# Climate and Weather Extremes in the UK: Learning from the past and preparing for the future

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# Author's Declaration

I declare that this thesis has been composed by myself and that it has not been submitted, in whole or in part, to any previous applications for a degree. I declare that the work presented in this thesis is my own except where stated otherwise by reference or by acknowledgement.

Emma L. Yule
September 2023

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# Abstract

As global surface temperatures continue to rise, both the duration and intensity of heatwaves in Europe and the UK are expected to increase. The 2022 European summer heatwave broke a number of temperature records and was associated with a range of societal impacts that were felt unequally across society. Heatwaves cause health impacts and fatalities with the 2003 European heatwave resulting in the loss of life of up to 70,000 people. However, compared to hazards with more visible consequences such as flooding events, the impacts of heatwaves can be overlooked leading them to be termed "silent killer" events. It is therefore important to improve our understanding of heatwaves and their impacts and how these may change in a warming world.

The first part of this thesis explores what we can learn from past examples of heatwave events. Past events can provide points of reference to help with future decision making, allowing us to learn from the past. As extreme events are relatively rare by definition, by focusing on detecting early heatwaves, the sample of extreme events available for further analysis is extended. We detected and analysed historical heatwave events prior to 1927 in the UK and compared these to more recent events, including the 2022 heatwave event, allowing us to place modern events into historical context. We found that while there is a clear warming trend in the monthly data, the heatwave activity at the daily scale between 1878 and 1926 was considerable and in some cases comparable to modern heatwave events therefore, early events could be used as case studies to help us learn more about potential future heatwave events. We find that some impacts of early events are similar to those impacts today, such as the disparity in impacts of high and low-income regions. The second part of this thesis uses these examples of early heatwaves as case studies to analyse how the intensity of such events could change in the future. While many studies focus on the changing return periods of events in a warmer climate, fewer studies focus on a past event, from the early 20$^{\text{th}}$ century for example, and how it may look in a warmer climate based on a range of potential warming scenarios. We used a flow analogue methodology to explore what the early extreme events may look like in the future. We find that heat events such as the UK heatwave in 1923 increase in intensity at a similar rate to climatology as the global temperature increases, according to the models used. We find that at 4°C of global warming, the mean summer days during the 1923 heatwave in England is between 4.9

and 6.4 degrees warmer than pre-industrial levels across the three models used. Mean temperatures during analogous events, events of similar circulation patterns as 1923, over England range from 6.9 to 10.7°C higher than pre-industrial levels, for three different climate models used at 4°C. In addition, we comment on the limitations of this approach as well as the potential benefits, particularly as a communication tool to improve decision making around extreme heat.

The interface between the scientific study of extreme event risk and how this is communicated and used by decision makers is currently a knowledge gap. The third part of this thesis investigates what tools, data and knowledge may aid adaptation decision makers while identifying what barriers exist in creating policies to increase resilience to extreme events. This research uses the Scottish public sector as a case study and we find that the majority of organisations are still at the planning phase of adaptation. We highlight key challenges including capacity and lack of organisational awareness of the need for adaptation and potential solutions to increase adaptation action in Scotland, including adaptation literacy training, tighter legislation and the use of boundary organisations or knowledge brokers. This research can help bridge the gap between climate science and decision makers by highlighting some key data requirements to help accelerate adaptation action and how it is monitored and evaluated.

The novelty of this thesis is in the interdisciplinary approach taken, with contributions made throughout the impact chain, from hazard to risk and impacts. Overall, this interdisciplinary research provides a method for learning from the past, while also exploring what is required to prepare for the future.

# Lay Summary

Due to climate change, we expect to see heatwaves in the UK become hotter and to happen more frequently. The 2022 European summer heatwave broke temperature records across Europe and resulted in health impacts, travel disruption and water scarcity. The impacts due to heatwaves are not felt equally in society, for example, those with underlying medical conditions can be more impacted by heat events. This research asks what can we learn from past heatwave events and asks if they could make credible and interesting case studies to help us prepare for future heatwave events. We examined past heatwave events in the UK and compared these to more recent events, including the 2022 heatwave, allowing us to place modern events into historical context and to extend the sample of extreme events that can be used as case studies. While we still see the warming trend in the data, some extreme past heatwaves were found to be comparable to more modern heatwave events. The next part of this research explores how the past heatwave events we found could look like in the future when global temperatures are higher. We used an analogue methodology to explore what heatwaves with similar weather conditions to these early extremes may look in a warmer world. This allows us to evaluate how much hotter heatwaves events would be in the future that look like those in the past. We discuss the pros and cons of using this technique and how it may be helpful to use as a tool when making decisions about how we need to prepare for future heatwaves. More research is needed to understand the links between the science of extremes events and how this is communicated and used by those in decision making spaces such as local governments. The third part of this research asks what tools, data and knowledge may help adaptation decision makers. We identify what barriers are in place for the Scottish public sector when it comes to adapting to weather extremes including heatwaves. This includes capacity challenges and the lack of an organisational awareness of the need to adapt to climate change. We find that most organisations are in the early stages of planning for adaptation, we set out ways that progress could be increased including potential solutions such as ensuring staff in the public sector have access to adaptation literacy training. We think this research could help bridge the gap between scientists that work on extremes and those who need to make decisions about how we adapt to extreme weather. Overall, this research spans academic disciplines and provides a method for learning from the past, and what is required to prepare for the future.

# Contents

**Author's Declaration** iv

**Acknowledgements** v

**Abstract** vi

viii

**1 Introduction** 1

1.1 Introduction Overview . . . . . 1

1.2 Extreme events and heatwaves . . . . . 1

1.2.1 Why heatwaves matter . . . . . 2

1.2.2 Causes of heatwaves . . . . . 2

1.2.3 How heatwaves are defined . . . . . 3

1.3 Exploring past heatwaves . . . . . 5

1.3.1 Early instrumental datasets . . . . . 5

1.3.2 Documentary evidence . . . . . 6

1.3.3 Renalyses . . . . . 7

1.3.4 Importance of data from the past . . . . . 8

1.3.5 Considerations when using past data . . . . . 8

1.4 Heatwaves and climate change . . . . . 9

1.4.1 Introducing extreme event attribution . . . . . 9

1.4.2 Analogues . . . . . 10

1.5 Preparing for heat and extreme events . . . . . 11

1.5.1 What is climate adaptation? . . . . . 12

1.5.2 How is adaptation measured? . . . . . 13

1.5.3 Climate risk . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 14

1.5.4 Communicating climate risk . . . . . . . . . . . . . . . . . . . . . . . 15

1.5.5 Key considerations in risk and adaptation decision making . . . . . 20

1.5.6 Comparison of methodologies for exploring potential future events . 21

1.6 Interdisciplinary research . . . . . . . . . . . . . . . . . . . . . . . . . 24

1.6.1 What is interdisciplinary research? . . . . . . . . . . . . . . . . . . . 24

1.6.2 Why interdisciplinary research is important . . . . . . . . . . . . . 24

1.6.3 Interdisciplinary research in this thesis . . . . . . . . . . . . . . . . 25

1.7 Motivation and PhD structure . . . . . . . . . . . . . . . . . . . . . . . 26

1.7.1 Knowledge gaps and thesis motivation . . . . . . . . . . . . . . . . 26

1.7.2 PhD structure . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28

**2 Analysing Past Extremes in the UK** **31**

2.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 32

2.2 Detecting heatwaves using station data . . . . . . . . . . . . . . . . . . 34

2.2.1 Datasets used . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34

2.2.2 Defining heatwaves . . . . . . . . . . . . . . . . . . . . . . . . . . 35

2.2.3 Detecting heatwave years . . . . . . . . . . . . . . . . . . . . . . . 36

2.3 A comparison of past and modern heatwaves . . . . . . . . . . . . . . . 37

2.3.1 Heatwave trends from past to present . . . . . . . . . . . . . . . . . 37

2.3.2 Comparing past and modern heatwave events . . . . . . . . . . . . 38

2.4 Daily vs monthly temperatures . . . . . . . . . . . . . . . . . . . . . . 39

2.4.1 Are monthly data suitable to detect heatwaves? . . . . . . . . . . . 39

2.5 Case studies of heatwave years . . . . . . . . . . . . . . . . . . . . . . . 41

2.5.1 Did detected early heat events cause impacts? . . . . . . . . . . . . 42

2.6 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 45

**3 UK Extremes in a Warmer World** **46**

3.1 Introduction . . . . . . . . . . 47

3.2 Datasets and models used . . . . . . . . . . 49

3.3 Choice of heatwave events . . . . . . . . . . 49

3.4 General method . . . . . . . . . . 51

3.5 Results . . . . . . . . . . 54

3.6 Discussion . . . . . . . . . . 60

3.6.1 Methodological choices . . . . . . . . . . 60

3.6.2 Limitations of analogues . . . . . . . . . . 62

3.6.3 Can analogues be used as storylines? . . . . . . . . . . 63

3.7 Conclusion . . . . . . . . . . 64

**4 Extreme Event Risk and Adaptation** **66**

4.1 Introduction . . . . . . . . . . 67

4.2 Method . . . . . . . . . . 68

4.2.1 Public Bodies Climate Change Reports analysis . . . . . . . . . . 69

4.2.2 Interview analysis . . . . . . . . . . 70

4.3 Results . . . . . . . . . . 71

4.3.1 Top adaptation priorities for public sector bodies . . . . . . . . . . 71

4.3.2 Mitigation & adaptation . . . . . . . . . . 72

4.3.3 Public sector bodies risk assessment progress . . . . . . . . . . 75

4.3.4 Tools & frameworks . . . . . . . . . . 78

4.4 Critical analysis and discussion . . . . . . . . . . 81

4.4.1 Complexity and drivers . . . . . . . . . . 82

4.4.2 Risk and uncertainty . . . . . . . . . . 83

4.4.3 Collaboration and the number of actors . . . . . . . . . . 87

4.4.4 Measurements and targets . . . . . . . . . . . . . . . . . . . . . . . . 88
4.5 Summary & Take-aways . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90

**5 Discussion & Conclusions** **92**
5.1 Key research conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . 92
5.2 Reflections on interdisciplinary research . . . . . . . . . . . . . . . . . . . . 96
5.3 Potential future work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 98
5.4 Perspective and research impact . . . . . . . . . . . . . . . . . . . . . . . . 100

**Bibliography** **102**

**A Supplementary material for Chapter 2** **147**

**B Supplementary material for Chapter 3** **150**

**C Supplementary material for Chapter 4** **154**

# Chapter 1

# Introduction

## 1.1 Introduction Overview

The following introduction is structured in order to dedicate a section to each of the key topics relevant to this research. Firstly, extreme event and heatwaves are defined and their causes and impacts discussed. Approaches to exploring past heatwaves are discussed including the importance of learning from past data and weather events. Next, heatwaves and what they could look like in the future is explored. The importance of climate risk and adaptation is then discussed including some key literature on how risk is communicated and how interdisciplinary research can play a key role in ensuring that adaptation decision makers have the data, tools and knowledge to implement effective adaptation actions. Lastly, the knowledge gaps addressed in this thesis are set out as well as the structure that this PhD follows.

## 1.2 Extreme events and heatwaves

**This PhD explores how we can learn from past extreme events and how we can prepare and build resilience to future events. Extreme events are those which are severe or unusual, in other words, at the extremes of historical distributions. Extreme events have a range of potential impacts on natural and human systems that are felt unequally across society. This research has a strong focus on heatwaves. In this section, the definition and causes of heatwaves will be outlined.**

### 1.2.1 Why heatwaves matter

The IPCC has concluded that it is virtually certain that heatwaves have become more intense and more frequent across most land areas since 1950 (Field et al., 2012; Calvin et al., 2023) which is likely to continue as global temperatures rise. Global surface temperatures have risen to 1.1°C in 2011-2020 from pre-industrial levels principally by the emission of greenhouse gases through human activities (Calvin et al., 2023). The National Weather Service in the USA regard heatwaves as the major cause of weather-related fatalities most years (Robinson, 2001) and in Europe, recent heatwaves have resulted in the loss of life of thousands of people (Robine et al., 2008; Ballester et al., 2023). As well as having adverse impacts on human health, heatwaves can cause disruptions to transport, agricultural activities (Lobell et al., 2007) and can lead to forest fires (Westerling et al., 2006). In contrast to other hazards such as flooding for example, heatwaves have been labelled as "silent killers". They tend to cause less visible damage to property for example while causing more fatalities than other events, a key reason why understanding heatwaves and their impacts is critical (Bogdanovich et al., 2023). Health impacts of heatwaves are usually felt more acutely amongst the elderly population, very young children and those with underlying health conditions. The impacts of heatwaves are not felt equally in society and inequalities commonly arise due to differing income levels (King et al., 2018). For example, high-income locations tend to have more easily accessible green spaces that can provide shade during a heatwave event. There are also race, class and gender disparities in who is most heavily impacted by heatwaves (Benz et al., 2021; Chakraborty et al., 2019; Steen et al., 2019). An understanding of heatwaves, their causes, mechanisms and impacts will become increasingly important as heatwaves increase in intensity and frequency and, therefore, this is a key focus of this PhD research.

### 1.2.2 Causes of heatwaves

Heatwaves tend to be caused by a high-pressure event, often a blocking event. In the case of the 2003 European heatwave, it is thought that soil moisture deficit and sea-surface temperatures (SST) also played an important role (García-Herrera et al., 2010). It was concluded that the heatwave could not have occurred without the anomalous SST and soil moisture values during the previous winter and spring of 2003. This highlights the importance of a thorough analysis of the periods prior to an event occurrence when focusing on the causes of a particular heatwave. Impact analysis is usually based on the damage to health, society and property after an extreme event. However, a "forensic"

(IRDR, 2016) approach to heatwave analysis can be taken. This involves an analysis of the socioeconomic causes of an extreme event, taking into account the fact that there are conditions or practices which can amplify or strengthen the impacts of an event. This could include environmental degradation or poor land development leading to soil moisture deficit for example. This highlights the importance of considering the causes, mechanisms and consequences of a heatwave event from both a physical and societal perspective, known as "storyline" framing, (Shepherd, 2019; Sillmann et al., 2021; Baulenas et al., 2023; Bruijn et al., 2016) particularly when aiming to compare heatwaves occurring at different time or spatial scales. It can also be a reason why definitions of heatwaves differ considerably by study focus.

### 1.2.3 How heatwaves are defined

How we define, measure and compare heatwaves across time and spatial scales must be clear and consistent in order to learn from the past and prepare for the future most effectively. Heatwaves are usually defined as an extended period of unusually high temperature, however, previous studies of heatwaves have used definitions with a variety of timescales and spatial scales (National Academies of Sciences, 2016). Timescales used can vary from a day to a year and spatial scales can be defined based on, for example, weather station location or political boundaries.

The large variety of definitions of heatwaves can make it difficult to objectively compare studies of events that have occurred in the past or those that have occurred in different regions or locations. Definitions are usually based on the exceedance of fixed absolute values or a deviation from the normal such as from a daily mean value (Robinson, 2001). In addition, definitions may also take into account the impact of the heatwave on society, for example by basing the definition on the criteria for heat stress (Freychet et al., 2022). Therefore, the idea of "thresholds" becomes important when considering the formulation of a definition of heatwaves. Should the threshold be purely statistical and based on a $90^{\text{th}}$ percentile exceedance for example, or be related to physiological or sociological thresholds? The World Meteorological Organisation (WMO) drafted a recommended definition of heatwaves as "A period of marked unusual hot weather over a region persisting for at least three consecutive days during the warm period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds" (WMO, 2018; McCarthy et al., 2019b). The WMO recommendations extend to how heatwaves are characterised which they state should include the magnitude of the event (i.e. the "climatological extremity"), the duration, the spatial extent and the severity (the damages and impacts caused by the heatwave). This highlights the fact that the definition need not be binary, but that "contextual information" can also be included.

Using the WMO guidelines, the UK MET Office set out a definition for UK heatwaves in 2019 (McCarthy et al., 2019a). The definition is: "three consecutive days in which the daily maximum temperature exceeds a heatwave threshold defined for recognised counties of the UK". The UK was split into different regions and the threshold for each region based on the 90$^{th}$ percentile of the daily maximum temperature for July, using a thirty-year reference period. When the reference period shifted from 1981-2010 to 1991-2020, thresholds were updated to reflect warming, with several regional thresholds shifting by a degree (McCarthy, 2022). When creating this definition, the key intention was to create a tool for communicating heatwaves effectively to the public and to the wider society along side other methods which could provide additional contextual information about individual weather events. In order to compare heatwaves occurring in different time and spatial scales, several indices have been created as a way of understanding the relative strength of different events. Indices can be created based on thresholds specific to a particular sector such as agriculture, health or power (Russo et al., 2014) and can be focused on the duration or magnitude of an event. The Heat Wave Magnitude Index for example is defined as "the maximum magnitude of the heatwaves in a year, where a heatwave is the period $\geq 3$ consecutive days with maximum temperature above the daily threshold for the reference period 1981–2010" (Russo et al., 2014). In this definition, the threshold is the 90$^{th}$ percentile of daily maxima for a 31-day period.

How heatwaves are defined and which thresholds and metrics are relevant depends on the region and climatic zones in which they occur. Different countries and regions tend to use different definitions aligned to the region's average temperature and relative humidity (Barriopedro et al., 2023). For example, in India there are different definitions of heatwaves, including those for hilly regions, plain regions and coastal regions. In Bangladesh an absence of pre-monsoonal rainfall for 10 consecutive days is defined as a heatwave and in Taiwan for example, 16 days of consecutive heat above a threshold temperature is defined as a heatwave (Awasthi et al., 2022).

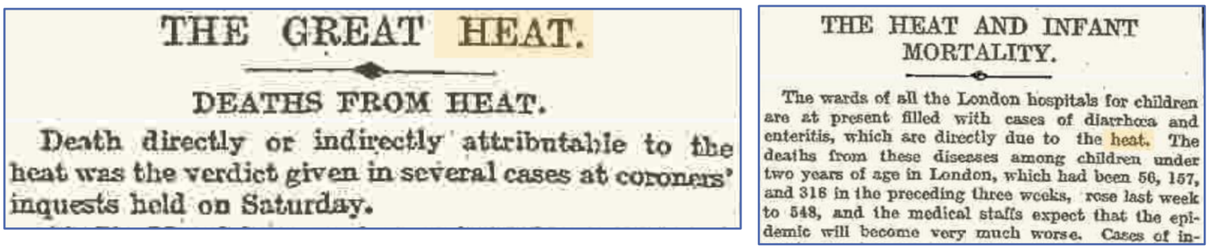
It is important to consider the drawbacks of using such an index and the threshold chosen, for example, if analysing an extreme weather event out-with the summer period or one that bridges two seasons. This highlights the importance of the choice of window length used to define a heatwave. For example, if a window length is used that extends into the autumn period this would make the heatwave threshold easier to breach. Therefore, the choice of window length and removing the seasonal cycle would yield different outcomes.

## 1.3 Exploring past heatwaves

**This section highlights the importance of learning from past data, weather and events. Some key early datasets that were fundamental to this thesis are outlined, as well as some considerations when using past data.**

### 1.3.1 Early instrumental datasets

By analysing long-term temperatures, it is possible to increase our understanding of natural climate variability and to place current changes and events into a historical context. 1850 is usually considered the approximate date from which major national weather services commenced as well as the introduction of the use of international standards. Records dating prior to 1850 are hence entitled "early instrumental data" (Brönnimann et al., 2019). The first barometers and reliable thermometers were developed during the $17^{\text{th}}$ century (Jones et al., 2006) at which time the first measurements of temperature and pressure were made in Europe (Brönnimann et al., 2019). A strong coverage of European measurements was established by the first half of the $18^{\text{th}}$ century (Lundstad et al., 2023). Some of the World's longest current temperature series include records from De Bilt, Berlin and Uppsala, with temperatures recorded from the 18th century and Paris Temperatures and the Central England Temperature (CET) records from the $17^{\text{th}}$ century. The CET dataset (Parker et al., 1992) was first published by Gordon Manley in 1874 providing monthly values for each year back to 1659 (making it the longest instrumental temperature record globally) and was subsequently updated and made available on a daily basis back to 1772 by Parker et al in 1992 (Jones et al., 2006). The CET dataset represents temperatures across the approximately triangular area enclosed by Lancashire, London and Bristol in the UK. Another example is the Radcliffe Meteorological station located in Oxford which has meteorological records dating back to 1772. From November 1813, a continuous daily



THE GREAT HEAT.

DEATHS FROM HEAT.

Death directly or indirectly attributable to the heat was the verdict given in several cases at coroners' inquests held on Saturday.

THE HEAT AND INFANT MORTALITY.

The wards of all the London hospitals for children are at present filled with cases of diarrhoea and enteritis, which are directly due to the heat. The deaths from these diseases among children under two years of age in London, which had been 56, 157, and 318 in the preceding three weeks, rose last week to 548, and the medical staffs expect that the epidemic will become very much worse. Cases of in-

**Figure 1.1:** Sample extracts from The Times archives highlighting impacts of the 1911 heat as discussed in chapter 2 (Times, 2020)

air temperature record exists. Rainfall and sunshine measurement records began in 1827 and 1880 respectively. This makes them the longest single-site weather records in the UK (Burt et al., 2019). Both the CET dataset and temperature measurements from the Radcliffe Observatory are used in chapter 2 of this PhD.

### 1.3.2 Documentary evidence

Documentary evidence such as log-book data, can also be used to understand past climate. This is particularly suited to better understand extremes and unusual weather as rare events are often recorded and discussed in historical documentation prior to the introduction of standardised temperature and meteorological records. The field of historical climatology (Brázdil et al., 2005; Brönnimann et al., 2018; Pfister et al., 2018; Cheval et al., 2021; White et al., 2023) studies and interprets descriptive documentary evidence, such as newspaper reports, relating to weather extremes (see Figure 1.1). This can be useful in understanding the evidence for weather and climate anomalies, the cause of past extremes as well as understanding the vulnerability of past societies to extreme events.

As well as historical documentation, other proxies can be used in order to determine past climate. A proxy is a record preserved in a natural archive which contains information about past climate. Such proxies include the use of ice-cores, pollen and tree-rings (PAGES2k Consortium et al., 2017). Networks of tree-ring proxy data have been used in order to create climate field reconstructions. Tree-ring data have been used in order to reconstruct summer wetness and dryness over Europe and the Mediterranean Basin throughout the Common Era (Cook et al., 2015), entitled the Old World Drought Atlas (OWDA).

### 1.3.3 Renalyses

Brönnimann et al. (2019) are working on the creation of a global inventory of meteorological measurements prior to 1850 and the commencement of national weather services. The NERC large grant GloSAT group, which funds this PhD, aims to generate new estimates of global surface air temperature extending over more than two centuries by the use of early marine surface air temperature records such as from the fleet of English East India Company from 1789 to 1834 as well as from land stations prior to 1850 (GloSAT, 2023). Retrospective analysis or "reanalyses" use a variety of atmospheric, land surface and ocean observations and assimilate them into a model. The aim of this is to provide dynamically consistent estimates of climate. Several reanalyses projects have been created, for example, the Twentieth Century Reanalysis (20CR) project aims to produce a global atmospheric circulation dataset spanning the $20^{th}$ century and into the $19^{th}$ century, and assimilating surface pressure reports. This reanalysis uses proxy data and early instrumental data alongside model simulations in order to create a 3D model of the atmosphere (Compo et al., 2011). This reduces the uncertainty compared to using sparse direct measurement data alone. This reanalysis assimilates surface observations of synoptic pressure and by using NOAA's Global Forecast System, sea surface temperatures and sea ice distribution are prescribed. This allows for estimates in variables such as temperature, pressure, winds and moisture. Some limitations of 20CR include the fact that fields tend to be less accurate in areas and time periods with sparse observations. This includes Southern Hemisphere fields for example which tend to be less accurate than Northern Hemisphere fields. It is thought that more observations could strongly effect performance of future versions of 20CR. In addition, as 20CR assimilates the surface pressure only, studies show that this may not be adequate for upper-atmosphere studies (Slivinski et al., 2021). The most recent version at the time of writing was used in this thesis, V3, which spans from 1836 to 2015 (Slivinski et al., 2019; Slivinski et al., 2021). This version shows an improved overall performance than previous versions of 20CR including in the $20^{th}$ and $21^{th}$ centuries (Slivinski et al., 2021). This allows past events to be reconstructed, exploring synoptic conditions during past events including floods and windstorms for example (Hawkins et al., 2023). As datasets are extended further back into the past, this creates an opportunity to find and analyse extreme events including heatwaves and droughts that have not previously been studied in great depth.

### 1.3.4 Importance of data from the past

Long datasets (including reanalyses datasets) provide vital information on the natural variability of the climate as well as allowing the impact of external factors such as volcanic activity and changing ENSO and NAO patterns (Dieppois et al., 2021) to be understood. Long term data sets can also provide model validation and can be used to assess the natural range of variation of extremes and rare events (Compo et al., 2011). Without long term temperature records the magnitude of natural forcing could be under or overestimated. This could lead to inadequate adaptation plans or being unprepared for future extreme events or weather conditions. This becomes particularly apparent when considering the analysis conducted on the extreme cold during 1740 following the unusual warmth of the 1730s (Jones et al., 2006). 1740 is one of the coldest years on record in the CET dataset resulting in what is considered the “forgotten famine” in Ireland. 1740 followed a rapid warming in the CET dataset from the 1690s to the 1730s showing a high magnitude of natural variability. Without this early analysis, it is possible that the spread of extremes could be underestimated. If the natural variability is underestimated or the range of variability unknown, then the range of potential future climate states could also be underestimated having a large impact on climate change adaptation and mitigation (Cook et al., 2015). Therefore, the study of past extreme events is critical in order to improve future predictions and scenarios.

### 1.3.5 Considerations when using past data

While long-term temperature records are vital to increasing our understanding of natural variability and providing numerous “samples” of extreme events, the data must be used with caution. Using data from the recent past provides more observations with more complete data and a higher universality to measurement practices when compared to early instrumental data (Hegerl et al., 2019). Prior to the introduction and acceptance of international standards of meteorological measurements, the issue of homogeneity arises. An example of such practice is the introduction of the Stevenson Screen around 1864. Prior to this, a hot bias for days of high sunshine could exist for those stations and measurements that were not sheltered by a screen (Böhm et al., 2010). This therefore needs to be taken into consideration when analysing extremes in the past record to ensure that biases are taken into account.

## 1.4 Heatwaves and climate change

**Using past temperature datasets and expanding our understanding of past heatwaves allows us to put current events into historical context and allows us to learn lessons from the past. However, due to climate change, heat events have changed and will become more intense and more frequent in the future. The following section outlines extreme event attribution, a method for understanding the influence of anthropogenic climate change on present day extreme events. We introduce the analogue method which is used in chapter 3 to explore what heatwave intensity could look like in the future under different warming scenarios.**

### 1.4.1 Introducing extreme event attribution

In order to identify the role of human influence on a weather event, extreme event attribution can be used. This technique is used to explore the extent to which anthropogenic climate change impacts the likelihood and intensity of an observed event (WWA, 2023; Otto et al., 2016). Extreme event attribution can be conducted using observational records and climate models. Observational records can be used to determine changes in the probability or magnitude of a particular type of event. The rarity of a particular event can be determined using long-term historical data. This means that extreme event attribution can be difficult for events that occur in regions with a lack of historical observations (Otto et al., 2020). Observations can also be used to see the dynamic context and contribution of different factors leading to an extreme event which can then be used as a benchmark in future model simulations (National Academies of Sciences, 2016) Models, on the other hand, are used to isolate the effect of anthropogenic warming in the event. This is completed by simulating the event and comparing the likelihood and intensity of the event in today's climate and a hypothetical world with no anthropogenic warming (Van Oldenborgh et al., 2021). Confidence in the models comes from the assurance that models are reproducing anomalies for the right cause, in other words, that they are representing underlying mechanisms accurately (Fischer et al., 2015; Stott et al., 2016; Van Oldenborgh et al., 2021; Otto et al., 2018).

Attribution studies completed by the World Weather Attribution group (WWA, 2023) aim to determine how climate change influences the intensity and likelihood of an extreme weather event days or weeks after the event unfolds. This allows scientifically robust information to be factored into decision making and public communication at the time of, or just following an event. Studies also investigate how vulnerability prior to the event impacted outcomes. For example, it was found that climate change made the extreme heat in North America, Europe and China during July 2023 much more likely, (Philip et al., 2023) with the heat experienced in US/Mexico and the South of Europe being virtually impossible to occur without global warming. On the other hand, increasing population and water consumption were found to increase vulnerability during the 2014-2015 drought in the Southeast of Brazil. In this example, anthropogenic climate change did not have a major influence on the event (Otto et al., 2015).

Currently, we have a strong understanding of the effect of climate change on extreme heat and have high confidence in capabilities for attributing specific extreme hot periods to anthropogenic climate change (National Academies of Sciences, 2016) however, challenges remain. For example, many changes can drive local or regional heatwave trends that can enhance the intensity of heatwaves or counteract the impacts of climate change. This includes processes such as land use change, air pollution or a change in local vegetation as well as soil moisture for example (Van Oldenborgh et al., 2022). Studies such as this are vital when considering the risks that extreme events pose to society as well as considering how human activities are now changing these risks, particularly through the emission of greenhouse gases. Risks faced by society include; loss of life, rising food and energy prices as well as increasing cost of disaster relief and insurance (National Academies of Sciences, 2016). An assessment of climate and non-climate causes of extreme events can, therefore, allow for accurate evaluation of changing risks over time and can be used in planning for the future in risk management assessments.

A further example of attribution was conducted by Fischer et al. (2015) in which an estimation was made of the fraction of heavy precipitation and hot extremes attributable to warming globally, as opposed to an individual event. In the study, it was concluded that 75% of moderate daily hot extremes today can be attributed to warming. It was found that the probability of a hot extreme at 2°C of warming is approximately double the probability at 1.5°C and around five times higher than present day levels.

### 1.4.2 Analogues

The event attribution technique known as the analogue method, developed by Yiou et al. (2007) can be used to analyse temperature anomalies based on past relationships between temperature and atmospheric circulation (Cattiaux et al., 2010; Vautard et al., 2016). This method aims to separate the thermodynamic from the dynamic elements of extreme events. Thermodynamic elements of climate change are quite certain, whereas dynamic elements including atmospheric and oceanic circulation tend to be highly uncertain (Shepherd, 2016). The analogue technique can also be used to determine relationships between atmospheric circulation and rainfall (Wilcox et al., 2018) and atmospheric circulation and soil moisture content (García-Herrera et al., 2019) as well as temperatures (Harrington et al., 2019; Jézéquel et al., 2018c; Jézéquel et al., 2018b; Undorf et al., 2020a).

A key example of the use of the flow analogue methodology is in relation to the 2010 winter in Europe (Cattiaux et al., 2010). The winter of 2009/2010 featured several severe cold spells. By finding previous winter cold spells with similar circulation patterns, it was found that the winter of 2010 was actually warmer than what would be expected for the types of circulation patterns encountered. The analogous conditions from past winters were linked to much colder temperatures than were witnessed during 2010. This is therefore considered as a cold extreme in the context of a warming climate. This study is also politically relevant as the cold spells during this winter were discussed following the Copenhagen climate negotiations, fueling debate about climate change impacts and global warming.

Analogues will be explored further in chapter 3 where this technique is used to understand what the heatwave events selected in chapter 2 would look like in today's climate, i.e. projecting the heatwave from the past (19$^{th}$ or 20$^{th}$ century) to the future.

## 1.5 Preparing for heat and extreme events

**After exploring past heatwaves in chapter 2 and potential future heatwaves in chapter 3, this thesis then analyses how public sector organisations in Scotland are approaching risk assessments and adaptation. The following section introduces the concept of adaptation before discussing climate risk in detail which is a fundamental part of adaptation planning. This section covers some key approaches and methodologies for communicating and understanding the risk of extremes including how attribution is used in this context as well as "storylines". These are interdisciplinary approaches to climate risk and adaptation with input from the physical and social sciences.**

### 1.5.1 What is climate adaptation?

Adaptation refers to the adjustment of human systems to expected or actual climate impacts. The overall aim of adaptation is to reduce risk, where risk is defined as the interaction of hazards, exposure and vulnerability. Key stages of adaptation are awareness, risk identification and assessment, implementation followed by monitoring and evaluation (Moser et al., 2013; IPCC, 2023; Jones et al., 2011).

| **Term** | **Definition** |
|---|---|
| Adaptation | Managing and reducing the negative impacts of climate change |
| Mitigation | Reducing greenhouse gas emissions that contribute to climate change |
| Risk | Interaction of a hazard, exposure and vulnerability where a hazard is a physical event such as a flood or heatwave, exposure is the regional area in which the hazard may occur and vulnerability refers to the propensity of those exposed to suffer. |
| Resilience | Building long-term capacity and enhancing a regions ability to absorb shocks or to recover from a hazard or impact of climate change. Leading to transformative change. |
| Maladaptation | Poor or insufficient adaptation action. When actions that were implemented to reduce the impacts of climate change actually increase risk or vulnerability. |
| Transformative adaptation | Similar to resilience, transformative adaptation looks to address the root causes of vulnerability, leading to societal or systems change. |
| Climate Ready | With no standard definition, "climate ready" usually relates to the organisation or nation's plans to adapt and to reduce the negative impacts of climate change. In certain circumstances the term relates both to climate adaptation and mitigation plans. |
| Adaptive Capacity | The ability of a system to adapt its behaviours or characteristics to the impacts of climate change and to expand the range of climate variability or future climate conditions it can cope with. |

**Table 1.1:** Adaptation key definitions

Typical adaptation actions include flood barriers (Coaffee, 2019) such as the Thames Barrier, nature-based solutions including tree planting to reduce flooding risk and to provide shade during heatwaves and lastly, training and preparing for heatwaves. For example, in Ahmedabad, India, 1300 lost their lives during a heatwave in 2010. Following this event, the region implemented a Heat Action Plan including training health staff, water distribution and painting roofs with white, reflective paint (GCA, 2019).

Discussions and research on adaptation have been hindered in previous years by a stronger focus on climate mitigation. The terms "mitigation" and "adaptation", as well as commonly used terms such as "resilience" are defined in Table 1.1. These terms and concepts are explored further in Chapter 4. It was thought that reducing global emissions would make adaptation unnecessary (IPCC, 2023). Mitigation and adaptation were considered to be competitive methods of reducing the impact of climate change on society and so a strong focus on adaptation was thought to be a sign of 'giving up' on climate mitigation or, at the very least, taking critical resources away from mitigation action (Urban et al., 2021). Adaptation research has increased greatly since the 1990s, however, adaptation gaps remain both in knowledge and in implementation (Milhorance et al., 2022; UNEP, 2022). Chapter 4 outlines key adaptation implementation challenges highlighted by public sector bodies in Scotland and the strong policy focus on mitigation as opposed to adaptation is mentioned here.

### 1.5.2 How is adaptation measured?

A key knowledge gap in adaptation science research is in relation to measuring and monitoring "effective" adaptation (Singh et al., 2022; Dilling et al., 2019; Schipper, 2022; IPCC, 2023). The fact that mitigation efforts are more easily measured in comparison to adaptation was a reason given for why adaptation implementation is seen as more complex than mitigation in the Scottish public sector, meaning policy implementation is lagging behind mitigation. Gaps in adaptation implementation are also found at a global level (UNEP, 2022). The Paris Agreement in 2015 created the Global Goal on Adaptation (GGA) aiming to increase resilience and reduce vulnerability to climate change by developing adaptive capacity. Since 2022, more than a third of countries have incorporated some form of quantified adaptation targets, however, the majority of these targets do not capture the outcomes of adaptation action and are instead process related outcomes such as those related to tree planting or developing adaptation plans (UNEP, 2022). Scotland sets out its national adaptation strategy through the Scottish Climate Change Adaptation Plan (SCCAP). Progress reports are completed independently by the Climate Change Commission and in the 2022 report to the Scottish Parliament the CCC recommends that the Scottish Government set quantified targets for SCCAP outcomes to increase accountability. Would having UK or sub-national adaptation targets increase adaptation action? This question is discussed in the Discussion and Conclusions chapter.

### 1.5.3 Climate risk

Assessing climate risk is a key part of adaptation planning and implementation including making climate risk visible in decision making (Currie-Alder et al., 2021). The key objective of the UNFCCC is to "prevent dangerous human interference with the climate system" (*UNFCCC* 2019). Following the agreement made during COP21 in Paris in 2015, this aim was developed into the Paris Agreement which entered force in November 2016. The Paris Agreement aims to reduce the risks and impacts of climate change on a global scale and to strengthen the global response to global warming. In light of the Paris Agreement, and subsequent Conference of Parties, researchers in the field of climate science began considering in earnest what the key priorities for climate research should be (Sutton, 2019)? What role should the field of climate science and individual climate scientists take in providing policy-relevant information (Jebeile et al., 2023; Dilling et al., 2011)? How best can climate science be communicated to the public sphere and who is responsible for ensuring successful communication? How can studies of extreme events and attribution aid adaptation and risk management related decisions? Sutton (2019), states that "climate change is a problem in risk assessment and risk management". A risk assessment should include not only what events are possible and their likelihood but also the impact and consequences of such an event. The IPCC state that risk is determined by a hazard i.e. a weather or climate event as well as the exposure and vulnerability of the society or ecosystem impacted, see Figure 1.2. In other words, the hazard is not the sole driver or determinant of the risk. Climate risk emerges from the interactions amongst the determinants of risk; hazards, vulnerability and exposure. This is the definition or the risk concept that has been used in this research. IPCC AR6 uses this risk concept while also discussing how the overall risk is additionally shaped by responses to climate change. The future direction of risk concepts will likely include a response "propeller" to look at the potential risks from responses both to adaptation and mitigation. While this is discussed briefly in this research, the key risk concept used is that of risk emerging from the overlap

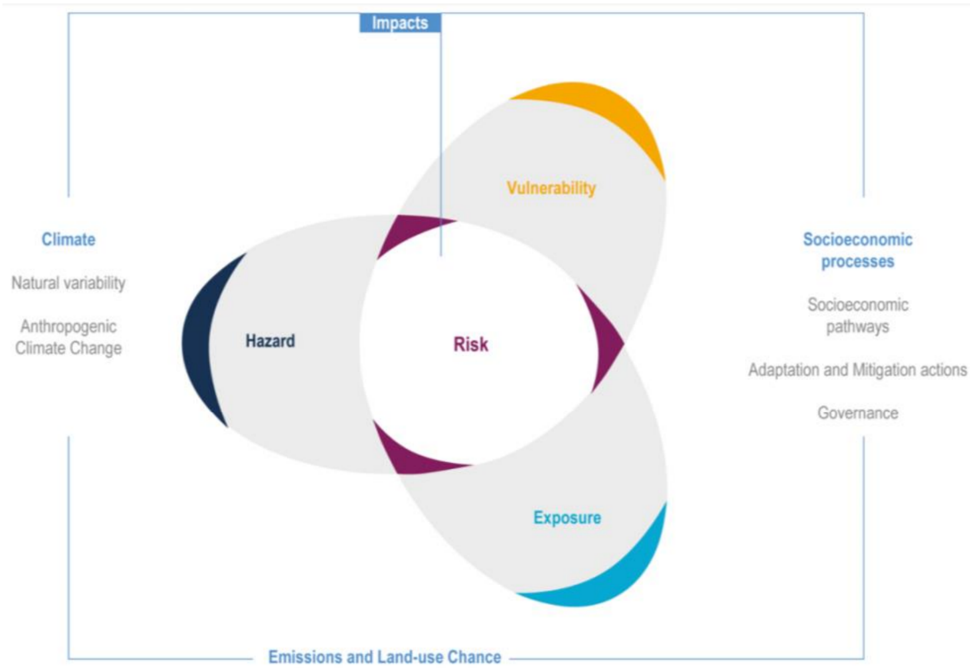



**Figure 1.2:** IPCC risk graphic showing risk as a function of hazard, exposure and vulnerability and highlighting the link between climate, socioeconomic processes and impacts (IPCC, 2023)

of a hazard(s), vulnerability and exposure (IPCC, 2023). A general approach to risk management commonly includes; risk identification, risk reduction, risk transfer and a form of disaster management. Although, it is evident that each sector considers and handles risk differently (Stott et al., 2013).

### 1.5.4 Communicating climate risk

As risk depends not only on the extreme event itself but also on exposure and vulnerability, any risk management or adaptation planning should focus on reducing this exposure and vulnerability as well as increasing resilience to impacts (IPCC, 2023). The importance of assessing the impacts of extreme events makes risk management an interdisciplinary field as expertise is required to provide information on future climate, biological systems and ecosystems as well as social science inputs (Sutton, 2019; Schipper et al., 2021). The fact that these disciplines are often siloed can dampen communication and information sharing which can lead to the development of different frameworks for analysis.

Extreme event attribution is a powerful tool used to communicate the risks associated with climate change and to what extent they are influenced by anthropogenic climate change. This approach has allowed the wider public to see the "fingerprint" of climate change in our everyday lives, making a direct link between climate change and changing weather events. Additional sectors including legal, state that attribution could be used in liability or damage and loss cases following extreme events (Stott et al., 2013). The use of attribution in future planning and adaptation decisions has been queried by some, including Hulme et al. (2011). He warns against the use of attribution as a means of allocating resources for adaptation as he believes the focus should be on building resilience and decreasing vulnerability regardless of whether events have been attributed to a greater or lesser extent to anthropogenic causes. However, extreme event attribution can be particularly useful for adaptation decision making and communicating climate risk by understanding the influences of different factors on an extreme event. For example, by understanding if events are more greatly influenced by anthropogenic climate change or by increased exposure or vulnerability (Otto et al., 2015). The use of attribution and analogues to understand the human influence on events as they occur or to explore what extremes could look like in the future could be a useful tool to help decision makers better understand current and potential future hazards. This research will also complement adaptation research into resilience building and how adaptation decisions can be made that are equitable, just and effective (IPCC, 2023; Malloy et al., 2020; Vogel et al., 2007).

Another method of communicating risk to help decision makers is the use of "storylines". Storylines tend to focus on the plausibility rather than the probabilities related to a certain event or pathway. There are different uses of the term storyline in the literature. In this PhD, the focus is on physical climate storylines. These are defined as a "physically self-consistent unfolding of past events, or of plausible future events or pathways" (Shepherd, 2019; Baulenas et al., 2023; Sillmann et al., 2021; Van Garderen et al., 2021). In the words of Sutton (2019), storylines could be considered "decision-relevant climate scenarios", they explore sequences of events from causes to impacts (Sánchez-Benítez et al., 2022; Van Garderen et al., 2021). Physical climate storylines tend to focus on the intensity of past or potential future events (Stott et al., 2023). The term "storyline" is also used in certain contexts to mean a narrative, or a discourse analytical approach. In this context, a narrative is made of storylines that characterise societal views or perspectives on a given subject. In addition, the term "storyline" is used in the context of scenario based approaches, such as in the IPCC Shared Socio-economic scenarios. The different uses of the term "storyline" are summarised in Table 1.2. In terms of adaptation, understanding how severe events could be and what events must be avoided can help in planning, and storylines could be a method used to explore this. They should have an emphasis on understanding the factors involved in driving an extreme event as well as the plausibility of those factors and can be used to communicate uncertainty of the physical aspects of an extreme event. By creating a "simulated experience" (Shepherd et al., 2018), potential futures can become more plausible which is important as human societies can have trouble responding rationally to risks, especially ones they have not experienced previously. This can cause problems, particularly when discussing risks or rare events. The storyline approach could be effective when considering compound events as well as past events or sequences of events. A compound event is defined here as a combination of climate drivers or hazards leading to large impacts such as a heatwave and a drought in a particular location occurring simultaneously (Zscheischler et al., 2018). In this case, the physical aspects of the event should be considered, for example, local circulation as well as the impact of the event and any adaptation measures put in place after the event. In this way, storylines can link the physical side of climate change to the human aspect. In a recent paper by Raymond et al. (2020) focused on understanding connected (or compound) events, storylines were discussed as being a "socio-physical approach" to connected events as opposed to a statistical approach or a modelling approach. In this paper, the strengths of using storylines were cited as being the fact that they can identify high-impact events or compound events that could be missed by using probabilistic assessments alone. The key weakness of storylines identified was the fact that they can require many assumptions about future scenarios if used to set out how an extreme event may unfold in a warmer world. Other uses of storylines are outlined in Table 1.3.

Storylines can merge a top-down approach i.e. the use of climate models for prediction, with a bottom-up approach i.e. focusing on past and present vulnerability of a location (Conway et al., 2019). There is a strong need to integrate both approaches and to consider the socio-economic and non-climate factors that are also relevant for adaptation planning.

By focusing on extreme events in the recent past, sensitivities and opportunities for learning could be found. An IPCC report focused on extremes (Field et al., 2012) states that there is a "lack of a comprehensive conceptual framework to facilitate common multidisciplinary risk evaluation", therefore, storylines (and regional scenarios) within an integrated top-down, bottom-up approach could help address this. Storylines applied to extreme event decision making is a relatively new approach and therefore there is limited literature at present offering a critique of the method or highlighting its effectiveness in practice. We find in this research, with reference to chapter 4, that while this is not a tool that is currently being widely used in the Scottish public sector, some believe it could be useful.

| **Type of climate storyline** | **Summary/Examples** |
|---|---|
| Narrative/discourse analytical approaches | Narratives tend to characterise societal views, understandings or perspectives on a given topic. Groups or sets of storylines may form a narrative that tend to be qualitative in nature. This includes the investigation and analysis of climate change discourses and how media or policy makers frame climate change for example. This form of storyline used in social science and policy fields, is used to explore societal perceptions on a topic and how this becomes embedded in public policy. |
| Scenario based approaches | Scenario based approaches tend to include qualitative descriptions of plausible futures. For example, this form of storyline is used in the IPCC Shared Socioeconomic pathways, describing the scenario and the potential future pathways in a qualitative way. |
| Physical climate storylines | Physical climate storylines are physically self-consistent unfoldings of plausible future events or pathways or past events. They aim to represent uncertainty in the physical aspects of climate change. Event-based storylines are examples of physical climate storylines where drivers and impacts of future weather (or past events) are investigated or analysed. |
| Commonalities: Emphasise qualitative understanding; focus on plausibility rather than probability of a certain event, pathway or future. | |

**Table 1.2:** Types of storylines (Baulenas et al., 2023; Shepherd et al., 2018)

| Use of physical climate storylines | Summary/Examples |
|---|---|
| Risk awareness | Storylines can help to improve risk awareness by making potential futures more tangible. Physical storylines tend to reproduce a climate event that people may have experienced or one that people can relate to hence addressing the availability bias where individuals may find it hard to relate to an event or potential future outside their own experiences. Storylines ask what events might be like in the future which relates more to our experience of events as opposed to a semantic approach which may be focused on the return period of an event for example. |
| Decision making | Storylines can be used in decision making contexts through, for example, stress testing. This can consist of working through potential events or compound events and the impacts they could have. This also allows one to work backward from the point in which a decision was made and also for the combination of different forms of climate change information. Understanding the strength of evidence behind different or competing explanations could help with decision making. This concept is similar to practices used in disaster risk management using "stress-testing" for emergency preparedness. This can be based on plausible future or past events with assumptions made on the potential exposure and vulnerability of the affected system or location. |
| Uncertainty Partitioning | Storylines can be used to separate the thermodynamic from the dynamic elements of extreme events. Thermodynamic elements of climate change are quite certain, whereas dynamic elements including atmospheric and oceanic circulation tend to be highly uncertain. Event analogues are a specific method for partitioning uncertainty. |
| Exploring worst case scenarios/boundaries of plausibility | Storylines can be used to explore low likelihood, high impact events. For example, events from the past could be explored as well as potential future events that are plausible in the place of interest. Storylines have been used in the field of hydrology for example to provide explainable and actionable information from deterministic physically-based hydrological models, driven with hydrometeorological events. In this context, storylines can support the understanding of risk causality including local conditions while placing the plausible impacts of extreme events into context that are not well captured by probabilistic representations alone. |

**Table 1.3:** Uses of storylines (Shepherd, 2016; Shepherd et al., 2018; Sillmann et al., 2021; Caviedes-Voullième et al., 2023; Hurk et al., 2023)

### 1.5.5 Key considerations in risk and adaptation decision making

A key consideration in risk assessments is communication effectiveness (Asrar et al., 2013), including the communication of uncertainties. While many studies have taken place related to extreme event attribution providing quantitative results, it can be more difficult to provide "sufficiently well calibrated information" to enable a user to fully understand the "limitations of the information" provided to ensure it is used correctly (Asrar et al., 2013). Indeed, a knowledge gap exists between extreme experts and non-experts (Field et al., 2012) and therefore strategies for the effective communication of climate risk and its associated uncertainties are required.

Many stakeholders will need to be active in this communication as local, regional and global actors will require different risk management approaches and strategies (Field et al., 2012). At the local level, areas that have not experienced extreme events may not be likely to respond until a "crisis" is perceived. A key focus for climate scientists has been to understand the likelihood or probable range of events as opposed to identifying low probability, high impact events (Sutton, 2019; Wood et al., 2023). Dessai et al. (2004) suggests that strategies should be put in place that can enhance "coping capacities", that can therefore work for a range of possible future scenarios, including low probability, high impact events. A methodology could be used to combine conditional probabilities with scenarios that are relevant for decision making. This could bring "robust information" to policy makers with assessments focused both on quantitative and qualitative elements. By focusing on probabilities and ranges of event occurrence alone there is a potential for some high impact potential scenarios to be missed, highlighting again the importance of communicating uncertainty. Storylines could play a key role in developing an understanding of low probability but high-impact events in order to allow a risk management assessment to cover the impacts of potential "worst-case" scenarios. Many risk assessments in the private sector are completed based on probabilities using time series of past data, or frequentist probabilities. Whereas any probabilities on future climate will have higher levels of uncertainty and so these practices should perhaps be differentiated appropriately.

Climate tipping points are usually considered to be examples of low likelihood, high impact events. A tipping point is a threshold over which a system reorganises often irreversibly. There are several Earth system components that act has tipping elements, i.e., they are susceptible to a tipping point. Such components include the collapse of the West Antarctic and Greenland ice sheets, boreal forest dieback and the collapse of the Atlantic Meridional Overturning Circulation, AMOC (Lenton et al., 2019). It has been suggested that the uncertainty around reaching climate tipping points could be used when considering climate policy and making decisions on both adaptation and mitigation (Lontzek et al., 2015). Discussing tipping points can, for example, increase the urgency and the understanding of the need to act on climate change amongst stakeholders. In addition, through the use of storylines, decision makers could stress test their decisions and practices helping them to understand their level of coping capacity. Globally, reaching certain tipping points could lead to increased rates of sea-level rise for example. Regionally, reaching climate tipping points could change weather patterns. For example, (Ritchie et al., 2020) show that an abrupt shut down of the AMOC could lead to a widespread loss of arable land in the UK due to a drier climate. Risk management approaches considering tipping points tend to focus on the importance of transformational adaptation that increases the capacity of systems or organisations to cope with potential future hazards or events that impact upon human or natural systems (OECD, 2022). We find that tipping points are being discussed in some Scottish public sector bodies, as examples of potential worst-case scenarios and also to motivate action on both adaptation and mitigation.

Researching past events and past time series can be useful for highlighting vulnerabilities in certain regions for adaptation actions and implementation (Asrar et al., 2013) however, as future warming could be unprecedented, working solely on past data will have its limitations (Dessai et al., 2004). How sensitive current risk management plans for key sectors are to changes in probabilities related to extreme events could be investigated, as well as the role of climate scientists in risk communication. Based on our research in chapter 4 we find that generally risk approaches in the Scottish public sector tend to rely heavily on past data and past events as opposed to using future-looking scenarios for example.

### 1.5.6 Comparison of methodologies for exploring potential future events

In this research, analogues as a form of storyline are used to explore potential future heatwave events. The key area of focus is to explore what potential heatwave events could look like in the future. Analogues of past events are used as this can increase the availability bias of stakeholders and decision makers. Decision makers can also stress test their strategies or decisions by exploring how they could cope with heatwaves at different levels of warming, if they were to occur. Analogues use models to ground the storyline in reality using models as a tool as opposed to making quantitative predictions. Alternative approaches include a more probabilistic lens, asking how more or less likely events are in the future. These tend to focus on events in general as opposed to using lessons from unique events in the past and tend to focus on the probability of future events as opposed to the plausibility of future events. This approach can also be useful to decision makers, to understand how likely events are in the future although the uncertainty associated can sometimes be difficult to communicate. In addition, return periods can be misunderstood by decision makers as highlighted in Chapter 4. Alternative probabilistic approaches tend to attach likelihoods to future states or events. A method of investigating this is through a generalized extreme value (GEV) theory approach. When applied to heatwaves, changes in temperatures during events can be characterised using the generalized extreme value distribution which can estimate changes in the probability of rare and extreme events (Slater et al., 2021). GEV theory enables the calculation of return values for rare, extreme events including heatwaves (Schär et al., 2004; Chan et al., 2020). For example, (Slater et al., 2021) show that once-in-a-decade summer extremes could occur almost every year in a high warming scenario in the future.

An alternative to selecting analogues of an observed event, is to perform simulations and constrain models to reproduce aspects of the event of interest. This method can be called "nudging" hence ensuring dynamics between events are similar. This method requires judgements about how boundary and initial conditions as well as the thermodynamics are perturbed (Wiel et al., 2021; Sillmann et al., 2019).

Rare event algorithms provide a similar approach in which simulations are focused on trajectories leading to heatwaves over a specific region. This focus on extreme events optimises computational cost and resources and allows for the analysis of return periods of such events. A selection algorithm is used over an ensemble simulation and a weight is given to each trajectory which allows for the population of the tail end of the distribution of hot days over a specific region (Ragone et al., 2021). This technique, known as importance sampling can be used alongside circulation analogues principles to simulate extreme events realistically (Yiou et al., 2020a). The methods of nudging or rare event algorithms approaches are useful for simulating seasons and are less useful for the analysis of shorter events. Studies do also tend to focus on a larger spatial area than the area of focus in this PhD.

In summary, the analogue/storyline approach used in Chapter 4 was used in this research as it was deemed the most appropriate method for studying short-lived heatwave events over a relatively small region. The method focuses on the plausibility rather than the probability or likelihood of future events which allows decision makers to use results as a stress-test of potential future events. Stakeholders are able to relate to realistic weather events and ones that have happened in the past and the analogue method is generally well established and can be relatively easily communicated with stakeholders.

| **Method/ Approach** | **Key Focus** | **Salience (Relevance to decision makers)** | **Credibility (Scientific adequacy)** | **Legitimacy (Unbiased incorporation of divergent values)** |
|---|---|---|---|---|
| Analogues/ Storyline approach | Plausibility of future events | *High*<br>Decision makers can stress-test using storylines including investigating low-likelihood, high impact events | *High*<br>However, have been considered less scientific due to the focus on communication with stakeholders | *Medium High*<br>Can include stakeholders or expert elicitation particular to understand potential impacts or countermeasures |
| Nudging storyline/ Rare event algorithms approach | Likelihood or probability of future events | *Medium High*<br>Likelihood of future events is important for decision making but can be more difficult to communicate, including communicating uncertainties | *High*<br>An established approach | *Medium High*<br>Usually does not involve a large number of stakeholders - can make it more difficult to be used in a decision making space |
| GEV theory approach | Likelihood or probability of future events | *Medium High*<br>Studies tend to be over a larger geographic area less relevant for local decision making | *High*<br>An established approach | *Medium High*<br>Usually does not involve a large number of stakeholders – can make it more difficult to be used in a decision making space |

**Table 1.4:** Summary and comparison of methods

## 1.6 Interdisciplinary research

**This PhD research spans social science and physical science, addressing what we can learn from past heat extremes, what they might look like in the future and how data and knowledge such as this can be used to make adaptation decisions. This PhD therefore spans the climate impact chain from hazard to risk (Estoque et al., 2022). The following section highlights what interdisciplinary research is and why it is important in the study of extreme events and how we can prepare for them.**

### 1.6.1 What is interdisciplinary research?

Interdisciplinary research can be defined in a range of ways varying from field to field. In general terms, interdisciplinary research can be conducted by a team or an individual that integrates information, data, techniques, tools or perspectives from two or more disciplines or bodies of specialised knowledge in order to work on problems that cannot be solved through the lens of a single discipline (Academies, 2004; Lyall, 2019). This includes research that links disciplines with differing epistemic resources which can lead to divergent or hybrid research approaches or the creation of connections or bridges between disciplines (Müller et al., 2019). Interdisciplinary research can be split into two key categories that are not mutually exclusive, namely "academically oriented" and "problem focused" (Lyall, 2019). Academically oriented interdisciplinarity tends to focus on the potential creation of new or sub-disciplines that follow new or unique methodologies whereas problem focused interdisciplinarity is research that focuses on addressing social, technical or policy relevant problems. This form of research can be between disciplines or between academia and stakeholders or policy makers for example (Barry et al., 2008) with both types of interdisciplinary research suggesting that academia should consider how knowledge is applied and perhaps interpreted by the wider society.

### 1.6.2 Why interdisciplinary research is important

Interdisciplinary research is thought to be crucial in order to develop the innovative tools and approaches required to meet modern, complex challenges, such as climate change. This is evident from governmental bodies and funders in Europe and the UK, (Müller et al., 2019; Wohlgezogen et al., 2020) with funding bodies (UKRI, 2022) stating that they recognise that a number of pressing research challenges require interdisciplinary approaches. Climate change is a key area where there is political pressure for interdisciplinary research to propose and implement solutions (Schipper et al., 2021; Müller et al., 2019; Wohlgezogen et al., 2020). Due to the far-reaching impacts and potential future impacts of climate change and the requirement for solutions, environmentalism and climate are key areas where interdisciplinarity is discussed. Interdisciplinarity is considered a method for allowing coherent dialogue between researchers and stakeholders, leading to action (Wohlgezogen et al., 2020; Jeffrey Conklin, 2006). The IPCC working groups and reports are a clear example of different disciplines contributing to climate research as well as interdisciplinary climate research centres. It has been contested however that this mostly consists of interdisciplinarity between related disciplines as opposed to interdisciplinarity between the natural and social sciences (Wohlgezogen et al., 2020; Bjurström et al., 2011). In order to ensure that adaptation solutions are effective while avoiding maladaptation, collaboration between natural and social science is vital. By collaborating effectively, data and framework that meet the needs of decision makers can be developed and communicated effectively, ensuring a multitude of stakeholder needs are identified and included.

### 1.6.3 Interdisciplinary research in this thesis

In this PhD, the interdisciplinary approach taken is closer to a problem focused approach that includes "interacting" between or "linking" aspects of social science and natural science on the topic of extreme weather and adaptation (Frodeman, 2017). The aim of this research was to explore what we can learn from past extremes and how they may change with global warming to allow us to prepare for the future. While this research question could encompass many more disciplines, I focus on exploring the hazard (heatwaves in particular) which traditionally sits in physical science or the science of extremes as well as exploring how this type of data or knowledge about hazards is being used by policy makers. The aim was to close the gap between climate science research and the political context in which decisions are made by uncovering key implementation challenges (Schipper et al., 2021) around adaptation and the preparation for extremes in local government and the wider public sector.

The PhD is set out into four key research chapters where chapter 2 and 3 focus on the physical science of extreme heat events from the past to potential futures and chapter 4 focuses on the social science-based question of how public sector bodies are adapting to climate change. This was completed in collaboration with practitioners based in Scotland. Even though these are set out as discrete and separate chapters, information and lessons learnt from each one has been used to inform and make key decisions within the others.

For example, the Climate Change Committee advise organisations in the UK (Climate Change Committee, 2021a) to adapt to 2°C of global warming and to assess the risks for 4°C – therefore this was the focus provided to chapter 3 as it became evident that less research is focused on this as opposed to 1.5 and 2°C of global warming. Key questions were raised in this research around what knowledge and data is most useful for making decisions about extreme events and adaptation but also how this should be communicated. What kind of knowledge is needed to take adaptation action and how this knowledge is communicated is a key challenge. There are challenges associated with communicating or co-producing knowledge alongside stakeholders of different disciplines (Porter et al., 2017; Kirchhoff et al., 2015). There is also debate about whether this type of question fits within the realm of climate science as a discipline. However, usable climate information is fundamental to the future of this field of research and methods such as exploring risk, extreme event attribution and analogues are already offering new ways of conducting climate science that have a strong focus on how key findings are communicated and used by decision makers.

## 1.7 Motivation and PhD structure

**This section sets out the motivations behind this PhD and the key knowledge gaps this research contributes to. The structure of the PhD is also discussed and summarised in Figure 1.3.**

### 1.7.1 Knowledge gaps and thesis motivation

In a warmer world, it is very likely that the duration and intensity of heatwaves across most land areas will increase (IPCC, 2023). Due to the impacts that extreme heat events can have on society, such as on health, agriculture and critical infrastructure, an understanding of how society can best prepare and adapt to future extreme events is critical. It is becoming increasingly important to further our understanding of the causes, mechanisms and impacts of such events in order to ascertain the risk associated with weather extremes and to build resilience in current and future societal systems and infrastructure (Coaffee, 2019).

The study of past extreme events can increase our understanding by allowing current extreme events to be placed into historical context (Brönnimann et al., 2019). Early extreme events can provide information on natural variability in the climate system (Jones et al., 2006) as well as providing points of reference to assist future decision making, in order to allow us to learn from the past. Additionally, the study of a single event will add to the sample of observed events, thereby improving the understanding of mechanisms involved in heatwave events. Events can then be analysed in order to understand the difference in causes, mechanisms and consequences if they occurred in a warmer world. It is therefore important to study and learn from individual events in the past that have not yet been analysed fully as more early instrumental data becomes available. This form of study is vital to the wider public in order to be used in future planning and decision making (Baulenas et al., 2023; Sillmann et al., 2021; Shepherd, 2019). Therefore, this PhD begins with an exploration of past extreme heat events in the 19$^{th}$ and 20$^{th}$ century. This research identifies past heatwaves in the UK and makes comparisons to present day heatwave events. Some of the key impacts associated with these heatwaves are also explored. In this way, this PhD adds to the literature on early extreme events, providing case studies of early events that could be used in further research.

While many studies have focused on the changing return periods of events in a warmer climate (Stott et al., 2011), less studies focus on a particular region and outline what a past event, for example from the early 20$^{th}$ century, may look like in terms of intensity, in a warmer future (Cowan et al., 2020). In this PhD, we identify early heatwaves and project what they may look like in the future under different levels of global warming. We use the analogue method to do this, adding to the field of literature detailing this approach and exploring its limitations when used to analyse potential future heatwaves. In this PhD the focus is on how heatwaves may change in intensity which could be particularly beneficial for decision makers, for example, through the use of storylines.

The method of communicating the changing risk due to extremes is also an important current knowledge gap. This link between scientific study and the use of risk as a communication tool for the wider society has been identified as a knowledge gap in the IPCC special report on extreme events (Field et al., 2012). An evaluation of current risk management strategies is also cited as a knowledge gap in the special report on extremes events as well as the evaluation of risk management strategies (Field et al., 2012). A study into how risk is communicated is therefore required as well as how key sectors' risk management allows for the insertion of new hazard information. This could be beneficial for organisations completing risk assessments as certain industries are moving away from traditional risk assessment procedures towards a risk governance approach (Lass et al., 2011) where an understanding of the potential future intensities of hazards is important. As there is a lack of progress in the adaptation space in Scotland highlighted by the Climate Change Committee, we focus our research on Scotland. The 2022 report to the Scottish Parliament highlighted a lack of analysis of the adaptation section of public bodies duties reports in Scotland and this PhD research provides the first in-depth analysis of this section of the report at the time of writing. Therefore, this PhD addresses directly a knowledge gap identified by the Climate Change Committee (Climate Change Committee, 2022). Overall, this can help bridge the gap between climate science and decision makers by making it clearer what the requirements are for future tools, models and data to help accelerate adaptation action and how it is reported and evaluated.

### 1.7.2 PhD structure

The PhD is split into three key, interconnecting chapters detailed below and summarised in Figure 1.3:

Chapter 2, Analysing Past Extremes aims to understand the causes, mechanisms and impacts of past extreme heatwave events. This chapter includes a systematic search for past extreme heatwaves in the UK in the 19$^{th}$ and 20$^{th}$ century using instrumental and reanalysis datasets. The events detected in the past are then compared to more recent heatwaves, particularly the 2022 heatwave, in order to place this event into a historical context. This chapter also outlines some of the impacts suffered at the time of these past heatwaves from documentary evidence from the 19$^{th}$ and 20$^{th}$ century. This chapter is published as an article in the Royal Meteorological Society journal (RMetS) “Atmospheric Science Letters”.

Chapter 3, Extremes in a Warmer World explores how these past events may unfold in the future under different degrees of global warming. The past events are projected onto potential future climates using the analogue methodology. In this chapter, the limitations and benefits of using this technique to identify analogues and analyse potential future heatwaves are outlined. This chapter will be submitted to the journal “Environmental Research: Climate” in late 2023.

Chapter 4, Extreme Event Risk & Adaptation examines the progress made by the public sector in Scotland from risk assessment to adaptation planning and implementation. Key challenges faced by the Scottish public sector that are leading to a lack of progress in this space are discussed as well as some potential solutions. The Extreme Event Risk chapter

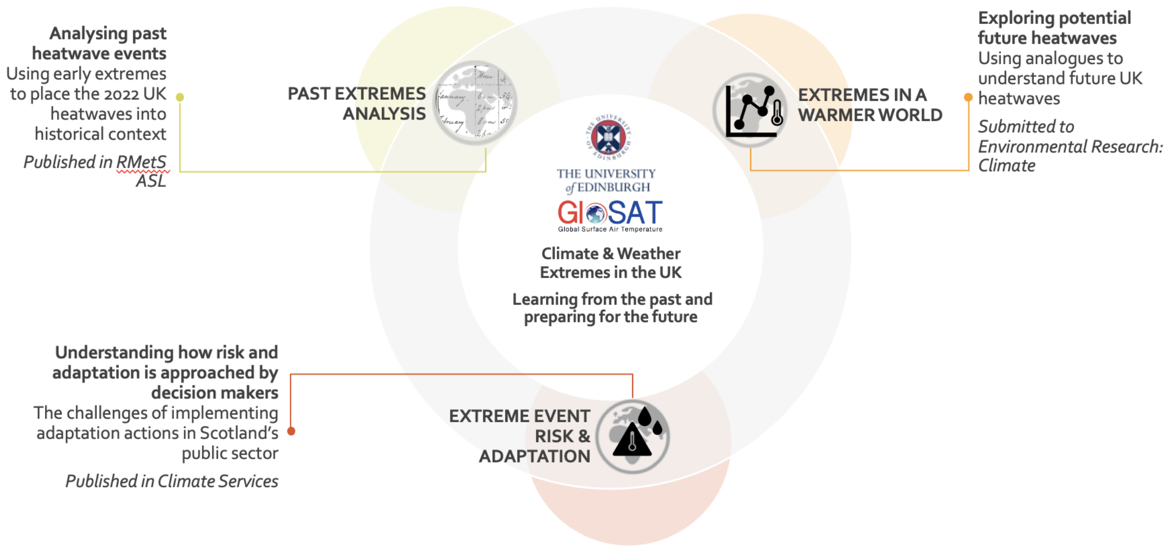



**Figure 1.3:** PhD Overview Diagram: Learning from the past to help understand the present and how to create a resilient future.
*(While the sections of the PhD presented in this diagram relate and overlap, the Past Extremes Analysis relates to Chapter 2 in this thesis, Extremes in a Warmer World to Chapter 3, Extreme Event Risk to Chapter 4)*

focuses on the link between the scientific study of extremes and what data and knowledge is currently being used or could be useful to decision makers. This chapter is the first in-depth analysis of public sector adaptation reports in Scotland addressing a key gap highlighted by the Climate Change Committee. This research has subsequently been used to create a framework for future annual report analysis which will allow adaptation trends over time to be understood in Scotland. This chapter has been accepted for publication in the journal "Climate Services".

The perspectives and conclusions are detailed in chapter 5 which covers the key outcomes from each chapter as well as perspectives on potential future work and interdisciplinarity. The term 'we' is used throughout this thesis, to refer to my supervisors and co-authors who are acknowledged at the beginning of each research chapter. I conducted and led the research presented in this thesis.

To summarise, this PhD has added to the scientific literature about early extreme heat events, allowing us to put the 2022 heatwave in the UK into historical context. Secondly, an investigation into what these events might look like in a warmer world was undertaken using the analogue methodology and focusing on the less frequently studied potential impacts at higher global temperatures. Thirdly, this PhD explores how Scotland's public sector is preparing for these changing extreme events directly addressing a knowledge gap identified by the IPCC and the Climate Change Committee. This comprised of undertaking the first national study of risk tools and approaches used by the public sector in Scotland for adaptation decision making and implementation.

The novelty of this PhD also lies in the interdisciplinary approach taken. This research focused on bridging the gap between the physical science of extreme events and risk management practices in the wider community. There is a strong requirement for applied climate science that meets the needs of practitioners and decision makers. This PhD brings together two conventionally separate research streams: the study of past and potential future heatwaves and risk data applications for adaptation. This interdisciplinary approach addresses a key knowledge gap highlighted in the third UK Climate Change Risk Assessment (CCRA3) that of investigating the end-to-end chain of risk, from hazard to adaptation implementation and the uptake of climate science by decision makers (Slingo et al., 2021). The PhD is split into four separate chapters to ensure enough depth is provided to each field; however, each chapter is interconnected using knowledge learned in one to influence others. This allows for discussion and investigation into what information, knowledge and data from extreme event science is most useful for policy makers and decision makers in the adaptation space, a critical step in preparing for future extremes and the impacts of climate change. The research that forms this PhD is therefore of interest to both the physical science community and the social science community. The scientific findings have been shared with the wider scientific community through journals and conferences and the adaptation research has been used by the Scottish public sector and by the Scottish Government, feeding into the development of Scottish Government Policy such as the third Scottish Climate Change Adaptation Plan (SCCAP3).

# Chapter 2

# Analysing Past Extremes in the UK

This first research chapter in the PhD is focused on early heatwaves, understanding what we can learn from past, summer heatwave events in the UK. This chapter aims to detect and analyse historical heatwave events, from around the early 20$^{th}$ century and to compare these with recent events, particularly, 2022, which featured four summer heatwave events in the UK. This allows us to understand how noteworthy historical extremes are in comparison to those in recent decades, to place modern events into historical context, and to extend the sample of extreme events that can used in further research. Summer heatwaves have been detected between 1878 and 2022 from long station data in the UK. Heatwave extent, duration, and intensity have been analysed to compare past heatwaves to the recent 2022 heatwaves. This research chapter has been published as an article in the Royal Meteorological Society journal (RMetS) "Atmospheric Science Letters":

*Citation: Yule, Emma.L., Hegerl, Gabi., Schurer, Andrew and Hawkins, Ed., 2023. Using early extremes to place the 2022 UK heatwaves into historical context. Atmospheric Science Letters [Online], 24(7), p.e1159.*
*Available from: https://doi.org/10.1002/asl.1159.*

**Table of Contents**

2.1 Introduction . . . . . . . . . . 32
2.2 Detecting heatwaves using station data . . . . . . . . . . 34
2.3 A comparison of past and modern heatwaves . . . . . . . . . . 37
2.4 Daily vs monthly temperatures . . . . . . . . . . 39
2.5 Case studies of heatwave years . . . . . . . . . . 41
2.6 Conclusion . . . . . . . . . . 45

## 2.1 Introduction

The magnitude and the frequency of heatwave events in Europe and around the world are expected to increase as the globe continues to warm (Fischer et al., 2010; Masson-Delmotte et al., 2021; Perkins, 2015; Russo et al., 2015; Schär et al., 2004). The National Weather Service in the USA regard heatwaves as the major cause of weather-related fatalities most years (Robinson, 2001) and in Europe, the 2003 heatwave resulted in the loss of life of up to 70 000 people (García-Herrera et al., 2010; Robine et al., 2008). The heat throughout summer 2022 has been estimated to have led to the death of 15 000 people in Europe and 3200 in the UK (WHO, 2022). There are race, class and gender disparities in heat extremes and who is most heavily impacted by them (Benz et al., 2021; Chakraborty et al., 2019; Steen et al., 2019). These disparities can relate to the heat island effect, the level of tree cover and green spaces in high versus low-income areas as well as to the density of the built environment amongst other factors. While a single day of heat will not generally result in increased mortality, two days of consecutive heat can lead to a substantial increase, particularly when night time temperatures are high (Perkins, 2015).

Heatwaves are normally defined as an extended period of unusually high temperature. Previous studies of heatwaves have used definitions with a variety of time and spatial scales (National Academies of Sciences, 2016; Xu et al., 2016). Definitions are usually based on the exceedance of fixed absolute values or a deviation from the normal such as from a daily mean or maximum value (Cowan et al., 2014; Donat et al., 2016; Robinson, 2001).

In this chapter, heatwave events that occurred in the 19$^{\text{th}}$ and 20$^{\text{th}}$ century in the UK are detected and analysed. A more detailed analysis of early observed events can help to understand decadal variability in heatwave activity (Beckett et al., 2022; Burt, 2004; Hegerl et al., 2019; Sanderson et al., 2017) and improve the sampling of conditions that lead to rare extreme heat, and with that improve preparedness for events with similar mechanisms in the future. While many studies focus on recent heatwave events, including attribution (National Academies of Sciences, 2016; Stott et al., 2016) for example, past events in the early instrumental record contain useful information and can provide samples of heatwaves to learn more about the mechanisms behind them and anticipate future heatwaves that may not always be well captured by climate models (Van Oldenborgh et al., 2022). By analysing past events we ensure that the study of extreme events is not limited to today's climate state, and we extend the sample of analysed extreme events to be used in future studies. They can also be used to place modern events, such as the 2022

European summer heatwaves, into historical context (Hawkins et al., 2022; Hegerl et al., 2019). We define early heatwaves as those that occurred in 1926 or earlier and compare these to heatwaves that occurred between 1927 and 1974 and those that occurred after 1975. Early heatwaves such as the 1923 heatwave are less studied than those occurring later such as the 1976 heatwave (Baker et al., 2021; Kendon et al., 2024). In addition, the heatwaves in 1911 and 1923 also lasted 3 consecutive days, comparable to the most intense 2022 July heatwave.

We focus on summer events due to the impact of such events on human health. How events have changed from past to present is investigated in terms of their frequency, and individual events from the past are compared to more recent heatwave events, such as the 2022 heat events in the UK. We detect 19$^{\text{th}}$ and early 20$^{\text{th}}$ century heatwaves using temperature data from central England where there are existing long observational records. The definition of a heatwave used here has been designed to work best for the central England region. This paper also makes use of reanalysis data to determine the spatial extent and synoptic situation that was involved in generating the heatwave, and to understand if long regional datasets can be used to detect large scale heatwaves.

Heatwaves are generally described using daily data, however, monthly data are available further back in time and with better spatial coverage than daily data for many time periods and regions. We investigate to what extent monthly data can capture anomalous heat by understanding if monthly temperature is indicative of a heatwave event occurring at the daily level. In addition, testing for overlaps between heatwaves detected on a monthly basis versus daily could push the study of heatwaves further back in time. To allow for this, the daily heatwave events are detected for each month of summer separately.

Lastly, archival documentary data is used to understand if any impacts were felt during the events detected and selected from the station and gridded data sets. This illustrates whether these early heatwaves had consequences for the UK population at the time.

## 2.2 Detecting heatwaves using station data

### 2.2.1 Datasets used

The instrumental data used for this analysis includes the Met Office Hadley Centre Central England Temperature Data (HadCET) (Parker et al., 1992) as well as the station data from the Radcliffe Observatory site in Oxford (Burt et al., 2019). These datasets were selected due to their long instrumental record of temperature as well as due to the fact they have been homogenized and corrected, including for the introduction of the Stevenson screen, and they are regularly updated. The HadCET dataset is the longest instrumental temperature record in the world with the monthly temperature series dating back to 1659, the daily-mean series beginning in 1772 and the daily maximum series dating back to 1878. The dataset is representative of a triangular area of the UK which encloses Lancashire, London and Bristol. The data has been adjusted for urban warming from 1974 with a correction of -0.2°C applied to mean temperatures. HadCET has been used in other recent heatwave studies (King et al., 2015). The Radcliffe Observatory site in Oxford has monthly mean data dating back to 1813 and daily maximum and minimum values from 1815.

Maximum daily temperatures were used from the HadCET dataset in order to detect and analyse early heatwave events in this paper. The Oxford dataset was analysed as an independent verification as it was not used as a station in the HadCET daily maximum temperature record from 1878 (Parker et al., 2005) and is based on a single station measurement. We use data between 1878 and 2022 where data is available from both datasets. The 2022 heat broke many temperature records across Europe and the UK. The UK exceeded 40°C for the first time on record on 19$^{\text{th}}$ July 2022 (UK MET Office, 2022) and records for maximum daily temperatures were set at the Radcliffe Observatory site in Oxford (Burt et al., 2019) and for the Met Office Hadley Centre Central England Temperature Data (HadCET) (Parker et al., 1992) on the 19th of July 2022.

The 20$^{\text{th}}$ Century Reanalysis version 3 (20CR) was used to examine pressure patterns linked to selected early heat events and to understand the spatial extent of the events detected (Compo et al., 2011; Slivinski et al., 2021). NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996) was used to determine the pressure pattern and spatial extent of the July

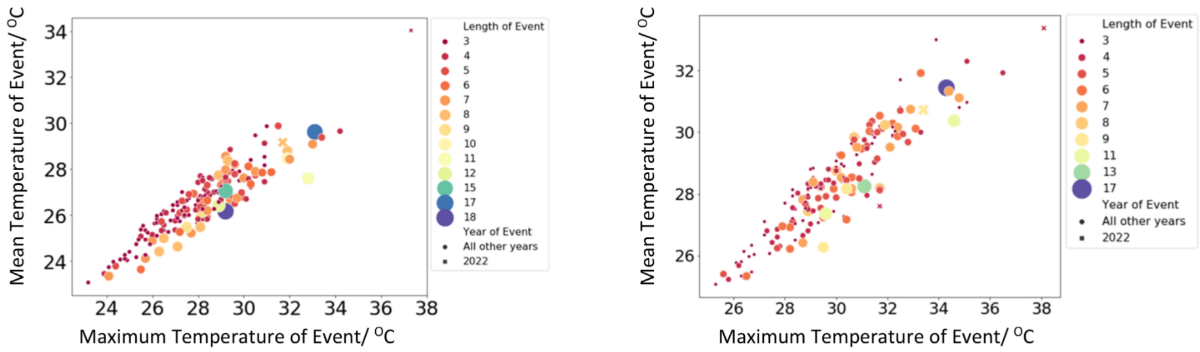
2022 event as 20CR does not have data for this time period. A comparison of 20CR with HadCET for monthly means of daily maximum temperature (1878-2015) for each month of summer is provided in Appendix A.1. While 20CR is cooler than CET overall it shows very similar interannual variations and trends to the observations.

To understand any societal impacts that resulted from the past heatwave events, the Times newspaper archives (Times, 2020) were used. The online archives hold newspaper articles from 1785 to 1985 and allow the user to search for key words, related to heat and specific impacts from heat. The term "heat" was used in this search which uncovered impacts relating to human health, agriculture and impacts on sports. These are noted in section 2.5.1 and, although not an exhaustive list of impacts, shows that the events detected using station data had associated societal impacts in the majority of cases.

### 2.2.2 Defining heatwaves

The definition used in this paper is at least three consecutive days of daily maximum temperature above the $90^{th}$ percentile, where the $90^{th}$ percentile is calculated based on a 15-day calendar window using daily data from 1878 to 2022. We have not detrended the data in our main study in order to treat past heatwaves the same as more recent events, but we evaluate sensitivity to doing so. The $90^{th}$ percentile was used as this is a commonly used percentile threshold in the research of heatwave events (Perkins, 2015; Russo et al., 2015). Other windows were tested with the Oxford and HadCET datasets including 1, 5 and 15-day windows (see Appendix A.2).

Heatwaves are usually defined as at least 3 consecutive days above a certain temperature threshold although this definition can be extended to 4 or more consecutive days of heat (Horton et al., 2016; Perkins, 2015). In order to understand if there is a relationship between the intensity of a heatwave and its length, the maximum temperature reached during events and the mean temperature of events is plotted in Figure 2.1. The Pearson's correlation between the maximum temperature reached during a heatwave and mean heatwave temperature reached is large (0.91). In contrast, the correlation between heatwave length and maximum event temperature is relatively weak (0.32) and even weaker with mean event temperature (0.15). Thus, while there is a tendency for low intensity events to be shorter events, there are some short events with high intensity. In order not to miss such events with potential health consequences (Cowan et al., 2014; Horton et al., 2016; Perkins, 2015), we require only 3 or more days of anomalous daily maximum temperature when defining a heatwave.




(a) (b)

**Figure 2.1:** Comparison of maximum temperature reached during events and mean temperature of heatwave events in Central England from the HadCET dataset (a) and the Oxford dataset. (b) Note the exceptional nature of 2022 (top right corner)

### 2.2.3 Detecting heatwave years

Heatwave years are defined as years where at least one heatwave occurred in the summer (June, July or August) of that year. A heatwave is considered to have taken place in a particular summer month if at least 3 days of consecutive heat fall within that month (Figure 2.2). This approach is used for the remainder of the paper in order to understand if monthly temperatures are generally indicative of a heatwave occurring based on daily data. In June, out of the 145 years between 1878 and 2022, 49 heatwave years were detected from the Oxford dataset and 51 from the HadCET dataset. Out of the 51 heatwave years detected in HadCET, 28 years were prior to 1975 and 12 years were between 1878 and 1926. In July, 47 heatwave years were detected between 1878 and 2022 in both the Oxford dataset and HadCET with 25 prior to 1975 and 14 years between 1878 and 1926 and for August, 19 out of 37 heatwave years were prior to 1975, emphasising the added sampling gained by studying early heat events. If the analysis uses detrended data, the fraction of early heatwaves is even higher: Based on HadCET, the number of heatwave years prior to 1975 in June increases from 28 to 30, in July this increases from 25 to 27 and in August this increases from 19 to 26 (see Appendix A.3). Using HadCET, in June, 9.8% of the heatwave years had more than one heatwave occur that year, while that number was higher in July (27.7%) and more so in August (32.4%). For June, the Oxford and HadCET datasets agree for 135 out of a total of 145 years i.e. 93.1% agreement. For July they agree for 91.7% of years and for August they agree for 89% of years. The Pearson's

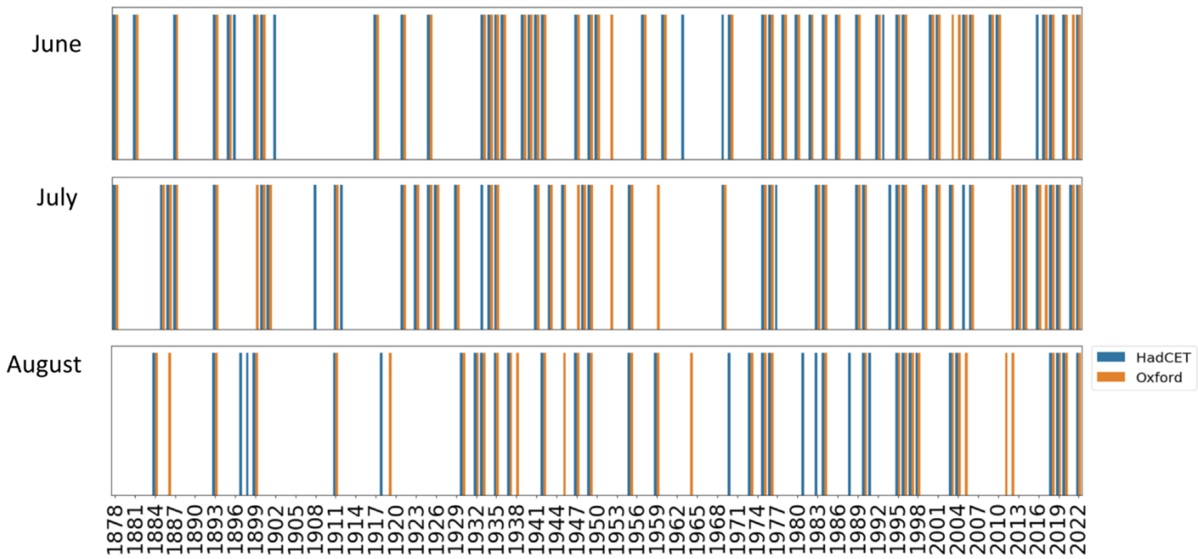


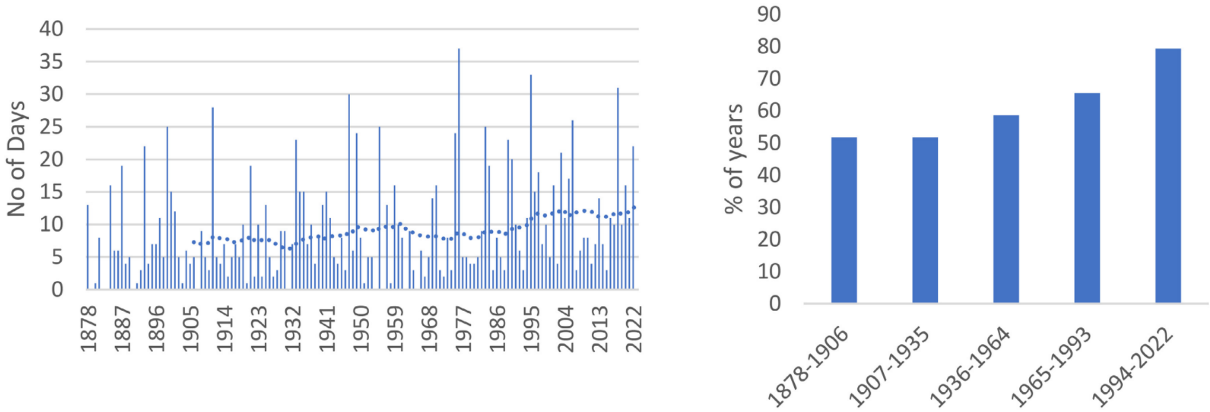

**Figure 2.2:** Comparison of heatwaves detected in HadCET (blue) and Oxford (orange). A bar is used to represent a year where at least one heatwave occurred that month—split into the months of June, July, and August. If a heatwave was detected in both HadCET and Oxford both blue and orange bars are plotted. In June, 93% of heatwave years detected occurred in both time series, in July 91.7% and in August 89%

correlation between the maximum monthly temperatures for the HadCET and Oxford datasets varies between 0.93 and 0.95 for the months of June, July and August (Figure 2.2). Due to this similarity, and since HadCET dataset covers a larger land area, we use HadCET for the remainder of the analysis in this paper.

## 2.3 A comparison of past and modern heatwaves

### 2.3.1 Heatwave trends from past to present

Figure 2.3 shows an increase in the number of days above the 90$^{th}$ percentile and in the number of heatwave events per year from 1878 to 2022. The summer with the highest number of days above the 90$^{th}$ percentile in central England was in 1976 with 37 days during June, July and August. During the summer of 1911 there was a total of 28 days above the 90$^{th}$ percentile and in 2022 there were 22 days. Figure 2.3 shows the percentage of years in each 29-year period between 1878 and 2022 in which at least one heatwave occurred. In the most recent period, between 1994 and 2022, at least one heatwave occurred in 79% of years which is higher than the previous 29-year periods (51-65% of years).




(a) (b)

**Figure 2.3:** (a) A total number of days above the 90th percentile using HadCET in June, July, and August per year between 1878 and 2022 with a 29year running mean shown by the dashed line (b) the percentage of years per 29year period from 1878 to 2022 where at least one heatwave occurred that summer (these years were selected to allow five equal bins for comparison)

### 2.3.2 Comparing past and modern heatwave events

To compare past heatwave events to those that have occurred more recently, individual heatwave events have been ranked (Figure 2.4). Intensity of an individual event is defined as an equally weighted average of the mean temperature of the event and the maximum temperature reached during the event, and only the single hottest event for each month was used. Based on our ranking, the highest intensity events in June between 1878 and 2022 occurred in 1947 and 1976, the highest intensity event in July in 2022 and the most intense event in August was in 1990. While recent years contain many strong and highly ranked heatwave events, there are also some strong past events that occurred in the year 1926 or earlier (Figure 2.4). Overall, in each of the summer months one of the top ten events, in terms of intensity, occurred before 1927, emphasising the value of analysing early heat events. While there is an increasing trend in the number of days above the $90^{th}$ percentile and number of heatwave events, there is less of an increase over time in terms of individual heatwave characteristics including mean and maximum temperatures of heatwave events and length of heatwave events.

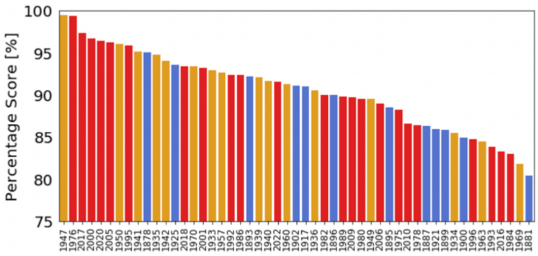
The UK 2022 summer heatwaves broke daily maximum temperature records across the country. The most intense event occurred between the $17^{th}$ and $19^{th}$ of July, 2022. This event was ranked as the most intense in any July between 1878 and 2022 in the HadCET dataset. The maximum temperature reached during this event was 37.3°C and the mean temperature across the event was 34°C. In comparison, the second most intense July event, 11-13$^{th}$ July 1976, reached a maximum temperature of 33.1°C and the mean temperature across the event was 31.2°C (see Table 2.2). The August 2022 heatwave between 8-15$^{th}$ was ranked as the second most intense August heatwave between 1878 and 2022 behind a 1990 heatwave event and the 2022 June event between 15-17$^{th}$ was ranked 24$^{th}$ most intense, behind some early heatwaves including 1878, 1925 and 1893.

## 2.4 Daily vs monthly temperatures

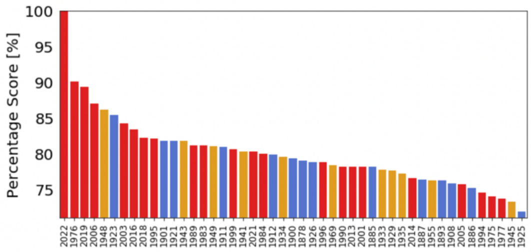
### 2.4.1 Are monthly data suitable to detect heatwaves?

While we use daily data to define heatwaves, monthly data are available further back in time and could therefore be used to investigate heatwaves prior to 1878. We explored to what extent the occurrence of a heatwave event (defined on a daily level) can be indicated by using monthly data alone. Figure 2.5 plots the monthly means using the HadCET dataset since 1878 and their coincidence with heatwaves detected from the daily data. Summer months with at least one heatwave detected (red bars) show a significantly different distribution of monthly temperatures compared to those without (blue bars). This was verified with the use of the two-sample Kolmogorov-Smirnov test where the p-value was below 0.05 for each month of summer. Thus, summer months with heat waves tend to show significantly higher monthly averages.

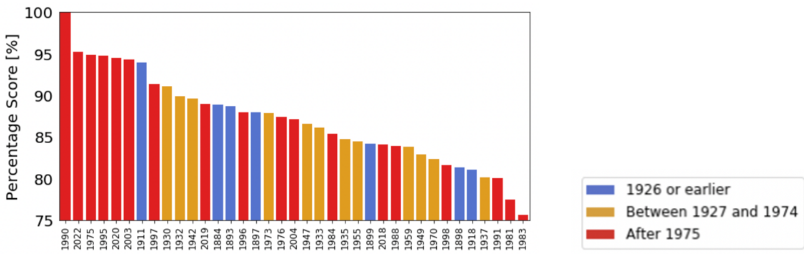
How indicative are high monthly temperatures of the presence of heat waves? To address this, we calculate the percentage of months containing at least one heatwave (based on the earlier defined daily criteria), for all months, and the upper and lower terciles of monthly mean temperatures (Table 2.1). The likelihood of a heatwave having occurred in a warm month compared to an average month increases by more than a factor of two in June, July and August, with between 64.6 and 77.1% of months in the upper tercile also showed the occurrence of at least one heatwave. One striking result is that in July, no heatwave events were detected in months in the lower temperature tercile. This suggests that the longer HadCET monthly temperature timeseries starting in 1659 can be used as a proxy for the presence of heatwaves before daily data were available, although not a perfect one. June 1676 for example is the second warmest June on record and August 1747 is




(a) June




(b) July




(c) August

**Figure 2.4:** Rank of heatwave events based on intensity metrics (choosing the most intense event per year) in (a) June, (b) July, and (c) August split between heatwaves that occurred in 1926 or earlier (blue), between 1927 and 1974 (orange) and those occurring after 1975 (red). Percentage Score $= \left(\frac{\bar{T}_i}{\max \bar{T}_i} + \frac{T_i^x}{\max T_i^x}\right)$. Where $T_i$ is the mean temperature of event and $T_i^x$ is the maximum temperature of event. For June , for July $i \in \{1, \ldots, 45\}$, for August $i \in \{1, \ldots, 38\}$

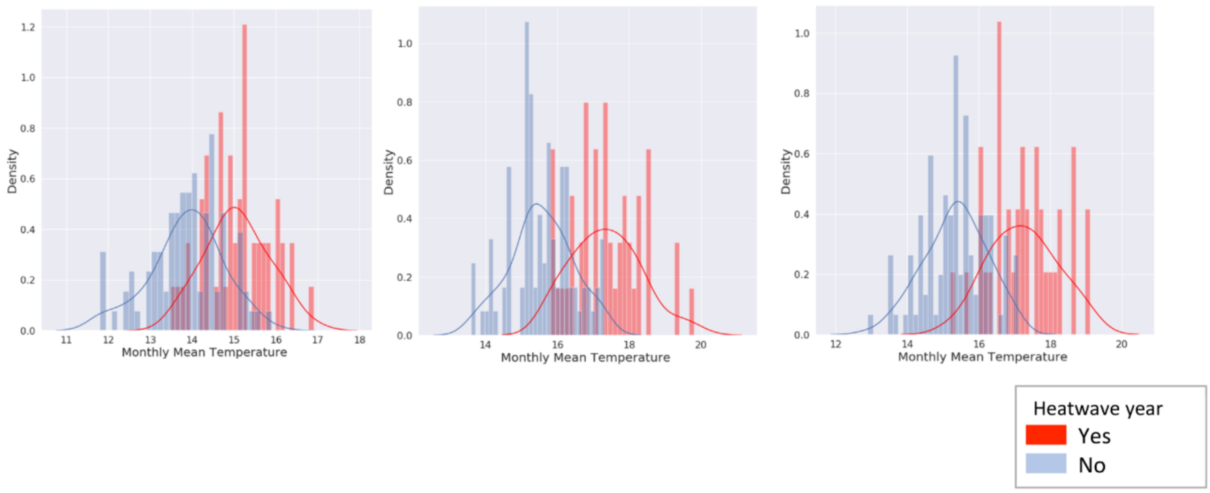



**Figure 2.5:** The monthly mean temperature from HadCET plotted against their occurrence. Red represents a month where a heatwave occurred that year and blue if a heatwave that did not occur that year for years between 1878 and 2022. As a reference, the monthly mean temperatures for 2022 are June, 14.9°C; July, 18.2°C, and August 18.7°C.

the 7th warmest August on record and may hold interesting heatwaves to compare with more recent heatwaves. This could extend the record and samples of extreme temperature events in order to place contemporary events, like 2022, into an even longer historical context.

## 2.5 Case studies of heatwave years

How representative are early heatwaves detected in HadCET of large-scale European heat, and what were the atmospheric circulation anomalies that led to them? The 20th Century Reanalysis v3 (20CR) was used to analyse the weather conditions under which the heatwaves occurred and the spatial extent of anomalous heat, focusing on two heatwave events for each summer month that are ranked highest in Figure 2.4 and occur prior to 1927. While extreme temperatures from reanalysis are more uncertain than from station data, 20CR has successfully been compared to station data for the US dustbowl heat events (Cowan et al., 2017). The heatwave events shown are compared to the highest intensity July 2022 heatwave. The highest intensity heatwave events in June were in 1878 and 1925, in July 1923 and 1901, and in August, 1911 and 1884. Temperature anomalies during the heatwave events in these years are shown in Figure 2.6, together with the co-occurring geopotential height at 500hPa (Z500). All six events analysed, in common

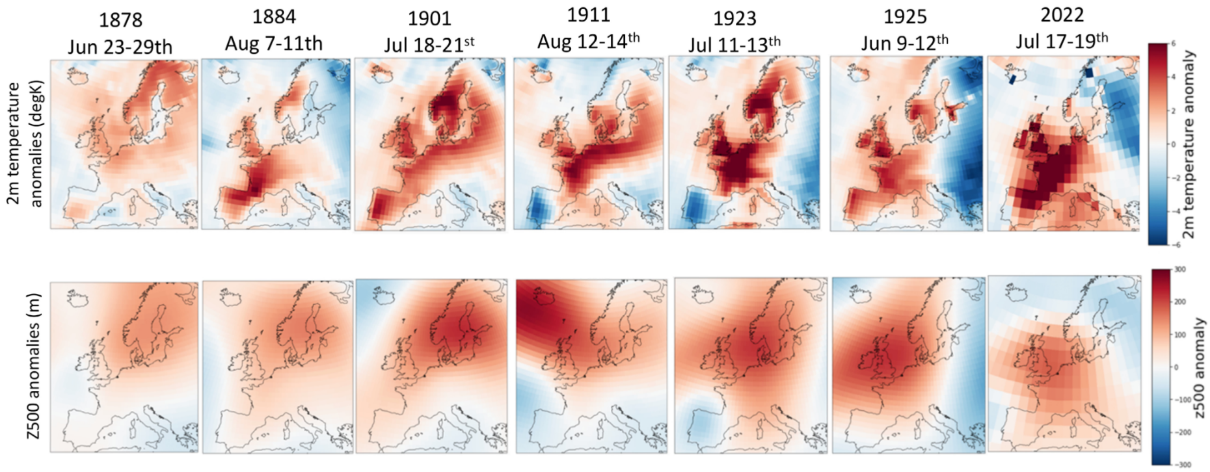



**Figure 2.6:** Monthly 2m temperature and Z500 anomalies for the six most intense early events (with reference to Figure 2.4) and the highest intensity 2022 event. Reference period for anomalies is 1981–2010. 20$^{th}$-century reanalysis v3 data and NCEP-NCAR Reanalysis 1 data provided by the NOAA/OAR/ESRL PSL, Boulder, CO 20CR was used for the early heatwaves and NCEP-NCAR was used for 2022, a similar model to 20CR.

with the July 2022 heatwave, show a positive temperature anomaly and a positive Z500 anomaly over central England. The highest temperature anomaly over central England was during the event in 2022 followed by July 1923 (see Table 2.2). The analysis shows that the most intense heatwaves detected in central England are part of much larger scale extreme heat events linked to extensive high-pressure systems, and that long homogeneous station data can be used to find events with impacts across Europe, although some strong early European heatwaves with weak extension into the UK may not have been detected in HadCET. Figure 2.6 also illustrates that the location of extreme heat varies between heatwaves, and is closely linked to the circulation anomaly associated with them.

### 2.5.1 Did detected early heat events cause impacts?

The Times newspaper archives (Times, 2020) were used to determine if any impacts of extreme heat were reported during the most intense events detected using instrumental data. This is done to evaluate if early events were considered impactful at the time, and provides a further, indirect evaluation of the detected early heat.

The term “heat” was used in a key word search across the days of each of the events detected in the instrumental data. This was completed for all the heatwaves across each summer month of the six selected years with reference to Table 2.2. The top ten results in the archive search, which tend to be most relevant, were analysed in order to note any

| % of heatwave years | Total (Expected) | Warmest months (top third) | Coldest months (bottom third) |
|---|---|---|---|
| June | 35.2% | 70.8% | 6.3% |
| July | 32.4% | 77.1% | 0% |
| August | 24.8% | 64.6% | 2.1% |

**Table 2.1:** Percentage of summer months containing at least one heatwave (Total (Expected)) compared to the percentage of heatwaves in the warmest and coldest months (based on the monthly mean) from 1878 to 2022. The fraction of months with a heatwave is more than twice that in a warm month compared to an average month in June, July and August.

impacts. In addition, the term "sunstroke" was searched across the entire summer season for each of the six years as a proxy for severe health impacts. This term was generally used in the time period to discuss heat and health impacts rather than similar terms such as "heat stroke". This allowed for delayed impacts to be detected following a heatwave event.

UK impacts before 1927 included disruption to travel and sporting activities, agricultural impacts and health impacts. Deaths from sunstroke were reported during or shortly after the June 1878 heatwave, the July 1901 heatwave, the July 1911 and July 1923 heatwaves. Other reported impacts include mentions of heat heavily impacting smells from sewage systems and drains in London as well as vermin infestations that were blamed on heat affecting hop markets in the UK during the June 1878 heatwave, for example. Health impacts were mentioned in relation to forge and steel workers, and "agricultural labourers" with reports of work needing to be ceased in the UK in these sectors during heatwave events such as in August 1911. Horses suffering from heat were also reported on during several heatwave events including during 1911 leading to disruption to travel and also impacting the agricultural sector.

This qualitative information illustrates that these early heatwaves were associated with local impacts around the UK with some themes, including heat mortality and impacts to agriculture and transport, being similar to those felt by modern society during the 2003 and 2022 heatwaves for example (Barriopedro et al., 2011; García-Herrera et al., 2010; WHO, 2022).

| Year | Month | Event Dates | No of days above 90th percen tile | Max Temp reached (°C) | Mean Temp reached (°C) | Heatwave Event Ranking* (heatwave years between 1878-2022 per month) | Monthly Mean Ranking (all years between 1878-2022 per month) | UK Impacts (reported in the Times Archives for 1878-1926) |
|---|---|---|---|---|---|---|---|---|
| | *Events from early period (1878 to 1926)* | | | | | | | |
| 1878 | June | 23-29th | 7 | 29.4 | 26.7 | 10 | 31 | Health/Agriculture/Sports |
| | July | 17-22nd | 6 | 29.0 | 27.3 | | 48 | Sports |
| 1884 | August | 7-11th | 11 | 29.3 | 27.5 | 13 | 18 | Health/Sports/Agriculture |
| | | 22-24th | 11 | 28.0 | 26.7 | | | No direct impacts found |
| 1901 | July | 18-21st | 6 | 29.4 | 28.9 | 11 | 12 | Health/Sports |
| 1911 | July | 6-8th | 13 | 27.1 | 26.6 | | 8 | Health |
| | | 11-14th | 13 | 28.0 | 27.4 | | | Health/Fire |
| | | 27-29th | 13 | 29.8 | 27.9 | | | Health/Drought |
| | August | 8-10th | 10 | 30.9 | 28.2 | | 7 | Health/Drought/Agriculture |
| | | 12-14th | 10 | 30.5 | 29.5 | 7 | | Health/Drought/Agriculture /Sports |
| 1923 | July | 5-7th | 7 | 29.5 | 27.9 | | 20 | No direct impacts found |
| | | 11-13th | 7 | 31.0 | 29.9 | 6 | | No direct impacts found |
| 1925 | June | 9-12th | 7 | 28.4 | 26.8 | 13 | 37 | Health |
| | July | 12-14th | 6 | 25.6 | 25.5 | | 40 | No direct impacts found |
| **2022** | **June** | **15-17th** | **5** | **28.2** | **25.8** | | **42** | |
| | **July** | **10-12th** | **7** | **29.9** | **27.3** | | **10** | |
| | **July** | **17-19th** | **7** | **37.3** | **34.0** | **1** | | |
| | **August** | **8-15th** | **10** | **31.7** | **29.2** | | **3** | |

**Table 2.2:** Highest intensity early heatwave years compared to 2022, and their associated characteristics including: the number of days reached above the 90$^{th}$ percentile per month; the maximum temperature reached during the event; the mean temperature reached during the event; other events that occurred in the summer of that year and the ranking of the month compared to all years from 1878 to 2022 (145 years) using monthly mean temperature. *Red rows indicate the most intense events per year and the ranking of these heatwave events compared to other years from 1878 to 2022 have been included from Figure 2.4. Where further heatwaves occurred in the same summer, these are also listed in the table.

## 2.6 Conclusion

The aim of this paper was to detect historical heatwaves and compare these to more modern heatwave events to understand if any past events are noteworthy in comparison to more recent events including the 2022 summer heatwaves. Between 1878 and 2022, the number of days above the 90$^{th}$ percentile and the number of heatwave events have increased. In the latest 29-year period, between 1994 and 2022, 79% of years had at least one heatwave in the summer months which is higher than any of the previous 29-year periods and consistent with a warming trend of monthly average temperatures. However, some individual heatwave events from the past are comparable to modern heatwave events in terms of the mean and maximum temperatures reached during each event and therefore could be used as case studies alongside more modern events, and are of similar magnitude and consequence as more recent events. When ranked based on the intensity of the event, the 10$^{th}$ strongest event that occurred in June to date was in the year 1878, the 6$^{th}$ most intense event to have occurred in July was in 1923 and the 7$^{th}$ most intense event to have occurred in August was in the year 1911. The most intense heatwave to have occurred in July was in 2022 where a maximum temperature of 37.3°C was reached during the event from 17$^{th}$ to 19$^{th}$ July. This is the most intense heatwave event on record. The second most intense heatwave event to have occurred in August was in 2022. Analysis of early detected heat wave data in the 20$^{th}$ Century Reanalysis shows that these early heatwaves were parts of widespread extreme heat over Europe associated with extensive high-pressure anomalies. Historical documentation illustrates that these early heatwaves caused impacts on health, food agriculture and outdoor activities in the UK. Monthly mean temperatures in the HadCET dataset tend to be high for months that contain heatwaves defined on the daily level. Between 64.6 and 77.1% of summer months in the upper tercile contained heatwaves, and no heatwave years were found in the coldest tercile of monthly anomalies in July, suggesting that prior to availability of daily data, monthly data may be indicative of heatwave conditions which could allow heatwaves even earlier in the record to be detected.

Chapter 3

# UK Extremes in a Warmer World

In this chapter, some of the most extreme UK past heatwaves detected in chapter 2 are used as case studies as we explore how their intensities may change in a warmer world. The analogue methodology is used in this chapter to analyse how these past heatwave events may change under different global warming scenarios. This gives us a way of finding heatwaves that are similar to the early events in terms of their circulation patterns. Exploring how the intensity of past events may change in the future could be an effective risk communication tool for adaptation decision making particularly if past events are stored in society's memory, for example, if they are well-known or remembered. We comment on the effectiveness and the limitations of the analogue method to explore potential future summer heat events in the UK. This chapter will be submitted to the journal "Environmental Research: Climate" in late 2023. Co-authors include: Gabi Hegerl, Andrew Schurer, Andrew Ballinger and Ed Hawkins.

**Table of Contents**


3.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47

3.2 Datasets and models used . . . . . . . . . . . . . . . . . . . . . . . 49

3.3 Choice of heatwave events . . . . . . . . . . . . . . . . . . . . . . . 49

3.4 General method . . . . . . . . . . . . . . . . . . . . . . . . . . . . 51

3.5 Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 54

3.6 Discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 60

3.7 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 64

## 3.1 Introduction

Heatwave events consist of prolonged periods of high temperatures during periods of anticyclonic atmospheric circulation (Kornhuber et al., 2017; Perkins, 2015; Yiou et al., 2020b; Krueger et al., 2015). Heatwaves cause a variety of societal impacts including on agriculture, biodiversity and human health (Ebi et al., 2021; Shivanna, 2022). For example, during the summer of 2003 in Europe, over 70 000 deaths occurred and, more recently, over 60 000 heat related deaths have been estimated in Europe during the summer of 2022 (Ballester et al., 2023; Robine et al., 2008). Impacts of heatwaves on society are not felt equally, there are race, class, and gender disparities in who is most heavily impacted by them (Benz et al., 2021; Chakraborty et al., 2019; Gallo et al., 2012). Globally, heat extremes have increased in frequency and intensity and are expected to increase further due to global warming (Fischer et al., 2010; Masson-Delmotte et al., 2021; Perkins-Kirkpatrick et al., 2020; Russo et al., 2014). Furthermore, heat in Europe is projected to increase at a disproportionate rate compared to the global mean temperature (Rousi et al., 2022; Russo et al., 2015). Currently, warming in Europe compared to pre-industrial is almost 1°C higher than the average global increase which is currently higher than any other continent (Ballester et al., 2023; Copernicus, 2022; Simmons, 2022). It is therefore vital that adaptation measures are put in place to reduce the societal impacts associated with heatwave events and to reduce vulnerability to such events.

Analogues have been identified as an approach for analysing future impacts under a changing climate aiding adaptation decision making (Rosenzweig et al., 2021) particularly as past extreme events can be stored in a society's collective memory and understanding how these events may change due to global warming could raise the level of concern, a requirement for adaptation action (Hazeleger et al., 2015; Vasileiadou et al., 2014). Temporal analogues use data from past events to serve as analogues of expected future conditions. It is a way to estimate temperatures observed during similar pressure or "flow" conditions to a past event. Using this approach means that events that actually occurred are used to characterise potential future events. This could be useful for local-based adaptation and be a useful way to study extremes that could be missed using statistical models alone.

Our research uses the analogues method, similar to that developed by Yiou et al. (2007). We define "analogues" as days with a similar atmospheric circulation pattern to the heatwave days we are interested in exploring. This is based on the premise that circulation patterns influence local temperatures and therefore examples of past relationships between atmospheric circulation and temperatures can be used to analyse potential future temperature anomalies with similar atmospheric flow, but different external forcing and climate in order to separate thermodynamic and dynamic contributions to an event. A similar approach has been used in a number of other studies (Cattiaux et al., 2012; Cattiaux et al., 2010; Cowan et al., 2020; Harrington et al., 2019; Jézéquel et al., 2018c; Jézéquel et al., 2018a; Jézéquel et al., 2018b; Yiou et al., 2017; Yiou et al., 2007), where the circulation patterns during an event are used to find analogous circulations in other time periods and a variable such as temperature or rainfall is compared between the two. While originally used in fields including weather forecasting, analogues have recently been used in attribution and storyline-based research to understand how extreme events are impacted by climate change and to decompose the dynamical and thermodynamical impacts on such events (Harrington et al., 2019; Otto et al., 2016; Shepherd, 2019; Shepherd et al., 2018; Trenberth et al., 2015). Storylines, defined as plausible, physically self-consistent unfolding of past events (Shepherd et al., 2018) could be a powerful tool in risk related decision making and could be linked with the human aspects of climate change to create effective adaptation plans.

In this chapter, we aim to understand how past heatwave events in the UK could look in the future under different degrees of global warming. We identify the circulation patterns of several past UK heatwaves in reanalyses and models to find heat anomalies associated with analogous situations to them in the future. While many studies, including attribution studies, focus on recent events, past events can provide increased samples of heatwaves while improving preparedness for similar events in the future (Harrington et al., 2019; Hegerl et al., 2019; Otto et al., 2016; Stott et al., 2016). We, therefore, use the heatwaves occurring in the summers of 1911 and 1923 from which we aim to find analogues in the present and the future in order to explore any differences in the frequency in which the circulation is found as well as in the heat anomalies associated to the analogues. These are both examples of early heatwaves detected in chapter 2 of this PhD. Heatwaves in 1911 and 1923 in the UK and Europe were associated with societal impacts and reached a similar intensity in terms of maximum temperatures reached and mean temperatures across the event as more recent heatwave events such as 2003 (although not as intense as the 2022 heatwave) with reference to chapter 2.

We aim to explore the limitations of using circulation analogues to examine potential future heatwave events as well as exploring and discussing different methodological approaches to identifying analogues. We also explore if this approach could form a "tale" or storyline (Hazeleger et al., 2015) that is relevant for decision makers. We explore what the 1923 heatwave could look like at different degrees of global warming, particularly at 2 and 4°C which is the Climate Change Committee recommendation for adaptation planning in the UK (Climate Change Committee, 2021a).

## 3.2 Datasets and models used

The 20th-century reanalysis version 3 (20CR) was used to explore the circulation patterns and temperatures associated with the heatwave events in 1911 and in 1923 (Compo et al., 2011; Slivinski et al., 2019). While the NCEP reanalysis I dataset (Kalnay et al., 1996) is often used for similar studies (Jézéquel et al., 2018b), this only provides data starting from 1948 and therefore earlier occurrences of heat extremes cannot be studied. 20CR also has the advantage of being a longer dataset and therefore increases the sample from which analogues can be searched within.

Five ensembles were used from three different CMIP6 models (Eyring et al., 2016), UKESM1-0-LL (UKESM), CanESM5 (CAN) and MPI-ESM1-2-LL (MPI) in order to find analogues under different warming scenarios. SSP5-8.5 was used between 2015 and 2100 as well as their associated historical runs. This scenario was chosen as we are interested in exploring analogues at higher degrees of warming, including 4°C. These three models were selected as they have been used in previous studies that sampled model uncertainty to first order as well as having relatively many ensemble members (Slater et al., 2021).

## 3.3 Choice of heatwave events

We have selected the past heatwave events that occurred in 1911 and 1923 as the basis of this research due to their intensity, associated impacts and due to the differences in their circulation patterns, as detailed in chapter 2. Between 12-14$^{th}$ August 1911 an intense heatwave event occurred in UK and across the European continent. Impacts associated to this event include those related to sunstroke in the UK and the need to cease work outdoors including forge and steel work and agricultural work, also discussed in chapter 2.

When using HadCET (Met Office Hadley Centre Central England Temperature) dataset, the maximum temperature reached in the Central England region was 30.5°C and August 1911 is the 7$^{th}$ warmest month on record in Central England between 1878 and 2022 (Parker et al., 1992; Yule et al., 2023). In chapter 2, the definition of heatwaves used is at least three consecutive days of daily maximum temperature about the 90$^{th}$ percentile based on a 15-day calendar window between 1878 and 2022 (in this case the data has not been detrended to treat past events in the same way as more recent events). In 1923, a heatwave between 11-13$^{th}$ July reached 31.0°C in Central England and was the 6$^{th}$ warmest July between 1878 and 2022. Per heatwave event and based on the maximum temperature reached and the mean temperature across events, this was a stronger event than the July heatwave during 2003 in Central England which reached a maximum temperature of 30.9°C during the most intense 3-day event. This therefore allows us to explore past heatwaves and add to the sampling record with events that would still be considered intense in today's climate by using past events that are noteworthy in comparison to more recent events. Both events show positive temperature anomalies over the UK in 20CR that stretches over large parts of Northwest Europe. They are associated with high pressure over the UK, however they both have different circulation patterns (see Figure 3.1). By studying both the 1911 and 1923 events we can comment on the effectiveness of the analogue technique by comparing the results for these two events.

The circulation patterns and temperature anomalies associated with the 1911 and 1923 heatwave events are shown in Figure 3.1. The geopotential height at 500hPa (Z500) is plotted with anomalies relative to 1850-1900 as well as maximum temperature anomalies. The yellow dashed lines show the area used in which to find analogues in the top two plots and the area over which the England temperature anomaly was calculated (bottom plots). We can see in Figure 3.1 the difference between the two heatwave events with the highest pressure being over Iceland in 1911 and over Scandinavia during the 1923 event. The temperatures for both events are comparable over most of Europe with the exception of Iceland that is warmer during the 1911 event than 1923 and North Scandinavia where the inverse is true.

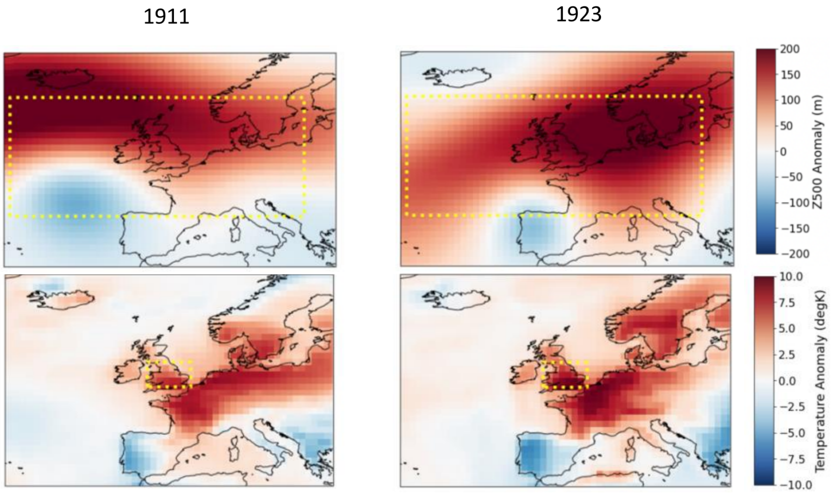



**Figure 3.1:** 2m maximum temperature anomalies and Z500 anomalies (reference period for anomalies is 1850- 1900). 20$^{th}$-century reanalysis v3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, US. The z500 anomaly patterns were used to search for analogues for the 1911 and 1923 events. The 1911 event took place between 12-14$^{th}$ August and the 1923 event between 11-13$^{th}$ July. These heatwave events have been selected as they represent the most intense early heatwaves in August and July respectively based on HadCET data. The yellow dashed line represents the areas used to find analogues (top) and to analyse temperature anomalies over England (bottom).

## 3.4 General method

The associated circulation patterns and temperature anomalies were taken from 20CR for both 3-day events in July 1923 and August 1911. The average Z500 height and maximum daily temperature anomalies were calculated across each event and the anomalies were relative to 1850-1900 as detailed in chapter 2. The 3-day mean Z500 anomalies were used to find analogues both in 20CR and in UKESM, CanESM5 and MPI using historical runs between 1850 and 2015 and using SSP5-8.5 ensembles between 2015 and 2100. This provided a large sample from which to detect analogues. Results were similar if searching for analogues for individual days yet using 3 consecutive days allows build-up of heat and was therefore preferred. Analogues were searched for within a 31-day window (15 days before the event and 15 days after) centred on the heatwave event.

In order to search for analogues in the model space, the Z500 heights from 20CR were regridded to match the grid resolution of each model. The 3-day rolling mean of Z500 was used to search for analogues. Z500 was used as a diagnostic of circulation as opposed to SLP which aligns with previous studies (Jézéquel et al., 2018c) that suggest that Z500 analogues probably perform better compared to SLP due to processes related to thermal lows. SLP patterns can be blurred by warm air masses causing local depressions which makes the identification of an anticyclone sensitive to warming and more difficult to detect.

When selecting the area from which we compare the circulation patterns, we aimed to include an area large enough to contain the distinct features (areas of low and high Z500 height) of the circulation pattern while being small enough to avoid finding analogues that do not result in a high-pressure system over the UK. We have selected areas that include the most relevant features of the circulation patterns, shown in Figure 3.1, as has been done in previous studies (Jézéquel et al., 2018c).

We used a smaller region from which to extract the temperature anomalies associated with the analogues (circulation patterns). We used a region over England (with a land-sea mask applied) as the original events used were selected due to their high temperatures over central England. We use a 3-day rolling mean of the daily maximum temperatures associated to the analogues.

We have used several metrics to define an “analogue” to the 1911 and 1923 heatwave events. We select suitable analogues by maximising the Spearman correlation between the Z500 maps and we also experiment with minimising the Euclidean distance. Spearman’s rank correlation coefficient is often denoted by rho ($\rho$), named Spearman’s rho. It is a measurement of the strength and direction of the monotonic relationship between the geopotential height values of the event of interest and those that occur in the model or dataset of interest. It is used as a way to analyse the degree of similarity in Z500 spatial patterns, hence a method for finding analogues. Rho is a value between -1 and 1 with a value close to 1 indicating a strong, positive relationship between the event of interest and the potential analogue event. As rho is determined based on rank only, the amplitude of the spatial pattern is not considered.

Minimising the Euclidean distance is another method of finding analogues as a measure of similarity or dissimilarity between the geopotential height values of the event of interest and potential analogue events. It is a representation of the straight-line difference between two sets of values in a multi-dimensional space. The differences between methods are discussed further in section 3.6.1.

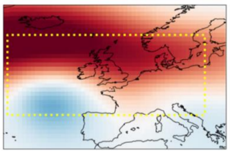
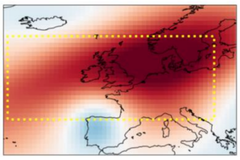
| Heatwave events | Rho ($\rho$) values | | | | | | |
|---|---|---|---|---|---|---|---|
| | 23-29th Jun 1878 | 7-11th Aug 1884 | 18-21st Jul 1901 | 9-12th Jun 1925 | 13-16th Jul 2003 | 17-19th Jul 2022 | 12-14th Aug 1911 relative to 11-13th Jul 1923 |
| **12-14th Aug 1911**  | 0.38 | 0.53 | 0.28 | 0.18 | 0.58 | 0.04 | 0.36 |
| **11-13th Jul 1923**  | 0.65 | 0.71 | 0.71 | 0.52 | 0.75 | 0.55 | |

**Table 3.1:** Comparison of rho values between the 1911 and 1923 events as well as a sample of other intense heatwave events using the area within the yellow rectangle in Figure 3.1. This gives an idea of the level of similarity between two heatwave events in terms of their circulation pattern.

We define analogues as the top 10% of days based on the value of rho and we also explored using a cut-off value for rho and find that this does not change greatly but can render possible analogues inconsistently sampled. Taking analogues to be the top 5% based on rho values after maximising the Spearman correlation as opposed to taking the top 10% of days did not qualitatively change our results.

The circulation pattern of the 1923 event appears to be a more traditional or common high-pressure system over Europe. When we calculate the rho values (to get an idea of the similarity in circulation pattern between 1911, 1923 and other heatwave events in Europe) we see that more heatwave events are similar to 1923 than to 1911 with reference to Table 3.1. We compare the 1911 and 1923 summer heatwaves to those of other similarly intense heatwaves over the UK from 1878 to 2022. We see that the rho value between all other tested events and 1923 is over 0.5 whereas only two of the other events have a rho value above 0.5 when compared to the 1911 event. The rho value when comparing the 1911 and 1923 event is 0.36.

## 3.5 Results

Figure 3.2 shows the climatology around the events for each decade (in a 31-day window) compared to the England temperature anomaly associated with analogues of each event (1911 and 1923). Decadal distributions of the rolling 3-mean average maximum temperature anomalies are shown from 5 ensemble members from UKESM using the historical runs for the 1850-2014 period and the SSP5-8.5 scenario for the time period from 2015 to 2100. The orange box and whiskers plots show the climatology around the events (a 31-day window) centred on 12-14$^{th}$ August (LHS) and 11-13$^{th}$ July (RHS) for each decade. The climatology includes the complete distribution of sampled days. We can see how the decadal climatology changes through the decades between 1850 and 2100 as the England temperature anomaly increases with global warming.

The red dashed lines in Figure 3.2 represent the England temperature anomaly during the heatwave of interest, from 12-14$^{th}$ August (LHS) and 11-13$^{th}$ July (RHS). A red star shows the decade in which the heatwave took place. Both the 1911 and 1923 heatwave events were relatively extreme for their respective time periods, both being outwith the 95$^{th}$ percentile for their respective climatologies. This is expected as these events were selected for being examples of extreme heat events. However, the temperatures reached during the 1911 event fall within the 25-75$^{th}$ percentile of the climatology distribution during the 2040-2049 period and falls belows the 25$^{th}$ percentile in the time period 2070-2079. The 1923 event shows a similar progression, the event that was extreme during the time it occurred falls into the 25-75$^{th}$ percentile of climatology by the end of the century.

Analogues are defined here as the top 10% of sampled days based on their rho values, by maximising the Spearman correlation. They are a subset of the climatology that have a geopotential height that most closely matches that of the original event. In Figure 3.2, the analogues are represented by the blue box and whiskers plots. We see that the decadal distributions of analogues have a higher median England temperature anomaly value than the climatology for each decade, however, there is a large spread in the England temperature anomaly values associated to analogues. This suggests that using geopotential height (Z500) alone to find analogues does not provide a strong constraint and does not necessarily find "hot" events.

We find that the events themselves were still relatively extreme compared to the analogues from their respective decades (both outwith the 25-75$^{th}$ percentile), but by the end of the century both are outwith the distribution for analogues and even cool for a summer period.

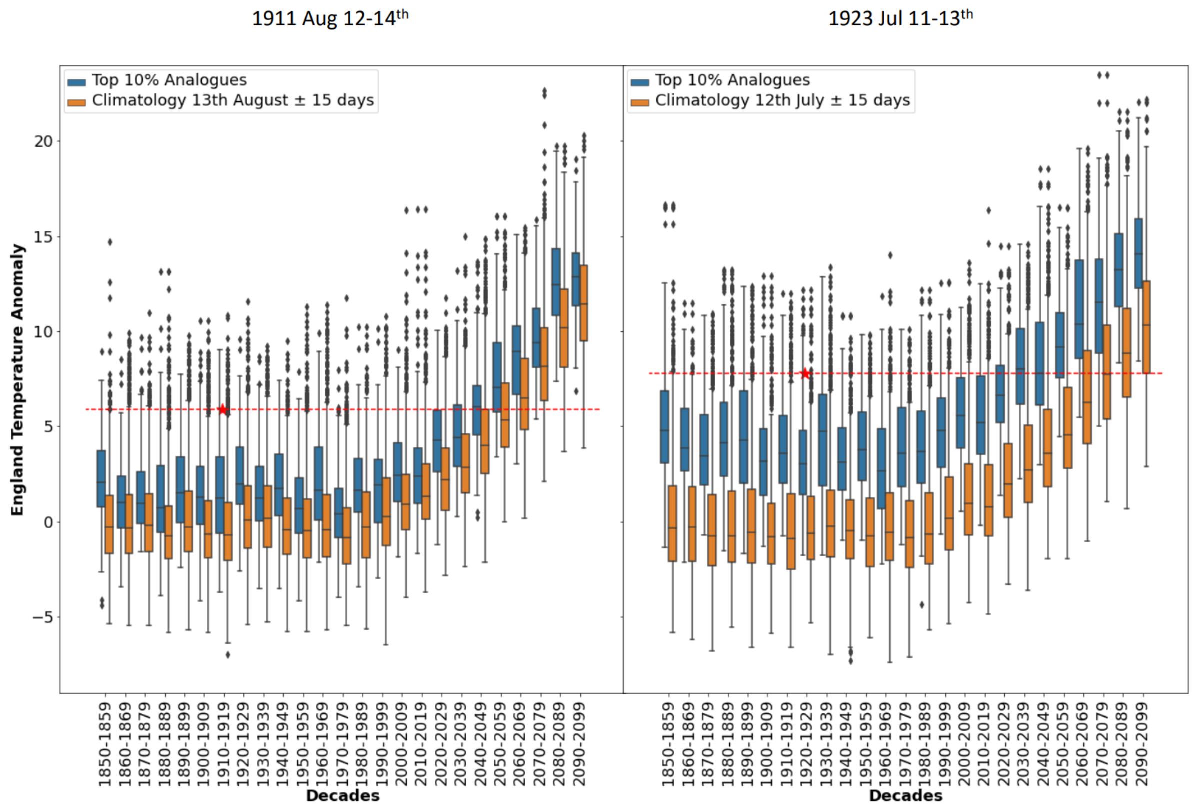



**Figure 3.2:** Decadal distributions of rolling 3-day average maximum temperature anomalies from UKESM1.0 (5 ensemble members; historical [1850-2014] and SSP5-8.5 [2015-2100] experiments) for 11-13$^{\text{th}}$ July (+-15 days) (right) and for 12-14$^{\text{th}}$ August ($\pm$15 days) (left), averaged over England. The orange box and whiskers show the complete distribution of sampled days (n = 1510; 31days x 10years x 5 ens. members), and blue shows the distribution of the subset chosen such that the associated geopotential height (Z500) anomalies most closely match the event from 20CR (the top 10% of analogue 3-day periods, as measured by the Spearman's rank correlation coefficient over pan-European sector). Coloured boxes span the 25$^{\text{th}}$-75$^{\text{th}}$ percentiles of the distribution, with the whiskers showing the 5th and 95$^{\text{th}}$ percentiles; individual outliers are shown by black dots). Red dashed line indicates the equivalent temperature anomaly over England for the original event from 20CR.

With reference to Figure 3.2 we can see the difference between the 1911 and 1923 heatwave event. We see that the 1923 event tends to have analogues with a temperature distribution over England that reaches a higher value (larger difference from the climatology) than for the 1911 event. The 1911 event is discussed frequently in literature and many impacts were felt at the time (Times, 2020; Ancestry, 2020). The event was also associated with drought (Ecology & Hydrology, 2020), and therefore an analogue that considers rainfall deficit and heat together, as a compound event (Zscheischler et al., 2018), may provide more information in this case. Going forward we focus our analysis on the 1923 event since this is more indicative of a range of other heat events in the UK including heatwaves in 2003 and 2022 with reference to Table 3.1.

In Figure 3.3, UKESM climatology and analogues are plotted and now the climatology and analogues from two other models, namely CanESM5 and MPI are introduced for comparison. Figure 3.3 shows the England temperature anomalies for the climatology and the analogues compared to global warming levels. Global warming levels are defined here as the decadal mean anomaly with respect to 1850-1900. Analogues are calculated for the decade where the mean global warming crosses each respective global warming level i.e. 1°C, 1.5°C, 2°C, 3°C and 4°C for each model's decadal ensemble mean, relative to the 1850-1900 period. For each model, the analogues have a higher mean temperature value than their respective climatologies for each level of global warming.

We have compared the climatologies and analogues found using UKESM, CanESM5 and MPI to those found using 20CR from 1850 to 2009 in order to validate the models used (results are shown in Appendix B.1). All three models are more variable than 20CR which could be expected given that models are sampled differently from 20CR which is driven with observed SSTs. UKESM shows the most variability and in the period 1970-2009, the period where we begin to see the impacts of global warming, CanESM5 seems to be most similar to results using 20CR in terms of the mean value of England temperature anomaly for analogues.

The climatology of a 31-day window centered on 11-13$^{\text{th}}$ July shows an increase in temperature with global warming. At 4°C of global warming the mean temperature in England is between 4.9 and 6.4°C warmer than pre-industrial levels with UKESM showing the largest increase and MPI the smallest. Means of analogues, events of similar circulation patterns as 1923, over England during this period range from 6.9 to 10.7°C with maximum temperature reached ranging from 11.7 to 19.6°C higher than pre-industrial levels. The 1923 event reached 7.8°C above pre-industrial levels over England. It is evident from

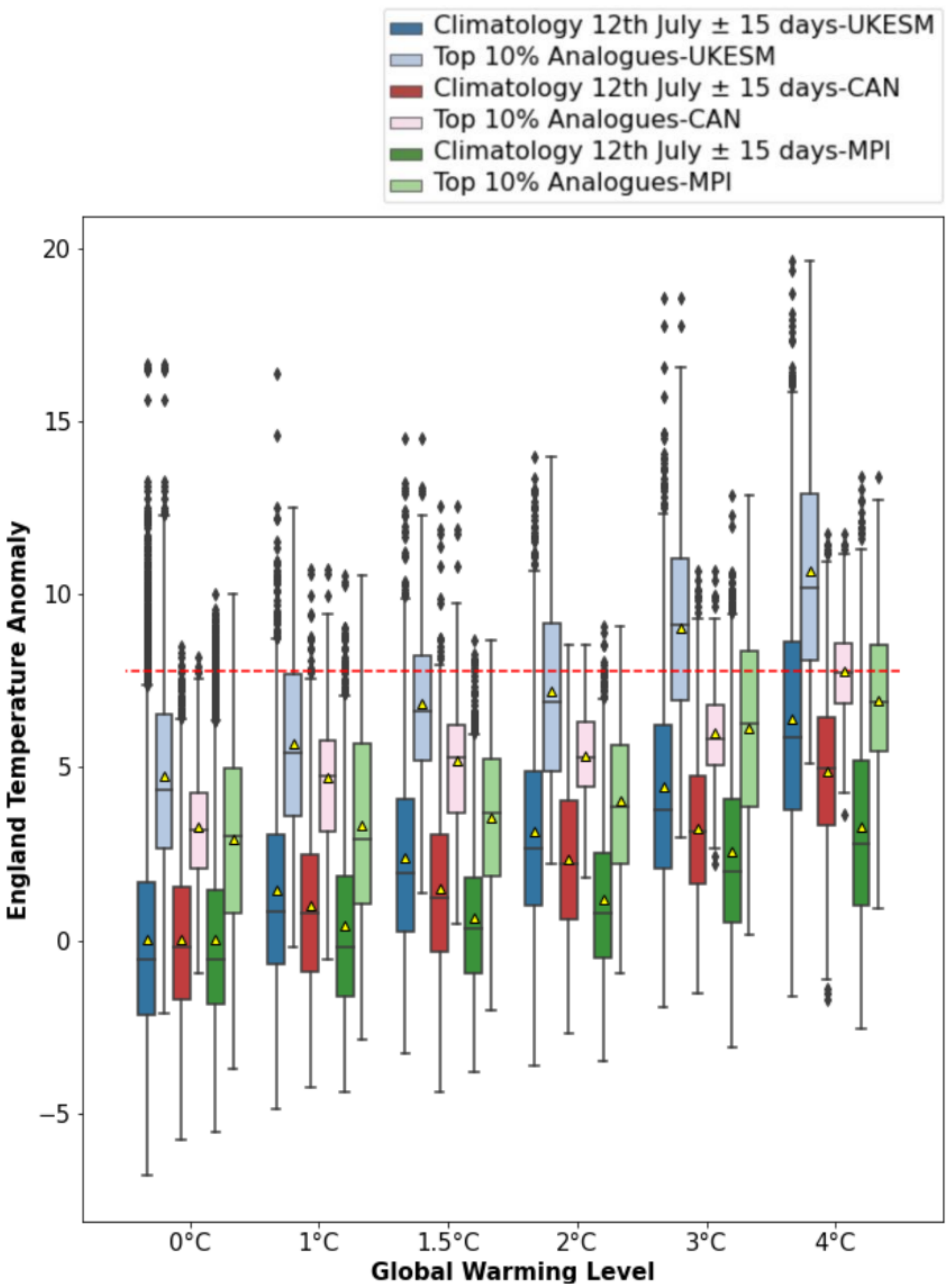



**Figure 3.3:** Boxplots showing analogues and climatology of the period around the 1923 event for the decade where the global warming levels (1°C, 1.5°C, 2°C, 3°C and 4C°) are reached for all three models, UKESM, CanESM5 and MPI. 0°C is also included which is taken to be 1850-1900. Coloured boxes span the 25th-75$^{th}$ percentiles of the distribution, with the whiskers showing the 5$^{th}$ and 95$^{th}$ percentiles; individual outliers are shown by black dots). The red dashed line indicates the England temperature Anomaly during the 1923 heatwave.

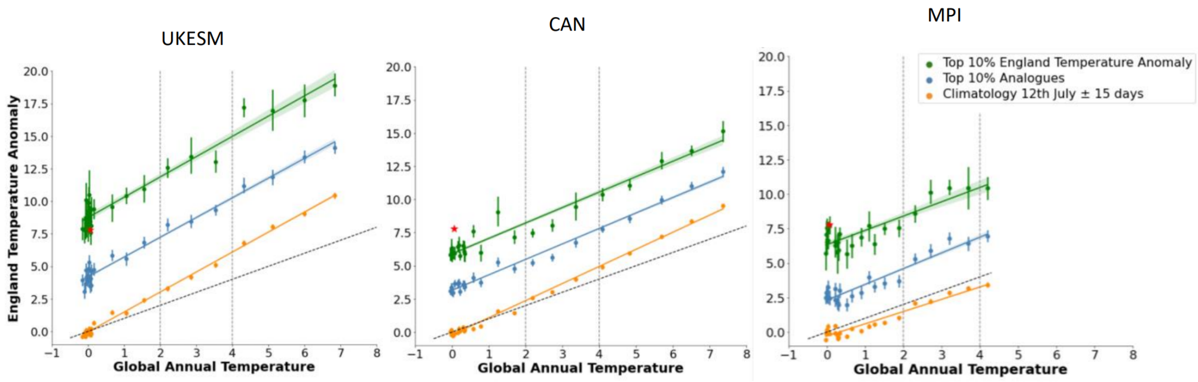



**Figure 3.4:** Scatter plot showing the climatology for the period around the 1923 event (orange) compared to the temperature over England of similar circulation patterns to the original event (in blue) and the top 10% of temperatures from those with similar circular patterns (green). Dark grey dashed vertical lines show warming levels of 2°C and 4°C. The light grey line represents a 1:1 trend. A red star represents the temperature over England during the original heatwave event in 1923 from 20CR. Climatology (orange) Top 10% Analogues (blue) Top 10% England Temperature Anomaly (green).

| Model/Metric | Climatology | Top 10% Analogues | Top 10% England Temperature Anomaly |
|---|---|---|---|
| UKESM | 1.53 (0.01) | 1.52 (0.02) | 1.56 (0.06) |
| CAN | 1.29 (0.01) | 1.17 (0.01) | 1.16 (0.03) |
| MPI | 0.89 (0.01) | 1.14 (0.04) | 1.04 (0.08) |

**Table 3.2:** Rates table with the standard error associated with each value in brackets. The black lines in Figure 3.4 show a rate of 1 between Global Annual Temperature and England Temperature Anomaly.

Figure 3.3 that there is a significant difference between models, particularly when looking at the extremes in temperature. This highlights the dangers of using a single model for exploring extreme events and to feed into adaptation decision making. For example, if a decision maker aims to focus on high risk or an example of a worst-case scenario, this changes depending on the model selected.

Figure 3.4 shows the rates of change of climatology and analogues compared to global annual temperature. The orange lines represent the climatology (around 11-13$^{th}$ July) for each model. The black lines in Figure 3.4 represent a 1:1 rate of change between global annual temperature and England temperature anomaly. We can see that for UKESM and CanESM5 the climatology over England is warming at a faster rate than global warming (at a rate of 1.53 and 1.29 respectively with reference to Tables 3.2 and 3.3). However, MPI shows a rate of warming of England temperature anomaly that is below the global

| Model/Metric | Climatology vs Top 10% Analogues | Climatology vs Top 10% England Temperature Anomaly |
|---|---|---|
| UKESM | 0.4250 | 0.764 |
| CAN | 1.61e-12 | 0.0214 |
| MPI | 3.62e-13 | 0.162 |

**Table 3.3:** p-value table (using t-test) Green boxes indicate where the null hypothesis can be rejected and rates can be considered statistically significant with a 5% threshold.

average. To summarise, at 2°C of global warming the warming in the three models for England temperature varies between 1.78 and 3.06°C. In this plot we introduce a new metric, "Top 10% England Temperature Anomaly". This is the top 10% of temperatures from the analogues, a subset of analogues. This allows us to explore analogues that lead to hot extremes over England by providing this additional constraint.

In UKESM, the rate of change of the top 10% of England temperature anomaly analogues is 1.56 (standard error = 0.06), only slightly higher than the climatology. For UKESM, when comparing the climatology rate with that of the top 10% analogues and with top 10% England temperature anomaly analogues we find that we cannot reject the null hypothesis that these rates are significantly different using a 5% threshold with reference to Table 3.1.

In CanESM5 the rate of change of both the top 10% analogues and the top 10% England temperature anomalies are slightly lower than that of climatology. Using the same 5% threshold we find that when comparing the rate of change in decadal climatology between that of the top 10% analogues and the top 10% England temperature they are significantly different.

And in MPI, the top 10% of anomalies shows a higher rate of change than its climatology at 1.14 (standard error = 0.04). The rate of climatology to top 10% analogues is significantly different but we cannot reject the null hypothesis that the rates are significantly different between the climatology and the top 10% of England temperature.

Overall, we may expect the climatology to increase at a higher rate than 1:1 as Europe is currently warming at a higher rate than the global average (Rousi et al., 2022; Russo et al., 2015) although England may warm less than more continental regions in Europe. The rates for the top 10% England temperature anomaly analogues, i.e. regimes with similar circulation patterns to the 1923 event that show the highest temperature anomalies over England, seem to be similar to that of climatology, particularly for UKESM and MPI. By the end of the century, UKESM shows 6.8°C warming above pre-industrial, CanESM5 reaches 7.4°C and MPI just passes the 4°C mark by 2100.

## 3.6 Discussion

### 3.6.1 Methodological choices

Figure 3.5 shows the rho thresholds (the cut-off value of rho) when considering the top 10% (based on rho value) to be analogues. The rho threshold or cut-off values vary between models with CanESM5 tending to have a higher threshold than UKESM or MPI. The 10% cut-off varies between 0.45 and 0.73 and the 5% cut-off varies between 0.59 and 0.78. In terms of the associated temperatures over England, taking the 5% or 10% cut-off did not significantly impact results. We therefore have chosen a 10% cut-off to increase our sample size. Using a cut-off/threshold value for rho of 0.5 as opposed to 10% yields similar results.

We can see, with reference to Figure 3.5, that the rho threshold, before detrending, increases over time in both UKESM and CanESM5. This is mainly due to an increase in the mean Z500 height from 1850 to 2100 as the global temperature increases. Appendix B.2 shows this increase in Z500 height from pre-industrial times to the end of the century. The largest increase in Z500 is in CanESM5 which is expected as this is the model that warms the most by 2100, by 7.4°C compared to pre-industrial. The areas of highest Z500 increase for both UKESM and CanESM5 are in the locations of highest pressure during the 1923 event, namely over Scandinavia. Therefore, this aligns with an increased rho cut-off value from 1850 to 2100. MPI in comparison only warms by 4.2°C at 2100 and therefore the mean Z500 height does not increase by the end of the century as much as for UKESM and for CanESM (see Appendix B.2). Interestingly, the area over Scandinavia seems to be the area of least height increase in MPI in contrast to UKESM and CanESM5.

Figure 3.5 shows the rho thresholds after being corrected for this height increase from 1850 to 2100. The correction was completed removing the mean Z500 values for each decade from that decade's values leaving the underlying pattern. As expected, we see that the rho thresholds for UKESM and CanESM5 are corrected downwards towards the

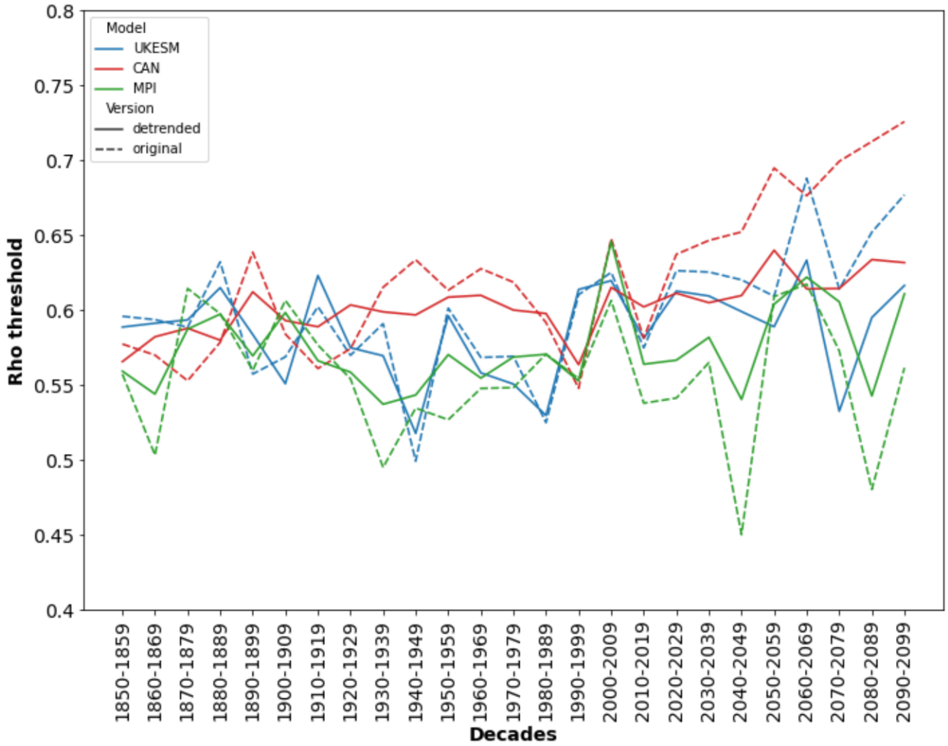



**Figure 3.5:** Showing rho cut-off value/threshold for top 10% of analogues per decade for each model and the comparison to the detrended values.

end of the century. When MPI Z500 heights are corrected this moves the rho threshold upwards. This aligns with the fact that the lowest pressure increase was over Scandinavia in comparison to UKESM and CanESM5 where the areas of largest Z500 height increase matched the areas of highest pressure during the 1923 event.

Correcting for the increase in Z500 height makes little difference to the analogues found and their associated England temperature anomaly values (see Appendix B.3). However, this correction is vital if Euclidean distance is used instead of maximising the Spearman correlation (see Appendix B.4). This is because the Spearman correlation method is less sensitive to the magnitude of the difference between the two datasets when compared to using the Euclidean distance and focuses more on the underlying pattern. The Spearman correlation considers the rank order of values as opposed to directly considering the magnitude of differences between values and therefore may be less influenced by increasing geopotential height. This highlights the benefit of using the method of maximising the Spearman correlation particularly when looking into potential future conditions and events. This correction is also important when exploring any changes in the frequency of occurrence of events similar to 1923 between 1850 and 2100.

### 3.6.2 Limitations of analogues

Analogues have been used in many studies to successfully place events into historical context as well as to attribute anthropogenic warming to particular heatwaves or extreme events (Cattiaux et al., 2010; Harrington et al., 2019; Jézéquel et al., 2018c; Otto et al., 2016). This research, however, aims to determine the effectiveness of using the analogue methodology to explore potential future heat events. A key limitation of using this approach is the dependency on models and their ability to get the circulation patterns right in the future under different warming scenarios. Results will also depend on how many instances there are of a particular event in the model. Both temperature and Z500 height will increase as the globe warms. This may lead to different types of weather regimes unlike those that are currently experienced or that have been witnessed in the recent past (Rousi et al., 2022; Rousi et al., 2023; Yang et al., 2022). This could impact the frequency and severity of heatwaves and would not be picked up in an analogue-based study such as this one, unless these future changes are reflected in the models. However, the most "extreme" analogues in terms of England temperature anomaly in the climatology do tend to be picked up when focusing on the top 10% analogues.

We also are limited by the definition of what an analogue actually is and how to define it most effectively. The choice of spatial extent over which analogues are detected can influence results for example. We find that when taking top 10% of analogues based on their rho value that these lead to a range of temperatures over England. For example, with reference to Figure 3.4, at 2°C the top 10% analogues from UKESM range from 2.21 to 13.97°C above pre-industrial over England. We therefore sub-selected analogues based on heat (taking the top 10% of temperatures over England from the top 10% of analogues based on rho value) to explore how analogues that lead to heat over the UK only compare to climatology for example. The fact that using circulation patterns alone to find analogues does not always lead to heat events over the UK can be considered a limitation of this technique.

In addition, this method does not take into account compound events such as drought and heat which is likely to have played a role in the 1911 event for example. The method does not take into account soil moisture deficit or land-atmosphere feedbacks that can play a key role in heatwaves particularly at the local level (Seneviratne et al., 2010; Vogel et al., 2017) and so analogues found are only based on the circulation pattern. This method could potentially be expanded to include analogues for more than one variable with more of a focus on a number of preceding conditions to the event of interest. Additionally, we find analogues based on a snapshot of past events, in other words, the mean value over a heatwave event. A future study could investigate finding analogues by using the evolution of the event as the days leading up to an event could also be important.

In this analysis, we find that for most models the rate of change of global temperature to England temperature anomaly is similar for climatology and the extremes (the top 10% of England temperature analogues). However, this could be an example of the limitations of using climate models for this type of analysis as previous studies suggest that in North-West Europe, the hottest summer days are warming approximately twice as fast as summer days of mean temperatures between 1960 and 2021, a trend that is not captured by climate models (Patterson, 2023) including those used in this study. Other studies focused on the UK also conclude that extremes of temperature in the UK are changing faster than average temperatures (Kendon et al., 2023).

### 3.6.3 Can analogues be used as storylines?

It can be shown, particularly with reference to Figure 3.4, that different models lead to different results and temperature ranges for potential future heatwaves. Figure 3.6 shows examples of heatwaves that are analogous to the 1923 event at 1, 2 and at 4°C of global warming. These examples show the hottest analogue events found over England for each model at the two levels of global warming. At 2°C the temperatures over England range from 8.5 to 14.0°C above pre-industrial levels and for 4°C the range is between 11.7 and 19.6°C. This large range between models highlights the danger of only using one model to make adaptation decisions related to future heatwave events. This also provides challenges when communicating results to decision makers and how ranges and uncertainties in future extreme events should most effectively be communicated and used to make adaptation decisions. The use of workshops or serious games are considered effective methods for making decisions under uncertainty where a storyline approach could be used (Rumore et al., 2016; Shepherd et al., 2018; Undorf et al., 2020b). In this case, an organisation could discuss their resilience level to heatwaves reaching the different temperature ranges calculated in this research as a form of "stress-testing" adaptation strategies. Analogues give the additional benefit of being based on an historic heatwave event, perhaps one that lives in shared societal memory or one that a population has lived through, and therefore could help motivate adaptation action (Garcia et al., 2022).

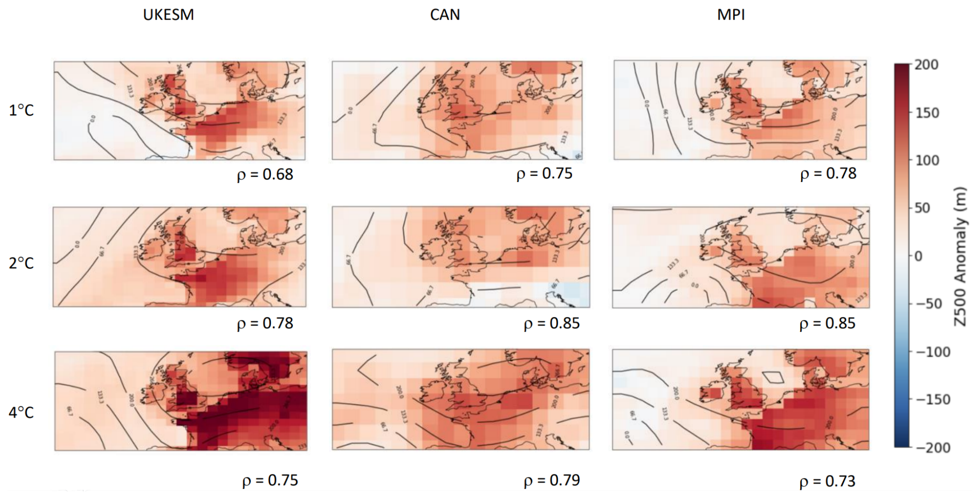



**Figure 3.6:** Spatial plots showing the circulation pattern and temperature anomalies relative to pre-industrial (1850-1900) for the most extreme heatwave analogues found (in terms of their England temperature anomaly) Rho values associated to each are included below each plot.

## 3.7 Conclusion

In this chapter, we use an analogue methodology based on atmospheric circulation to analyse how past heatwave events may change under different global warming scenarios. We comment on methodology choices and the limitations of using this method. For example, we are using geopotential height (Z500) to search for analogues without taking into account preceding conditions, such as drought. Therefore, compound events such as drought and heat, such as in 1911, may lead to less effective analogue selection than if using a method that includes drought as a preceding factor (Cowan et al., 2020). We are also limited by the frequency of the high pressure system of interest in the dataset and to what extent models can reliably contruct potential future events. 1923 seems to be a more common high-pressure circulation pattern over Europe that leads to heat and therefore leads to clearer results than 1911. On the other hand, 1923 is similar to the pattern involved in other strong heat events in the record, making it relatively less distinct and again querying to what extent atmospheric circulation alone is suitable to select the best analogues, as not all analogues provide strong heat events. This suggests using additional information, such as drought preconditioning, the strength of the atmospheric anomaly (which is neglected in correlation statistics) or prior build-up of heat might be necessary to identify analogue events that sample preferentially intense heat.

For the 1923 event, it would be considered an extreme heat event at the time it occurred (above the 75$^{th}$ percentile of the analogue distribution), whereas at 4°C of global warming the same event would be at the lower end of the distribution, below the 25$^{th}$ percentile of the analogue distribution. When comparing the rate of change between global annual temperature and England temperature, the rate of change of climatology is similar to that of the hottest analogues over England. This could highlight a key limitation of using analogues to find future heatwave events as evidence suggests that in the UK, extremes are warming faster than mean temperatures (Kendon et al., 2023; Patterson, 2023).

We compare the analogues found before and after detrending for increasing pressure levels as the global temperature warms. We find that there is little difference in the analogues found when maximising the Spearman correlation but a considerable difference when minimising the Euclidean distance to identify analogues. This is because the Spearman correlation method is less sensitive to the magnitude of the difference between the two datasets and therefore is a more robust metric for finding analogues in future warming scenarios. Despite its limitations, analogues could be an effective method of communicating climate risk, particularly to demonstrate the need to adapt to changing extremes. This method takes an event that people are aware of from the past and gives an idea of what we may need to prepare for in the future which could aid in discussions about future preparedness and resilience building.

Future research could take into account other variables or preceding conditions, such as drought, as well as the pressure which could create more realistic or reliable analogues to past events as well as being able to inform adaptation decision making for compound events. In addition, this chapter focused on summer heatwaves in the UK. Looking at different types of events or heatwaves in other regions or in different seasons could lead to different results and conclusions. Future work could extend this research to compare with other seasons or events or to events in other regions.

# Chapter 4

# Extreme Event Risk and Adaptation

The aim of this research chapter is to help bridge the gap between climate science and decision makers by making it clearer what the requirements are for future tools, models and data to help accelerate adaptation action and how it is reported on and evaluated. This chapter examines the progress made by the public sector in Scotland from risk assessment to adaptation planning and implementation. We highlight some key challenges faced by the public sector in Scotland that are leading to a lack of progress in the adaptation space as noted in a recent UK Climate Change Committee report, "Is Scotland climate ready? – 2022 Report to Scottish Parliament". This report highlighted the lack of analysis of the adaptation section of public bodies duties reports in Scotland and our research is the first in-depth analysis of this section at time of writing supplemented by interviews with a range of public sector bodies. First, the key challenges currently facing the public sector in Scotland are set out, and then a range of potential solutions are presented that could be implemented in Scotland to increase adaptation action. This chapter has been accepted for publication in the journal Climate Services and is currently available as a pre-print:

*Citation: Yule, Emma and Donovan, Kate and Graham, June, How Public Sector Organisations are Conducting Climate Risk Assessments for Adaptation in Scotland. Available at SSRN:*
*https://ssrn.com/abstract=4358937 or http://dx.doi.org/10.2139/ssrn.4358937*

**Table of Contents**


4.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 67

4.2 Method . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 68

4.3 Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 71

4.4 Critical analysis and discussion . . . . . . . . . . . . . . . . . . . . . . . 81

4.5 Summary & Take-aways . . . . . . . . . . . . . . . . . . . . . . . 90

## 4.1 Introduction

The ability to manage climate risks and adapt to climate change is becoming increasingly important as the intensity and frequency of extreme weather events increase (Masson-Delmotte et al., 2021). In Scotland, winters are becoming wetter and sea level rise around the coast has increased up to 3cm per decade over the last 30 years (Climate Change Committee, 2022). The average temperature in Scotland has increased by 0.5°C over the same time period. While adaptation is a key component of international climate agreements, (Lee et al., 2022; UNEP, 2021) "adaptation gaps" have been identified worldwide in relation to planning, finance and implementation (Goldstein et al., 2019). Scotland responds both to a UK and Scottish climate change policy framework mainly through the UK Climate Change Act 2008 and the Climate Change (Scotland) Act 2009. A Climate Change Risk Assessment (CCRA) is required by the UK act every five years which forms the basis of adaptation policy in the UK and in Scotland (Adaptation Scotland, 2022). Scotland's adaptation plan is set out in its second Scottish Climate Change Adaptation Programme (SCCAP2) (Government, 2019) which addresses the Scottish specific impacts identified in the UK CCRA. Progress towards the goals set out in SCCAP2 is independently assessed by the Climate Change Committee whose recent report "Is Scotland climate ready? – 2022 Report to Scottish Parliament" (Climate Change Committee, 2022) highlighted that Scotland's progress in delivering its adaptation aims had stalled across most sectors and it emphasised the need to raise the level of adaptation response. Public bodies in Scotland have a duty to annually report their climate mitigation actions as well as their contribution to delivering SCCAP2 (Sustainable Scotland Network (SSN), 2021). They do so, by reporting to the Scottish Government through Public Bodies Climate Change Duties (PBCCD) reporting. However, the adaptation section of the reports are currently not being analysed routinely by the Scottish Government and therefore have provided minimal evidence of approaches public sector bodies are taking to assess risk, plan and implement adaptation as well as the challenges they are facing (Climate Change Committee, 2022).

The concept of applying a risk management framework in the context of climate change is strongly developed, particularly since IPCC AR5 where risk was presented as a product of hazard, exposure and vulnerability (Sainz de Murieta et al., 2021; Reisinger et al., 2020). An IPCC cross-working group report as part of AR6 stated the core definition of risk as the "potential for adverse consequences" (Reisinger et al., 2020). While many public and private sector bodies have processes in place to conduct risk assessments, those related to climate change and climate risk pose challenges (Goldstein et al., 2019) due to the level of uncertainty involved. Traditional risk assessments tend to be appropriate for situations where knowledge about possibilities and probabilities are unproblematic (Stirling, 2010). This is infrequently the case when assessing climate risk where complex systems are involved that may have nonstandard variation across time (Wassénius et al., 2022). Climate risk assessments therefore require input from a range of disciplines and perspectives using both quantitative and qualitative information, providing information on likely scenarios and on high impact, low probability events.

Our key research questions in this chapter are: "What tools, frameworks, data and knowledge are currently being used to conduct risk assessments for adaptation?"; "What kind of tools, frameworks, knowledge and data may be helpful for decision makers in this space?" and "What challenges and barriers exist for public sector bodies throughout their adaptation journeys?" While literature exists around creating data, tools and science that are useful to decision makers in this space (Deubelli et al., 2021; Lee et al., 2022; Sainz de Murieta et al., 2021; Tisch et al., 2018; Wilson et al., 2020) fewer studies aim to understand what kind of tools decision makers are currently using and where the key challenges lie when accessing, interpreting and using this information, even though the "translation gap" between climate researchers and decision makers has been documented (Bremer et al., 2019; Deubelli et al., 2021; Milhorance et al., 2022). By analysing the regulatory reporting for adaptation, we have set out the challenges currently facing the public sector in Scotland and solutions that may progress the implementation of adaptation actions in the Scottish public sector. We discuss the barriers in relation to mitigation which is felt to have progressed further and faster in comparison to adaptation in order to understand how adaptation action may be accelerated. After setting out the method in section 4.2, we outline the key results from the report analysis and the interviews conducted before providing an in-depth critical analysis and discussion in section 4.4.

## 4.2 Method

An inductive approach was taken in this research. Two adaptation questions in the regulatory public bodies climate change reports were analysed and interviews conducted with a range of individuals in the public sector who have key roles in the completion of the duties reports.

### 4.2.1 Public Bodies Climate Change Reports analysis

We analysed the Sustainable Scotland Network (SSN) Public Bodies Climate Change Reporting 2019/20 and 2020/21 reports (Sustainable Scotland Network (SSN), 2021). The reporting timeframe was selected to align with the publication of the Second Scottish Climate Change Adaptation Programme (SCCAP2) 2019-2024 which was published in September 2019.

Public sector organisations in Scotland have a statutory duty to both reduce greenhouse gas emissions and to prepare for the impacts of climate change while reporting on progress made annually (Sustainable Scotland Network (SSN), 2021). In terms of mitigation, 75% of public bodies have at least one emission target and over 20 organisations have set a net zero target with others setting sectoral targets. This research however is the first in-depth analysis that has been completed at time of writing on the adaptation section of the reports despite this section being part of the report since the first reporting year, 2015/16. Two key questions from the adaptation section have been analysed in this research, for the purpose of this research these will henceforth be labelled as Q1 and Q2, Q1: "What are the body's top 5 priorities for the year ahead in relation to climate change adaptation?" and Q2:"Has the body assessed current and future climate-related risks?" Two out of eight questions were selected from the reports as they allowed for an analysis of key themes and the responses to each question were distinct from one another. These questions were also selected as they were completed by more bodies in comparison to other questions. In the 2020/21 reporting year, 155 bodies answered the former question and 163 the latter out of 180 (Table 4.1). The responses to each question were thematically analysed using Nvivo2.

For Q1 each priority listed was coded at least once depending on how many themes it covered. For the reporting year 2019/20 this resulted in the creation of 76 codes initially each with between 1 and 51 references each. These codes were then regrouped into the 27 over-arching "themes" that are presented in the results section. This process was duplicated when analysing year 2020/21. Since many of the answers remained constant from year to year this process also helped to ensure validity of codes and themes created for the 2019/20 reporting year. For Q2 a similar approach was taken in order to produce the 11 themes specifically about risk management, in this case, in addition to the five categories created for the bodies' responses to Q2, "Has the body assessed current and future climate-related

| Sector | Number of bodies that responded to Q1: *"What are the body's top 5 priorities for the year ahead in relation to climate change adaptation?"* | | Number of bodies that responded to Q2: *"Has the body assessed current and future climate-related risks?"* | | Number of bodies in sector |
|---|---|---|---|---|---|
| | **2019/20** | **2020/21** | **2019/20** | **2020/21** | |
| Local Authorities | 31 | 30 | 31 | 32 | 32 |
| National Health Service | 18 | 17 | 18 | 17 | 19 |
| Educational Institutions | 39 | 40 | 42 | 42 | 44 |
| Transport Partnerships | 7 | 7 | 7 | 7 | 7 |
| Others* | 42 | 46 | 41 | 48 | 48 |
| Integration Joint Board | 14 | 15 | 15 | 17 | 30 |
| Total | 151 | 155 | 154 | 163 | 180 |

**National and regional public bodies*

**Table 4.1:** Number of public bodies per sector in reporting years 2019/20 and 2020/21 (including Integration Joint Boards which act as partnerships between the National Health Service and council in local regions around Scotland with a focus on the planning and delivery of local social care).

risks?". Q2 was independently analysed by the SSN secretariat for the Summary Analysis Report 2022 (Sustainable Scotland Network (SSN), 2021). This provided a comparative reference and ensured validity. An inductive approach was used in the thematic analysis of both Q1 and Q2 in an attempt to reduce the effect of researchers' bias.

### 4.2.2 Interview analysis

Ten targeted interviews were conducted with representatives of public sector bodies, at differing levels of adaptation planning and risk assessment and from different geographies around Scotland. The individuals selected from public sector bodies were those who complete or have significant input into the completion of the public bodies duty reports. The purpose of the interviews was to provide further depth to the responses presented in the reports, exploring the research questions further.

Semi-structured interview questions included: "Have you suffered from any extreme weather events in the past and are there any particularly on your radar?"; "What information, knowledge or data do you use in decision making/risk management related to extreme events?"; "Do you face any challenges around risk assessments or accessing data, information or knowledge?". In addition, questions were asked in relation to the bodies' specific report responses in the adaptation section of the public bodies duties reports. Therefore, semi structured interviews allowed the freedom to discuss different challenges or barriers with each interviewee while still addressing the key research questions.

Interviews were conducted online and were recorded. The transcriptions were then imported into Nvivo2 for analysis. Similar to the analysis of the report questions, an inductive approach was taken in the interview analysis where each interview was coded in a grounded theory "lite" approach (Braun et al., 2006; Glaser et al., 2010). Saturation was reached by interview 9 where few new codes were added either for interview 9 or 10. A similar approach has been taken by others in similar fields (Boiral et al., 2019; Ivory et al., 2020; Tisch et al., 2018).

## 4.3 Results

### 4.3.1 Top adaptation priorities for public sector bodies

Table 4.2 provides a breakdown of the key themes per sector in relation to adaptation priorities from responses to Q1:"What are the body's top 5 priorities for the year ahead in relation to climate change adaptation?". Table 4.2 highlights the most common themes across all sectors such as "Develop Plan" and "Risk & Impacts" as well as indicating sector specific recurring themes such as "Climate Justice" that only emerges from responses from Local Government for example. Figure 4.1 shows the themes emerging from this question across all sectors from two consecutive reporting years, 2019/20 and 2020/21. The two years were compared in order to understand how the adaptation priorities may change year on year since the publication of SCCAP2. Between the reporting years of 2019/20 and 2020/21 the themes discussed did not change significantly. "Develop Plan" has been the most referenced theme of these two reporting years suggesting that adaptation within the public sector in Scotland remains largely in its planning phase, a finding that aligns with the latest Climate Change Committee progress report (Climate Change Committee, 2022). When comparing the two reporting years, there are less references to "Develop Plan" in 2020 compared to 2019 and more references to "Implement & Deliver Plan" in 2020 suggesting some limited progress made between years. Appendix C.1 gives examples of different priorities that fall under each theme. From the interviews, key adaptation

| Theme | Transport partnerships | Local Government | National Health Service | Integration Joint Boards | Others | Educational Institutions | Total |
|---|---|---|---|---|---|---|---|
| Awareness & Communication | 3 | 2 | 3 | 11 | 6 | 5 | 4 |
| Behavioural Change | 3 | 0 | 0 | 0 | 2 | 2 | 1 |
| Buildings & Infrastructure | 3 | 3 | 1 | 6 | 6 | 7 | 5 |
| Climate Justice | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Community Planning Partner & Place Based Adaptation | 0 | 3 | 0 | 6 | 0 | 0 | 1 |
| Demonstrate work & best practice | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| Finance & Costs | 0 | 5 | 2 | 0 | 3 | 2 | 3 |
| Employee Engagement | 0 | 0 | 0 | 0 | 3 | 3 | 2 |
| Energy Use & Emission Reduction | 0 | 6 | 6 | 6 | 8 | 11 | 8 |
| Ensure service to customers | 3 | 1 | 1 | 0 | 2 | 1 | 1 |
| Extreme weather & hazards | 9 | 12 | 2 | 0 | 5 | 7 | 7 |
| Flexible & Virtual working | 3 | 0 | 1 | 0 | 4 | 1 | 2 |
| Food & Agriculture | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Human & Public Health | 6 | 1 | 0 | 0 | 0 | 0 | 1 |
| Learning & Training | 6 | 3 | 3 | 0 | 6 | 6 | 4 |
| Nature Based | 3 | 8 | 2 | 0 | 4 | 3 | 5 |
| Implement & Deliver Plan | 0 | 10 | 4 | 11 | 4 | 4 | 6 |
| Develop Plan | 11 | 17 | 14 | 11 | 11 | 12 | 13 |
| Recruitment | 0 | 1 | 4 | 0 | 1 | 1 | 1 |
| Reduce waste & Recyling | 0 | 0 | 3 | 0 | 3 | 2 | 2 |
| Risks & Impacts | 14 | 8 | 18 | 11 | 9 | 9 | 10 |
| Supply chain & Procurement | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Sustainable Development | 0 | 1 | 0 | 0 | 2 | 4 | 2 |
| Targets Metrics KPIs & Standards | 3 | 0 | 5 | 6 | 1 | 3 | 2 |
| Travel & Transport | 14 | 1 | 7 | 6 | 6 | 4 | 5 |
| Use of Data Tools Models & Frameworks | 6 | 5 | 15 | 17 | 4 | 6 | 6 |
| Work in Partnerships & Collaborations | 14 | 12 | 6 | 11 | 7 | 5 | 8 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

**Table 4.2:** Adaptation priorities per sector (% of total number of references per theme split by sector) from Q1. Darker shaded segments relate to the higher number of references that public sector bodies made to a particular priority. Themes with the highest number of references include: developing a plan for adaptation, examining risks and impacts, using or developing relevant data sets, tools and frameworks for risk assessment or adaptation planning and working in partnership.

priorities include creating databases of past events in order to learn from instances of past hazards as well as infrastructure and building based projects and nature-based solutions approximately aligning with the most referenced themes identified through the report analysis and with reference to Figure 4.1.

Overall, this analysis identified common cross-cutting themes related to current adaptation discourse within the Scottish public sector at the time of reporting. These include linkages between adaptation and mitigation, risk assessments and the tools and frameworks currently used to complete them (Arribas et al., 2022; Klein et al., 2005; Lee et al., 2022; Sharifi, 2020; Wassénius et al., 2022).

### 4.3.2 Mitigation & adaptation

A common challenge for all public sector bodies is the separation between mitigation and adaptation in both the policy and scientific arena. The reports and interviews indicate that despite prioritising risk assessments, there remains confusion between the two areas. In particular limited progress on adaptation has been blamed on its broad and vague nature particularly when compared to mitigation. Therefore, the top adaptation priorities for the year ahead listed by the bodies (in Table 4.2) were reviewed in order to ascertain

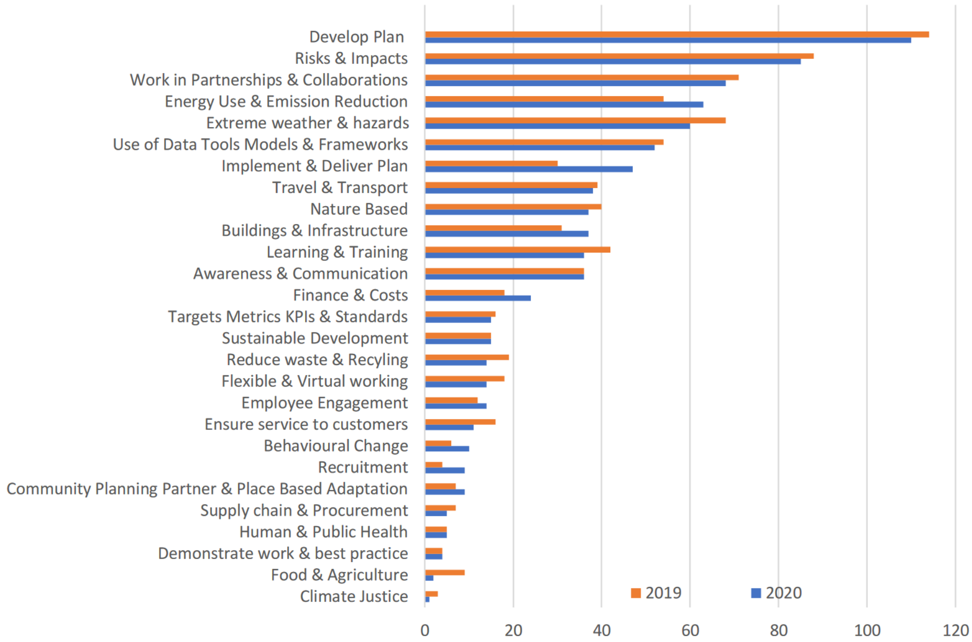



**Figure 4.1:** Themes emerging from Q1: comparing 2019 and 2020 across all sectors which shows that bodies priorities are relatively stable across the two reporting years. This plot shows the number of references bodies across all sectors made to certain themes in their reports.

whether they were in fact adaptation focused as opposed to mitigation and to identify priorities that could be considered to be both a mitigation and adaptation action. During the interviews, this was further explored via questions relating to the inter-relationship between mitigation and adaptation and the existence of any synergies or trade-offs. Priorities were categorized according to the IPCC definitions of adaptation and mitigation (IPCC, 2023).

Figure 4.2 illustrates that while 55% references across all themes were made to adaptation actions while discussing priorities for the year ahead, 20% of references were made to purely mitigation actions. Exploring each theme individually, Figure 4.3 shows that that the split between adaptation and mitigation differs even within each theme. For example, under the theme "Energy Use & Emission Reduction" the majority of references were made to mitigation such as investing in renewables to reduce greenhouse emissions while some references were made to both mitigation and adaptation for example insulation to improve energy efficiency and building resilience. Since there is a separate section dedicated to mitigation in the public bodies duties reports, bodies should not be reporting on mitigation actions within the adaptation section of the report unless there are significant areas of overlap. Most themes include priorities that cover both adaptation and mitigation demonstrating the interconnectedness between the two and the potential for synergies. For example, themes around raising awareness, training and behavioural change have the potential to include and address both concepts.

The idea that adaptation is secondary to mitigation in terms of progress made was raised by several interviewees, with one stating that “we are getting progress now and people asking questions, but the focus still tends to be on carbon reduction”; and another noting that “most public sector organisations are aware of adaptation but I think it’s been the poor relation to mitigation”. The first cited reason for this is the idea that mitigation is “a bit easier for people to understand” whereas adaptation is believed to be more complex. An example was provided in which a public sector employee who was hired to work on adaptation, biodiversity and mitigation found that they struggled to “get their head around adaptation or the adaptation agenda” they felt “it was difficult to learn about” when the employee “came from a standing start across their remit... but felt they could take on” the biodiversity and mitigation work more so than adaptation. A second key reason is around measurement and how interviewees believe that “climate change mitigation is easier to measure” than adaptation. Furthermore, the targets and drivers to reduce carbon emissions were cited as a reason for adaptation lagging behind mitigation in terms of planning and implementing actions. While co-benefits and synergies between mitigation and adaptation were discussed, the fact that measurable targets are in place for emission reductions as well as the funding available for mitigation was cited as a key reason for the lag in adaptation action with individuals stating they “need to work a bit on bringing an equal or even more focus on adaptation”. Lastly, targets for mitigation can also be longer term, whereas creating a long-term adaptation strategy is felt to be more difficult due to short-term political influences and annual budgeting, “we’d have a [long-term] target in terms of carbon neutral and net-zero by 2045... but certainly no written down plan [for adaptation]”.

Another key difference between mitigation and adaptation cited by the majority of interviewees was in relation to the complex terminology used in relation to adaptation. The need for a “translation” of acronyms was raised and there was also discussion about the difference between the terms “adaptation”, “resilience” and “climate ready” with the idea that “adaptation is probably not understood across the organisation”. The translation of terms and emergence of new terms is a common challenge for cross sectoral work such as in adaptation and risk reduction (Vogel et al., 2007). This can lead to challenges around reporting with interviewees mentioning that their organisation is likely to be con-

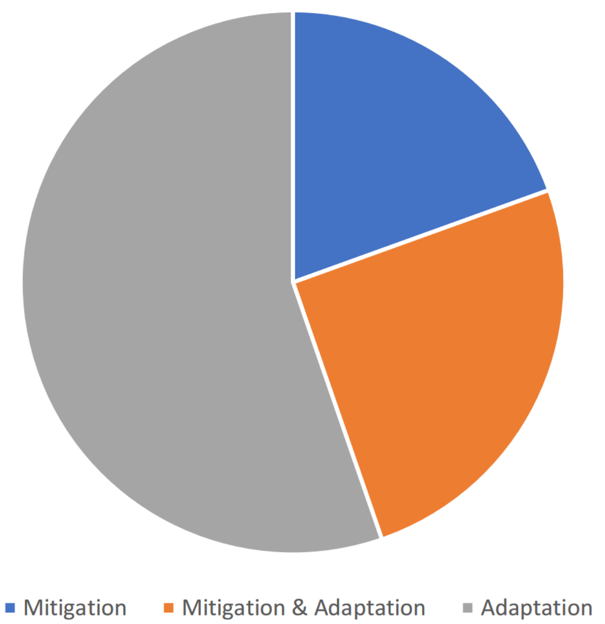



**Figure 4.2:** Total references (across all themes) split into mitigation, adaptation or mitigation and adaptation 2020

ducting unrecognised adaptation actions, "it's the tricky part because people won't see it as adaptation, like in housing for example, they will just see it as energy efficiency"; "all these services are probably doing adaptation... it's just not captured in that way'. Although synergy between mitigation and adaptation is widely accepted as beneficial, evidently this has challenges for reporting on adaptation action as well as the ability to evaluate and monitor progress including any inter-relationships between mitigation and adaptation.

### 4.3.3 Public sector bodies risk assessment progress

A range of risk assessment approaches and methodologies are currently being used by the public sector in Scotland. Risk assessments can be hazard focused or centred on a particular infrastructure or nature-based asset. With reference to Figure 4.4, 33% of public sector bodies report that they are currently assessing their current and future climate risks based on analysis of the reports. However, interviewees question whether the risk assessments conducted are fit for purpose and if undertaking a risk assessment is leading to the successful implementation of adaptation actions.

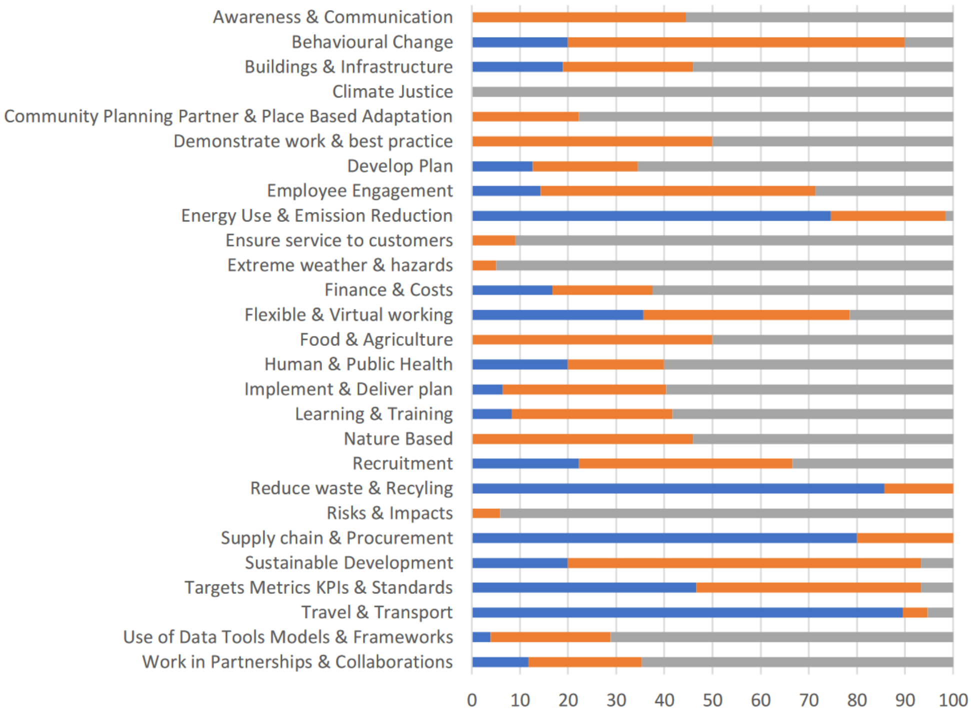



**Figure 4.3:** Total references split into mitigation, adaptation or mitigation and adaptation per theme 2020. There are a number of areas that clearly speak to mitigation within the adaptation reporting, areas relating to travel and transport as well as recycling or emission reduction illustrate confusion when reporting on adaptation and a blurring of the boundaries between mitigation and adaptation.

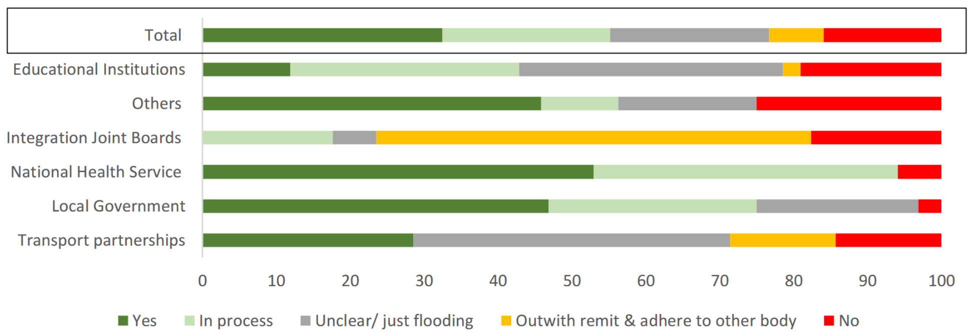



**Figure 4.4:** Responses to Q2 Has the body assessed current and future risks? For reporting year 2020 demonstrates that the majority of local authorities (government) consider themselves to have made considerable progress in risk assessment whilst educational institutes are lagging behind. As a fundamental step in adaptation planning, the implementation of risk assessments provides a good indication of progress towards adaptation.

Key challenges around risk assessment identified by interviewees relate to knowledge requirements, capacity and implementation. Bodies voiced concerns about the level of knowledge about climate change hazards and potential future risks that are required to conduct a comprehensive climate risk assessment. One specifically noted instances where work on completing a risk assessment has been delayed in order to increase understanding, "we needed to understand climate change before risk assessments took place". Some bodies who had conducted comprehensive risk assessments felt they still lacked preparedness during a hazardous event and therefore questioned uncertainty and difficulties capturing residual risks, stating "I didn't know what I didn't know". Bodies during interviews also cited capacity issues as a barrier to completing a risk assessment with some discussing the idea of working with regional partners to allow for "economies of scale and learning from each other".

In addition, questions arose around the link between completing a risk assessment and implementing adaptation actions. For example, bodies suggested that "often action comes from identification of a physical need on the ground... and not necessarily a risk assessment". For risk assessments that lead to implementation, a focus needs to be given on actions, "it's not just about assessing the risk it's deciding the action from that", "we can't just have a better risk assessment". The chain of challenges from knowledge and capacity to implementation can be summarised by the following, "I think quite often without enough knowledge and understanding it's easy for them [risk assessments] to end up just being paper work exercises without leading to change."

Furthermore, there is a recognition amongst several interviewees that getting from reactive approaches to longer term planning is a critical challenge with one interview stating, "if there's an issue or something's happened then you would [take] a sort of reactive approach rather than maybe use scenarios", "I think that [risk assessments] are perhaps less developed than you would expect". Since hazards and adaptation actions are generally reactive, adaptation decision making and planning tends to use past events with little consideration given to potential future events and scenarios, "what you might be doing is investing in something in response to something rather than the likelihood it will happen again", there needs to be "a clear demonstration that something's already happened in that area". This is in part due to public pressure to respond to events and ensure that a similar event that happens in the future does not impact that region as severely as

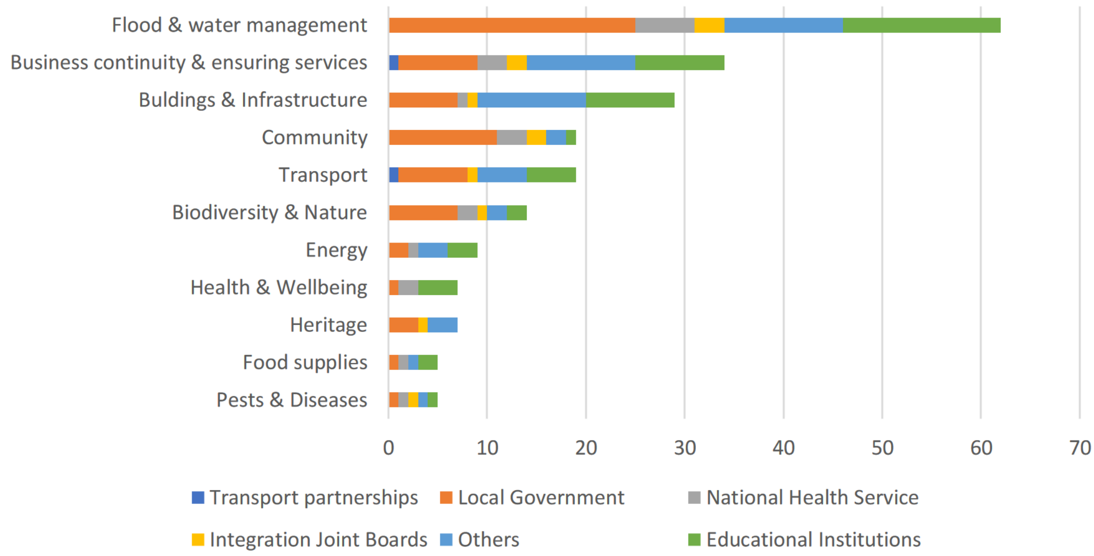



**Figure 4.5:** Themes discussed by bodies in Q2 responses in reporting year 2020

well as the fact that events tend to bring adaptation higher up the agenda. In addition, taking a long-term approach to adaptation requires longer term planning with interviewees citing the challenge of public bodies having year to year budgets and short-term policy influences.

Understanding the potential impacts of extreme weather and hazards is a fundamental aspect of undertaking risk assessments for the creation of adaptation plans. Figure 4.5 shows that the theme of flood and water management was referenced most often in responses to Q2. Several bodies reporting on their climate risk assess only part of their risk by focusing only on flooding. Furthermore, 62% of references made to extreme weather and hazards in Q1 were specifically about flooding. This is perhaps unsurprising given that the annual average rainfall in the period 2010-2019 was 9% wetter than the 1961-1990 average (UK Climate Risk, Sniffer, 2021).

### 4.3.4 Tools & frameworks

Information and tools used in adaptation are required to meet two distinct purposes. Firstly, to understand the hazards and potential impacts that may impact the organisation in order to create robust adaptation plans and secondly to get buy-in from senior stakeholders and colleagues who are not convinced that adaptation action is required.

A wide range of tools and frameworks are currently being used by public sector organisations, with a large spread of tools being used by bodies within the same sector, with reference to Figure 4.6. Climate change risk assessment reports, conducting local climate impact profiles and guidelines and frameworks from Adaptation Scotland (Adaptation Scotland, 2022) are used most commonly across the public sector.

Almost all interviewees stated that poor knowledge of hazards, impacts or adaptation options in general was a key barrier with one interviewee stating that they believe "the challenge is getting that level of expertise and knowledge within an organisation to... drive it [adaptation action] forward." Public sector bodies require local or regional data and analysis tools in order to understand what global warming "actually means regionally", "how it's going to affect our region", and to ascertain if "we [are] positioning ourselves to make sure we're in a good place going forward". Interviewees identified that tools and datasets required must be easy to interpret. This is pertinent due to capacity issues that can make interpreting complex datasets challenging with one interviewee stating that there "probably is a reasonable amount of information to allow you to... undertake an assessment, our issue is that we just haven't had the capacity... to dig into it". With others noting that "pretty complex datasets... need quite a lot of analysis to get what you need out of it". Tools identified as missing relate to accessing and interpreting local data and information so bodies can best understand the potential impacts of hazards in their region or organisation and can communicate this risk to stakeholders.

In the majority of cases, where interviewees mention progress made in conducting risk assessments and implementing adaptation actions this has been down to an individual in the team as opposed to an organisational approach, "if we are advanced, it's in no small part to an individual with a high knowledge level". In another example, an individual within the organisation worked directly with data producers including the UK MET Office in order to "get what we need out of it [the] pretty complex datasets". Interviewees highlighted that guidance could help public sector bodies conduct fit for purpose risk assessments. For example, having "feedback on that [risk assessment and reporting] and being held accountable on that" as well as more of a standardised template for risk assessments. In addition, the idea was put forward that all bodies should be planning for the same level of warming in a consistent approach, "if the Scottish Government agreed on a single plan for it, then we'd be planning for the same thing, probably 3°C". This reflects the Climate Change Committee's recommendation to adapt to 2°C while preparing for 4°C which could be standardised across public sector bodies (Climate Change Committee, 2021a).

In chapter 3 we discuss potential heatwave events using the flow analogue approach at 2 and 4°C of warming which could be an effective tool in adaptation decision making based on this recommendation. The need for tighter legislation and "pushing [adaptation] up the agenda" was also discussed.

The second requirement of data and frameworks according to interviewees is to help receive buy-in from senior stakeholders and colleagues who are unconvinced of the need to adapt. The most prominent reasons from this lack of buy-in, as cited by interviewees, include the lack of understanding that extreme events are linked to climate change and the belief that their local area will not be severely impacted by extreme events. Tools around visualisation and storytelling were mentioned here as a way to address the latter. Tools that allow for "conceptualizing…what it will look like when it floods", "not a table, it's not a graph, it's not a map, it's a photograph". Having a "data bank with pictures and stories about climate change affecting certain things in society" was also suggested, "making it real does help". One interviewee summarized this with the following, "But it's getting that story, the simplified story between. This is what's happening. These are the impacts and this is what we have to do. And that sort of simplistic narrative." A number of interviewees stated that they have received push back on adaptation, around the role that climate change has in changing the severity and frequency of extreme events and the level of risk posed by potential future hazards in Scotland. In addition to visualisations and storylines, cost-benefit analysis tools were mentioned for their potential to incentivise adaptation action. The "ability to quantify some sort of value of the risk…the cost associated with not doing that or not responding to that risk", "it's easy to define the cost of building a wall but not necessarily the cost of not building a wall".

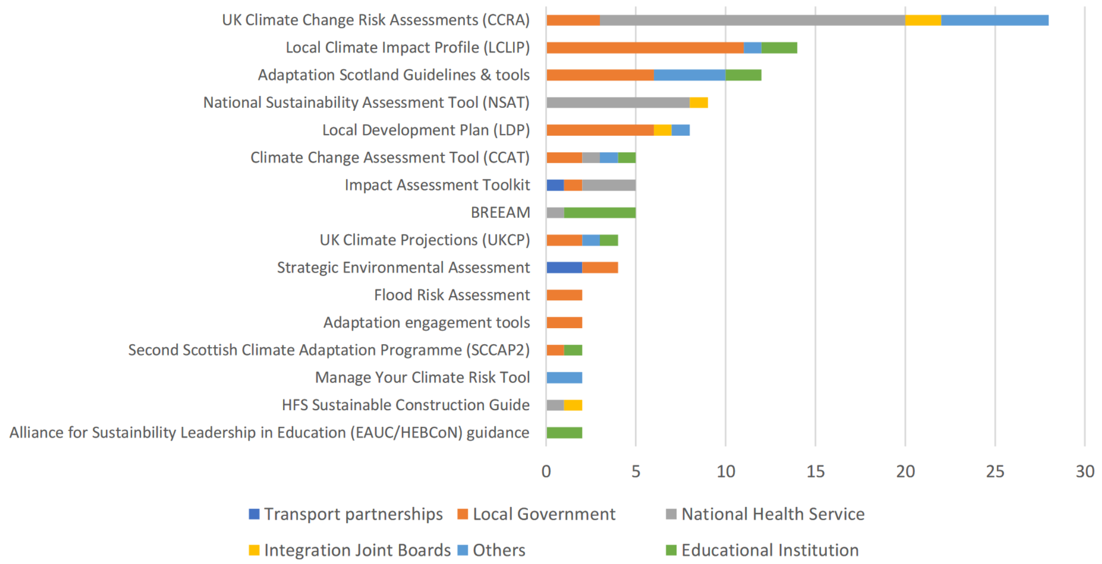



**Figure 4.6:** All tools mentioned by bodies across Q1 and Q2 in reporting year 2020

## 4.4 Critical analysis and discussion

This research set out to reflect on the progress made by the Scottish public sector in regard to adaptation. Section 4.3 highlighted some critical areas of concern and challenges for the public sector in progressing adaptation. In particular, the lack of progress for adaptation compared to mitigation. This section will offer further critical analysis and discussion around the differences and similarities between mitigation and adaptation in terms of: the complexity and drivers associated with progressing adaptation and mitigation actions, the risk and uncertainty involved, collaboration and the number of actions required and measurements and targets associated with mitigation compared to adaptation.

Whilst it is evident that mitigation and adaptation are intrinsically linked, by reducing greenhouse gas emissions there will be less need for adaptation action in the very long run, yet adaptation and mitigation tend to be separated in policy, practice and in research applications (Sharifi, 2021; Sharifi, 2020). This is partly due to the apparent inherent differences between them. The majority of studies present the differences between mitigation and adaptation at the global scale and not at the level of local implementation (Klein et al., 2005; Klein et al., 2007; Sharifi, 2020).

### 4.4.1 Complexity and drivers

Adaptation is understood to be more complex than mitigation within the Scottish public sector. This complexity relates to understanding the link between climate change and increased occurrences of hazards as well as how to implement adaptation action and how to monitor progress made.

A key challenge facing individuals within the public sector is a lack of buy-in from senior stakeholders and colleagues. While some interviewees felt colleagues took them at their word and implemented adaptation action, in other instances, particularly if the lack of buy-in comes from senior stakeholders, this creates an almost insurmountable barrier to adaptation action. Buy-in from senior stakeholders is critical for climate action, both for mitigation and for adopting adaptation planning (Hoffman et al., 2007; Kythreotis et al., 2017; Lawrence et al., 2017; Rosenzweig et al., 2011). Lack of buy-in was most commonly associated by interviewees due to a lack of awareness and understanding of climate change and how this may impact extreme events in their local area. Lack of awareness is a commonly cited factor leading to lack of climate action both in the mitigation and adaptation space (Rickards et al., 2014b).

Some interviewees mentioned using images in order to tell a local story of adaptation and climate impacts to increase the availability bias of colleagues and senior stakeholders. Visualisations have been shown to help improve likelihood of taking action in some cases, (Chapman et al., 2016; O'Neill et al., 2014) particularly if it can raise a visceral concern in audiences, for example, if images show an area they are familiar with being damaged or destroyed by extreme weather events or by sea-level rise. Extreme weather events may also have the potential to induce adaptation-focused policy change (Giordono et al., 2020) and therefore creating a database of hazards in Scotland could help to demonstrate the impacts that adaptation actions could reduce, demonstrating the need for action.

In addition, individuals within public sector bodies have the challenge of simplifying messages to communicate the need for adaptation within their teams as lack of knowledge can be a key disincentive to climate action (Rickards et al., 2014b). Therefore, there is a requirement for upskilling across organisations including at the senior management level to understand the need for adaptation. A potential solution could be training to increase awareness of adaptation in the public sector, for example, by ensuring adaptation is present in carbon literacy training. Raised awareness of climate change through for example carbon literacy training could increase staff engagement (Khatibi et al., 2021; Milena Büchs et al., 2021). This could make more of the organisation aware of what adaptation actions they are currently taking and what adaptation actions are required, helping to move from an individualist to an organisational approach.

Where individuals do make progress on adaptation, in many instances the individual does not remain within the organisation and therefore any advancements made on the adaptation agenda stalls leading to capacity issues. Therefore, increasing adaptation literacy at an organisational level across the public sector is a vital tool (Rickards et al., 2014a; Johnston, 2020). Recruiting skilled adaptation professionals could also reinvigorate teams within the public sector, particularly in circumstances when senior stakeholders' disciplinary backgrounds or perspectives, such as a bias towards short-term gains, could be limiting buy-in to adaptation action taking (Rickards et al., 2014b).

In terms of drivers, interviewees mention that external drivers for mitigation are stronger than those for adaptation in terms of deliverables and funding. The Scottish Government could push adaptation up the agenda an external pressure that could lead to greater buy-in particularly from senior stakeholders in the public sector (Rickards et al., 2014b). Legislation is felt to be required in order to make significant progress in adaptation planning and implementation by increasing awareness.

### 4.4.2 Risk and uncertainty

Individuals within the public sector require knowledge, data and tools to complete fit for purpose risk assessments and adaptation plans. While capacity is cited as a key barrier in regard to this, the fact that datasets and knowledge relating to climate impacts and risk is "complex" is a key, addressable concern. The level of risk and uncertainty involved in decision making is a key difference between mitigation and adaptation. This is in relation (Sharifi, 2020) to uncertainty involving hazards and climate impacts and how they may change in the future in relation to emission pathways and socio-economic behaviours. Ways of making decisions under uncertainty is vital to make progress in adaptation. Stirling (2010) suggest that a plurality of approaches is required for decision making under uncertainty, while a discussion and comparison of the methods is outwith the scope of this research, it is helpful to understand what quadrant of the uncertainty matrix different approaches being suggested by the public sector fall within with reference to Figure 4.7. Currently, risk assessments and cost-benefit analysis as well as expert consensus are being discussed or completed most prominently in the Scottish public sector. These approaches fall under the quadrant (see Figure 4.7) that assumes that knowledge about possibilities and probabilities are "unproblematic". Political pressures do tend to mean that focus is given to this quadrant due to, for example, a lack of funding

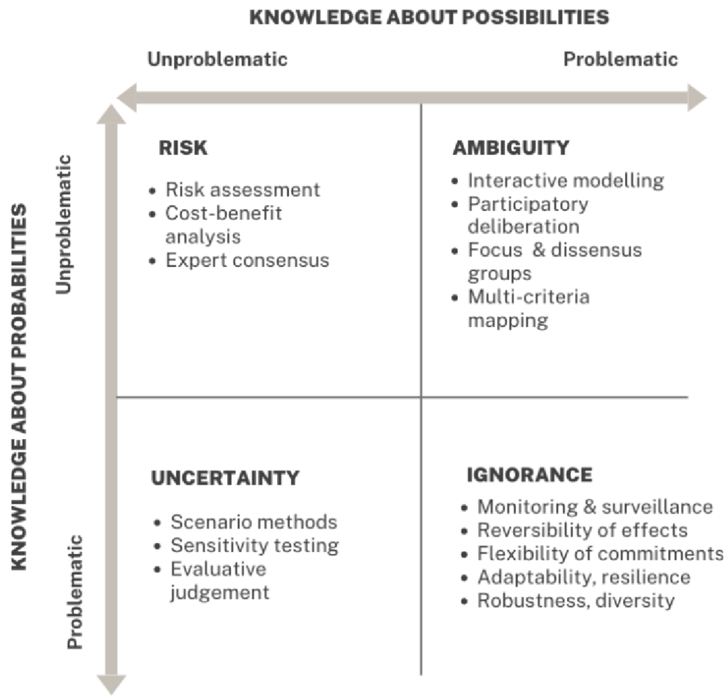



**Figure 4.7:** Uncertainty Matrix adapted from Stirling et al (2010)

and time pressures (Wassénius et al., 2022).This suggests that a wider range of approaches must be brought into decision making around adaptation in the public sector in order to prepare for an unknown future where knowledge about possibilities and probabilities are problematic (see Figure 4.7). Several interviewees mentioned the need for scenario methods and narrative building, participatory deliberation with local groups as well as "resilience", moving from the top left to the bottom right quadrant. While the concept of resilience is wider than dealing with uncertainty, it is considered a way of tackling uncertainty when the past is not a reliable indicator of the future (Wassénius et al., 2022). Since many traditional risk assessment frameworks were developed for less complex situations than is the case for today's world (the top left of the quadrant) it is important that approaches to risk are adapted and adjusted in order to take into account higher levels of uncertainty and make use of interdisciplinary, quantitative and qualitative approaches.

Wassénius et al. (2022) suggest ways in which risk assessments can be adjusted in order to be usable under complexity. For example, risk assessments should aim to deal with connections between risks including across disciplines. An interdisciplinary approach to risk therefore appears to be critical. This requires an understanding of low-likelihood, high-impact events not only the most probable events. This could take the form of storylines, "physically self-consisted unfolding of past events or of plausible future events" to assess and communicate scientific evidence in decision relevant terms. These regional climate scenarios, that interviewees have expressed a requirement for, would need to include high-impact scenarios with quantified conditional impacts and risks including multihazard and correlated risks (Bruijn et al., 2016; Shepherd et al., 2018; Sutton, 2019). By exploring differing storylines or narratives or through serious games where decisions are made under uncertainty, organisations can experience decision making for an unknown future, under different conditions from the past while gaining experience of making legitimate decisions under high uncertainty levels (Lawrence et al., 2017; Rumore et al., 2016; Wu et al., 2015). This form of risk management, through scenarios, or climate narratives, ensures that risk assessments do not rely on occurrences of events or on the likelihoods of past events alone (Wassénius et al., 2022) as is currently the process in the Scottish public sector for a number of bodies based on interviews and report analysis.

A suggested way forward is to adopt an adaptive process to continuously re-assess risk. This links to the idea of flexibility of commitments and reversibility of effects in the bottom right quadrant of Figure 4.7. Adaptation pathways could be a method used to deal with uncertainty and complexity by offering planning approaches that are able to deal with changing conditions over time. They are considered as sequences of actions that can be implemented through time depending on future conditions (Haasnoot et al., 2013; Haasnoot et al., 2011; Werners et al., 2021; IPCC, 2023). Adaptation pathways can be one of or a combination of "performance-threshold oriented pathways", "multi-stakeholder-oriented pathways" or "transformation-oriented pathways". These key forms of adaptation pathways may be useful to different public sector bodies (Kingsborough et al., 2017; Werners et al., 2021). The performance-threshold-oriented pathway tends to be used when adaptation goals can be quantified and there is a clear, non-contested mandate. For example, an adaptation pathway has been used in relation to the Thames barrier in London where potential future measures are put into place depending on different climate scenarios (Coaffee, 2019). Multi-stakeholder-oriented pathways highlight the multi-stakeholder setting of adaptation planning and implementation. Different stakeholders define and identify thresholds important for local communities as opposed to setting thresholds based on hazard or environmental conditions. The aim is to create pathways that include different forms of knowledge while promoting collaboration. Lastly, transformation-oriented pathways aim to focus on the root causes of vulnerability and recognize a need for changes to values and governance arrangements while also following a participatory and collaborative approach. Werners et al. (2021) highlights key outcomes of adaptation pathways, relevant to the aims of the public sector, namely, meeting short and long-term adaptation needs, promoting collaborative learning, adaptive planning and adaptive capacity and accounting for complexity and long-term change, including a potential need for transformation. Adaptation pathways offer a way to engage a range of stakeholders and collaborate while also monitoring and evaluating to learn from experiences whilst also addressing root causes of vulnerability to climate change (Malloy et al., 2020).

While there are methods of dealing with risk and uncertainty involved in adaptation-related risk assessment and management, capacity issues and lack of training mean that building the knowledge and skills required internally is challenging for the public sector. Where bodies have made progress on risk assessment, partnerships have been made with researchers or organisations who are able to “translate” or interpret regional scenarios for decision making purposes. Having embedded researchers within the public sector who could take the role of creating or interpreting local regional scenarios by way of co-production could be a solution here (Webb et al., 2019). Public sector bodies require information and tools that allow an understanding of how climate change is going to affect their region on a local level. This is not a new request, however regional scenarios and case studies are still lacking, hindering local decision making. The role of embedded researchers or “climate translators” has been mentioned in other regions (Hill et al., 2020) as a way to develop the skills and knowledge required to understand potential regional impacts and to create regional scenarios or storylines. Another method for developing the skills required for adaptation scenario planning could be the creation of a “boundary organisation” (Kirchhoff et al., 2013). There are several organisations in Scotland that provide information, tools and knowledge to the public sector including ClimateXChange and Adaptation Scotland (Adaptation Scotland, 2022; Wreford et al., 2019) that could fill this role for the public sector. While bodies are receiving guidance on adaptation, the requirements for adaptation (including what scenarios bodies are required to use) remain unclear. The role of a boundary organisation for the public sector would be to co-produce scenarios and storylines for regions in the public sector while allowing for collaboration between regions and bodies. This organisation could also facilitate the creation of adaptation pathways bringing together public sector bodies and communities where collaboration is paramount and help to fill the current skills gap and capacity challenges.

### 4.4.3 Collaboration and the number of actors

Collaboration was a key theme discussed in the adaptation section of reports and had the third highest number of references made to it in question 1. In addition, all interviewees mentioned either the partnerships or collaborations they have built and how further collaboration may help progress adaptation actions. Collaboration is also a commonly cited difference between adaptation and mitigation as well as the number of actors involved as mitigation is often considered to consist of a few key actors (Klein et al., 2005) mainly the energy and transport sector, while adaptation represents a larger number of actors and sectors including urban planning, nature conservation, coastal management and tourism. Public sector bodies in Scotland are responsible for or play a part across multiple sectors required for adaptation. This makes them a key interface to tackle the challenge of the need for multiple actors (Climate Ready Clyde, 2020; Heidrich et al., 2013). While collaboration and co-production can be challenging (Porter et al., 2017), there is evidence that collaboration is currently happening in the public sector and therefore there is scope to further develop it.

Collaboration is required in the production or co-production of knowledge used to create scenarios or adaptation plans where a range of perspectives and disciplines are required as well as potentially with a knowledge broker or boundary organisation (Kirchhoff et al., 2013). Transformative climate science, which refers to science-policy approaches that allow for engagement with various kinds of stakeholders, could play a role here. These approaches tend to focus on interlinkages between different causes of underlying vulnerability to climate change and potential rebound effects (Tàbara et al., 2019) and focuses on in-context science that is co-produced for the use of society. Collaboration could be increased through co-created adaptation plans for continual shared learning. Coordination of plans could ensure that they are aligned with the national climate framework as well as ensuring that decisions are made with local community groups and stakeholders (Climate Ready Clyde, 2020).

The fact that current siloes, both departmental and sectoral, are acting as a barrier to adaptation was raised by a number of interviewees.. This poses challenges for creating an organisational approach to adaptation however also raises an opportunity as the importance of departments of Government being strong and helpful was raised by interviewees. Local authority boundaries lead to a silo effect of funding. An example was given of the need for "collaboration at the landscape scale" when for example a measure in one authority may reduce the impact of a hazard in another authority region for example in the case of a flood. This is also the case for ensuring that maladaptation does not occur.

A key similarity between mitigation and adaptation is their relation to power structures. It is crucial to investigate the power relating to risk creation, who creates the risk and who is most impacted by it (Wassénius et al., 2022) as well as who is present and has the power over the creation of adaptation pathways and when deciding how to monitor progress. The central role of power has also been cited as a key barrier in the reduction of emissions globally from largely unchallenged forms of power related to the control of institutions and economic and financial structures which aim to build a future very similar to that of today (Stoddard et al., 2021). An examination of power structures and power relations is therefore critical to progress adaptation in Scotland, both from within bodies themselves and also in relation to heightening collaboration between bodies and with local community groups and stakeholders.

### 4.4.4 Measurements and targets

A reason why mitigation is believed to have progressed more than adaptation in the Scottish public sector is largely attributed to the existence of a mitigation target i.e. net-zero by 2045. Interviewees mention they have no long-term plan or target for adaptation. However, there is some debate about the effectiveness of long-term emission reduction targets. For net-zero targets to be credible they require milestones and an implementation plan (Rogelj et al., 2021) and the latest UK Climate Change Committee net-zero assessment report states that there is relatively little detail on how, in practice, emissions will be reduced (Climate Change Committee, 2021b).

Mitigation progress and actions can be measured under one metric, CO2-equivalents, whereas measuring adaptation progress is more complex as benefits can take multiple forms including monetary losses avoided, human lives saved or cultural values loss avoided (Klein et al., 2007). Singh et al. (2022) conducted a review of adaptation literature in order to put forward 11 principles for effective adaptation. The idea being that combina-

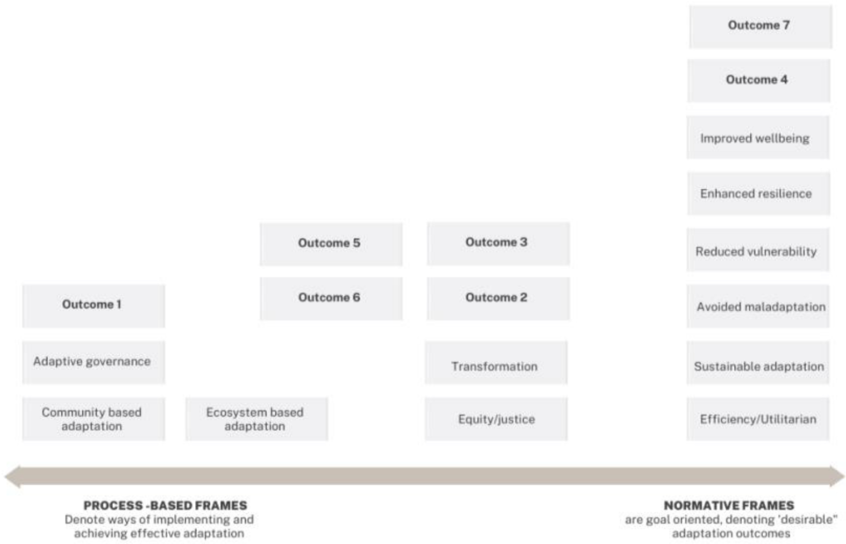



**Figure 4.8:** SCCAP2 outcomes mapped onto measurement frames adapted from Singh et al. (2022) (SCCAP2 outcomes are listed in Appendix C.2)

tions of frames can be used for tracking progress in adaptation with careful consideration given to the strengths and weaknesses of each frame as some frames provide goal oriented and outcome-based perspectives such as minimizing costs or improving wellbeing while other frames are process-based that are around the ways of implementing and achieving effective adaptation such as adaptive governance or community-based adaptation. Other approaches to adaptation such as transformative adaptation and ecosystem-based adaptation sit between the two perspectives. This demonstrates the difficulties of creating metrics in order to measure effective adaptation while also highlighting the potential danger of a sole adaptation metric that is likely to limit the scope of adaptation, potentially leading to maladaptation or an increase in vulnerability to hazards (Dilling et al., 2019; Schipper, 2022).

Figure 4.8 shows where the SCCAP2 outcomes lie relative to process-based and normative-frames. The spread in where these outcomes lie show the difficulty and potential dangers of creating a single metric for adaptation. An alternative approach (Dilling et al., 2019) could be to focus on building long-term adaptive flexibility and capacity. In other words, to focus on the capabilities required to respond to climate change and hazards including, access to healthcare, increased social support and good governance as well as tackling the causes of underlying vulnerability to climate change.

## 4.5 Summary & Take-aways

This research reflects on the progress made by public sector bodies in Scotland from risk assessment to implementing adaptation actions. The most commonly referenced theme from the analysis of the adaptation question on priorities for bodies was "Develop Plan" suggesting that the public sector in Scotland is in the planning phase of adaptation. 33% of public sector bodies are currently reporting on risks based on their response within the public bodies duties reporting however questions have arisen about how fit for purpose these risk assessments are and if undertaking a risk assessment leads to the implementation of adaptation actions.

Our research highlights some key challenges faced by the public sector in Scotland that could be underpinning the lack of progress made in the adaptation space. A key theme that emerged from the analysis of the report and from interviews was the distinction between mitigation and adaptation with numerous interviewees stating that the implementation of adaptation actions is lagging behind mitigation. Our discussion therefore reviewed the key commonly cited differences between adaptation and mitigation at a local level. Differences arise between the two in terms of the complexity associated with each, the risk and level of uncertainty involved, the collaboration and number of actions required and in terms of measurements and targets in the current policy space. A key similarity between mitigation and adaptation however is that there is a current gap between planning and implementation. Therefore, a method to advance adaptation could be connecting to other key policy areas around health and education for example as well as mitigation. Developing an understanding of the synergies between mitigation and adaptation actions in the Scottish public sector is crucial and is a key strategy for accelerating adaptation action in other regions globally (Sharifi, 2021; Sharifi, 2020).

Individuals within public sector bodies currently have the considerable task of trying to gain buy-in from stakeholders and senior managers while also upskilling in interpreting past data as well as future projections in order to assess climate risk and to create an adaptation plan and implement actions. In summary, key individuals, adaptation "champions" or small teams within public sector bodies are responsible for: gaining buy-in from colleagues, upskilling and implementation. This leads to capacity issues as individuals aim to fill this role both for adaptation and mitigation. These key barriers have been previously identified (Adger et al., 2009; Arribas et al., 2022; Kirchhoff et al., 2015; Lee et al., 2022; Milhorance et al., 2022) in other locations and yet, despite being well acknowledged are still posing challenges to adaptation progress.

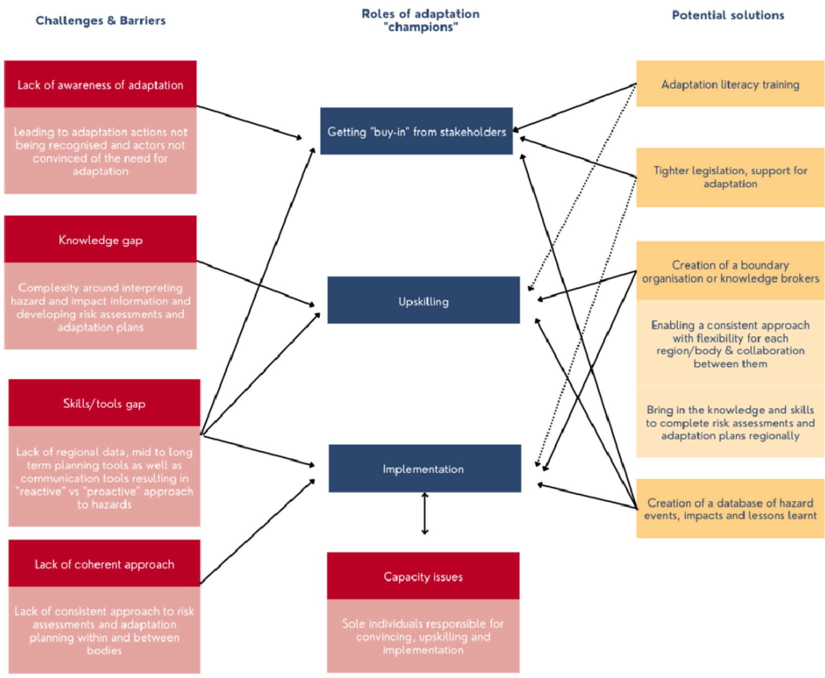



**Figure 4.9:** Links between challenges and potential solutions addressing the role of adaptation "champions" and the lack of organisational approaches to adaptation

Therefore, any solutions must work to reduce this burden on key adaptation individuals, "champions", while creating an organisational framework for adaptation and addressing the knowledge and skill gap that currently exists while addressing the key challenges identified including making decisions under uncertainty and working collaboratively with a large number of actors (see Figure 4.9).

Further research questions identified from this research include how best to enable collaboration between and within public sector bodies as well as further research on vulnerability to hazards and how to understand and measure local capacity building. A greater understanding of the synergies, co-benefits and trade-offs between mitigation and adaptation actions as well as the links to other policy areas including reducing poverty and healthcare we believe would bolster effective adaptation action. Research is required on different methods of co-producing knowledge which is quantitative, qualitative and transdisciplinary. In other words, in-context science that is useful to society.

# Chapter 5

# Discussion & Conclusions

## 5.1 Key research conclusions

This interdisciplinary thesis brings together two conventionally separate research areas, the science of extremes, particularly heatwaves, and how risk data is applied in adaptation decision making. This interdisciplinary approach addresses a key knowledge gap highlighted in the third UK Climate Change Risk Assessment (CCRA3), that of investigating the end-to-end chain of risk, from hazard to adaptation implementation and the uptake of climate science by decision makers (Slingo et al., 2021). This research also explores an additional knowledge gap, that of how future adaptation options could be tested under different future climate scenarios.

This PhD explores past heatwave events and what we can learn from them, including how their intensities may change under different global warming levels in the future. To address the current gap between extreme event science and decision making, this PhD also explores the progress made by the Scottish public sector from risk assessment to adapting to extreme events and hazards.

From the work on past extremes, we find that there were, at the daily level, heatwave events from the past that are comparable to some more modern heatwave events and could be used as case studies. This includes heatwaves in the summer of 1911, 1923 and 1976, for example. We find that the heatwaves detected by using station data alone tend to also be large-scale European heatwaves. This finding could be explored further as it could be useful to investigate heatwaves in regions where data is sparse. We find that most of the early events found through instrumental datasets had associated societal impacts in documentary evidence. Most impacts were either health related or in relation to sports or agriculture. Similar impacts result from present day heatwaves, particularly in relation to health however today transport disruption and interruptions of power supplies are associated with heatwaves (Lobell et al., 2007). A similarity between past and present heatwave impacts is the link to inequality. Heatwaves impact those in low-income regions more, known as heat-stress inequality (Alizadeh et al., 2022). This therefore should be a fundamental element of adaptation decision making, asking who is most impacted by extreme weather and why, if they are part of the decision making process and what adaptation actions would be most effective at reducing vulnerability in which locations.

The study of past extremes, particularly in the recent past, is also important when it comes to decision making and adaptation as evidence suggests that decisions tend to be made using past events or those in societal memory (Hazeleger et al., 2015; Vasileiadou et al., 2014). This was also found within our research in the Scottish public sector. Learning from past events can be useful for decision making, however without exploring how these events may change in the future could lead to under preparedness or maladaptation. From our research, 2022 was the most intense heatwave to have occurred on record from 1878 and is an example of a heatwave in a warming climate where high temperatures of 40°C would have been extremely unlikely without anthropogenic climate change (Zachariah et al., 2022).

The Climate Change Committee (Climate Change Committee, 2021a) recommend that organisations in the UK adapt to 2°C of warming from pre-industrial levels and assess the risks for 4°C. However, there are less scientific studies available for this as opposed to a focus on 1.5 and 2°C (Masson-Delmotte et al., 2018). This is also related to the political targets as part of the Paris Agreement to limit the global temperature increase to 1.5°C and to hold the increase to well below 2°C above pre-industrial levels.

In this PhD, we take examples of past heatwaves and explore how their intensities may change from 1.5 to 4°C of global warming in order to fill this gap. We focus on the intensities of these potential events acting as storylines of potential future events which is thought to be beneficial for adaptation decision making (Baulenas et al., 2023; Sillmann et al., 2021; Shepherd, 2019; Krauß, 2020). We find that the heatwave in 1923 could reach maximum temperatures of between 11.7 and 19.6°C higher than pre-industrial times across all models used. We also found that events that are analogous to the 1923 heatwave increase with global warming at a similar rate to how the climatology increases with global warming, which is higher over England than the global level for two out of three models. However, other studies show that, in the UK, extremes are warming faster than mean temperatures (Kendon et al., 2023; Patterson, 2023). Analogues could be an effective method of exploring how extremes may change in future climates, particularly by using an event from the past such as one in societal memory to increase the availability bias

(Garcia et al., 2022). We show that different types of circulation, like that of the 1911 heatwave compared to 1923 lead to different results, highlighting potential limitations of this approach. A drought occurred in the summer of 1911 in which the heatwave took place and, therefore, perhaps by including multiple variables or preceding conditions this could improve results. This would also help to address knowledge gaps around compound events such as droughts and heatwaves (Kopp et al., 2017; Field et al., 2012). We find that there is a considerable difference between models that highlight the importance of using multiple models in decision making contexts. This also shows the level of uncertainty that must be dealt with when making adaptation decisions and raises questions about the most effective ways of communicating the findings (and associated uncertainties) of climate science experiments to decision makers.

A limitation of the approach used in chapter 3 is that only atmospheric circulation, through the use of geopotential height, is used to define and find analogous events to the 1911 and 1923 heatwaves. This did not provide a particularly strong constraint as the analogues found had a range of associated temperatures, we therefore, add the additional constraint of temperature to explore analogues that have a similar circulation pattern to the original event as well as being hot events. Analogues could be used as storylines by decision makers for adaptation purposes. If a storyline is required that matches a past event closely, then more constraints will likely be required including, for example, preceding conditions such as drought or rainfall. However, events in the future are unlikely to be very similar across multiple variables as past events. Therefore, using the distribution or range of potential future temperatures of extremes like those explored in chapter 3 could be useful for adaptation decision making. For example, "stress-testing" approaches could be used by decision makers, asking if their organisations are able to deal with extremes that reach various potential levels of temperature increase. This holds a greater focus on resilience building than the use of probabilities alone and is one potential way of making decisions under uncertainty (Lawrence et al., 2017; Rumore et al., 2016; Wu et al., 2015; Undorf et al., 2020b). However, how decisions are currently being made about hazards and extremes requires further research. We found from our research on the Scottish public sector that most bodies are still in the early stages of risk assessment with many different tools and frameworks being used.

From our research on the Scottish public sector's approach to adaptation we find that most bodies are in the planning phase of adaptation. 33% of public sector bodies are currently reporting on risks based on their response within the public bodies duties reports. However, questions have arisen about how fit for purpose these risk assessments are and if undertaking a risk assessment leads to the implementation of adaptation actions. A key difference between progress made in mitigation and adaptation was thought to be the presence of a clear "target". We find from our research on the potential role of adaptation targets that any targets created would need to include: a vision of a "well-adapted" society, a focus on reducing vulnerability, integration with mitigation and other policies and a focus on flexibility to allow failure and learning. Lastly, collaboration was considered a key principle in the creation and implementation of usable and useful targets. These findings, both on the stage that bodies are at with regards to adaptation, as well as investigating the role of targets for adaptation, is particularly timely as the Climate Change Committee in the UK reports that there remains an implementation gap in Scotland and in the UK and a key recommendation is the creation of quantitative adaptation targets. Additionally, the global adaptation framework that came out of COP28 gives the goal of 2030 for all Parties to have created and brought into operation a system for monitoring and evaluating their national adaptation efforts. Therefore, creating targets for adaptation is a key requirement for policy makers currently. For mitigation, current targets are centred on emission reduction over certain time periods, with the end state being net-zero or zero emissions. For adaptation however, it is generally acknowledged that is there is no "adapted state" but instead an "adapting state". Setting targets for a changing landscape is challenging and they would therefore need to be flexible, evolving with societal changes and with climatic changes such as the impacts of extreme events. Additionally, adaptation can be incremental, involving marginal changes within the current system or it can be transformative which looks to address the root causes of vulnerability, leading to systems change. Certain targets could focus on incremental changes, perhaps even hindering transformational adaptation if they do not address underlying causes of vulnerability including health and income inequalities.

Effective adaptation requires collaboration and input from a range of disciplines and actors (Klein et al., 2005). From our research on the Scottish public sector, there is evidence that collaboration on adaptation is happening and that it is deemed important for making progress on adaptation. We uncover several examples of risk assessments being completed where an effective collaboration between researchers and practitioners takes place. The issue of uncertainty was raised by a number of those interviewed in the Scottish public sector in relation to their adaptation planning. Even with the climate and weather data available and the expected trends in this data, many practitioners still struggle to access and make use of this information. This can be because of the need for the data to be translated to a more local level. Additionally, we find that different data and knowledge is currently required. On one hand, there is still felt to be a gap in local climate and weather data including on previous and potential future impacts on social systems. On the other, there is a need for information to be translated in such a way to justify or provide evidence for decision making and to make the case that adaptation action is required to organisational leaders. A large uncertainty is the socioeconomic and wider attitude to adaptation (and climate) policies. One reason why embedding adaptation in other policy areas could be vital (Climate Change Committee, 2023). Researchers from different disciplines collaborating can be challenging with communication issues arising (Porter et al., 2017) and therefore, interdisciplinary researchers could help to bridge the gap between disciplines, for example, between extreme event science and adaptation science and research, helping to make weather and climate data usable and accessible to particular decision-making contexts. An adaptation skills gap is broadly recognised within the Scottish public sector and we conclude that adaptation is seen as being more complex as opposed to the skills required to create and implement mitigation plans for example. It has been found that the research community within the UK also find it difficult to recruit interdisciplinary researchers with adequate experience (Lyall, 2019). Perhaps developing interdisciplinary researchers focused on adaptation from multiple angles could help to fill this skills gap.

## 5.2 Reflections on interdisciplinary research

Another aim of this PhD was to take an interdisciplinary approach to extreme weather events and adaptation. I had read about and witnessed in previous roles, the miscommunications that can happen between those working on hazards on the physical science of extremes and practitioners who have to make decisions about how we adapt at a local level. I felt that my previous experience in different disciplines and roles would help me to work across the risk and impact spectrum, producing work that is valuable to both sides of the spectrum. During my PhD, I met with other researchers taking a similar approach to their thesis and we founded the Sustainable Development Goals (SDG) network for researchers and students working on one or more of the SDGs in an interdisciplinary way. This network allowed us to share experiences and challenges. A key challenge is around publishing and finding journals that focus on interdisciplinary work. Another key challenge is around depth and academic "rigour", a concern I held that is shared by many in the interdisciplinary community. Catherine Lyall, an interdisciplinary researcher at Edinburgh University includes a quote in her book from Schön (1983, p42) who states: "Shall the practitioner stay on high ground, hard ground where he can practice rigorously ...

but where he is constrained to deal with problems of relatively little social importance? Or shall he descend into the swamp where he can engage the most important or challenging problems if he is willing to forsake technical rigor?" (Lyall, 2019; Schön, 1983). My aim for this PhD was to be able to add to the scientific literature of extremes while also exploring how adaptation is being implemented, adding to social science literature. To try to ensure "technical rigor" in this research, the PhD is split into three research chapters each asking a unique question, the first two fitting more into traditional physical science and the last fitting into more traditional adaptation or social science. However, each chapter and approach has been influenced by the others with a core goal being the production of collaborative work that is useful for decision makers. I believe that this type of research is required to ensure that societal challenges such as adapting to climate change and weather extremes are approached in an effective way with solutions that reduce vulnerability. I have found that this apparent trade-off between rigour and practicability has not posed problems during my research. I have found that lessons learnt from each chapter can inform other areas of my research.

This PhD has also allowed me to find and understand some key differences in perspective between climate science research and adaptation research that could lead to miscommunication or challenges, lessons I will take forward in future research.

A key difference between climate science research and adaptation science is in regional scale, although there is evidence to suggest that this is changing (IPCC, 2023). However, the climate science and extreme event science required by decision makers in the public sector tends to be local or hyper local whereas climate science research tends to be global or continental. This is potentially an area where interdisciplinary researchers can play a key role. Additionally, in chapter 4 we suggest that embedded researchers or boundary organisations (Kirchhoff et al., 2015; Hill et al., 2020) may help bring multiple forms of knowledge or disciplines together since a key gap is around collaboration not only between extreme event science, climate science and adaptation but also involving a range of stakeholders and local communities. A boundary organisation or embedded researchers from physical and social science working in collaboration with local communities and local decision makers could help ensure that risk assessments completed for a local area are comprehensive. This would require understanding the hazard, understanding local exposure to hazards and extremes and also understanding where and why vulnerabilities lie. This could help avoid maladaptation and ensure that adaptation measures are implemented in a just way (Malloy et al., 2020; Schipper, 2022).

## 5.3 Potential future work

This raises a key question, how can we co-produce knowledge effectively? Who is or should be included in the co-production of adaptation or risk related research? This is a fundamental area of enquiry as well as understanding where power lies in this co-production and asking if this leads to effective adaptation. I think this is critical to the future of adaptation and extremes research (Nightingale et al., 2020; Singh et al., 2022; IPCC, 2023).

A future line of research could explore the role of interdisciplinarity in specific adaptation research questions. For example, building on the exploration of the benefits and challenges of an interdisciplinary, collaborative approach in creating and designing adaptation targets (Steynor et al., 2020; Daniels et al., 2020; Bojovic et al., 2021). I believe that interdisciplinary approaches to climate change problems, including adaptation, lead to considered and well-rounded implementations, with collaboration in adaptation leading in some cases to a higher focus on equity and reducing vulnerability (Alizadeh et al., 2022; Schipper, 2022; Singh et al., 2022). How to achieve this successfully while avoiding pitfalls is therefore a key area for future research. While collaboration and co-production of knowledge is often cited as important in adaptation science e.g. (Nightingale et al., 2020), there are limited case studies focused on adaptation to test this theory. Some initial research we conducted on adaptation targets, also highlighted the need for co-production in the development of adaptation targets. This research involved a survey and a workshop with a range of adaptation professionals from the public and private sector as well as researchers. Some key themes emerging from this research was the need for adaptation targets to have a focus on reducing vulnerability, being flexible enough to be relevant for a number of organisations and the need for targets to be co-designed and co-produced by experts, communities and those vulnerability to hazards. Future research could involve comparing targets created by different stakeholders including policy makers and communities independently and together and any difference in themes discussed and the targets created analysed. Research into co-production such as this could provide examples of co-production in practice in the field of climate adaptation, looking into its effectiveness and the challenges related to this approach. In addition, future work could look more deeply into how adaptation can be better implemented and embedded across a range of policy areas. This was a critique of the UK's National Adaptation Plan (NAP3) (Climate Change Committee, 2023) where adaptation policies were considered separate from other key policy areas. How can adaptation be considered and implemented in the decision making processes related to mitigation policies as well as health and transport policy for example?

The kind of knowledge that is required for responding to extremes and hazards effectively is perhaps not a traditional climate science question, however, it is fundamental to responding to climate change (Schipper et al., 2021) and perhaps is a key area for interdisciplinary research and researchers. Particularly focused on effective ways of combining different forms of knowledge (including scientific and local knowledge) to create and implement adaptation solutions.

In addition, more research is required that focuses on the motivation for taking adaptation action. From the Global Goal on Adaptation to National Adaptation Plans there are policies in place for adaptation and yet an implementation gap remains. In addition, there are tools available to support organisations, for example Adaptation Scotland (Adaptation Scotland, 2022) has provided route maps and risk assessment tools for the private and public sector and communities in Scotland. We find in our research into the Scottish public sector that Adaptation Scotland guidelines and tools are the third most referenced tool used by the public sector. In addition, Adaptation Scotland provides networking opportunities for public sector bodies to share ideas and knowledge exchange. While the tools provided are being used and felt to be useful to the public sector bodies involved in this research, there are some challenges that are more difficult to address through such tools directly. This includes, for example, resource and capacity issues with bodies citing that even though tools and guidelines exist, there is not the capacity to complete them or use them adequately. In addition, lack of leadership was found to be a key challenge in bolstering adaptation action from our research. Why there is a lack of motivation from leadership to implement adaptation action is a key area that requires further research in order to better understand what could be used to resolve this such as tighter regulations from central government.

Future work could be conducted further exploring the benefits and limitations of using analogues to analyse potential future events. This could include an analysis of compound events such as drought and heatwave events (Zscheischler et al., 2018). I think this will be a key area of research in the climate science community going forward in order to better understand the plausibility and probability of compound events occurring which can have a large societal impact. This would be relevant to explore how analogues could be used in this way scientifically and is also crucial for adaptation decision making. Using analogues to explore potential future extremes also requires further understanding of how climate models portray extreme events relative to the mean or to the climatology.

## 5.4 Perspective and research impact

My aim within this PhD was to work in collaboration with those in multiple disciplines and with decision makers, to produce results that add to the scientific community as well as being beneficial to decision makers working in hazards, extremes and adaptation. There are differing views in the scientific community about the role of climate scientists and society and if climate science should focus on scientific process and outcomes or on science that is most effective to serve society (Sutton, 2019; Dilling et al., 2011; Jebeile et al., 2023; Coen et al., 2022). New approaches such as extreme event attribution look to address both developing scientific methodologies while ensuring that timely information is provided to decision makers, offering a new model of doing climate science (Otto, 2019).

When I started this PhD, I felt it was important that the research produced from it was beneficial and completed in partnership with those I worked with, scientists and practitioners alike. I aimed to provide research and insights that were of wider societal benefit. After working with the Sustainable Scotland Network on the research in chapter 4, I was invited to join their steering group. The research and outputs from this chapter have been used as part of the annual analysis reports used by the public sector and Scottish Government that link to the development of adaptation policy in Scotland. The approach developed in this PhD for analysis of the annual climate change reports has now been used in subsequent years' reports and I now partner with the core team to analyse and write the adaptation section of these reports. This will allow us to determine any trends in the data going forward, which will be critical in informing adaptation decision making in Scotland. In addition, outcomes from this thesis will feature in the Adaptation Statutory Guidance for the public sector that is developed by the Scottish Government and the SSN steering group, I am one of the key authors of this section. I am currently the lead author of the adaptation introductory section of the Statutory Guidance due to be published in 2024. The work in this PhD has also been discussed, particularly that about heatwaves and adaptation, with community groups through the Scottish Communities Climate Action Network (SCCAN) to involve and gain the perspectives of local communities. I have since joined

SCCAN as a board member and director. I believe an important part of research, particularly interdisciplinary research, is knowledge exchange. I have joined various research groups and community of practices in order to keep up to date with the latest research from multiple disciplines and to share ideas. I am currently co-chair of the adaptation community of practice at Edinburgh University, aiming to bring together practitioners and academics from various disciplines to share knowledge and research around adaptation. Therefore, I feel this work and my approach to it has been useful to groups within and outwith academia, to those understanding what we can learn from past extremes and hazards and how we can prepare for them today and in the future.

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# Appendix A

# Supplementary material for Chapter 2

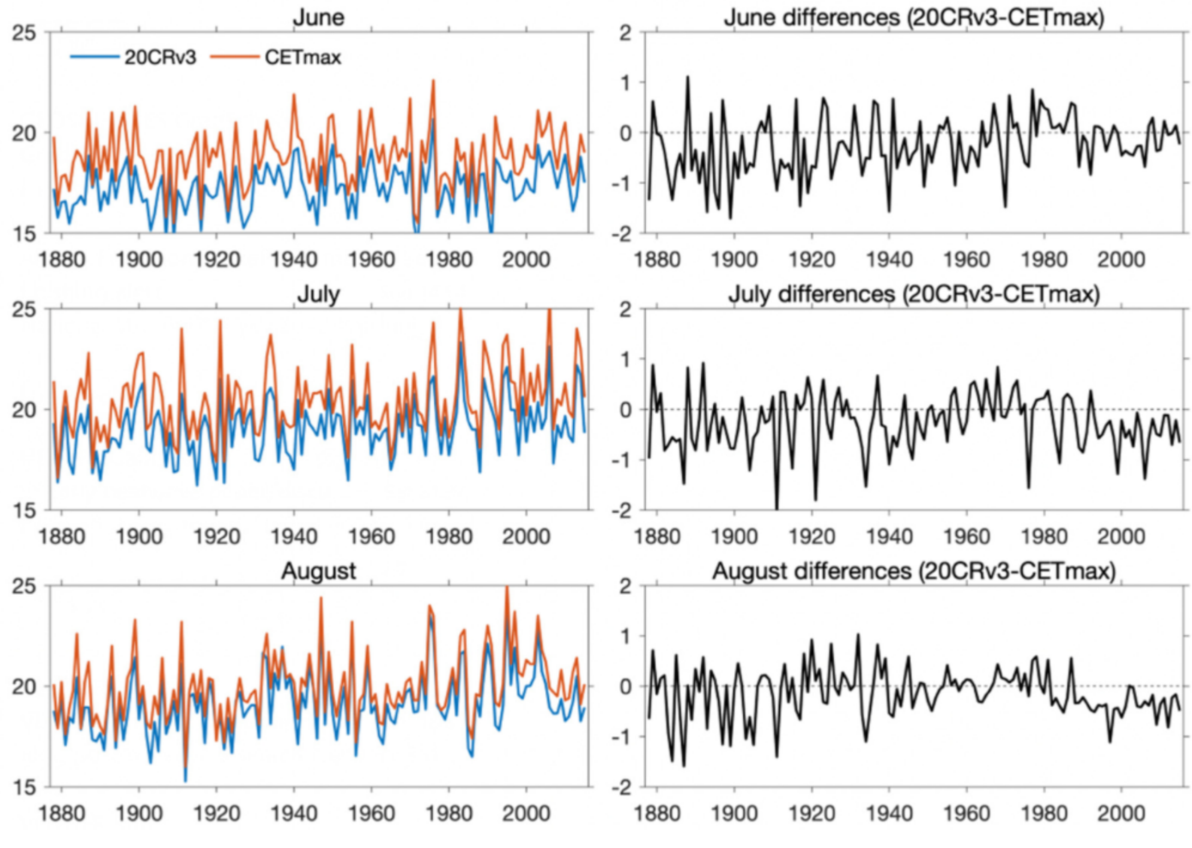


**Figure A.1: Comparison of 20CR with HadCET** Comparing 20CR with HadCET for monthly means of daily maximum temperature (1878-2015) for each month of summer. (left) Absolute temperatures, and (right) the difference between the series after accounting for a mean bias using a 1961-1990 baseline. 20CR is cooler than CET overall but shows very similar interannual variations and trends to the observations. There are hints that 20CR warms more than the observations before 1961-1990, and warms less than the observations after that period, but these differences are small compared to the size of year-to-year variations. CET does have an urban adjustment applied after 1970 which reduces the observed trend.

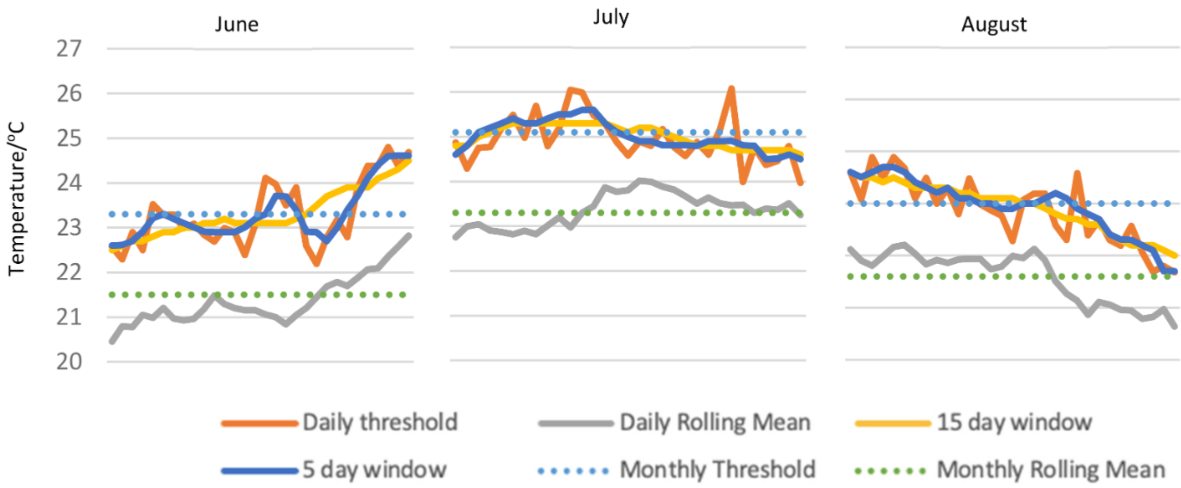


**Figure A.2: Comparison of threshold windows** The monthly threshold (dotted blue) is too low for the end of June and is too high for the end of August and does not take into account the range of temperatures across the month. The daily threshold (orange) is highly variable and is therefore highly dependent on the particular dataset. The 5 day window (blue) is also highly variable whereas the 15 day window (yellow) smooths out any noise in the data and follows the expected climatology for the summer season in Central England. The rolling mean methods were consistently lower than expected. The most appropriate method for calculating the 90$^{th}$ percentile is therefore considered to be the 15 day window method which was used in this chapter.

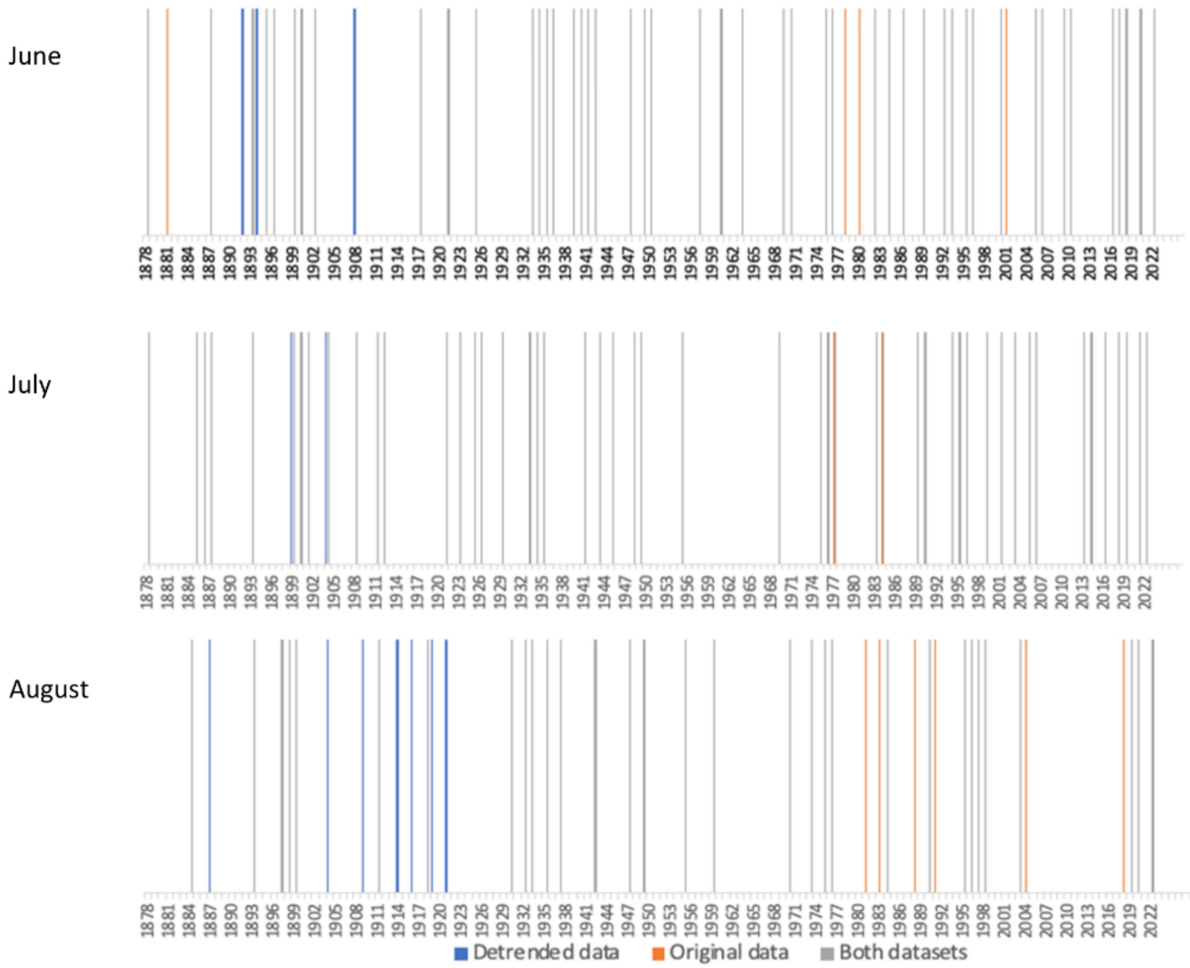


**Figure A.3: Comparison of heatwave years in original (raw) HadCET daily maximum data with detrended data** Grey bars represent heatwave years in both datasets, orange bars represent heatwave years in the original HadCET maximum daily temperature dataset and blue bars represent heatwave years only found in the detrended dataset. In June, the original and detrended datasets agree for 138/145 heatwave years ie 95.2% of years, in July the agree for 97.2% of years and in August for 91.7% of years. HadCET maximum daily temperature data was linearly detrended separately for each summer month.

# Appendix B

# Supplementary material for Chapter 3

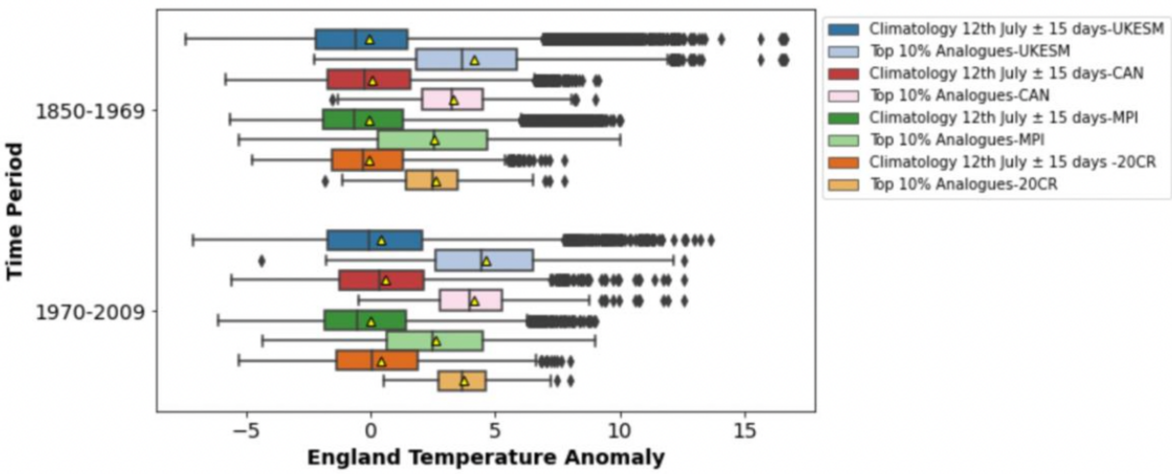


**Figure B.1:** Climatology and top 10% analogues and their associated England temperature anomaly for UKESM, CanESM5 and MPI as well as for 20CR. This plot demonstrates the higher variability in models when compared to 20CR. UKESM exhibits the most variability.

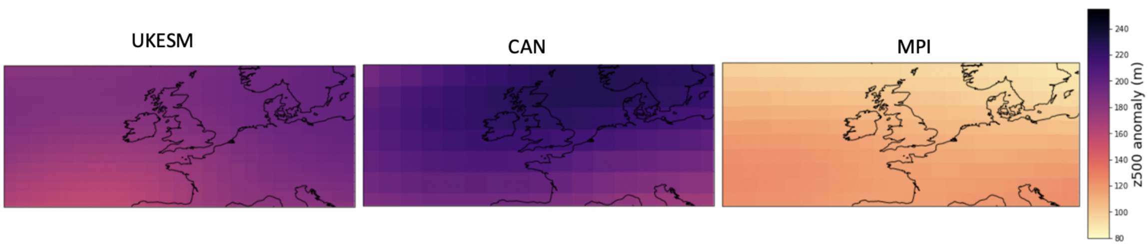


**Figure B.2:** Z500 anomalies in 2090-2100 relative to 1850-1900 for climatology period 12th July ±15 days for UKESM, CanESM5 and MPI. The areas of higher pressure increase tend to be in North-Eastern Europe in UKESM and CanESM5 whereas this is not the case for MPI. MPI shows the lowest increase in pressure out of the three models which is expected as it is also the model that warms the least by the end of the century.

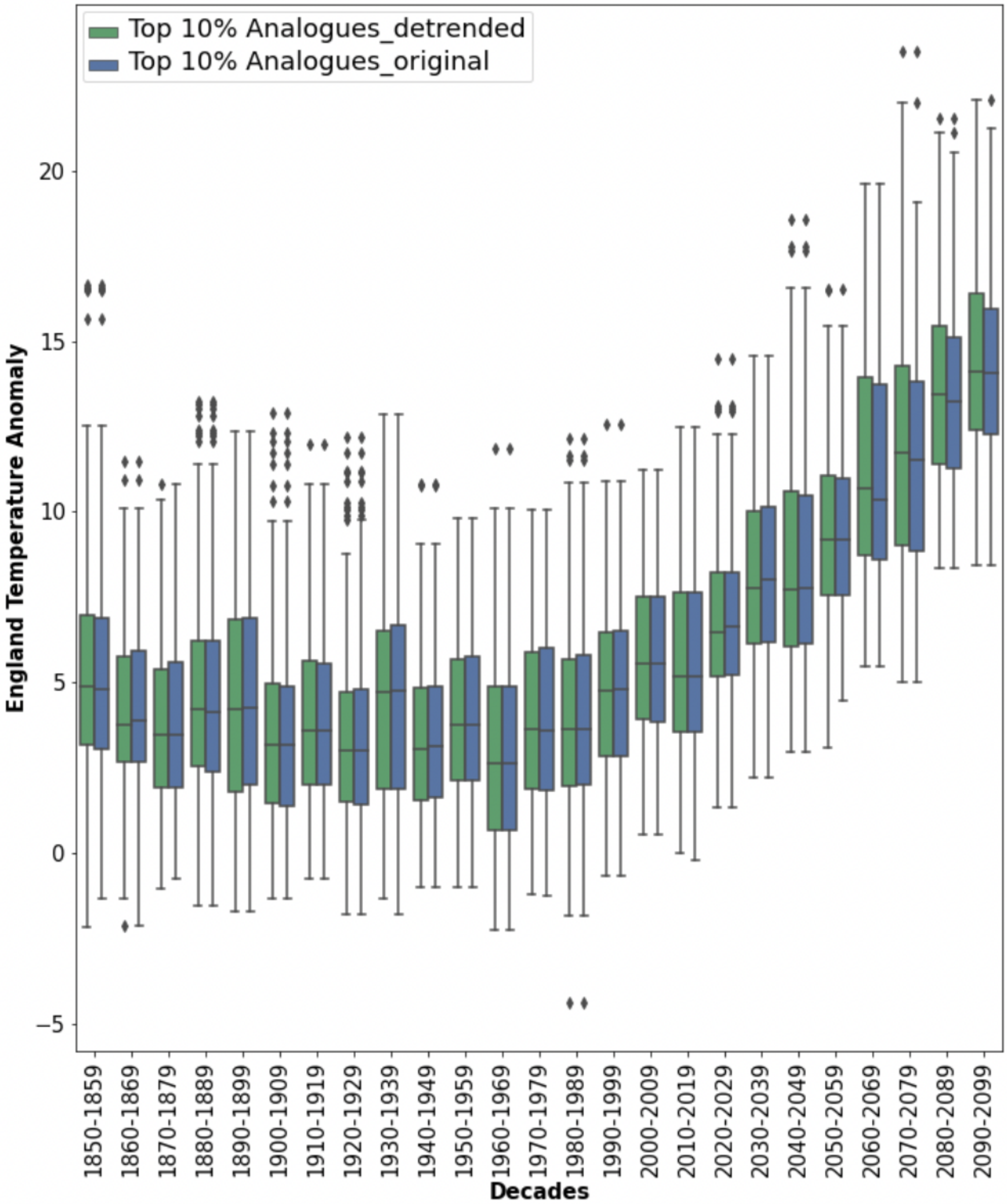


**Figure B.3:** Comparing the analogues found when correcting for Z500 height differences between 1850 and 2100. This plot highlights the similarity in analogues found with and without detrending for the increasing pressure between 1850 and 2100.

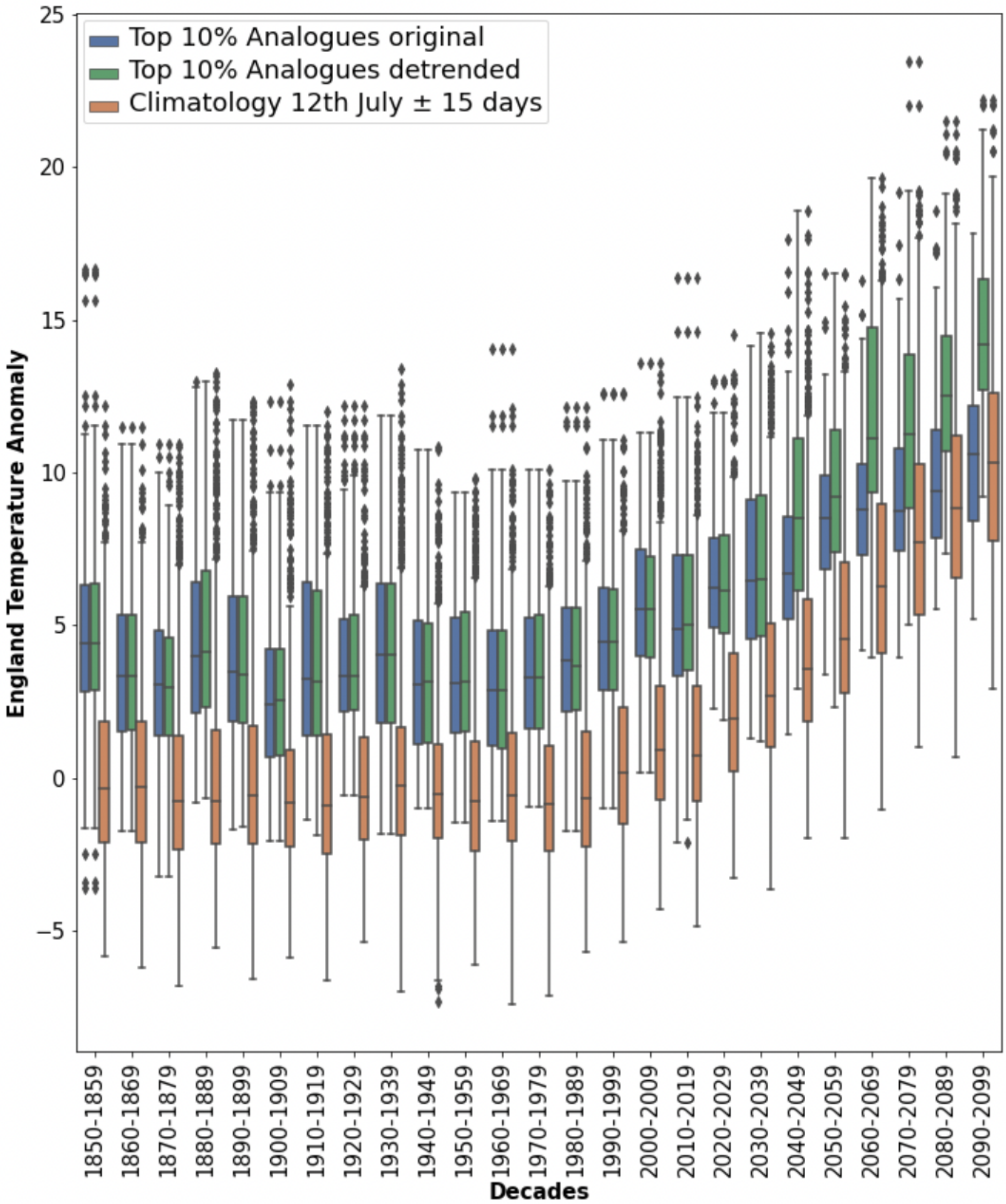


**Figure B.4:** Comparing the analogues found when correcting for Z500 height differences between 1850 and 2100 using minimum Euclidean distance. This plot highlights the difference in analogues found with and without detrending for increasing pressure when using Euclidean distance to identify analogues.

# Appendix C

# Supplementary material for Chapter 4

| **Theme** | **Priorities** |
|---|---|
| Awareness & Communication | • Raising awareness of climate change impacts in schools and youth groups<br>• Increase awareness of climate change and the need to adapt with key stakeholders and with employees<br>• Raising public awareness of climate change impacts<br>• Raising awareness of flooding and disruption due to weather |
| Behavioural Change | • Influence behavioral change encouraging staff to become more socially responsible<br>• Behavioral change in relation to transportation<br>• Increase promotion of sustainable behaviors |
| Buildings & Infrastructure | • Inspecting and maintaining roofs and ensuring they are watertight<br>• Developing smart buildings<br>• Increasing efficiency of buildings<br>• Maintenance of drainage infrastructure<br>• Assessing risks of extreme weather on highway infrastructure |

**Table C.1 (continued)**

| **Theme** | **Priorities** |
|---|---|
| Climate Justice | • Understand how climate justice can be incorporated in equality impact assessments<br>• Ensuring just transitions are prioritized in decision making |
| Community planning partner & Place-based adaptation | • Working Community Planning Partnerships<br>• Co-producing adaptation strategies |
| Demonstrate work & Best practice | • Publicise work and ongoing actions<br>• Organising summits and workshops to demonstrate best practice |
| Develop Plan | • Developing adaptation plans and strategies<br>• Reviewing plans<br>• Finalising plans |
| Employee engagement | • Implementing sustainability working groups<br>• Work with staff to create grounds for local wildlife<br>• Updating policies to improve employee involvement |
| Energy use & Emission reduction | • Energy-efficient buildings as part of local housing strategies<br>• Promote/invest in the use of renewable technologies<br>• Local Heat and Energy Efficiency Strategies (LHEES)<br>• Offsetting<br>• Switching to LED lighting |

Table C.1 (continued)

| Theme | Priorities |
|---|---|
| Ensure service to customers | • Updating business continuity plans<br>• Reviewing and updating service plans<br>• Including climate change risks on corporate and service risk registers |
| Extreme weather & hazards | • Local flood management plans<br>• Developing/continuing flood protection schemes and studies<br>• Assessing impacts of extreme weather<br>• Reviewing severe weather plans |
| Finance & Costs | • Economic impact assessments<br>• Securing funding<br>• Costing climate change risks and impacts |
| Flexible & virtual working | • Working groups created to review opportunities for home working<br>• Investments in digital systems and services<br>• Implementing teleconferencing facilities |
| Food & Agriculture | • Developing food strategies<br>• Control and prevention of disease in agriculture<br>• Long-term water resource and system planning<br>• Reviewing specialist equipment |

**Table C.1 (continued)**

| **Theme** | **Priorities** |
|---|---|
| Human & Public Health | • Promote healthier transport choices<br>• Surveillance of public health trends<br>• Introduce gardens to promote well-being |
| Implement & Deliver Plan | • Delivering a plan or strategy<br>• Continuing or commencing implementation of plan or strategy |
| Learning & Training | • Training and guidance in impact assessment toolkits<br>• Deliver training to business owners relating to energy efficiency<br>• Undertaking workshops to collect and share information<br>• Developing training for employees |
| Nature-based | • Nature-based solutions as drainage solution<br>• Developing a healthy protected and productive environment as adaptation<br>• River restoration projects along with modeling and topographical studies<br>• Identifying habitats and species at greatest risk from climate change<br>• Reviewing tree planting options |
| Recruitment | • Recruiting a climate change strategy post<br>• Recruiting project management teams for adaptation initiatives |

**Table C.1 (continued)**

| **Theme** | **Priorities** |
|---|---|
| Reduce waste & Recycling | • Increasing recycling rates<br>• Monitoring waste to reduce<br>• Reduction of plastic onsite<br>• Introducing composting initiatives |
| Risks & Impacts | • Reporting on climate risks<br>• Assessing climate risk<br>• Developing risk registers<br>• Defining climate risks on sites<br>• Identifying ways to manage climate risks<br>• Monitoring climate change risks and impacts |
| Supply chain & Procurement | • Sharing procurement<br>• Investigating supply chain and procurement processes |
| Sustainable Development | • Developing a sustainable development strategy<br>• Embedding sustainable development thinking and practices across the organisation<br>• Delivering education for sustainable development |

**Table C.1:** Examples of priorities discussed per theme from analysis of Q1 in chapter 4

| | |
|---|---|
| **Outcome 1** | Our communities are inclusive, empowered, resilient and safe in response to the changing climate |
| **Outcome 2** | The people in Scotland who are most vulnerable to climate change are able to adapt and climate justice is embedded in climate change adaptation policy |
| **Outcome 3** | Our inclusive and sustainable economy is flexible, adaptable and responsive to the changing climate |
| **Outcome 4** | Our society's supporting systems are resilient to climate change |
| **Outcome 5** | Our natural environment is valued, enjoyed, protected and enhanced and has increased resilience to climate change |
| **Outcome 6** | Our coastal and marine environment is valued, enjoyed, protected and enhanced and has increased resilience to climate change |
| **Outcome 7** | Our international networks are adaptable to climate change |

**Table C.2:** Climate Ready Scotland: Scottish climate change adaptation programme (SCCAP2) outcomes used within chapter 4