Understanding Compound Heatwave-Extreme Rainfall Events for Building Climate Resilience

By

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DECLARATION OF AUTHENTICITY AND AUTHOR'S RIGHTS

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Paper 2: Sauter, C., Fowler, H. J., Westra, S., Ali, H., Peleg, N., & White, C. J. (2023). Compound extreme hourly rainfall preconditioned by heatwaves most likely in the mid and high latitudes. *Weather and Climate Extremes, 40, 100563*, doi: https://doi.org/10.1016/j.wace.2023.100563.

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- Simmonds, R., White, C. J., Douglas, J., **Sauter, C.** & Brett, L. 2022. A review of interacting natural hazards and cascading impacts in Scotland, url: https://eprints.gla.ac.uk/267515.

- Vogel, J., Rivoire, P., Deidda, C., Rahimi, L., **Sauter, C. A.**, Tschumi, E., Van der Wiel, K., Zhang, T. & Zscheischler, J. 2021. Identifying meteorological drivers of extreme impacts: an application to simulated crop yields. *Earth System Dynamics*, 12, 151-172, doi: https://doi.org/10.5194/esd-12-151-2021.

The abstracts/summaries of these publications can be found in Appendix E.

Oral Presentations related to the thesis:

- Presentations at the European Geosciences Union (EGU) General Assembly 2021 (virtual) and 2022 (in person)

- Presentation at the Australian Meteorological and Oceanographic Society Annual General Meeting (AMOS) 2021 (virtual)

- Public seminars at University of New South Wales (UNSW) and the Bureau of Meteorology (BoM), Australia, 2022 (in person)

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ABSTRACT

Extreme rainfall can lead to (flash) flooding which can cause high impacts on society. It has been shown recently that the intensity and likelihood of extreme rainfall can be increased if it occurs immediately after a heatwave, amplifying the chance of flash flooding compared to non-heatwave conditions. However, many aspects about the relationship between heatwaves and extreme rainfall remain poorly understood, making any assessment of the risk difficult. This thesis addresses the gaps in understanding these compound heatwave-extreme rainfall events by investigating their characteristics, including their likelihood, spatial distribution, and underlying mechanisms. In a case study for Australia, it is shown that in most regions extreme rainfall is both more frequent and more intense after a heatwave compared to climatological conditions, irrespective of which definitions and thresholds are used. Similar results are then also found on a global scale, where it is shown that in many regions the likelihood of extreme rainfall events after heatwaves is higher compared to climatological conditions. Hotspots are found in the higher latitudes such as in Central Europe, where extreme rainfall likelihood can be increased by factor four or more. In general, compound heatwave-extreme rainfall events are most likely to occur in moderate and colder climates, specifically if the local climate is characterised by sufficient rainfall. Finally, analysis of the driving mechanisms behind compound heatwave-extreme rainfall events in Europe and Australia reveals that both synoptic-scale and thermodynamic drivers (i.e., fronts and thunderstorms) are strongly associated with heatwave-to-extreme rainfall transitions. Additionally, high atmospheric moisture content is identified to be a necessary condition for heatwaves to be followed by extreme rainfall. The advances in understanding compound heatwave-extreme rainfall events demonstrated in this thesis are crucial to understanding current and future risk and provide the basis for increasing long-term resilience to these events.

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Af, Am, Aw, BWh, BWk, BSh, BSk, Csa, Csb, Csc, Cwa, Cwb, Cwc, Cfa, Cfb, Cfc, Dsa, Dsb, Dsc, Dsd, Dwa, Dwb, Dwc, Dwd, Dfa, Dfb, Dfc, Dfd, ET, EF	Köppen-Geiger climate classifications. For definitions, see Table B1.
CAPE	Convective available potential energy
CC-relationship	Clausius-Clapeyron relationship
CIN	Convective inhibition
CO, CF, CFT, FO, FT, H, TO, U, UFC, WF	Weather types. For definitions, see Chapter 6.4.3
CS, EC, MB, MN, RL, SS, SSWF, WT,	Sub-divisions in Australia. For definitions, see Chapter 4.3.3
CTN90pct, CTX90pct	Heatwave definitions after Perkins and Alexander (2013)
DAMOCLES	Cost Action 17109 - Understanding and modelling compound climate and weather events
EPSRC	Engineering and Physical Sciences Research Council
ERA5	ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis dataset (Hersbach et al., 2020)
GSDR	Global Sub-Daily Rainfall dataset (Lewis et al., 2019)
HW	Heatwave
IPCC	Intergovernmental Panel on Climate Change
L	Likelihood
NERC	Natural Environment Research Council
R	Ratio

SILO	Australian climate dataset (Jeffrey et al., 2001)
TCWV	Total column water vapour
T_{max}, T_{min}	Daily maximum temperature, daily minimum temperature
UKCP18	High-resolution climate projections for the UK (Lowe et al., 2018)
UKRI	UK Research and Innovation

CHAPTER 1

INTRODUCTION

> It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time, in particular for temperature extremes.

Intergovernmental Panel on Climate Change (IPCC)
Sixth Assessment Report, Ch. 11

1.1 Motivation

Natural hazards such as heatwaves, droughts, and floods can lead to high impacts, including on human health, agriculture, or infrastructure. The economic damages arising from natural hazards in the 2010s have been estimated to account to a yearly average of 170 billion USD, an increase of 145% compared to the 1990s (UNDRR, 2022). Hazards such as heatwaves or flood-inducing extreme rainfall events, while already causing considerable damages, are projected to become even more frequent and intense in a warming climate (Seneviratne et al., 2021). Therefore, understanding their mechanisms and dependencies is crucial in estimating the future risk from these events.

Natural hazards, however, mostly don’t occur in isolation of each other. Often the highest impact occurs where there is a combination of multiple hazards or their drivers (Zscheischler et al., 2018). If multiple weather conditions coincide or interact in a particular manner, the impact can be extreme even without the weather conditions being extreme themselves (van der Wiel et al., 2020). The field of compound events specifically studies how multiple hazards or drivers interact and how that affects the risk associated with them (Leonard et al., 2014, Zscheischler et al., 2018). In many cases, the hazards are connected due to shared large or smaller scale drivers or feedbacks. These connected hazards therefore co-occur more frequently than if they were independent of each other (Zscheischler and Seneviratne, 2017). Heatwaves for example have been shown to often coincide with droughts, a compound hazard that severely affects agriculture (Ciais et al., 2005), water resource management (Lund et al., 2018) and fire risk (Libonati et al., 2022). High temperatures are also important, however, for providing conditions associated with extreme rainfall, which, even if the duration of the rainfall is not very long, can lead to severe flash floods (Fowler et al., 2021a). This follows from the fact that hotter air can hold more moisture than cooler air which allows for precipitation to be more extreme (Trenberth et al., 2003). Indeed, the increase of precipitation extremes with higher temperatures is not only a theoretical concept, but has been demonstrated in observations as well (e.g., Westra et al., 2013).

As heatwaves usually occur in combination with dry conditions (Miralles et al., 2019), rainfall associated with the heatwave is mostly associated with the termination of the heatwave. Rainfall itself during hot conditions is usually associated with cooling of surface-near temperatures, which can occur from a number of factors including from the evaporated cooling of the rain itself or the introduction of cooler air normally associated with low-pressure systems (Bao et al., 2017). Therefore, the most plausible compound event of heatwaves and extreme rainfall is where extreme rainfall follows the heatwave within a short time space. This potentially leads to rainfall with is more intense and more likely to be extreme than without the influence of a preceding heatwave (a *preconditioned* compound event, see Chapter 2). As heatwaves are projected to become more intense and frequent in a warming climate (Seneviratne et al., 2021), extreme rainfall connected to hot conditions are likely to change as well.

However, in a wider frame, heatwaves and extreme rainfall are not the only hazards associated with the transition from hot to wet extremes. Because heatwaves influence the occurrence and intensity of droughts (Miralles et al., 2019) and fires (e.g., Srock et al., 2018), and extreme rainfall increases the risk of floods (e.g., Wasko et al., 2021), compounding heatwave-extreme rainfall can potentially be the connecting link between a wider range of hot and dry, and successive wet hazards (Figure 1). These other hazards are interconnected as well, as rainfall weakens droughts and extinguishes fires, and droughts impact soil moisture which modulates flood risk (Bennett et al., 2018). However, it is crucial to improve the understanding of the heatwave-extreme rainfall connection, as changes to either hazards, or their relationship is also likely to influence the interplay with other connected hazards and risks.

1.2 Aim of the thesis and guiding research questions

Compound heatwave-extreme rainfall events can lead to devastating impacts by causing intense flash floods, however, the relationship between the two hazards is still poorly understood. A detailed understanding of this relationship, however, is essential for estimating current and future risk from these events and building climate resilience. Basic characteristics of compound heatwave-extreme rainfall events which are needed to estimate those risks are still unclear, including where the event occurs globally, how likely they are, how the likelihood varies with location as well as what exact mechanisms are causing them.

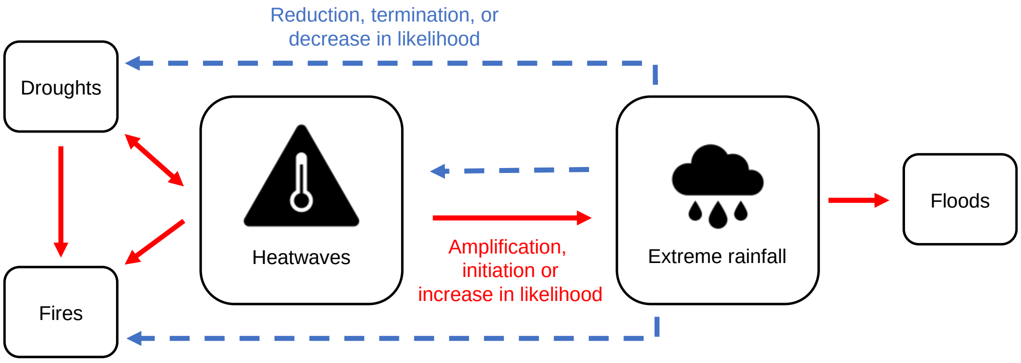

Figure 1 Schematic of interactions in compound heatwave-extreme rainfall events and connected hazards.

The aim of this thesis is therefore to improve the understanding of key properties of compound heatwave-extreme rainfall events, including their location, frequency, intensity, and underlying mechanisms. A better knowledge of these events provides the basis for evaluating the risk from resulting floods and other potential impacts. In addition, a better understanding of compound heatwave-extreme rainfall events allows for evidence-based decision making on appropriate response measures. Climate resilience, specifically to flash floods, can be improved by several measures. If future probabilities and intensities of these events are known, risks can be mitigated through adaptation measures. In urban areas those can include building flood resistant houses and flood shelters, but resilience strategies can also include community education and engagement about climate resilience planning (Tyler and Moench, 2012). On a shorter timescale, better knowledge of the underlying mechanisms and their interactions can help improve event forecasting and early warning systems.

To address the knowledge gaps in understanding compound heatwave-extreme rainfall events, the thesis will address the following research questions (RQ):

RQ1: Until now, compound heatwave-extreme rainfall events have only been demonstrated in China, but is this phenomenon found in other parts of the world as well? Australia is a country that is climatically diverse, has long and high-quality data records and experiences many natural hazards on a frequent basis, including both heatwaves and extreme rainfall. What can Australia teach us about this compound event?
(Addressed in Chapters 4 and 5)

RQ2: Extreme events can be defined in many ways. Are any findings robust to different definitions, thresholds, and timescales of heatwaves and extreme rainfall, as well as temporal data resolution?
(Addressed in Chapter 4)

RQ3: Vulnerability to natural hazards depends on many factors including the location of the event (IPCC, 2022). Where globally is the relationship between heatwaves and extreme rainfall the strongest?
(Addressed in Chapter 5)

RQ4: Both heatwaves and extreme rainfall vary in different regions. How does this relationship change in different climatic regions?
(Addressed in Chapter 5)

RQ5: Understanding the mechanisms behind compound heatwave-extreme rainfall events helps estimate future changes of this event and could contribute to improved forecasting. Which exact mechanisms cause increases in intensity and frequency of extreme rainfall after heatwaves? What roles do thermodynamic and synoptic-scale drivers play?
(Addressed in Chapter 6)

A summary of how the results address the research questions is given in Chapter 7.2.

1.3 Thesis structure

The thesis is divided into 6 sections following this introduction. The main analyses and results are presented in Chapters 4, 5, and 6 which are written as journal articles and therefore contain their own independent abstract, introduction, discussion, conclusion, and acknowledgement sections. Each of these chapters contains a preface and an afterword that introduce the general ideas behind the paper as well as explain the conceptual and methodological linkages between them. The thesis also includes a general literature review (Chapter 2), methodology chapter (Chapter 3) and conclusion section (Chapter 7).

Chapter 2 introduces the concept of compound events, and highlights the complexity of natural hazards, when viewed in a compound framework. It also explains how extreme rainfall is connected to high temperatures, both on a thermodynamical as well as a meteorological basis. Finally, the existing research on compound heatwave-extreme rainfall events is examined, highlighting what is known about this hazard and what further research is required.

Chapter 3 highlights and justifies the methodological changes between the analysis chapters in the context of the entire thesis. As each analysis chapter has different objectives, the methodological choices such as study region, used datasets, heatwave definition and identification as well as extreme rainfall thresholds are adapted to suit the respective objectives.

Chapter 4 tests various definitions and thresholds for analysing compound heatwave-heavy rainfall events in Australia, which is known to experience many different and severe natural hazards. Until the publication of this work, this particular type of compound event had only been shown in China and using daily rainfall data only. The work in this chapter demonstrates the existence of compound heatwave-heavy rainfall events outside China in a country well known for extreme weather and uses hourly rainfall observations which is more in agreement with the durations of convective storms. The study further highlights that the likelihood of extreme rainfall after heatwaves varies strongly depending on location. The study in this chapter has been published in the *International Journal of Climatology* (Sauter et al., 2022).

Chapter 5 investigates how the likelihood of extreme rainfall after a heatwave varies on a global scale. This is the first study on a global scale and reveals how the likelihood of this compound event varies depending on the location. This study builds on the methodology and results of Chapter 4; however, it uses all available rainfall data and incorporates small methodological improvements. Considerable differences in likelihood are revealed which are dependent on the location, with high likelihoods in densely populated areas such as Central Europe or Japan. Regional differences are even found within individual countries. Further, the use of Köppen-Geiger climate classifications shows that the likelihood of extreme rainfall after heatwaves is significantly higher than climatology only in certain climate classifications, predominately those in the mid and high latitudes. The study in this chapter has been published in the journal *Weather and Climate Extremes* (Sauter et al., 2023).

Chapter 6 explores the mechanisms behind the increase in likelihoods of extreme rainfall after heatwaves. This study uses the knowledge of spatial distribution and frequency of compound heatwave-extreme rainfall obtained in the previous chapters, but now focusses on its drivers. Until the submission of this work, research had only investigated convection as a potential driver and not analysed potential dynamical drivers. This chapter demonstrates the importance of both dynamical and convective drivers in increasing likelihood and intensity of extreme rainfall after heatwaves. Specifically, fontal systems, high moisture availability and atmospheric instability are shown to be associated with end-of-heatwave extremer rainfall. Understanding the mechanistic drivers behind compound heatwave-extreme rainfall is important for assessing how well this phenomenon is represented by weather and climate models and how it might change in a warming climate. The study in this chapter is under review for *Journal of Geophysical Research: Atmospheres*.

Chapter 7 concludes the thesis by discussing the results, answering the research questions posed in chapter 1.2 and proposing directions of future research.

CHAPTER 2

BACKGROUND

2.1 Compound events – an overview

Natural hazards such as heatwaves, droughts, floods, and fires can have devastating impacts on society and ecosystems. Until only a decade ago, these hazards were studied almost exclusively on an individual hazard-by-hazards basis, neglecting the risk arising from the interplay with other hazards. This changed after the publication of Intergovernmental Panel on Climate Change (IPCC) special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX, Field et al., 2012) which was the first IPCC report to include a section on compounding extremes. Compound hazards (usually referred to as *compound events*) often lead to disproportionate impacts that exceed those of the individual hazards due to the interplay of multiple hazards and their drivers (Leonard et al., 2014, Zscheischler et al., 2018), and in recent years there has been a considerable rise in interest in compound events from the scientific community.

This focus on impacts has also led to the most commonly used definition of compound events today, which defines them as “the combination of multiple drivers and/or hazards that contributes to societal or environmental risk” (Zscheischler et al., 2018). Figure 2 illustrates the interaction of different components in a compound event that ultimately contribute to an impact. In a compound event, the impact is caused by one or more hazards, which in turn are caused by one or more drivers. These drivers might be influenced by a modulator such as the El-Niño Southern Oscillation (e.g., Hao et al., 2018b) which usually acts on a different temporal or spatial scale to the driver(s). Modulators, Drivers, and Hazards are all affected by climate change, which ultimately affects the impact as well.

Modulators, drivers, and hazards can interact with each other in many ways, and therefore there have been efforts to introduce classifications of compound events with similar characteristics. One possible categorisation has been suggested by Zscheischler et al. (2020) which divides compound events into

(1) *preconditioned* events, in which the impact arises from one of more hazards only because of a pre-existing climatic condition,
(2) *temporally compounding* events, in which the impact arises from successive hazards in the same location,

(3) *spatially compounding* events, in which the impact arises from multiple hazards occurring in short time in multiple connected locations, as well as
(4) *multivariate* events, in which the impact arises from multiple drivers and/or hazards in the same location at the same time.

While this categorization works well for some more simple compound events, others are more ambiguous as the interplay of drivers, hazards and impacts is very complex.

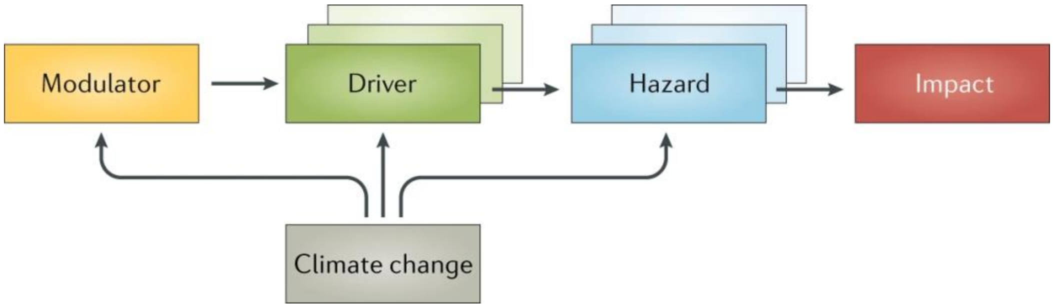

Figure 2 Illustration of the different components of a compound natural hazard. From Zscheischler et al. (2020).

The Australian 'Black Summer' in 2019/2020 is illustrative of the potential complexity of a compound event, which also had devastating impacts on humans and ecosystems (Kemter et al., 2021). Hot and dry conditions over several months lead to widespread bushfires. The rainfall that finally extinguished the fires, however, was so heavy that it caused flooding in some regions. Further, due to the high amount of ash and debris from the fires, the water quality in the rivers was severely impacted (Kemter et al., 2021). A schematic of the succession of hazards in 2019/2020 in Australia is shown in Figure 3. The compound event of the 2019/2020 Australian Black Summer highlights the importance of viewing hazards in a holistic, compounding way, as most impacts arise from the interaction of multiple hazards or their drivers. Therefore, it is often difficult to categorize such a complex event, even with the categorisation above. However, focusing on the impact of interest (e.g., impacts from either fires, flood, or low water quality) helps investigating the hazards contributing the impact, and in turn also allows for an easier classification.

Besides the categorisation proposed by Zscheischler et al. (2020), compound events may also be divided into dry or wet events (Ridder et al., 2020). Due to land-atmosphere interactions and certain large-scale atmospheric conditions simultaneously favouring hot conditions and dry conditions, these conditions often occur simultaneously (Miralles et al., 2019). As a result, compound hot and dry events occur more often than expected from the joint probability of independent events (Zscheischler and Seneviratne, 2017). Hot and dry events can lead to devastating impacts on ecosystems and agriculture and have been shown to increase significantly as a result of a warming climate (Mazdiyasni and AghaKouchak, 2015, Sharma and Mujumdar, 2017, Hao et al., 2018a, Kong et al., 2020, Bastos et al., 2021). Similar to most extreme events, there is no universally used definition for either hot or dry events. Studies have used definitions based on a range of different temporal scales ranging from individual hot and/or dry days up to several days for heatwaves and months or years for droughts (e.g., Zargar et al., 2011). Additionally, heatwave and drought definitions vary in their use of parameters and indices. Most commonly, heatwave definitions use some kind of temperature variable (Perkins and Alexander, 2013) and droughts are often (but not always) defined by abnormally low precipitation, moisture or streamflow/water levels (Zargar et al., 2011, Svoboda and Fuchs, 2017). However, despite the wealth of commonly used definitions for hot and dry extremes, there is scientific consensus that hot and dry events have been increasing over the last century and will further increase in the future (Seneviratne et al., 2021).

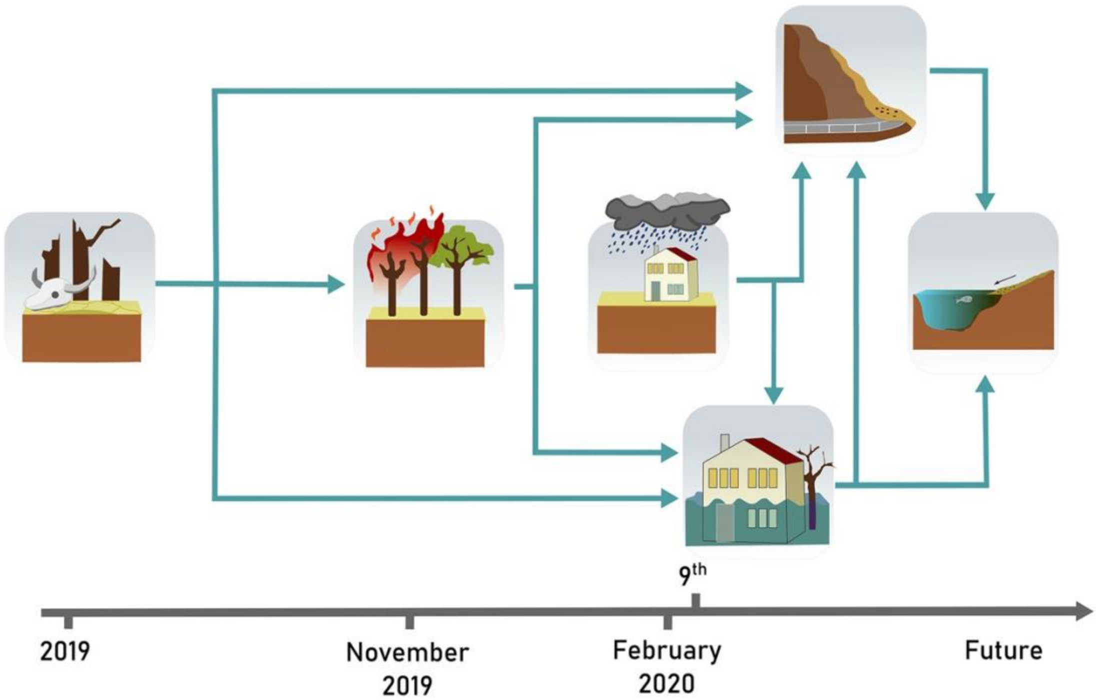

Figure 3 Illustration of the interplay of hazards during the 2019/2020 'Black Summer' in Australia. Drought and heatwaves provided ideal conditions for fires. The fires were followed by extreme rainfall, causing floods, landslides, and reduction of water quality due to increased ash and soil in the rivers. Due to the many hazard interactions and spatial/temporal scales of this event, there is no one single suitable compound event classification. From Kemter et al. (2021).

Besides dry extremes, wet extremes can have similarly devastating impacts. Compound wet extremes often arise from the complex interactions during storms. For example, flood risk can occur due to the combination of extreme rain and storm surge (Zheng et al., 2013, van den Hurk et al., 2015, Wahl et al., 2015, Wu et al., 2018, Bevacqua et al., 2019), sea level rise and fluvial flooding (Moftakhari et al., 2017, Ward et al., 2018), or other combinations variables that increase flood risk, such as sea level and storm surge (Haigh et al., 2016) or storm surge and fluvial flooding (Couasnon et al., 2020). Another variable adding to the complexity of (storm-related) wet extremes are extreme wind speeds. Extreme winds during floods can further damage infrastructure and delay efforts of response teams to reach affected areas as roads might be blocked by displaced objects such as trees or structures (Martius et al., 2016). Similar to other compound wet or dry events, these variables are not independent of each other and are caused by the same drivers such as cyclones (Owen et al., 2021, Messmer and Simmonds, 2021) or atmospheric rivers (Waliser and Guan, 2017).

2.2 The connection between high temperature and extreme rainfall

While many compound extremes fall into hot/dry or wet categories, hot and wet extremes themselves are also related. The intensity of rainfall is largely dependent on the availability of moisture in the surrounding atmosphere, with more moisture allowing for more extreme rainfall. The physical constraints as to how much moisture air can hold before it reaches saturation is described by the Clausius-Clapeyron (CC) relation. For every degree Kelvin increase in temperature, air can hold ~7% more water vapour (Trenberth et al., 2003). Therefore, rainfall extremes are expected to increase in a warming climate by the rate given by the CC, though other cloud processes and interactions influencing rainfall intensity are also likely to change with higher temperature (Fowler et al., 2021a). Observations have confirmed increases in daily precipitation extremes in line with the CC relationship (i.e., the median intensity of daily extreme rainfall increases with changes in global mean temperature at a rate of ~7% per K, Westra et al., 2013). However, on shorter timescales, rainfall extremes have been shown to increase with temperature at even higher rates than the CC relationship suggests in some cases (Fowler et al., 2021a, Guerreiro et al., 2018, Lenderink and van Meijgaard, 2008), but there is no consensus as to why these above CC-scaling relationships occur. Sub-daily rainfall extremes are further expected to increase in the future due to a warming climate (Westra et al., 2014, Prein et al., 2016). This has serious implications as an increase in short-duration rainfall extremes is likely to translate into higher flash flood risks (Fowler et al., 2021a, Fowler et al., 2021b).

2.3 Hot and wet extremes in a compound event framework

While considerable research has focused on how rainfall extremes scale with day-to-day temperature, compound hot and wet extremes have only started to be analysed in recent years. With differences in approaches, definitions, and temporal and spatial scales, comparisons between studies are difficult and result in uncertainty of what aspects of compound hot and wet extremes have been analysed. Therefore, many aspects of the interaction between the two hazards are still unclear. This section provides a state-of-the-art summary on compound hot-wet extremes, including work published shortly before the submission of this thesis. Short references to the contributions of this thesis have also been made in the according sections to highlight their place in the literature.

First evidence that joint occurrences of monthly hot and wet extremes have become more frequent in recent decades was demonstrated by Hao et al. (2013). Though the increase is shown to be robust over many areas globally, the use of monthly extremes for hot and wet events complicated the interpretation of the underlying physical connection, as the immediate drivers of extreme precipitation (convective or synoptic) act on timescales of several days or less.

The first demonstration of a compound hot-wet extreme on a shorter timescale was provided by Zhang and Villarini (2020) who showed that heat stress events (defined as a single day of high dry bulb and dew point temperature) were usually followed by heavy rainfall and floods in the Central United States. The authors classified this event as a preconditioned compound event, as hot and humid conditions provided the basis for high rainfall rates and increased flooding risks.

You and Wang (2021) showed that heavy rainfall was more likely to occur after heatwaves (three or more consecutive days of high maximum temperature) than without in China. They also demonstrated that heatwaves are more likely to be followed by heavy rainfall if they are shorter and hotter. This work was the first to demonstrate a connection between heatwaves – usually associated with dry weather - and heavy rainfall. However, it was unclear if this phenomenon occurred outside China, providing the motivation for Chapter 4 which demonstrates compounding heatwave-extreme rainfall in different regions in Australia as well. Further, Chapter 5 shows the strength and frequency of this compound event globally, while identifying climate zones where is it most frequent.

Chen et al. (2022) investigated extreme rainfall following heatwaves in the Chinese Yangtze River Valley demonstrating that hourly rainfall rates high enough to trigger flash floods were more likely after heatwaves. They also found that extreme rainfall pre-conditioned by heatwaves are projected to increase faster than non-preconditioned extreme rainfall. They further showed that the influence of the heatwave on rainfall and CAPE can last up to several days after the heatwave termination, though the strongest response occurs on the day after the termination.

Gu et al. (2022) investigated future changes for co-occurring heatwaves and floods (both heatwaves followed by floods and floods followed by heatwaves) on a global scale. They found that floods and heatwaves co-occurring within 7 days of each other are projected to increase in almost all climate zones, with the strongest increase in the Tropics. However, the two sequences of hazards involve different drivers and might therefore respond differently to global warming (Gu et al., 2022), making interpretations of each individual hazard sequence difficult.

Most other studies on compound hot-wet extremes focussed on China as well. They found that in China compound hot-wet extremes have increased over the last decade (Wu et al., 2021, Ning et al., 2022). Further, it has been shown that urban areas enhance compound hot-wet extremes via heat island effects (Wu et al., 2021, Li et al., 2023).

2.4 Mechanistic drivers of extreme rainfall after heatwaves

Understanding how and why extreme rainfall is connected to heatwaves is important for estimating how well they are represented in climate models and thus how they might change in the future. Due to the thermodynamic link between temperature and rainfall (Chapter 2.2) it is likely that the increase in extreme rainfall intensity and frequency after heatwaves is – at least to some part – thermodynamically driven.

On a synoptic scale, such extreme rainfall events are often the result of convective thunderstorms. Thunderstorms associated with deep moist convection and extreme rainfall usually have three characteristics, making conditions associated with thunderstorms easily identifiable (Johns and Doswell, 1992): Firstly, the troposphere must be sufficiently unstable with respect to moist convective ascent. Secondly, high moisture content is required in the lower and mid troposphere. And finally, a lifting mechanism to initiate convection is required. The latent instability of the troposphere is usually described by the convective available potential energy (CAPE), the calculation of which is based on the tropospheric temperature profile. High values of CAPE have been shown to act as useful proxy variables for sufficient instability associated with thunderstorms and extreme precipitation (Groenemeijer and van Delden, 2007, Brooks, 2013, Meyer et al., 2022). Moisture in the atmosphere can be described using various variables. However, most useful in the context of moisture availability for extreme rainfall are variables describing absolute moisture content and are therefore independent of other measures such as the ambient temperature. Commonly used variables of absolute moisture are specific humidity or total column water vapour, both shown to be useful proxies for identifying moisture thresholds needed for extreme rainfall from convective thunderstorms (Meyer et al., 2022). The lifting mechanism is mainly responsible for the initiation for the thunderstorms and is usually not easily determined from conventional climate model output. Lifting mechanisms are often related to convergence zones from gust fronts or sea breeze fronts (e.g., Weckwerth, 2000 and references therein), but can also be larger-scale synoptic systems such as fronts (Browning, 1986) or orographic features like mountains (Kirshbaum et al., 2018).

Indeed, the literature on compound heatwave-extreme rainfall events has demonstrated that many parameters found in (deep moist) convective thunderstorms are increased during these events. Specifically, there is evidence of increased (CAPE), Convective inhibition (CIN), moisture availability (in form of specific humidity or precipitable water), sensible heat flux, moisture convergence, and vertical velocity (Zhang and Villarini, 2020, You and Wang, 2021, Chen et al., 2022, Li et al., 2023). Therefore, it is very likely that extreme rainfall following heatwaves is to some degree driven by convection, and that a thermodynamic link exists between a hot event or a heatwave and extreme rainfall afterwards.

However, extreme rainfall can also be caused by synoptic systems such as fronts, cyclones, and atmospheric rivers, processes which also might coincide with, or even actively contribute to the termination of the heatwave itself by advecting cooler air. Extreme precipitation in the higher latitudes specifically, is usually associated with fronts and cyclones (Dowdy and Catto, 2017). The rainfall associated with the devastating 2021 floods in Germany, for example, was caused by a slow moving low-pressure system (Copernicus Climate Change Service (C3S), 2022). Besides cyclones, fronts are also known to be related to extreme rainfall, with about 50% of global precipitation extremes associated with them (Catto and Pfahl, 2013). Atmospheric rivers, which are narrow bands of moist air and are often related to fronts and cyclones, can also cause extreme rainfall (Lavers and Villarini, 2013).

Convective rainfall as seen in thunderstorms does not necessarily occur in isolation, but can also occur in combination with synoptic-scale drivers such as fronts. Dowdy and Catto (2017) showed that in the mid latitudes, the most common causes of extreme rainfall were combinations of cyclones and/or fronts with thunderstorm conditions. Synoptic-scale systems can play an important role in generating and sustaining the conditions favourable for moist convection (de Boer et al., 2013). In addition, fronts can act as a lifting mechanism for convection as well (e.g., Browning, 1986). However, it is unclear, to what extent synoptic-scale drivers such as cyclones or fronts contribute to end-of-heatwave extreme rainfall as well, proving the need to explore synoptic scale drivers beside thermodynamic (convective) drivers in compound heatwave-extreme rainfall events as well (Chapter 6).

Attributing extreme events to specific synoptic-scale systems is important for understanding their mechanistic drivers and improving the ability to forecast them. There have therefore been efforts to identify different weather types, which can be used to explain the synoptic-scale conditions associated with extreme events. Dowdy and Catto (2017) for example defined several weather types including storm types known to be associated with extreme rainfall. These storm types include fonts, cyclones, thunderstorms as well as combinations of them and have been used to identify past weather types in reanalysis data. Other methods of identifying synoptic-scale systems associated with extreme weather are defining weather patterns or clusters based on mean sea level pressure (e.g., Neal et al., 2016), or geopotential height (e.g., Folland et al., 2008). The benefit of weather patterns or clusters is that they can be more easily identified in medium- to long-range forecasts, allowing for an improved predictability of the likelihood of associated extreme events (Neal et al., 2016, Richardson et al., 2020).

2.5 Summary

Compound events, such as extreme rainfall after heatwaves, can lead to devastating impacts and the interactions of their drivers and hazards are often complex. As extreme rainfall intensity and likelihood is higher after heatwaves compared to non-heatwave conditions, the risk of flash floods is increased as well. In order to assess the full risk from this compound event, it is essential to better understand where it occurs, how likely it is and what the driving mechanisms are.

Though there have been recent advances in understanding compound heatwave-extreme rainfall events, many basic characteristics remain poorly understood. It is unclear how likely it is for a heatwave to be followed by extreme rainfall in general, how this event is distributed globally and what climatic conditions favour it. With respect to the mechanistic drivers, recent work has solely focused on moist convection as the driver of extreme rainfall after heatwaves due to the well-studied thermodynamic connection between hot temperatures and extreme rainfall. However, equivalent to the concept of compound events, impacts are often caused by the interaction of multiple different drivers, and synoptic-scale mechanisms are likely to be an important factor driving extreme rainfall as well.

The following chapters will therefore aim at filling those gaps, shedding light into spatial extent and likelihood of compound heatwave-extreme rainfall events on a smaller-scale case study in Australia (Chapter 4) as well as globally (Chapter 5), and then analyse how both thermodynamic (convection-based) and synoptic-scale drivers increase the intensity and likelihood of extreme rainfall after heatwaves (Chapter 6). Each chapter also includes a more detailed literature review in the introduction section which specifically highlights the literature relevant for the respective chapter.

CHAPTER 3

METHODOLOGY

The analysis chapters in this thesis (Chapters 4-6) investigate several aspects of compound heatwave-extreme rainfall events and the methodological choices made for each chapter reflect the different objectives. The objective of Chapter 4 is to serve as a case study to test methodological choices as well as provide a first look into the properties of compound heatwave-extreme rainfall. Chapter 5 expands the analysis from a local to a global scale to further deepen the understanding of the spatial distribution and frequency of this compound event. And finally, Chapter 6 analyses the mechanistic drivers behind compound heatwave-extreme rainfall. Together in these three chapters, compound heatwave-extreme rainfall will have been analysed on a local, more detailed scale (Chapter 4), on a large scale (Chapter 5) as well as their driving mechanisms explored (Chapter 6). This allows for an improvement of the overall knowledge of compound heatwave-extreme rainfall and a better estimate of the future risk from this event. The current risk from compound heatwave-extreme rainfall is shown to vary by geographical location and future changes to this compound event and the resulting risks can only be estimated with sufficient knowledge of their current mechanisms and properties.

The main methodological changes between the individual analysis chapters are the choice of geographical study region, datasets, heatwave definition and identification method as well as extreme rainfall threshold. How and why these changes were made are explained in this chapter with a short overview shown in Figure 4. A full description of the individual methodologies for each of the three studies can be found in the respective analysis chapters.

3.1 Study region

In Chapter 4 Australia was chosen as the study region for a case study. This was done for several reasons. Firstly, Australia is home to many natural hazards, including heatwaves and extreme rainfall and has many different climate zones which might indicate if and to what extent this compound event depends on the local climate. Further, there were many high-quality, long-term sub-daily rainfall observations available for this study. Finally, one of the co-authors is based in Australia, being able to provide local expertise. Moving forward, the aim of Chapter 5 was to expand the analysis of Chapter 4 to a global extent and therefore analyse all locations represented by GSDR stations were analysed. Besides Australia, Chapter 5 therefore also investigates compound heatwave-extreme rainfall in the United Kingdom, Portugal, France, Spain, Germany, Belgium, the Netherlands, Switzerland, Italy, Norway, Sweden, Finland, India, Malaysia, and New Zealand. Though these regions are not distributed equally on a global scale, all main climate zones are represented by one or more of these countries, giving insight into how this compound event is dependent on the local climate. The study region in Chapter 6, which focusses on the driving mechanisms of this compound event was determined by the availability of weather type datasets. As weather type datasets were only available for Australia and Western Europe, the study region was limited to these regions.

	Chapter 4	Chapter 5	Chapter 6
Objective	Testing of methods, Investigation of spatial distribution	Investigation of spatial distribution globally	Investigation of mechanistic drivers
Region	Australia	Western European countries, India, Malaysia, Australia, New Zealand, United States	Western European countries, Australia
Datasets	GSDR, SILO	GSDR, ERA5	GSDR, ERA5, Weather type datasets
Heatwave identification	Each station individually	Each station individually	At least 2 stations
Extreme rainfall threshold	95^{th} percentile	99^{th} percentile	99^{th} percentile

Figure 4 The main methodological changes throughout the thesis

3.2 Datasets

All rainfall data throughout this thesis is taken from the GSDR dataset (Lewis et al., 2019). This dataset provides quality-controlled hourly rainfall observations for many different locations. A quality-requirement of a minimum of 10 years of records for each observation (overlapping with the respective temporal availability of the temperature dataset) used for Chapter 4 is increased to 12 years in Chapter 5. This change was implemented due to the fact that a preselected dataset with this criteria already existed as a result of a different study (Ali et al., 2021a) and was available to use for the study in Chapter 5. The change was therefore not made to improve the selection of observations. Rainfall observations in Chapter 6 were further restricted to include 12 years of data within the temporal availability of the respective weather type dataset.

Temperature data used for identifying heatwaves was initially taken from the SILO dataset (Jeffrey et al., 2001) for Chapter 4, but was then replaced by ERA5 reanalysis data (Hersbach et al., 2020) for Chapters 5 and 6. While the use of ERA5 data provides some drawbacks compared to the SILO dataset such as a lower spatial resolution, a later starting point (in 1979), as well as a coarser spatial resolution, it provides global coverage instead of coverage of Australia only. ERA5 additionally provides many different atmospheric variables which were useful for studying the mechanistic drivers of compound heatwave-extreme rainfall (Chapter 6). In Chapter 5, results of this compound event in Australia using ERA5 were compared to those using SILO, and the results were found to be very similar (i.e., the change in temperature datasets did not strongly influence the results). For Chapter 6, two further weather type datasets were introduced to help analyse the underlying mechanistic drivers of compound heatwave-extreme rainfall.

3.3 Heatwave definition and identification

In Chapter 4 heatwaves are defined for each location individually where daily maximum surface temperature (T_{max}) is required to lie above the respective 95th percentile for at least 3 consecutive days and daily minimum surface temperature (T_{min}) is required to lie above the respective 95th percentile for at least the second and third day. A heatwave terminates if either T_{min} or T_{max} fall below their respective threshold. In Chapter 5 the same heatwave definition is used; however, with the addition of a further requirement for the heatwave termination. According to this addition, heatwaves only terminate after at least two days of below-threshold T_{min} or T_{max} temperatures. This ensures that longer heatwaves that are temporally interrupted for short periods of less than two days are still identified as a single heatwave instead of two separate heatwaves. As Chapter 6 focusses on the mechanistic drivers of compound heatwave-extreme rainfall, it is important to incorporate their spatial scales as well. Therefore, in this chapter, if multiple stations record a heatwave termination on the same day, this is considered to be the same heatwave. To minimise identifying localised drops in temperature as a heatwave termination, at least two stations are required to identify a heatwave termination. Though a higher minimum number of stations for heatwave identification might result in more accurate results, a minimum number of two stations ensures that the sample size of heatwaves in regions with a sparse coverage of stations, such as central Australia, is sufficiently high.

3.4 Extreme rainfall threshold

The threshold for extreme rainfall in Chapter 4 was set to the 95th percentile of all wet hours for each location. 90th and 99th percentiles were tested as well, however, for Australia it was found that using the 95th percentile provided a good compromise between high rainfall intensities and a sufficiently high sample size of the compound event of heatwaves and extreme rainfall. The results were found not to differ strongly with the choice of threshold. In Chapter 5 the extreme rainfall threshold was increased to the 99th percentile. Incorporating further study regions, especially in northern Europe and Japan allowed the use of a higher percentile number while still obtaining a sufficiently high number of compound events. This threshold was kept for Chapter 6 as well.

CHAPTER 4

TEMPORALLY-COMPOUNDING HEATWAVE-HEAVY RAINFALL EVENTS IN AUSTRALIA

Preface

This chapter (excluding preface and afterword) has been published in the *International Journal of Climatology* (Sauter et al., 2022). Numberings of chapters and figures have been adapted for consistency of the overall thesis.

The aim of the study in this chapter was to investigate the spatial distribution and frequency of compound heatwave-extreme rainfall in a case study as well as potential regional differences. In addition, this case study tests the methodology used for analysing this compound event. As this was the first analysis of this compound event outside China and using hourly rainfall observations, choices regarding the methodology were made based on the information available at the time of the design of the study and some were later modified with progression to a larger study area (Chapter 5) and focus on a different research aim (Chapter 6).

Notes on the temporal window of extreme rainfall after heatwaves. The thermodynamical influence of the heatwave on the subsequent rainfall is likely only to last for a short time (i.e., hours to a few days) after the heatwave. It is possible that heatwaves influence land and/or synoptic-scale properties in such a way that the influence of the heatwave is still seen in the rainfall response even after the temperatures have sunk. As the main assumed connection between heatwaves and extreme rainfall, however, is high temperature, the temporal window in which extreme rainfall is considered to be influenced by the heatwave is 36h beginning at noon on the last day of the heatwave. A longer temporal window was also tested for this study, but the signal of the heatwave on extreme rainfall was found to substantially weaken after the first day of the heatwave. This finding was later also supported by Chen et al. (2022).

Notes on the terminology. The term *significant* can have different meanings in this chapter. While describing data the term *significant* is used in a statistical context (i.e., *statistically significant*). This is used if the calculated value obtained from the observations lies outside the

5th to 95th percentile range estimated from resampling for the same region. In all other cases the term *significant* is used to convey general importance.

4.1 Abstract

Natural hazards often occur in combination with other natural hazards rather than as isolated events. While some combinations of hazards are well studied, and their physical connection is increasingly understood, other combinations have received considerably less attention. High temperatures are known to be an important component for conditions that lead to heavy rainfall; however, sequences of heatwaves followed by heavy rainfall are not well understood, especially in a compound event context. Here, we analyse heatwave-heavy rainfall events across Australia using rainfall observations at hourly resolution. Our results show that heavy rainfall is more likely to occur if preceded by a heatwave, demonstrating that heatwave-heavy rainfall sequences should be seen as temporally compounding events. In particular, many regions in Australia experience both more frequent and more extreme wet days immediately following a heatwave. This behaviour is strongest in coastal regions, especially on the Australian east coast. These findings highlight the need for heatwave-heavy rainfall sequences to be studied as compounding events, as future changes in either hazard is likely to have impacts on related risks such as flash flooding.

4.2 Introduction

The increased recognition that high-impact events tend to be ‘compound’ in character (Zscheischler et al., 2018, Leonard et al., 2014) has led to a recent focus on the processes that connect different classes of natural hazards either in space, time and/or across multiple atmospheric variables (Zscheischler et al., 2020). Whilst a common typology is to recognize relationships within either ‘hot and dry’ (Mazdiyasni and AghaKouchak, 2015, Sharma and Mujumdar, 2017, Miralles et al., 2019) or ‘wet’ categories (Wahl et al., 2015, van den Hurk et al., 2015, Zheng et al., 2013), the connections between hot conditions and subsequent wet extremes have received less attention. The sequencing between ‘hot and wet’ conditions nevertheless is important, particularly given the role of both antecedent catchment wetness conditions and heavy rainfall as determinants of flood risk.

There are numerous *a priori* reasons to suggest connections between these classes of extremes. At the large scale, drivers relevant to Australian conditions—such as the El Niño-Southern Oscillation or the Indian Ocean Dipole—provide a significant role in conditioning probabilities of localized weather conditions, influencing both hot (Marshall et al., 2013, Parker et al., 2014, Perkins et al., 2015) and wet weather (England et al., 2006, King et al., 2013, King et al., 2014, Ashcroft et al., 2019). At the regional scale, land-atmosphere processes cause higher co-occurrences of droughts and heatwaves as a result of feedbacks involving changes in sensible and latent heat due to reduced moisture availability in soil and vegetation (Herold et al., 2016, Hirsch et al., 2019, Miralles et al., 2019, Kong et al., 2020). Hot temperatures, however, are also known to be a key component of atmospheric conditions that lead to localized heavy rainfall events. Significant research has been conducted on the influence of atmospheric temperature on rainfall intensity, with warmer atmospheres generally leading to more intense rainfall provided there is access to adequate moisture (Berg et al., 2013, Westra et al., 2014, Ali et al., 2018, Guerreiro et al., 2018, Ali et al., 2021a, Fowler et al., 2021a).

With the possibility of both large-scale as well as regional drivers influencing hot and wet extremes in the same location, we hypothesized that rainfall following heatwaves would be more extreme than normal, implying a temporally-compounding relationship. To investigate this, we compared rainfall at sub-daily timescales during, and immediately after, heatwaves to the climatological normal for rainfall for the time of the year.

Recent studies have started to investigate this link. Zhang and Villarini (2020) demonstrated that summer flooding events in the Central United Stated were often linked to prior hot and humid weather conditions, which they described as a 'preconditioned compound event'. For South China, Wu et al. (2021) showed that extreme precipitation events were often preceded by hot weather. Further, You and Wang (2021) introduced the concept of consecutive heat wave and heavy rainfall events and showed that a higher percentage of heatwaves in China was followed by heavy rainfall events within seven days than what would be expected by chance. Direct comparisons between these studies themselves are difficult, as all three studies implement different definitions for extreme heat events and use different variables such as dry bulb temperature (Wu et al., 2021, You and Wang, 2021) or wet bulb temperature (Zhang and Villarini, 2020). Dry bulb temperature is also referred to as 'air temperature' and wet bulb temperature is the temperature a thermometer would show if covered by a wet cloth and can be derived from dry bulb temperature and relative humidity (Stull, 2011). All three studies have used rainfall data at daily resolution; however, we here examine rainfall events at hourly timesteps as it is more consistent with the timescales of convective storms (Trenberth et al., 2017).

The processes behind temporally-compounding heatwave-heavy rainfall events are largely unclear, providing uncertainty in how rainfall might differ in frequency and intensity following heatwaves in other regions. A better understanding of the link between heatwaves and subsequent heavy rainfall events—particularly how rainfall characteristics change if proceeded by a heatwave—is important due to the possibility of compounding and cascading impacts as well as the fact that heavy rainfall events have the potential to cause flooding events. Therefore, this paper examines the relationship between heatwaves and sub-daily extreme rainfall events in different regions in Australia, offering insight into frequency and intensity of extreme rainfall events after heatwaves. In particular, relative to climatology we will investigate 1) how frequently heatwaves are terminated by rainfall, 2) if rainfall shortly after heatwaves is more extreme and, 3) how hourly and daily rainfall extremes differ after heatwaves.

4.3 Data and Methods

4.3.1 Data

Quality-controlled sub-daily rainfall observations at hourly resolution were obtained from the Global Sub-Daily Rainfall Dataset (GSDR, Lewis et al., 2019). From the subset of Australian stations within the dataset, only stations that have a record length of at least 10 years, and that have less than 20% missing data (regardless of their record length), were used. In six cases where a station provided hourly aggregated data from both 1-minute and 5-minute records, we removed the shorter record length. These criteria resulted in 701 stations across Australia being used for the analysis. The selected stations have an average record length of 28.3 years (median: 22.1 years) from first to last record (including missing data) and an average of 10.7% missing data (median: 10.5%).

Rainfall data has been aggregated to hourly resolution, and we define an hour with >0.1mm rainfall as a wet hour. Aggregated to daily time steps, a day containing at least one wet hour is called a wet day in order to exclude cases where a wet day could contain no wet hours. Rainfall extremes are also defined on hourly timescales. For each station, an hourly rainfall extreme is defined as hourly rainfall exceeding the 95th percentile of all wet hours. To test the robustness of the results on the threshold selection, we also ran the analysis using the 90th percentile (Figure A5) and 99th percentile (Figure A6) as a threshold for extreme wet hours instead of the 95th percentile, however this did not significantly change the overall findings. Daily rainfall extremes, which in this study are only used for comparison, are defined as wet days with rainfall exceeding the 90th percentile of all wet days. These thresholds were selected to provide a balance between separating extreme from non-extreme rainfall events, while providing a statistically meaningful sample size for both categories. Different percentile thresholds have been chosen for hourly and daily rainfall to obtain a comparable frequency in extreme values in the dataset since the data lengths of wet hours and wet days differ.

In order to identify heatwaves, we use daily maximum and minimum temperature data (T_{max}, T_{min}, respectively) from the SILO climate database (Jeffrey et al., 2001) as temperature data is not provided within the GSDR dataset. We chose against using rainfall data from the SILO dataset or another reanalysis product, as the quality controlled GSDR dataset would provide the best representation of hourly rainfall extremes. SILO temperatures are based on observational data and are provided as an interpolated gridded dataset with 0.05° resolution (approx. 5km x 5km) that covers Australia and begins in 1889. For each station from the GSDR dataset, T_{max} and T_{min} are taken from the closest grid point, and heatwaves are only identified for times where rainfall records are available.

4.3.2 Heatwave definition

Although numerous studies have focused on heatwaves, no universal definition exists (e.g., Perkins and Alexander, 2013). Most heatwave definitions are therefore specific to an impact or study purpose. While many studies use definitions that focus on the human impact or changes to heatwave properties like frequency or duration, we require a heatwave definition that enables accurate delineation of the start and especially the endpoint of a heatwave while still resembling common traits that are associated with heatwaves in the literature.

Therefore, we define a heatwave to have the following properties. For a given location, a heatwave is identified if

- The daily T_{max} lies above its yearly 95th percentile value for at least three consecutive days, and
- The daily T_{min} lies above its yearly 95th percentile for at least the second and third day.

A heatwave ends when either T_{max} or T_{min} drop below their respective 95th percentile thresholds. The last day where the criteria above are still fulfilled is referred to as 'day 0'. The previous days are counted in descending order with negative numbers (i.e., '-1', '-2', ...), and days after a heatwave are counted ascendingly with positive numbers (i.e., '1', '2', ...). Figure 5(a) illustrates the heatwave definition for a 4-day heatwave identified on the grid box close to a rainfall station (33.86°S, 151.21°E).

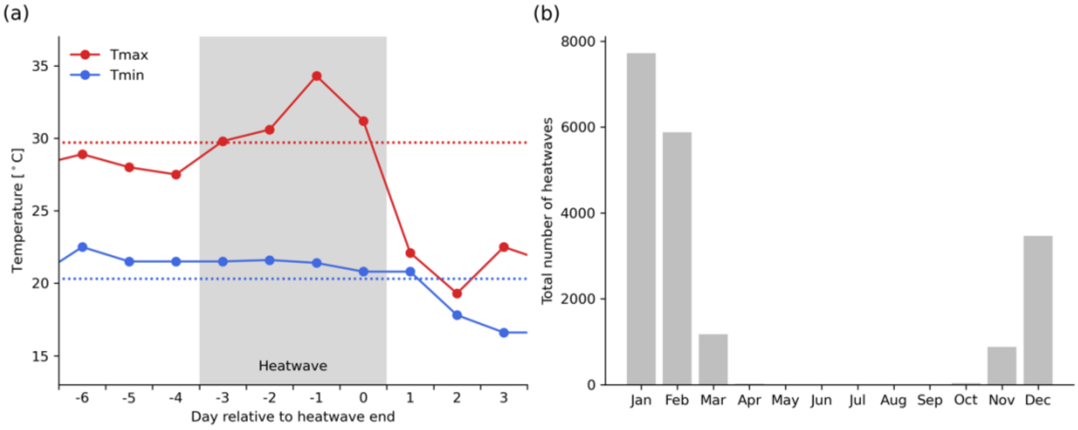

Figure 5 (a) Example of a heatwave from the SILO dataset, showing T_{max} (red solid line), T_{min} (blue solid line) and their respective 95th percentile temperatures (dotted lines with respective colours). The grey shaded region shows the days that have been identified as heatwave days. Day numbering on the x-axis is relative to the last day of the heatwave (see 2.2. Heatwave definition). (b) Monthly distribution of heatwaves aggregated for all stations. If a heatwave spans over two separate months, it is allocated to the month in which the last heatwave day (day 0) lies.

This definition slightly deviates from other heatwave definitions used in the literature. The Excess Heat Factor (Nairn and Fawcett, 2014) for example, also uses the 95th percentile (though for the mean daily temperature); however, the index is based on 3-day moving temperature averages. This, therefore, is not well suited to defining exact endpoints of a heatwave, with its primary purpose focused towards human impact. Heatwave definitions based on monthly temperature thresholds (e.g., Pezza et al., 2011, Cowan et al., 2014) are also not suitable for this study; we found that using these definitions led to heatwaves being predominately identified towards the end of a month when the average temperature was rising (during spring) or the beginning of a month when the average temperature was falling (autumn). Heatwave definitions based on daily thresholds (e.g., CTX90pct or CTN90pct), where the thresholds are based on 15-day windows (Perkins and Alexander, 2013) do not exhibit such biases. However, the threshold varies with the seasonal cycle, and thus involves identifying 'warm spells' in a relative sense during non-summer seasons, rather than focusing on absolute temperature. Since we also expect thermodynamical processes to contribute to end-of-heatwave rainfall, we chose to use an absolute threshold instead. To test the robustness of the results on the choice of heatwave definition, we also ran the analysis using the 90th percentile (Figures A1, A3) instead of the 95th percentile for T_{max} and T_{min}, as well as the CTX90pct definition (Figures A2, A4) for heatwaves.

Using the yearly 95th percentile means that, on average, ~18 days per year of T_{max} and T_{min} lie above the threshold. However, it is very unlikely that a location will experience 18 heatwave days in a given year since at least three consecutive days are required, as well as a temporal overlap of T_{max} and T_{min}. Averaged over all stations, the heatwave definition we use results in an average of 0.97 heatwaves per year per station. Though this is slightly lower than the daily percentile-based heatwave definitions analysed in Perkins and Alexander (2013), their setting allowed for heatwaves to occur during a 5-month period (Nov-Mar), while the absolute threshold used in this study identified heatwaves to occur mostly during a 3-month period from Dec to Feb, when average temperatures are at their highest (see Figure 5b). While we do not limit heatwaves to be identified to a summer timeperiod, the vast majority of heatwaves is identified from November to March, with very few exceptions in October and April (Figure 5b).

4.3.3 Methodology

Australia was chosen as the study area as the country has a good coverage of high resolution rainfall observations, has many different climate zones and is known to experience many different kinds of hazards in short timeframes, including heatwaves, droughts, bushfires or floods (e.g., Kemter et al., 2021)

We used the eight subdivisions for Australia provided by CSIRO and Bureau of Meteorology (2015, chap. 2) to account for differences in local climate. The subdivisions (regions), together with the locations of the rainfall stations used in this analysis are shown in Figure 6. These are the Central Slopes (CS), East Coast (EC), Murray Basin (MB), Monsoonal North (MN), Rangelands (RL), Southern Slopes (SS), Southern and South-Western Flatlands (SSWF) and Wet Tropics (WT). Each subdivision contains between 30 (WT) to 174 (EC) stations.

In order to provide results for potential changes in rainfall that are characteristic for each region, we first calculate averaged values of all heatwaves at each individual station within a region. We then show the averaged results over all stations, weighting contributions from each station within a subdivision equally. We also tested weighting each station’s contribution relative to the respective number of heatwaves detected. Although doing so slightly reduced the spread of the results, for simplicity we chose not to apply weights as the results did not show any significant changes.

The goal of this study is to determine if rainfall at the end of heatwaves is more extreme than its climatological mean. To obtain an estimate of average climatological rainfall conditions at similar times of year as the heatwaves, we use a resampling approach which ensures that resampled results are comparable to the original analysis. The method works as follows:

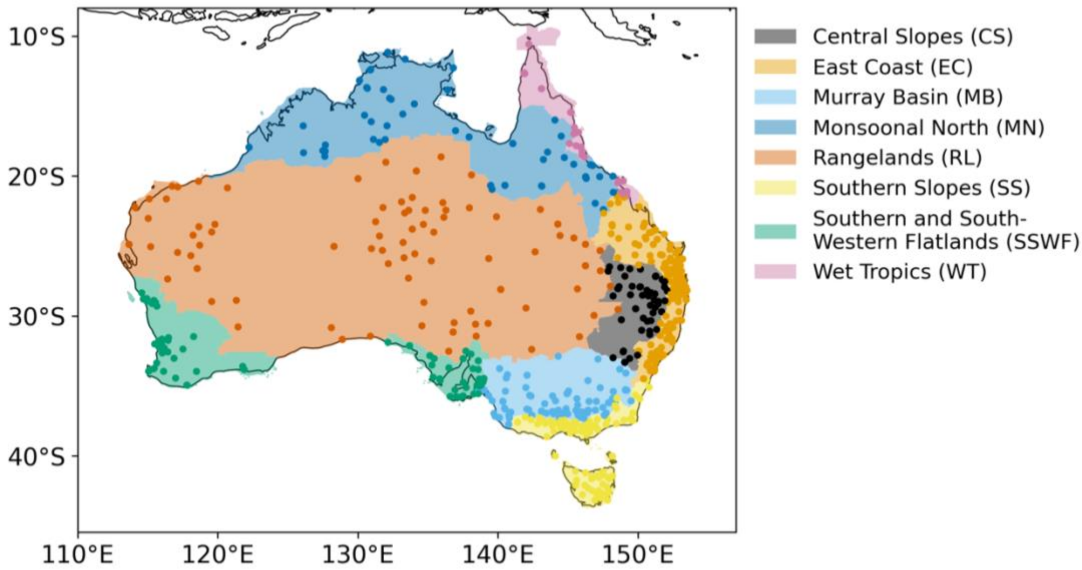

Figure 6 Eight subdivisions of Australia. Markers indicate locations of rainfall records used for the analysis.

In our analysis, we only analyse rainfall during and after heatwaves. Therefore, rainfall properties during these events cannot be compared directly to average rainfall properties throughout the year since heatwaves occur predominantly during summer months and rainfall climatology in summer differs to that in the rest of the year. We therefore construct a resampled dataset which contains rainfall predominantly during summer months and functions as a comparative climatology to the original dataset. We do so by resampling an alternative date for analysing rainfall for each heatwave at each station in the original dataset. To ensure climatologically comparable conditions, we only sample from the same month as the heatwave (but any year). We chose to resample from the same month as the heatwave instead of the same day of the year as the heatwave, as doing so would have resulted in a very small pooling sample size. The resampled date from the same month of the heatwave could also coincide with the same or a different heatwave (i.e., resampling with replacement). Doing so ensures the resampled dataset preserves the climatological characteristics of rainfall during the heatwave months but effectively cancels out any potential influence of a heatwave itself. This process is repeated 1000 times in order to represent the climate variability in the data.

4.4 Results

4.4.1 Increase in wet days at the end of a heatwave

Figure 7 shows that the likelihood of rainfall, here expressed as the likelihood of a wet day occurring, varies strongly depending on the timing relative to a heatwave. For all subdivisions, wet days before and during a heatwave are far less likely than expected from climatology. This is in agreement with studies that show hot and dry conditions often occur simultaneously – potentially driven by positive land-atmosphere feedbacks and stable atmospheric conditions. Even in the tropical subdivisions (MN, WT) we find reduced wet day occurrence during and before a heatwave. For almost all locations, the number of wet days is below climatology even 7 days before the end of the heatwave, suggesting that the heatwaves are associated with reduced rainfall likelihood even prior to heatwave onset. During, and shortly after the end of, the heatwave, however, we find that wet day occurrence is higher than expected from climatology. As the results for all subdivisions lie outside their respective 5th to 95th percentile resampled climatological range, we consider this to be statistically significant compared to the climatological behaviour. Wet day occurrence in most regions peaks on the day after a heatwave with high values occurring from day 0 up to day 2. In subsequent days, wet day occurrences return to climatological levels.

4.4.2 More hourly rainfall extremes in the last day of a heatwave

Following the result that the end of the heatwave is associated with rainfall more often than would be expected based on climatology, we now show that the rainfall that falls immediately following the end of a heatwave is often more extreme. In order to test if the accumulated heat of the heatwave affects the rainfall type or intensity, we choose a 36 hour time-window after 12:00 (local time) on the last day of the heatwave. According to the heatwave definition, the temperature will have dropped by the end of the first day after the heatwave termination (day 1) at the latest. Usually, T_{min} occurs in the early morning and thus before T_{max} occurs in the afternoon of the same day; however, the exact timing can vary. The drop in temperature which is associated with the end of a heatwave could therefore occur anytime between the measurement of T_{max} on day 0 and T_{max} on day 1. Assuming a cooling associated with rainfall occurs close to the timing of the rainfall, we chose an interval from 12:00 on day 0 to 00:00 on day 2 (36 hours) to ensure that any rainfall that co-occurred with a temperature drop is captured. The same intervals (starting at 12:00) are also chosen for resampling to ensure comparability in rainfall behaviour. We also tested a 60 hour time window starting at 12:00 on day 0, however, differences in rainfall intensity after a heatwave to climatology were smaller when averaging over the longer time window, further indicating the relationship between heatwaves and heavy rainfall is strongest immediately after the heatwave (Figure A7).

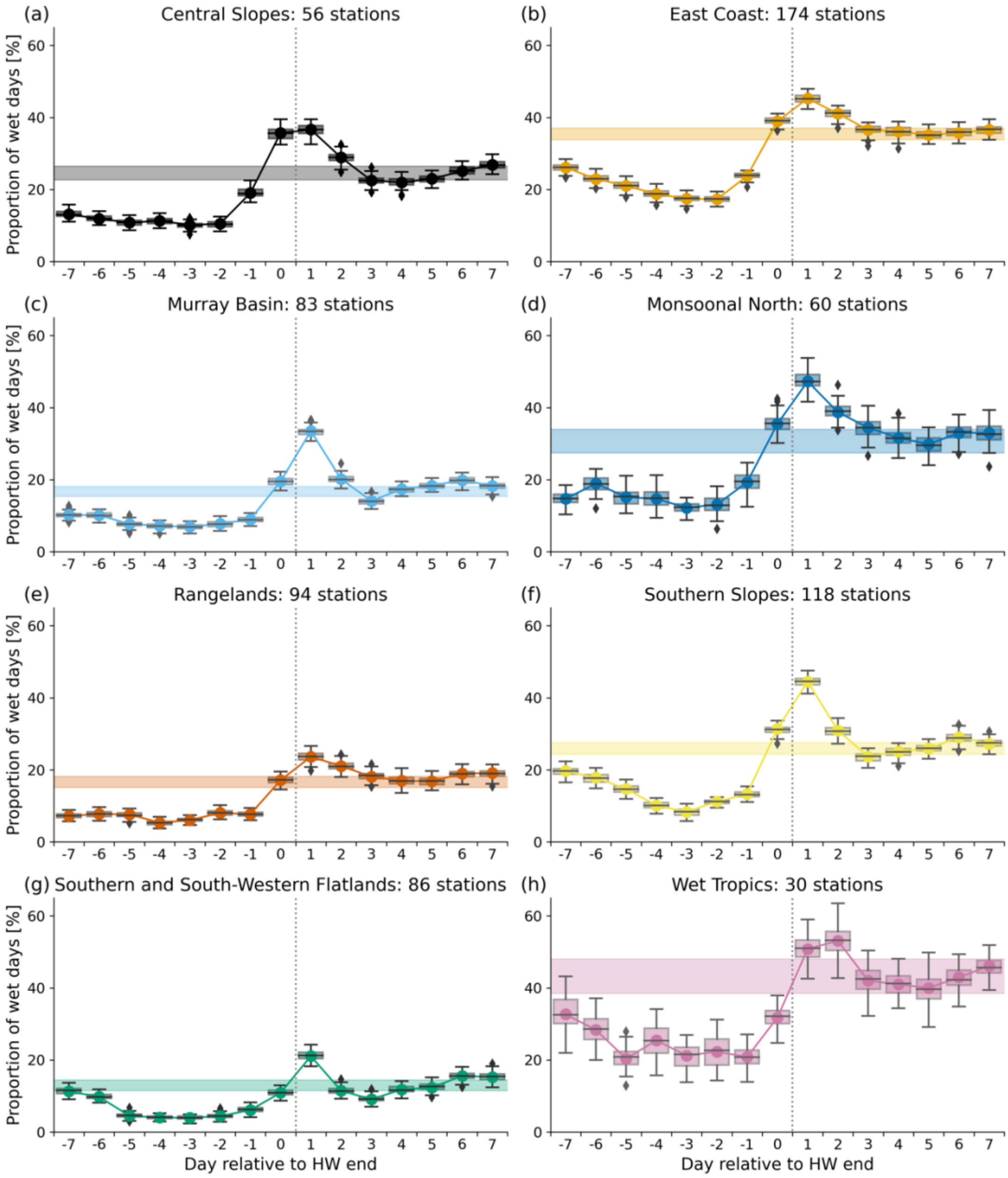

Figure 7 (a-h) Percentage of wet days across Australia relative to different days of a heatwave for the eight subdivisions. Continuous lines show station-averaged values for each day relative to the end of a heatwave. Coloured horizontal bars show the expected climatological 5th-95th percentile range obtained from resampling. Boxplots are calculated by randomly resampling 50% of the stations per region 100 times and indicate the uncertainty introduced by station-to-station differences. Connected dots show results for using all available stations. Dotted horizontal lines indicate the end of a heatwave.

Figure 8 shows that rainfall occurring within 36 hours of midday on day 0 contains a higher proportion of extreme to non-extreme wet hours when compared to resampled data from similar times of the year. This is the case for most regions (except for MB and RL). The highest difference to the climatological mean occurs in the East Coast region, where the average proportion of extreme events increases from approximately 8.4% to 11.0% after a heatwave. According to our definition, wet hours are extreme if the rainfall amount lies above the 95th percentile of all wet hours for the respective station and month and we would therefore generally expect results from the climatology to lie around the 5% mark. For all regions however, the resampled means lie above 5%. We attribute this to the fact that more rainfall extremes occur during the summer months, and rainfall for the climatology has been sampled during months when heatwaves were occurred, which was predominately during summer months. Additionally, rainfall intensity in Australia tends to peak in the afternoon/evening due to mechanisms such as convection (Evans and Westra, 2012). Thus, a 36h window which contains two half days and one night would contain a higher-than-average proportion of extremes.

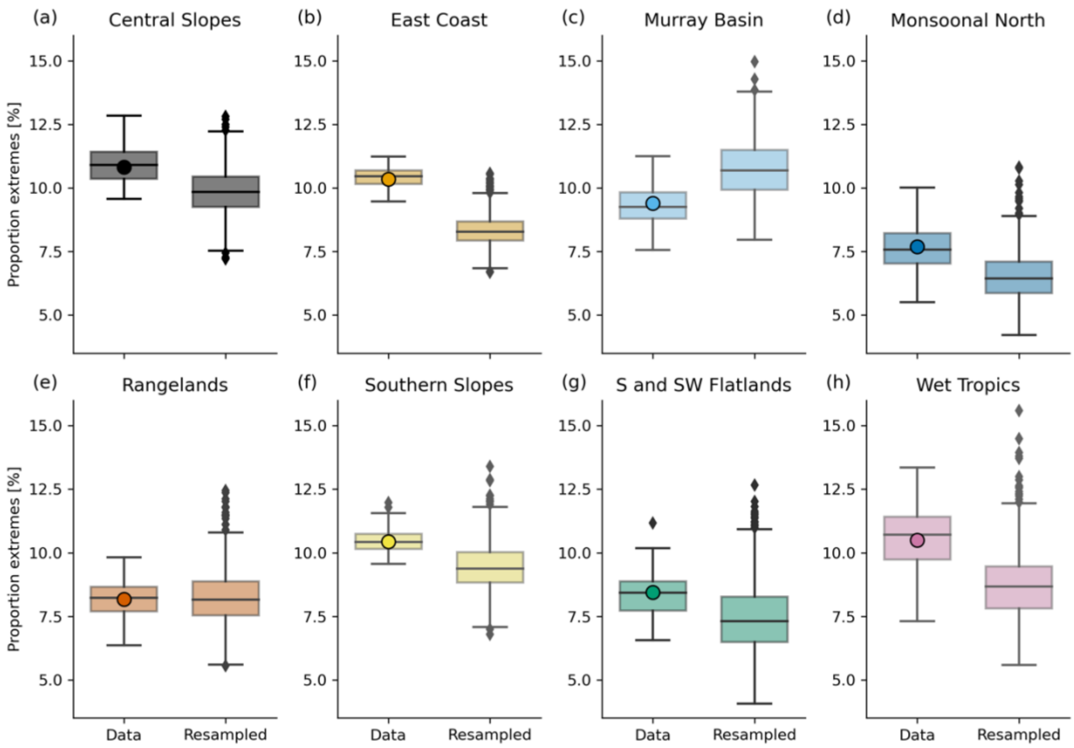

Figure 8 Proportion of extreme to non-extreme wet hours that occur within 36 hours of 12:00 (local time) on day 0 for the eight different subdivisions (a-h). Left boxplots show values obtained from randomly sampling 50% of stations per subdivision 100 times. Circles show fraction of extreme wet hours obtained from all stations within a subdivision. Right boxplots show climatologically expected fraction of extreme values which is obtained from 1000 resamples during similar times of the year (see 2.3 Methodology).

4.4.3 Comparing hourly and daily rainfall extremes during and after heatwaves

The greater availability of daily rainfall data compared to sub-daily rainfall data raises the question of what added-value sub-daily records provide, as using daily rainfall data allows the use of more data with greater spatial coverage. You and Wang (2021) previously showed increases in daily rainfall extremes after heatwaves in China using daily gridded precipitation observations. To analyse any differences in results at daily and hourly scales, we accumulated the GSDR hourly rainfall data to daily timescales to compare hourly and daily rainfall extremes.

Figure 9 compares the proportion of extreme rainfall values to non-extreme values on hourly and daily timescales for several days relative to the end of a heatwave. We find that hourly and daily rainfall extremes especially differ in the timing of their highest occurrences. On an hourly timescale, the highest proportion of extremes is generally found on the last day of the heatwave, and this substantially exceeds the average climatology. The proportion of extremes during the heatwave itself does not differ substantially from the average climatological behaviour, although it tends to be lower than the climatological average. The proportion of hourly extremes then decreases from the first day after the heatwave onwards to return to the climatology after 2 or 3 days. Using daily data, however, we find that the proportion of daily rainfall extremes to non-extreme wet days generally peaks on the first day after a heatwave, i.e., one day after the peak is seen in the hourly data. The proportion of daily rainfall extremes during the heatwave also tends to be much lower than average climatology – a behaviour that is not consistently seen in the hourly data. This is likely due to the fact that daily extremes usually result from longer-duration (up to 24h) rainfall which would be more likely to terminate a heatwave than an hourly rainfall extreme which could result from a short-duration rainfall event such as a convective storm. After the peak on the first day after a heatwave, the proportion of extreme wet days tends to drop to, or below, the climatological average within a day or two. Notably, regions that exhibit peaks in the proportion of rainfall extremes that are substantially higher than the climatological average do so either for hourly (CS, EC, WT), or for daily (MB, SS, SSWF) suggesting potentially different dominant mechanisms for heatwave termination in the different groupings.

4.5 Discussion and Conclusions

We have shown that, in Australia, rainfall at the end of heatwaves is often more likely and more extreme when compared to rainfall at similar times of the year during non-heatwave conditions (i.e., the climatological average). This results from an increase in wet days at the end of a heatwave as well as a higher proportion of extreme wet hours within 36 hours of the heatwave end. This increase in wet days at the end of a heatwave compared to climatology occurs in all regions of Australia. The intensification of rainfall immediately following the heatwave can be seen in all regions except for the central RL and MB, and especially on the East Coast (EC). However, the risk of these regions experiencing heatwave-breaking rainfall is still increased in absolute numbers due to higher wet-day frequency at the end of the heatwave.

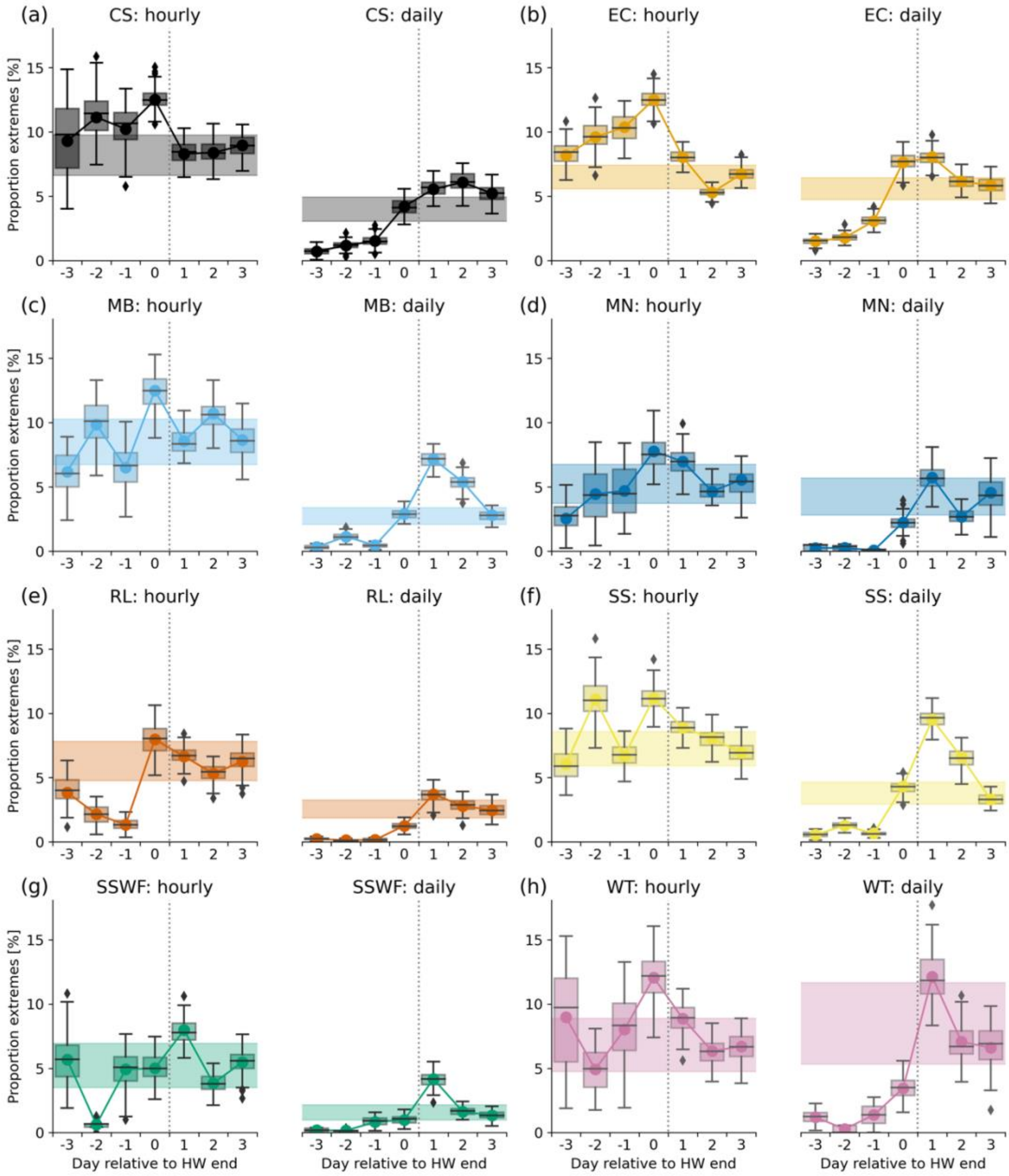

Figure 9 Comparison between proportion of hourly and daily rainfall extremes with respect to the last day of a heatwave for the eight regional subdivisions (a-h). Left plots for each region show proportion of extreme to non-extreme wet hours, right plots show proportion of extreme to non-extreme wet days. Continuous lines, coloured horizontal bars, boxplots, connected dots and dotted horizontal lines are derived analogue to Figure 7.

The investigation of rainfall data at daily and hourly timescales offers different perspectives on the occurrence of extreme rainfall at the end of heatwaves. We find increases in the proportion of extreme to non-extreme events at the end of heatwaves for both hourly and daily rainfall, but the results differ in the timing of the peak proportion of extreme events, the extent of the increase relative to the climatological average and the behaviour during the heatwave. We show significant peaks in the proportion of hourly rainfall extremes on the last day of the heatwave in the Central Slopes, East Coast, and the Wet Tropics. Peaks in the proportion of daily extremes are commonly found a day later, on the day after a heatwave terminates, and prominent in the Murray Basin, Southern Slopes, and the Southern and South-Western Flatlands. This could indicate differences in the mechanisms driving the heatwave termination in these regional groupings: clustered as North-Eastern regions (CS, EC, WT – peak hourly extremes on day of heatwave termination) and Southern regions (MB, SS, SSFL – peak daily extremes on day after heatwave termination). This suggests that the dominant mechanism for extreme rainfall terminating heatwaves in the North-Eastern regions is likely temperature-driven convection, while in the Southern regions the dominant mechanism may be synoptic variability.

While our study demonstrates a compounding relationship between heatwaves and rainfall extremes in Australia, we have not yet fully investigated the causal link between these extremes. However, it is likely that large-scale drivers and atmospheric synoptic-scale variability play the dominant role in providing rainfall to break the heatwaves in southern regions given the peak occurrence of daily extremes in the day after heatwave termination. Here, a reduction in temperature could be the result of cold air advection from a low-pressure system (Bao et al., 2017, Visser et al., 2020). However, in north-eastern regions the reduction in temperature may be a direct result of rainfall. Here, heatwave termination is associated with peaks of hourly extreme rainfall occurrence - localized high temperatures may favour convection causing intense short-duration bursts which lowers temperatures. Further research must be conducted to understand the regional interplay between heatwave termination and heavy rainfall.

The end of a heatwave is linked to an increase in wet days in all regions in Australia, and some regions, like the East Coast, additionally exhibit a high risk of short duration rainfall extremes during those wet days. As the East Coast region is highly populated, containing the cities of Brisbane and Sydney, and shows the strongest regional increase in hourly rainfall extremes after a heatwave, the potential impacts of temporally-compounding heatwave-heavy rainfall events may be significant. Impacts might also become exacerbated in the future due to changes in hazards in a warming climate. As heatwaves are projected to become more frequent (e.g., Cowan et al., 2014, Russo et al., 2014, Trancoso et al., 2020), this could have serious implications for potentially increasing the risk of heavy rainfall terminating heatwaves. More research is necessary to verify if this relationship holds true in a warming climate.

A benefit of recognizing extreme events as compound events is that it adds focus on potentially overlooked impacts, since high impacts often occur from a combination of hazards and/or drivers. However, the nature of possible impacts associated with compounding heatwave-wet extremes is poorly understood. One the one hand, heatwaves could reduce antecedent moisture conditions (Bennett et al., 2018) in the soil profile and short-term water storages (e.g. stormwater retention stores) relative to climatology, and may potentially lower flood magnitude following a heavy rainfall event. On the other hand, a quick transition from hot (which often occurs with dry conditions) to extreme wet conditions may pose additional risks to sectors such as water resources management or agriculture from those resulting from individual hazards alone. Further impacts can also result if wildfires were present during or before the heatwave, as this can affect runoff and erosion (Moody et al., 2013), as well as water quality (Murphy et al., 2015). The effect of this compounding behaviour on other impacts such as implications on heat stress (e.g., Sherwood and Huber, 2010, Raymond et al., 2020) and/or thunderstorm asthma (e.g., Taylor and Jonsson, 2004, Thien et al., 2018) are similarly poorly understood.

Previous studies analysing temporally compounding hot-wet extremes have been focussing on hazards or definitions for hot extremes that deviate from those used in this study, such as: daily wet bulb temperature extremes followed by flood events (Zhang and Villarini, 2020), daily extreme heat followed by rainfall extremes (Wu et al., 2021), or heatwaves based on maximum temperature followed by rainfall extremes (You and Wang, 2021). Due to these differences in hazards and definitions, it is not possible to draw direct comparisons between the results in this work and these studies. However, our results agree with the general findings of these studies, showing that hot events are often linked to an increase in subsequent wet extremes.

In conclusion, we show that in Australia there is evidence of temporally compounding hot-wet extremes. Although the implications of this compounding behaviour on impacts are not well understood, it is likely that interactions between heatwaves and heavy rainfall have the potential to significantly modify climate impacts and risks, and represents an important area for future investigation.

4.6 Acknowledgments

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Afterword

This chapter demonstrated compound heatwave-extreme rainfall in several locations in Australia. While several different climate regions are included, geographical differences in station density provide challenges for interpreting the results.

Using observational rainfall instead of other types of rainfall data is important to ensure best representation of sub-daily rainfall. However, the usefulness of other rainfall datasets with better spatial coverage such as reanalysis datasets should be investigated to increase the confidence in the results in observation-sparse regions such as central Australia. E.g., the Rangelands subdivision is the geographically largest subdivision used in the study yet has comparably few observations available. This makes the interpretations for results of these regions difficult, as spatial inhomogeneities due to the large area cannot be ruled out.

Australia was chosen as a study region for many reasons, including the fact that it experienced many natural hazards. Interestingly, while extreme rainfall is more likely after heatwaves compared to climatology, it is later found in the next chapter that compound heatwave-extreme rainfall is less strongly pronounced in Australia than in other regions. As seen later in Chapter 6, the availability of moisture is a key factor for increased extreme rainfall likelihood after heatwaves, however many regions in Australia are characterised by dry climates. Therefore, although Australia is vulnerable to many natural hazards, the risk from compound heatwave-extreme rainfall might be lower compared to other regions and other natural (compound) hazards. If and how the risk from this compound event in Australia changes in a warming climate, however, remains to be investigated.

The methodology used in this chapter to study compound heatwave-extreme rainfall has been proven to be useful and robust to changes in heatwave and extreme rainfall definitions. Some smaller modifications apart, the following chapter will use the methods tested in this study and apply them to an investigation of this compound event on a global scale.

CHAPTER 5

COMPOUND EXTREME HOURLY RAINFALL PRECONDITIONED BY HEATWAVES MOST LIKELY IN THE MID-LATITUDES

Preface

This chapter (excluding preface and afterword) has been published in the journal *Weather and Climate Extremes* (Sauter et al., 2023). Numberings and figures have been adapted for consistency of the overall thesis. Additional figures have been produced for this chapter which were not published in Sauter et al. (2023). These figures can be found in Appendix D. References to these figures as well as additional explanations are added to the text as footnotes.

The study in this chapter expands the analysis made in the previous chapter to a global extent. Analysing this compound event on a larger scale allows for the better detection of spatial patterns and hotspots, as well as how this compound event varies depending on the local climate. As the climate changes, regional climate zones are projected to change as well (Beck et al., 2018). Understanding in which climate zones extreme rainfall is the most likely after heatwaves provides first indications of in which regions the risk of this compound event might increase in the future.

Compared to the previous chapter the analysis remains similar. However, some adjustments were made in response to the greater spatial extent and findings from the previous case study for Australia with regards to dataset selection, heatwave definition and extreme rainfall threshold (see Chapter 3).

Notes on the terminology. Contrary to the previous chapter, compound heatwave-extreme rainfall is now referred to as a *preconditioned* compound event instead of a *temporally compounding* event. While both terms are technically correct, the term *preconditioned* lays more focus on the influence of the heatwave on extreme rainfall instead of the joint impact of heat and extreme rainfall. This change was motivated by an explanation provided by Chen et al. (2022) who argued that the true impact from this compound event was from the intensified extreme rainfall as a result of the heatwave rather than from consecutive heat and extreme rainfall. Besides the change in classification, the threshold for extreme hourly rainfall in this chapter has been increased from the 95th to the 99th percentile as explained in Chapter 3.4. As a result, rainfall above this threshold is now referred to as *extreme* rainfall instead of *heavy* rainfall. The term *significant* is used as in the previous chapter.

5.1 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.

5.2 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, Westra et al., 2014, Ali et al., 2018, Guerreiro et al., 2018, Ali et al., 2021a, Ali et al., 2021b, Fowler et al., 2021a) 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, Ning et al., 2022, Li et al., 2023) 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, 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.

5.3 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 7394 observations from the GSDR dataset that fit these criteria, mainly located in the United States, Europe, India, Malaysia, Japan, and Australia (Figure B1). 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 (Figure B1). 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 B1.

5.4 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. B2). We have also tested defining a heatwave using only Tmax, 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 <1mm rainfall during the last three days before the heatwave termination (Fig. B3-B5).

5.5 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 one hour of extreme rainfall within 36 hours, 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 Figure 10.

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 1,000 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 1,000 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:

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

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).

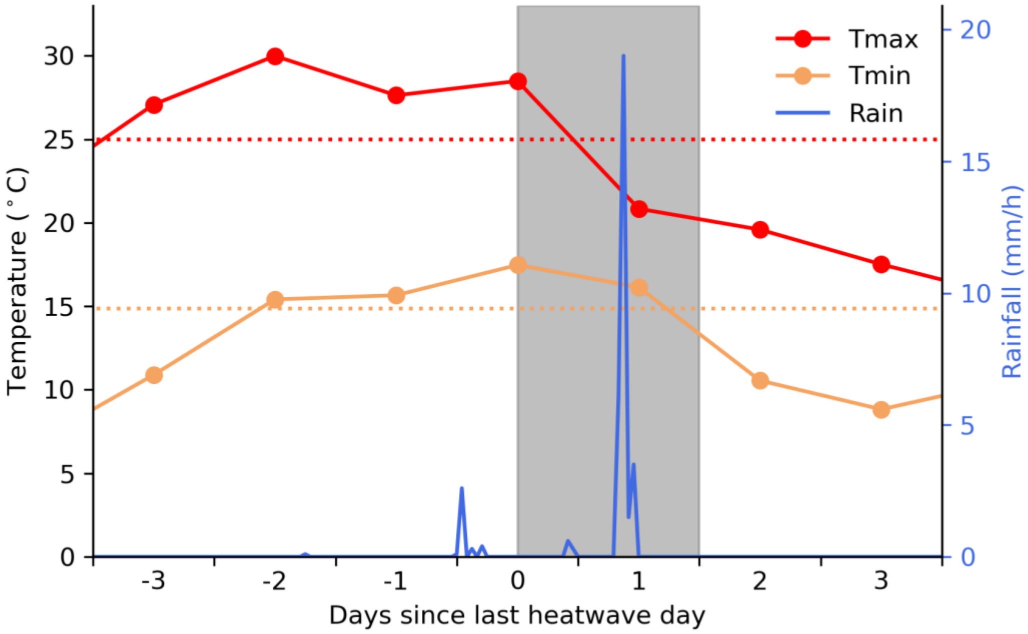

Figure 10 An example of a heatwave followed by extreme hourly rainfall from a station in Germany (51.6N, 10.3E). The x-axis denotes the day relative to the last day of the heatwave, with ticks spanning from midnight to midnight. The dashed lines show the 95th percentiles for T_{max} (red) and T_{min} (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.

5.6 Results

5.6.1 Likelihood of hourly extreme rainfall after heatwaves

Our results show that the likelihood of at least one hour of extreme rainfall occurring after a heatwave strongly varies depending on location (Figure 11). 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 (Figure B6). 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).

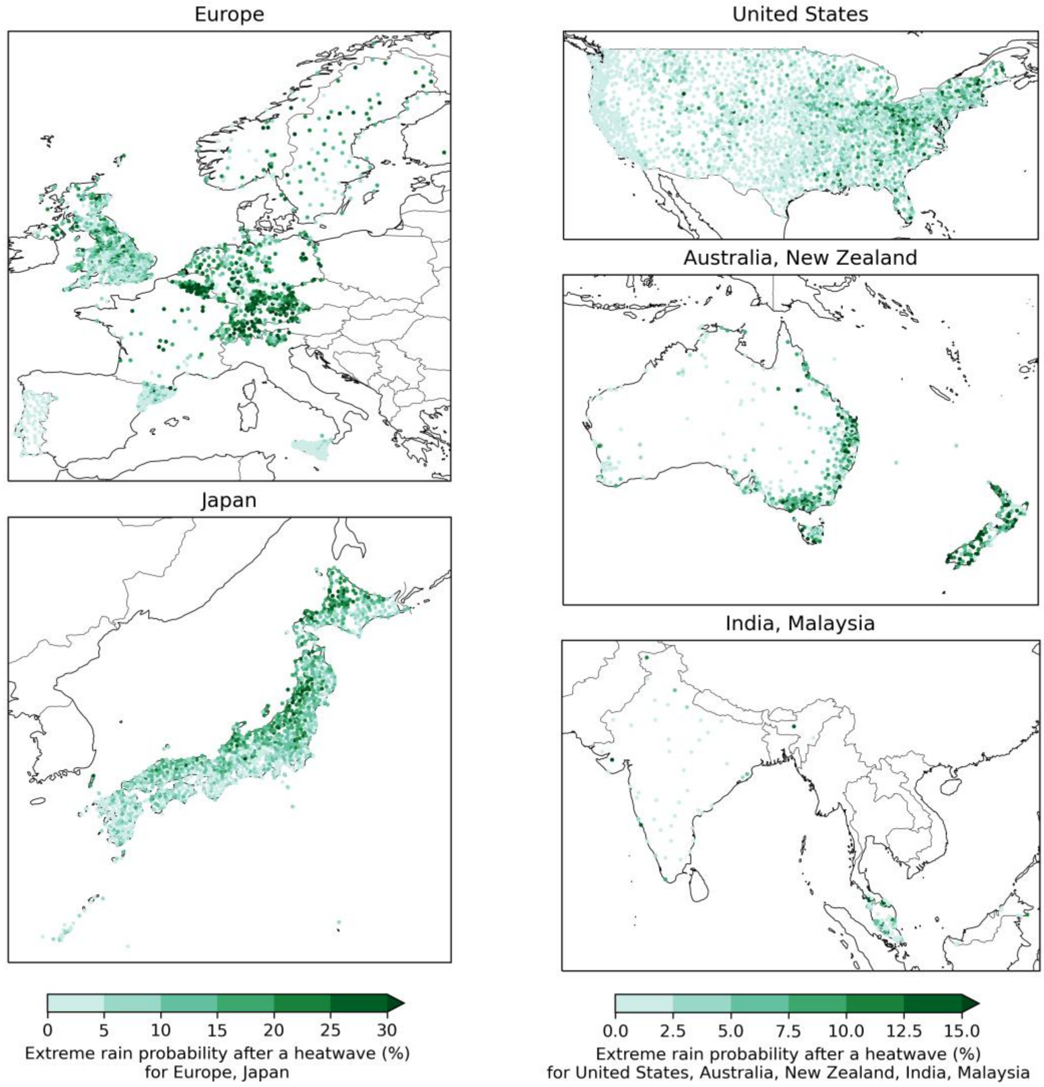

Figure 11 Probability of at least one hour of extreme rainfall occurring within 36 hours from noon on the last heatwave day for stations in Europe, Japan, the contiguous United States, Australia, India, and Malaysia. Note the change in scale in the righthand column.

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 (Figure B7). 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. 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 (Figure 11). 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 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).

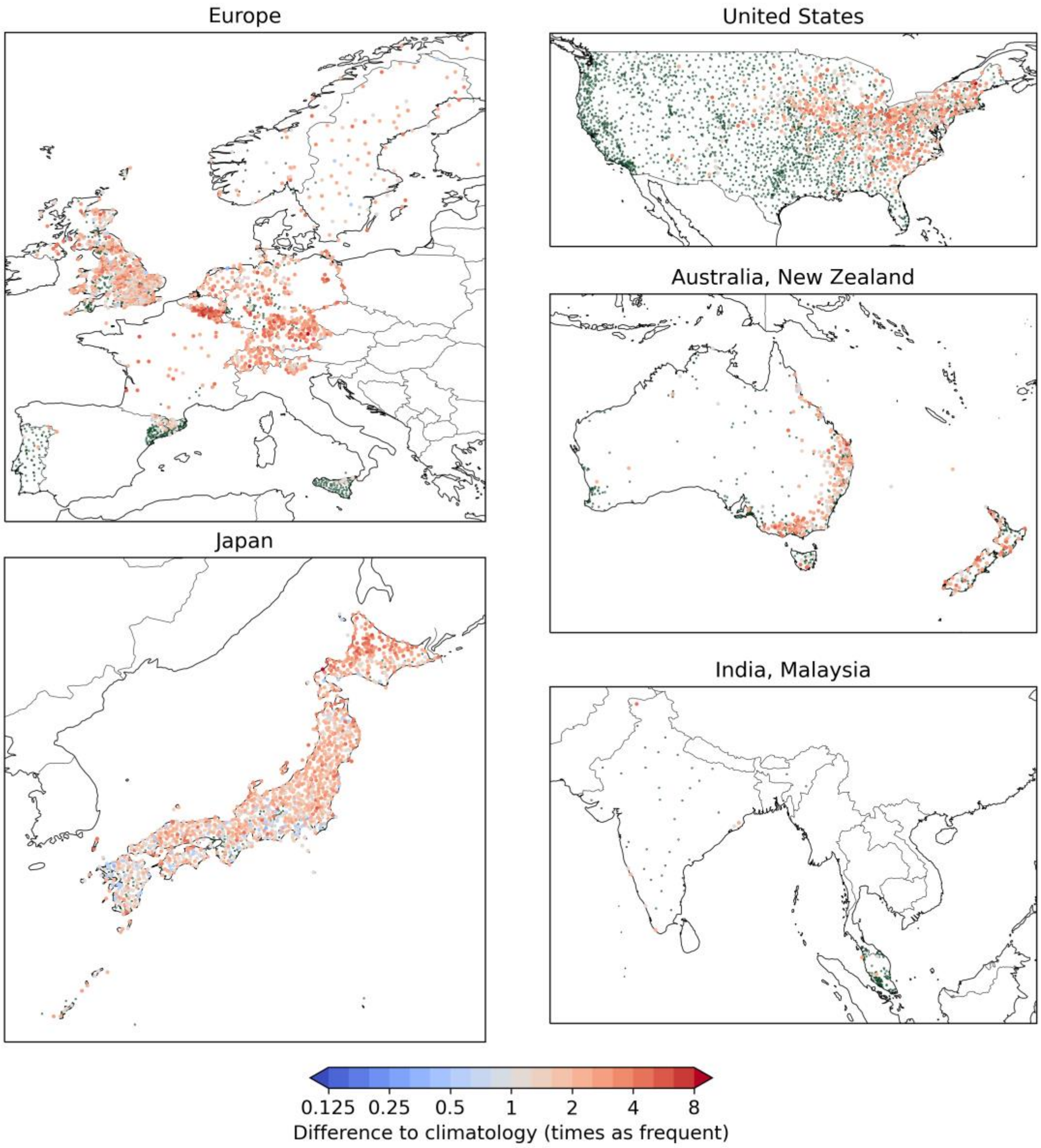

Figure 12 The difference in probability of extreme rainfall after a heatwave from expected probabilities from rainfall climatology (Eq. 1). Values >1 indicate that hourly extreme rainfall is more likely after a heatwave than for climatology. Comparisons are based on the median values from 1,000 resamples. 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.

5.6.2 Division by Köppen-Geiger climate zones

We use the Köppen-Geiger climate classification (Figure 13a) to further test if regional patterns in high compound heatwave-extreme rainfall occurrences are related to local climate conditions. Figure 13b shows the likelihood of at least one hour 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 Figure 13b. 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.[1] Similar results can also be found when analysing the intensity of the rainfall after heatwaves compared to that during climatology (Figure B8).

[1] Figures C1-C8 in Appendix C show the global distribution of all Köppen-Geiger climate zones where the hourly extreme rainfall probability lies outside the 5^{th} to 95^{th} percentile climatological range (Figure 12b, climate zones 'Cfa', 'Cfb', 'Cfc', 'Dfa', 'Dfb', 'Dfc', 'ET'), as well as the locations of the available stations within the respective climate zones. While these regions mark areas where it is likely that extreme rainfall probability after a heatwave is significantly higher than climatology, confidence is only high for areas represented by rainfall stations.

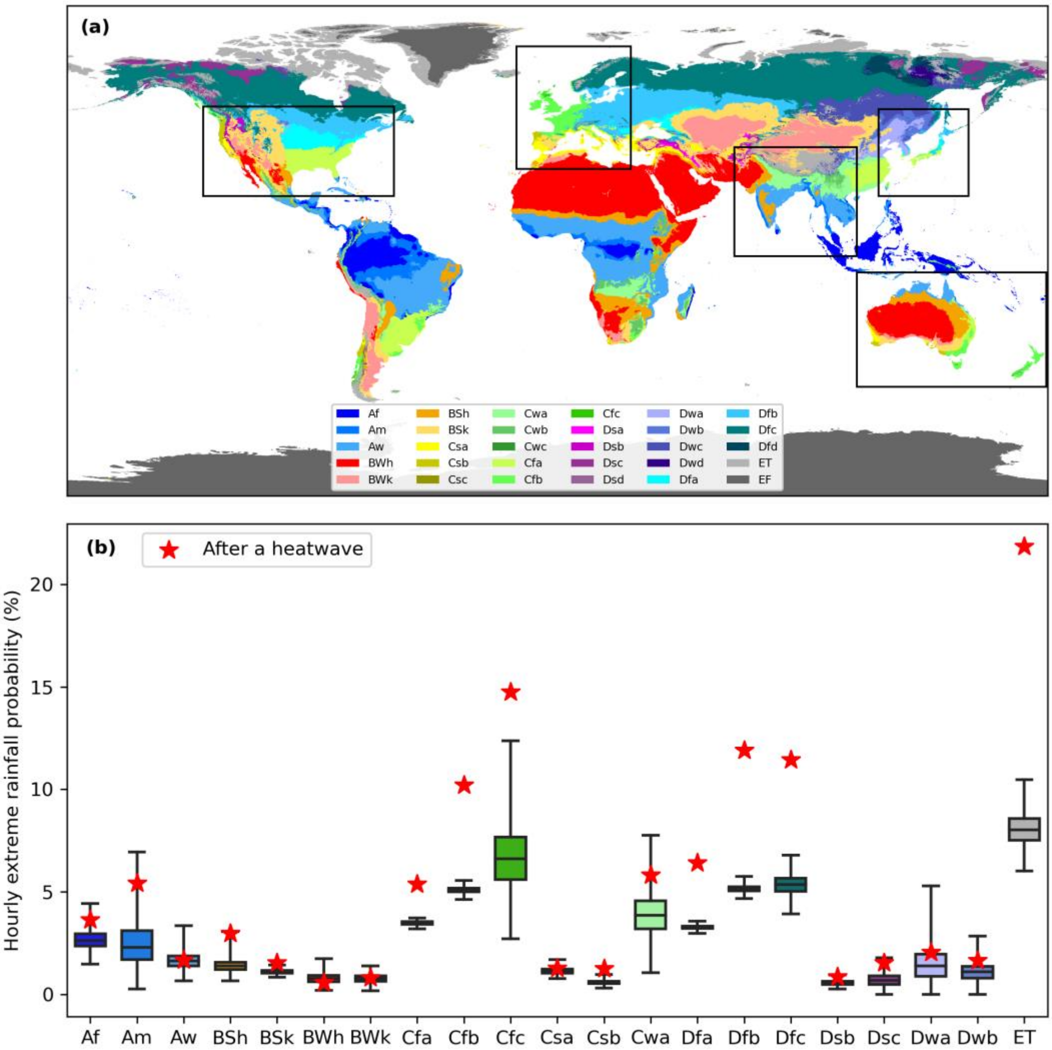

Figure 13 (a) Map of Köppen-Geiger climate regions after Beck et al. (2018). Black boxes mark areas where the majority of GSDR stations are located. A full description of the climate zones, including their defining criteria can be found in Table B1 in the Supporting Information. (b) Likelihood of occurrence of at least one hourly rainfall extreme within 36 hours 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.

5.7 Discussion

We have demonstrated that a preceding heatwave only increases the likelihood of extreme rainfall in particular climate zones (Figure 13b); 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 one hour 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: 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. B5), 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 (Figure B7). The Tropics, on the other hand, while experiencing both high temperatures and high rainfall amounts (Figure B7), do not exhibit noticeable increases in extreme rainfall after heatwaves (Figure 13). 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. B5). 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 1,000 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).

5.8 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.

5.9 Acknowledgments

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Afterword

This study demonstrated compound heatwave-extreme rainfall on a global scale. However, the main issue remains the spatial coverage of observations. Using gridded data as suggested in the previous chapter, would allow one to test the conclusions of this study, such as consistency of compound heatwave-extreme rainfall behaviour within each Köppen-Geiger climate zone. It remains the main weakness of this study design that due to the inhomogeneity of spatial observation distribution, the properties of this compound event cannot be extrapolated with confidence onto other regions of the same climate zone without observations. Therefore, large regions such as South America or Africa could not be analysed, while from a climate-zone perspective, it is not unlikely that compound heatwave-extreme rainfall is common in these regions as well.

Despite this, hotspots of compound heatwave-extreme rainfall have been identified in Japan and western central Europe. A more detailed analysis of how this compound event affects the risk in these regions would be useful to fully understand the impact. Further, the projected changes of climate zones should be investigated to assess if climate zones associated with high likelihood of extreme rainfall after heatwaves will become more common or shift geographically. The knowledge obtained in this study must also be combined with knowledge on climate resilience – both to heatwaves and to extreme rainfall. Therefore, different disciplines must come together to tackle the risk from compound heatwave-extreme rainfall events.

While the study design of the previous two chapters only allows for the analysis of the spatial distribution in areas with available observations, the next chapter will focus on the mechanistic drivers of compound heatwave-extreme rainfall events instead of investigating filling the spatial gaps. However, it remains important to analyse the spatial extent of compound heatwave-extreme rainfall using a dataset that covers the areas not represented by rainfall observations here.

Chapter 6

Compounding heatwave-extreme rainfall events driven by fronts, high moisture, and atmospheric instability

Preface

This chapter (excluding preface and afterword) is under review for *Journal of Geophysical research: Atmospheres.*

The study in this chapter aims at exploring the mechanistic drivers of compound heatwave-extreme rainfall events. Improved knowledge of the drivers is important in understanding how well this compound event can be represented in climate models and how it might change in a warming climate. Thus, with the focus of this study on investigating the driving mechanisms, the study approach differs from the two previous chapters and several changes to the methodology and definitions have been made.

Notes on the study locations. The study in this chapter focusses on Australia and Europe (see Chapter 3.1). An original draft of the study used three separate regions in Europe, divided into north, central and south. However, we decided to combine the northern and central regions for consistency, following the results of the previous chapter. This led to the combined region referred to as 'Central Europe', though 'North-Western Europe' might have been more intuitive. With regards to the observational coverage, the station density across Europe varies strongly depending on country, and even within countries such as within Spain. It is important to stress that many more stations, while available, did not have long enough records to be included in this study. For a full map of observations regardless of record length and number of missing data, see Lewis et al. (2019).

Notes on the terminology. The use of the word *significant* follows that from the previous chapters. In addition, differences between distributions were tested for significance using well-known statistical tests such as a Student's t-test. In these cases, the respective statistical test was stated.

Notes on the datasets. In this chapter we introduce two new weather type datasets for Europe and Australia. As they originated from different projects, there are slight differences in the number of weather types used, the reanalysis data they are based on as well as their available time periods.

6.1 Abstract

Heatwaves have been shown to increase the likelihood and intensity of extreme rainfall occurring immediately afterwards, potentially leading to increased flood risk. However, the exact mechanisms connecting heatwaves to extreme rainfall remain poorly understood. In this study, we use weather type datasets for Australia and Europe to identify weather patterns, including fronts, cyclones, and thunderstorm conditions, associated with heatwave terminations and following extreme rainfall events. We further analyse, using reanalysis data, how atmospheric instability and moisture availability change before and after the heatwave termination depending on whether the heatwave is followed by extreme rainfall, as well as the location of the heatwave. We find that most heatwaves terminate during thunderstorm and/or frontal conditions. Additionally, atmospheric instability and moisture availability increase several days before the heatwave termination; but only if heatwaves are followed by extreme rainfall. We also find that atmospheric instability and moisture after a heatwave are significantly higher than expected from climatology for the same time of the year, and that highest values of instability and moisture are associated with highest post-heatwave rainfall intensities. We conclude that the joint presence of high atmospheric instability, moisture, as well as frontal systems are likely to explain why rainfall is generally more extreme and likely after heatwaves, as well as why this compound hazard is mainly found in the non-arid mid and high latitudes. An improved understanding of the drivers of these compound events will help assess potential changing impacts in the future.

6.2 Plain Language Summary

Extreme rainfall which can lead to flash floods is more likely to occur if it is preceded by a heatwave. The exact reasons behind this connection, however, are not fully clear. In this study we investigate the mechanistic drivers connecting heatwaves to extreme rainfall in Europe and Australia by analysing which types of weather (e.g., fronts, cyclones, thunderstorms) are present during the transition from heatwaves to extreme rainfall. We also analyse how atmospheric characteristics associated with extreme rainfall during thunderstorms change depending on if a heatwave is followed by extreme rainfall or not. We find that heatwaves are usually followed by extreme rainfall when there are thunderstorm conditions and/or when there is the presence of a front. Further, we find that high amounts of moisture are present if heatwaves are followed by extreme rainfall and that atmospheric conditions favourable for thunderstorms, including high amounts of moisture are generally increased after heatwaves.

These findings help understand how heatwaves are connected to extreme rainfall and can help assess how the risk from these events might change in the future.

6.3 Introduction

Short-duration extreme rainfall has the potential to cause severe flooding and is projected to increase in intensity as well as frequency as a result of anthropogenic climate change (Prein et al., 2016, Fowler et al., 2021a, Seneviratne et al., 2021). One of the reasons for this projected increase is the thermodynamic connection between temperature and precipitable water in the atmosphere, since hotter air can hold more moisture (Trenberth et al., 2003). Heatwaves, where high temperatures persist over several days, usually coincide with dry weather due to land- atmosphere interactions (Miralles et al., 2019). While rainfall is therefore less likely *during* a heatwave, recent studies have shown a significant increase in extreme rainfall immediately *after* a heatwave (You and Wang, 2021, Chen et al., 2022, Ning et al., 2022, Sauter et al., 2022, Li et al., 2022). Heatwaves followed by extreme rainfall should thus be seen as a compound event (Leonard et al., 2014, Zscheischler et al., 2018), as the likelihood and intensity of the extreme rainfall event is increased compared to conditions without a heatwave.

This compounding hot-wet extreme event occurs predominately in the mid and high latitudes where there is ample moisture supply and high summer temperatures (Sauter et al., 2023). Several studies therefore point towards moist convection being the main driver of compounding heatwave-extreme rainfall events, as atmospheric instability tends to be high during the event (Zhang and Villarini, 2020, Wu et al., 2021, You and Wang, 2021, Chen et al., 2022). Indeed, from a theoretical standpoint, high temperatures related to the heatwave have the potential to enhance convective extreme rainfall, provided there is ample moisture supply, as extreme rainfall associated with convection is usually linked to high atmospheric instability and moisture (Groenemeijer and van Delden, 2007, Brooks, 2013, Púčik et al., 2015, Meyer et al., 2022). However, uncertainties remain as to how other synoptic-scale drivers contribute; cyclones or fronts could be the causal mechanism of both the reduction in ambient temperature during the heatwave termination as well as the associated rainfall. Further, it is unclear if the low likelihood of extreme rainfall after heatwaves in arid regions results from the absence of synoptic systems associated with rainfall, a lack of available moisture and atmospheric instability, or both.

Identifying convective- and synoptic-scale drivers for extreme events such as extreme rainfall is challenging as the drivers are identified using different atmospheric variables and methods. Recent studies have addressed this by identifying weather types such as thunderstorms, fronts, and cyclones that can also occur simultaneously in space and time (Dowdy and Catto, 2017, Pepler et al., 2020, Catto and Dowdy, 2021). Therefore commonly known drivers of extreme rainfall in Australia and Europe, such as east coast lows, tropical and extratropical cyclones, fronts, atmospheric rivers and/or thunderstorms (Catto and Pfahl, 2013, Lavers and Villarini, 2013, Villarini and Denniston, 2016, Dowdy and Catto, 2017, Dowdy et al., 2019), can be easily identified and causally related to an extreme event.

Here, we determine the predominant weather-types during heatwave terminations in Australia and Europe, giving insight into the importance of convective and synoptic-scale drivers of extreme rainfall following heatwaves. We further investigate how and why the strength of this compound event differs by region. Improved understanding of the driving mechanisms is crucial to estimating future changes to extreme rainfall after heatwaves and the resulting potential impacts.

6.4 Data

The selection of rainfall and temperature data, as well as the definition of heatwaves follows that of previous work (Sauter et al., 2022) where different definitions and thresholds have been tested and found not to impact results significantly. Due to the availability of weather type datasets in these regions, the analysis focusses on Europe and Australia.

6.4.1 Rainfall observations

We use hourly rainfall observations from the Global Sub-Daily Rainfall Dataset (GSDR) (Lewis et al., 2019) which have been extensively quality-controlled (Lewis et al., 2021, Ali et al., 2022). Here, we only consider stations with at least 12 years of rainfall records and less than 20% of missing data during any year (analogue to Ali et al., 2021a). As rainfall observations are paired up with temperature data as well as with weather type data, rainfall records are limited to starting from 1979 or later. This results in the analysis of 1987 stations in Europe and 581 stations in Australia. Extreme rainfall is defined for each station individually as an hourly rainfall event that exceeds the respective 99th percentile of all hours with >0.1mm/h within the entire rainfall record. This ensures that the 99th percentile rainfall threshold is higher than if using the 99th percentile of wet and dry hours, as excluding non-rainfall hours reduces the number of values and extreme values vary less between locations depending on the respective climatological number of dry days/hours per year.

6.4.2 Reanalysis data

We additionally use 2-m temperature, total column water vapour (TCWV), and convective available potential energy (CAPE) variables from the ERA5 reanalysis dataset (Hersbach et al., 2020). The data is provided at a horizontal resolution of 31km and the grid box closest to each GSDR station is selected. All variables are aggregated from hourly to daily timescales with respect to their local time zones (maximum and minimum daily temperatures; T_{max}, T_{min}, mean daily TCWV and CAPE). Other variables describing moisture (e.g., absolute humidity) and atmospheric instability (e.g., convective inhibition) are available from reanalysis as well; however, TCWV and CAPE are analysed as they have been found to serve well as proxy parameters for conditions associated with extreme precipitation (Meyer et al., 2022).

6.4.3 Weather type data

We use two weather type datasets that cover Europe and Australia respectively. For Europe we use a weather type dataset following Dowdy and Catto (2017) and Catto and Dowdy (2021) that determines cyclones, fronts, and thunderstorms from ERA5 data. The fronts are identified using an updated version of a thermal front parameter method (Sansom and Catto, in review, 2022), and the cyclones are identified using the Wernli and Schwierz (2006) method of identifying closed contours of mean sea level pressure. The thunderstorm environment is defined using CAPE, bulk wind shear from 0 to 6km, total totals index and a Laplacian of 500-hPa geopotential height (Dowdy and Brown, 2023) and the thresholds are based on lightning observations (Dowdy, 2020). The individual weather systems can occur by themselves or in combination with other systems. Therefore, the combination of these three identified systems means that the weather types included in the Europe region are Cyclone Only (CO), Front Only (FO), Thunderstorm Only (TO), Cyclone-Front (CF), Cyclone-Thunderstorm (CT), Front-Thunderstorm (FT), Cyclone-Front-Thunderstorm (CFT), and Undefined (U). The dataset is provided at 0.25° resolution, spanning 1980 to 2019.

For Australia, we use a weather types dataset from Pepler et al. (2020), based on the ERA-Interim reanalysis, which follows Dowdy and Catto (2017) but includes a number of additional identification algorithms. In this dataset, fronts are identified using both the thermal front parameter method (Hewson, 1998, Berry et al., 2011) , and a wind shift method (Simmonds et al., 2012). Cyclones are identified using mean sea level pressure with both the Wernli and Schwierz (2006) method and the University of Melbourne algorithm (Murray and Simmonds, 1991, Simmonds et al., 1999, Simmonds and Keay, 2000). If a front or cyclone is only identified with one of their respective two identification methods, they are classified as 'Unconfirmed Cyclones/Fronts (UCF)'. More detailed information about the identification of each individual weather system can be found in Pepler et al. (2020). For any given time and location, if none of the previous weather types is identified, the weather type at that location is 'Undefined' ('U'). Therefore, in addition to the eight weather types used in Europe, three additional weather types are included for Australia: High pressure (H), Warm-front (WF), 'Unconfirmed Cyclones/Fronts (UFC). The dataset for Australia is provided at a gridded 0.75° horizontal resolution from 1979 to 2015. For each GSDR station the corresponding grid box from the European or Australian weather type dataset are selected.

6.5 Methods

Heatwaves are defined for each location individually, where T_{max} lies above its 95th percentile for at least 3 consecutive days and T_{min} lies above its 95th percentile for at least the second and third day. To avoid a longer heatwave being identified as two or more shorter heatwaves, a heatwave is only terminated if T_{max}, T_{min}, or a combination of the two, fall below their respective thresholds for at least two consecutive days. The robustness of the heatwave-extreme rainfall signal has also been tested for different heatwaves definitions and thresholds in a previous study (Sauter et al., 2022), and these were not found to change the results significantly. However, to test the influence of different heatwave types on available moisture, we define day-time heatwaves as a minimum of three consecutive days where Tmax lies above its 95th percentile, while Tmin lies below its 95th percentile during the same days. Analogue to this definition, we define night-time heatwaves as a minimum of three consecutive days where Tmin lies above its 95th percentile, while Tmax lies below its 95th percentile during the same days.

To avoid identifying localised reductions in temperature as large-scale heatwave terminations, we only consider heatwave terminations where at least two stations agree on the timing of a termination. We found that requiring more stations does not significantly change the results, and therefore use two stations as a minimum to increase the number of identified heatwaves. For each heatwave termination, we select the weather type that is present at most of the affected stations at the termination. Weather type distributions are analysed at 12:00 on the last day of the heatwave. The distribution of weather types for different times throughout and after the heatwave is shown in Figs D1 and D2. For CAPE and TCWV, we calculate the station-mean of all affected stations.

The influence of a heatwave on the likelihood and intensity of extreme rainfall is strongest immediately (24 h to 48 h) after a heatwave (Chen et al., 2022, Sauter et al., 2022). We therefore consider any rainfall connected to a heatwave termination if it occurs within a 36-h time window starting on noon on the last day of a heatwave. Though the signal of a heatwave on subsequent rainfall can last up to several days, the strongest rainfall response occurs within the first day after a heatwave (Chen et al., 2022, Sauter et al., 2022).

All heatwave terminations are then divided further into three categories based on the rainfall following the heatwave:

(1) *Heatwaves followed by extreme rainfall;* At least one station records at least one hour of extreme rainfall after the heatwave.

(2) *Heatwaves followed by moderate rainfall;* At least one station records at least one wet hour (>0.1 mm/h) after the heatwave, but none of the stations record any extreme rainfall.
(3) *Heatwaves followed by no rainfall;* No station records any rainfall after a heatwave.

Figure 14 shows the location of GSDR stations used for this study in Australia (a) and Europe (b). Stations in Australia and Europe have been sub-divided to account for differences in climatic conditions. Australia is sub-divided into four (Northern Australia, Rangelands, Eastern Australia and Southern Australia) according to the regions suggested by CSIRO and Bureau of Meteorology (2015). Europe has been divided into two; Central Europe and Southern Europe, based on Köppen-Geiger climate classifications (Beck et al., 2018). Central Europe includes Moderate, Cold, and Polar climate classifications that are associated with high likelihoods of extreme rainfall after heatwaves (Köppen-Geiger sub-classes ‘Cfa’, ‘Cfb’, ‘Cfc’, ‘Dfb’, ‘Dfc’, and ‘ET’), and Southern Europe contains Arid and Moderate climate classifications associated with low likelihoods of extreme rainfall after heatwaves (Köppen-Geiger sub-classes ‘BSk’, ‘Csa’, and ‘Csb’) (Sauter et al., 2023). All major Köppen-Geiger climate classifications (Tropical, Arid, Moderate, Cold and Polar) are represented within at least one of the six regions.

Figure 14c shows that the likelihood of (extreme) rainfall after a heatwave varies depending on the region and climatic conditions. In Australia, extreme rainfall after heatwaves is most likely in Eastern Australia, followed by Southern Australia, while heatwaves in Northern Australia and the Rangelands are less likely to be followed by extreme rainfall. In Europe, heatwaves are far more likely to be followed by extreme rainfall in Central Europe than in Southern Europe.

To estimate the frequency of a particular weather type and atmospheric conditions such as TCWV and CAPE independent of any heatwave occurrence, we calculate climatological estimations for weather type frequencies, TCWV and CAPE for the same time of the year as the heatwave. For each heatwave termination (i.e., all stations whose heatwave ended on the same day), we calculate the weather type, TCWV and CAPE for the same day of the year for all available years in the respective record. If a heatwave termination falls on the last day of a year during a leap year, as in some instances in Australia, the 365^{th} instead of the 366^{th} day of the year is chosen in order not to reduce the sample size.

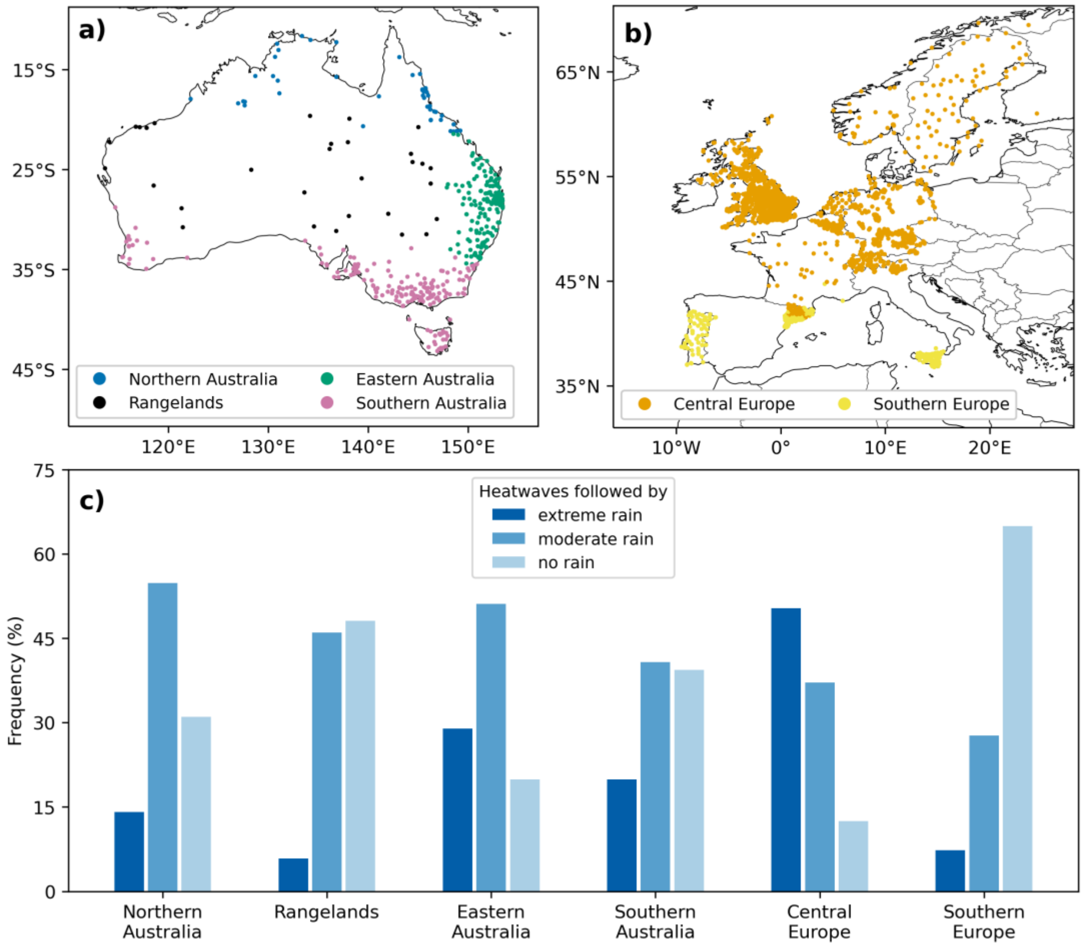

Figure 14 Location of rainfall stations used for Australia (a) and Europe (b). The stations are coloured according to their region used in this study (44 in Northern Australia, 165 in Eastern Australia, 30 in Rangelands, 186 in Southern Australia, 1479 in Central Europe and 227 in Southern Europe). (c) Percentage of heatwaves ending with extreme rainfall (dark blue), moderate rainfall (blue), or no rainfall (light blue) for each of the regions used within Australia and Europe.

6.6 Results

During any given time, multiple weather types can be present in one region, as illustrated in a case study example from a heatwave termination followed by extreme rainfall in summer 2002 (Figure 15). During this heatwave termination, most of Europe was under a thunderstorm environment. The termination of the heatwave and associated extreme rainfall, however, was associated with the passage of a front. Though part of the same fontal structure, the weather types dataset allows to separate frontal conditions that occur simultaneously with and without thunderstorm conditions (brown and purple areas, respectively). During the 36-h window from

12:00 on the last heatwave day, 16 of the 23 stations with heatwave terminations on that day recorded at least one hour of extreme rainfall.

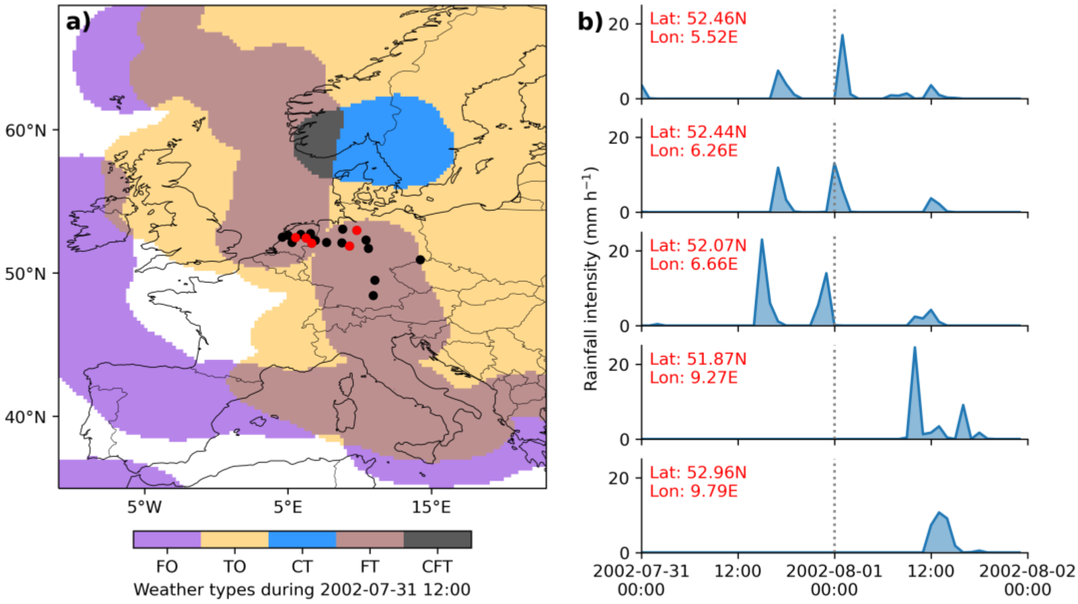

Figure 15 Case study of a heatwave termination with extreme rainfall on the 31.07.2002 in Central Europe. (a) Shadings show areas associated with a particular weather type during 12:00 on the last day of the heatwave. Dots indicate locations of all stations where a heatwave terminates on the 31.07.2002. Red dots indicate locations of the five stations with the highest recoded hourly rainfall of all stations affected by the heatwave termination, and their observed rainfall intensity is shown in (b), ordered from east to west (top to bottom in (b)). Vertical dashed lines indicate the end of the heatwave.

Heatwaves in Europe and Australia tend to terminate during frontal (F) and/or thunderstorm (T) conditions (Figure 16). While these weather types are also very common climatologically, there were statistically significant differences between the frequency of particular weather types during heatwave terminations and climatology. In all regions (except Central Europe), Thunderstorm Only conditions occurred significantly more often than expected from climatology (i.e., above the 95th percentile) in cases where a heatwave was followed by extreme rainfall. If a heatwave in the same regions was followed only by moderate or no rainfall, Thunderstorm Only conditions were mostly more likely than or comparable to conditions expected from climatology. Significantly higher Front Only conditions during all heatwave termination types compared to climatology were found in the Rangelands and Southern Australia but were comparable or less likely than climatology in the other regions. The combination of fronts and thunderstorms were significantly more likely than climatology during all heatwave endings in Southern Australia and Central Europe, but the signal is less clear in the other regions and dependent on the type of heatwave termination. There is some indication that Cyclone-Front-Thunderstorm conditions during heatwave terminations were also more likely than climatology in the Rangelands, Eastern Australia, Southern Australia, and Southern Europe. However, the absolute occurrences were comparably low and the difference to climatology is only significant for certain heatwave termination types such as heatwaves followed by extreme rainfall in Southern Australia or Central Europe. Cyclone Only weather type occurrences during heatwave terminations were usually not significantly different to climatology, except for the Rangelands, where heatwaves followed by no rain were associated with Cyclone Only conditions significantly more often than expected from climatology. Cyclone-Thunderstorm weather types during heatwaves mostly made up only a small contribution overall and were mostly comparable to climatology, with the exception of the Rangelands where Cyclone-Thunderstorm weather types were significantly more likely than climatology during all heatwave endings. High, Warm-front, and Unconfirmed Fronts/Cyclones weather types tended to be less frequent during heatwave terminations than climatology (often significantly less frequent, e.g., in Southern Australia), though there were some exceptions like in the Rangelands, where a significantly higher contribution of WF weather types compared to climatology occurred during heatwave terminations which were followed by extreme rainfall. The proportion of undefined (U) weather types was lower than expected from climatologic conditions during all heatwave terminations. Overall, weather types related to thunderstorms and fronts (i.e., Thunderstorm Only, Front Only, and Front-Thunderstorm) tended to be more likely during heatwave terminations, especially if a heatwave was followed by extreme rainfall.

The weather type analysis shows that the likelihood of a specific weather type during heatwave termination varies by region, but much less by whether a heatwave is followed by (extreme) rainfall and cannot fully explain why some heatwaves are followed by extreme rainfall while others in the same region are not. We therefore analyze if these differences in rainfall behavior after heatwaves can be explained by variations in atmospheric conditions. Specifically, we analyze the atmospheric instability and availability of moisture before and after the heatwave termination as these are important requirements for extreme rainfall in thunderstorms and their mechanistic roles in contributing to extreme rainfall is well known (Meyer et al., 2022).

Figure 17 shows convective available potential energy (CAPE) and total column water vapor (TCWV) for Australia and Europe during and after a heatwave conditional on whether the heatwave was followed by extreme, moderate, or no rainfall. In all the regions studied in Australia and Europe, if a heatwave is followed by extreme rainfall, CAPE increases during the heatwave until the last day or the day after the heatwave. However, the duration of the buildup in CAPE varies from only one or two days in the Rangelands or Southern Europe, to several days in the other regions. For a heatwave followed by only moderate rainfall, CAPE also increases, but at a lower magnitude. In contrast, a heatwave followed by no rainfall shows little to no increase in CAPE.

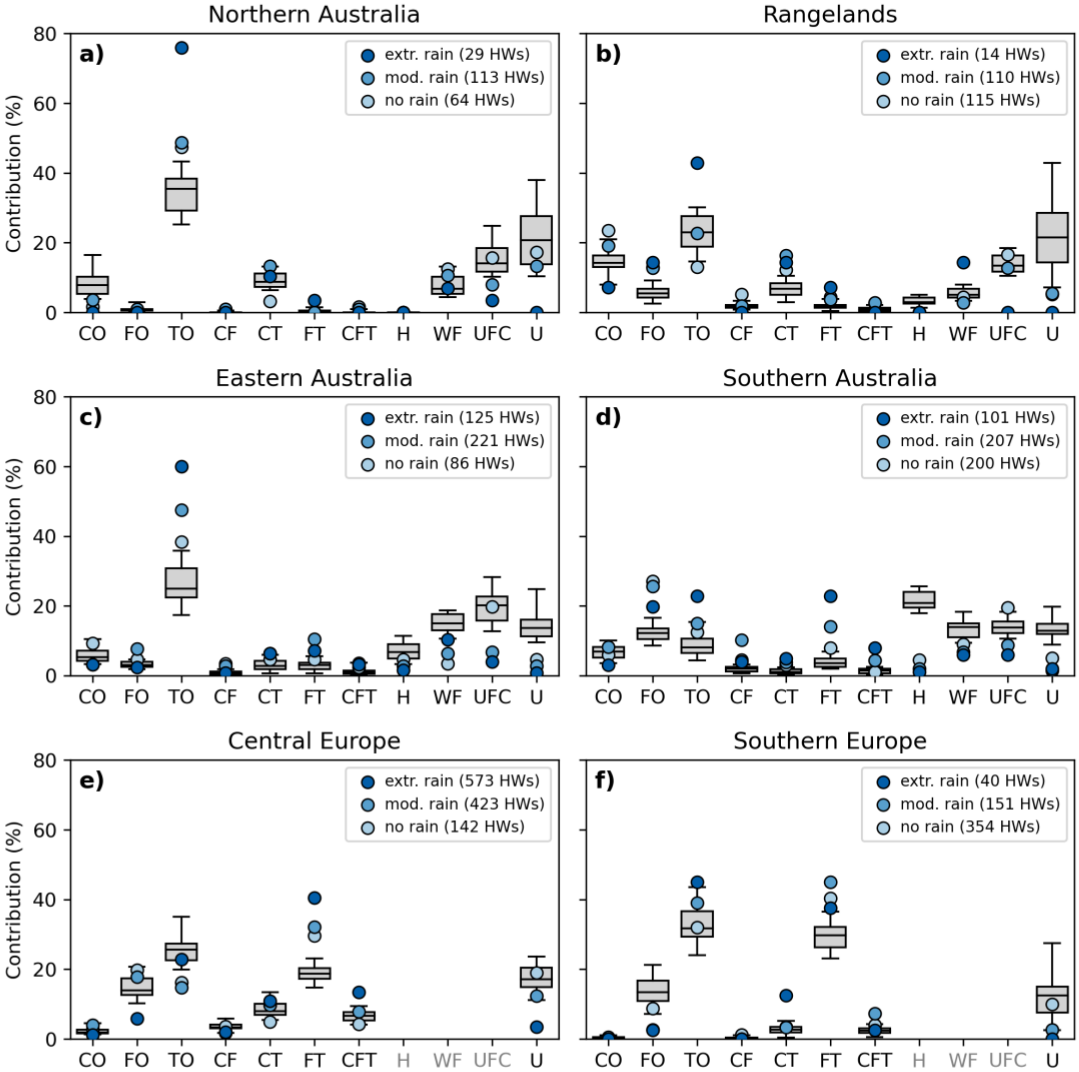

Figure 16 Frequency of each weather type at 12:00 on the last day of a heatwave for heatwaves followed by extreme rain (dark blue dots), moderate rain (blue dots) or no rain (light blue dots) for Northern Australia (a), Rangelands (b), Eastern Australia (c), Southern Australia (d), Central Europe (e), and Southern Europe (f). Grey boxplots show climatological distribution of weather types during the same time of the year as the heatwaves and whiskers extend from the 5th to 95th percentile. The number in brackets in the legends show number of heatwaves identified for each of the three heatwave endings in the respective region. The weather types High (H), Warm-front (WF), and Unconfirmed Fronts/Cyclones (UFC) are only available for Australia.

TCWV shows a similar behavior. A heatwave followed by extreme rainfall shows a strong increase in TCWV in the lead up to heatwave termination. TCWV values tend to peak on the first day after termination (except in Central Europe where the peak occurs on the last heatwave day) and are not necessarily linked with the peak in CAPE. A heatwave followed by moderate rainfall shows similar increases in TCWV, but at a lower magnitude. TCWV remains low for a heatwave followed by no rainfall.

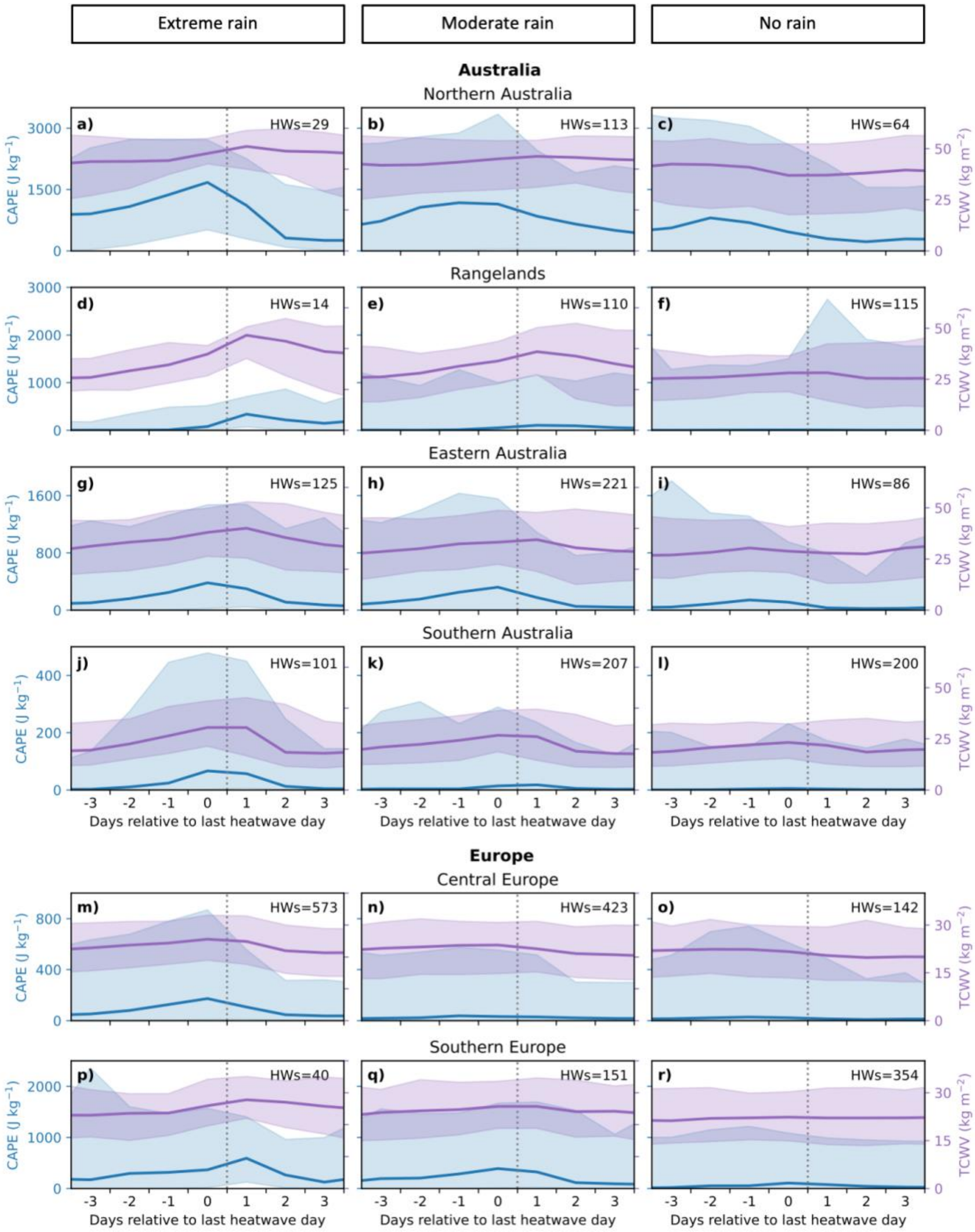

Figure 17 CAPE (blue) and TCWV (purple) during and after heatwaves for heatwave followed by extreme rain (left columns), moderate rain (center columns) or no rain (right columns). First four rows show CAPE and TCWV for four regions in Australia (Northern Australia, Rangelands, Eastern Australia, and Southern Australia; rows 1-4 respectively) and bottom two rows show CAPE and TCWV for two regions in Europe (Central Europe, and Southern Europe; rows 5-6, respectively). X-axis denotes the day relative to the last day of the respective heatwave. Solid lines show median values of CAPE and TCWV for each day relative to the heatwave and shading show the respective 5^{th}-95^{th} percentile ranges. Top right corner of

each plot shows number of heatwaves identified for the respective region and heatwave ending. Vertical dashed lines indicate the end of the heatwave.

CAPE, and to a lesser degree TCWV, also vary depending on the present weather type during a heatwave termination, as demonstrated here for Southern Australia (Figure 18). During thunderstorm conditions (TO and TF), both CAPE and TCWV show high values during a heatwave termination if a heatwave is followed by extreme rainfall. This is unsurprising, as CAPE is one of the two parameters used to determine the thunderstorm weather type (Section 5.4.3). CAPE during the Front-Thunderstorm weather type is lower than during the Thunderstorm-Only conditions. Heatwaves terminations associated with frontal conditions alone are associated with much lower values of CAPE. TCWV, however, remains high during both frontal and thunderstorm-related weather types. Highest values of TCWV and CAPE are still found in cases where a heatwave is followed by extreme rainfall and are lower where a heatwave is followed by moderate or no rainfall. Similar behaviors can be found in the other regions as well (Figures D3-D7).

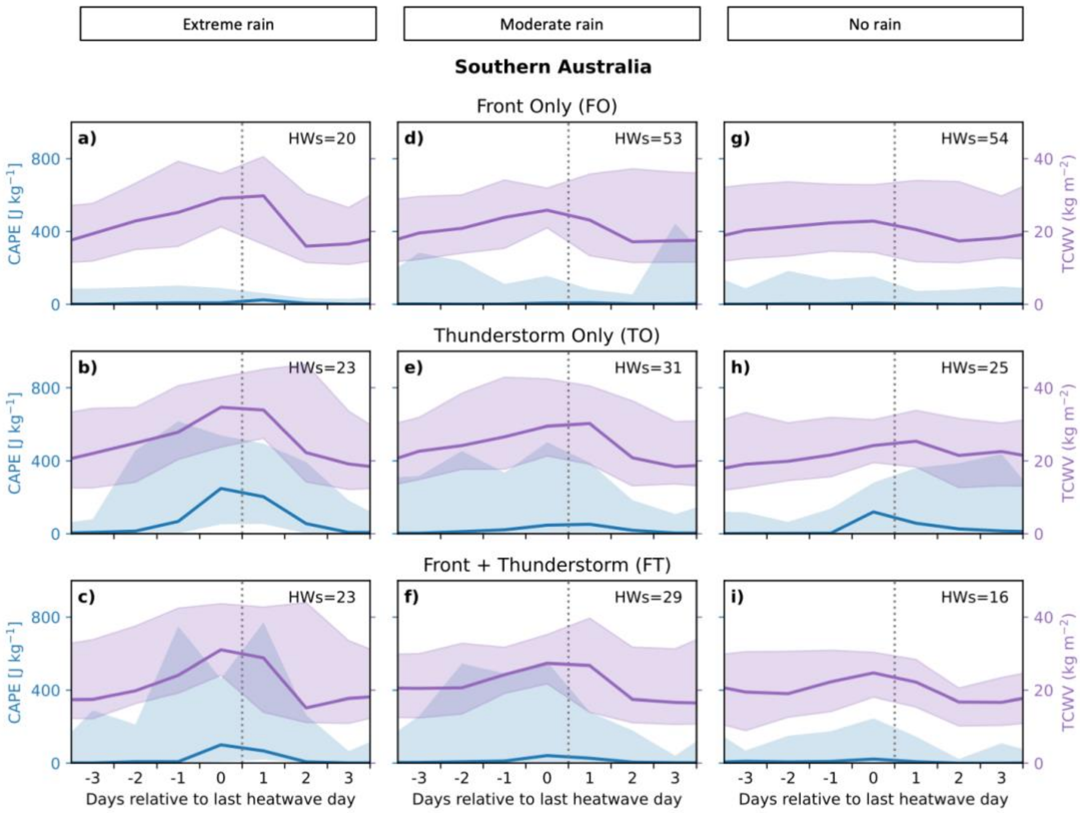

Figure 18 Like Figure 17, but for Southern Australia and showing heatwaves for the three most common weather types associated with heatwaves followed by extreme rainfall. Top row (middle row, bottom row) shows CAPE and TCWV during and after heatwaves if the dominant weather type during the heatwave termination at 12:00 was Front Only (FO) (Thunderstorm Only; TO, Front-Thunderstorm; FT). The other regions are shown in Figures C3-C7.

TCWV and CAPE on the last day the heatwave are also strongly related to the maximum 1h rainfall intensity after heatwave termination (Figure 19). The maximum 1h rainfall intensities are calculated as the highest hourly rainfall recorded at any station affected by the heatwave termination within 36h of 12:00 on the last heatwave day. In all regions, the highest rainfall events are also associated with high values of TCWV and CAPE for the respective region. Lower rainfall maxima are associated with lower TCWV and CAPE values. Heatwaves that terminate without rainfall also tend to have noticeably lower values of TCWV and CAPE. Dry regions such as Rangelands or Southern Europe produce high values of CAPE; however, TCWV is comparably low, especially for dry heatwave termination. In moderate climates such as Eastern Australia or Central Europe, high CAPE values are more strongly associated with high rainfall. The same relationship between CAPE, TCWV and 1h extreme rainfall can also be seen for CAPE and TCWV values on the day after a heatwave termination (Fig D8).

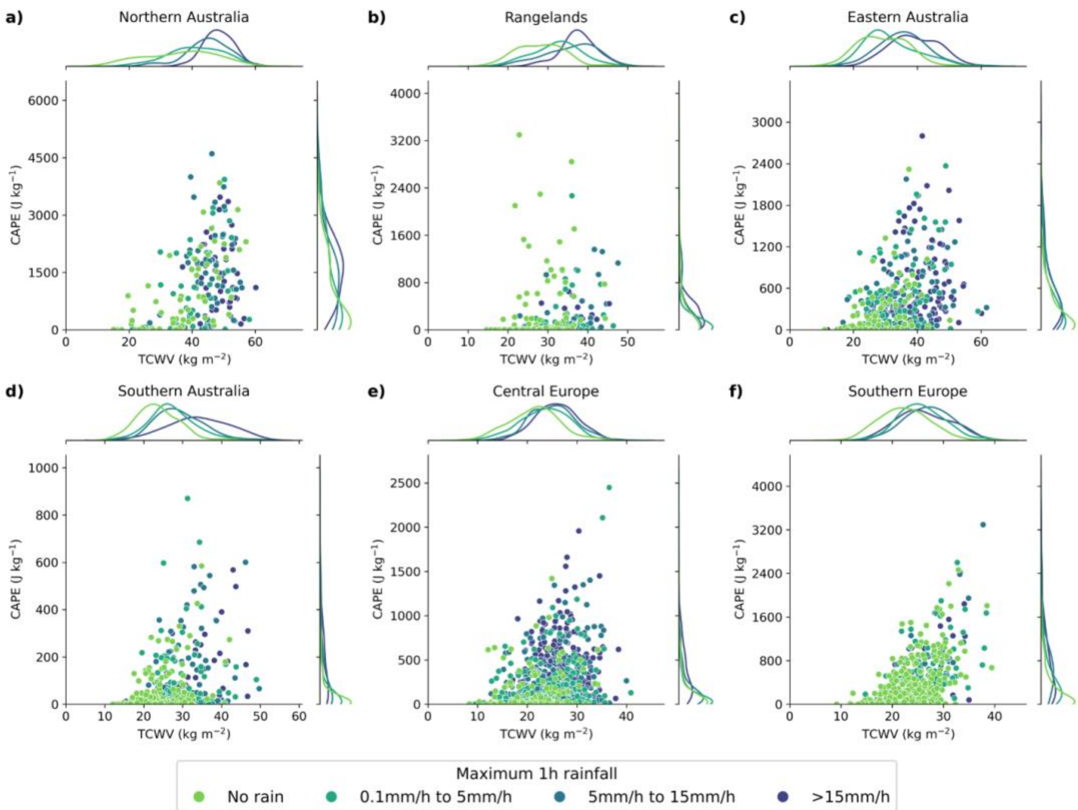

Figure 19 TCWV (x-axis) and CAPE (y-axis) for all stations on the last day of each heatwave for regions in Australia (a-d) and Europe (e-f). Data is separated by colour by the maximum 1-h rainfall of all stations experiencing a heatwave over a 36-h period starting from 12:00 on the last heatwave day. The 1-h rainfall maxima have been sorted into intensities of >15mm/h, 15mm/h to 5mm/h, 5mm/h to0.1mm/h as well as no rainfall. Curves above (to the right of) the scatter plots show normalized kernel density estimates (estimated distributions) of TCWV (CAPE).

To further investigate the influence of the heatwave on rainfall production, we compare distributions of TCWV and CAPE on the last day of the heatwave to climatology (Figure 20). TCWV on the last day of a heatwave is significantly higher ($p<0.01$ with a student's t-test) than expected from climatology for all regions except for Northern Australia. CAPE on the last day of the heatwave is also significantly higher ($p<0.01$ with a student's t-test)[2] for all regions except for the Rangelands. Similar differences in CAPE and TCWV compared to climatology can also been seen on the day after the heatwave (Figure D9). We further find that night-time heatwaves are associated with a higher moisture increase during the heatwave termination compared to regular heatwaves (high temperatures during day and night, Figures D10-D11). Day-time heatwaves on the other hand show an increase in TCWV compared to climatology only in Southern Australia and Central Europe, while in all other regions TCWV during the heatwave termination is lower compared to climatology.

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[2] As the distributions of Figure 20b from a visual perspective are not normally distributed, the distributions were further tested for differences using a Mann-Whitney *U* test. For all regions except the Rangelands, CAPE is significantly ($p<0.01$) higher after a heatwave compared to climatology.

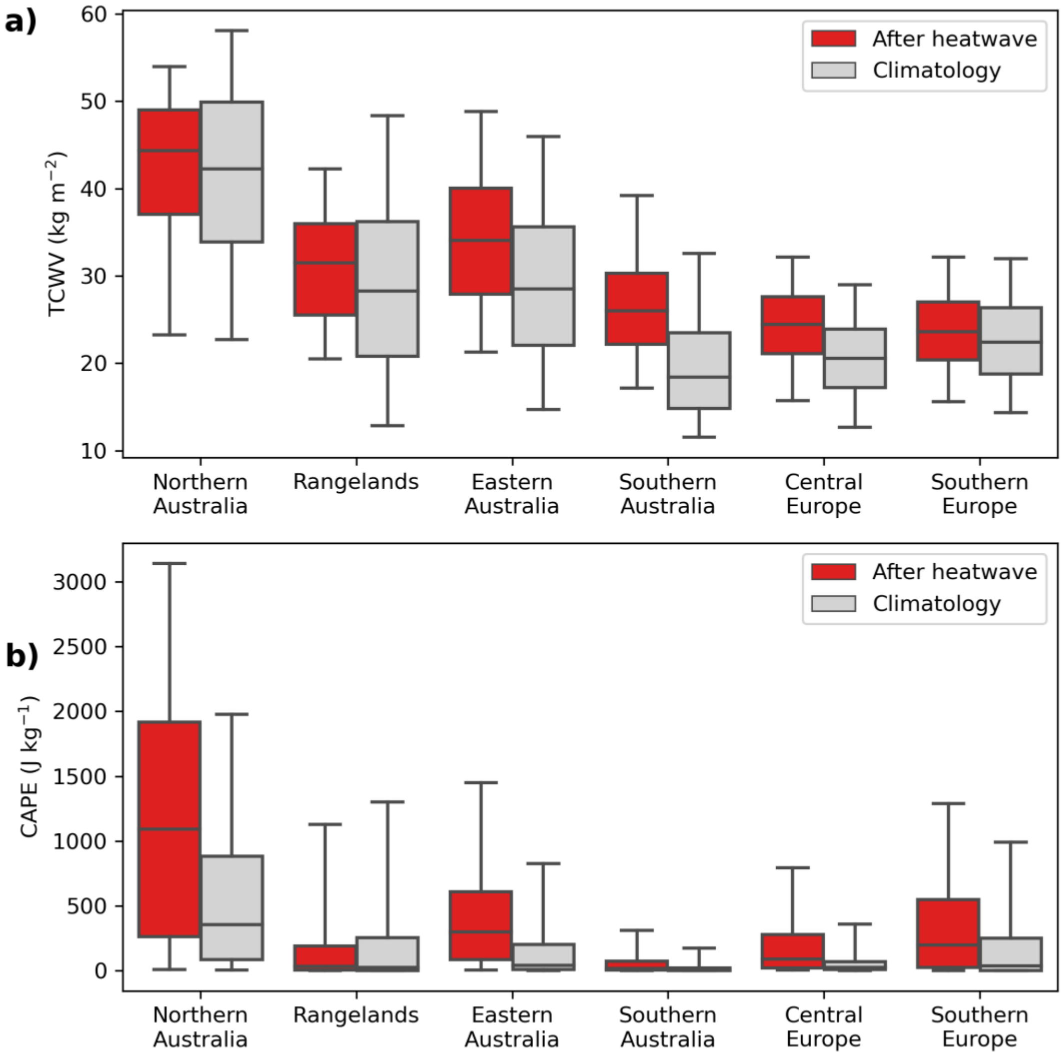

Figure 20 Distribution of TCWV (a) and CAPE (b) on the last day of the heatwave (red) and for climatology (grey) for the six regions used in this study. The boxplot whiskers extend from the 5th to 95th percentile.

6.7 Discussion

We have demonstrated that heatwaves mostly terminate during thunderstorm and/or frontal conditions. Thunderstorm-related environments are generally more likely during the warmer months of the year (Dowdy, 2020), and high temperatures during heatwaves are likely to favour thunderstorm conditions by increasing atmospheric instability. During heatwave terminations, thunderstorm environments are more common in cases where a heatwave was followed by extreme rainfall compared to a heatwave followed by moderate or no rainfall. In these cases, the frequency of thunderstorm conditions is significantly higher than expected from climatology. While thunderstorms are potentially enhanced by the heatwave itself, fronts might occur more independently of the heatwave but are likely the cause the heatwave termination. Cold fronts are associated with the advection of cooler air – and thereby reduce the ambient temperature. However, it is important to note that from our analysis alone it is not possible to distinguish with certainty if heatwaves increase the likelihood of synoptic disturbances, synoptic disturbances contribute to the termination of the heatwave, or both. Besides their role in terminating heatwaves, fronts can also contribute to extreme rainfall by introducing further moisture as they are often associated with atmospheric rivers (Catto and Pfahl, 2013, Lavers and Villarini, 2013). Further, fronts could also act as a dynamical trigger of convection (e.g., Browning, 1986). As thunderstorm conditions are common during a heatwave termination (Figure 16), the combined occurrence with a front could therefore contribute to the observed higher rainfall intensities and likelihoods of extreme rainfall after heatwaves.

We further show that the likelihood and intensity of (extreme) rainfall after a heatwave is influenced by atmospheric instability and moisture availability. Both CAPE and TCWV are highest during terminations of heatwaves that are followed by extreme rainfall compared to heatwaves followed by moderate or no rainfall. We find that CAPE and TCWV vary depending on the weather type, with high values of CAPE only found during thunderstorm-related conditions. High values of TCWV were found in cases where a heatwave was followed by extreme rainfall regardless of the present weather type, indicating that high values of moisture are an essential condition for extreme rainfall after heatwaves. Other studies have also demonstrated high values of atmospheric instability (Zhang and Villarini, 2020, You and Wang, 2021, Chen et al., 2022) and moisture (Zhang and Villarini, 2020) during the transition from a hot to a wet extreme. Both CAPE and TCWV may increase due to the arrival of a frontal system and the associated advection of moisture. However, it is likely that the conditions during the heatwave also contribute, since the increase in both variables can be observed for several days before the heatwave termination, even during frontal conditions.

These results further explain why extreme rainfall following heatwaves as a compound extreme is far more likely in mid to high latitudes (Sauter et al., 2023) than elsewhere. Mid and high latitudes are usually characterised by moderate to polar climates with high temperatures and comparably high moisture availability during summer, providing good conditions for high atmospheric instability and moisture during heatwave terminations. In arid regions, however, as represented here by the Rangelands and Southern Europe regions, most heatwaves are not accompanied by increases in CAPE or TCWV (Figure 17). Additionally, frontal systems tend to occur more in higher latitudes, such as in Central Europe and Southern Australia, where both regions are characterised by high likelihoods of extreme rainfall after heatwaves.

Using station-based observations to detect rainfall improves the representation of extremes; however, this might lead to instances where small-scale rainfall after heatwaves is not detected. This would lead to heatwaves being falsely categorised as followed by moderate rainfall even though rainfall elsewhere was extreme, or as followed by no rainfall even though there was rainfall elsewhere. This is more likely in cases where heatwaves were only identified for a small number of stations. However, we have found that using a higher minimum number of stations does not change the results significantly, while reducing the available heatwave sample size

6.8 Conclusions

In conclusion, we have shown that heatwave terminations in Australia and Europe are usually related to thunderstorm and/or frontal conditions. The likelihood of extreme rainfall occurring in the wake of a heatwave, however, is mainly governed by the atmospheric instability and moisture availability. The highest rainfall intensities after heatwaves are usually related to the highest values of atmospheric instability and moisture, which are in turn higher than without a heatwave. However, in the higher latitudes frontal systems are likely to contribute to the likelihood and intensity of extreme rainfall after heatwaves as well, as they can trigger convection and potentially introduce further moisture. Accurately estimating future changes to this compound event will therefore involve studying changes in both synoptic variability as well as the atmospheric parameters influencing convection.

6.9 Acknowledgments

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Afterword

This study showed that the mechanistic drivers behind compound heatwave-extreme rainfall can be complex and a combination of both thermodynamic and synoptic-scale drivers. Further, their relative contributions are shown to vary by region. Due to the limited availability of weather type data, it was only possible to use Western Europe and Australia as study regions. It is important however, to further analyse the drivers in other regions as well, especially as synoptic-scale drivers and moisture availability vary strongly depending on the location.

The influence of both synoptic-scale drivers and thermodynamic drivers on compound heatwave-extreme rainfall analysis provides a challenge for analysing this compound event in climate projections, as both drivers must be adequately represented. Before any analysis is done it must be ensured that the projections are of high enough resolution to capture small-scale moist convection as well as represent synoptic variability well. If a climate model can adequately represent both these components, further research could focus on investigating the individual contributions and if they change over time or by region. With this improved confidence in how and where compound heatwave-extreme rainfall will change in a warming climate, it will be easier to tailor building climate resilience to individual communities.

CHAPTER 7

DISCUSSION, CONCLUSIONS AND OUTLOOK

7.1 Discussion

This thesis has contributed to the understanding of compound heatwave-extreme rainfall events by analysing their frequency, spatial distribution and underlying mechanistic drivers. This section discusses to what extent the choice of definitions and data influences results, how the spatial distribution of compound extremes affects the risk from this event in different regions as well as how the improved knowledge of compound heatwave-extreme rainfall events could be translated into building climate resilience.

Thresholds and definitions of extreme events are often chosen arbitrarily, and there is no consensus on how to define the individual hazards of compound heatwave-extreme rainfall events. Though different definitions of heatwaves and extreme rainfall were tested in Chapter 4 (also RQ2), and the choice of definitions was found not to impact results significantly, it is preferable to use definitions which take the physical connections between the hazards into account. In line with findings in Chapter 6 that demonstrate the importance of sufficient moisture supply, some studies have chosen to focus on extreme rainfall after humid heatwaves (e.g., Zhang and Villarini, 2020, Li et al., 2022). Focussing on humid heatwaves instead of all heatwaves is likely a promising avenue for assessing future changes to this event and it is recommended to consider humid heatwave definitions for future work.

Due to the role of convective thunderstorms in driving heatwave-extreme rainfall events, it is important to analyse rainfall at sub-daily scales as convective storms tend to occur on sub-daily timescales as well (Trenberth et al., 2017). The analysis in this thesis therefore uses rainfall observations at a sub-daily (hourly) scale despite the fact that daily rainfall observations are easily available and have a higher spatial coverage. The comparison of hourly and daily extreme rainfall definitions (Chapter 4) indeed reveals that in regions where the main driver of compounding heatwave-extreme rainfall is convective (Chapter 6), an increase in extreme rainfall is mainly visible in hourly data. In regions where synoptic-scale drivers such as fronts are also associated with compounding heatwave-extreme rainfall transitions, strong increases in daily rainfall extremes were observed as well. This potentially indicates different overall rainfall volumes and temporal distributions associated with different drivers. However, more research is needed to clarify how extreme rainfall after heatwaves differs with respect to different drivers.

The likelihood of compound heatwave-extreme rainfall events is not distributed evenly and how much more likely and intense rainfall is after heatwaves strongly depends on the location of the event. In Australia, a country which experiences many natural hazards on a frequent basis (e.g., Westra et al., 2016, Kemter et al., 2021) and which is home to a wide range of different local climates, the strength of the compounding heatwave-extreme rainfall relationship varies between regions (Chapter 4). Extreme rainfall occurrence after heatwaves is more likely than expected from climatology in all regions, but the increase in intensity is only found along the eastern and south-eastern coast. Towards the centre of Australia, the intensity of extreme rainfall is either not significantly different to climatology, or slightly lower. The high likelihood of extreme rainfall after heatwaves in eastern and south-eastern coastal areas is potentially also associated with an increased risk of flash floods. Most of the Australian population lives close to the coast, and eastern and south-eastern Australia is home to large cities such as Sydney, Melbourne, and Brisbane. Flash floods from compound heatwave-extreme rainfall events can have severe impacts in these places and urban areas need to adapt in order to reduce future risk.

The spatial heterogeneity in compounding heatwave-extreme rainfall risk can mostly be explained by differences in local climate (Chapter 5), specifically moisture availability (Chapter 6). High increases in moisture shortly before and during the heatwave termination were found to be the strongest indicator of how likely a heatwave is to be followed by extreme rainfall. This is reflected in the Köppen-Geiger climate zones which were found to be associated with the highest increase in extreme rainfall likelihood after heatwaves compared to climatology. Climate zones with the sub-classification 'f' (i.e., no dry summers or winters in non-tropical regions, therefore on average sufficient moisture availability) showed significantly higher extreme rainfall likelihoods after heatwaves. This knowledge could also be used to make first assessments of future risks from this compound event. As climate zones are projected to change in a warming climate (Beck et al., 2018), it is important to analyse where climate zones associated with high likelihoods of extreme rainfall after heatwaves are located geographically. Regarding the implemented heatwave definitions, only heatwaves were investigated in this thesis which were defined with absolute temperature thresholds, most heatwaves were identified during hot seasons. Therefore, regions with adequate moisture supply during the hottest months are most likely to experience high likelihoods of extreme rainfall after heatwaves.

Overall, regions with 'f' sub-classifications are found in many areas in the mid and high latitudes. However, due to the use of observational data, an assessment of extreme rainfall likelihood after heatwaves can only be done with confidence in regions with a high density of observations. From all regions represented by rainfall observations, significant increases in extreme rainfall likelihood after heatwaves are found in the western US, Central Europe, Japan, eastern and south-eastern Australia, and New Zealand. Findings for the US are supported by Zhang and Villarini (2020). But beside the US, compound heatwave-extreme rainfall events have only been demonstrated in China (e.g., You and Wang, 2021, Chen et al., 2022). While no observations were available in China for this study, the eastern regions in China where compounding heatwave-extreme rainfall had been demonstrated are classified as ‘Cfa’ and ‘Cfb’ climate zones, both associated with increased extreme rainfall likelihoods after heatwaves (Chapter 5). Climate zones classified with the ‘f’ sub-classification also contain many densely populated urban areas, increasing the potential exposure to compound heatwave-extreme rainfall events. As cities are constantly changing, with a tendency for increased urbanisation in many regions (Dodman et al., 2022), adequate measures must be taken to increase resilience. This is especially important for large cities as there is evidence that urban environments further increase extreme rainfall intensity after heatwaves (Wu et al., 2021, Li et al., 2023). However, as coverage of quality-controlled sub-daily observations is limited, it is important to explore other sources of data with global coverage in order to make confident assessments of the risks for areas which are not covered by observational data (see Section 6.3). This might show that compound heatwave-extreme rainfall is present in many more regions than shown here, and there might be other local hotspots where the risk from this event is high. Given that compound heatwave-extreme rainfall is found in widespread areas in this study, it is further likely that it is present in regions of similar climate.

With respect to the mechanistic drivers, the increased extreme rainfall likelihood after heatwaves in mid/high-latitudinal regions such as Central Europe is likely driven by a combination of synoptic-scale and convective drivers. Chapter 6 demonstrates for Europe and Australia that extreme rainfall after heatwaves is often associated with both thunderstorm environments and frontal systems. Fronts are well known to be drivers of extreme rainfall, especially in the midlatitudes (Catto and Pfahl, 2013), and can also introduce high amounts of moisture (Lavers and Villarini, 2013). The same regions also show high values of atmospheric instability and moisture during heatwave terminations with extreme rainfall, indicating that the rainfall extremes are associated with moist convection as well. High values of atmospheric instability and moisture during compound heatwave-extreme rainfall events also supported by other studies (Zhang and Villarini, 2020, You and Wang, 2021, Chen et al., 2022). Both atmospheric instability and moisture are found to increase over several days before the heatwave termination, indicating possibilities for improving forecasting of compound heatwave-extreme rainfall events.

While this thesis does not specifically investigate how compound heatwave-extreme rainfall will change in the future, the improved knowledge in their spatial distribution and mechanisms help estimate how this could be analysed. Commonly, climate models are used to estimate future changes of weather and climate phenomenon. However, the choice of climate model will likely be important in order to study this compound event in the future. Many climate models operate on a large spatial grid and will likely not represent smaller scale convective storms well. Recent climate model designs such as the UKCP18 climate projections at 2.2km spatial resolution (Lowe et al., 2018) are promising tools for studying this compound event, as convective processes can be directly simulated as well. It remains to be investigated, however, if large-scale synoptic variability is sufficiently well represented in these models to account for the synoptic scale influence of fronts and cyclones on compound heatwave-extreme rainfall. As the frequency and intensity of both heatwaves and extreme rainfall are projected to increase in a warming climate (Seneviratne et al., 2021), due to the connection of the two hazards it is likely that compound heatwave-extreme rainfall will increase in frequency and intensity as well.

The methodology of studying compound heatwave-extreme rainfall evolved throughout the thesis depending on the specific research questions and the knowledge obtained throughout the individual studies. While it is important to highlight that many methodological choices such as heatwave definitions, exact study regions or extreme rainfall threshold could also be changed for future studies, the methodological choices used here have been vigorously tested and found to be useful for the investigation of compound heatwave-extreme rainfall. For studies on the spatial distribution of compound heatwave-extreme rainfall it is recommended to use the methodological setup of Chapter 5 (as it contains some refinements of the methodology of Chapter 4), and for the analysis of the mechanistic drivers that of Chapter 6. As a promising future direction of research involves using global gridded reanalysis data for sub-daily rainfall, the move from station-based observations to gridded data might require further modifications to the methodology.

The improvement in understanding compound heatwave-extreme rainfall events presented in this thesis helps pave the way for building climate resilience. Improved understanding of the mechanistic drivers allows for better forecasting, and knowledge of spatial distribution and hotspots allows for communities to better assess their individual risk. However, understanding the hazard is only the first step. It is important to translate this knowledge into action to mitigate the risks from compound heatwave-extreme rainfall events. In many cases, the research has already been done on how to improve climate resilience (e.g., Tyler and Moench, 2012) but there is little communication between individual disciplines. Research communities from different disciplines need to come together to make interdisciplinary decisions on how to best address the challenges of complex natural hazards such as compound heatwave-extreme rainfall events in a warming climate.

7.2 Conclusions

The aim of the thesis was to improve the understanding of compounding heatwave-extreme rainfall relationships. This was done by testing the methodology of analysing compound extreme rainfall events in a case study in Australia (Chapter 4), assessing the phenomenon on a global scale (Chapter 5), as well as investigating the mechanisms behind these events. (Chapter 6). Therefore, the research questions presented in Chapter 1.2 can be addressed as follows:

RQ1: *Until now, compound heatwave-extreme rainfall events have only been demonstrated in China, but is this phenomenon found in other parts of the world as well? Australia is a country that is climatically diverse, has long and high-quality data records and experiences many natural hazards on a frequent basis, including both heatwaves and extreme rainfall. What can Australia teach us about this compound event?*

Yes, this phenomenon is also found outside China. Within the case study provided in Chapter 4, compound heatwave-extreme rainfall events are demonstrated in several regions in Australia as well. Australia provides several different climatic conditions and is known to experience many natural hazards. Compound heatwave-extreme rainfall events, however, do not universally occur everywhere with the same likelihood. In Australia, the highest likelihood and intensity of heavy rainfall after a heatwave is found on the eastern and south-eastern coast, which are characterised by comparably moderate climate and comparably high moisture availability. Arid regions, such as the central Australian region, show little to no increase in heavy rainfall likelihood after heatwaves. The north of Australia which is characterised by tropical climate does show an increase in heavy rainfall likelihood after heatwaves, however, lower than found at the eastern and south-eastern coasts. This case study highlights that the occurrence and strength of compound heatwave-extreme rainfall events strongly varies from region to region and must therefore be studied at small spatial scales. Beyond Australia, significant compounding is also found in other regions globally (see RQ3).

RQ2: *Extreme events can be defined in many ways. Are any findings robust to different definitions, thresholds, and timescales of heatwaves and extreme rainfall, as well as temporal data resolution?*

Heatwaves and extreme rainfall have been defined in the literature using different thresholds, variables, and temporal scales. Chapter 4 tested the impacts of using higher and lower thresholds for heatwave and heavy/extreme rainfall definitions (90^{th}, 95^{th} percentiles for heatwaves and also 99^{th} percentile for extreme rainfall), as well as a commonly used alternative heatwave definition (CTX90pct, Perkins and Alexander, 2013). Testing these thresholds and definitions showed that the choice of thresholds and definitions had only little impacts on the frequency and intensity of compound heatwave extreme rainfall events. The comparison of hourly and daily rainfall data, however, reveals the peak in rainfall intensity often occurs on the last heatwave day for hourly rainfall extremes and on the day after the heatwave for daily rainfall extremes. Further, in some locations in Australia, a peak is found in either hourly or daily rainfall, suggesting the dominant causal mechanisms might differ between these areas as well. Though thermodynamic and synoptic scale mechanisms suggest heatwaves and extreme rainfall events are connected (Chapters 2, 6), it is unclear how long after a heatwave rainfall is still influenced by the preceding heatwave. In general, the strength of the connection between a heatwave and extreme rainfall gradually decreases with increasing time following the termination. Though some effect on rainfall can be seen several days after the termination, the strongest connection between heatwaves and extreme rainfall can be seen within the first day after the heatwave. It was therefore found to be sufficient to only consider rainfall until the end of the first day after a heatwave for analysing compounding heatwave-extreme rainfall relationships.

RQ3: *Vulnerability to natural hazards depends on many factors including the location of the event (IPCC, 2022). Where globally is the relationship between heatwaves and extreme rainfall the strongest?*

The highest likelihood of extreme rainfall after heatwaves is found in the mid and high latitudes. Within the areas represented by hourly rainfall observations, Central Europe and Japan show the highest increase in extreme rainfall after heatwaves. These areas are also densely populated with large urban areas which could further enhance rainfall intensity (Wu et al., 2021, Li et al., 2023). Higher likelihoods of extreme rainfall after heatwaves compared to climatology are also found in the eastern US as well as eastern and south-eastern Australia and New Zealand. There is some indication of increased extreme rainfall likelihood in monsoonal regions such as the western coast of India, however, the station density in these regions is too low so that any conclusions can only be drawn with low confidence. Due to limitations in data coverage, it is difficult to estimate the risk from compound heatwave-extreme rainfall events in other regions outside Europe, Japan, the US, Australia, New Zealand, India, and Malaysia.

RQ4: *Both heatwaves and extreme rainfall vary in different regions. How does this relationship change in different climatic regions?*

The likelihood of extreme rainfall after heatwaves does indeed vary depending on the climatic conditions (Chapter 5). Overall, the highest likelihood of extreme rainfall after a heatwave occurs in Moderate, Cold, and Polar climates according to the Köppen-Geiger climate classification. Within the Moderate and Cold climates, regions without a dry season ('f' sub-classifications) show likelihoods that are often double compared to climatology. Regions characterised by dry summers, however, do not show a significantly higher likelihood of extreme rainfall after heatwaves. In the Tropics, the likelihood is increased but within the estimated climatological range. However, as there is a lack of available stations in the Tropics, results are often inconclusive. Arid regions, likelihoods are often comparable to climatology. There are indications of higher likelihoods in arid regions that receive more rainfall, however, the likelihoods lie within the climatologic range. The biggest indictor for an increased likelihood is therefore sufficient climatologic rainfall and thus ample moisture supply. Provided these findings can be extrapolated to other regions with the same climate zones, most of the mid and high latitudes are potentially at risk of significantly increased likelihood of extreme rainfall after heatwaves. However, conclusions for areas outside data coverage are uncertain, and must be supported by further analysis.

RQ5: *Understanding the mechanisms behind compound heatwave-extreme rainfall events helps estimate future changes of this event and could contribute to im-proved forecasting. Which exact mechanisms cause increases in intensity and frequency of extreme rainfall after heatwaves? What roles do thermodynamic and synoptic-scale drivers play?*

Previous work on compound heatwave-extreme rainfall events has highlighted the role of atmospheric conditions related to moist convection on extreme rainfall (Chapter 2.4). Chapter 6 shows that in the studied regions of Europe and Australia these compound events are often driven by *both* thermodynamic (i.e., moist convection) and synoptic-scale mechanisms. In regions with a high percentage of extreme rainfall events after heatwaves (Central Europe and south-eastern Australia) fronts are important drivers of extreme rainfall following heatwaves. If conditions are favourable for moist convection, the occurrence of a front likely initiates or strengthens the convective rainfall by acting as a dynamical trigger of convection and by introducing more moisture. Atmospheric conditions associated with moist convection are also found to be significantly increased after a heatwave compared to non-heatwave conditions in most regions, highlighting the importance of the heatwave in increasing likelihood and intensity of extreme rainfall. Specifically, if a heatwave is followed by extreme rainfall, atmospheric instability and moisture is found to increase over several days before the heatwave termination. While both high atmospheric instability and moisture availability are important, high moisture availability is found to be the essential variable characterising heatwaves that are followed by extreme rainfall. This knowledge could help improve the forecast ability of heatwave-related extreme rainfall events and associated flash flood risks.

7.3 Recommendations for future research

While there has been considerable progress in the understanding of compound heatwave-extreme rainfall events, further research is required to explore other aspects of this event. Here I present the following recommendations for future research.

1. *Assess the viability of using reanalysis products for analysing compound heatwave-extreme rainfall events.* The studies in Chapters 4-6 use quality-controlled hourly rainfall observations from rainfall stations. While these observations, especially if quality-controlled, provide comparatively good estimates of hourly rainfall extremes, the station density and record length is often poor, with some global regions/countries hardly covered at all (Lewis et al., 2019). Reanalysis products such as ERA5 (Hersbach et al., 2020) offer global coverage of variables such as rainfall at hourly timescales since 1979 and could provide insight into areas not covered in Chapter 5. Though the intensity of extreme rainfall, especially at sub-daily resolution, is mostly underestimated in reanalysis products (Ali et al., 2021b), the timing and the extremeness of the rainfall might still be represented sufficiently well. This would allow to better assess the spatial scales of individual heatwave-related extreme rainfall events as well as explore the relationship in areas not or only sparsely covered by observations.

2. *Expand compound heatwave-extreme rainfall analysis to include their connected hazards and impacts.* Heatwaves are often connected to droughts and fires, and extreme rainfall to floods (Figure 1). The interactions are often complex, however, as demonstrated in the case of the Australian Black Summer (Chapter 2.1) many impacts arise from the interaction of multiple hazards. Therefore, it is important to include related hazards in the analysis as well and asses the interaction between each component on the impacts. Specific questions could include:

    - How do dry conditions during and before heatwaves influence the moisture availability and thus impact the likelihood and intensity of rainfall?
    - What factors influence the occurrence and magnitude of flash floods related to compound heatwave-extreme rainfall events?
    - Do dry soils after droughts repel water increasing the chances of flash flood risk? Or do dry soils reduce flash flood risk? To what extent is this behaviour catchment-dependent and what role does the soil type play?

   - How do flash flood and water quality change in response to ash and debris from fires before the rainfall event?

3. *Investigate the sources of moisture during compound heatwave-extreme rainfall events.* As shown in Chapter 6, high amounts of moisture are necessary for extreme rainfall after heatwaves. If heatwaves co-occur with droughts, the potentially available moisture in soil and vegetation is limited (Miralles et al., 2019). Therefore, the moisture needed for extreme rainfall must be advected from other regions. Depending on the region, moisture sources causing humid heatwaves can originate from different locations, including warm oceans or Tropical regions (e.g., Russo et al., 2017). Connecting compound heatwave-extreme rainfall events to their moisture sources could help improve the predictability of the events as well as help estimate their future changes in a warming climate.

4. *Explore methods for improving forecasting of compound heatwave-extreme rainfall events.* Weather services rely on ensemble forecasting systems to predict extreme events such as heatwaves or extreme rainfall, and increasing the prediction skill as well as forecasting range can help mitigate the impacts. One possibility of improving predictability could be the use of weather patterns (Section 2.4). The prediction skill of weather patterns in ensemble forecasts tends to be higher than that of extreme rainfall itself (Neal et al., 2016, Richardson et al., 2020). Future work should therefore explore if compound heatwave-extreme rainfall events are linked to particular weather patterns. If an association between these events and one or more weather patterns exists, the prediction of the associated weather patterns could serve as an early indicator of a compound heatwave-extreme rainfall event, helping mitigate the impacts.

5. *Understanding the risk from and building resilience to compound heatwave-extreme rainfall events.* The impact-focussed view is a key component in compound event research. Understanding how hazards compound on a physical level (such as heatwaves and extreme rainfall) is essential in estimating the risk they pose and how they will change in the future. However, dedicated work needs to be done to analyse the risk from compound heatwave-extreme rainfall events and how that knowledge can be translated into improving climate resilience, especially as compound events currently are often not considered in risk management (van den Hurk et al., 2023). Besides the hazards, the risk on an event is also dependent on the vulnerability and exposure to an event (Simpson et al., 2021, Ara Begum et al., 2022). Further research should therefore focus on understanding what aspects make communities vulnerable and who is disproportionately exposed. The risk from floods, for example, can be

unevenly distributed among communities, leaving disadvantaged populations at an even higher risk (Sanders et al., 2022). It is therefore also essential to adapt to compound hazards and develop appropriate responses. Besides improving forecasting (Suggestion 4), areas of high risk could be identified, and appropriate planning strategies implemented. Urban planning must also take future changes in heatwaves and corresponding extreme rainfall into account to reduce the risk of catastrophic flash floods. In conclusion, the risks from compound heatwave-extreme rainfall events should be analysed in a holistic view with an emphasis on exploring how to build resilience to them.

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APPENDIX A.

SUPPORTING INFORMATION FOR CHAPTER 4

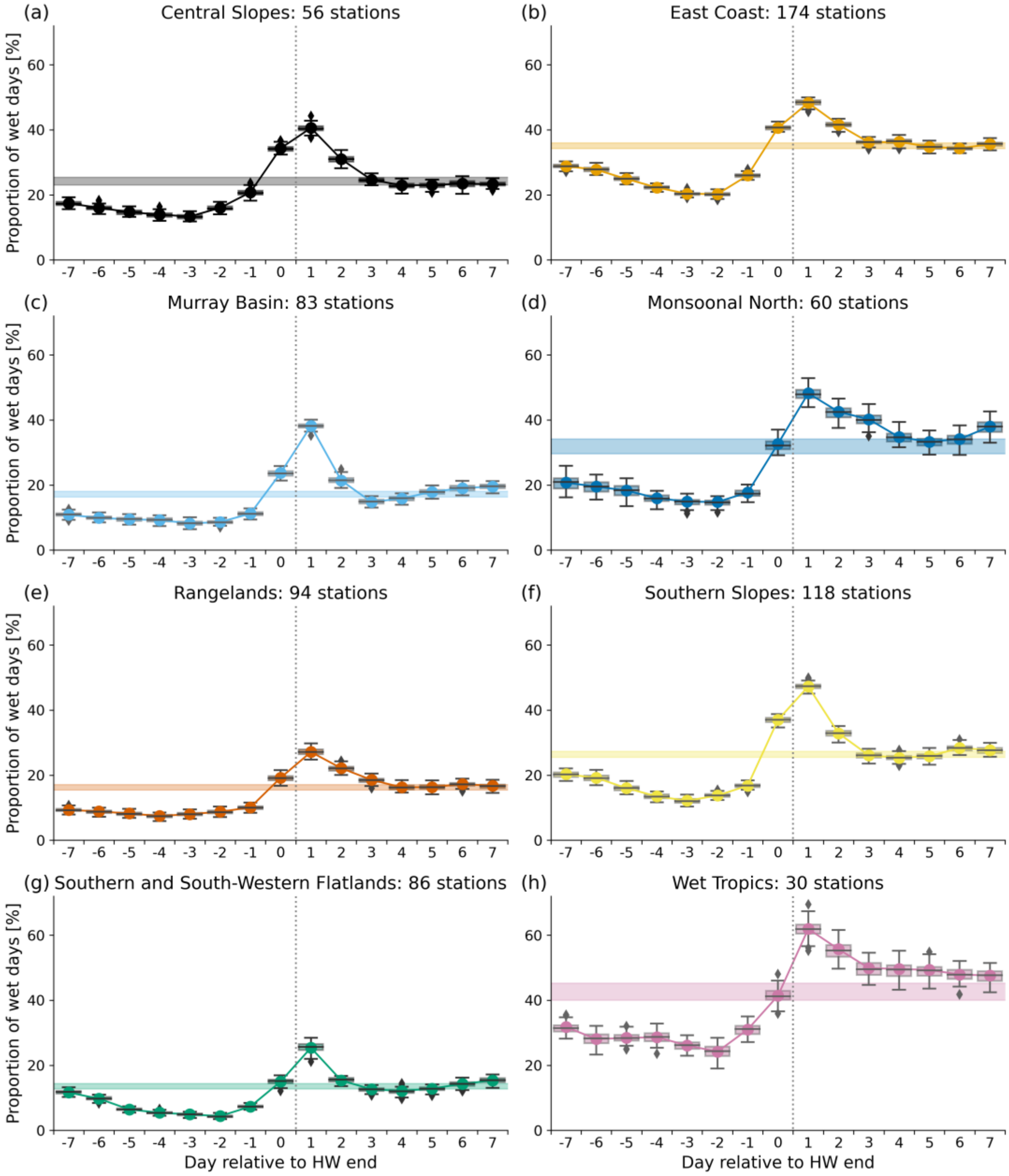

Figure A1 Analogue to Figure 7 but using the 90th percentile instead of the 95th percentile as a threshold for Tmax and Tmin for the identification of heatwaves.

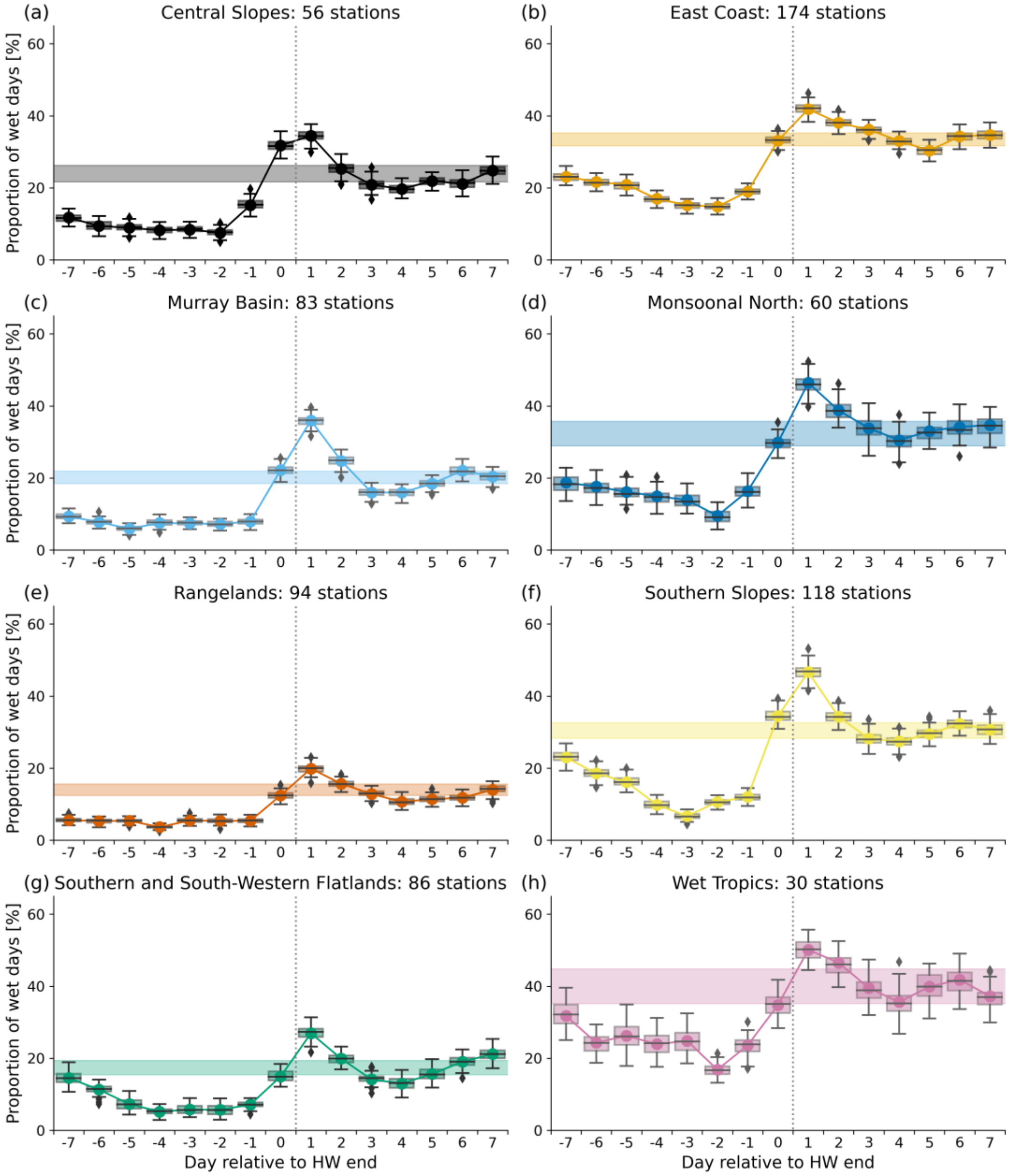

Figure A2 Analogue to Figure 7 but using the CTX90pct (Perkins and Alexander, 2013) for the identification of heatwaves.

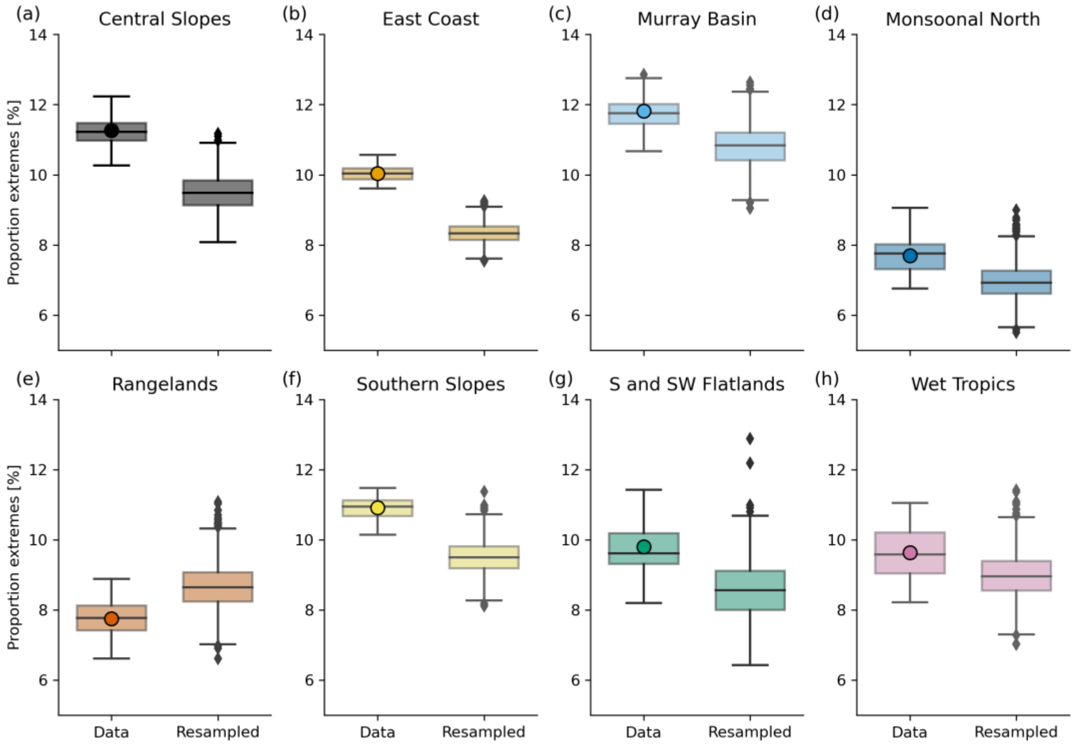

Figure A3 Analogue to Figure 8 but using the 90th percentile instead of the 95th percentile as a threshold for Tmax and Tmin for the identification of heatwaves.

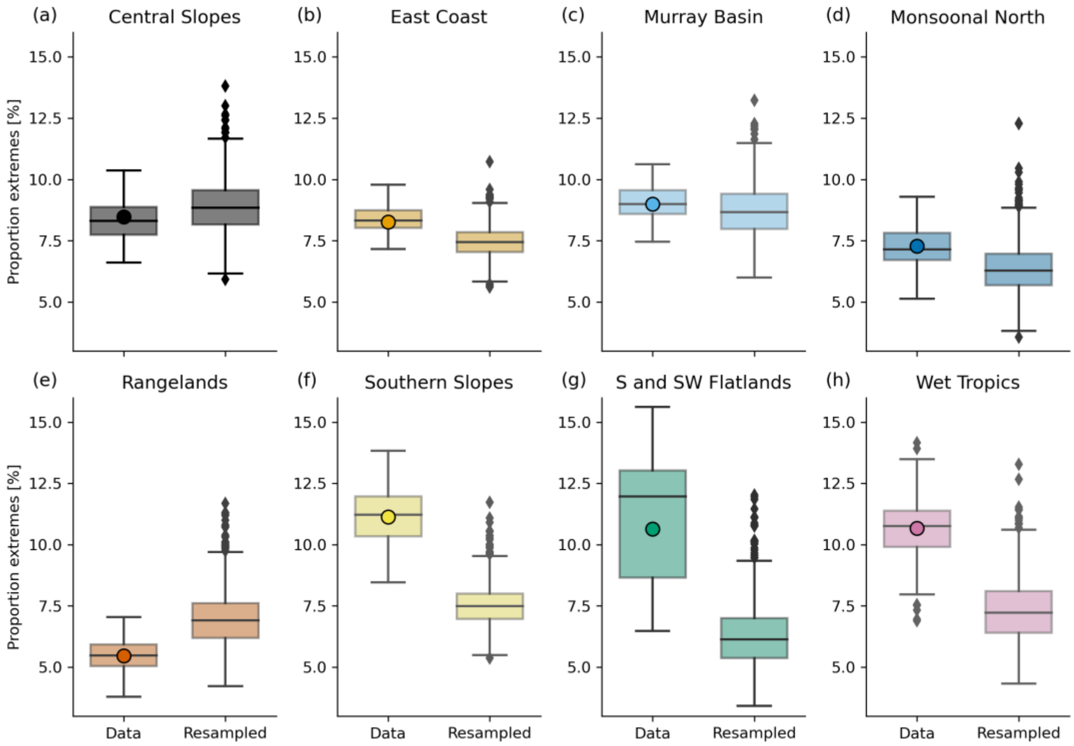

Figure A4 Analogue to Figure 8 but using the CTX90pct (Perkins and Alexander, 2013) for the identification of heatwaves.

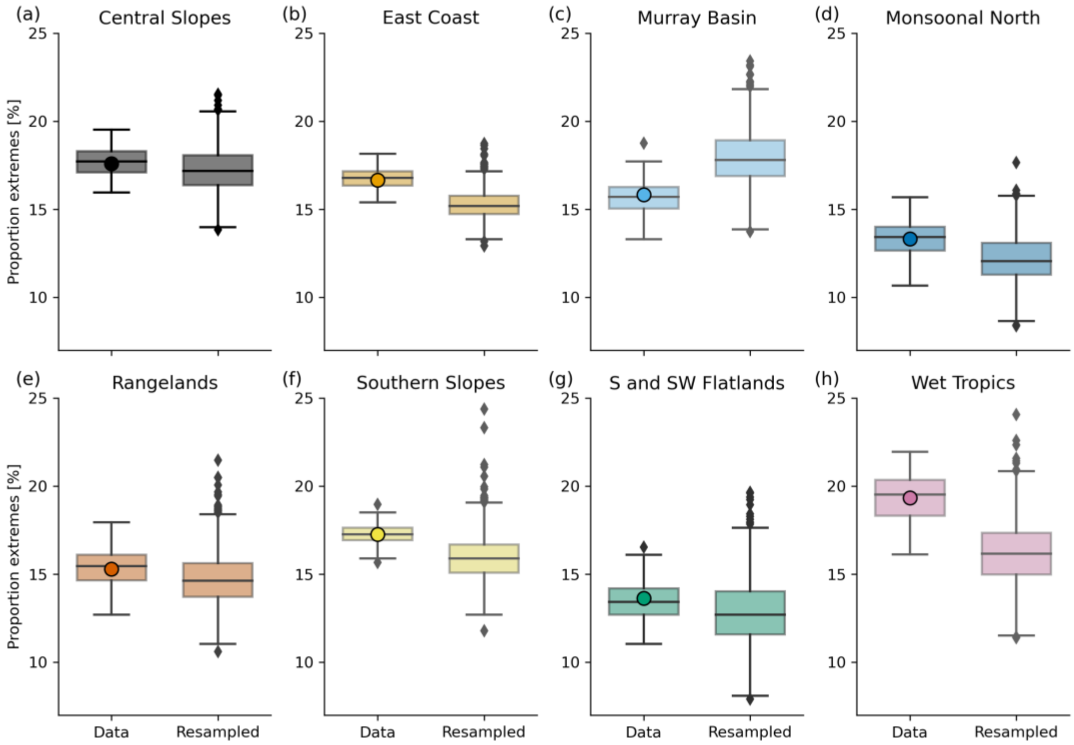

Figure A5 Analogue to Figure 8 but using the 90th percentile instead of the 95th percentile as a threshold for extreme hourly rainfall.

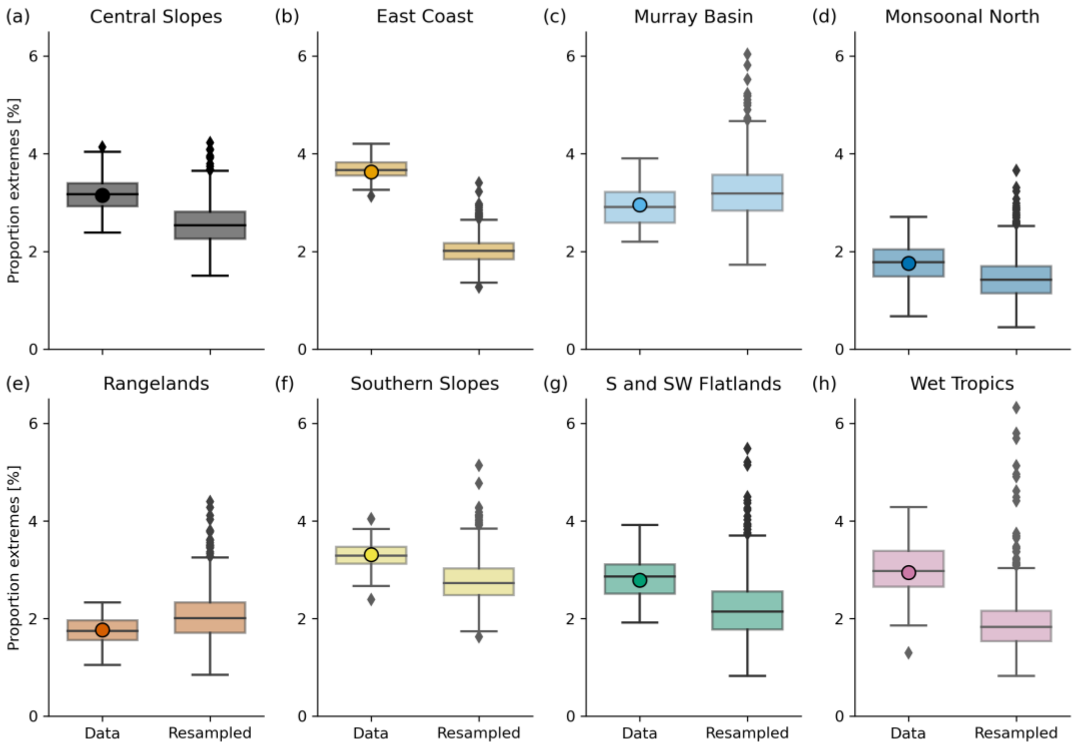

Figure A6 Analogue to Figure 8 but using the 99th percentile instead of the 95th percentile as a threshold for extreme hourly rainfall.

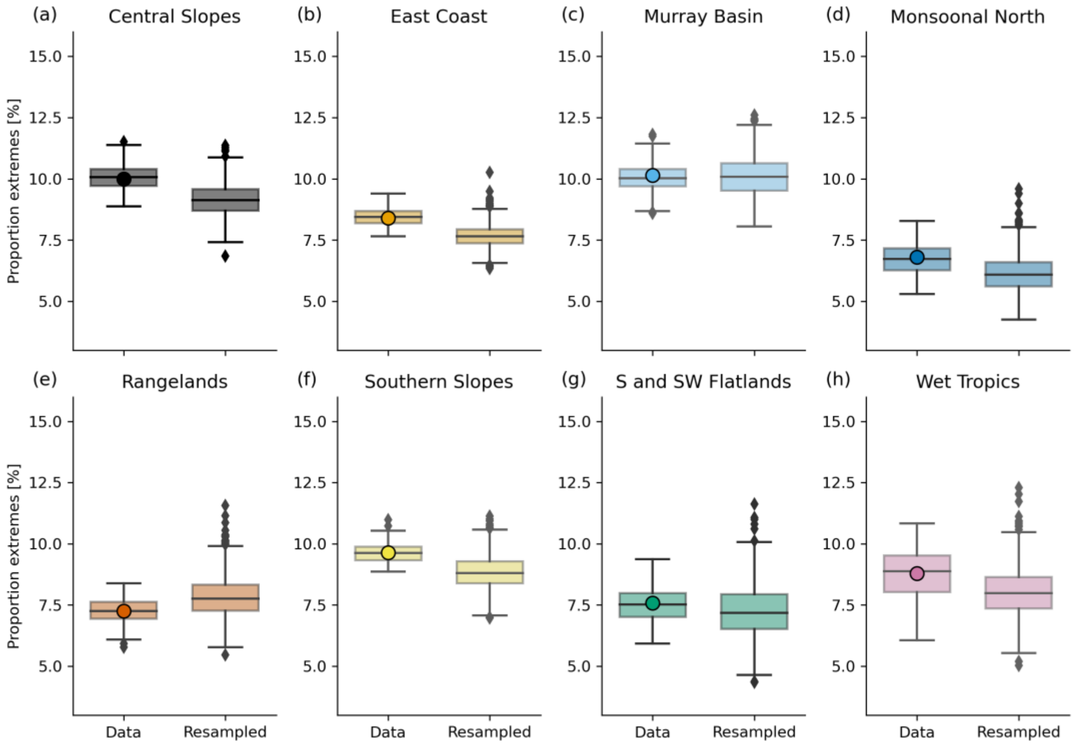

Figure A7 Analogue to Figure 8 but using a 60h time window starting at 12:00 on the last heatwave day instead of a 36h time window.

APPENDIX B.

SUPPORTING INFORMATION FOR CHAPTER 5

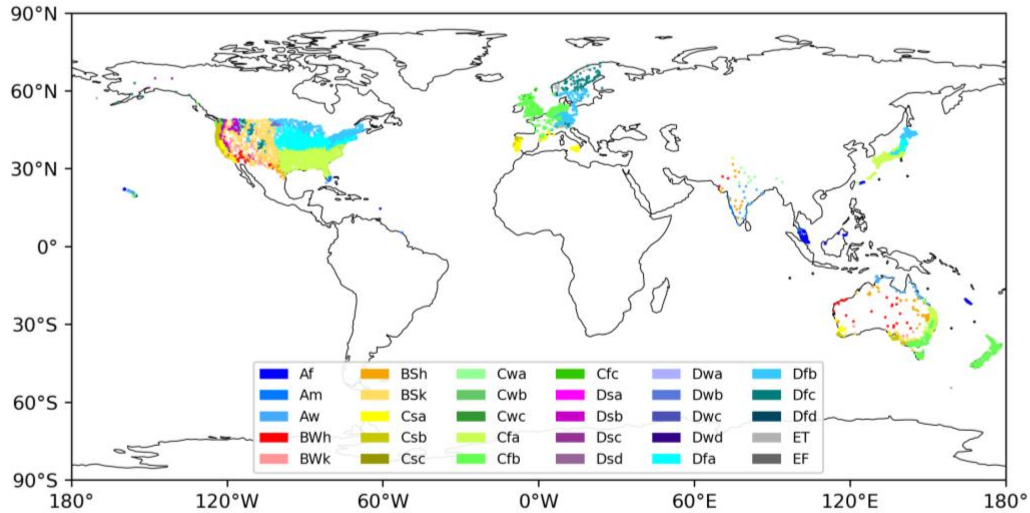

Figure B1: Location of GSDR stations used for this study coloured by their corresponding Köppen-Geiger climate zone. 21 out of 30 Köppen-Geiger climate zones are represented by at least one GSDR station (number of stations in brackets): 'Af' (168), 'Am' (22), 'Aw' (93), 'BSh' (88), 'BSk' (535), 'BWh' (53), 'BWk' (60), 'Cfa' (1764), 'Cfb' (1579), 'Cfc' (11), 'Csa' (367), 'Csb' (238), 'Cwa' (28), 'Dfa' (1025), 'Dfb' (1039), 'Dfc' (148), 'Dsb' (92), 'Dsc' (20), 'Dwa' (6), 'Dwb' (14), and 'ET' (44). The Köppen-Geiger classes are described in Table B1.

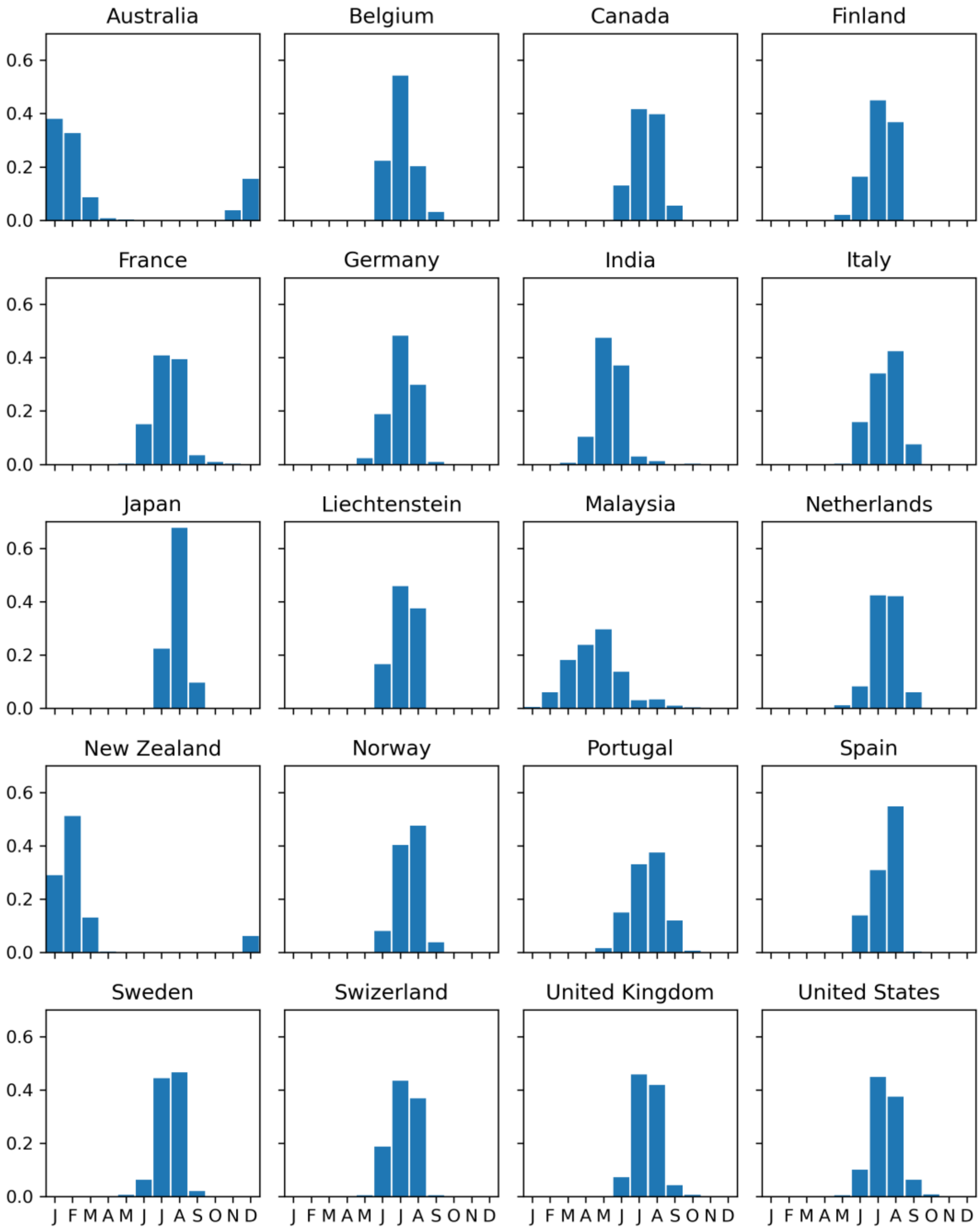

Figure B2: Normalised monthly distributions of heatwave terminations for each country.

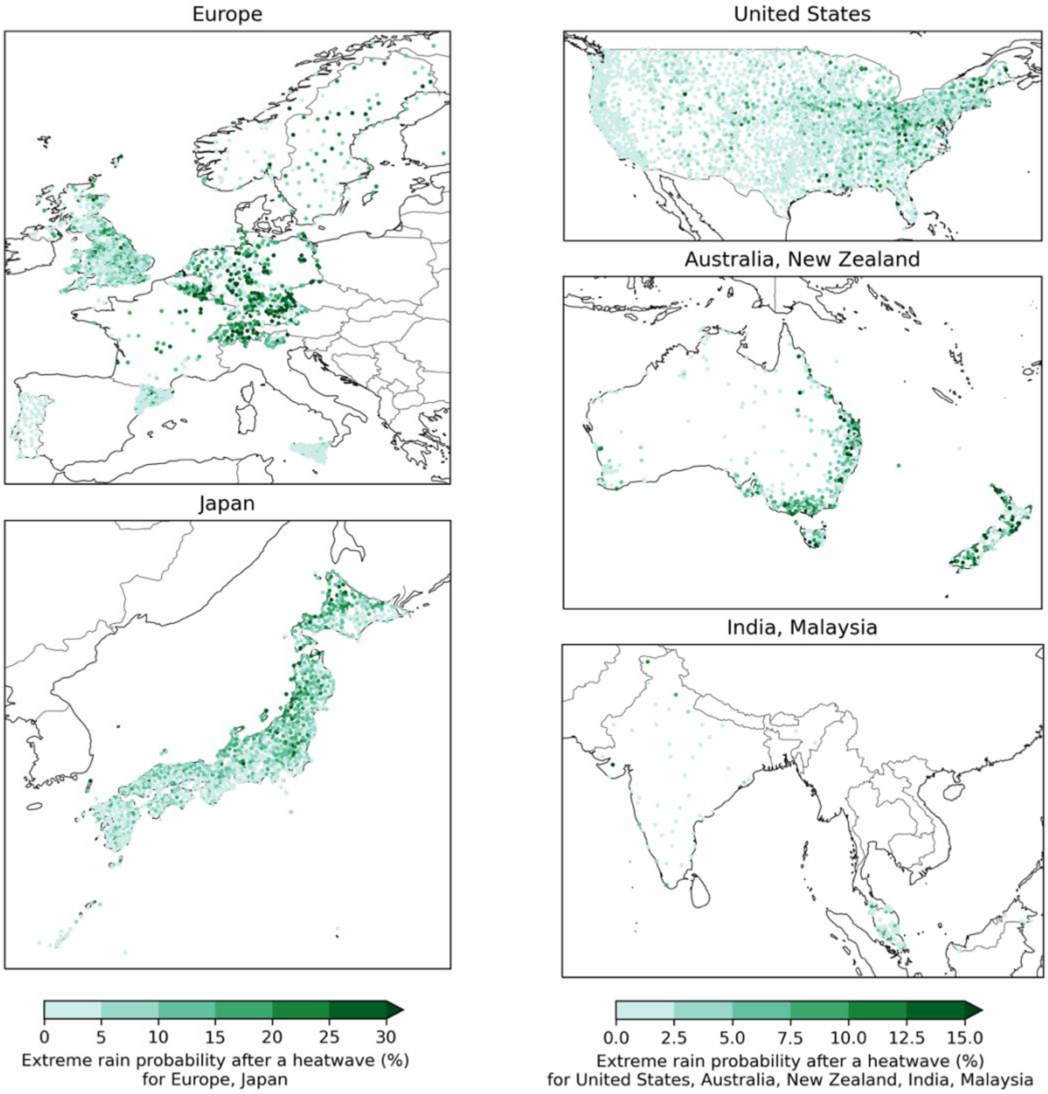

Figure B3: Analogous to Figure 10, but for dry heatwaves.

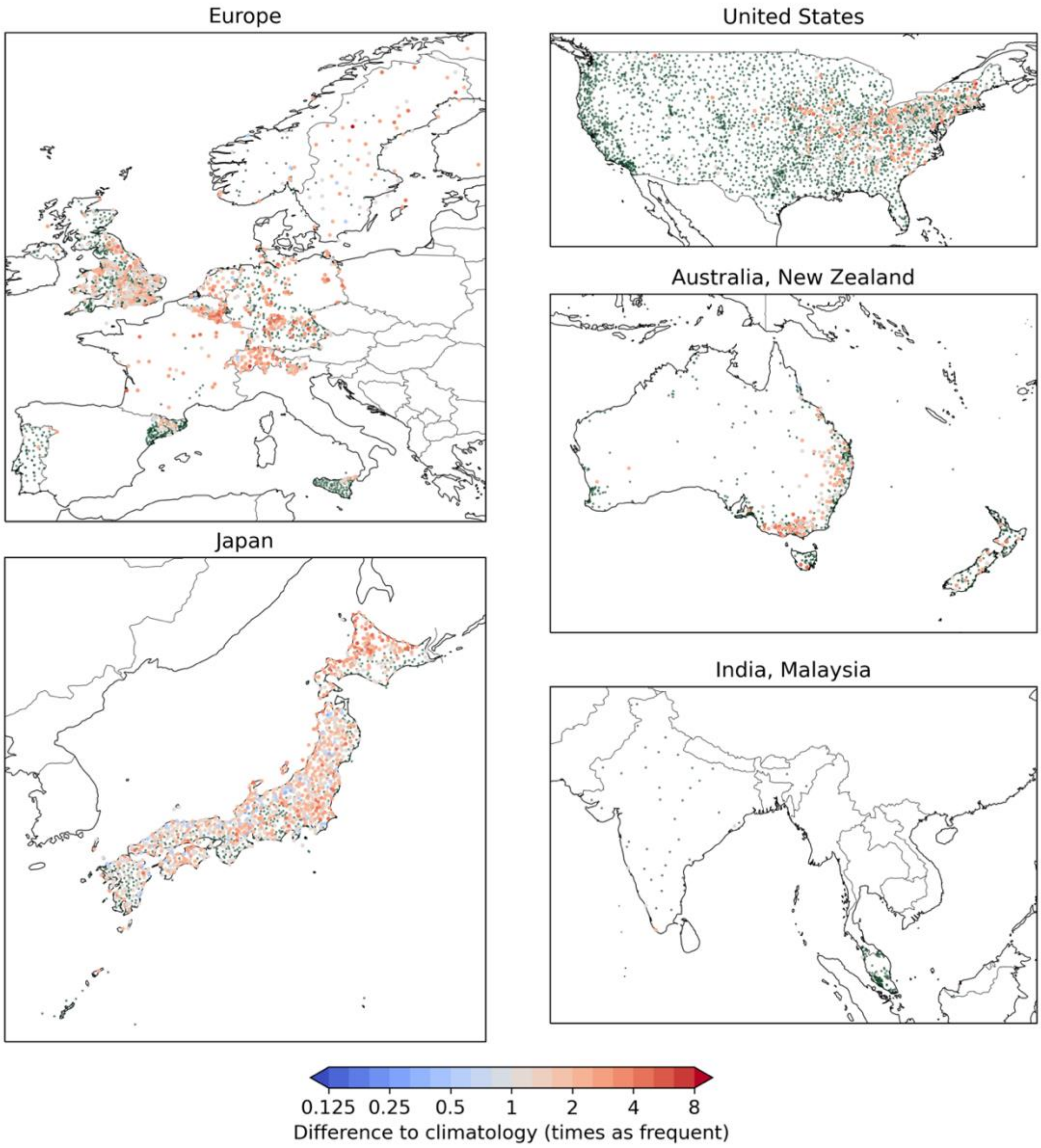

Figure B4: Analogous to Figure 11, but for dry heatwaves

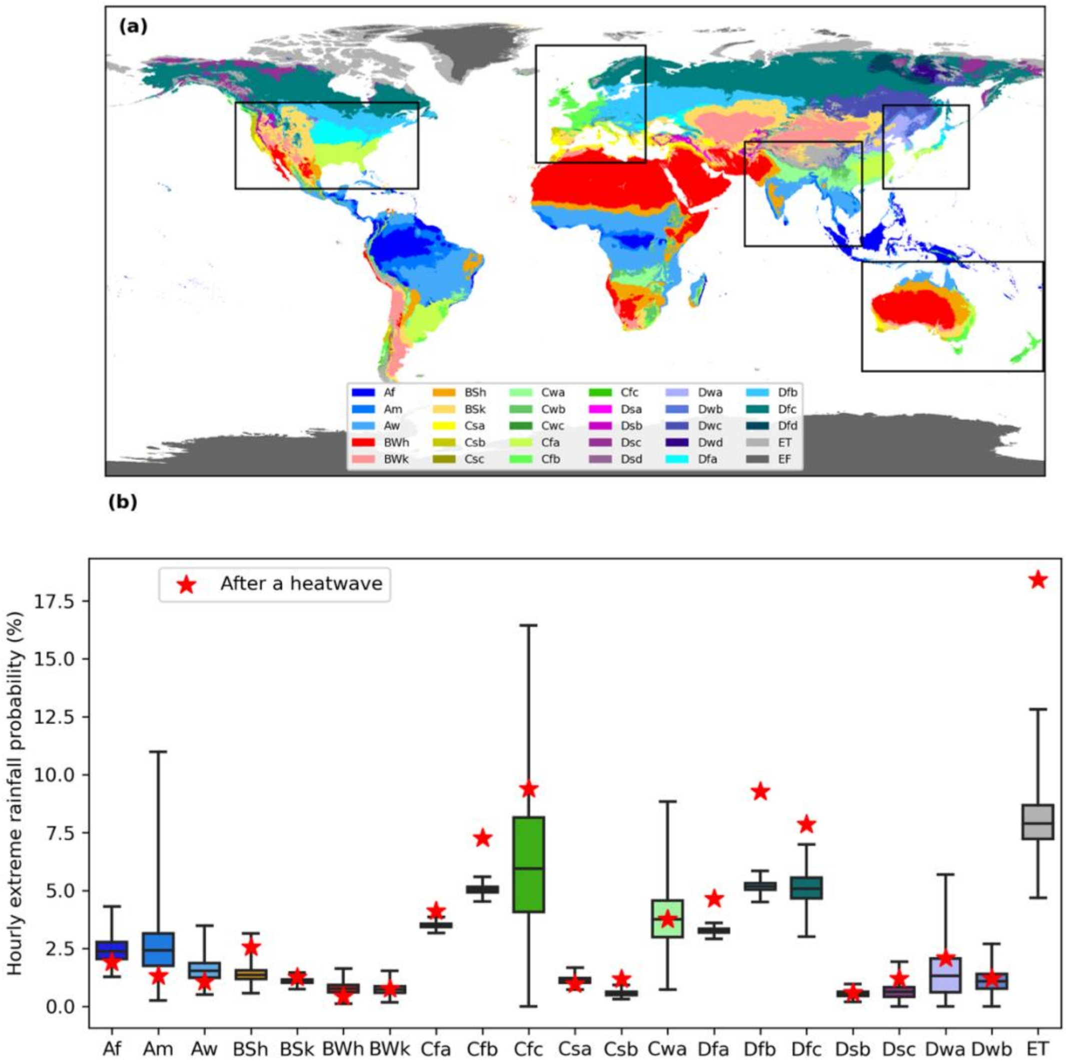

Figure B5: Analogous to Figure 12, but for dry heatwaves

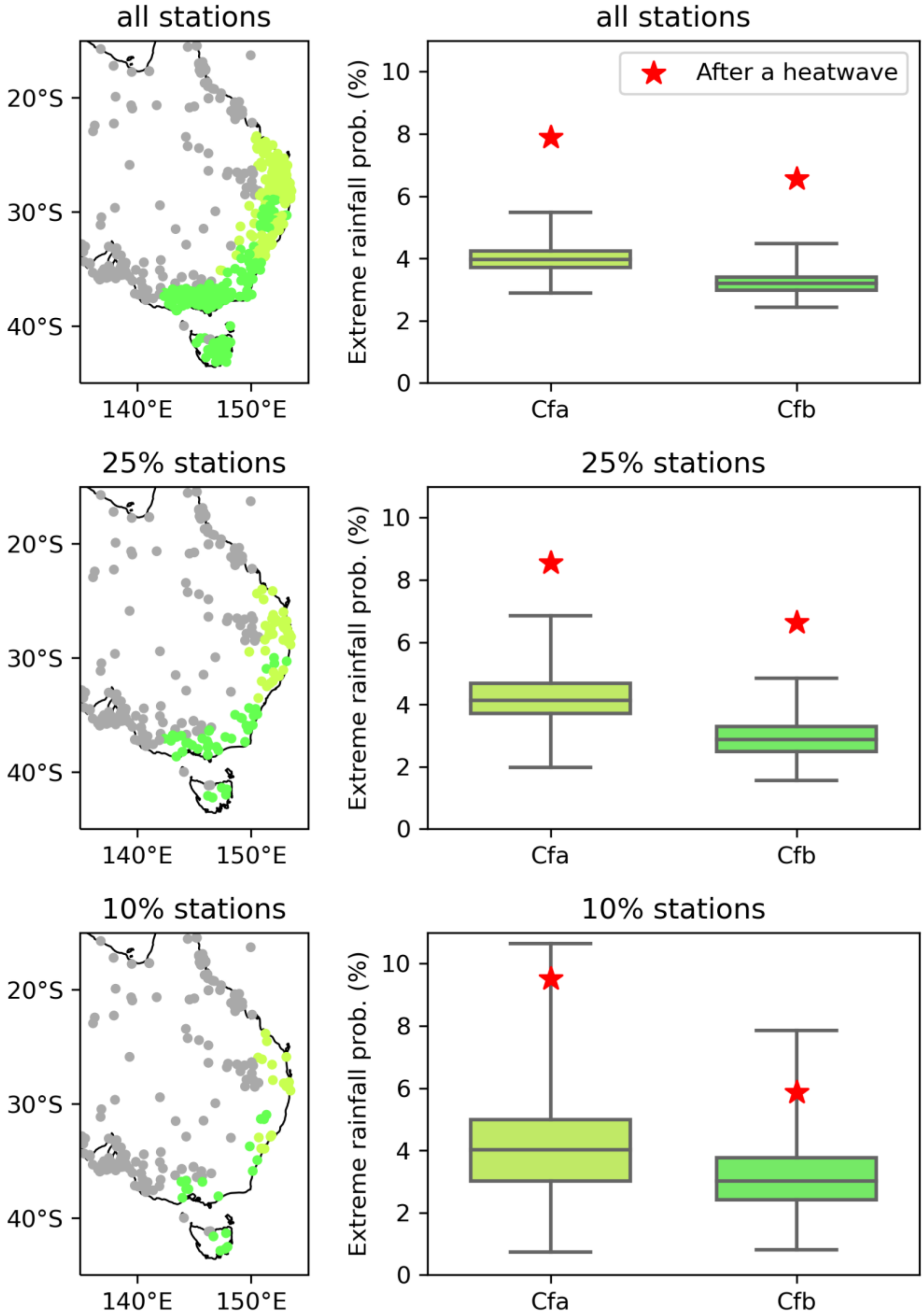

Figure B6: Likelihood of occurrence of at least one hourly rainfall extreme within 36 h (analogue to Figure 13b) for climate zones 'Cfa' (light green) and 'Cfb' (dark green) if all stations are considered (top panel), 25% of stations are considered (centre panel) or 10% of stations are considered (bottom panel). Boxplots show the 25%-75% (whiskers 5%-95%) range of estimated climatological likelihood of extreme rainfall based on the stations available in the left panel. The stations were randomly reduced, and grey points show stations within other climate zones.

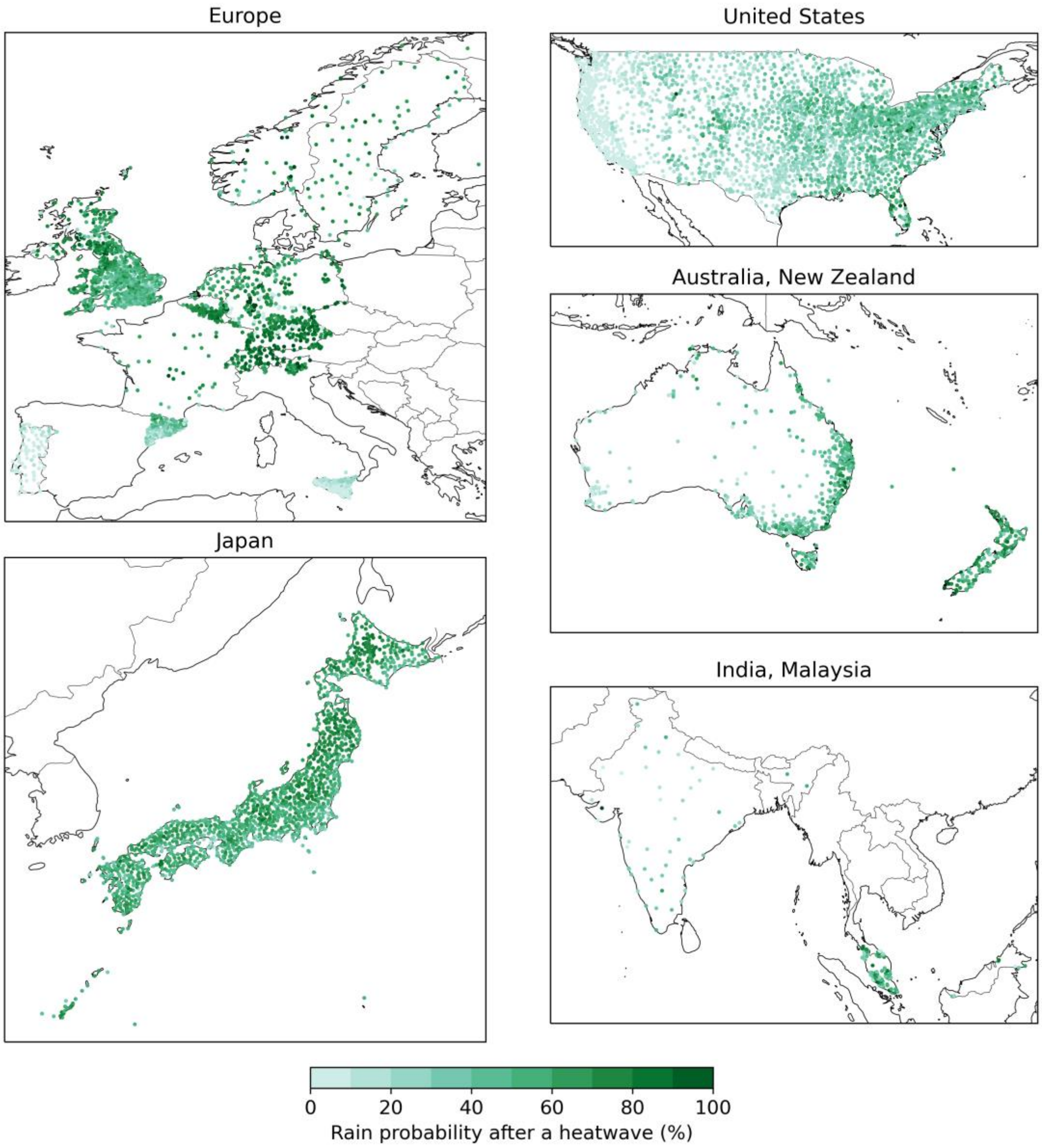

Figure B7: Analogous to Figure 12, but showing the probability of at least one hour with at least 0.1 mm h^{-1} within 36-h from noon on the last heatwave day.

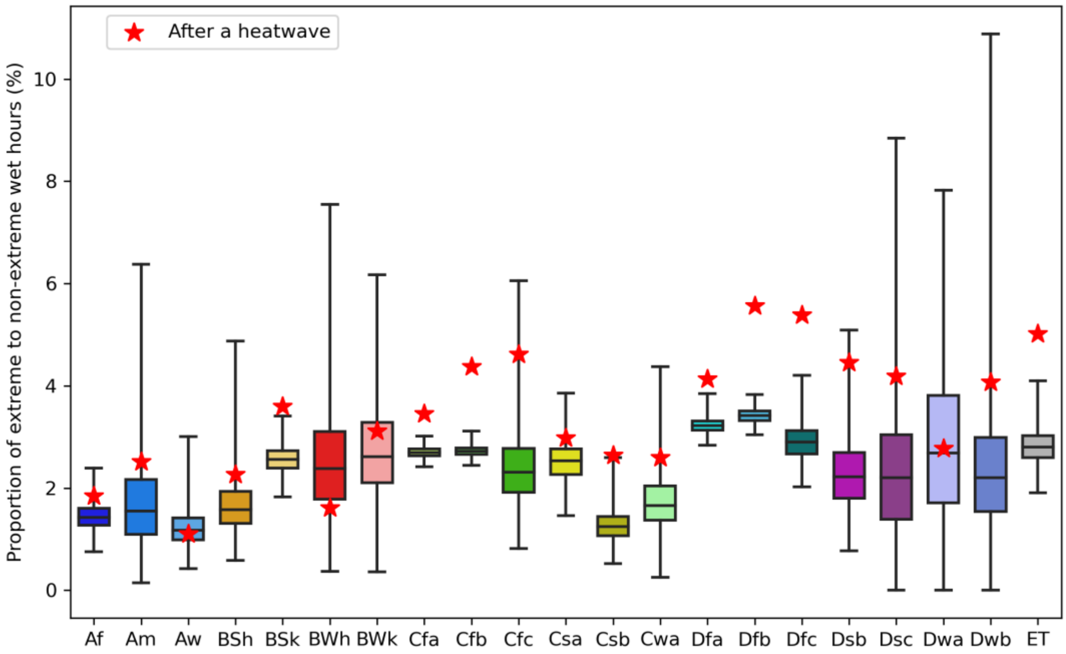

Figure B8: Analogous to Figure 13b but showing the average proportion of extreme to non-extreme wet hours (hours with >0.1 mm h-1) within the 36-h time window after a heatwave (red stars). Boxplots show the25%-75% (whiskers 5%-95%) range of estimated proportion of extreme to non-extreme wet hours for climatology as estimated by resampling. Following the extreme wet hour definition, on average only 1% of all wet hours are extreme, however higher values such as seen in the climatology above result from seasonal effects such as higher extreme wet hour occurrence during summer and choice of time window.

Table B1: Köppen-Geiger classes with descriptions and criteria. Adapted from Peel et al. (2007) and Beck et al. (2018).

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry	Summer $P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
		f	- Without dry season	Not (Cs) or (Cw)

		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

*Variables

MAP: mean annual precipitation (mm $year^{-1}$)

MAT: mean annual temperature (°C)

T_{hot}: temperature of the hottest month (°C)

T_{cold}: temperature of the coldest month (°C)

T_{mon10}: number of months where the temperature is above 10 (unitless)

P_{dry}: precipitation of the driest month (mm $month^{-1}$)

P_{sdry}: precipitation of the driest month in summer (mm $month^{-1}$)

P_{wdry}: precipitation of the driest month in winter (mm $month^{-1}$)

P_{swet}: precipitation of the wettest month in summer (mm $month^{-1}$)

P_{wwet}: precipitation of the wettest month in winter (mm $month^{-1}$)

$P_{threshold}$: 2 × MAT if >70% of precipitation falls in winter, $P_{threshold}$ = 2 × MAT+28 if >70% of precipitation falls in summer, otherwise $P_{threshold}$ = 2 × MAT+14

Summer (winter) is defined as the warmer (colder) six-month period between April-September and October-March

APPENDIX C.

ADDITIONAL FIGURES FOR CHAPTER 5

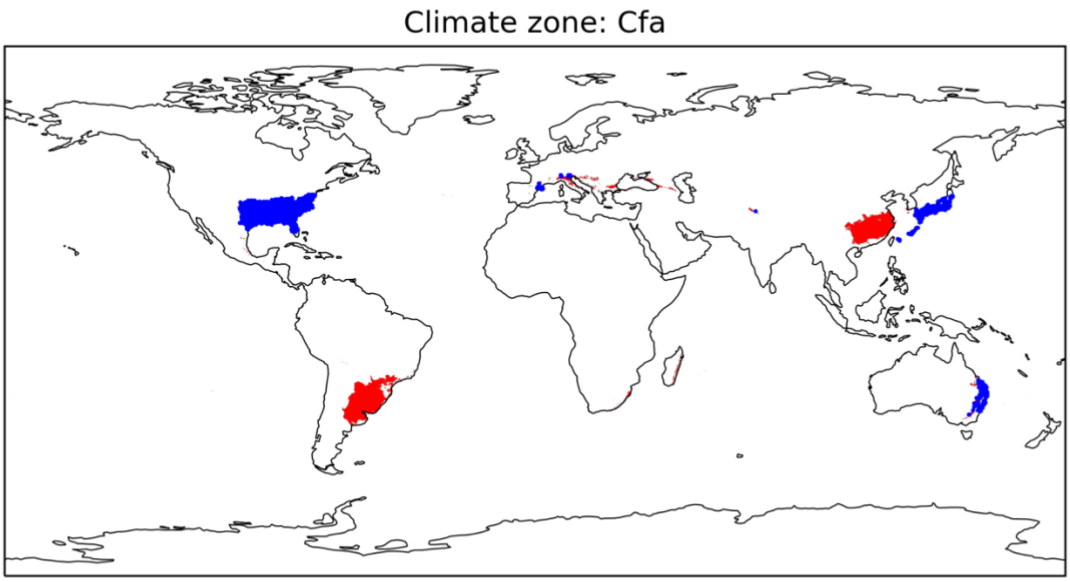

Figure C1: Red areas show all regions identified as 'Cfa' climate zones. Blue dots show available GSDR stations within the same climate zones.

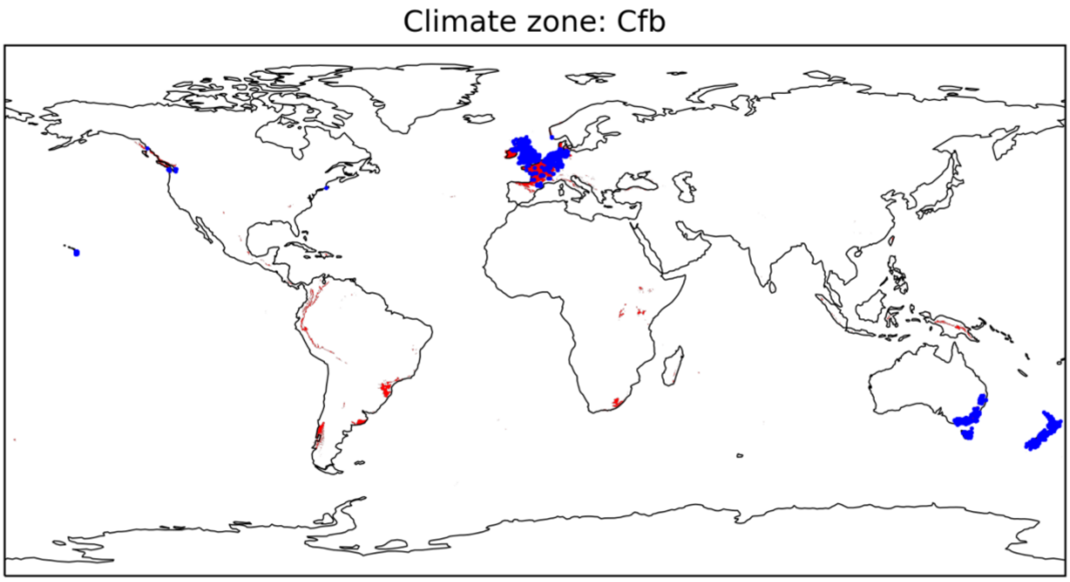

Figure C2: Like Figure C1, but for 'Cfb' climate zones.

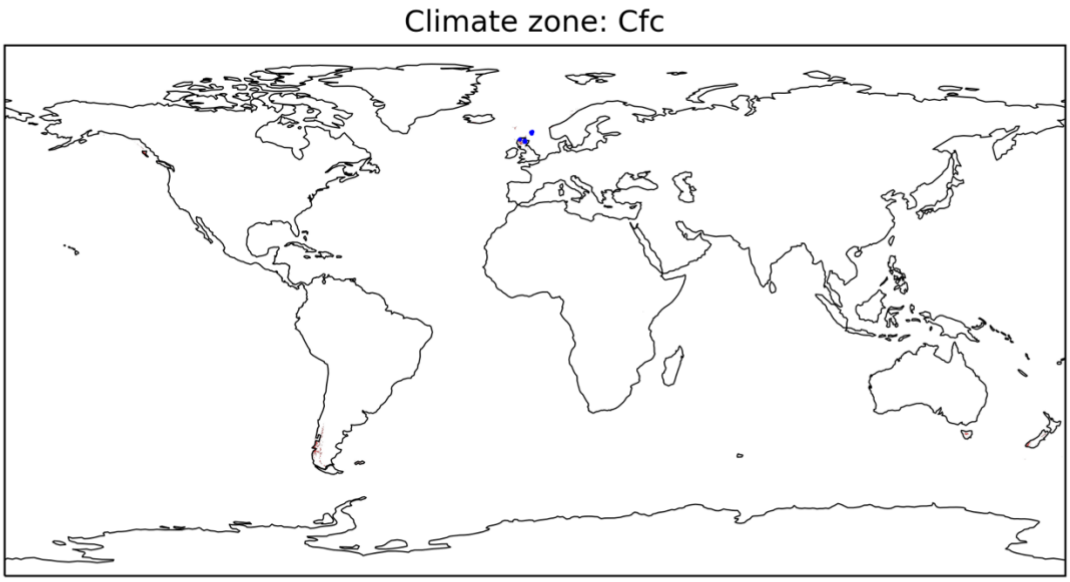

Figure C3: Like Figure C1, but for 'Cfc' climate zones.

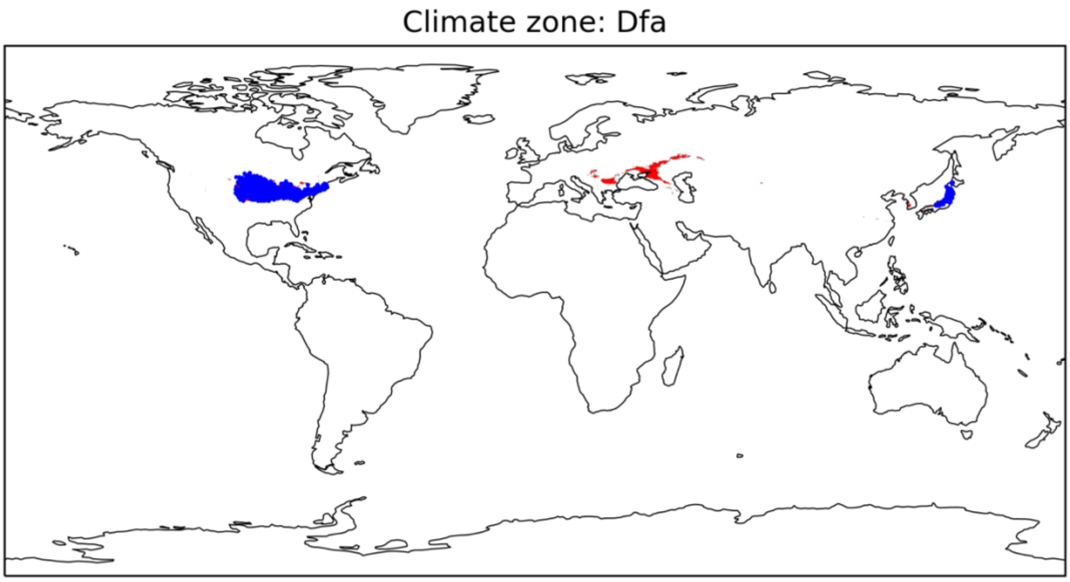

Figure C4: Like Figure C1, but for 'Dfa'' climate zones.

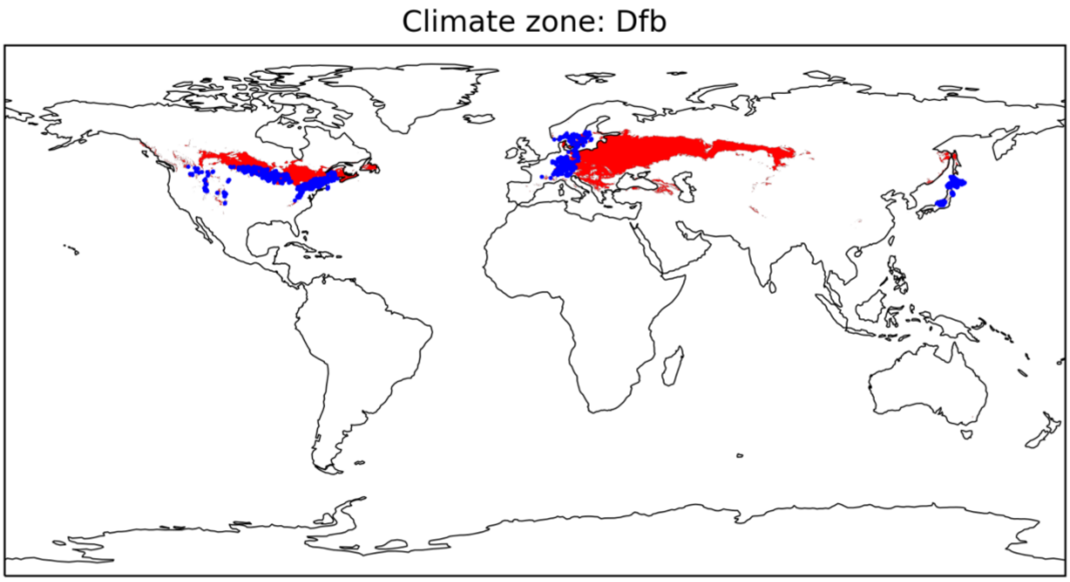

Figure C5: Like Figure C1, but for 'Dfb' climate zones.

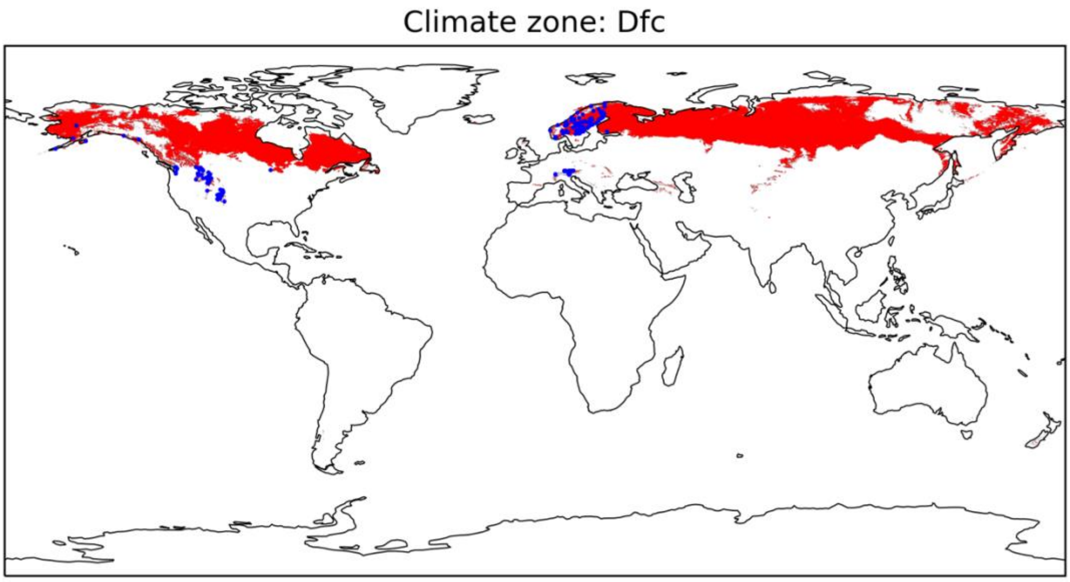

Figure C6: Like Figure C1, but for 'Cfc' climate zones.

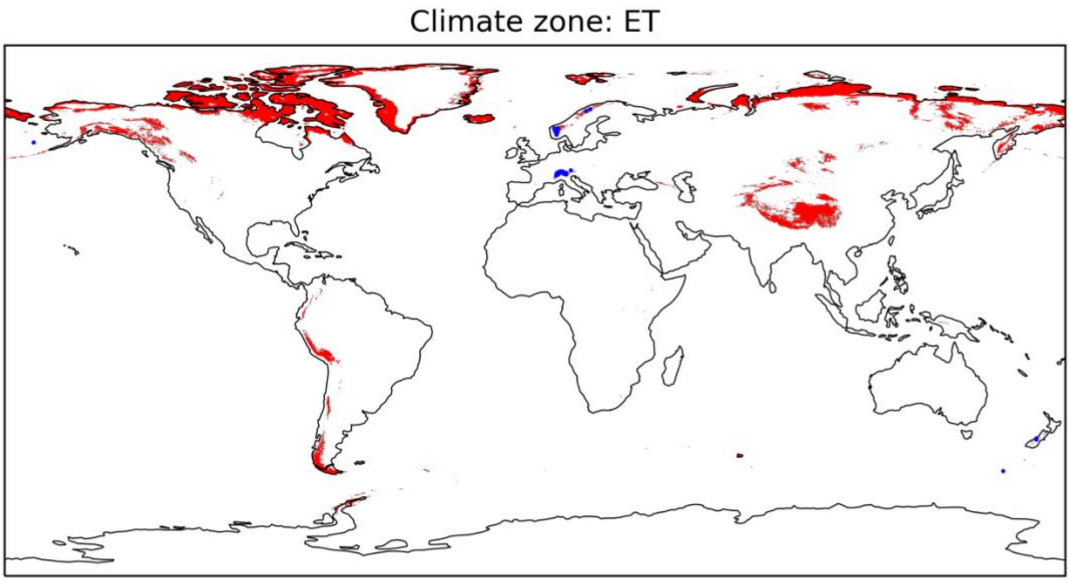

Figure C7: Like Figure C1, but for 'ET' climate zones.

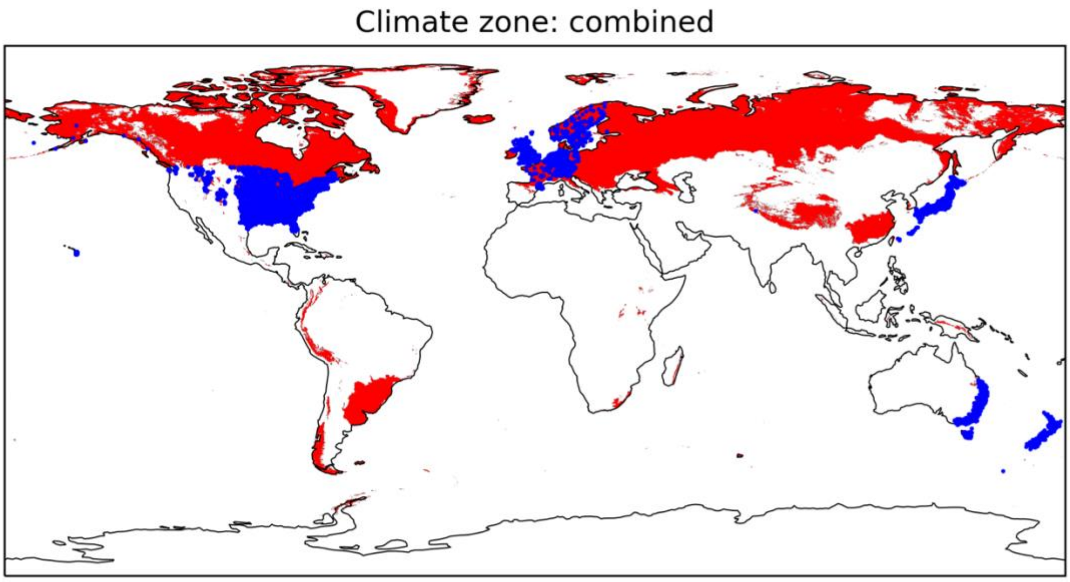

Figure C8: Like Figure C1, but for 'Cfa', 'Cfb', 'Cfc', 'Dfa', 'Dfb', 'Dfc', and 'ET' climate zones.

APPENDIX D.

SUPPORTING INFORMATION FOR CHAPTER 6

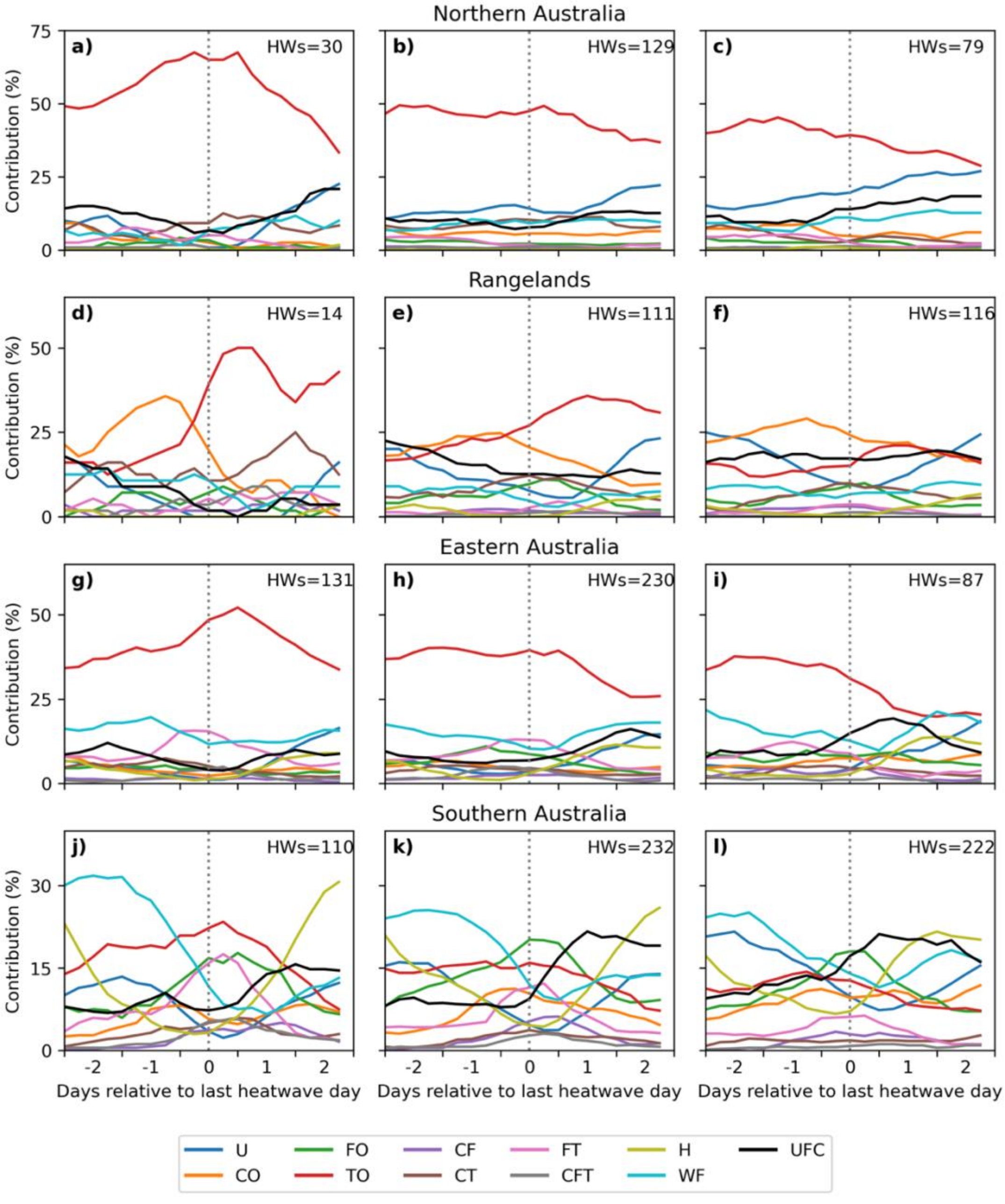

Figure D1: Frequency of each weather type during and after the heatwave if the heatwave was followed by extreme rainfall (left column), moderate rainfall (centre column), and no rainfall (right column) for four regions in Australia. Curves are smoothed with a 24h running mean to reduce diurnal effects. Vertical dotted line marks 12:00 local time on the last day of the heatwave during which the contributions were taken for Figure 16 (Note contributions in Figure 16 were not smoothed with a 24h running mean). Top *right corner of each plot shows number of heatwaves identified for respective region and heatwave ending.*

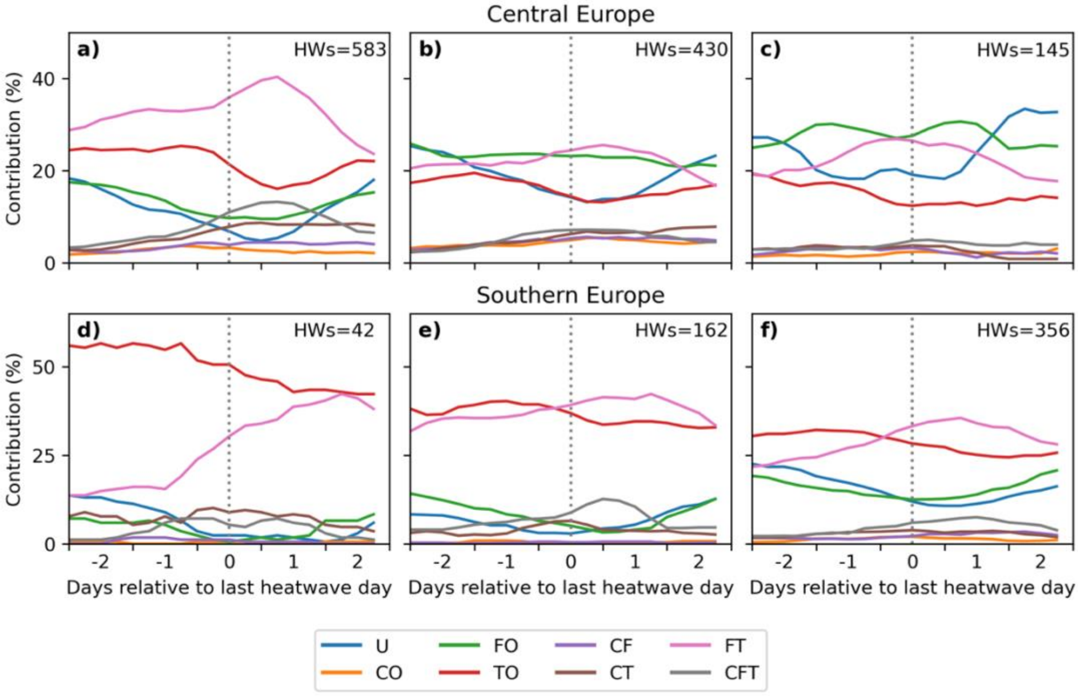

Figure D2: Same as Figure D1, but for regions in Europe.

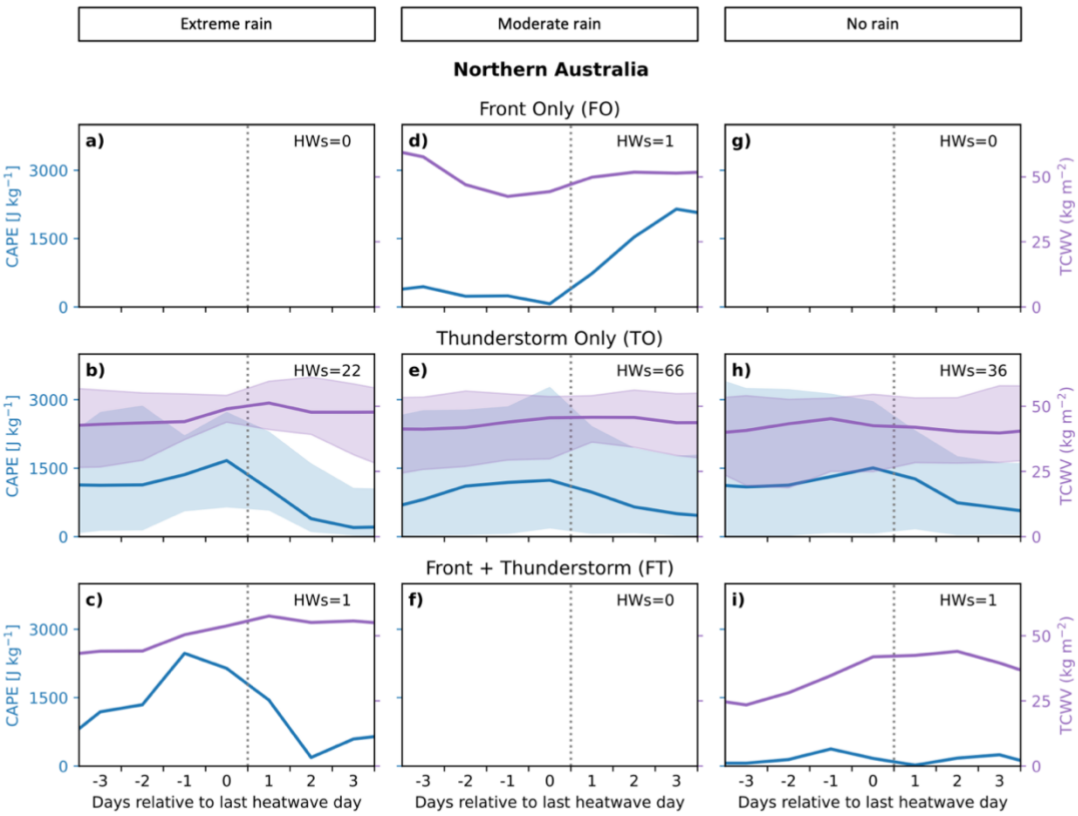

Figure D3: Same as Figure 18, but for Northern Australia only.

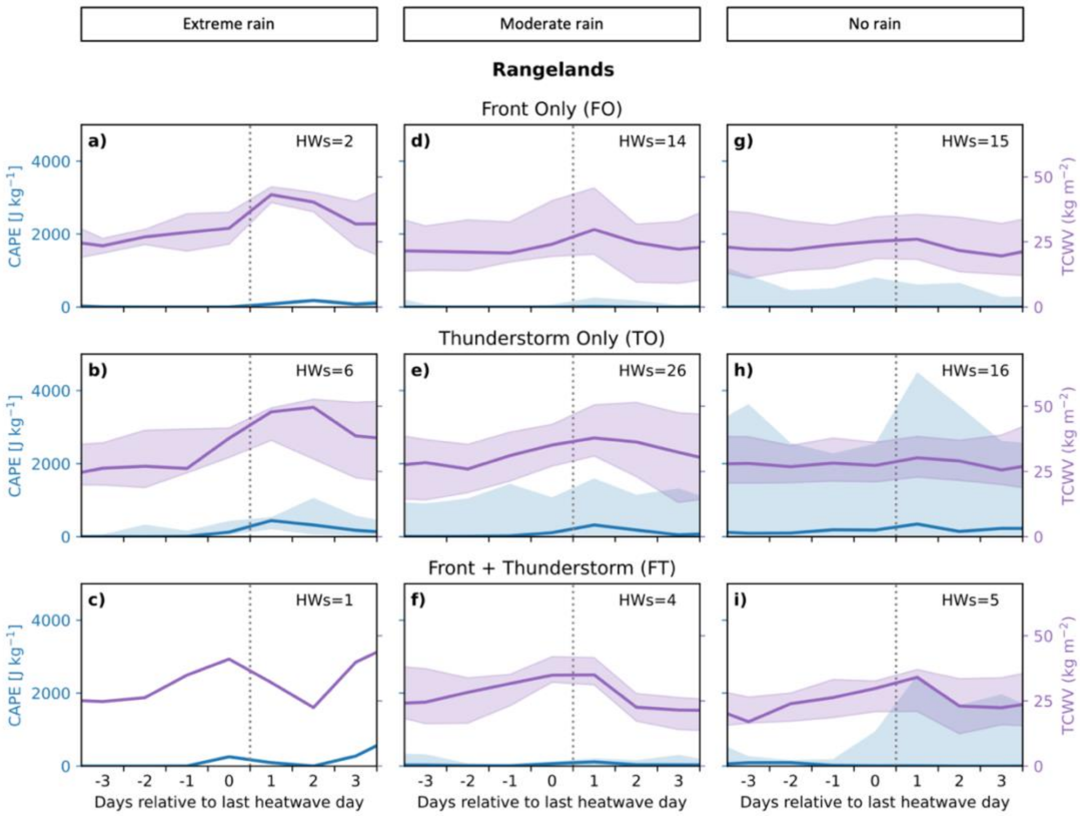

Figure D4: Same as Figure D3, but for Rangelands.

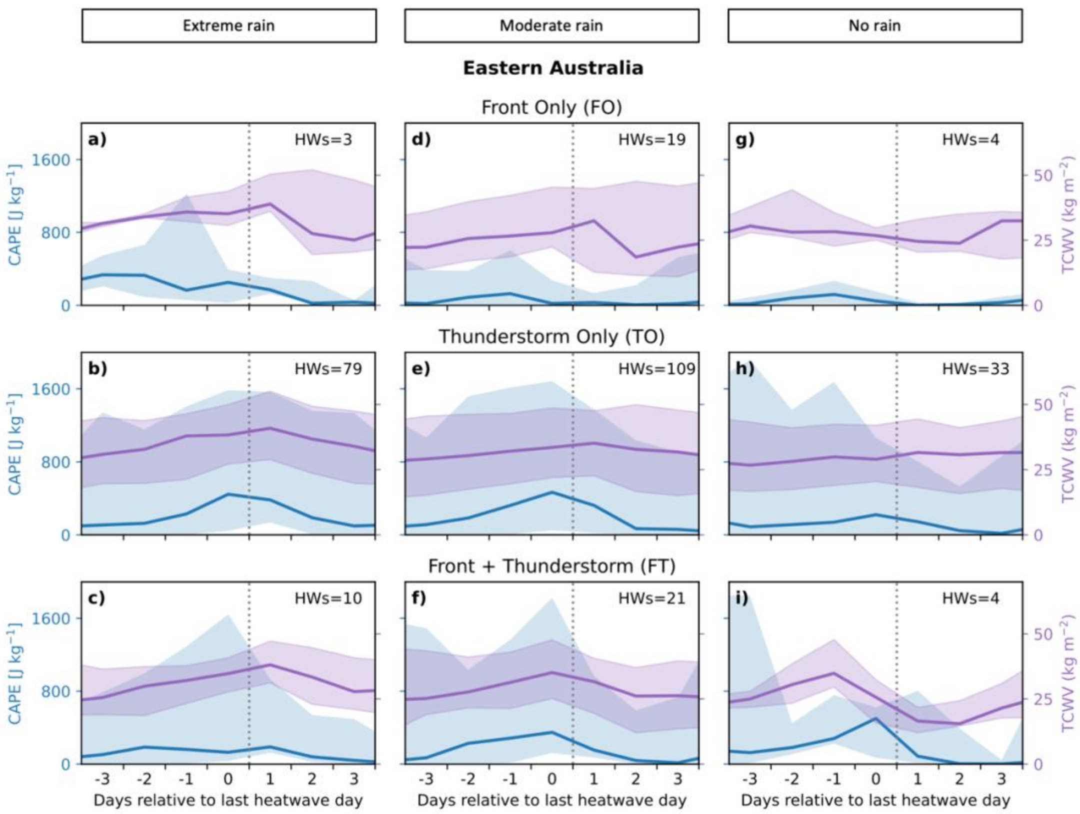

Figure D5: Same as Figure D3, but for Eastern Australia.

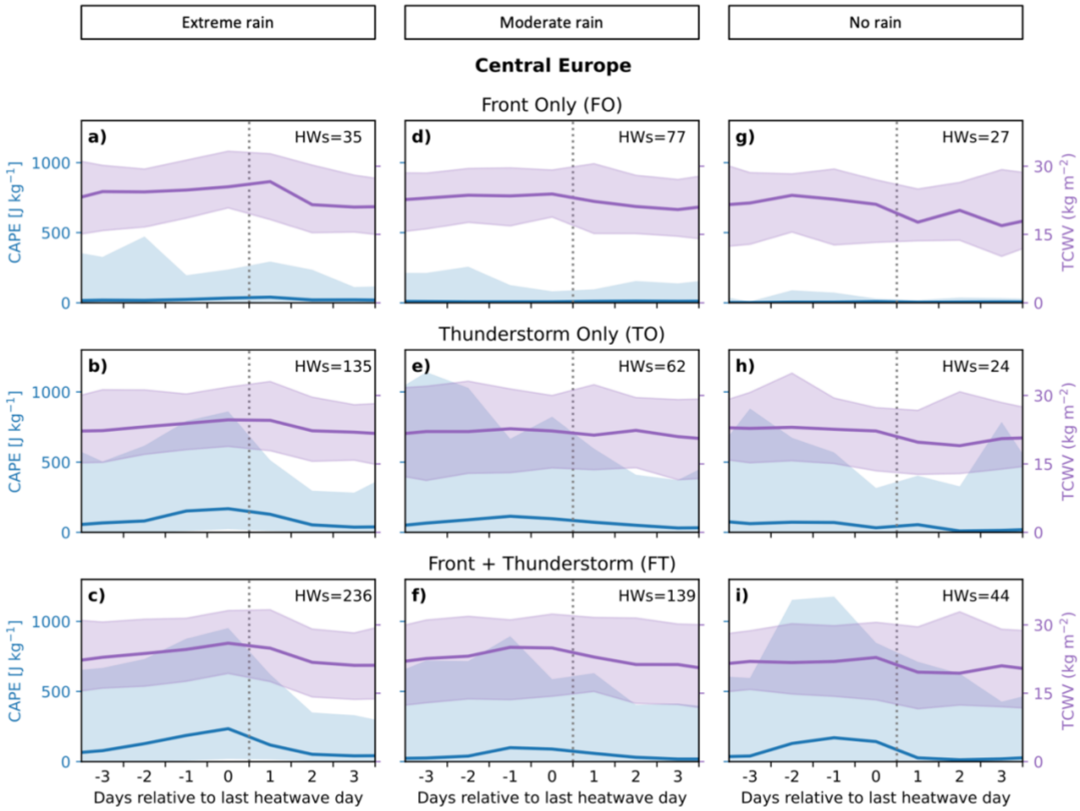

Figure D6: Same as Figure D3, but for Central Europe.

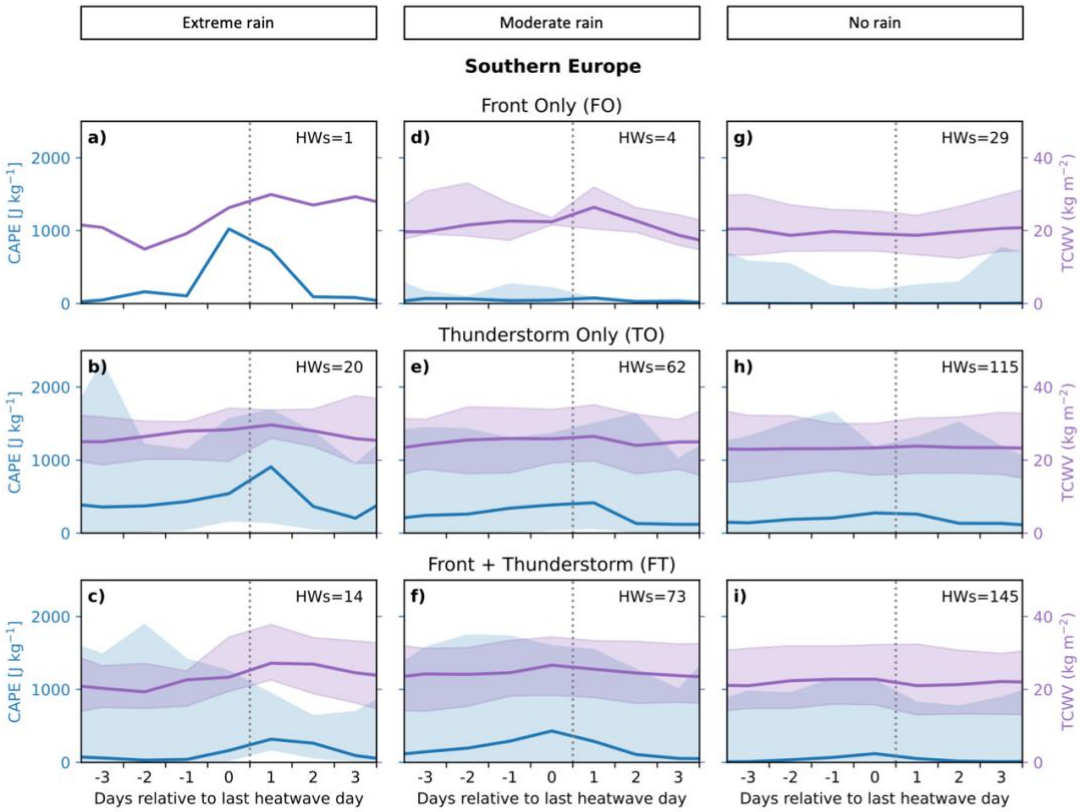

Figure D7: Same as Figure D3, but for Southern Europe.

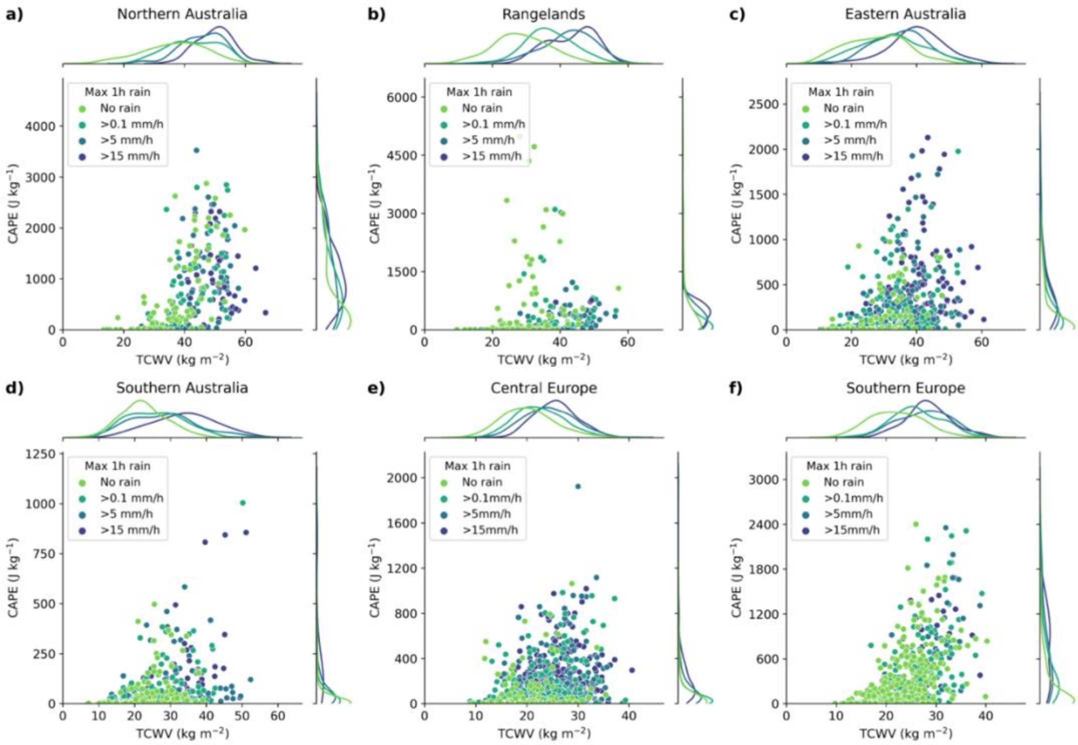

Figure D8: Like Figure 19, but for the first day after the heatwave.

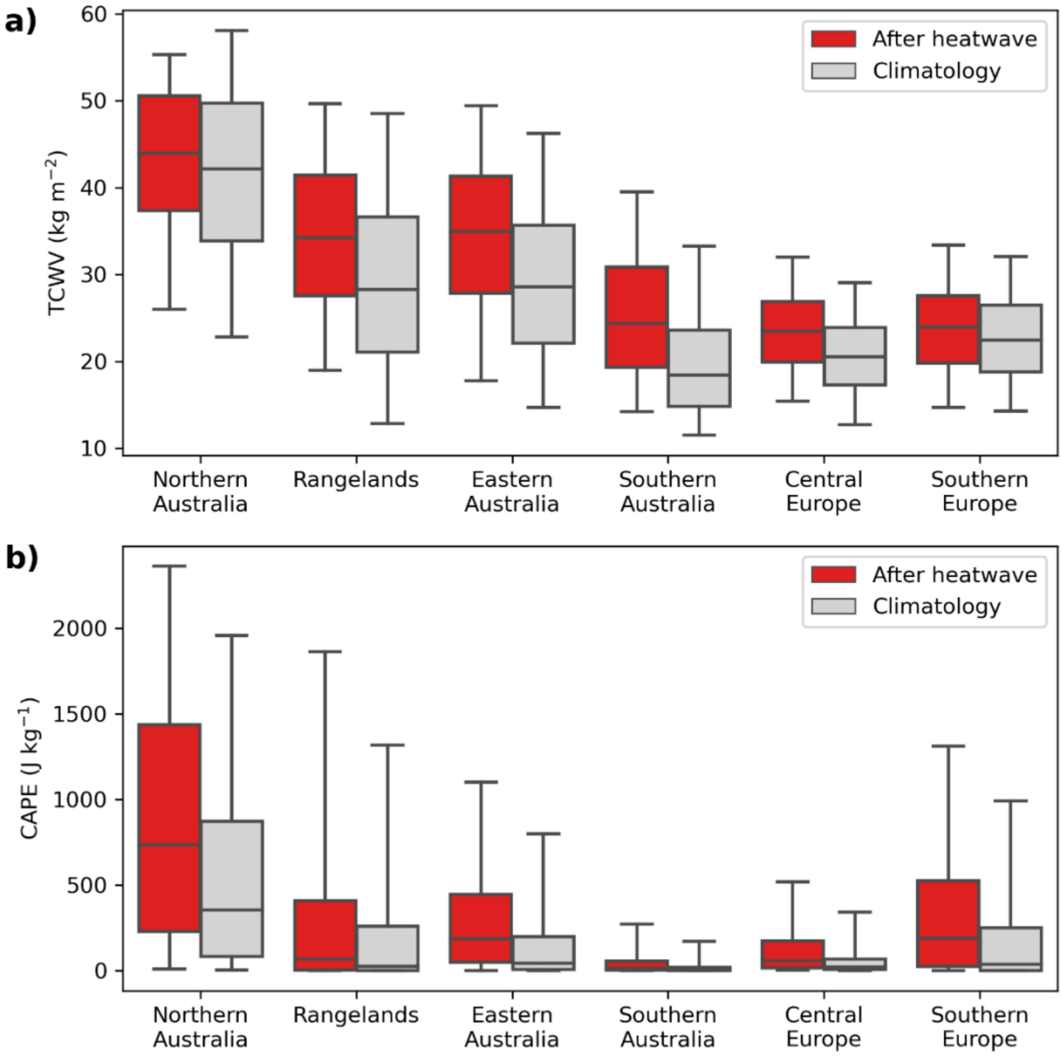

Figure D9: Like Figure 20, but for the first day after the heatwave

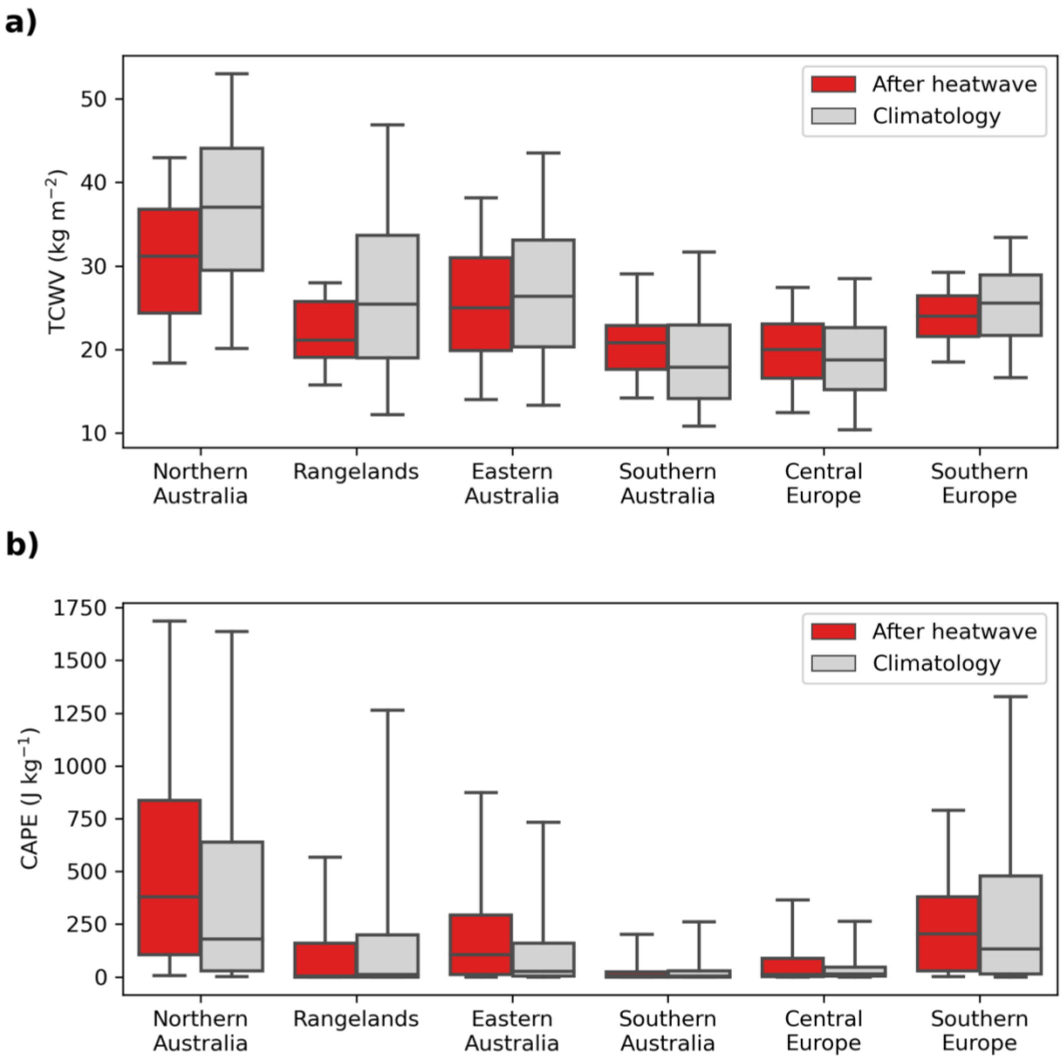

Figure D10: Like Figure 20, but for day-time heatwaves only

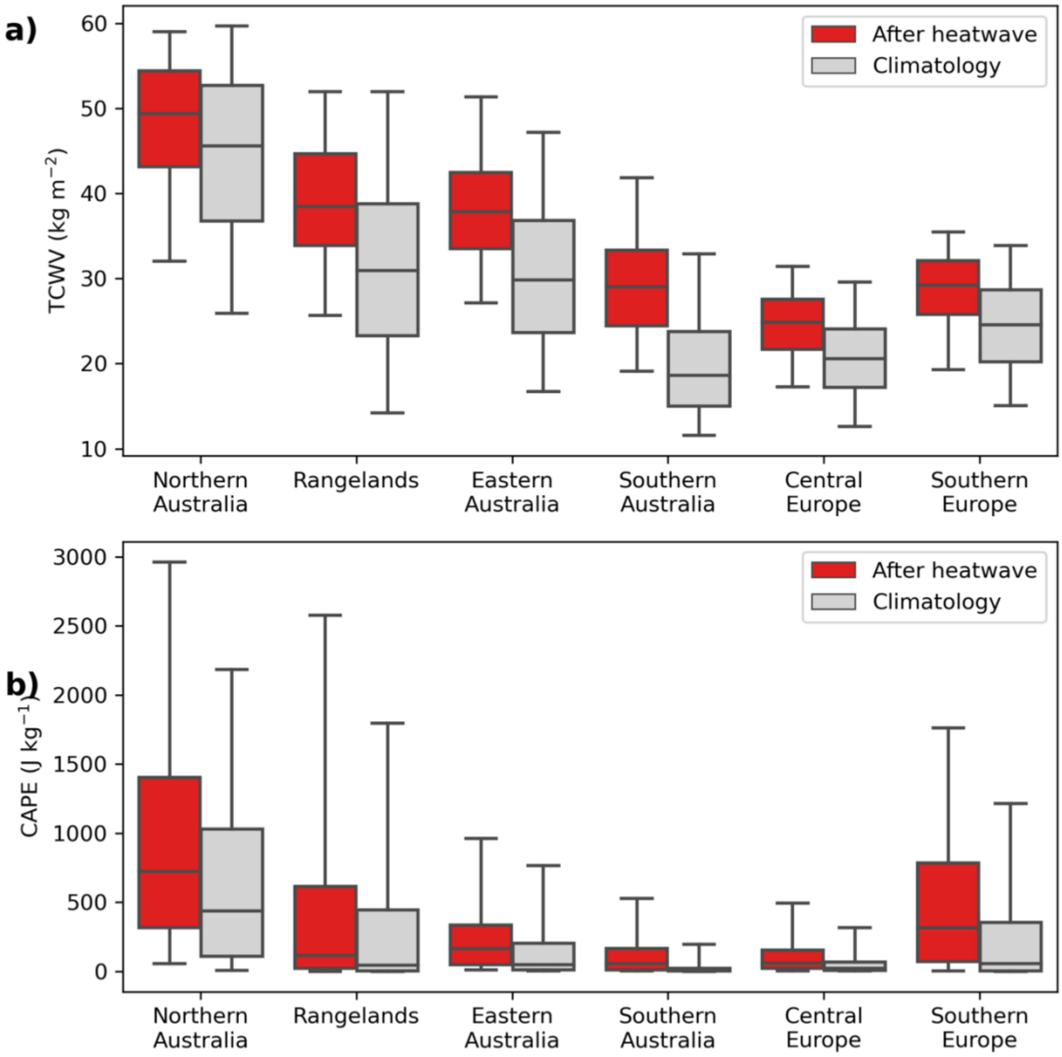

Figure D11: Like Figure 20, but for night-time heatwaves only

APPENDIX E.

ABSTRACTS OF FURTHER PUBLICATIONS (NOT INCLUDED IN THE THESIS)

E.1 Abstract for the journal paper "The Bristol CMIP6 data hackathon"[3]

The Bristol CMIP6 Data Hackathon formed part of the Met Office Climate Data Challenge Hackathon series during 2021, bringing together around 100 UK early career researchers from a wide range of environmental disciplines. The purpose was to interrogate the under-utilised but currently most advanced climate model inter-comparison project datasets to develop new research ideas, create new networks and outreach opportunities in the lead up to COP26. Experts in different science fields, supported by a core team of scientists and data specialists at Bristol, had the unique opportunity to explore together interdisciplinary environmental topics summarised in this article.

E.2 Executive summary for the report "A review of interacting natural hazards and cascading impacts in Scotland"[4]

Weather-driven interacting natural hazards (referred to as 'multi-hazards' or 'compound events') cause significant disruption and damage to environmental and human systems in Scotland every year. Commonly, natural hazards are considered individually; however, natural hazards often arise from a combination of contributing, interacting physical processes. Failure to consider the multiple causes and drivers behind an event and the associated cascading impacts can lead to an underestimation of risk. Due to our changing climate, it is expected that many weather-related hazards will increase in intensity, occur more widely and more often than before, thereby increasing exposure to emerging hazards.

This report provides an overview for Scotland of the nascent research field of compound events and cascading impacts. It provides conclusions concerning how these events and impacts have and may affect Scotland with climate change in the coming decades. The

[3] Mitchell, D.M., Stone, E.J., Andrews, O.D., Bamber, J.L., Bingham, R.J., Browse, J., Henry, M., MacLeod, D.M., Morten, J.M., Sauter, C.A, Smith, C.J., et al. 2022. The Bristol CMIP6 data hackathon. *Weather*, 77(6), pp.218-221, doi: https://doi.org/10.1002/wea.4161.
[4] Simmonds, R., White, C. J., Douglas, J., Sauter, C. & Brett, L. 2022. A review of interacting natural hazards and cascading impacts in Scotland, url: https://eprints.gla.ac.uk/267515.

literature review identified publications relating to compound events and cascading impacts, but highlighted a significant lack of Scottish multi-hazard studies. This gap in knowledge is despite strong evidence that interpreting Scottish natural hazards using the framework of compound events and cascading impacts would significantly improve our understanding of these hazards, and potentially lead to improved resilience.

Natural hazards in Scotland were reassessed here using a recently proposed typology for compound events based on their characteristics. Events and publications were re-evaluated and re-categorised as one or more of the types: multivariate (combination of drivers); spatially compounding (hazards affecting multiple locations); preconditioned (enhancement/triggering from antecedent conditions); and temporally compounding (succession of hazards). From this, a portfolio of case studies was created, providing initial evidence on each type and their significant impacts in Scotland. The events include: the concurrence of hot and dry conditions in North European spring/summer 2018; UK flooding from rain on saturated soil in 2019/2020; debris flows from rain on saturated soils in 2015/2016; and successive UK droughts to floods in 2012. This storytelling approach helps elucidate the complexities of compound events.

Finally, a narrative of compound hazard events in Scotland was presented based on literature, the case studies, climate projections and an initial analysis of near future (2031-2060) multi-hazard pairings. This highlighted potential cascading risks and impacts across sectors and the environment in a changing climate.

The literature review exposed a significant gap in Scotland-focused multi-hazard research, even for those more commonly expected pairings of hazards like compound flooding. By revisiting notable, recent weather events in Scotland with a multi-hazard focus, evidence of vulnerability to types of compound hazards was elucidated. This showed how interactions between hazards cause impacts that cascade across human and natural environments in a complex, interconnected network. Many of our identified compound hazard risks correspond to the CCRA3 priority climate risks for UK adaptation. Climate change is projected to intensify and increase the occurrence of compound hazards across

spatial and temporal scales. Combining climate projections, CCRA3 priority future risks and our initial multivariate pairing analysis with the information from our re-categorised multi-hazard case studies reinforces the need for a greater understanding of compound hazards and their cascading impacts to ensure resilience.

To better understand multi-hazards in Scotland, we propose the following eight (non-prioritised) high-level recommendations:

1. Re-categorise and reconsider notable single hazards as compound events;
2. Conduct Scotland-focused studies into the compound impacts of: hot and dry conditions, intense rainfall on saturated soil resulting in flooding and landslides, snowfall patterns resulting in changes to streamflows, winter windstorms, and wildfires;
3. Assess temporal sequencing across multiple compound event types;
4. Undertake research to better understand the drivers of compound events;
5. Improve the understanding of multi-sectoral cascading impacts and risks;
6. Assess indicative thresholds and feedback loops for critical infrastructure;
7. Apply storyline approaches to different adaptation and resilience scenarios; and
8. Develop a holistic, multi-sectoral impact-based multi-hazard approach.

E.3 Abstract for the journal paper "Identifying meteorological drivers of extreme impacts: an application to simulated crop yields"[5]

Compound weather events may lead to extreme impacts that can affect many aspects of society including agriculture. Identifying the underlying mechanisms that cause extreme impacts, such as crop failure, is of crucial importance to improve their understanding and forecasting. In this study, we investigate whether key meteorological drivers of extreme impacts can be identified using the least absolute shrinkage and selection operator (LASSO) in a model environment, a method that allows for automated variable selection and is able to handle collinearity between variables. As an example of an extreme impact, we investigate crop failure using annual wheat yield as simulated by the Agricultural Production Systems sIMulator (APSIM) crop model driven by 1600 years of daily weather data from a global climate model (EC-Earth) under present-day conditions for the Northern Hemisphere. We then apply LASSO logistic regression to determine which weather conditions during the growing season lead to crop failure. We obtain good model performance in central Europe and the eastern half of the United States, while crop failure years in regions in Asia and the western half of the United States are less accurately predicted. Model performance correlates strongly with annual mean and variability of crop yields; that is, model performance is highest in regions with relatively large annual crop yield mean and variability. Overall, for nearly all grid points, the inclusion of temperature, precipitation and vapour pressure deficit is key to predict crop failure. In addition, meteorological predictors during all seasons are required for a good

[5] Vogel, J., Rivoire, P., Deidda, C., Rahimi, L., Sauter, C. A., Tschumi, E., Van der Wiel, K., Zhang, T. & Zscheischler, J. 2021. Identifying meteorological drivers of extreme impacts: an application to simulated crop yields. *Earth System Dynamics*, 12, 151-172, doi: https://doi.org/10.5194/esd-12-151-2021.

prediction. These results illustrate the omnipresence of compounding effects of both meteorological drivers and different periods of the growing season for creating crop failure events. Especially vapour pressure deficit and climate extreme indicators such as diurnal temperature range and the number of frost days are selected by the statistical model as relevant predictors for crop failure at most grid points, underlining their overarching relevance. We conclude that the LASSO regression model is a useful tool to automatically detect compound drivers of extreme impacts and could be applied to other weather impacts such as wildfires or floods. As the detected relationships are of purely correlative nature, more detailed analyses are required to establish the causal structure between drivers and impacts.