found in the case of return periods beyond 20 years. Declines in crop yields after exceeding temperature thresholds have been reported previously [49]. Thereby, the sensitivity of crop yields to climate depends on crop type and climate regime [49–52], which needs to be taken into account by regional agricultural management and adaptation. Similar results, but weaker threshold behavior, is found in the case of heat wave impacts on property damage. These impacts can be caused by heat-induced damage to infrastructure such as power transformers and (rail) roads; moreover heat waves can induce fires causing further damage. Heat waves have also been shown to reduce economic activity [53, 54]. Surprisingly, frost impacts on mortality are strongest for the weaker events. This might be due to potentially increased efficiency of early warnings [48] for exceptionally strong events as awareness and predictive skill are higher.

Figure 3 maps impacts across European countries. The figure reveals that there is substantial variation in the impacts across countries indicating different exposures and vulnerabilities, like for example between southern and northern Europe in the case of heat waves. Vice versa, for the same impact domains the results confirm the findings from figure 1, such as for example strongest impacts of storms and floods on property damage and attention. Again, we also find varying geographical impact patterns, for instance for attention between storms and floods. This suggests that the relative overall importance of event types in terms of impacts shown in figure 1 does actually not apply in each individual country. For example, while droughts seem overall more influential on photosynthesis than storms (figure 1), the opposite is found for Estonia and the United Kingdom. This highlights that extreme event impacts are complex and depend on the vulnerability and exposure to the respective event types which differ between countries, and likely also

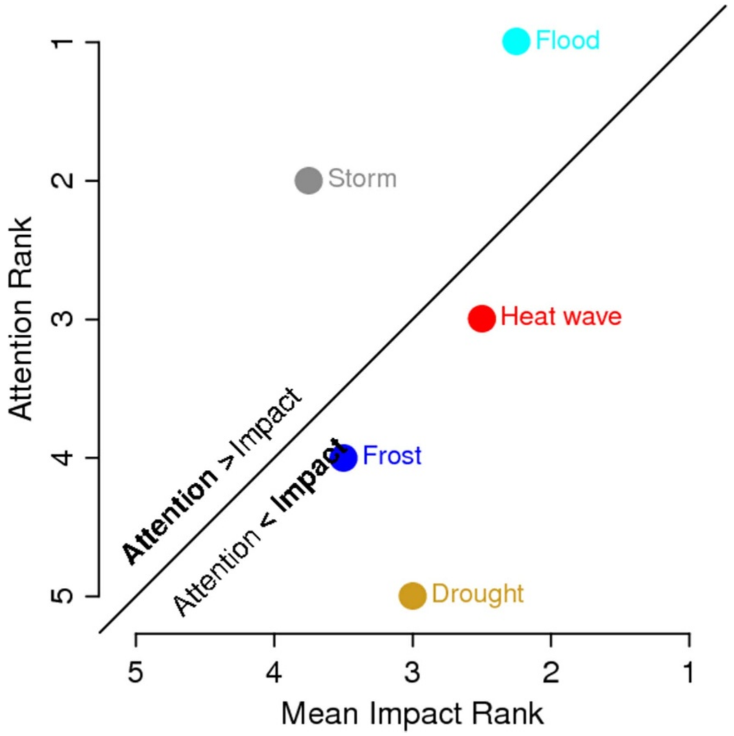

Figure 4. Little attention for drought despite impacts in other domains. Comparison of the relative ranking of the considered extreme event types with respect to attention (figure 1(e)), and other considered impacts (figures 1(a)–(d)), including both significant and non-significant results.

within countries. The findings from this analysis help to indicate (groups of) countries which are underprepared for particular types of extreme events. Note, however, that the statistical significance of differences between individual countries is generally low due to the low number of underlying extreme events.

In a next step, we focus in more detail on the public attention to extreme events, and on the extent to which this reflects the impacts diagnosed in the other considered domains. Increased public attention in the case of extreme events has been reported across event types, mostly based on case studies focusing on particular events [36–38]. Here, we compare the public attention to several extreme event types (figure 1(e)) with the respective impacts in terms of ecosystems and socio-economic metrics (figures 1(a)–(d)). For this purpose we compute impact rankings of the extreme event types in each impact domain. Then, for each event type, we relate the mean rank across the ecosystem and socio-economic impact domains with the rank in the attention domain. For simplicity, this assumes equally relevant impacts in the ecosystem and socio-economic impact domains while the actual relevance might be different depending on the perspective. Figure 4 reveals that attention overall scales weakly with impacts; floods and storms receive higher attention than what would be expected given their impacts, while interest in frost, heat waves and droughts is surprisingly low in the light of their impacts. Floods and storms might be more directly visible and tangible than the other event types. For heat waves it has been reported previously that attention might be lower as it affects predominantly underserved population [55]. This might also be true for frost and drought, while the particularly strong drought perception bias might further be due to the usually slow and hardly recognized drought development. Soils can dry out over time despite intermediate rain events due to overall too little precipitation and/or high evapotranspiration [7]. Also, emergency management and response employ social media for information and early warning, and as this information is redirected and distributed, apparent public attention develops [56]. This is more pronounced for storms and floods [57] as immediate action is often required, somewhat in contrast to the other event types. Note that the web search interest used here as attention metric is at least partly driven by monetary concerns, probably supported by corresponding media coverage. This is indicated by the remarkable similarity between attention and property damage results (figures 1(d)–(e)) with storms and floods inducing the strongest losses and attention increases.

In addition to public attention, we also analyze the scientific interest in the considered extreme event types (figure S4). For this purpose we count the scientific articles with at least one researcher with a European affiliation related to each extreme event type published during the study period 2001–2015 (see supplementary material for details). Note that hence these estimates are not related to particular

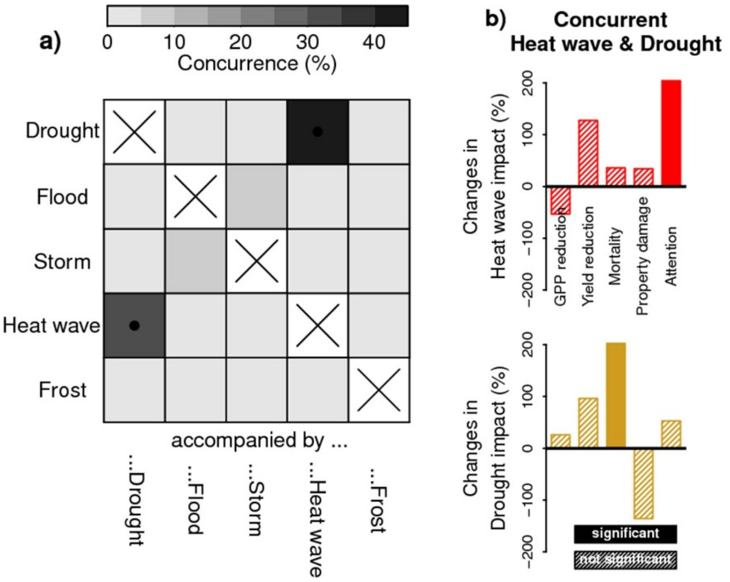

Figure 5. Amplified impacts in jointly occurring heat waves and droughts. (a) Concurrence rates of all considered extreme event types, computed as population-weighted mean rates across all 24 European countries. Dots indicate statistically significant rates. (b) Respective impact changes for compound versus single events for the example of joint heat waves and droughts. All events with return times exceeding 4.7 years, occurring in any of the 24 European countries, are used.

extreme events. Highest scientific interest is found for floods, and lowest for heat waves. Repeating the analysis from figure 4 with scientific interest replacing public attention unveils that the number of heat wave papers is very low compared with its impacts (figure S5). It remains unclear if this reflects insufficient research or can be explained by other factors such as the affected spatial scales and/or changes in these extremes induced by climate change.

Overall, such deviations between public and scientific attention with actual impacts are important to highlight as they could potentially contribute to underestimating the relevance of droughts and heat waves, and thereby undermine sufficient respective management and adaptation action.

Photosynthesis, mortality and attention data are available at sub-annual time scales which allows us to compute the evolution of these impacts before, during and after the extreme event peaks (figure S6). This is done by computing mean temporal evolutions first across all events in each country, and then as a composite obtained through weighted averaging across the country results (see also supplementary material). In the case of mortality, the peak impacts occur mostly simultaneously with the peak of the hydrometeorological anomalies. The attention results show that storms mainly receive attention during their peak intensity while floods receive most attention in the preceding month, probably following continuously increasing precipitation and runoff amounts (see figure S2) and effective early warning. In contrast, photosynthesis impacts of droughts are about 2 weeks delayed. This is likely related to slow changes in plants' leaf area index, chlorophyll content and physiology and as such a direct, lagged effect [5]. This delayed response could also partly explain the surprisingly low public attention on droughts (figures 1 and 4). The duration of significant impacts of extreme hydrometeorological events is mostly within 1–2 months. Most significant impacts are found within 4–6 weeks after the events.

Impacts of extreme events can be enhanced as they occur jointly [58–60]. We aim to quantify and compare this effect across impact domains. First we analyze the fraction of jointly occurring events among all events in the 24 countries using the 40 year hydrometeorological data. This reveals that concurrent heat waves and droughts are the most relevant concurrent extreme in Europe from the event types analyzed here, occurring jointly in roughly 30%–40% of the cases (figure 5(a)). Similar results are obtained with crop and land area-weighted averages across countries (figure S7). Such co-occurrence of hot temperatures and dry soils tends to be favored by atmospheric processes [61, 62] and land-atmosphere feedbacks [63]. While the preferential drought and heat co-occurrence is in line with previous studies [42, 59], we move beyond the state-of-the-art by quantifying respective empirical impacts in multiple domains, thereby identifying particularly vulnerable domains where impacts of these compound events are most amplified. For this purpose, we compare impacts of concurrent droughts and heat waves with those resulting from droughts or heat waves alone. This is done by computing the respective ratio of impacts for each impact domain and country, before deriving the weighted averages across countries. In the latter step any ratios larger than 5, or smaller than −5 are set to 5 and −5, respectively, to minimize the impact of outliers resulting from very small values in the denominators of the ratios. While these limits are arbitrary choices, results are not much affected with slightly different min-max values (not shown). Note further that a return period of 4.7 years is used in this analysis to sample a sufficient number of droughts and heat waves occurring jointly as well as separately (see supplementary material for further details).

Increased impacts are found across most domains (figure 5(b)). In the case of heat waves, particularly public attention and crop yield impacts are amplified when they are accompanied by droughts. In the case of droughts we find significant increases of impacts on mortality when these events occur jointly with heat waves. The latter finding underlines the well-known temperature control on human mortality [43]. These enhanced impacts are partly caused by stronger heat waves and droughts in the case of concurrent occurrence; return times in the case of droughts are increased by 20%–50% (depending on weighting used to average results across countries), and even by 100%–120% in the case of heat waves.

There are noteworthy limitations to the approaches and data employed in this study, which also indicate avenues for future empirical impact analyses of extreme events: (1) There is no universal definition of extreme events in terms of (a) the underlying hydro-meteorological variables and (b) their respective time scales [2]. We have chosen a simple and straightforward approach to detect each event type from one respective hydro-meteorological variable (see table 1), but e.g. for heat wave impacts, humidity can additionally play a role and for flood impacts also precipitation can be relevant. Further, extreme events occur across temporal scales, for example droughts might mostly last longer than wind storms. We account for this by determining events at different time scales; droughts and heat waves are determined from half-monthly means, while storms, floods and frosts are determined from daily extremes within a half-monthly-period (table 1). Also, figure S6 shows that the impacts of different event types are of comparable duration. While extreme events detected and determined with the variables and time scales chosen in this study are impact-relevant in several of the considered domains (e.g. figure 1), future research is needed to explore the role of different and multiple characterizing variables and event time scales for respective impacts, and to establish more universal extreme event definitions. (2) Hydro-meteorological extreme events occur at variable spatial scales and across regions which not necessarily match with (the size of) countries. Therefore, some events might be missed by our analysis as they occur only in a small part of a large(r) country. However, this does not seem to be a critical problem as no systematic difference is found in the results between countries of different size (figure 3). (3) The impact of extreme events does not depend solely on the hydro-meteorological anomalies, but also on vulnerability, which can vary locally and regionally. This means that impact signatures identified in this study should be viewed as continental-scale averages rather than locally applicable relationships. (4) Impact data records of 15 years are relatively short to analyze rare extreme events. We counter this with a space-for-time approach where we consider events across 24 countries to compute average impacts across all countries where events of particular types occurred. Further, the longer 40 year hydro-meteorological time series are used to robustly compute return periods [30] for detecting events. Yet, given the limited duration of the impact time series we focused on extremes with return times exceeding 7 years. Analyzing even more extreme events from longer data records once they are available in the future could lead to more robust impact signature results because extreme event impacts vary with event's return times (figure S3). (5) Analyzing impact metric anomalies during times of detected extreme events does not imply causality. Rather, our comprehensive analysis across countries, event types and domains indicates impact hot spots through statistical inference. We aim to mitigate the influence of processes other than the extreme events through detrending and deseasonalizing the impact time series. Nevertheless the impact signals determined in this way might be influenced somewhat by other confounding factors than the extreme events. Further, the impacts reported in this study are the result of a complex interplay between natural processes and anthropogenic influence. Given this complexity we can only formulate hypotheses for surprising and novel findings (such as for example the decreasing mortality with increasing flood and storm magnitude shown in figure 2 or the low scientific attention for heat waves shown in figures S4 and S5), while future research is needed for respective in-depth assessments. (6) Considering event-based impacts rather than cumulative impacts might overstate the role of high-magnitude events. As weaker events occur more frequently, the sum of their impacts might be (more) comparable to that of stronger events [64]. Finally, (7) the obtained conclusions are valid for Europe, whereas similar studies in other regions could find contrasting results due to different vulnerabilities related to different climate or socio-economic conditions.

4. Conclusions

In summary, this study highlights impact signatures of common extreme event types in Europe. This is enabled by our comprehensive approach to analyze the empirical impacts of hydro-meteorological extremes across extreme types, domains, and countries. In particular, we highlight contrasting impacts of extreme events on biophysical and social domains; photosynthesis, crop yields and human mortality are mostly affected by drought, flood, heat, and frost, whereas property damage and public attention is rather triggered by storm and flood. Note, however, that these findings are based on the country-scale, half-monthly spatiotemporal resolution of the impact data. As more high-resolution impact datasets become available, future research should focus on determining impact fingerprints across different spatial and temporal scales to determine impact-relevant spatial and temporal scales for each type of extreme.

Overall, the distinct impact signatures between extreme event types shown here illustrate different vulnerability patterns across impact domains; this information can guide more targeted extreme event management and adaptation and help to enable a more efficient allocation of resources across time scales, i.e. in the short term for forecasted events, and in the long term for climate change-related changes in the frequency or magnitude of the various event types. Furthermore, we find that impact signatures change for compound events; in the case of concurrent drought and heat, impacts are amplified in most domains but to different extents. For instance, in the case of crops, droughts contribute the major share of the compound drought-heat impact (figure 5(b)), which is consistent with regional crop impact assessments [65]. Therefore, our study allows to contextualize previous research on individual extreme events, domains or countries. Vice versa, the fact that previous research confirms several aspects of our results supports our conclusions.

While our study is performed at country-scale, disaster management and adaptation is implemented at regional scales and needs to take into account local circumstances to be effective. For example, vulnerability against disaster damage varies across regions with e.g. different population density, age groups or crop types. But such regional efforts require information on the general impact patterns which we derived at the national level where also more data is available to allow more robust analyses. This way, identifying respective typical affected domains by the main types of extreme events in this study can inform national response strategies to mitigate impacts. In particular the impact signatures across multiple domains can support the implementation of respective management plans. Moreover, pinpointing the (most) relevant extreme event types for each impact domain, alongside attention biases, temporal impact evolutions, and compound event impacts, can inform and guide future research and adaptation [10].

Data availability statement

All datasets used in the current study are publicly available from the references indicated.

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

R O performed the analyses for the figures. All authors conceived the study and analyses, and contributed to the writing.

Conflict of interest

The authors declare no competing interests.

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