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Summary report

Oxfordshire County Council

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EXTREME TEMPERATURES AND RAINFALL IN OXFORDSHIRE

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Contents

INTRODUCTION

This report presents a gridded analysis of extreme temperatures and rainfall in Oxfordshire under current conditions and future climate scenarios.

Executive Summary

Mounting evidence suggests that extremes are being underestimated and the chance of extreme heat and rainfall events is greater than previously thought. This study presents an Extreme Values Analysis of baseline gridded data for Oxfordshire and combined this evidence with UKCP18 projections to estimate future extremes.

The record temperatures of 40.3°C in Coningsby in Lincolnshire and 38.1°C in Oxford on 19th July 2022 were **far greater extremes than modelled in the UKCP18 climate projections for the 2020s and not anticipated until the 2050s**. The high temperatures were due to a combination of climate change and natural variability influenced by high pressure over continental Europe and a 'heat dome' with falling air in the atmosphere trapping warm air at the surface[1].

Oxford[2] has experienced **extremely dangerous heat,** with very high temperatures and high relative humidity**,** on 4 occasions since 1961, all in the last 5 years in July 2022, July 2021 and July 2020 and **dangerous heat** on 44 days since 1961. Average relative humidity in July in Oxfordshire can be high, between 63% and 79% causing dangerous heat index values when combined with very high temperatures.

Following very high temperatures in 2019 and 2022, the Met Office and World Weather Attribution group completed studies that found that human-caused climate change has already made the chance of 40°C in the UK about **ten times more likely when compared with the pre-industrial period.**

Heatwaves are the most studied hazard in climate attribution studies, with a unanimous consensus of a strong attributable signal of human-induced climate change in their increased frequency and intensity over the last century[3].

Higher temperatures are also changing the odds for extreme rainfall in England, with similar climate attribution studies suggesting that the risk of heavy daily rainfall will become 1.2 to 2 times more likely than the pre-industrial period[19]. However, the strength of the attribution signal is weak, compared to heatwave attribution[3].

There is a 1 in 3 chance that the Oxford maximum temperature extreme will be exceeded within the next decade. Our analysis shows that the chance of exceeding 40°C in Oxford in any year is 1 in 250 (0.4%) (a similar result to previous Met Office studies) but the annual chance of exceeding the recent Oxford record of 38.1°C is just 1 in 25 (4%); this equates to a chance of a more extreme event happening in the next decade of around 1 in 3 (33%)[4].

The chance of exceeding 40°C somewhere in Oxfordshire is lower than the odds for Oxford City at around 1 in 50 (2%) (which is a higher chance than projections reported in recent research literature); odds are reduced when considering larger areas and some parts of the county are also marginally warmer. This equates to a chance of exceeding 40 degrees within the next decade of around 1 in 5 (or precisely 18%).

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[1] Met Office. 2022. Report on the July 2022 heatwave. Prepared by Mike Kendon, National Climate Information Centre. 2022_03_july_heatwave_v1 (metoffice.gov.uk)

[2] Oxford is used to illustrate key points, due to the availability of a very long term weather record. The findings would be similar for other Oxfordshire towns and the report shows results from other sites as well.

[3] Reviewing climate change attribution in UK natural hazards and their impacts (University of Bristol, Exeter and Met Office Hadley Centre) Reviewing climate change attribution in UK natural hazards and their impacts (ukclimaterisk.org)

[4] Using event probabilities for a specific duration rather than annual probability. $Pe = 1 - \left(1 - \frac{1}{T}\right)^n$
Sayers, 2016 Communicating the chance of a flood: The use and abuse of probability, frequency and return period.

The probability of extreme temperature and heavy rainfall is increasing every year; the chance of a 100-year temperature extreme occurring in the 2020s is likely to increase fourfold under a ‘medium’ scenario and eight-fold under ‘high’ scenario by the by the 2050s. The chances of heavy rainfall are not evolving as rapidly, and increases are likely to be 1.25 times and 1.4 times greater than historical averages under the same scenarios by the 2050s. Changes in heavy rainfall risk increase markedly by the 2080s.

Recent research has shown that such trends in extremes can only be reversed under radical mitigation scenarios that stabilise the rate of warming. For example, Dittus *et al* showed that the drying out of Southern Europe could be reversed under net zero scenarios[5].

This analysis has wide ranging implications for Oxfordshire and the need to be prepared for the impacts of extreme temperatures in the next decade as well as the impacts of higher daily rainfall events in the next 30 years. Extreme heat causes wide ranging health impacts, not limited to those most vulnerable to extreme heat, leading to serious illness and danger to life. Extreme heat also highlights the need to adapt working practices, increases the risk of failure of heat sensitive equipment and causes significant transport delays. Heavy rainfall is the primary cause of surface water flooding, which has significant economic impacts in Oxfordshire, further to water ingress and mould in buildings and triggers extensive Combined Sewer Overflows across the county.

[5] Dittus et al., 2024. Reversal of Projected European Summer Precipitation Decline in a Stabilizing Climate - Dittus - 2024 - Geophysical Research Letters - Wiley Online Library

1. Introduction

The heatwave of July 2022 resulted in the highest ever recorded temperature in the UK of 40.3 ˚C on 19th July in Coningsby, Lincolnshire, and exceeded a threshold that many scientists believed was not possible until later this century. The extreme heat was extensive, covering a large area across England, but was also short-lived, with the highest temperatures above 35°C lasting two days. Oxford Radcliffe Observatory[6] (ORO) recorded a maximum temperature of 38.1°C on 19th July, 1.6°C higher than the previous record set in 2019. Nearby at Headington Quarry a temperature of 39.7°C was observed[7]. Despite the short duration of the event, consequences were significant with 2,227 excess deaths (10.4% above average) recorded in England and Wales, including 47 in Oxfordshire, during the period of 10th to 25th July[8]. In 2022, there were 5 hot periods in total, resulting in a total of 65 excess deaths across Oxfordshire[9].

There have also been a series of heavy rainfall events in Oxfordshire since 2020, associated with winter flooding and named storms, most recently in January 2024 associated with Storm Henk. While no single event was unprecedented, 2023 was the 4th wettest calendar year since 1827 in Oxford, and January and February 2024 were 136% and 262% wetter than the 1991-2020 averages, making the last 14 months one the wettest periods on record in Oxford. In England as a whole, the 18 months preceding March 2024 was the wettest since 1836 and the 12-month rainfall from March 2023 to February 2024 was the highest since 1766[10,11]. The highest daily rainfall recorded in Oxford in recent years was 60 mm in 2020, but this is only the 5th ranked daily rainfall event on record since 1827 and was exceeded by much larger events in 1951 (84.8 mm), 1960 (81.3 mm) and 1968 (87.9 mm). In recent flood events, daily rainfall of ca. 20 to 30 mm on already saturated soils has caused extensive flooding in small watercourses across Oxfordshire as well as major flooding on the Thames in Oxford.

This report's premise is that we are already facing risks of more extreme heatwave and rainfall events due to climate change, and these risks are much greater than anticipated based on any historical analysis of past events and application of some UK Climate Projections 2018 (UKCP18) products. It presents a gridded analysis of extreme temperatures and maximum daily rainfall in Oxfordshire under current conditions and future scenarios based on Met Office data. It considers the consequences of these events and how risks may evolve under several climate change scenarios with a further one to four degrees warming above the 1981-2020 period. The study is based on a literature review, original analysis of observations and climate change scenarios to quantify the risks of extreme high temperatures and heavy rainfall in Oxfordshire.

- In Section 2, a short literature review considers the UKCP18 probabilistic extremes and climate change attribution studies and what these studies show about the changing risks of extreme conditions in the UK.
- In Section 3 the methodology for 're-trending' the annual maximum temperatures and Extreme Value Analysis of maximum temperature and maximum daily rainfall is summarised.
- In Section 4, the results of the extreme temperature and daily rainfall analyses are presented for the '2022 climate' and under 2 future scenarios based on UKCP18 'medium' and 'high' scenarios (RCP4.5 and RCP8.5) for the 2050s and 2080s.

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[6] ORO, which is operated by University of Oxford has recorded temperatures since 1815 and provides open data to assess local climate change https://www.geog.ox.ac.uk/research/climate/rms/reports.html

[7] Based on a review of live observations 19th July 3pm Met Office WOW - Home Page

[8] Excess mortality during heat-periods - Office for National Statistics (ons.gov.uk)

[9] This analysis uses the UK Health Security Agency (UKHSA) definition of a heat-period as either: day(s) on which a Level 3 Heat Health Alert (HHA) is issued or day(s) when the mean Central England Temperature (CET) is greater than 20°C

[10] Based on monthly reports from Weather at Oxford: Reports | School of Geography and the Environment

[11] Based on analysis by Ed Hawkins using Met Office data and reported in the FT England drenched after the wettest 18 months since records began in 1836

- In Section 5, the evidence is triangulated to present results on current and future risks and recommendations for monitoring impacts to inform adaptation planning.
- The data sets used are summarised in Appendix A and the methodology is presented in further detail in Appendix B.

The Met Office HadUK dataset provides a 1km gridded climatology, which has been interpolated from weather stations using a gridding method that considers elevation, terrain, coastal influence and urban land use[12]. A range of climate variables are available, including maximum temperatures (tasmax) and precipitation (rainfall), used in this study. The quality of the data is best starting from the early 1960s when the number and density of installed weather stations increased, particularly for daily rainfall. The number of stations peaked in 1974 for rainfall and 1994 for temperature and has since declined marginally[13].

In this study, these datasets are used to provide the best estimate of extremes under a '2022' climate, taking account of trends in temperature and the climate change signal that is already clearly evident in these data. The methodology includes a re-trending step that produces a stationary time series that represents 2020s climate conditions and reveals that the risks of extreme temperatures are already far greater than would be estimated considering non-stationary historical data over the same period.

The UKCP18 climate projections included probabilistic projections of extremes for maximum temperatures and maximum daily rainfall. These projections arguably under-estimated the possibility of the extreme temperatures experienced in England in 2022 and only provide coarse estimates of heavy rainfall (see Section 2); in this study they are used to provide uplifts to maximum temperature and daily rainfall between 2022 and the 2050s and 2080s under 'medium' and 'high' climate change scenarios (central RCP4.5 and RCP8.5 estimates). These uplifts are applied to the 1km 'baseline' EVA analysis to estimate the magnitude and frequency of future events.

[12] Hollis et al., 2019. HadUK-Grid gridded and regional average climate observations for the UK. **https://doi.org/10.1002/gdj3.78**. Also see HadUK-Grid Overview - Met Office

[13] Perry and Hollis, 2004. The generation of monthly gridded datasets for a range of climatic variables over the United Kingdom Memo (metoffice.gov.uk)

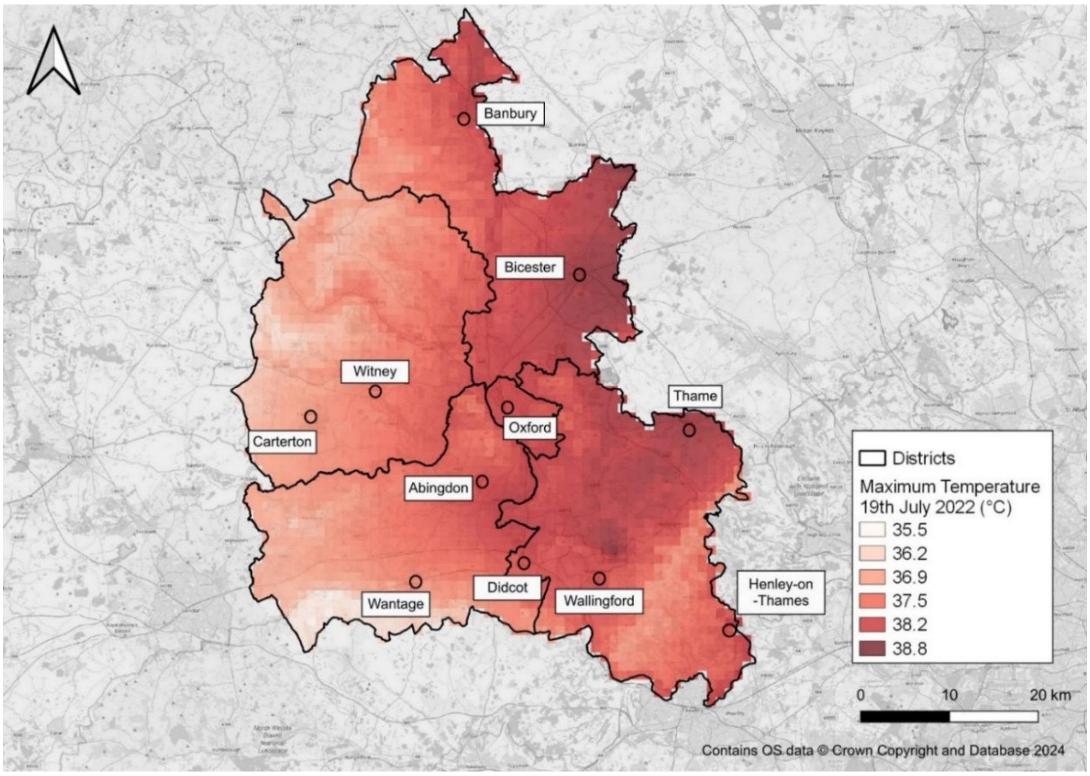

Figure 1-1 - Observed maximum daily temperatures at a 1km scale on 19th July 2022

2. Literature review

2.1 Climate extremes

2.1.1 UKCP18 Probabilistic Extremes

The UKCP18 Probabilistic Projections of Climate Extremes provide information on 21st Century temperature and precipitation extremes across the UK on a 25km grid[14,15]. They provide estimates of extremes for 1 in 20 year, 1 in 50 year and 1 in 100 year events, under different emission scenarios for any year between 1961 and 2099. As such they provide an estimate of likely extremes based on the Met Office climate modelling, which informed the UKCP18 projections.

According to these data, under a high scenario, a 1 in 100-year maximum temperature in Oxford was estimated at 36.3°C (5^{th}–95^{th} percentiles 34.8–38.5°C) in 2022, which has been exceeded in both 2019 and 2022. The record observation of 38.1°C was just within the wide uncertainty bands of the UKCP18 analysis but was not expected until the 2050s for the 50^{th} percentile, as shown on Figure 2-1 by the intersection of the black and red-dotted lines.

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[14] ukcp18_factsheet_probabilistic_projections.pdf (metoffice.gov.uk)

[15] Murphy JM, Brown S and Harris G (2020). UKCP Additional Land Products: Probabilistic Projections of Climate Extremes, Met Office. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcpprobabilistic-extremes-report.pdf. OPEN ACCESS.

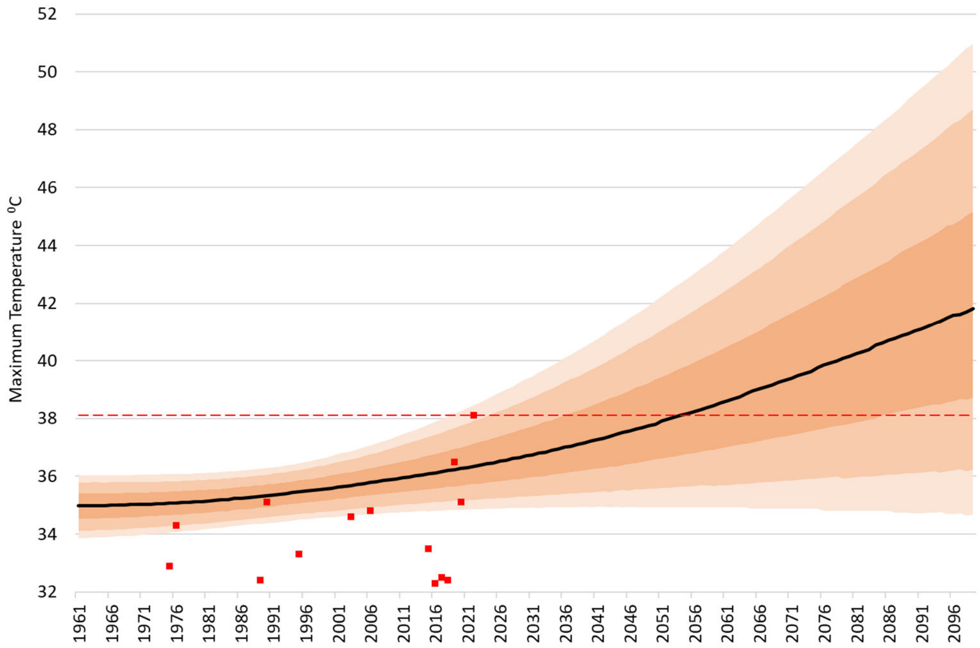

Figure 2-1 - UKCP18 Probabilistic Extremes 1 in 100-year extreme temperature under a 'high' climate change scenario (RCP8.5) (black with uncertainty bands, 5th, 10th, 25th, 75th, 90th & 95th percentiles) and annual maximum observations in Oxford (red)

UKCP18 rainfall extremes averaged over a 25 km^2 grid are not directly comparable with observations at ORO (see Box 1), due to the much higher spatial and temporal variability of rainfall at the point scale. Figure 2-2 summarises the UKCP18 probabilistic extremes data for winter rainfall (Dec-Feb), under a high emissions scenario, for a 1 in 100-year rainfall averaged over a 25km^2 area; the estimate for 2022 is 36.3 mm, whereas point estimates will typically be double this value for the same return period. In Section 4, we show the results of the 1km^2 gridded analysis that indicates 1 in 100 daily rainfalls of between 50.8 and 113.7 mm across Oxfordshire, with an average 1 in 100-year rainfall of 70.2 mm.

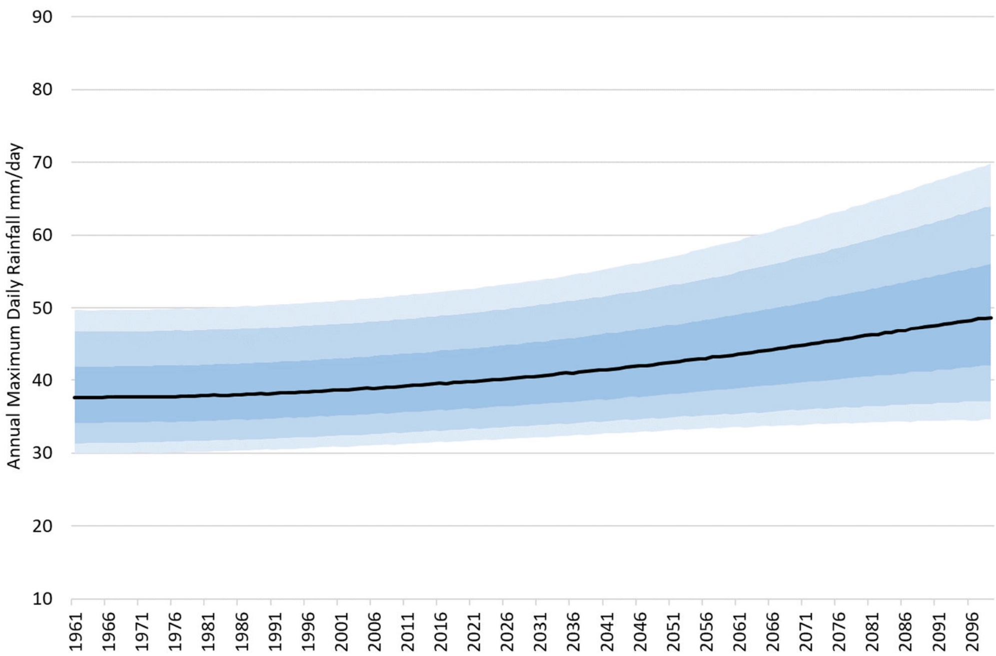

Figure 2-2 - UKCP18 Probabilistic Extremes 1 in 100-year maximum rainfall under a 'high' climate change scenario (RCP8.5) (black with uncertainty bands, 5th, 10th, 25th, 75th, 90th & 95th percentiles) and annual maximum observations in Oxford (blue)

Box 1: Oxford Radcliffe Observatory (ORO)

The ORO is the longest single-site weather record in the United Kingdom and one of the oldest records in the world. Records commenced in 1772, with unbroken daily air temperature records since 1813, daily rainfall from 1827 and sunshine from 1880[16]. This greatly valued record is maintained by the University of Oxford School of Geography and Environment and is highly important in observing the impact of climate change on temperature and rainfall. Data from the ORO is publicly available with past and recent observations available for download in both daily and monthly summaries[17]. For this reason, ORO data are used to illustrate several findings of this report, but additional information is also provided for other locations from the gridded analysis.

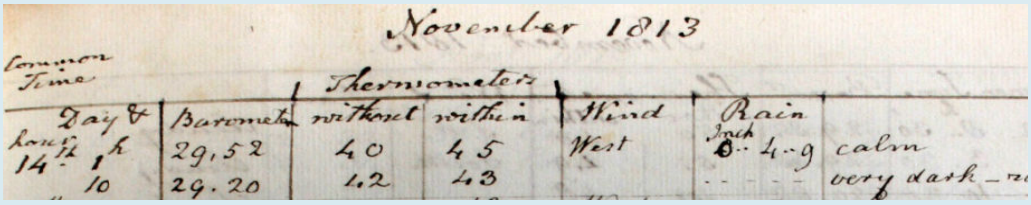

Figure 2-3 – An extract from the ORO logbook for November 1813[16]

2.1.2 Climate attribution studies

Alternative estimates of extremes, how these extremes are evolving with climate change and the extent that individual events can be attributed to climate change, can be assessed using climate attribution studies[18,19]. These typically use climate models to produce estimates of extreme events, with and without greenhouse gas emissions, and then estimate how climate change has altered the chance of extreme events happening in today's climate compared to pre-industrial periods (or more recent baseline periods) with lower temperatures. These studies aim to disentangle the different drivers of extreme weather from human-induced climate change; the results are not always conclusive, but their application is increasing, including use in climate litigation and policy making[20].

Following record UK temperatures in July 2019, the Met Office published the results of climate attribution studies that found that temperatures above 35°C were becoming increasingly common in the southeast of England. Summers with days above 40°C *somewhere in the UK* were estimated to have a return period of 100-300 years.

[16] Overview and Brief History of the Radcliffe Meteorological Station | School of Geography and the Environment (ox.ac.uk)

[17] Daily Data from the Radcliffe Observatory site in Oxford | School of Geography and the Environment.

Burt, Stephen and Burt, Tim, 2019. Oxford Weather and Climate since 1767. Oxford University Press, 544pp.

[18] Ben Clarke *et al* 2022 Environ. Res.: Climate 1 01200. DOI 10.1088/2752-5295/ac6e7d Extreme weather impacts of climate change: an attribution perspective - IOPscience

[19] Otto, F., van Oldenborgh, G., Eden, J. *et al.* The attribution question. *Nature Clim Change* **6**, 813–816 (2016). https://doi.org/10.1038/nclimate3089

[20] Home - Climate Attribution includes over 600 scientific resources in climate attribution.

Without mitigating greenhouse gas emissions, this could decrease to a return period of 3.5 years by 2100[21] (Figure 2-4).

A second study following the July 2022 UK heatwave by the World Weather Attribution (WWA) group suggested that the UK temperatures in the height of the heatwave, averaged over two days, had a probability of around 1% (1 in 100 years) but the daily maximums were unprecedented and indicated a probability as low as 1 in 1000 years or 0.1%[22]. Both the Met Office and WWA studies found that human-caused climate change has already made the chance of 40°C in the UK about **ten times more likely when compared with the pre-industrial period.**

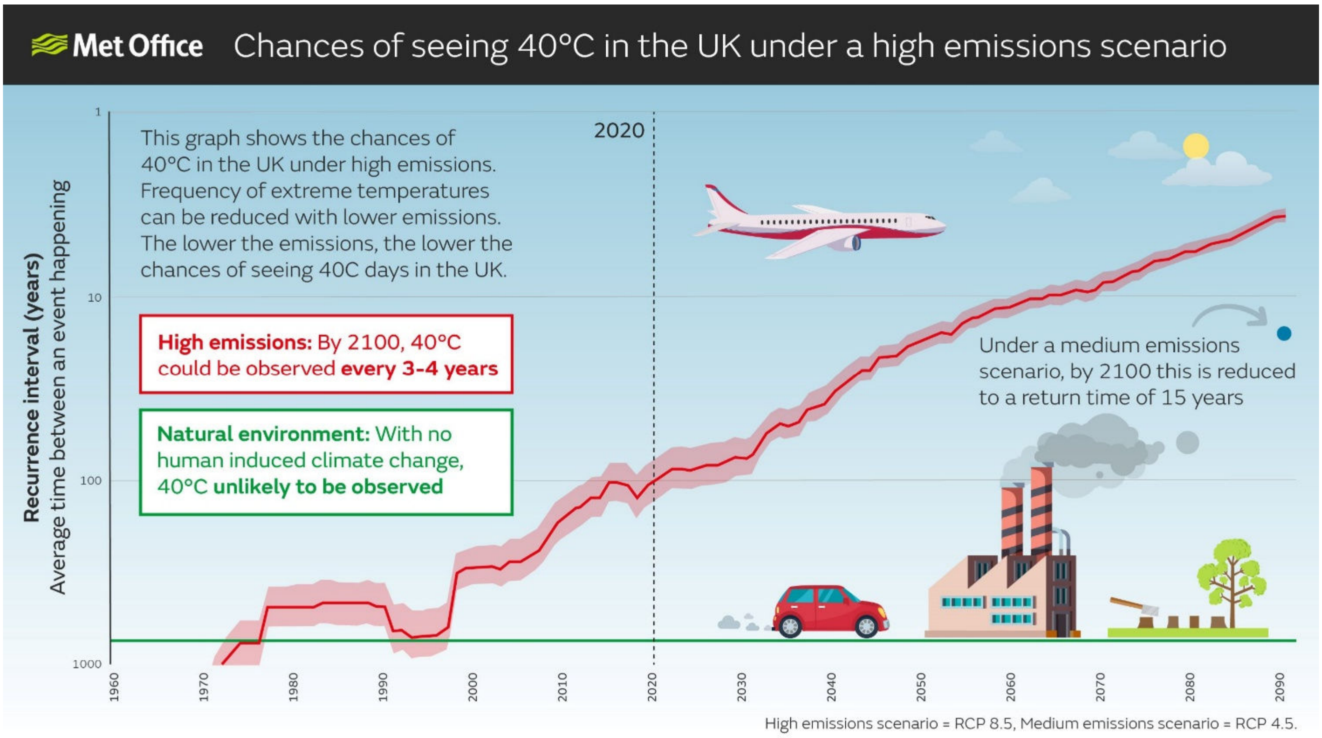

Figure 2-4 - Met Office 2020 assessment of the likelihood of seeing 40°C in the UK under High and Medium Emissions scenarios.

Attribution of heavy rainfall events and flooding to climate change is more complex than heatwaves and generally indicates weaker linkages and smaller increases in the change of flooding in today's climate compared to the pre-industrial period. This is because extreme rainfall has greater natural variability and the greater complexity of processes linking heavy rainfall to floods, which are also influenced by antecedent rainfall conditions, land use change and other catchment characteristics. For example, in a study of extreme rainfall across Western Europe in July 2021, which caused severe flooding and substantial impacts, the likelihood of such an event was increased by 1.2 to 1.9 times since pre-industrial period due to warmer conditions today[23]. Similar studies in the UK have suggested that the chance of heavy rainfall events has increased due to climate change, with a risk factor of 1.4

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[21] Christidis, N., McCarthy, M. & Stott, P.A. The increasing likelihood of temperatures above 30 to 40 °C in the United Kingdom. Nat Commun 11, 3093 (2020). https://doi.org/10.1038/s41467-020-16834-0

[22] Zachariah, M., et al., 2022. Without human-caused climate change temperatures of 40°C in the UK would have been extremely unlikely. UK heat scientific report (worldweatherattribution.org)

[23] Tradowsky, J.S., Philip, S.Y., Kreienkamp, F. et al. Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021. Climatic Change 176, 90 (2023). https://doi.org/10.1007/s10584-023-03502-7

times more likely since the pre-industrial period[24]. In Ireland, extreme rainfall linked to Storm Babet that caused extensive flooding in County Cork in October 2023 was linked to climate change, with a risk factor of 2 times more likely due to climate change[25]. Overall, the impact of climate change under current conditions on heavy rainfall in the UK is far less significant than on extreme temperatures, with quoted risk factors of 1.2 to 2 times for rainfall, compared to 10 times for extremely high temperatures.

2.1.3 International analogues on extreme heat

The Canadian heat dome in 2021 was one of the deadliest weather events in Canadian history. The heat dome was caused by a high-pressure system which brought unprecedented high temperatures and increased concentrations of ground-level ozone and fine particulate matter[26]. Daily temperatures reached 49.6°C in Lytton, Canada and were 16-20°C above seasonal norms, leading to 740 deaths in the province of British Columbia in western Canada. Mental health impacts were associated with the heat dome event with a 13% increase in average climate change anxiety levels among residents in British Colombia[27]. The event was deemed almost impossible without climate change, with a risk factor of 150x more likely due to human-induced climate change[28].

The extreme heat observed around the world in 2023, has broken all previous records. In Bangladesh, Dhaka observed the highest maximum temperature recorded in decades of 40.6°C on 15th April. In India, several northern and eastern cities recorded maximum temperatures above 44°C on 18th of April. Thailand recorded its highest ever temperature of 45.4°C on 15th April in the city of Tak. The Sainyabuli province in Lao PDR reported 42.9°C on 19 April as its all-time national temperature record. Vientiane, the capital of Lao PDR, recorded 41.4°C on 15th April, the hottest day ever for the capital. On the same day, Luan Prabang in Lao PDR reported 42.7°C. Combined with high humidity the extreme heat in April 2023 created “dangerous” heat index conditions in India, Bangladesh, Thailand and Laos, placing millions of vulnerable people at risk[29].

Climate attribution studies cite the main cause of extreme temperatures as climate change, but climate scientists have struggled to explain why global land surface and sea temperatures have persistently overshot previous records by up to 0.2°C each month during 2023. No combination of events including higher greenhouse gas emissions, El Niño in the second half of the year, volcanic activity or other factors can fully explain the observations. According to Gavin Schmidt, Director of NASA’s Goddard Institute of Space Studies *“If the anomaly does not stabilize by August (2024) — a reasonable expectation based on previous El Niño events — then the world will be in uncharted territory. It could imply that a warming planet is already fundamentally altering how the climate system operates, much sooner than scientists had anticipated”.*[30]

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[24] Friederike E L Otto et al 2018 Environ. Res. Lett. 13 024006 Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond„a real-time event attribution revisited (iop.org)

[25] Clarke, B., et al. 2023. Climate change made the extreme 2-day rainfall event associated with flooding in Midleton, Ireland more likely and more intense (imperial.ac.uk)

[26] Lee et al. (2023) Available from: Chronic Diseases Associated With Mortality in British Columbia, Canada During the 2021 Western North America Extreme Heat Event (wiley.com)

[27] Heat dome and other climate events have growing impact on mental health—study - SFU News - Simon Fraser University

[28] Philip, S. Y. et al.2022. Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021, Earth Syst. Dynam., 13, 1689–1713, https://doi.org/10.5194/esd-13-1689-2022

[29] Zachariah et al., 2023 Extreme humid heat in South Asia in April 2023, largely driven by climate change, detrimental to vulnerable and disadvantaged communities (imperial.ac.uk)

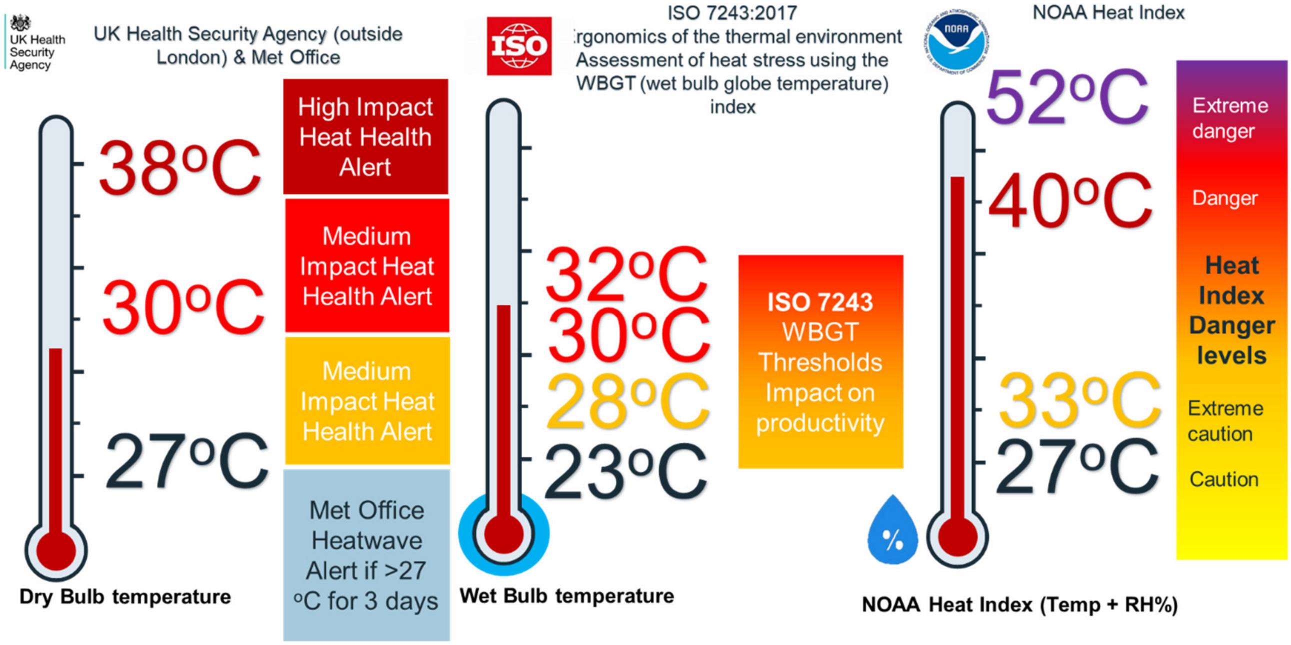
[30] Climate models can’t explain 2023’s huge heat anomaly — we could be in uncharted territory (nature.com)

2.2 Impacts of extreme heat

Extreme heat has a range of direct and indirect impacts on people, infrastructure, and the environment. Of particular concern are the impacts on people's health caused by a combination of high heat and high humidity, which is often compounded for vulnerable people living in care settings or homes with poor insulation properties, such as high-rise flats[31].

2.2.1 Thermal comfort

High heat and humidity have direct impacts on human health, as the human body cannot cool down effectively in very hot humid conditions, as well as impacts productivity and urban infrastructure systems. Exposure to excessive heat has wide-ranging health impacts, often amplifying existing conditions and resulting in premature death and disability[32]. Several combined temperature and humidity indices provide information on heat risks[33]. For example, the UK Health Security Agency thresholds for Oxfordshire are 27°C, 30°C and 38°C for 'low', 'medium' and 'high' impacts[34]; the NOAA Heat Index is based on temperature and relative humidity with key thresholds of equivalent or 'feels like' temperatures at 27°C, 33°C, 40°C and 52°C (Appendix B). The danger level of 40°C is a key threshold for health impacts. For wet-bulb globe temperatures (WBGT) thresholds vary from 23°C to 33°C depending on the level of exertion based on ISO 7243 WBGT reference values; thresholds of 28°C, 30°C or 32°C are typically applied and are known to impact productivity[35]. Concepts used in building design, such as the 'Thermal Comfort Zone' standards are based on an 'Adaptive Comfort Approach' and adopt thresholds between 24°C to 35°C for dry bulb temperatures.



[31] Tsoulou et al. 2022. Assessing the Current and Future Risk of Overheating in London's Care Homes: The Effect of Passive Ventilation. In: Proceedings of Building Simulation 2021: 17th Conference of IBPSA. (pp. pp. 2650-2657). International Building Performance Simulation Association (IBPSA)

[32] World Health Organisation Heat and Health (who.int)

[33] Schwingshackl et al. 2021. Heat Stress Indicators in CMIP6: Estimating Future Trends and Exceedances of Impact-Relevant Thresholds - Schwingshackl - 2021 - Earth's Future - Wiley Online Library https://doi.org/10.1029/2020EF001885

[34] UK Health Security Agency Weather-health alerting system - user guide (publishing.service.gov.uk)

[35] ISO 7243:2017 - Ergonomics of the thermal environment — Assessment of heat stress using the WBGT (wet bulb globe temperature) index

Figure 2-5 – Key temperature thresholds for Oxfordshire that can impact on thermal comfort and health.

Based on an analysis of maximum temperatures and relative humidity, Oxford has experienced **extremely dangerous heat** on 4 occasions since 1961, all in the last 5 years (July 2022, July 2021 and July 2020) and **dangerous heat** on 44 days since 1961. Average relative humidity in July in Oxfordshire can be high, between 63% and 79%, causing dangerous heat index values when combined with very high temperatures. During the July 2022 heatwave, relative humidity in Oxfordshire ranged between 60% and 68% (Appendix B). Heat Index data for Oxford are shown in Figure 2-5 but note that this analysis is based on historical data (without 're-trending') and may underestimate current risks.

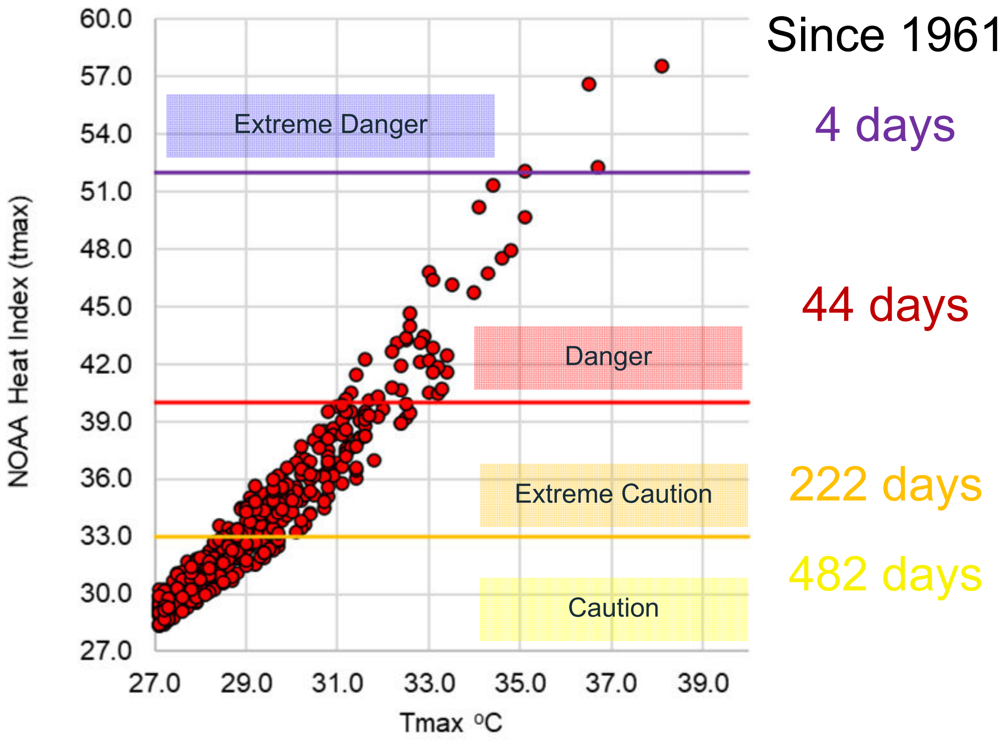


Figure 2-6 – Maximum heat indices experienced in Oxford since 1961 based on maximum temperatures from ORO and Relative Humidity from Met Office HadUK.

2.2.2 Health

Extreme heat adversely impacts physical and mental health, leading to an increased demand on healthcare services due to increased mortality and morbidity. Extreme heat can directly cause dehydration, heat exhaustion, heart attacks, heatstroke and increase risk of lung illnesses[36]. Extreme heat can also interact with poor air quality which further exacerbates increased temperatures[37]. In total, 65 excess deaths were recorded during five heat periods in Oxfordshire in 2022[38]. Increased temperatures in the future are likely to result in a larger number of excess deaths. Extreme heat can disproportionally affect vulnerable groups which have a lower coping capacity and elderly people who are at greatest risk from heat health impacts. Extreme heat can also have a significant impact on children and people who work or regularly exercise outside.

[36] Come rain or shine, adverse weather matters for our health - UK Health Security Agency (blog.gov.uk)

[37] 962_Climate_Change_and_Air_Pollution.pdf (ids.ac.uk)

[38] Excess mortality during heat-periods: 1 June to 31 August 2022 - Office for National Statistics (ons.gov.uk)

Mental health impacts from extreme heat can include increased rate of mental health conditions. There was an increased risk of suicide and evidence of increased hospital admissions for mental illnesses during increased temperatures[39]. Sleep patterns can also be impacted during extreme heat and result in isolation if people are unable to leave their homes during extreme heat warnings.

2.2.3 Productivity

Extreme heat can result in lower employee productivity, which businesses are highly reliant on. As periods of extreme heat become more frequent, productivity will be adversely affected especially those who work outside due to health impacts from extreme heat (for example heat exhaustion and heatstroke)[40]. Increased high temperatures could lead to trebling of health and productivity impacts[41]. Increased rates of home working due to COVID-19 presents an increased risk of overheating in homes which may be less well adapted to heat than offices[42]. Businesses can also fundamentally rely on wider infrastructure such as energy, ICT, transport, and water supply which can be disrupted by extreme heat, in turn disrupting employee productivity[43].

2.3 Impacts of heavy rainfall

Heavy short duration rainfall has a range of direct impacts on buildings and drainage as well as contributing to surface water and fluvial flooding, which are two of the main risks for Oxfordshire[44]. Of particular concern are water ingress into housing stock, which can lead to damp, mould, and poor housing conditions, impacts on drainage and surface water flooding risks and more frequent use of Combined Sewer Overflows (CSOs).

According to the CCRA3, the damage due to surface water flooding is projected to increase by 30%-36% by the 2050s under +2°C pathway and 48%-56% under +4°C pathway assuming current levels of adaptation. From our previous study the flood vulnerability model indicates that flood risk remains very high in 2050s under all scenarios, particularly in Oxford, Abingdon, Witney, and Banbury. The frequency of surface water flooding is projected to increase by +29% and 46% for under the +2°C pathway and +4°C pathway[45].

Heavy rainfall on top of saturated soils heightens the risks of flooding and CSO discharges. Groundwater infiltration in ageing drainage and sewerage infrastructure means that there is insufficient capacity in the system to cope with extreme heavy rainfall. In such situations, systems designed to cope with 1 in 30-year events may struggle to perform effectively with much lower rainfall depths.

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39 Adverse Weather and Health Plan: Supporting evidence (publishing.service.gov.uk)
40 Chapter 5: Health, Communities and the Built Environment - UK Climate Risk
41 Risks to health, wellbeing and productivity from overheating in buildings - Climate Change Committee (theccc.org.uk)
42 CCRA3-Briefing-High-Temperatures.pdf (ukclimaterisk.org)
43 Chapter 6: Business and Industry - UK Climate Risk
44 AtkinsRéalis, 2024. A Summary of the Current and Future Climate Vulnerability of Oxfordshire. Prepared for OCC.
45 AtkinsRéalis, 2024b. Technical Report on Current and Future Climate Vulnerability of Oxfordshire. Prepared for OCC.

3. Methodology

To complete the investigation of maximum temperature and heavy rainfall associated with present climate conditions under a range or annual probabilities or return periods, a General Extreme Value (GEV) approach was used on the annual maximum values for the historical period, and appropriate UKCP18 temperature and rainfall uplifts were applied to develop future ‘medium’ and ‘high’ scenarios for the 2050s and 2080s. The GEV distribution is used in flood hazard analysis and applied climate science; it combines three types or families of statistical distributions and is regarded as the most robust statistical approach to estimate extreme values (Appendix B provides more information.

AtkinsRéalis developed a GEV approach for mapping large areas as follows:

- **The daily timeseries from 1960-2022 (63 years of HadUK-grid data), were aggregated to the annual maximum for a total of 63 calendar years.** This was done for each 1km grid square covering the Oxfordshire area, for a total of 2830 grid cells. While this period was not the longest record available, it includes a sufficiently long record and focuses on the time period with higher quality observations data, as the number of weather stations included in HadUK to estimate maximum temperature and particularly daily rainfall is far greater from the 1960s[12].

- **For maximum temperatures, data were ‘re-trended’ to 2022.** In this way the trend of climate change was added to the dataset from 1960-2022, so that the 62 years of the dataset represent the same climate conditions as is experienced in the 2020s and include climate change experienced to date. This process also introduced stationarity to the dataset prior to the EVA being undertaken. Automated checks were undertaken for every 1km grid cell to ensure the re-trending step removed non-stationarity in the dataset. The stationarity and the re-trending process is covered further in 6.Appendix B.[46]

- **The EVA was applied to estimate annual maximum temperature and daily rainfall extremes for a range of annual probabilities** (1 in 25, 50, 100, 250 etc..) for the present period, based on the climate in 2022. The method provided a ‘best estimate’ of return levels and lower and upper confidence intervals for 10 and 90 percentiles, respectively. Example plots of extreme temperatures and rainfall are shown in Section 4 and 6.Appendix B.

- **Climate change uplifts were applied** based on the results of the UKCP18 Probabilistic Projections for Climate Extremes (PPCE) data for Oxfordshire under RCP4.5 and RCP8.5 scenarios. Central estimates were applied but data are also provided on the uncertainty around these projections.

- **Maps were produced of selected extreme temperatures and rainfall for the whole of Oxfordshire, including inset maps of Oxford and other major towns.** These focus on three annual probabilities 1 in 25, 50 and 100 but further information is provided in Appendix 2, including information on upper and lower confidence intervals of the 10^{th} and 90^{th} percentile of EVA model solutions. Table 3-1 in 6.Appendix B shows the UKCP18 PPCE future rainfall uplifts expressed as a relative change from the 2022 RCP8.5 estimate. Purple cells represent the uplifts applied to all return periods of rainfall.

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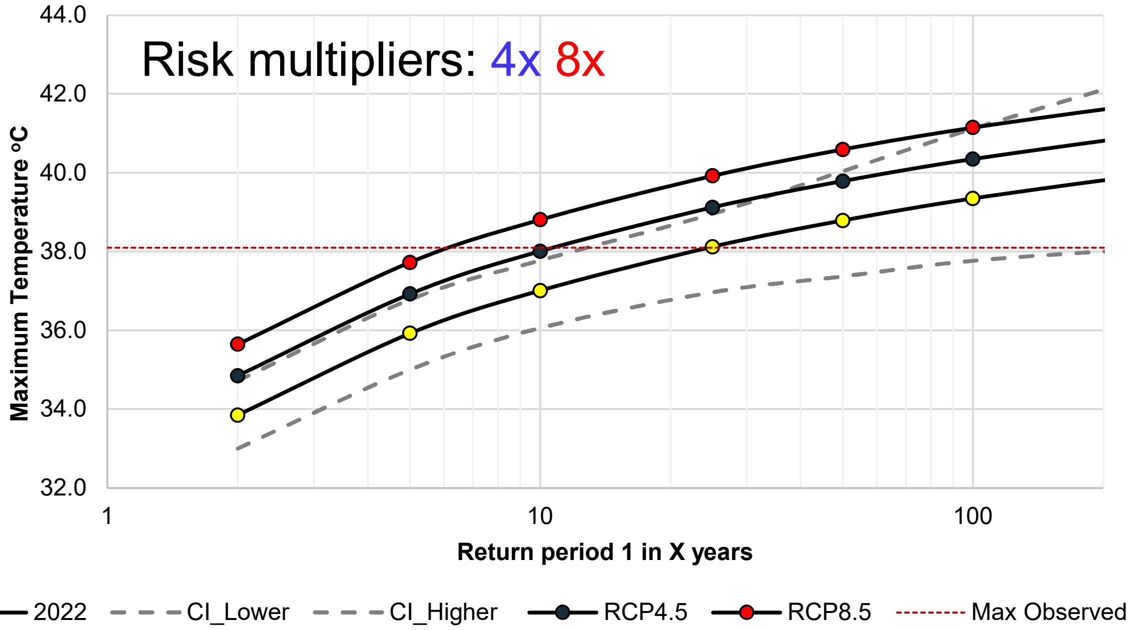
[46] This was not done for rainfall, as no clear upward trend was seen and 81% of the annual maximum series passed the stationarity test; if anything rainfall annual maxima (AMAX) indicated a downward trend from 1950-2023. For this reason we concluded that using both re-trending and use of temperature as a covariate for rainfall analysis was not appropriate for a rapid mapping study, but further work could be done for site specific assessments.

4. Results

This section presents the EVA results on both the annual maximum temperatures and rainfall. Maps were produced for a range of return periods to represent the current risks, including climate change to 2022, as well as results for the 2050s and 2080s to indicate how extreme rainfall and temperatures will change between now and future periods. Figure 4-1 shows example results for a 1km square in Jericho, Oxford. The lowest solid curve represents current conditions, and the upper curves show centrals estimates for the 2050s under 'medium' and 'high' climate scenarios. The risk multipliers indicate the increase in frequency of events under these scenarios.



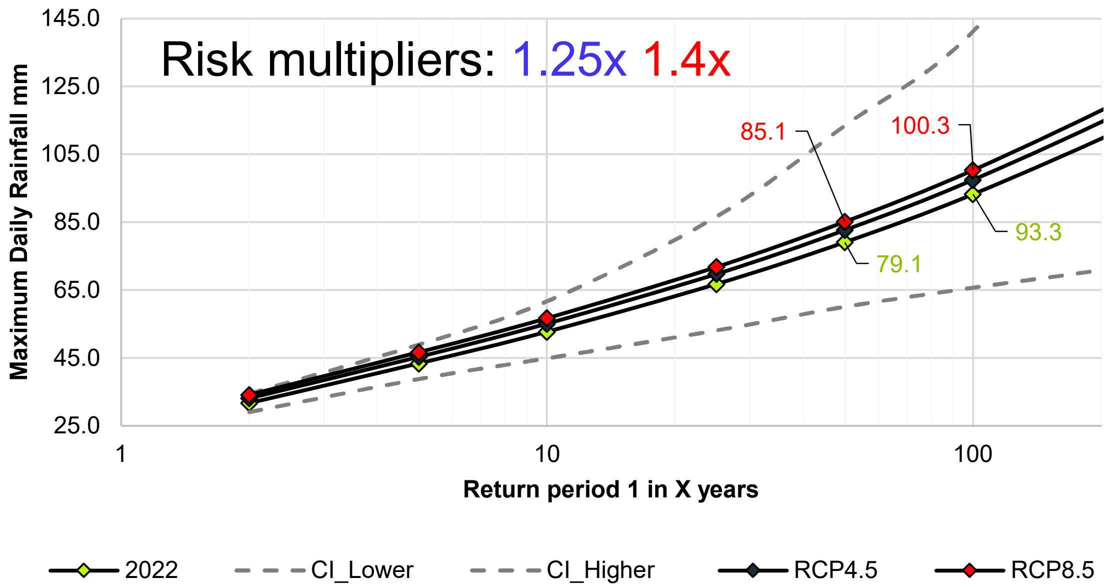


Figure 4-1 – Example plots showing results for (a) maximum temperature and (b) heavy rainfall for the 2020 climate and 2050s and (c) risk multipliers indicating the increased frequency of events under RCP4.5 and RCP8.5 scenarios. Location 450500, 207500, Oxford.

4.1 Temperature

Table 4-1 summarises the extreme temperatures for Oxfordshire, Figures 4-2 to 4-6 map current risks and Figure 4-7 to 4-13 map future risks for Oxfordshire as a whole and for Oxford, Abingdon and Witney. A typical high temperature, defined as the 1 in 2 year event under a 2020s climate, is now 33.1˚C. This kind of extreme heat is anticipated every other year.

- **There is a 1 in 3 chance that Oxfordshire will experience maximum temperatures above 37.5 ˚C within the next decade.** Our analysis shows the chance of exceeding 37.5˚C is just 1 in 25 (4%); this equates to a chance of a more extreme event happening in next decade of around 1 in 3 (33%)[47]. The hottest parts of the county could exceed 39˚C under the same scenario.
- **There is significant variation in the chance of extreme temperatures across the county;** in general, the hottest areas are to the east in the Thames Valley and cooler areas in the west and at higher elevations. The EVA model predicts a higher chance of very high temperatures in the Wantage area[48].
- **The impacts of climate increase extreme temperatures by approximately 2 and 4 degrees <u>above 2020s</u> data for the 'medium' and 'high' climate scenario.** This is a higher rate of warming than for average temperatures and dangerously high temperatures are likely to occur almost every year under the 'high scenario'.

Table 4-1. Statistical summary of the best estimates of the 1 in 25, 1in 50 and 1 in 100 temperatures extremes across Oxfordshire. A 1 in 2 extreme temperature in 2020 is presented as an example of a typical high temperature under the current climate.

Scenario	Annual probability %	Mean (°C)	Min (°C)	Max (°C)	Range (°C) (spatial variability)
2020s 1 in 2	50%	33.1	31.6	34.3	2.7
2020s 1 in 25	4%	37.5	36.0	39.5	3.5
2020s 1 in 50	2%	38.2	36.7	41.0	4.3
2020s 1 in 100	1%	38.8	37.2	42.5	5.3
rcp4.5_2055_25rp	4%	38.5	36.9	40.4	3.5
rcp4.5_2055_50rp	2%	39.2	37.6	42.0	4.3
rcp4.5_2055_100rp	1%	39.8	38.2	43.5	5.3
rcp4.5_2085_25rp	4%	39.5	38.0	41.5	3.5
rcp4.5_2085_50rp	2%	40.2	38.7	43.0	4.3
rcp4.5_2085_100rp	1%	40.8	39.2	44.5	5.3
rcp8.5_2055_25rp	4%	39.3	37.7	41.2	3.5
rcp8.5_2055_50rp	2%	40.0	38.5	42.8	4.3
rcp8.5_2055_100rp	1%	40.6	39.0	44.3	5.3
rcp8.5_2085_25rp	4%	41.7	40.2	43.7	3.5
rcp8.5_2085_50rp	2%	42.4	40.9	45.2	4.3
rcp8.5_2085_100rp	1%	43.0	41.4	46.7	5.3

[47] Using event probabilities for a specific duration rather than annual probability. $Pe = 1 - \left(1 - \frac{1}{T}\right)^n$
Sayers, 2016 Communicating the chance of a flood: The use and abuse of probability, frequency and return period.
[48] The reasons for this are statistically nuanced as the observed data gridded data in this area of the map had a higher average annual maxima, which affected the model fit.

4.1.1 Current climate

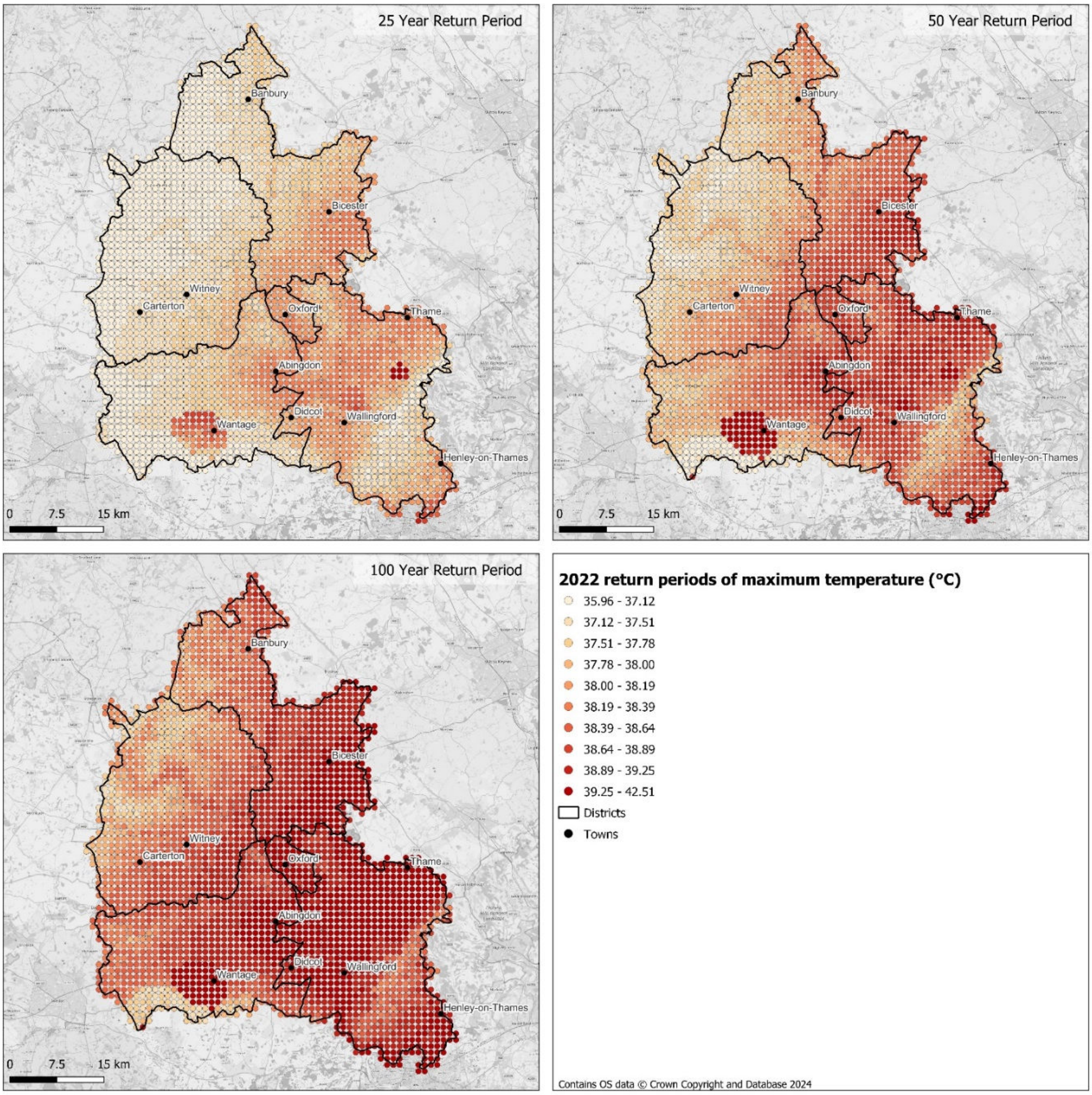


Figure 4-2 – Extreme temperatures for the current climate (25-year, 50-year, 100 year)

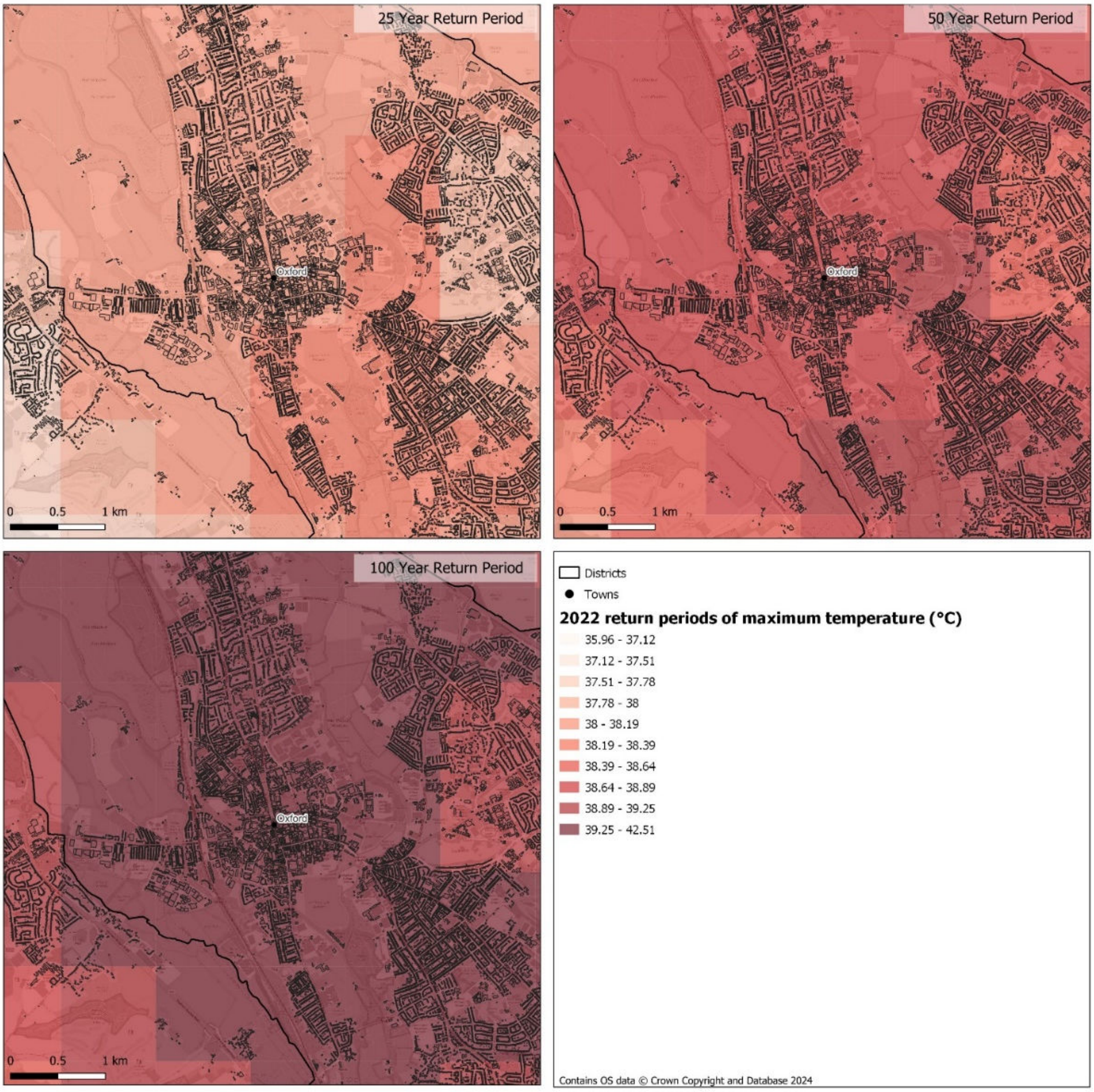


Figure 4-3 - Oxford extreme temperatures for the current climate (25 year, 50 year, 100 year)

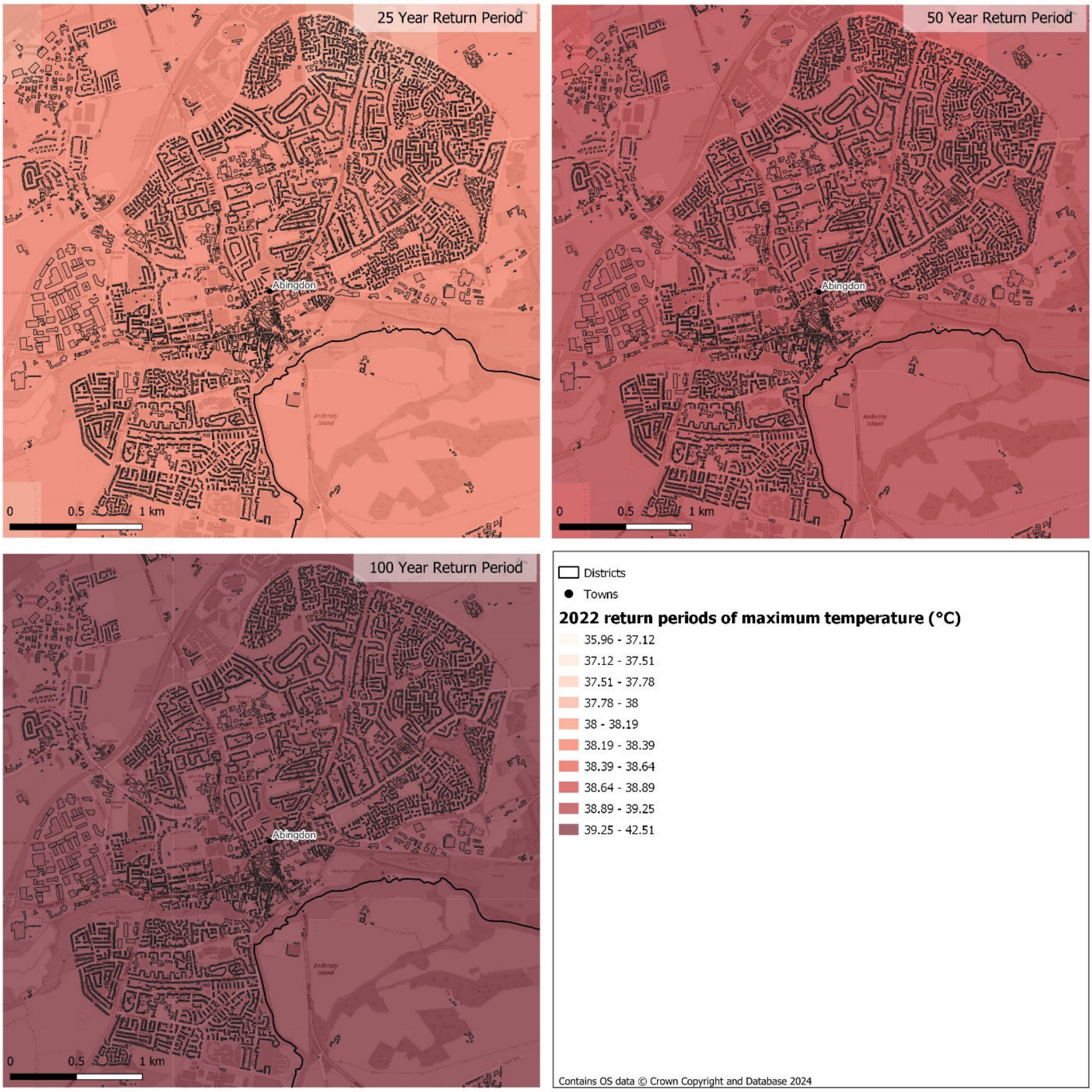


Figure 4-4 – Abingdon extreme temperatures for the current climate

Figure 4-5 – Witney extreme temperatures for the current climate

4.1.2 Future climate

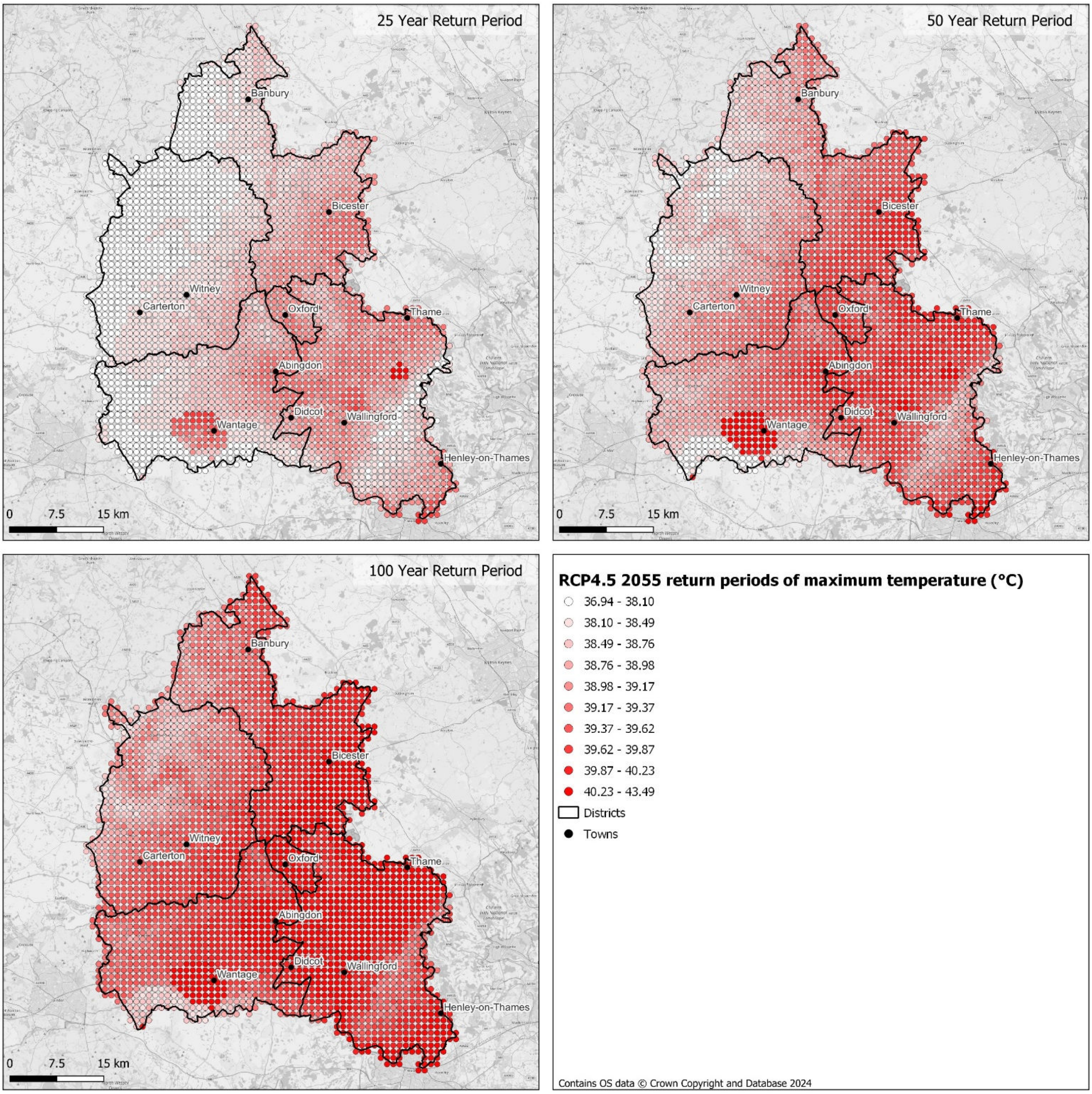


Figure 4-6 –Extreme temperatures for future climate, 2055 RCP4.5 (medium emissions scenario)

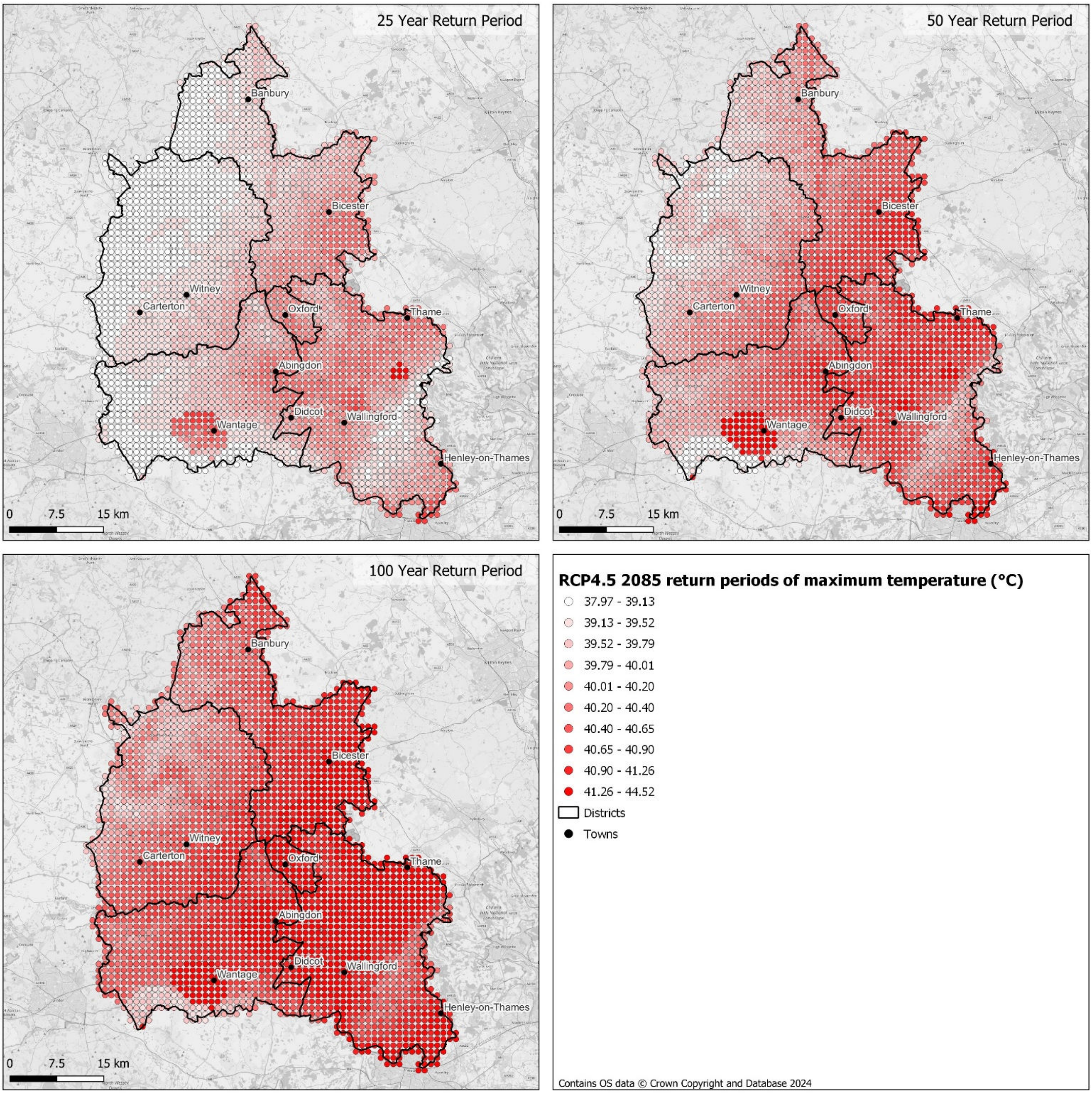


Figure 4-7 – Extreme temperatures for future climate, 2085 RCP4.5 (medium emissions scenario)

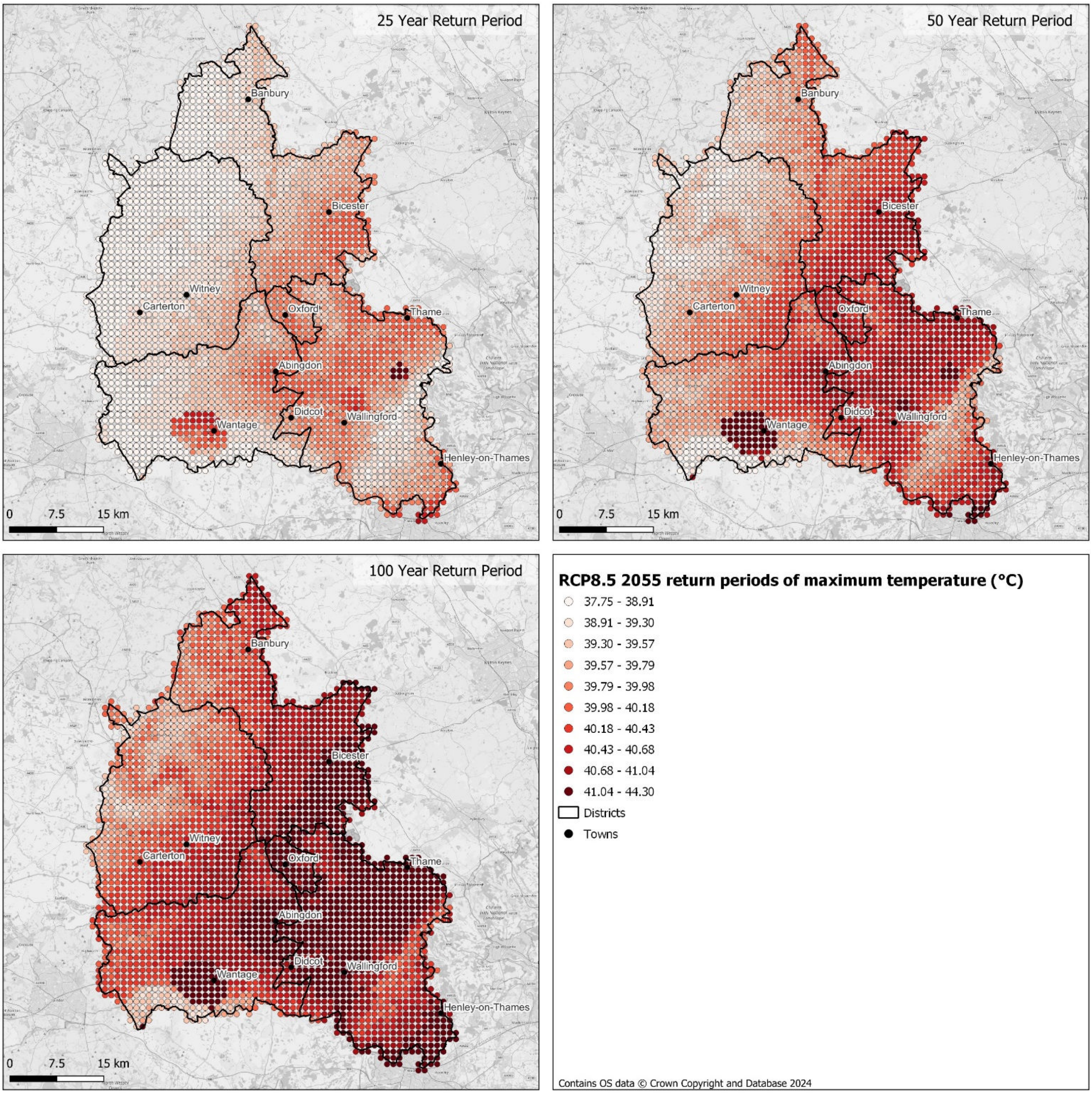


Figure 4-8 – Extreme temperatures for future climate, 2055 RCP8.5 (high emissions scenario)

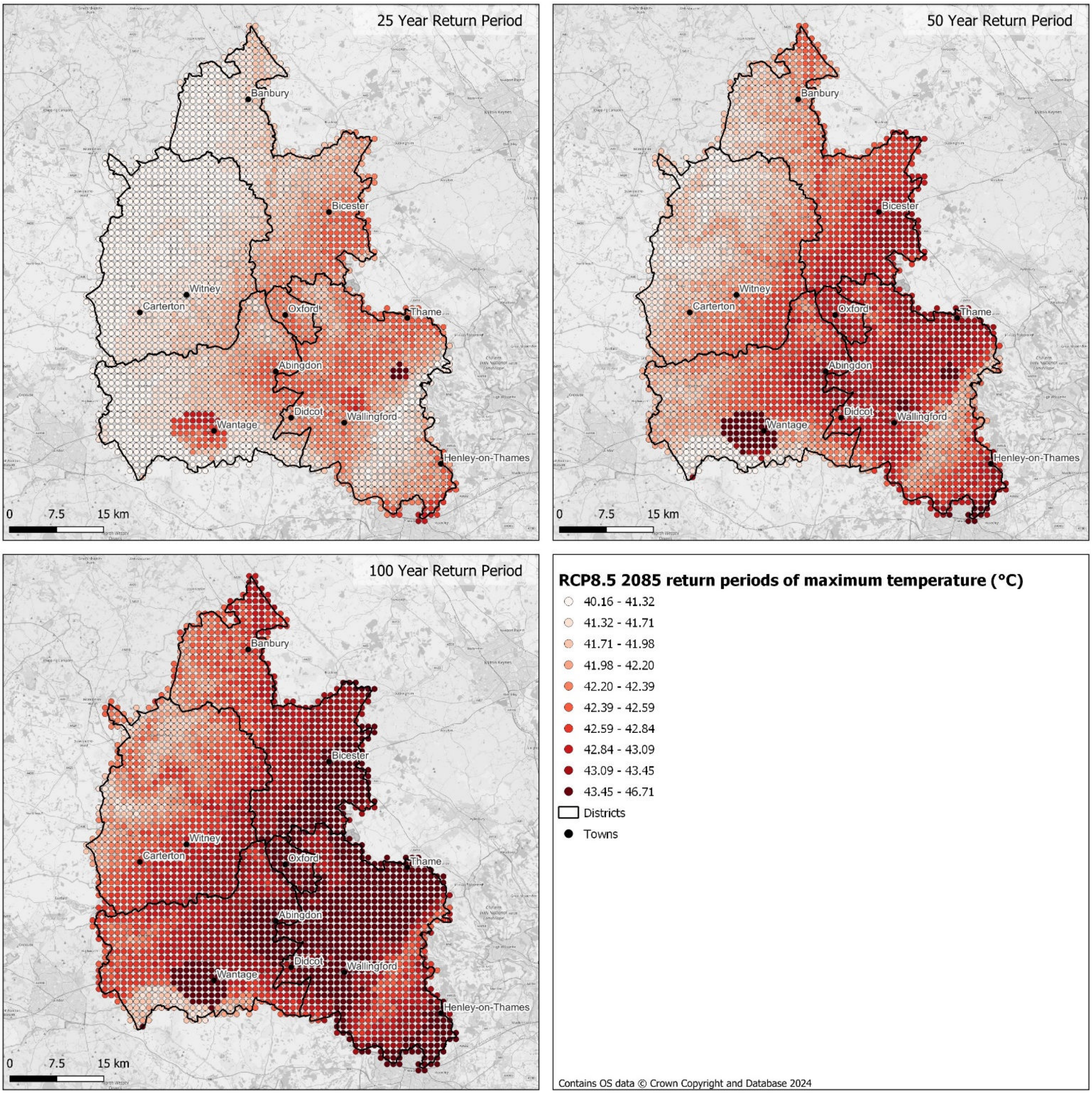


Figure 4-9 – Extreme temperatures for future climate, 2085 RCP8.5 (high emissions scenario)

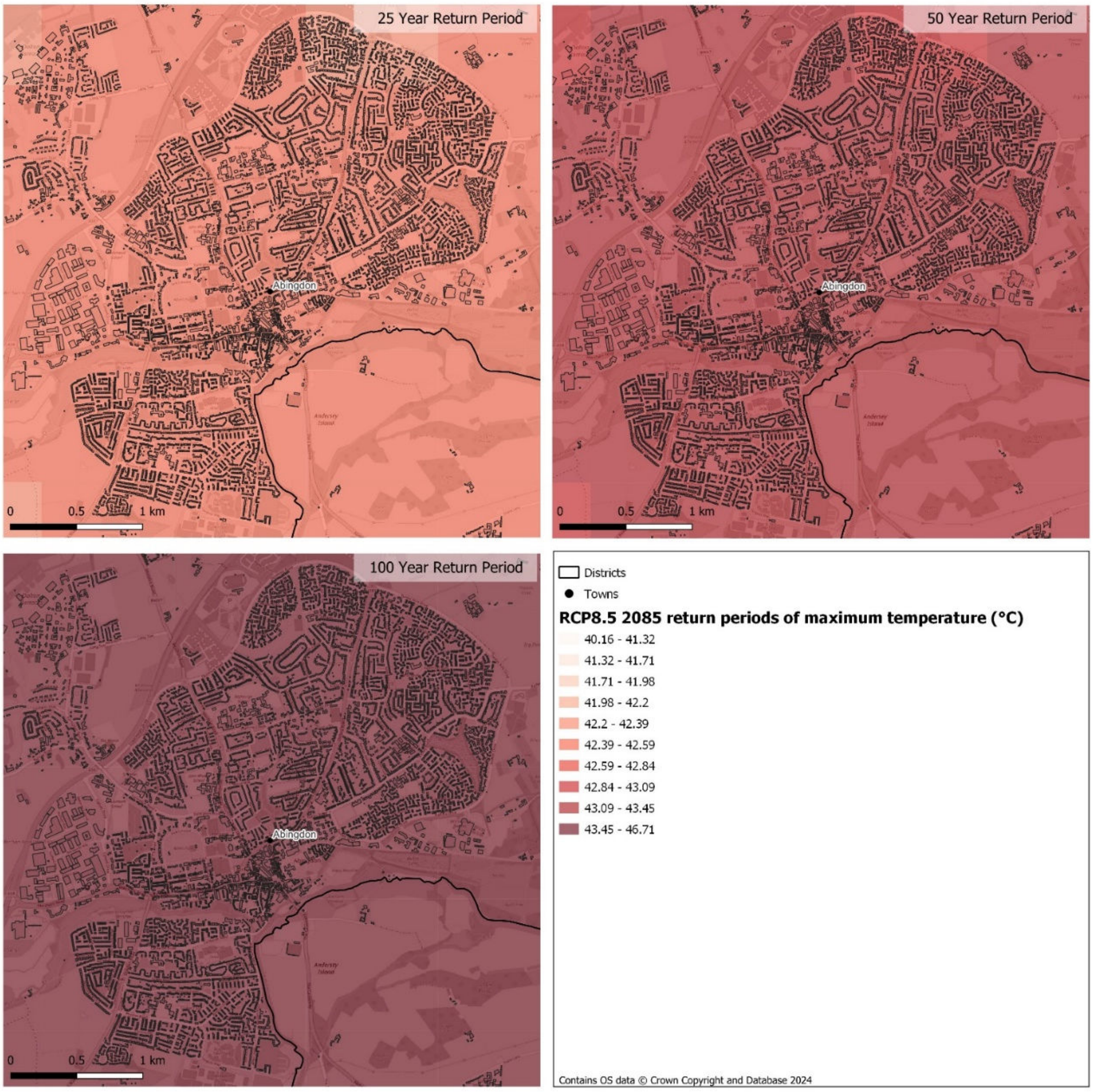


Figure 4-10 – Abingdon extreme temperatures for future climate, 2085 RCP8.5 (high emissions scenario)

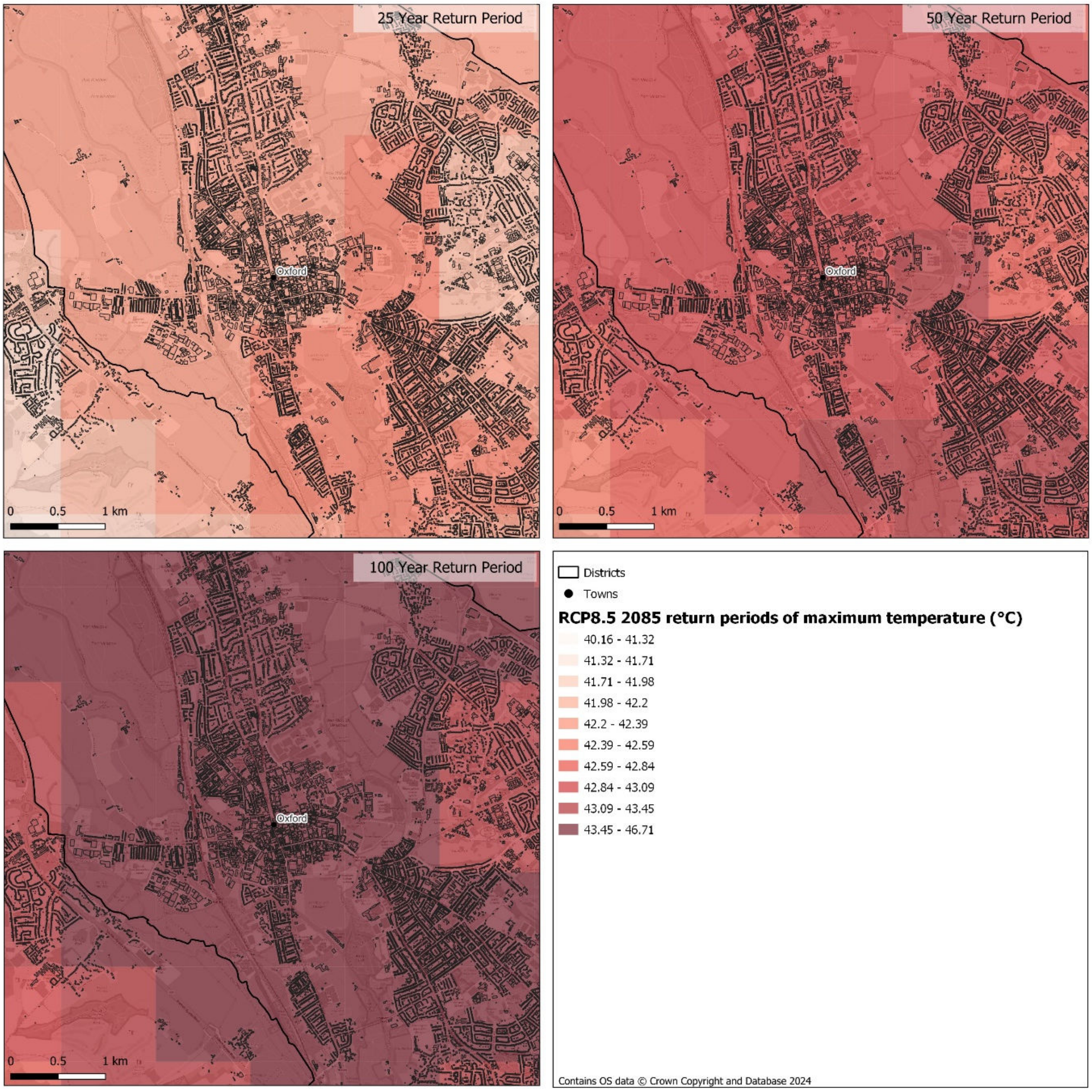


Figure 4-11 – Oxford extreme temperatures for future climate, 2085 RCP8.5 (high emissions scenario)

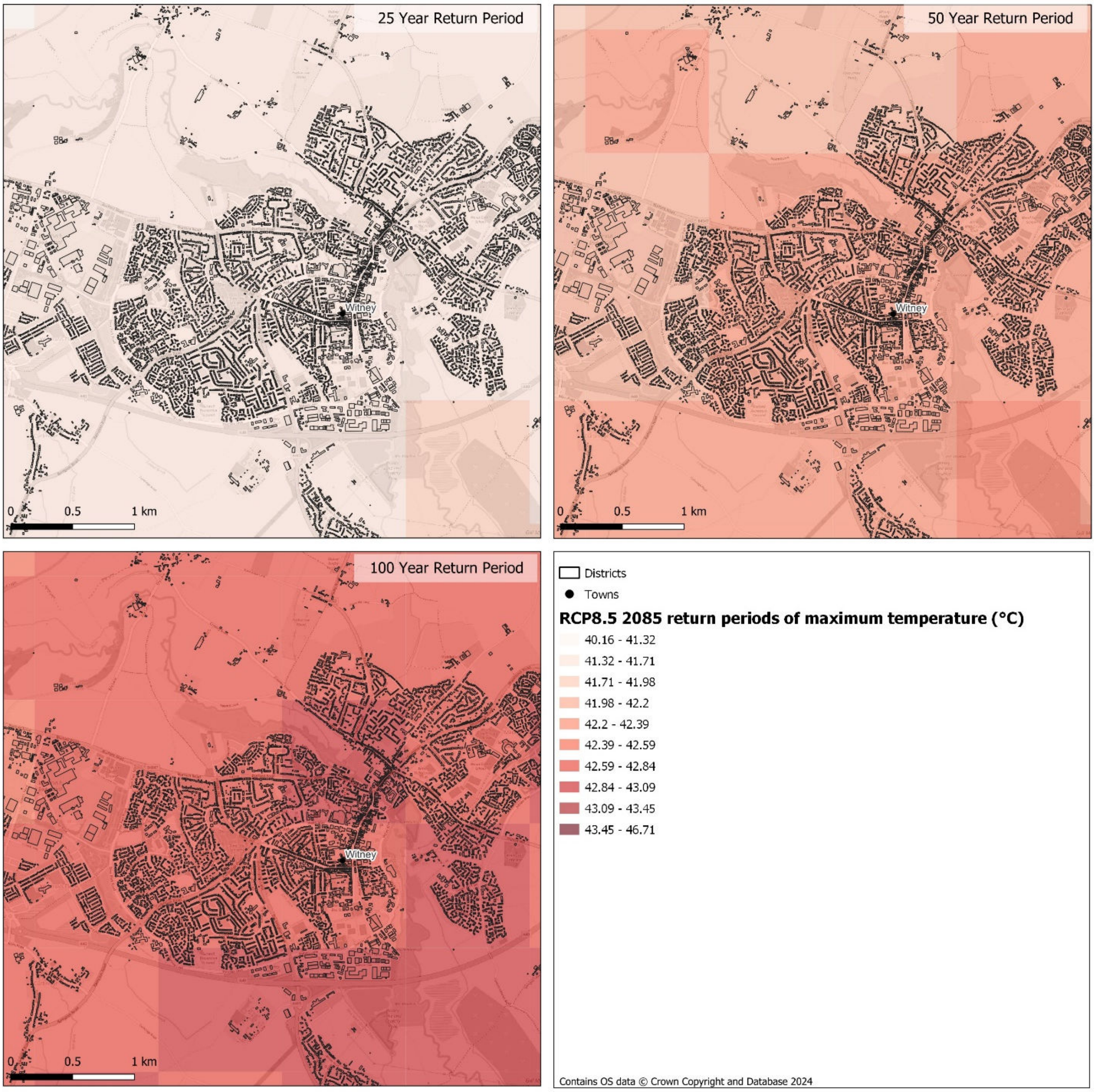


Figure 4-12 – Witney extreme temperatures for future climate, 2085 RCP8.5 (high emissions scenario)

4.2 Rainfall

Table 5-1 summarises the extreme temperatures for Oxfordshire. Figures 5-1 to 5-5 map current risks and Figure 5-6 to 5-12 map future risks for Oxfordshire as a whole and for Oxford, Abingdon and Witney. A typical heavy rainfall event, defined as the 1 in 2 year event, is approximately 30 mm over 24 hours. This kind of event is expected every other year on average, however the county has already experienced in excess of 30 mm/day at least twice in 2024.

- **There is a 1 in 3 chance that Oxfordshire will experience heavy rainfall events with greater than 50 mm/day within the next decade.** This is based on the current 1 in 25 year analysis which indicates events averaging 55.2 mm and a range of 42.3 to 79.4 across Oxfordshire.
- **There is significant variation in the chance of heavy rainfall across the county;** in general, the chance of heavy rainfall is greatest in the west at higher elevations and in the area around Oxford. Although rainfall extremes are lower in the Thames Valley, rivers flows will respond to whole catchment rainfall with more rainfall and runoff generated in the headwater of the Thames.
- **The impacts of climate increase heavy rainfall by up to 18% above 2020s data by the 2080s;** this is based on the central results of the UKCP18 probabilistic extremes and larger uplifts of up to 40% can't be ruled out if the full range of uncertainty is considered.

Table 5-1. Statistical summary of the best estimates of the 1 in 25, 1 in 50 and 1 in 100 heavy daily rainfall extremes across Oxfordshire. A 1 in 2 year rainfall estimate is presented as an example of a typical heavy rainfall event.

Scenario	Annual probability %	Mean (mm)	Min (mm)	Max (mm)	Range (mm) (spatial variability)
2020s 1 in 2	50%	30.4	24.8	38.2	13.3
2020s 1 in 25	4%	55.2	42.3	79.4	37.1
2020s 1 in 50	2%	62.5	46.6	95.2	48.6
2020s 1 in 100	1%	70.2	50.8	113.7	62.8
rcp4.5_2055_25rp	4%	57.7	44.2	83.0	38.7
rcp4.5_2055_50rp	2%	65.3	48.7	99.5	50.8
rcp4.5_2055_100rp	1%	73.4	53.1	118.8	65.7
rcp4.5_2085_25rp	4%	60.2	46.1	86.5	40.4
rcp4.5_2085_50rp	2%	68.1	50.8	103.8	53.0
rcp4.5_2085_100rp	1%	76.5	55.4	123.9	68.5
rcp8.5_2055_25rp	4%	59.4	45.5	85.4	39.8
rcp8.5_2055_50rp	2%	67.2	50.1	102.4	52.3
rcp8.5_2055_100rp	1%	75.5	54.7	122.2	67.6
rcp8.5_2085_25rp	4%	64.7	49.6	93.1	43.4
rcp8.5_2085_50rp	2%	73.2	54.6	111.6	57.0
rcp8.5_2085_100rp	1%	82.3	59.6	133.2	73.7

4.2.1 Current climate

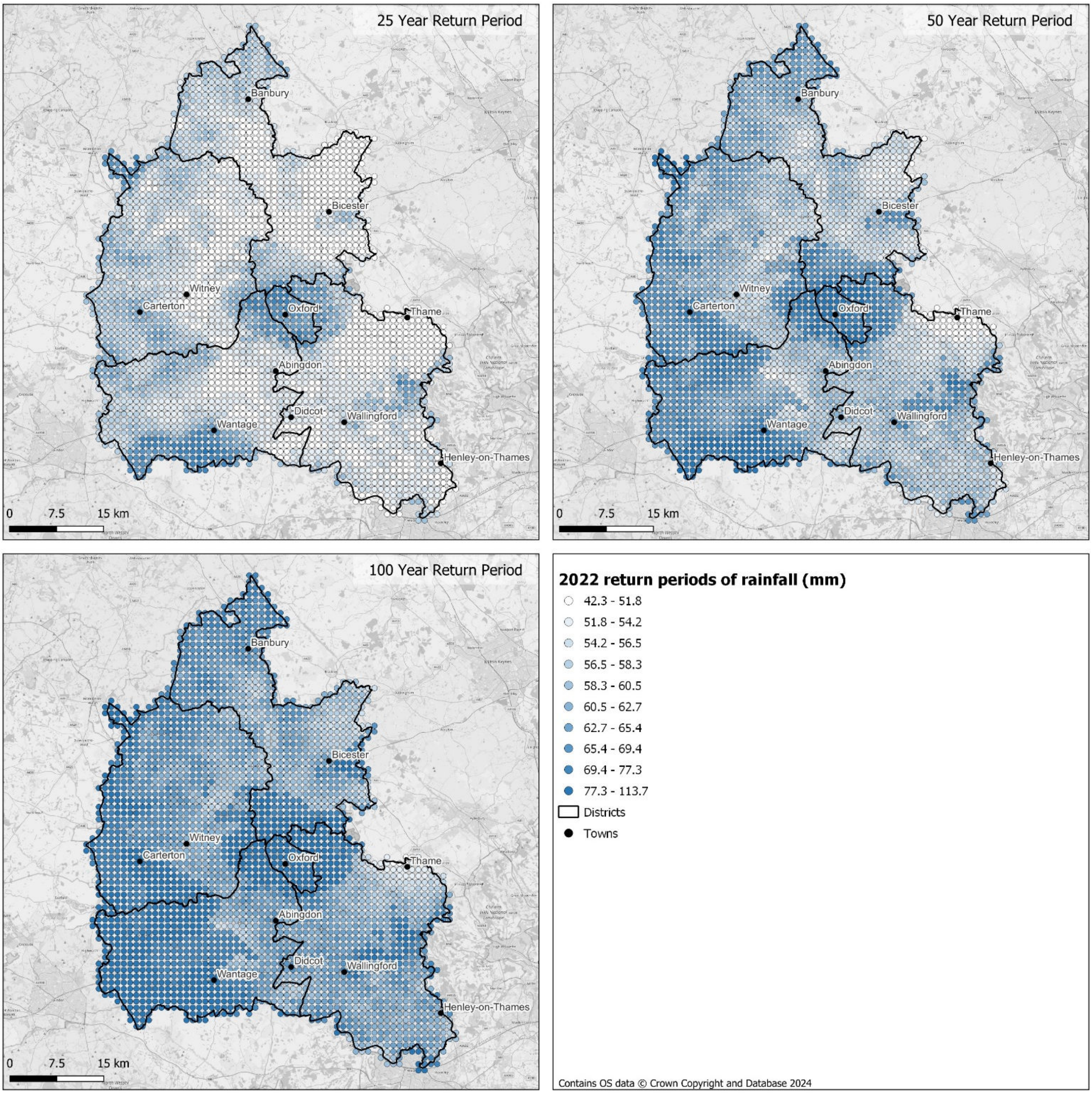


Figure 4-13 – Extreme rainfall in the current climate for 25, 50 and 100 year return periods

4.2.2 Future climate

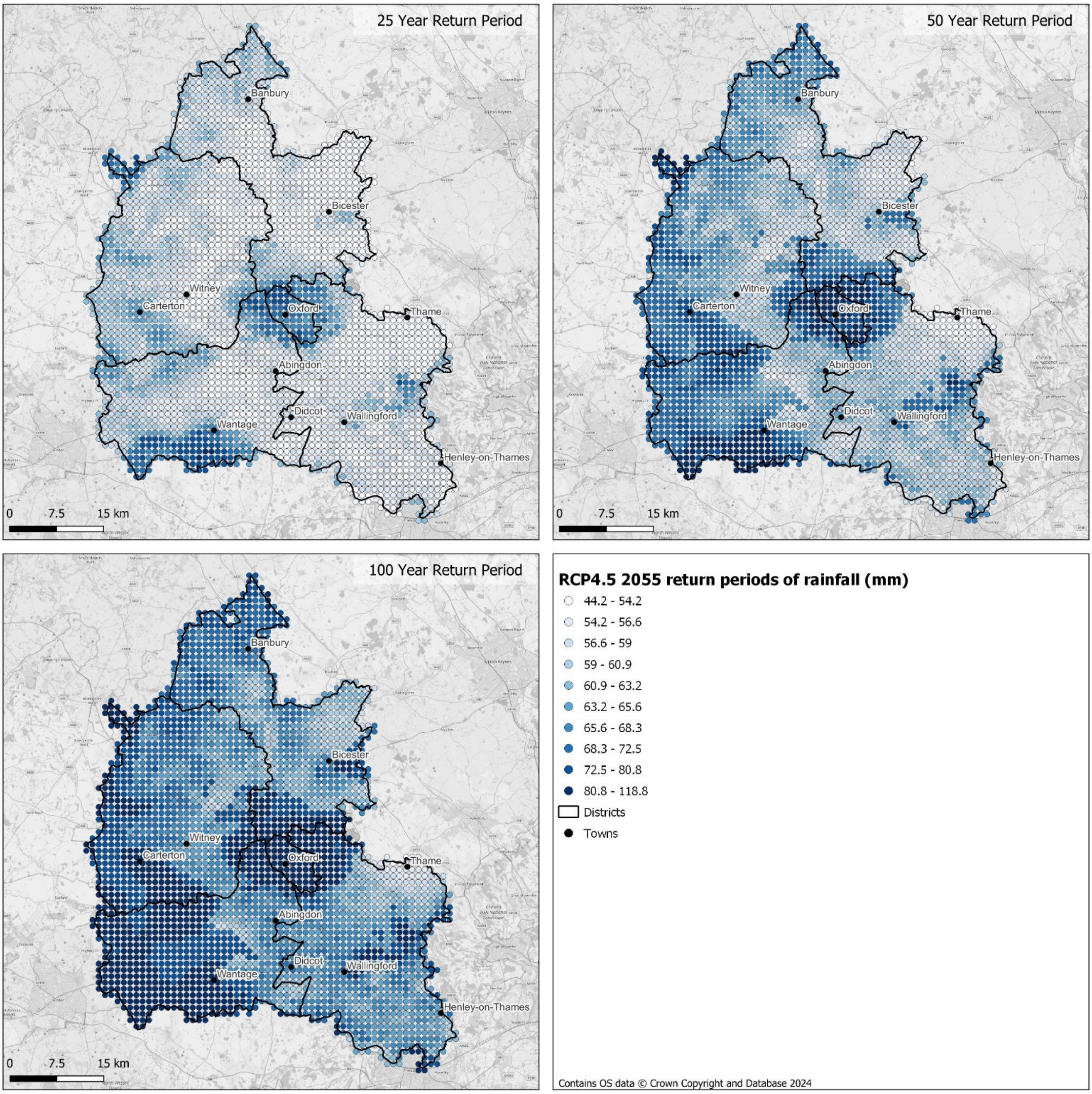


Figure 4-14 – Extreme rainfall for future climate, 2055 RCP4.5 (medium emissions scenario)

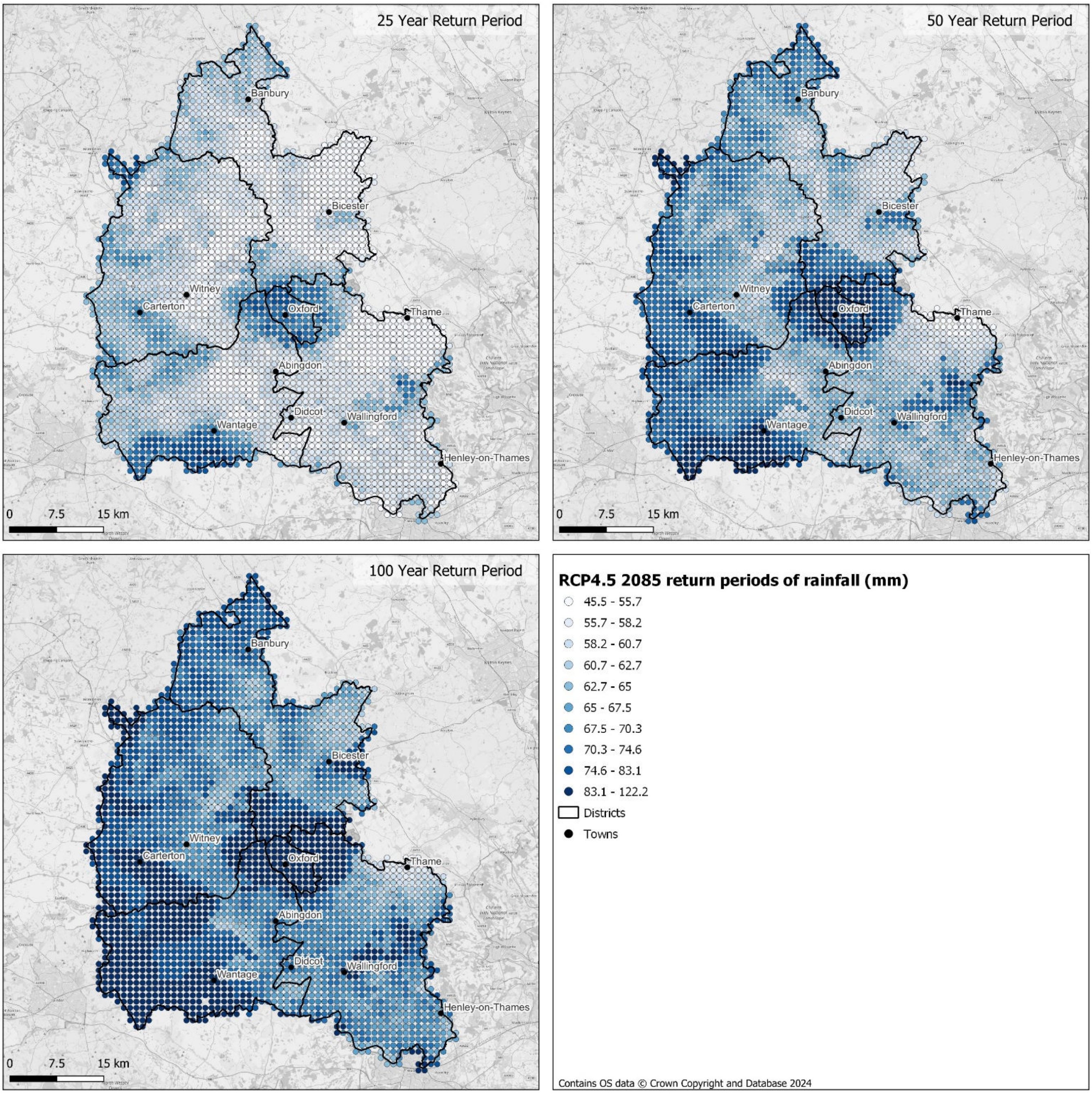


Figure 4-15 – Extreme rainfall for future climate, 2085 RCP4.5 (medium emissions scenario)

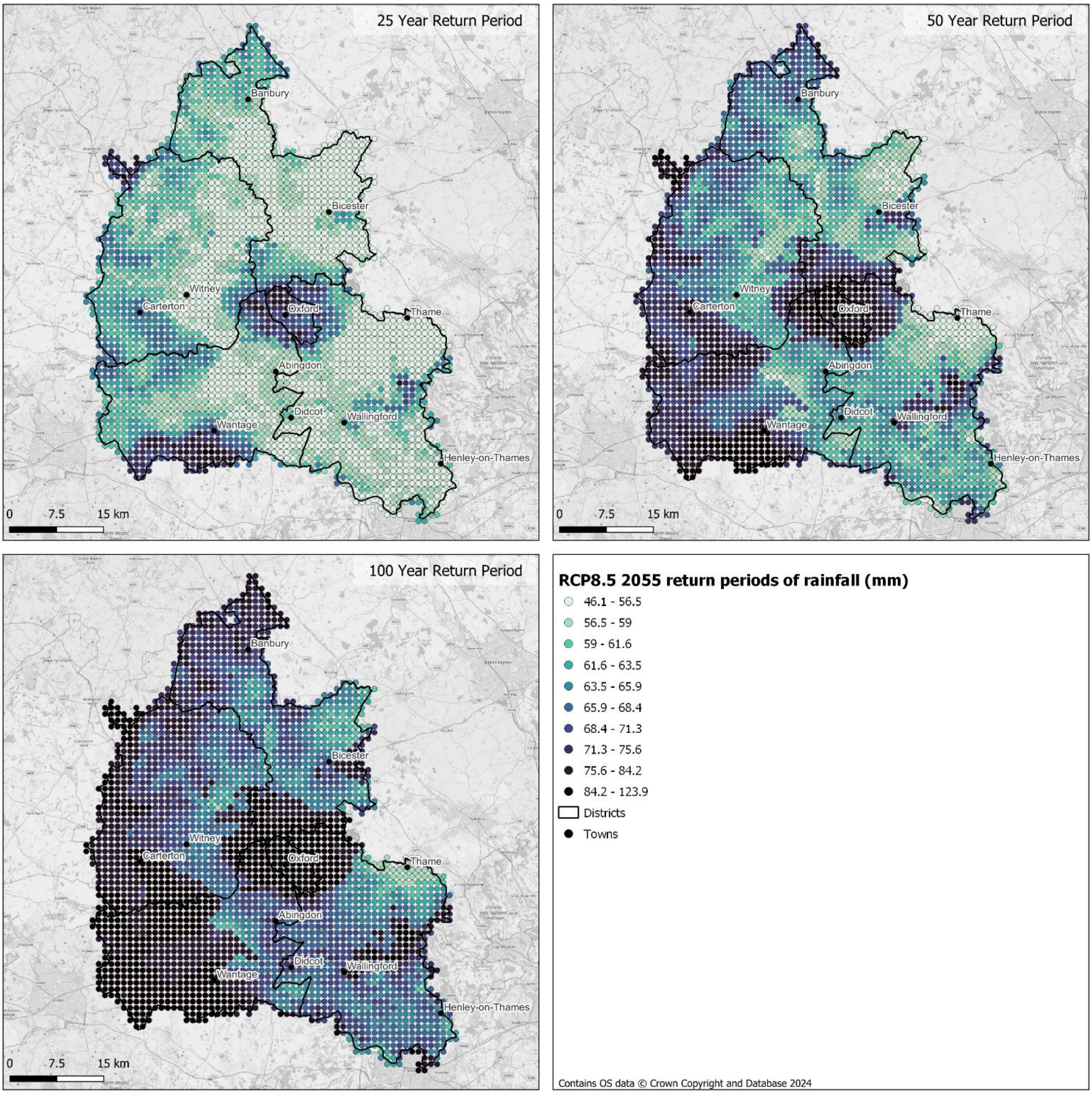


Figure 4-16 – Extreme rainfall for future climate, 2055 RCP8.5 (high emissions scenario)

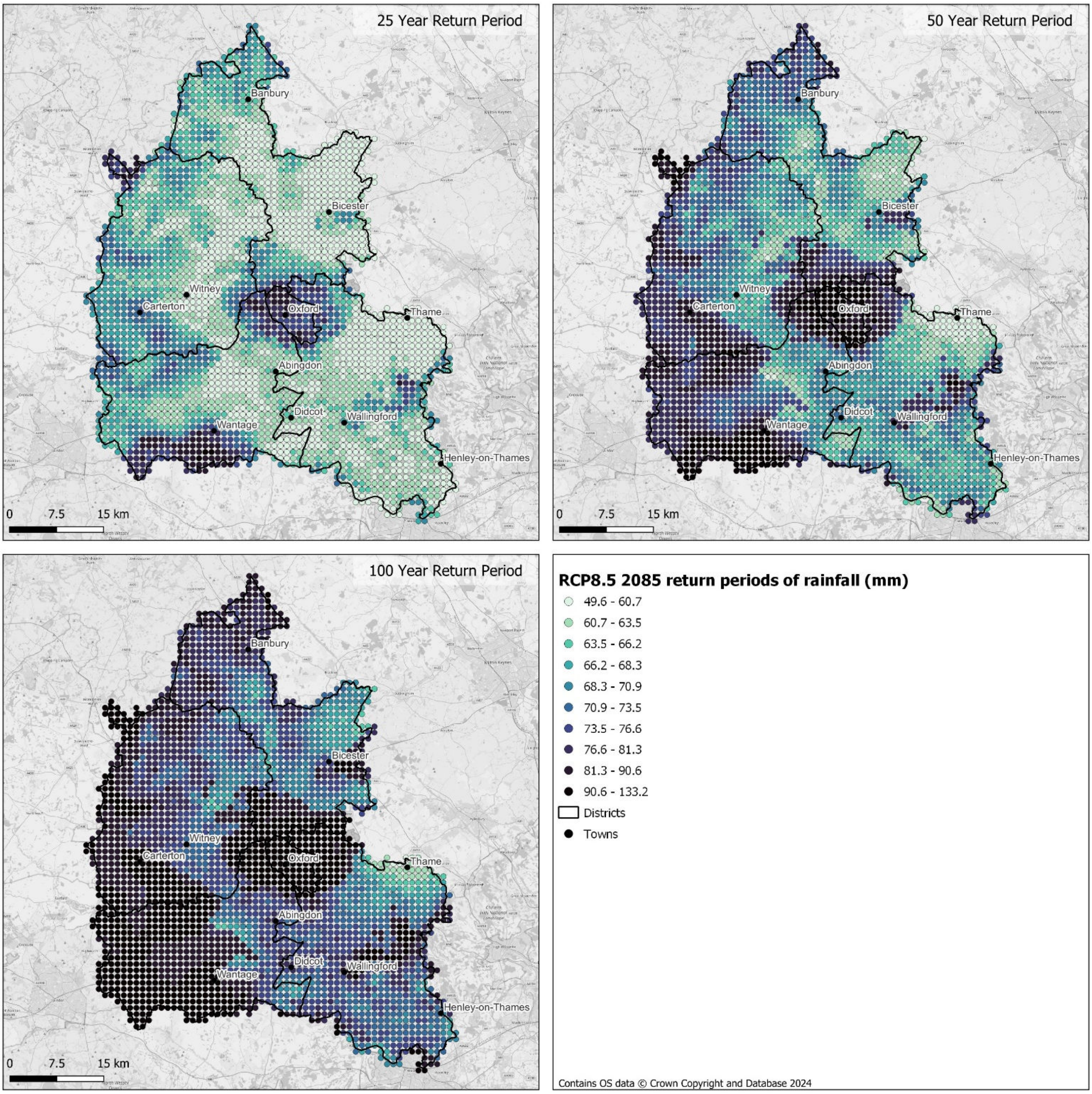
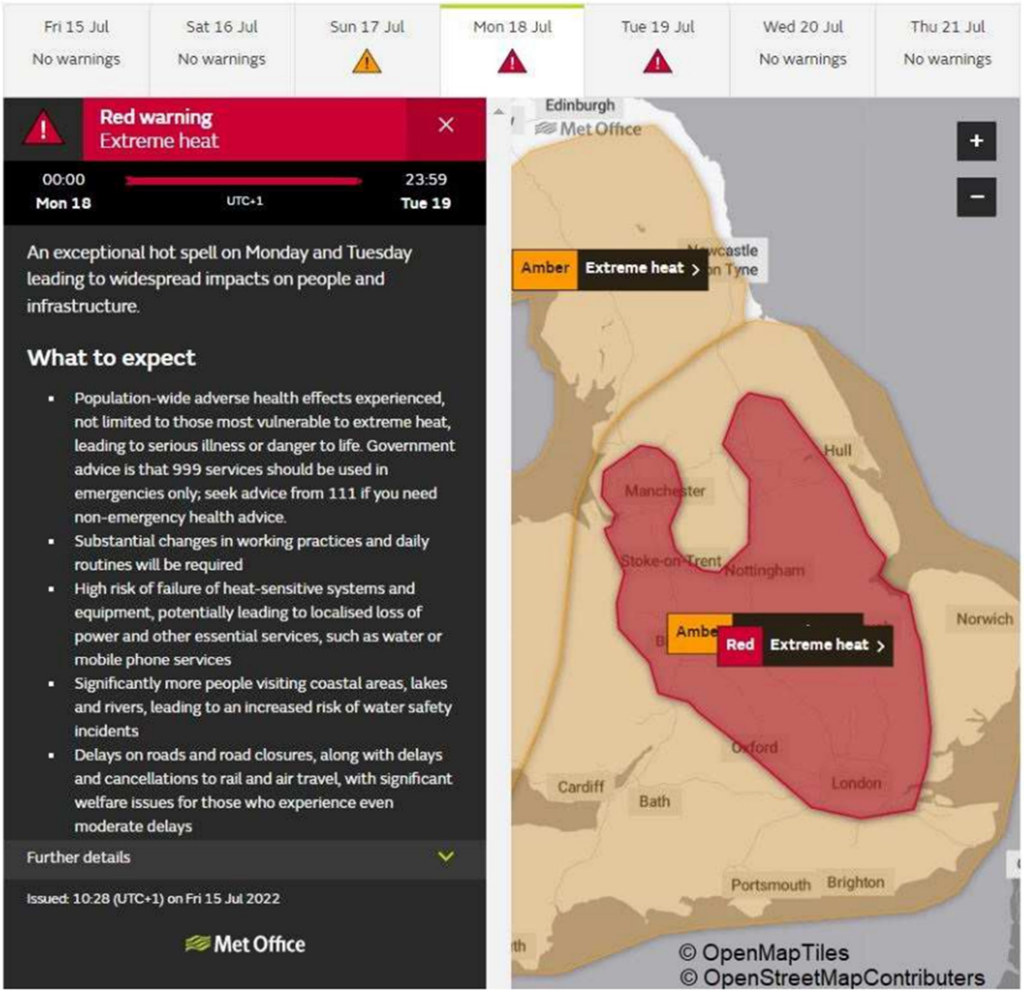


Figure 4-17 – Extreme rainfall for future climate, 2085 RCP8.5 (high emissions scenario)

5. Consequences for Oxfordshire

The Extreme Heat National Weather Warning Service was introduced in June 2021, and therefore the July 2022 heatwave was the first time that red heat alerts were issued (Figure 5-1). The UK Health Security Agency and Met Office also issued a level 4 alert for the first time since the heatwave plan was introduced for England in 2004, resulting in the Government declaring a national emergency.

Figure 5-1 Red and Amber Heat Alerts issues by the Met Office in July 2022 and associated expected impacts.



The consequences of extreme heat and heavy rainfall for scenarios explored in this report for the '2020s' current climate are summarised in Table 5-1, based on impacts observed during the July 2022, recent flood events, the Work Package 1 Technical Report and further literature sources[49]. The scenarios presented are based on the current climate and indicative for the next 10 years; the frequency of events increases under all scenarios (Figure 4-1) due to climate change.

[49] Including the [Weather-health alerting system - user guide (publishing.service.gov.uk)]

Table 5-1 Impacts of Extreme Heat and Heavy Rainfall in Oxfordshire

Theme	Scenario	Oxfordshire Impacts Narrative[50]
Heatwaves	Hot summer > 27 ˚C	• Met Office heatwave alerts issued, potential for 'Low' impact Heat Health Alerts and heat indices enter 'caution' area where some activities and vulnerable groups may be affected. • Expected 10% increase in excess mortality rates in most vulnerable groups. • Local issues of high heat affecting urban areas and the most vulnerable buildings, which may include hospitals, care homes and schools. (This threshold has been exceeded on an average of 11 days per year since 2001).
	1 in 2 year extreme hot day	• Extreme temperatures exceeding 32˚C across Oxfordshire and 33.8˚C in Oxford, triggering 'Medium' impact Heat Health Alerts. • Observed increase in mortality, particularly in elderly with health conditions. • Excess mortality rising to above 20%, based on estimated mortality using data from UK Health Security Agency (Table 5-2). • Increased demand for NHS services; risks to vulnerable people living independently and in care settings.
	1 in 25	• Extreme temperatures breaking previous records in Oxfordshire, triggering 'High' Heat Health Alerts. • Significant increase in the demand in health and social care settings. • Impacts on service delivery due to heat effects on the workforce and travel delays. • Increase in 999 calls as people seek assistance for vulnerable people and increased mortality across all groups. • Excess mortality rising to above 40%, based on estimated mortality using data from UK Health Security Agency. • Rail services severely disrupted due to tracks buckling and overhead cables sagging, likely advisories against travel. • Increased risk of fatalities due to open water swimming.
	1 in 50	• More acute and widespread health impacts. • Excess mortality rising to around 49%, based on estimated mortality using data from UK Health Security Agency. • As above with further impacts on national critical infrastructure, including roads melting. • Similar consequences to the July 2022 heatwave, with impacts on productivity and a range of services. • Significant increases in water demand. • Elevated risks of wildfires.
	1 in 100	• More acute and widespread health impacts and critical infrastructure impacts. • Excess mortality rising to around 55%, based on estimated mortality using data from UK Health Security Agency. • Similar consequences to the July 2022 heatwave, with impacts on productivity and a range of services; likely closure of schools and some workplaces. • Water supply balance impacts due to increased demand and increased drought risk when combined with low rainfall.

Notes: Excess mortality refers to lives lost earlier than would otherwise have been anticipated and there will also be morbidity impacts of lower consequences. Mortality figures are estimates using general guidance from UKHSA and the results of the EVA with the '2022' climate. See Table 5-2.

[50] UK Health Security Agency and Met Office. Weather-health alerting system - user guide (publishing.service.gov.uk)

Theme	Scenario	Oxfordshire Impacts Narrative
Heavy rainfall	1 in 2 year	• Moderately high rainfall with potential local surface water runoff and flooding, if combined with very wet antecedent conditions. • Potential to cause local flooding in areas where watercourses are not maintained, or drainage systems are blocked. • Likely to trigger many CSOs across Oxfordshire with impacts on water quality. • Potential water ingress in poorly maintained buildings, particularly if combined with high winds.
	1 in 25	• High daily rainfall causing some local surface water flooding, particularly when combined with high antecedent rainfall and in low lying urban areas. • Potential to impact directly on more than 200,000 buildings in Oxfordshire[51] • Potential to cause significant flooding in areas where water courses are not maintained or drainage system are blocked, including on OCC highways. • Potential for flooding of river paths and cycleways affecting amenity. • More extensive CSO spills with impacts on water quality. • More extensive damage to buildings and some travel disruption.
	1 in 50	• Very high rainfall for Oxfordshire causing more extensive surface water flooding and significant disruption to transport systems. • River flooding, particularly in smaller rivers and ordinary watercourses. • Potential road closures, including main roads in Oxford if combined with high antecedent rainfall causing the Thames to flood. • Potential for significant damage to road surfaces and floodings of railways. • Potential for subsidence of embankments and river bank erosion. • Increased risks to people and property from flooding.
	1 in 100	• Very high rainfall with the potential to exceed historical records in some parts of the county. Over 100 mm of rainfall at some higher elevations in the south and west. • More extensive, higher depth and velocity surface water and river flooding. • Potential to impact directly on more than 300,000 buildings in Oxfordshire[51]. • Sustained groundwater flooding following rainfall, in some groundwater dominated catchments. • Increased risk of travel disruption including embankment failure on railway or road cuttings. Potentially affecting 100s km of road and up to 168km of railway. • Potential for significant damage to road surfaces and bridges. • Increased risks to people and properties from flooding, due to higher depths, velocities, and presence of debris in flood water. • Potential for outage for water supply, energy, and ICT systems due to flood damage. • Significant social and economic costs due to indirect impacts on businesses and communities.

Notes: Flood risk is location specific, so this narrative provides a general description of increases consequences across Oxfordshire. For information on the most vulnerable areas for flood risks refer to the main Atkins 2023 report[52].

Table 5-2 presents an estimate of increase mortality based on the temperature extremes in Table 4-1. Elevated levels of increased mortality of around plus 20% are likely to be the norm over the next decade. Extreme events

[51] Based on a count of building footprints within the current surface water floodplain without climate change.
[52] Atkins, 2023. Current and future climate risk and vulnerability and health impacts assessments in Oxfordshire. Prepared for OCC.

exceeding the 1 in 100 year extremes and the recent July 2022 event could cause excess mortality of more than 50%. There may be spatial variation in mortality across the county and not all events will be as extensive as the July 2022 heatwave.

Table 5-2. Statistical summary of the best estimates of the 1 in 25, 1 in 50 and 1 in 100 extreme heat related mortality in Oxfordshire, based on UKHSA evidence and the non-stationary Extreme Value Analysis.

Scenario	Annual probability %	% mortality increase	Min	Max	Range
2020s 1 in 2	*50%*	*21%*	*16%*	*26%*	*9%*
2020s 1 in 25	4%	44%	34%	61%	27%
2020s 1 in 50	2%	49%	38%	78%	41%
2020s 1 in 100	1%	55%	41%	101%	60%
rcp4.5_2055_2rp	*50%*	*25%*	*19%*	*30%*	*11%*
rcp4.5_2055_25rp	4%	52%	40%	71%	32%
rcp4.5_2055_50rp	2%	58%	45%	93%	48%
rcp4.5_2055_100rp	1%	64%	49%	120%	71%
rcp4.5_2085_2rp	*50%*	*29%*	*23%*	*36%*	*13%*
rcp4.5_2085_25rp	4%	61%	47%	85%	38%
rcp4.5_2085_50rp	2%	69%	53%	110%	57%
rcp4.5_2085_100rp	1%	77%	58%	142%	84%
rcp8.5_2055_2rp	*50%*	*28%*	*22%*	*35%*	*13%*
rcp8.5_2055_25rp	4%	59%	45%	82%	36%
rcp8.5_2055_50rp	2%	67%	51%	106%	55%
rcp8.5_2055_100rp	1%	74%	56%	137%	81%
rcp8.5_2085_2rp	*50%*	*42%*	*33%*	*52%*	*19%*
rcp8.5_2085_25rp	4%	89%	68%	123%	55%
rcp8.5_2085_50rp	2%	100%	77%	159%	83%
rcp8.5_2085_100rp	1%	111%	84%	206%	122%

Notes: Excess mortality refers to lives lost earlier than would otherwise have been anticipated and there will also be morbidity impacts of lower consequences. Mortality figures are estimates using general guidance from UKHSA and the results of the EVA with the '2022' climate. The analysis assumes extensive heatwaves that impact on the whole county.

6. Conclusion

The record temperatures of 40.3 ˚C in Coningsby in Lincolnshire and 38.1°C in Oxford on 19th July 2022 were **far greater extremes than modelled in the UKCP18 climate projections for the 2020s and not anticipated until the 2050s**.

Oxford has experienced **extremely dangerous heat,** with very high temperatures and high relative humidity**,** on 4 occasions since 1961, all in the last 5 years in July 2022, July 2021 and July 2020 and **dangerous heat** on 44 days since 1961. Average relative humidity in July in Oxfordshire can be high, between 63% and 79%, causing dangerous heat index values when combined with very high temperatures.

Following very high temperatures in 2019 and 2022, the Met Office and World Weather Attribution group completed studies found that human-caused climate change has already made the chance of 40°C in the UK about **ten times more likely when compared with the pre-industrial period.**

Higher temperatures are also changing the odds for extreme rainfall in the England, with similar climate attribution studies suggesting increases in the risk of heavy daily rainfall of 1.2 to 2 times more likely than the pre-industrial period.

Unprecedented extreme temperatures and flood events have been observed around the world in the last 3 years, such as the heat dome in Canada Daily where daily temperatures reached 49.6°C in the town of Lytton, extreme temperatures, and dangerous heat conditions across Southeast Asia in April 2023. Scientists can't fully explain why global land surface and sea temperatures have persistently overshot previous records by up to 0.2°C each month during 2023.

Mounting evidence suggests that extremes are being underestimated and the chance of extreme events is greater than previously thought. This study used Extreme Values Analysis of baseline gridded data for Oxfordshire and UKCP18 projections to uplift this new analysis to estimate future extremes and reveal the possibilities of extreme conditions today and in near and far future scenarios.

There is a 1 in 3 chance that the Oxford maximum temperature extreme will be exceeded within the next decade. Our analysis shows that the chance exceeding 40˚C in Oxford in any year is 1 in 250 (0.4%) (a similar result to previous Met Office studies) but the annual chance of exceeding the recent Oxford record of 38.1˚C is just 1 in 25 (4%); this equates to a chance of a more extreme event happening in next decade of around 1 in 3 (33%)[53].

The chance of exceeding 40˚C somewhere in Oxfordshire is lower than the odds for a single location at around 1 in 50 (2%) (which is a higher chance than reported in recent research literature); this equates to a chance of exceeding 40 degrees within the next decade of around 1 in 5 (18%).

Our analysis indicates the chance of much higher temperatures than estimated in the UKCP18 Probabilistic Extremes, for example around 3 degrees higher for the 1 in 100-year event. It is likely that an updated analysis using the UKCP18 PE methodology would produce much higher temperatures because it would consider recent extreme events in 2019 and 2022 observations data.

The probability of extreme temperature and heavy rainfall is increasing every year; the chance of a 100-year temperature extreme in the 2020s is likely to increase fourfold under a 'medium' scenario and eight-fold under 'high'

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[53] Using event probabilities for a specific duration rather than annual probability. $Pe = 1 - \left(1 - \frac{1}{T}\right)^n$
Sayers, 2016 Communicating the chance of a flood: The use and abuse of probability, frequency and return period.

scenario by the by the 2050s. The chances of heavy rainfall are not evolving as rapidly, and increases are likely to be 1.25 times and 1.4 times greater risk under the same scenarios by the 2050s. Changes in heavy risk increase markedly by the 2080s.

Recent research has shown that such trends in extremes can only be reversed under radical mitigation scenarios that stabilise the rate of warming, for example Dittus *et al* showed that the drying out of Southern Europe could be reversed under net zero scenarios[54].

[54] Dittus et al., 2024. Reversal of Projected European Summer Precipitation Decline in a Stabilizing Climate - Dittus - 2024 - Geophysical Research Letters - Wiley Online Library

APPENDICES

Appendix A. UKCP18 data sets

This section describes the data sets sourced from the Met Office's UK Climate Projections (UKCP18), used for the EVA analysis and the data management processes in place for this project.

A.1 Input data

A.1.1 HadUK

https://www.metoffice.gov.uk/research/climate/maps-and-data/data/haduk-grid/haduk-grid

HadUK-Grid is a collection of gridded climate variables derived from the network of UK land surface observations. The data have been interpolated from meteorological station data onto a uniform grid to provide complete and consistent coverage across the UK. The data sets cover the UK up to 1km x 1km resolution and a range of other resolutions to allow for comparison to data from climate projections and across a country, administrative regions and river basins. The dataset spans the period from 1836 to present, but the start time is dependent on climate variable and temporal resolution. The grids are produced for daily, monthly, seasonal and annual timescales, as well as long term averages for a set of climatological reference periods. Variables include air temperature (maximum, minimum and mean), precipitation, sunshine, mean sea level pressure, wind speed, relative humidity, vapour pressure, days of snow lying, and days of ground frost.[55]

AtkinsRéalis downloaded the rainfall and maximum temperature datasets ranging between 1960-2022 (63 years of HadUK-grid data) from the Centre for Environmental Data Analysis (CEDA) archive in January 2024. Checks were carried out on the derived annual maxima series prior to analysis using Python.

A.1.2 UKCP18 Probabilistic Extremes

These data were downloaded from the Met Office's UKCP18 User Interface Welcome to UKCP (metoffice.gov.uk) in March 2024 as *.csv files for different scenarios. These data are based on research that preceded the 2019 and 2022 heatwaves and project lower values than observations in the 2018-2023 period.

Header length	17
Area	462500.0 212500.0
Baseline	1981-2000
Data Source	Land probabilistic projections
Data Type	cdf
Return Period	100 years
Scenario	RCP 8.5
Show Labels	TRUE
Software Version	WPS-2.9.0-DP-2.9.0-CV-1.0.10
Spatial Representation	25km grid

[55] Met Office; Hollis, D.; McCarthy, M.; Kendon, M.; Legg, T. (2023): HadUK-Grid Gridded Climate Observations on a 1km grid over the UK, v1.2.0.ceda (1836-2022). NERC EDS Centre for Environmental Data Analysis, *30 August 2023*. doi:10.5285/46f8c1377f8849eeb8570b8ac9b26d86.

Temporal Average Type	Seasonal
Time Period	June July August
Time Slice Type	1-year time slices
Variable	Maximum air temperature at 1.5m (Â°C)
Year Maximum	2100
Year Minimum	1961

A.2 Metadata for generated grids

All data analysis tasks including the extraction of the daily timeseries, aggregation to the annual maximum resolution, re-trending and EVA processes are managed in Python ‘Jupyter’ notebooks. Intermediate and final results were saved as *.xlsx format and were also converted into ESRI shape files, compatible for further geospatial analysis and mapping. Spot checks were carried out on the metadata files, based on a random selection of four points ensuring an independent set of analysis yielded the same results.

Documents > Oxford County Council Climate Programme > 7. WIP > Extreme Value Analysis > Output > **Run_20240315-110902**

Name	Modified
tasmax_summary	March 18
rainfall_1000rp_clip.xlsx	March 26
rainfall_100rp_clip.xlsx	5 days ago
rainfall_10rp_clip.xlsx	March 25
rainfall_250rp_clip.xlsx	April 3
rainfall_25rp_clip.xlsx	March 25
rainfall_2rp_clip.xlsx	March 25
rainfall_500rp_clip.xlsx	March 23
rainfall_50rp_clip.xlsx	6 days ago
rainfall_5rp_clip.xlsx	March 25
tasmax_1000rp_clip.xlsx	March 26
tasmax_100rp_clip.xlsx	April 3
tasmax_10rp_clip.xlsx	April 2
tasmax_250rp_clip.xlsx	April 3
tasmax_25rp_clip.xlsx	April 3
tasmax_2rp_clip.xlsx	5 days ago

Appendix B. Extreme Value Analysis Methodology

B.1 ‘Re-trending’ HadUK temperature data

To correctly apply a GEV or GPD, the observed data must be statistically independent and considered ‘stationary’ – i.e., exhibit no long-term trends. Anthropogenic influences dating from as far as the industrial revolution in early 1900s have affected global temperatures, causing them to gradually increase[56]. These global temperature rises affect the UK and will continue to do so. Therefore, the temperature dataset over the UK between 1960-2022 is not considered to be a stationary dataset. Before any statistical approach can be applied, the data requires detrending. Following detrending, the block maxima of the data can be selected and a GEV fitted to the data and the upper and lower confidence interval (CI) is calculated. While a detrended time series would typically mean one without climate change, we use the term re-trending to describe the time series created that represents the climate in 2022, which includes around 1.4˚C of warming above pre-industrial average temperatures. As previously reported and shown in Figure 3-1, trends in maximum temperature are far greater than average temperatures[57].

B.1.1 Choice of regression

Figure 6-1 shows the annual maximum temperature timeseries at the 1km location representing Oxford, Banbury, Whitney, and Abingdon before and after detrending where detrending is centred around the year 2022. The grey line shows the observed dataset before the re-trending process, the dashed red line shows a polynomial of the second order fitted to the data. The solid black line shows the re-trended observed data. In this way the trend of climate change is added to the dataset from 1960-2022, so that the 63 years of the dataset represents the same climate conditions as is experienced in 2022, including climate change. In this way, stationarity is introduced to the dataset and a GEV approach can be subsequently applied to the annual maximum data.

B.1.2 Stationarity tests

The annual maximum temperature timeseries data for the four locations were used in stationarity testing, after detrending the data by fitting a third order polynomial to the data and centring the fit around 2022 to uniformly add the climate change trend to the whole dataset between 1960-2022. Stationarity testing was carried out using two commonly used methods:

- Augmented Dicky Fuller (ADF) test and
- Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test[58]

Table 6-1 below shows the grid coordinates selected for the four locations in Oxfordshire. The stationarity tests were undertaken before and after the re-trending process using both the ADF and KPSS tests methods described above, with results showing the stationarity being satisfied once the re-trending process was carried out. Looking again at Figure 6-1, these plots show there is a clear trend present before detrending (seen in the upward trend in the temperature) and the trend being removed shown by the horizontal blue lines.

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56 Met Office Climate Dashboard

57 AtkinsRéalis. 2023. Current and future climate risk and vulnerability and health impacts assessments in Oxfordshire. Technical Report prepared for OCC.

58 A Gentle Introduction to Handling a Non-Stationary Time Series in Python

Table 6-1 - Coordinates of the four locations in BNG and check on stationarity before and after re-trending.

Location	Easting	Northing	Stationarity test before re-trending	Stationarity tests after re-trending
Oxford	447500	210500	False	True
Banbury	445500	240500	False	True
Whitney	435500	209500	False	True
Abingdon	449500	197500	False	True

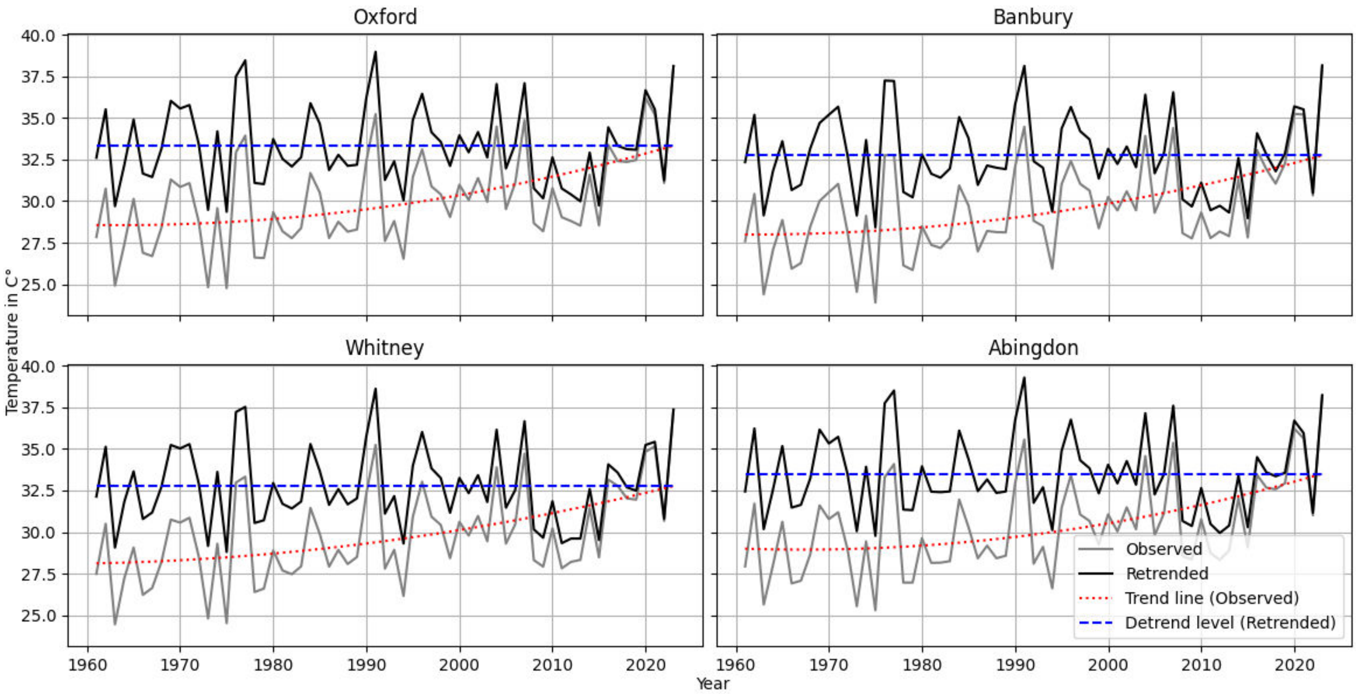

Figure 6-1 - Plots showing the annual maximum temperature timeseries before and after re-trending in grey and black lines respectively for Oxford, Banbury, Whitney and Abingdon. Red indicates the second order polynomial regression line used for re-trending the data, blue the new trend level.

B.2 Extreme value analysis

There are two EVA approaches for determining extremes within an observational data record: (i) block maxima and (ii) threshold exceedances (also known as peak-over-threshold or POT). The block maxima approach divides the data into sections or blocks, which commonly represent time (e.g., years) and then the maximum value in each block is selected (e.g., the maximum daily temperature value per year). Threshold exceedance methods set a high threshold, often taken as a quantile of the observational data (for example the 95th quantile) and exceedances above the threshold are retained.

Once the extremes have been selected, a distribution is fitted. The generalised extreme value distribution (GEV) is fitted to extremes defined by the block maxima approach, while a generalised Pareto Distribution (GPD) is fitted to extremes defined by the threshold exceedance method. The distribution is then used to extrapolate from the observed data to extreme levels and estimate return levels of rare events. As GEV is synonymous with the block maxima method of identifying extremes and GPD is synonymous with the threshold exceedance method of identifying extremes, these are further referred to as the GEV approach and GPD approach, respectively.

For the purposes of this work, a GEV approach has been used for the following reasons:

- Although a point-over-threshold method is preferred when dealing with statistical extremes, setting an appropriate threshold level can be subjective and vary on a point-by-point basis, and can therefore be very time consuming and expensive; in engineering practice this approach is reserved for site specific investigation or design of critical infrastructure, such as new nuclear powers stations or large flood defence schemes.

- As the motivation of the investigation was to produce maps over the county to a high resolution of 1km, to robustly calculate maximum temperatures associated with a range of events and to ensure quality control over an investigation of this size (i.e., over 2,800 grid cell EVAs were calculated to produce a map at 1km spatial resolution), automation of quality assurance was required which was more easily achievable using the GEV method.

- The frequency analysis in the investigation mainly considers the 1 in 25, 50 and 100-year events, using a data timeseries of 63 years (1960-2022). As a rule of thumb extrapolation of return periods by ca. 1.5 times the length of record is generally acceptable but extrapolating to higher return periods (lower annual probabilities) may be unreliable. Therefore, we place less emphasis of more extreme events.

- AtkinsRéalis ensured the robustness of this method of detrending and applying a GEV post-detrending processing to generate best estimates of the various return values through discussion with academic partners[59]. Our methods mirror those methods previously presented by Eastoe and Tawn, 2008, that support this simple approach[60].

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[59] Dr Theo Economou University of Exeter and former Met Office Scientist

[60] "Modelling non-stationary extremes with application to surface level ozone", E Eastoe and J Tawn, Journal of the Royal Statistical Society, Applied Statistics, 58, Part1, 25-45, 2009.

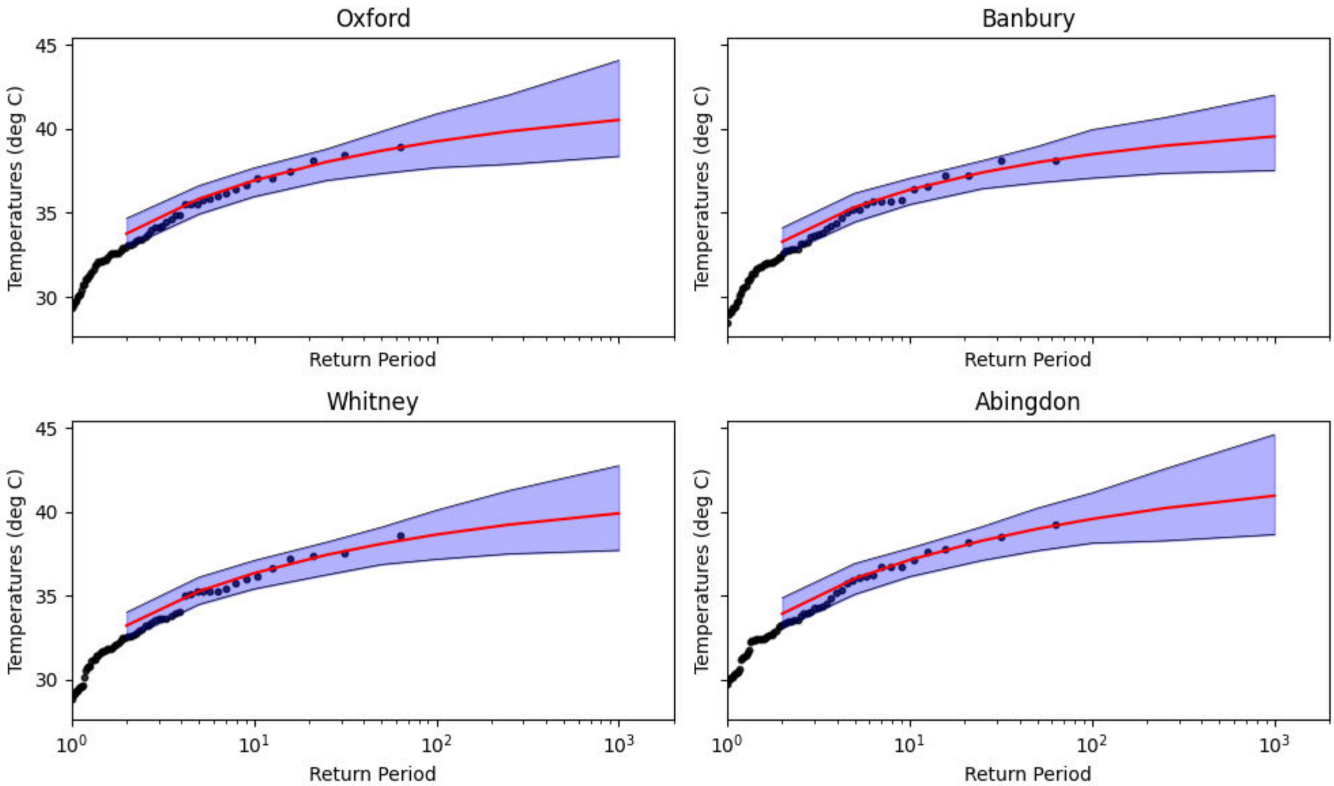


Figure 6-2 – Example plots showing the annual maximum temperature EVA after re-trending for Oxford, Banbury, Whitney and Abingdon. The red line shows the best estimate where the shaded blue areas show the confidence intervals.

B.3 Effects of climate change

The Probabilistic Projections of Climate Extremes[61] provides information on 21st century temperature and precipitation extremes across the UK. They use a similar methodology to the UKCP18 Probabilistic Projections published in 2018 (PP2018), augmented by use of General Extreme Value (GEV) theory to support projections of long return-period events. The PP2018 provide estimates of monthly, seasonal and annual mean changes whereas the PPCE provide an estimate of extreme daily values. Information is provided at 25km resolution at UKCP18 user interface for the five concentration pathways (RCP2.6, 4.5, 6.0 and 8.5, and SRES A1B).

The PPCE are produced using an updated version of extreme value theory based presented by Brown et al. (2014)[62] where a dependence is assumed between probability distributions, parameters and global mean surface temperatures. Specifically, extreme value parameters are estimated by fitting to time series of extreme values from climate model simulations, using an assumed linear dependence on global mean surface temperature (GMST) to represent effects of climate change. When making projections, time-dependent values for extreme value parameters are created by adding climate change components derived from model simulations to baseline values representative of observations. This approach constitutes a form of bias correction, which allows the final return level projections to be presented as absolute rather than anomalous values. For further information on the methods

[61] Probabilistic Projections of Climate Extremes
[62] "Climate projections of future extreme events accounting for modelling uncertainties and historical simulation biases.", Brown SJ, Murphy JM, Sexton DMH, Harris GR, Climate Dynamics. 43:2861-2705.

applied to generate the PPCE via the Bayesian projection method at global and national scales, please see Murphy et al., 2020[63].

Following the EVA of annual temperatures (re-trended to 2022) and the rainfall, the impacts of the climate change from the PPCE data were added to the outputs. For future climate change, AtkinsRéalis used the PPCE best estimates (50th percentile) for the 1 in 20, 50 and 100 years under RCP8.5 and RCP4.5 over the county area to determine magnitude uplifts to be directly applied back to the EVA outputs. Magnitude uplifts were determined by comparing the change in each climate variable for a specific future year against values for the **2022 RCP8.5**, with rainfall uplifts expressed as a relative increase and temperature uplifts expressed as an absolute increase.

The uplifts for climate change are shown below in Table 6-2 and

[63] “UKCP Additional Land Products: Probabilistic Projections of Climate Extremes”, Murphy JM, Brown S and Harris G, Met Office, (2020).

Table 6-3. The uplifts factors derived for the three return periods are very similar, for example the absolute maximum temperature uplift for RCP8.5 2055 across all three return periods was 1.8°C compared to 2022 and around 2.6°C above the 2000 estimated extremes. Therefore, the maximum uplift factor was selected to apply across the return periods (see cells highlighted in purple). For example, looking at the 2050s under RCP8.5, the relative increase from 39.9 mm to 43.0mm is a **7.6% increase** from 2022. This uplift was then applied across the entire 2022 dataset to changes the return levels and to estimate the increase in frequency of specific events under climate change scenarios.

The greatest value of our approach is developing the 1km gridded baseline and EVA and the climate change step is relatively straightforward. Therefore, alternative scenarios including considering wider climate change uncertainties can easily be incorporated.

Table 6-2 - UKCP18 PPCE future rainfall uplifts expressed as a relative change from 2022 RCP8.5. Purple cells represent the uplifts applied to all return periods of rainfall.

RCP8.5	**Values (mm)**			**Uplifts from 2022 (% change)**		
Year	100 yr	50 year	20 year	100 yr	50 year	20 year
2000	38.6	35.0	30.3	-3.2%	-3.4%	-3.4%
2022	***39.9***	***36.2***	***31.4***	0.0%	0.0%	0.0%
2055	43.0	38.9	33.7	**7.6%**	**7.5%**	**7.5%**
2085	46.8	42.4	36.8	**17.3%**	**17.2%**	**17.3%**

RCP4.5	**Values (mm)**			**Uplifts from 2022 (% change)**		
Year	100 yr	50 year	20 year	100 yr	50 year	20 year
2000	38.6	35.0	30.4	-3.2%	-3.1%	-3.2%
2022	39.8	36.1	31.3	-0.3%	-0.4%	-0.4%
2055	41.6	37.8	32.7	**4.2%**	**4.5%**	**4.3%**
2085	43.5	39.4	34.1	**9.0%**	**8.9%**	**8.7%**

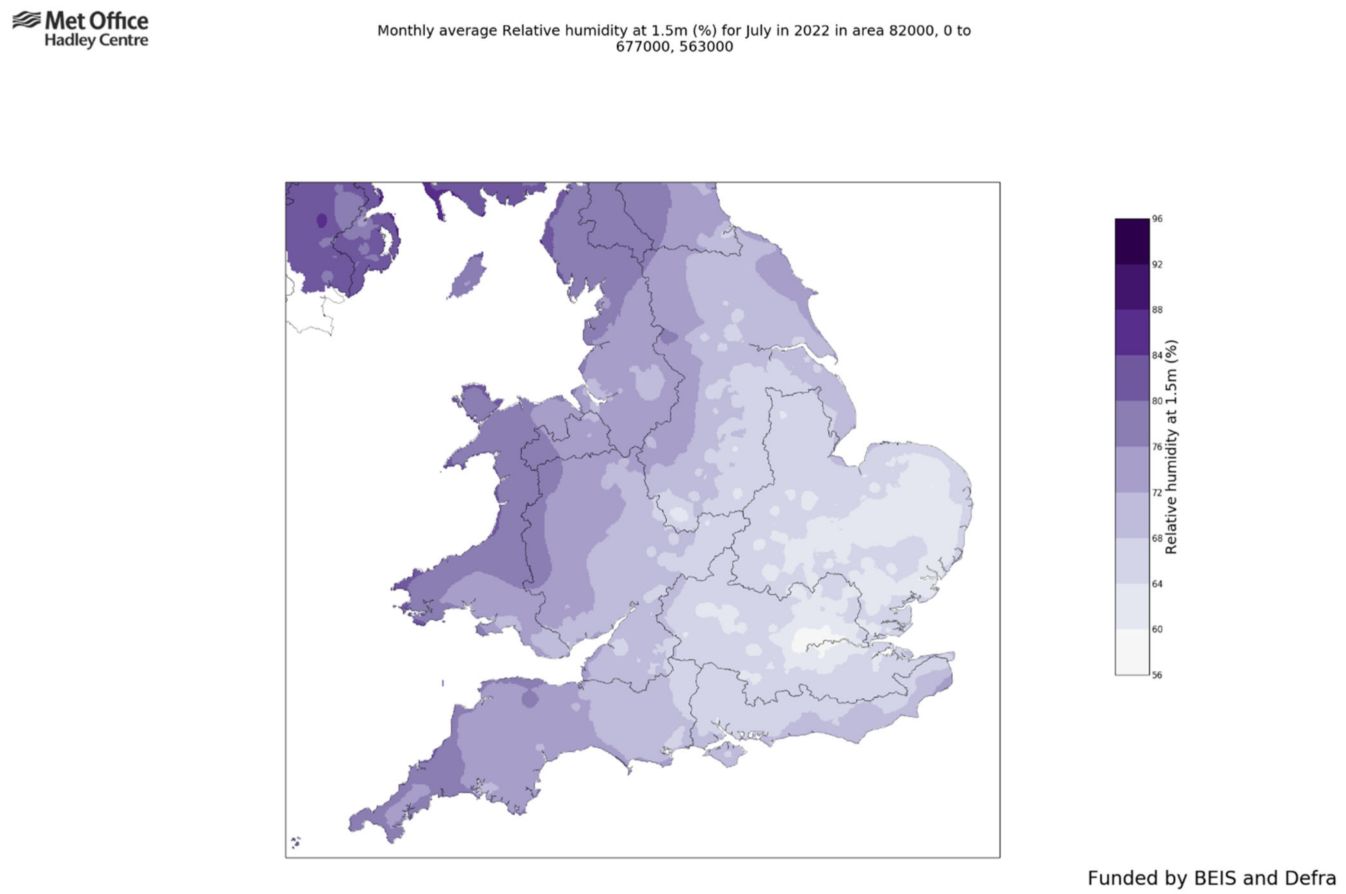
Table 6-3 - UKCP18 PPCE future temperature uplifts expressed as an absolute change from 2022 RCP8.5. Purple cells represent the uplifts applied to all return periods of maximum temperature.

RCP8.5	Values (°C)			Uplifts from 2022 (absolute)		
Year	100 yr	50 year	20 year	100 yr	50 year	20 year
2000	35.6	35.2	34.5	-0.8	-0.8	-0.7
2022	36.3	36.0	35.3	0.0	0.0	0.0
2055	38.2	37.8	37.0	**1.8**	**1.8**	**1.8**
2085	40.6	40.2	39.4	**4.3**	**4.2**	**4.1**

RCP4.5	Values (°C)			Uplifts from 2022 (absolute)		
Year	100 yr	50 year	20 year	100 yr	50 year	20 year
2000	35.6	35.2	34.5	-0.7	-0.7	-0.7
2022	36.2	35.8	35.2	-0.1	-0.1	-0.1
2055	37.3	36.9	36.2	**1.0**	**0.9**	**1.0**
2085	38.3	38.0	37.3	**2.0**	**2.0**	**2.0**

B.4 Relative Humidity

The figure below shows Relative Humidity in July 2022; the boundaries are river catchments, and the West Thames basin defines the western edge of Oxfordshire.



The table below summarises the NOAA heat index and combinations of temperature and relative humidity that cause dangerous conditions.

NOAA national weather service: heat index

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors: Caution | Extreme caution | Danger | Extreme danger

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