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Compound extreme hourly rainfall preconditioned by heatwaves most likely in the mid-latitudes

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ABSTRACT

The potential compounding behaviour of heatwaves and extreme rainfall have important implications for a range of hazards, including wildfires and flooding, yet remain poorly understood. In this global study, we analyse the likelihood of extreme 1-hr rainfall immediately following a heatwave, and identify climate zones where this phenomenon is most pronounced. We find the strongest compounding heatwave-extreme rainfall relationships in central Europe and Japan, where the likelihood of extreme rainfall after a heatwave is increased by approximately four times compared to climatology. Significant compounding is found mainly in temperate or colder climates, provided these areas receive ample moisture. As both heatwaves and extreme rainfall are expected to become more frequent in the future, our results indicate that the potential impacts from compounding heatwave-extreme rainfall events might significantly increase as well.

1. Introduction

Heatwaves can lead to devastating impacts by themselves (e.g., on human health, Campbell et al., 2018); however, the potential impacts are often greater and more varied if heatwaves occur in combination with other hazards. Most commonly, heatwaves are associated with dry weather (Mazdiyasni and AghaKouchak, 2015; Sharma and Mujumdar, 2017; Miralles et al., 2019), leading to impacts on agriculture (Matiu et al., 2017; Ribeiro et al., 2020) and bush fire risk (Sutanto et al., 2020; Richardson et al., 2022). Indeed, for many regions, such as North America, Europe, and Australia, the most common precipitation- and temperature-related compound weather and climate event is the combination of heatwaves and low precipitation (Ridder et al., 2020). Although hot weather can amplify dry conditions (and vice versa, e.g., Miralles et al., 2019), high temperatures on a daily scale have also been shown to be associated with precipitation extremes (Berg et al., 2013; Westra et al., 2013, 2014; Ali et al., 2018, 2021a, 2021b; Guerreiro et al., 2018; Fowler et al., 2021) via thermodynamic mechanisms such as convection. However, until recently, it has been unclear to what extent longer hot periods such as heatwaves, which are commonly associated with dry weather, are followed by extreme rainfall. Recent work has demonstrated the existence of temporally-compounding hot-wet extremes in Australia (Sauter et al., 2022), China (Wu et al., 2021; You and Wang, 2021; Chen et al., 2022; Li et al., 2022, 2023; Ning et al., 2022) and the United States (Zhang and Villarini, 2020), though definitions and variables vary between the studies making comparisons between the regions difficult. Further, GU et al. (2022) demonstrated that co-occurrences between floods and heatwaves (floods up to 7 days before or after a heatwave) are projected to increase in most climate zones, especially in the Tropics.

As the heatwave before the precipitation event is often linked to a dry event and sometimes wildfires, the possible impacts from a compounding event range further than the individual two hazards themselves. High precipitation events after wildfires or bushfires that are associated with hot-dry events can lead to increases in debris flows (e.g., Moftakhari and AghaKouchak, 2019; Touma et al., 2022), or reduce water quality (Murphy et al., 2015; Kemter et al., 2021; Nyman et al., 2021). Further, dry weather impacts on antecedent soil moisture which,

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together with high precipitation, are important modulators for flooding (Bennett et al., 2018; Sharma et al., 2018; Ali et al., 2019).

While there is growing evidence on the occurrence of compounding heatwave-extreme rainfall events, the mechanisms behind the events remain largely unclear. As to why extreme rainfall events occur after a dry synoptic system, previous work has focused primarily on convection as the main driver (Zhang and Villarini, 2020; Wu et al., 2021; You and Wang, 2021; Chen et al., 2022) with limited focus on other potential mechanisms, such as cyclones, cold fronts, or atmospheric rivers. In general, the frequency and intensity of this type of compounding event would be expected to vary depending on the location, as the most common mechanism for extreme rainfall (cyclones, fronts, thunderstorms, or a combination of the three) varies with location (Dowdy and Catto, 2017).

Here, for the first time, we analyse the frequency and spatial occurrence of extreme rainfall preconditioned by a heatwave on a global scale using an extensive global observational dataset at hourly resolution. In particular, we identify (1) regions where heatwaves are most likely to be followed by extreme rainfall, and (2) climate conditions in which compounding heatwave-extreme rainfall events occur most often. Improved knowledge on the spatial occurrence and prevalent climate conditions for compound heatwave-extreme rainfall events will help disentangle their underlying mechanisms, potentially improve the predictability of heatwave-related extreme rainfall, and provide a basis for estimating future risk from these compound events.

2. Data

We use quality-controlled rainfall observations at an hourly scale from the Global Sub-Daily Rainfall Dataset (GSDR) (Lewis et al., 2019; Ali et al., 2022). The observational records vary in length as well as the start and end dates; therefore, we only use stations with at least 12 years of record length and with less than 20 percent missing data in any given year (analogue to Ali et al., 2021a). Since temperature data is only available from 1979 onwards, we also limit rainfall observations to start from 1979 or later. This results in 7 394 observations from the GSDR dataset that fit these criteria, mainly located in the United States, Europe, India, Malaysia, Japan, and Australia (Fig. S1). We define hourly extreme rainfall as rainfall greater than the 99th percentile of all hours with intensities larger than 0.1 mm h^{-1} within the rainfall record.

In order to identify heatwaves for the locations of the rainfall observations, we use daily maximum and minimum 2-m air temperature data (T_{max} and T_{min}, respectively) from the ERA5 reanalysis dataset, as temperature data was not available in the GSDR dataset. ERA5 temperature data is provided at a horizontal resolution of 31 km (Hersbach et al., 2020). For each GSDR rainfall station, the corresponding ERA5 grid box was selected. T_{max} and T_{min} are aggregated from hourly values with respect to the local time zone of each GSDR station.

To investigate the prevalent climate conditions of areas with heatwave-extreme rainfall events, we use the Köppen-Geiger classifications from Beck et al. (2018). GSDR stations are sorted into the respective Köppen-Geiger climate zones. Out of the 30 possible classifications, 21 are represented by GSDR stations (Fig. S1). As station density and coverage vary depending on the climate zone, we further tested the sensitivity to station density by randomly reducing the number of stations of the most densely represented climate zones in Australia ('Cfa' and 'Cfb') by 75% and 90% respectively. A full description of the climate zones, including their defining criteria, can be found in Table S1.

3. Heatwave definition

Heatwaves were identified using T_{max} and T_{min} for each observational location individually with respect to the local temperature climatology for that location following the definition used in Sauter et al. (2022). During any time of the year, a heatwave is identified if (1) the maximum daily temperature lies above its 95th percentile of all days during the record for at least three consecutive days, and (2) the minimum daily temperature lies above its 95th percentile of all days during the record during at least the second and third day. A heatwave is only terminated if T_{max}, T_{min}, or a combination of the two, are below their respective threshold for at least two consecutive days. This ensures that a longer heatwave that is temporarily interrupted by a day of colder temperature is not classified as two shorter heatwaves. The last day where both T_{max} and T_{min} lie above their respective thresholds is referred to as the 'last day of the heatwave'. As this heatwave definition is based on absolute temperatures, heatwaves are usually found in the hottest months of the year (Fig. S2). We have also tested defining a heatwave using only T_{max}, however, have found that this definition does not change the results considerably. In general, the analysis of frequency and intensity of extreme rainfall after heatwaves tends to be insensitive to the choice of temperature-only based heatwave definitions (Sauter et al., 2022). To investigate potential differences between wet and dry heatwaves, we also performed our analysis for dry heatwaves by introducing a restraint of $<$1 mm rainfall during the last three days before the heatwave termination (Figs. S3–S5).

4. Methods

The methods for extreme rainfall identification and estimating climatological rainfall behaviour follow those of Sauter et al. (2022). We consider a heatwave to be followed by extreme rainfall if there is an occurrence of at least 1 h of extreme rainfall within 36 h, beginning at noon local time on the last day of a heatwave until midnight on the following day. This time-window is long enough to capture extreme rainfall events related to the heatwave; the 36-h window begins at noon on the last heatwave day to ensure the capture of any rainfall that might occur shortly after the diurnal temperature peak in the afternoon. Longer time-windows, such as 60 h were tested by Sauter et al. (2022); however, the differences in extreme rainfall likelihood after a heatwave compared to climatology decreased for times longer than one day after the heatwave termination (see also Chen et al., 2022). For an illustration of a heatwave followed by extreme hourly rainfall, see Fig. 1.

To estimate how the heatwave-extreme rainfall relationship influences the extreme rainfall probability, we also calculate the climatological probability of extreme rainfall at similar times of the year as the heatwaves via a resampling approach. We take 1000 resamples for each heatwave and station in turn. The resample takes station data for the same month of the last day of the respective heatwave (but during any year, including the original date); this ensures similar climatological conditions for the resample as the original heatwave date, as heatwaves are likely not evenly distributed during the year (or even during the hot season). The 1000 resamples for each heatwave are then used to estimate climatological variability. We estimate the climatological probability of extreme rainfall for a specific station by then calculating the probability of at least one hourly extreme rainfall occurring within the same 36-h window for all resampled dates. We then calculate the difference in probability of hourly extreme rainfall after a heatwave compared to climatology as:

$$R = \frac{P(Rain \mid Heatwave)}{P(Rain)} \quad \text{Eq 1}$$

where R is the ratio of the likelihood of hourly extreme rainfall given a preceding heatwave *(P(Rain | Heatwave)*, see Fig. 2) to the climatological hourly extreme rainfall likelihood *P(Rain)*.

5. Results

5.1. Likelihood of hourly extreme rainfall after heatwaves

Our results show that the likelihood of at least 1 h of extreme rainfall

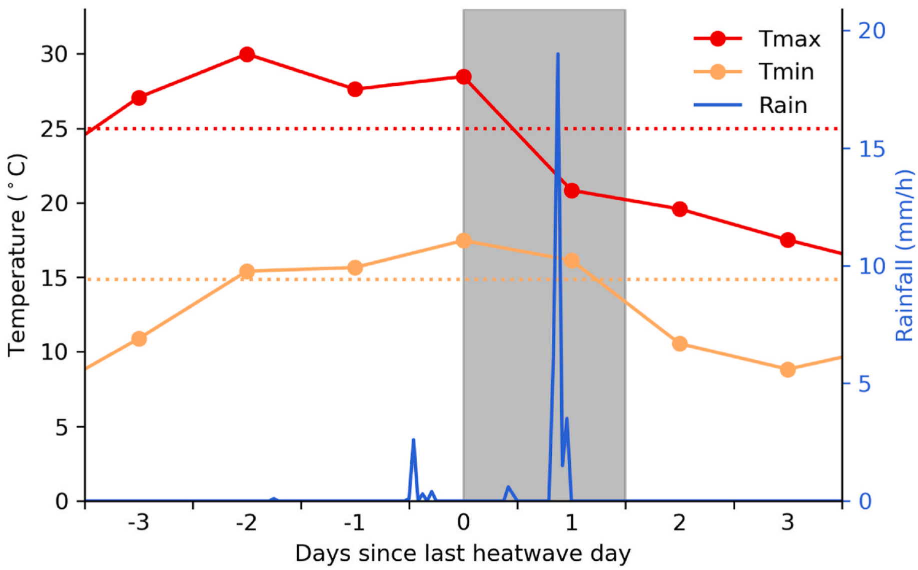

Fig. 1. An example of a heatwave followed by extreme hourly rainfall from a station in Germany (51.6N, 10.3E). The x-axis denotes the day relative to the last day of the heatwave, with ticks spanning from midnight to midnight. The dashed lines show the 95th percentiles for T_{max} (red) and T_{min} (orange). The grey shaded area marks the 36-h time interval, starting at 12:00 on the last heatwave day, considered for extreme hourly rainfall. Markers for T_{max} and T_{min} are plotted at 12:00 on each day for simplicity although they can occur at any time of the day. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

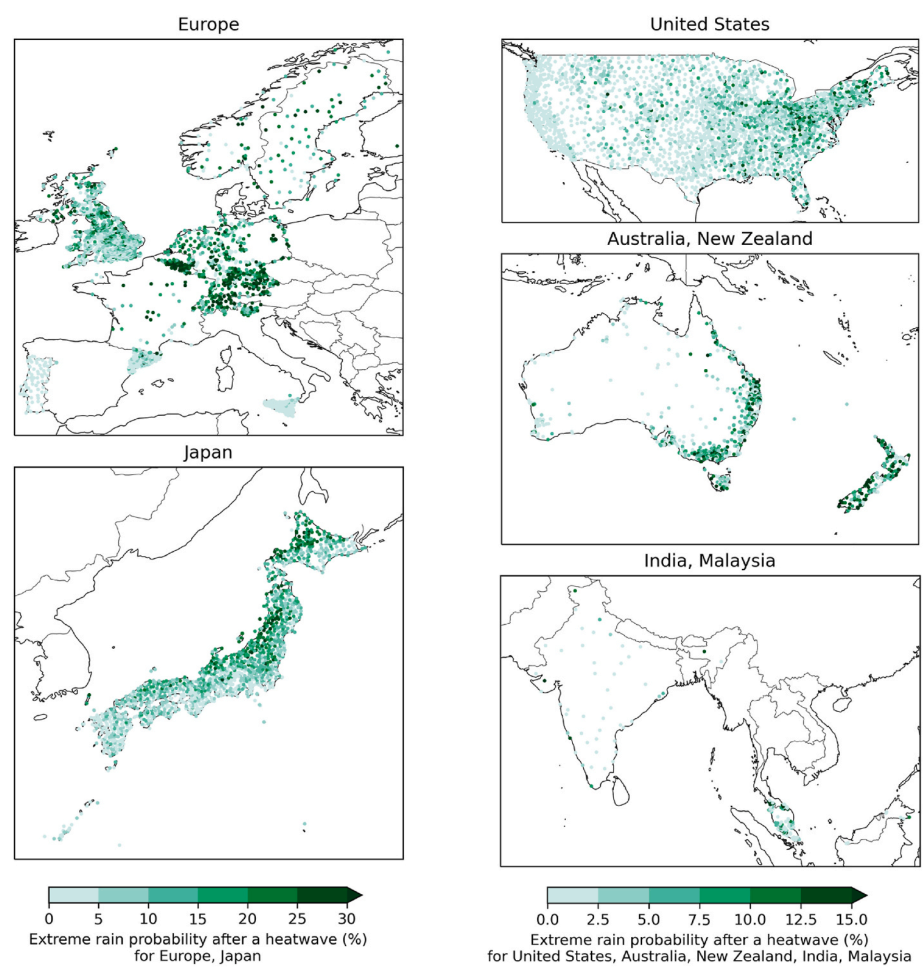

Fig. 2. Probability of at least 1 h of extreme rainfall occurring within 36 h from noon on the last heatwave day for stations in Europe, Japan, the contiguous United States, Australia, India, and Malaysia. Note the change in scale in the righthand column.

occurring after a heatwave strongly varies depending on location (Fig. 2). The data-covered areas with the highest probabilities of extreme rainfall after a heatwave are central Europe (Germany, Switzerland, northern Italy, and Belgium) as well as the northern and north-eastern coast of Japan, where 30% or more heatwaves are followed by extreme rainfall. In southern Europe, fewer than 5% of heatwaves, on average, are followed by extreme rainfall. Within the contiguous United States, the northeast shows the highest likelihood of extreme rainfall after a heatwave, whereas western and central areas show a very low likelihood. For Australia, the east and south-eastern coasts exhibit higher likelihoods of heatwaves followed by wet extremes than the rest of the country. Results are robust even when accounting for the difference in station density (Fig. S6). However, higher likelihoods of extreme rainfall compared to climatology are more likely to lie within the sampled uncertainty of climatology if station density is low and therefore might not be interpreted as significantly different from climatology. India and Malaysia show overall low likelihoods of extreme rainfall after heatwaves. There are some weak indications that the extreme rainfall likelihood might be increased on the western coast of India, however, robust conclusions for India in general cannot be made due to the low density of available stations and a generally high spatial heterogeneity of extreme precipitation (e.g., Singh et al., 2014).

Regions that show low likelihoods of extreme rainfall after heatwaves also show low likelihoods of rainfall in general (i.e., extreme and non-extreme) after heatwaves (Fig. S7). This is mainly the case in southern Europe, east United States and India. In turn, regions with a high likelihood of extreme rainfall after heatwaves also show a high likelihood of any rain falling after heatwaves.

The preceding analysis shows the probability of extreme rainfall following a heatwave event; however, it does not describe the potential role of the heatwave in modifying the probability relative to a climatological baseline. Fig. 3 therefore shows the ratio of the likelihood of hourly extreme rainfall after a heatwave to the climatological hourly extreme rainfall likelihood (Eq. (1)). In central and northern Europe, hourly extreme rainfall is significantly more likely if preceded by a heatwave, with the highest values located in Belgium (over four times more likely on average) and southern Germany (over three times more likely on average). For the southern European regions represented by GSDR stations, most heatwaves were either not followed by extreme rain, or the median climatological likelihood of extreme rainfall at similar times of the year as the heatwaves was zero. In Japan, extreme rainfall is more likely after a heatwave than expected from climatology for most stations, with the highest differences in northern parts of the country. For the southern parts of Japan, the signal is more ambiguous, with some areas showing lower likelihoods of extreme rainfall after a heatwave compared to climatology. Within the contiguous United States, most regions show no extreme rainfall events after heatwaves, or the median climatological extreme rainfall likelihood was zero. However, in the north-eastern parts of the country, extreme rainfall is either comparably likely or more likely if preceded by a heatwave. Australian stations also show increased likelihoods of extreme rainfall after a heatwave for the eastern and south-eastern coast, whereas New Zealand shows increased likelihoods of extreme rainfall after a heatwave for the entire country. For both India and Malaysia, most stations show no difference in the probability of occurrence of extreme rainfall after heatwaves.

Areas showing an increased likelihood of extreme rainfall after heatwaves compared to climatology are predominantly the same that show overall high extreme rainfall likelihoods after heatwaves (Fig. 2). This indicates that high extreme rainfall occurrences after heatwaves are unlikely to result from higher climatological extreme rainfall likelihoods during hot seasons alone. Overall, the highest likelihood of extreme

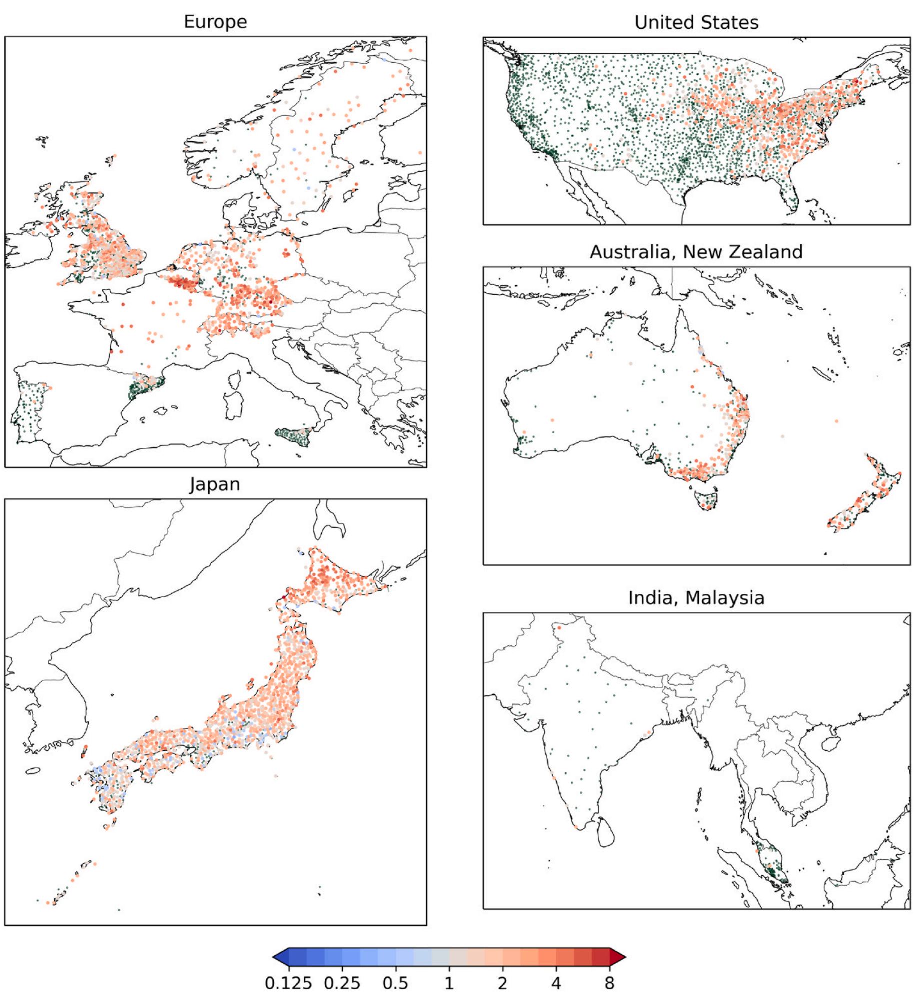

Fig. 3. The difference in probability of extreme rainfall after a heatwave from expected probabilities from rainfall climatology (Eq. 1). Values > 1 indicate that hourly extreme rainfall is more likely after a heatwave than for climatology. Comparisons are based on the median values from 1000 resamples. Smaller dark green dots show stations where there was no hourly rainfall extreme occurrence after any of the heatwaves or the median climatological probability of an hourly rainfall extreme was zero. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

rainfall after a heatwave compared to climatology occurs in the non-arid and non-tropical regions of the investigated areas, though any assertions of extreme rainfall likelihoods in tropical climates are weak due to limited station coverage and density. This is especially true for the monsoonal climates, where extreme rainfall likelihood is higher than climatology, however, within the range of sampled uncertainty due to the low number of stations (only 22 stations in the ‘Am’ climate zone).

5.2. Division by Köppen-Geiger climate zones

We use the Köppen-Geiger climate classification (Fig. 4a) to further test if regional patterns in high compound heatwave-extreme rainfall occurrences are related to local climate conditions. Fig. 4b shows the likelihood of at least 1 h of extreme rainfall after a heatwave day by the Köppen-Geiger climate zone. Overall, the likelihood of extreme rainfall after a heatwave strongly varies with climate zone, with average likelihoods spanning from close to 0% to over 20%. The average likelihood of extreme rainfall occurring climatologically during similar times of the year varies between close to 0% and almost 10%. Generally, Tropical (type ‘A’) and Arid (‘B’) climate zones show lower likelihoods of extreme rainfall compared to other main Köppen-Geiger climates, both after a heatwave and for climatology. For Temperate (‘C’) and Cold (‘D’) climates, extreme rainfall likelihoods are comparably higher both after a heatwave and in climatology, but strongly depend on the climatological sub-class, with the ‘f’ subclass (climate with no dry season, i.e., no ‘dry’ summer or winter: see Table S1 for definition) being the strongest indicator of increased likelihood.

Crucially, for most climate zones, we find the likelihood of an extreme wet hour occurring after a heatwave is higher than expected from climatology. Only in the Arid subregion ‘Bhw’ is extreme hourly rainfall likelihood lower if preceded by a heatwave when compared to climatology. The largest – and most consistent – difference is found in Temperate (‘C’), Cold (‘D’), or Polar (‘E’) climates, where the likelihood of extreme rainfall is considerably higher after a heatwave than from climatology as can be seen by the distance between the ‘after heatwave’ probability and the resampled distribution in Fig. 4b. This is especially the case for stations located in the ‘f’-subclass, where extreme rainfall probabilities after heatwaves lie outside the resampled climatological distribution. Similarly, the Tundra subclass (‘ET’) shows that the likelihoods of extreme rainfall after heatwaves are on average more than twice as high as for climatology. Overall, most regions showing high likelihoods of extreme rainfall after heatwaves, which also lie outside the climatological range, are in the mid- and high-latitudes. Similar results can also be found when analysing the intensity of the rainfall after heatwaves compared to that during climatology (Fig. S8).

6. Discussion

We have demonstrated that a preceding heatwave only increases the likelihood of extreme rainfall in particular climate zones (Fig. 4b); i.e., in Moderate, Cold, and Polar regions according to the Köppen-Geiger classification (‘C’, ‘D’ and ‘E’ regions, respectively). It is important to note that the results are based on the subset of stations available for each respective climate zone, and therefore extrapolating results to another ungauged location characterized by the same climate zone must be done with caution. Within the Köppen-Geiger subclasses, regions that experience ‘no dry season’ (sub-class ‘f’) show significantly higher likelihoods of at least 1 h of extreme rainfall after heatwaves compared to the climatological conditions for these regions. Our findings support the results from other studies that have examined “hot-wet” extremes:

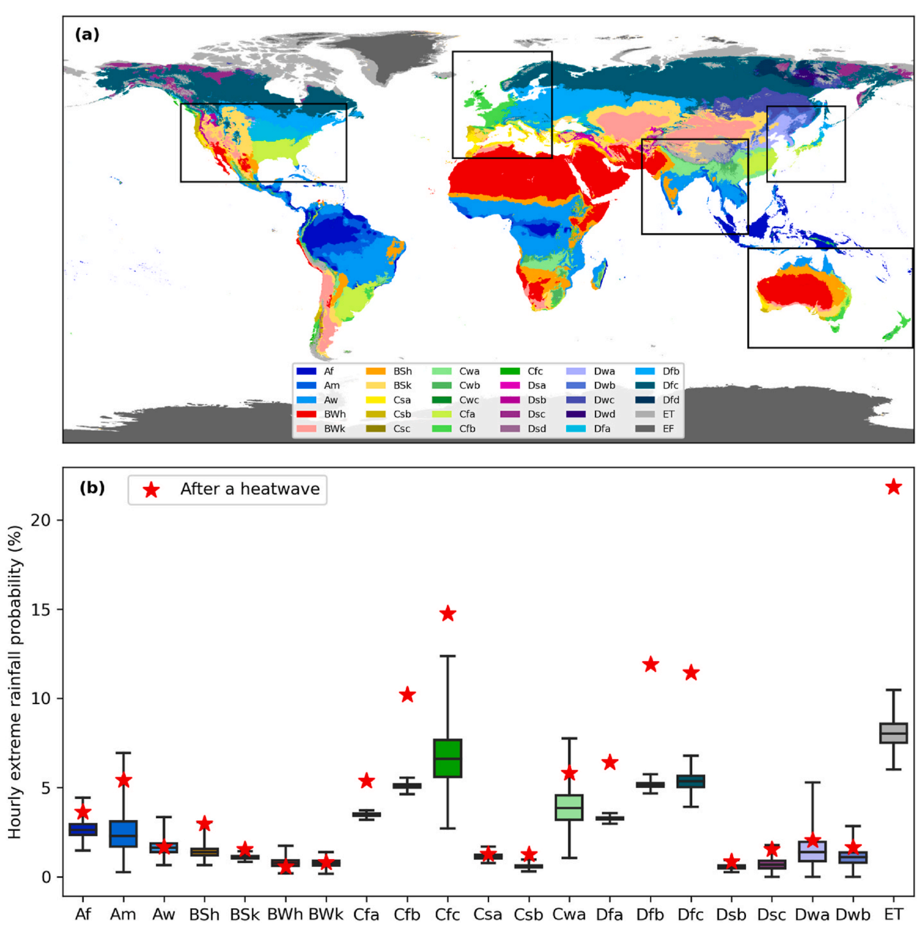

Fig. 4. (a) Map of Köppen-Geiger climate regions after Beck et al. (2018). Black boxes mark areas where the majority of GSDR stations are located. A full description of the climate zones, including their defining criteria can be found in Table S1 in the Supporting Information. (b) Likelihood of occurrence of at least one hourly rainfall extreme within 36 h from noon on the last day of the heatwave (red stars) for Köppen-Geiger climate zones that were represented by GSDR stations. Boxplots show the 25%–75% (whiskers: 5%–95%) range of climatological likelihoods of hourly extreme rainfall for 36-h periods during similar times of the year obtained from resampling. Results are based on the subset of stations that were available for the respective climate zone. Boxplot-whiskers span from minimum to maximum values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Zhang and Villarini (2020) found evidence of floods after heat-stress events in the central-east of the United States, and similar findings to ours were reported in China (Wu et al., 2021; You and Wang, 2021; Chen et al., 2022; Ning et al., 2022). Although no precipitation data for China was available for this study, the Köppen-Geiger climate zones identified as associated with heatwave-extreme rainfall are also present in China (e.g., 'Cfa' in Eastern China). In Australia, our previous work found compounding heatwave-extreme rainfall events predominately for the eastern and south-eastern coast (Sauter et al., 2022), which is also in agreement with the findings of this study.

Compound heatwave-extreme rainfall events are most likely in temperate or colder climates ('C', 'D', 'E'), provided there is no 'dry season' ('f' sub-climate). This indicates that ample moisture supply is essential for this kind of compound event. As hourly extreme rainfall is more likely compared to climatology even if only considering dry heatwaves (Fig. S5), it is likely that extreme rainfall after heatwaves in these regions is not solely convection driven, but that synoptic-scale drivers such as fronts or cyclones play are associated with extreme rainfall after heatwaves as well. Arid regions, while producing high temperatures, may lack the moisture supply for conditions leading to rainfall during the hot season (Bisselink and Dolman, 2008). This is evident in our results as these regions show a low likelihood of rainfall in general after heatwaves (Fig. S7). The Tropics, on the other hand, while experiencing both high temperatures and high rainfall amounts (Fig. S7), do not exhibit noticeable increases in extreme rainfall after heatwaves (Fig. 4). Temperature-related convection is undoubtably an important driver of high rainfall intensities in the tropics (Dowdy and Catto, 2017). However, we have found here that higher-than-normal temperatures, especially over multiple days, may not substantially increase extreme rainfall likelihood over the Tropics. This may be explained by the fact that the air is considerably less enriched with moisture during dry heatwaves in comparison to hot-wet days that are common in Tropical climates (Roderick et al., 2019). Indeed, extreme rainfall likelihood after dry heatwaves in the tropics is lower than the average climatological extreme rainfall likelihood (Fig. S5). In monsoonal climates like India, we found weak evidence of increased likelihoods of extreme rainfall after heatwaves on the east coast, however, the station density in India (and for monsoonal climate zones in general) is too low to draw clear conclusions.

We have investigated compounding heatwave-extreme rainfall in many different global locations, including 21 from the 30 Köppen-Geiger climate zones. However, Köppen-Geiger regions are classified based on average temperature and precipitation metrics and do not take into account the meteorological/climatological processes behind these variables. Thus, confidence in the intensity and frequency of compounding heatwave-extreme rainfall events is highest for areas covered by the GSDR rainfall stations. It is possible that other regions and countries not represented by rainfall stations in this study could similarly be exposed to high compounding heatwave-extreme rainfall events, even if the likelihood of extreme rainfall for their respective Köppen-Geiger region was not found to be significantly higher than climatology in this study, and vice versa. Nevertheless, the Köppen-Geiger classification provides a useful tool to estimate areas where compound heatwave-extreme rainfall events might occur but are not represented by rainfall observations.

Limitations also arise from the use of resampling for the estimation of climatological rainfall. The resampling method assumes spatial-temporal independence of heatwave dates between the stations. Stations near one another may identify the same heatwave event and be influenced by the same synoptic conditions driving (the lack of) rainfall. This spatially-correlated behaviour is difficult to accurately simulate with a resampling approach, as each heatwave varies with spatial extent and location. Thus, for regions with a high density of stations, the distribution estimated by the resampling approach is likely too narrow, even after 1000 repetitions. However, the average rainfall behaviour is still estimated accurately.

The estimated probability of extreme rainfall following a heatwave depends on the methodology used, such as the choice of the temporal window after a heatwave and the definitions of both heatwaves and extreme rainfall metrics. In a previous study in Australia (Sauter et al., 2022), different definitions of heatwaves and extreme rainfall metrics, as well as a longer temporal window after heatwaves, were tested, and the overall findings were found to be robust to these methodological choices. However, given the importance of available moisture for extreme rainfall, we suggest future analysis on heatwave-extreme rainfall relationships should test the usefulness of humidity-based heatwave definitions (such as the wet bulb temperature used by Zhang and Villarini, 2020).

7. Conclusions

We have shown that extreme hourly rainfall is more likely to occur after a heatwave than for climatology for North America, Europe, Australia, and parts of Asia. These temporally-compounding heatwave-extreme rainfall events are particularly common in central Europe and Japan, and, to a lesser extent, in the eastern U.S. and the eastern and south-eastern coast of Australia, which are all densely populated areas. For these regions, we have demonstrated that the likelihood of extreme hourly rainfall can be locally increased by up to several factors if preceded by a heatwave.

Our findings have implications for assessing the risk associated with heatwave-extreme rainfall events. Both heatwaves and hourly extreme rainfall are projected to become more frequent and intense in a warming climate (Seneviratne et al., 2021) and our findings show that a significant area globally is already potentially affected by these compound extremes, including highly populated areas. However, it is still unclear how the spatial extent and strength of the relationship between heatwaves and extreme rainfall, as well as their associated impacts, might change in the future.

Author statement

Christoph Sauter: Conceptualization; Data curation; Formal Analysis; Visualization; Writing – Original Draft Preparation; Writing – Review & Editing Hayley J. Fowler: Conceptualization; Writing – Review & Editing Seth Westra: Conceptualization; Writing – Review & Editing Haider Ali: Data curation; Writing – Review & Editing Nadav Peleg: Data curation; Writing – Review & Editing Christopher J. White: Conceptualization; Funding Acquisition; Writing – Review & Editing.

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.

Data availability

Data will be made available on request.

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processing ERA5 data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2023.100563.

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