

UK Climate Risk  
Independent  
Assessment  
(CCRA4)

# Technical Report

## Chapter 1: State of the Climate

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# 9 1.1 Chapter Summary

10 The global climate is rapidly changing. Human activities have increased the concentrations of greenhouse gases  
11 in the atmosphere to levels not experienced for over a million years, trapping more heat within the atmosphere  
12 and oceans. Globally, temperatures, precipitation and extreme weather phenomena such as heatwaves and  
13 downpours are rising and breaking historic records by bigger margins. The rate of global sea-level rise has  
14 increased, with significant contributions from melting glaciers and ice sheets, as well as from the thermal  
15 expansion of warmer sea water. In the 2024 calendar year, global mean surface temperature (GMST) exceeded  
16 1.5 °C above pre-industrial temperatures for the first time since observational records have existed.

17 National temperature records around the world are now frequently broken, in some cases by several degrees  
18 Celsius. The heatwave in July 2022 broke the UK temperature record, set only in 2019, by 1.6 °C; the heat  
19 exceeded 40 °C and contributed to approximately 2,200 excess deaths from 10 to 25 July. A warmer atmosphere  
20 can also hold more moisture, enabling larger precipitation and hydrological extremes. In 2015, Storm Desmond  
21 broke 48hr UK rainfall records and caused record breaking floods over a broad swathe of Northern England. The  
22 Environment Agency estimates the winter floods in 2015 caused £1.7-2.5 billion in economic damages (Flood  
23 and Coastal Erosion Risk Management Research and Development Programme, 2021). In 2023, the storm series  
24 Babet, Ciarán, and Debi caused insured losses of about £570 million in the UK (Association of British Insurers,  
25 2025). In 2023 the sea level was the highest on record at the Newlyn tide gauge, one of the longest available sea  
26 level records in the UK, recording data since 1915. This continues the long-term increase in sea level around the  
27 coast of the UK. Further increases in temperature, changes in rainfall and increases in sea level are projected to  
28 occur over the coming decades. Some future changes are already locked-in, and the magnitude of these changes  
29 is dependent on greenhouse gas emissions.

## 30 Observed Changes in the UK Climate

31 The UK has become warmer, wetter, and sunnier. It is warming at a rate of approximately 0.25 °C per decade.  
32 This is sufficient to push the UK climate outside the range of historical observations and greatly increase the  
33 frequency and intensity of impactful weather and climate hazards. Recent warming has far exceeded any  
34 temperature observed in data sets spanning more than 300 years. Rainfall has increased over the winter half  
35 year. For example, the period October to March 2023-2024 was the wettest such period for England, and second  
36 wettest for the UK, in a series from 1836 (Kendon *et al.*, 2025).

## 37 Changes in UK Temperature-dominated Hazards

- 38 • All the UK's top ten warmest years, in a series from 1884, have occurred since 2000; the most recent  
39 three years (2022, 2023, 2024) are all in the top five warmest years.
- 40 • Extreme high temperatures are occurring more frequently across the UK. The temperature of the  
41 hottest summer day is increasing at more than double the rate for mean temperature.
- 42 • Without climate change, the record breaking 40 °C heat in 2022 would have been extremely unlikely.  
43 The likelihood of such events is already six times higher than in the 1980s, and there is a 50% chance of  
44 UK temperatures exceeding 40 °C again within the next 12 years.
- 45 • Hotter, drier weather that can fuel wildfires is becoming more common, but it is unclear if wildfires are  
46 happening more often due to climate change.
- 47 • Extreme cold events are occurring less often and for shorter time periods.
- 48 • Attribution studies indicate that human-induced climate change has increased the likelihood of extreme  
49 high temperatures and reduced the likelihood of extreme low temperatures.

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- Near-coastal UK ocean temperatures are steadily rising. In the decade from 2015-2024 they were 0.9 °C warmer than in 1961-1990. In June 2023, an intense 2-week heatwave caused ocean temperatures of 5 °C warmer than average, contributing to a record-breaking warm June for the UK.
  - The urban heat island effect in major towns and cities increases the severity of hot weather and reduces the severity of cold weather, especially at night.

55 Changes in Water-dominated Hazards

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- The UK's climate is getting wetter. The most recent decade (2015-2024) was 10% wetter than 1961-1990. The winter half-year (October to March) was 16% wetter, with little change for the summer half-year (April to September). Since 2000, five of the top 10 wettest years, but none of the 10 driest, have occurred, in a dataset collected since 1836.
  - The likelihood of wet winters has increased by at least 1.5 times, with winter daily precipitation extremes now 1.4 to 2.6 times more likely.
  - The influence of human-induced climate change was detected in the record wet February 2020, extreme daily rainfall in October 2020, and in heavy rainfall leading to the record wet winter of 2023/24.
  - Widespread snow events are less frequent and less severe than in 1961-1990.
  - Some parts of the UK are experiencing lower water levels in rivers and reservoirs, and drier soils in summer, but the relative contributions from climate change, natural variability, and water management are uncertain.
  - Sea level rise around the UK is accelerating. Tidal gauge records show a rise of 19.5 cm since 1900, with two-thirds of this occurring in the last 30 years. Since 1993 the rate of UK sea level rise has tripled to 4.2 ± 1.0 mm per year, compared to the long-term average since 1900. This is much faster than any rise in the past 3,000 years.

72 Changes in Wind-dominated Hazards

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- There is no clear long-term pattern in UK severe storms, with decadal and year to year variability. The 1990s were especially stormy, with fewer damaging storms since 2000.
  - Fewer maximum gust speeds have exceeded 40 knots in the last two decades compared to the 1980s and 1990s. This has not been attributed to specific drivers but is likely to relate, at least in part, to long-term natural variability in storminess.
  - Sequences of several multi-hazard storms, producing extreme wind and heavy rainfall, have become more common.
  - Sustained absences of wind from summer hot-dry high-pressure periods have become more common.
  - Sea-level rise, combined with multi-hazard storm sequences, is increasing the frequency of extreme coastal flooding and intensifying coastal erosion.

83 Future Changes in the UK

84 Unprecedented extreme events will continue to occur with increasing frequency and severity over the coming

85 decades. The severity of climate risks we will experience depends on levels of global greenhouse gas emissions.

86 Current global policies will likely cause 2.5 to 3 °C global warming by 2100, but pathways to limiting warming to

87 well below 2 °C are still plausible if climate action is increased around the world. Sea-level rise will continue well

88 beyond the 21<sup>st</sup> century in all plausible scenarios, but lower emission scenarios slow this rate of rise.

89 In the UK in the future there is a greater chance of hotter, drier summers and wetter, warmer winters, with

90 rising sea levels and increases in some extreme events.

91 The Future of Temperature-dominated Hazards

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- As greenhouse gas concentrations increase, the UK will experience more frequent hot summers and more extreme high temperatures, with more severe heatwaves reaching higher temperatures and lasting longer.
  - Hot days that exceed 30 °C are expected to increase in frequency from 1.3 days now to over 20 days per year for the 2070s high scenario at a Global Warming Level (GWL, as described in section 1.2.1) of 3.5 °C, with the greatest increases across south and east England.
  - Wildfire is an emerging risk for the UK. High fire weather days, which provide conditions conducive to wildfire activity, double at a GWL of 2 °C and increase fivefold at a GWL of 4 °C relative to the 1850-1900 baseline.
  - Summer heat will likely extend to later in the year, with a longer wildfire season projected into late summer.
  - Cold winters and extreme low temperatures are expected to become less frequent and less intense, but cold extremes will still be a hazard.

105 *The Future of Water-dominated Hazards*

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- Short-duration (1-3 hours) extreme rainfall will become more intense and will likely cause increased flash flooding.
  - Daily rainfall extremes are increasing, and this is projected to continue, with increasing risk of flooding. The latest climate science indicates greater increases in peak river flows than previously thought.
  - Hot, dry summers are expected to occur more frequently, reducing river flows and potentially worsening drought risks.
  - Centuries of sea level rise (SLR) are already committed due to past emissions. The specific rate and amount of future SLR depend on greenhouse gas emissions. By 2100, global sea levels will likely rise by 0.28-0.55 m under a low emission (likely range, SSP1-1.9) and 0.63-1.02 m under a high emission (likely range, SSP5-8.5) scenario, respectively.

116 *The Future of Wind-dominated Hazards*

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- Extreme damage-producing windstorms will continue to be driven by natural cycles.
  - Recent high-resolution climate modelling studies indicate that human-induced climate change is expected to intensify both the jet stream, which drives UK storm systems, and future near-surface wind speeds.
  - There is increased potential for combined impacts from extreme winds and extreme rainfall (wet-windy) in future windstorms, with a doubling of storms with both high wind and river flow risks at 3 °C GWL.
  - Severe convective storms are expected to increase in the warm season, with increases in lightning occurrence. Hailstorms are expected to decrease in frequency but may produce more large hailstones. Little is known about future changes to tornadoes or wind gusts within thunderstorms.

126 In addition to the above, the likelihood of very severe hot-dry summer (heat, drought, fire, hail, tornado, wind, subsidence) and wet-windy winter (wind, flooding, landslide, storm surge) seasons containing multiple, linked, high-intensity events (e.g., a heatwave or storm) is expected to increase.

129 *Tipping Points of the Global Climate System and Impact on the UK*

130 Tipping points in the climate system are defined as critical thresholds beyond which the climate system reorganizes, often abruptly and/or irreversibly. Tipping points in the climate system may cause rapid changes in oceanic and atmospheric circulation, in ice sheets, the Amazon rainforest or boreal forests, and permafrost. Changes in climate may also cause tipping points in regional climate or ecological systems, such as permafrost, mountain glaciers or tropical corals.

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- Our current understanding of the effect of triggering specific tipping points is very uncertain, but they may pose major risks.
  - Reaching a tipping point may be significantly earlier, in some cases several decades or more, than experiencing impacts from this tipping point transition.
  - Some tipping points could affect the UK directly, such as a shutdown or severe slowdown of ocean circulation in the North Atlantic, which would cool the UK relative to the rest of the world (unlikely in the 21<sup>st</sup> century).
  - As global warming continues, the probability of crossing tipping points increases, with some tipping points already possible, but uncertainties in these estimates are very large. This implies an urgent need for improved monitoring of tipping points and planning of potential adaptative responses.
  - When tipping processes have started the changes can be rapid, they can change the regional trajectory of climate change, and can be slow to reverse.

147 Scientific Advances and Knowledge Gaps

148 This report outlines key scientific advances since the CCRA3 Independent Assessment Technical Report and  
149 identifies remaining gaps in our understanding of future climate change. Observational data and model  
150 projections now provide robust evidence that the UK climate has already shifted, with some further change  
151 inevitable. Increasingly frequent and severe extreme weather events, both globally and within the UK, pose  
152 escalating risks to economic, social and ecological stability. Many knowledge gaps do remain, including around  
153 the precise amounts by which the climate will change in the future, and especially the conditions that could  
154 trigger tipping points.

155 **Visual Summary:**

156 The following table and maps provide a set of summary statistics to illustrate UK climate projections at a range  
157 of GWLs. These values, drawn from UKCP climate models, represent plausible scenarios that could occur at the  
158 indicated GWLs, and are compared to the equivalent observed extremes for the period 2005-2024. These values  
159 represent a median value, meaning that approximately half of years at that GWL would be expected to be higher  
160 and half of years would be expected to be lower than this value. These values are included to illustrate the  
161 nature of changing climate hazards for the UK. These values are consistent with the wider body of evidence  
162 presented in this chapter, but the values are not intended to be used in isolation for adaptation or policy  
163 decisions, as they do not account for the full range of potential outcomes. For more comprehensive climate  
164 projections, including a full assessment of the associated uncertainties in future climate change, readers are  
165 directed to the range of products provided through the UK Climate Projections (UKCP).

166 The maps below show the 'change' in climate between a 1981-2000 baseline compared to the recent climate  
167 (2005-2024) and for the range of GWL scenarios.

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Table 1.1: Summary of selected climate hazard metrics for recent past along with Central and High estimates under Global Warming Level scenarios. [Note that the metrics tables and maps within the State of the Climate chapter may be subject to minor amendments following Community Review. These will not materially impact any of the conclusions of the chapter.]

		2005-2024	2030s		2050s		2070s	
Metric	Region	Recent Past	Central	High	Central	High	Central	High
	GWL:	1.0 °C	1.5 °C	2.0 °C	2.0 °C	2.5 °C	2.5 °C	3.5 °C
<b>Hot Summer Days</b>	Average number of days per year exceeding 30 °C.							
	London	4	6	20.5	10	23.5	13.5	41
	Belfast	0	0	0.5	0	2	0	5
	Edinburgh	0	0	1	0	1.5	0	6.5
	Cardiff	0	2.5	12.5	3.5	17	7	29.5
<b>Frost Days</b>	Average number of days per year with a minimum temperature below 0 °C.							
	London	45.5	34	36.5	27	38.5	25	27.5
	Belfast	47.5	36	46	33	42	26	33.5
	Edinburgh	82	70	78.5	59	71	52	57.5
	Cardiff	45	36.5	40	28.5	39	25.5	29
<b>Maximum Summer T<sub>max</sub> (°C.)</b>	Average of the maximum daily temperature in Summer (June, July, August).							
	London	33.0	34.2	38.3	34.5	38.2	35.0	39.8
	Belfast	25.9	27.1	31.4	27.8	31.2	27.8	33.1
	Edinburgh	26.8	27.8	30.8	28.7	30.8	29.1	34.1
	Cardiff	29.6	31.4	36.5	32.4	36.9	33.0	39.2
<b>Summer Wet Days</b>	Average of the maximum 1-day rainfall (mm) in June, July and August.							
	London	33.3	33.7	38.8	32.7	36.5	32.1	42.1
	Belfast	34.1	31.2	38.8	31.5	36	31.4	39.3
	Edinburgh	34	35.5	42.3	35.1	46.3	37.6	50.5
	Cardiff	38.4	34.3	39.7	32	45.8	33.5	41
<b>Winter wet spells (mm)</b>	Average of the maximum 5-day precipitation accumulation (mm) in December, January, and February.							
	London	44	48.6	55.9	47.4	64.4	49.1	59.6
	Belfast	54.4	57.3	68.8	58.9	74	61	69.2
	Edinburgh	67.9	59.9	70.9	60.4	68.5	59.4	76.7
	Cardiff	79.1	87.8	104.4	89.3	108.5	89.9	120
<b>Winter windy Days</b>	Number of days in December, January and February, where winds exceed the 98 <sup>th</sup> percentile of the baseline (1 °C GWL).							
	London	3	3	4.5	3	4.5	4	6
	Belfast	3	2.9	4	3	4.5	3	4.7
	Edinburgh	3	3.9	5	3	5.8	4	4.9
	Cardiff	3	3	4	3	4.5	3	4.5

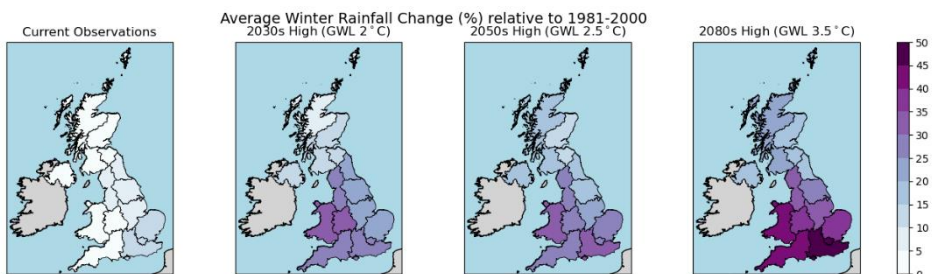
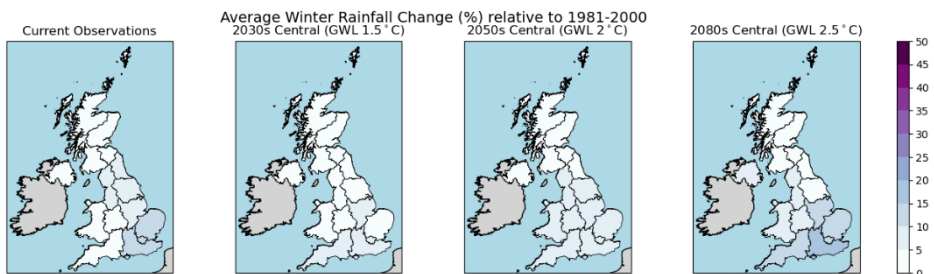
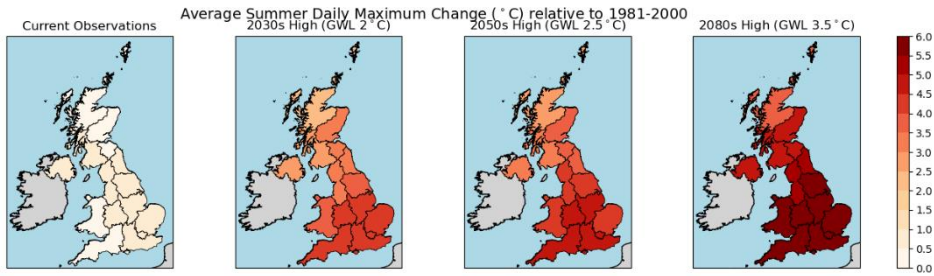
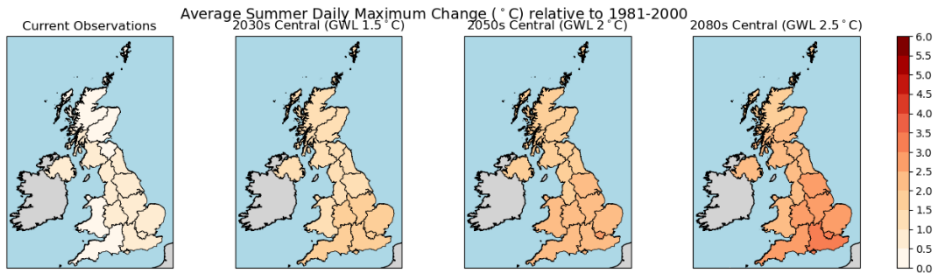


Figure 1.1: Maps showing current (2005-2024) and future changes in summer daily maximum temperature and winter rainfall relative to a 1981-2000 baseline. Panels are provided for the CCRA4 central and high scenarios for UK administrative regions. Temperature change is presented in °C and rainfall changes are presented as a % of the baseline value. [Note that the metrics tables and maps within the State of the Climate chapter may be subject to minor amendments following Community Review. These will not materially impact any of the conclusions of the chapter.]

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## 1.2 Introduction

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This chapter provides an overview of observed changes and model projections for several climate hazards for the Technical Report of the Fourth Independent Assessment of UK Climate Change Risk (CCRA4-IA-TR). The chapter provides a review of relevant literature and key datasets, a summary of major scientific advances, and details of remaining knowledge gaps.

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Observational data form the foundation for examining past climate change; however, the short durations of many records and their incomplete spatial coverage present notable challenges. Model simulations can enhance our understanding of historical trends and variability. Climate model projections further extend this insight by providing information on how climate might change under a range of alternative global greenhouse gas emission scenarios. They also allow exploration and quantification of uncertainties arising from future emissions, model representations of climate processes, and natural variability. Their results are often presented as time series for different future emission scenarios. Figure 1.2 shows global mean surface air temperature (GMST) anomalies relative to the 1995–2014 average (left axis), and to the 1850–1900 baseline (right axis). The two axes are offset by 0.82 °C, representing the multi-model mean and closely matching the observed best estimate.

Scenario	Value
Historical	51
SSP1-1.9	11
SSP1-2.6	30
SSP2-4.5	33
SSP3-7.0	26
SSP5-8.5	32

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Figure 1.2: Global mean surface air temperature (GMST) anomalies relative to the 1995–2014 average (left axis) and to the 1850–1900 baseline (right axis) from the CMIP6 climate models for historical (black) and a range of future emission scenarios (blue, yellow and red). The shading represent the 5%-95% range for SSP1,2,6 and SSP3-7.0. Vertical grey shading highlight 20 year segments centred on the 2030s, 2050s and 2090s. The two axes are offset by 0.82 °C, representing the multi-model mean and closely matching the observed best estimate. Reproduced from [Figure AR6 WG1 | Climate Change 2021: The Physical Science Basis](#). doi: [10.1017/9781009157896.006](https://doi.org/10.1017/9781009157896.006)

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208 Climate models are used to explore how changes in atmospheric greenhouse gas concentrations affect the  
209 climate system. These computer-based tools represent our current understanding of climate processes and can  
210 reproduce many of the patterns observed in the real world. They are used to create climate projections;  
211 estimates of how the climate might change in the future. While climate models provide a credible basis for  
212 understanding possible future weather and climate conditions, their results are best interpreted alongside other  
213 sources of evidence, including expert judgement and observations of past climate and extreme events. The  
214 latter is also provided by the suite of products in the latest UK national climate projections (UKCP18) (Lowe *et*  
215 *al.*, 2018). This integrated approach is important for understanding potential changes in specific atmospheric  
216 circulation patterns, where some evidence suggests that models underestimate future changes, particularly for  
217 extreme events.

218 Global climate models (GCMs) simulate the whole Earth's climate, but their resolution is quite coarse, with each  
219 grid cell representing an area of around 60 km across. We can get more detail feeding global climate model  
220 results into regional models. These smaller-scale models focus on specific regions and work at much higher  
221 resolutions (typically 2-5 km), similar to the models used for national weather forecasts, and are included in  
222 UKCP18. Although climate models are valuable tools that can simulate many features of the current and past  
223 climate, they have limitations and may not capture all aspects of future changes.

### 224 1.2.1 Climate Framing

225 The climate framing adopted within the CCRA4-IA-TR considers changes to UK climate risks for specified levels of  
226 global warming (GWLs), as described in the Methods chapter. Since the reviewed literature adopts several  
227 different framings, where possible we interpret these in the context of the GWL framing for CCRA4-IA-TR.  
228 Limitations of the GWL approach are summarised in the Methods chapter.

229 To quantify how climate has already changed, and how it might change in future, we compare it against a  
230 baseline or reference climate. The published literature uses several baseline time periods. Where these are  
231 relevant to the conclusions, this will be stated. The most common baselines are summarised below:

- 232 • Global Warming Levels (GWLs) typically use a pre-industrial baseline of 1850-1900, i.e., a 2 °C GWL is  
233 equivalent to the global mean surface temperature (GMST) being 2 °C higher than the GMST in the  
234 1850-1900 reference period.
- 235 • The World Meteorological Organization (WMO) defines the climatological standard normal as the most  
236 recent 30-year period ending in a year that ends with zero. Currently, this period is 1991-2020. The  
237 WMO uses this baseline for routine climate monitoring and for international comparison, as it  
238 represents the average climate of the recent past.
- 239 • The WMO also maintains a standard reference period of 1961-1990 for assessing long-term climate  
240 change. This baseline is particularly important for observational studies, as reliable records may not be  
241 available before this time.
- 242 • The UK Climate Projections (UKCP18) uses a 20-year baseline of 1981-2000 as a common reference  
243 period.

### 244 1.2.2 Drivers of UK climate change

245 Climate change in the UK is ultimately driven by global emissions of greenhouse gases such as carbon dioxide,  
246 methane and nitrous oxide. These are well mixed in the atmosphere and directly warm the global (and UK)  
247 climate. Emissions of atmospheric aerosols have a more regional effect and different aerosols can offset some  
248 warming from greenhouse gases or add to their warming effect. Processes in the climate system, known as  
249 feedbacks, can amplify or reduce the warming. For example, a warmer atmosphere holds more water vapour,

250 which leads to further warming as water vapour is itself a greenhouse gas. Changes in clouds can warm or cool  
251 local temperatures depending on the type of cloud, time of year, and other factors.

252 UK climate change is also strongly affected by changes in ocean and atmospheric circulation, especially in the  
253 Atlantic. In particular, the Atlantic jet stream drives UK weather variations: climate change will likely change its  
254 strength, position and variability. UK weather is also affected by other more distant phenomena, including  
255 weather in the tropics, and processes linked to the El Niño Southern Oscillation.

256 Local feedback effects can also impact UK weather phenomena and are important in estimating climate risks. For  
257 instance, together rainfall drought and enhanced evaporation of water from the land surface can lead to strong  
258 localised warming, enhancing heatwaves, due to insufficient soil moisture for further evaporative cooling.

259 Climate models reproduce many processes that control UK climate risks. However, there is still uncertainty  
260 around processes driving the jet stream, and some processes are simply not simulated or realistically  
261 represented within models. The latter is especially the case for coarse GCMs which cannot directly simulate local  
262 processes and feedbacks.

## 263 1.3 UK Climate Hazards

### 264 1.3.1 Temperature-dominated Hazards

#### 265 1.3.1.1 Heat

##### Headlines

- 1 Extreme high temperatures are increasing faster than average temperatures. Average daily maximum temperature in the UK was 1.2 °C higher from 2015-2024 than during 1961-1990, whereas the hottest day of the year increased by 2.7 °C during the same period. This highlights a rapid increase in heat hazard for the UK in recent decades (**High confidence**).
- 2 Hot summers and extreme high temperatures are expected to become more frequent and more intense. For instance, heatwave-drought events with a 1% chance of occurring today are projected to become five times more frequent by the 2040s (**High confidence**).
- 3 UK extreme temperature risks are increasing more rapidly than previously thought as a result of the direct effects of human-induced climate change and changes to large-scale weather patterns.
- 4 Large-scale weather patterns that produce UK heatwaves are influenced by changes to climate elsewhere in the world. There is still uncertainty on how well these responses are represented in climate models.

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267 This section considers hazards relating to increases in UK annual mean temperature, summer mean temperature,  
268 hot days, and heatwaves. The table below identifies the risks to which this hazard is particularly (but not  
269 exclusively) relevant.

#### Risks affected per Sectoral Impact Category

Land, Nature and Food	Economy	Health and Wellbeing	Built Environment	Infrastructure
N1, N2, N3, N4, N5, N6, N7, N8, N9, N10	E1, E2, E3, E4, E6, E7, E8	H1, H3, H4, H5, H6	BE1, BE5, BE7, BE8, BE9	I1, I2, I3, I4, I5, I6, I7, I8, I9, I10

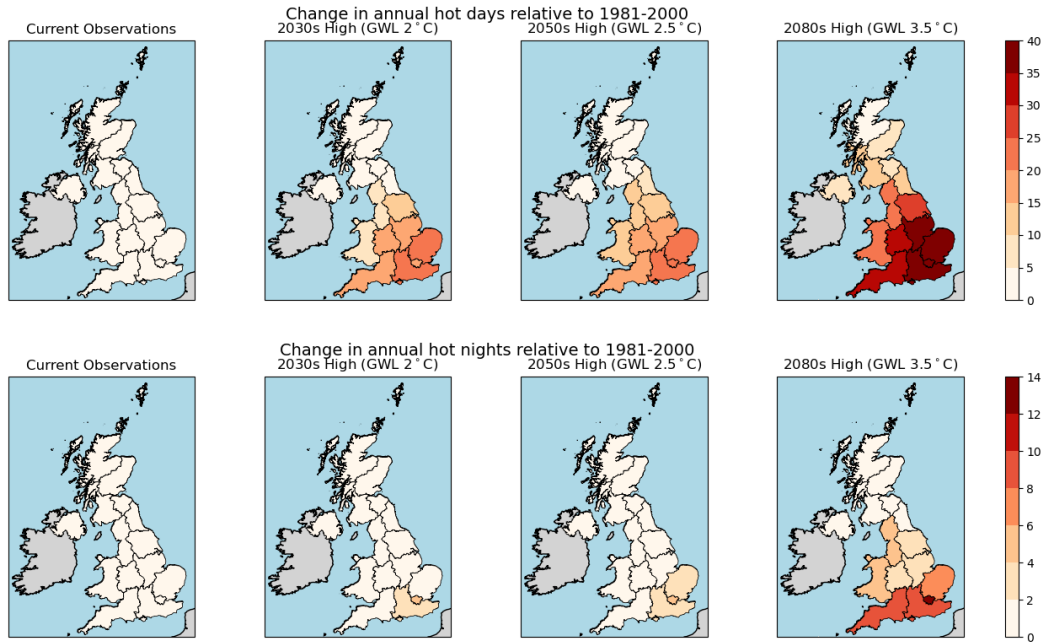
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271 *Table 1.2: Summary of annual average hot summer days, hot summer nights, and maximum summer temperature*  
 272 *for recent past (2005-2024) and under GWL central and high scenario. [Note that the metrics tables and maps*  
 273 *within the State of the Climate chapter may be subject to minor amendments following Community Review. These*  
 274 *will not materially impact any of the conclusions of the chapter.]*

		2005-2024	2030s		2050s		2070s	
Metric	Region	Recent Past	Central	High	Central	High	Central	High
	GWL:	1.0 °C	1.5 °C	2.0 °C	2.0 °C	2.5 °C	2.5 °C	3.5 °C
<b>Hot Summer Days</b>	Average number of days per year exceeding 30 °C.							
	London	4	6	20.5	10	23.5	13.5	41
	Belfast	0	0	0.5	0	2	0	5
	Edinburgh	0	0	1	0	1.5	0	6.5
	Cardiff	0	2.5	12.5	3.5	17	7	29.5
<b>Hot Summer Nights</b>	Average number of days per year with a minimum temperature above 20 °C.							
	London	0	0.5	5	1.5	5	2.5	14.5
	Belfast	0	0	0	0	0	0	1
	Edinburgh	0	0	0	0	0	0	0
	Cardiff	0	0	1.5	0	2	0	7.5
<b>Maximum Summer <math>T_{max}</math> (°C.)</b>	Average of the maximum daily temperature in Summer (June, July, August).							
	London	33.0	34.2	38.3	34.5	38.2	35.0	39.8
	Belfast	25.9	27.1	31.4	27.8	31.2	27.8	33.1
	Edinburgh	26.8	27.8	30.8	28.7	30.8	29.1	34.1
	Cardiff	29.6	31.4	36.5	32.4	36.9	33.0	39.2

275

276



277

278

279 *Figure 1.3: Maps showing current (2005-2024) and future changes in hot summer days and hot summer nights*  
 280 *relative to a 1981-2000 baseline. Panels are provided for the CCRA4 high scenarios for UK administrative regions.*  
 281 *[Note that the metrics tables and maps within the State of the Climate chapter may be subject to minor*  
 282 *amendments following Community Review. These will not materially impact any of the conclusions of the chapter.]*

283 **Introduction**

284 In 2024 global mean surface temperature (GMST) exceeded 1.5 °C above the 1850-1900 baseline for the first  
 285 time (WMO, 2025). For the most recent decade (2015-2024), GMST has been 1.24 °C above the 1850-1900  
 286 baseline, with human-induced warming contributing to about 1.22 °C of this (range from 1.0 to 1.5) (Forster *et*  
 287 *al.*, 2025).

288 The UK has warmed at a higher rate than the global average. Observed data in the Central England Temperature  
 289 series shows the most recent decade (2015-2024) was 1.6 °C warmer than the 1850-1900 baseline. Warming has  
 290 occurred in all seasons, with the UK’s warmest year, warmest summer, and extreme heat events all made more  
 291 likely by climate change (Ciavarella and McCarthy, 2024; Kay *et al.*, 2025; Logan *et al.*, 2025)

292 Observational data indicates that both hot and cold extremes of temperature are changing more than average  
 293 temperatures. Hot days, hot spells and heatwaves are major climate hazards for the UK. Table 1.2 and Figure 1.3  
 294 summarise the changing hazards of hot days and hot summer nights for the central and high GWLs. The  
 295 frequency of hot days increases in all regions, rising from an average of four days in London in the recent past to  
 296 over 40 days per year in the 2070s high scenario at 3.5 °C GWL. The increase is largest in south and east England,  
 297 but hot days increase everywhere. Hot summer nights, which are relatively rare in the current climate, also  
 298 increase, particularly in London, with increases across many regions of England and Wales under the high  
 299 scenario.

300 **Observed change**

301 UK weather and climate records continue to be broken. Four of the top ten hottest summers in a dataset from  
 302 1884 have occurred since 2015 (2025, 2018, 2022, and 2023). The average temperature associated with the

---

303 record-breaking 2025 summer is now around 70 times more likely than in a pre-industrial climate and has a 20%  
304 chance of being exceeded in the near-future (Logan *et al.*, 2025). An extreme summer (with a roughly 1%  
305 probability) in the near-future could be as much as 1 °C warmer than summer 2025 (Kay *et al.*, 2020).

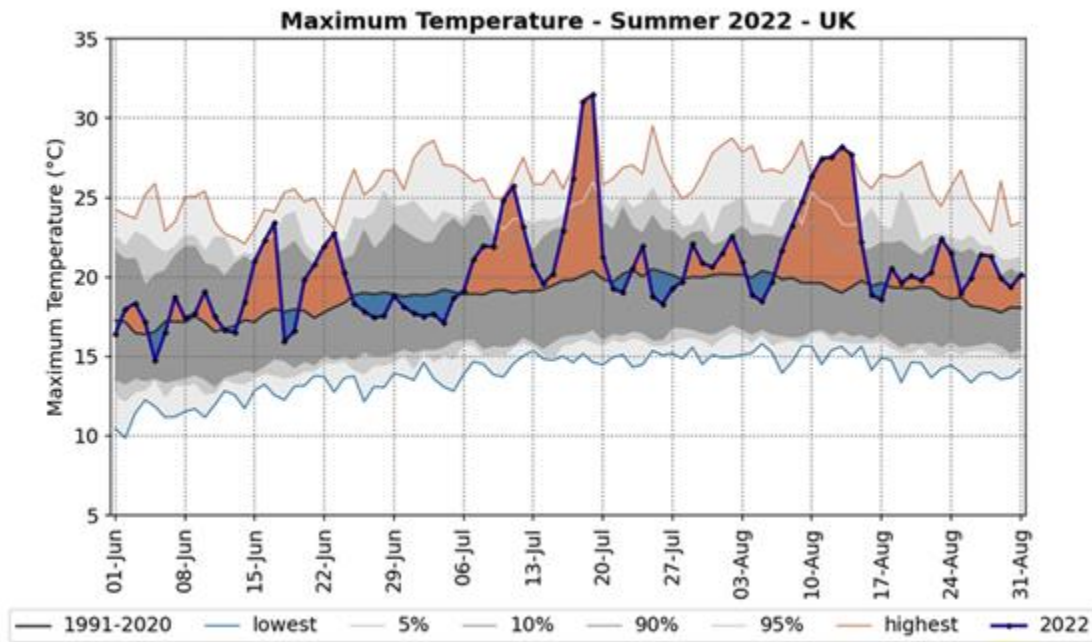
306 The number, duration, and extent of UK hot days and heatwaves have increased in observational data. The  
307 average daily maximum temperature was 1.2 °C higher from 2015-2024 than during 1961-1990, whereas the  
308 hottest day of the year (the highest daily maximum temperature) has increased even faster, by 2.7 °C. The  
309 frequency of very hot (higher than 30 °C) and extremely hot (higher than 32 °C) days has more than trebled  
310 (Kendon *et al.*, 2025).

311 Extreme high temperature records have been broken in many European countries in recent years. In the UK, the  
312 probability of temperatures exceeding 40 °C in any year in the current climate is about 4%, a six-fold increase  
313 compared to the 1980s (Kay *et al.*, 2025). The likelihood of exceedance is increasing rapidly, and there is an  
314 estimated 50-50 chance of reoccurring 40 °C heat in the UK within the next 12 years.

### 315 **Extreme Heat - Summer 2022**

316 Summer 2022 was the UK's fifth warmest summer in the Met Office national series (1884-present) cooler only  
317 than the summers of 2025 (Logan *et al.*, 2025), 2018 (McCarthy *et al.*, 2019), 2006 and 2003. Notably, the  
318 summer of 1976 is now only the sixth warmest. The high ranking of summer 2022 was in part a consequence of  
319 two significant heatwaves in mid-July, and mid-August as shown in Fig 1.4. The hottest of these heatwaves was  
320 substantially stronger than previously recorded heatwaves (Yule *et al.*, 2023).

321 In July 2022, high pressure across western Europe caused persistent hot and dry conditions, with UK  
322 temperatures regularly exceeding 30 °C. By mid-July heatwave temperatures exceeded 40 °C in Spain, France,  
323 Germany and the UK, exacerbated by dry heat drawn north from Africa. On 18 and 19 July 2022, the UK-wide  
324 average daily maximum temperature exceeded 30 °C. Overnight, temperatures remained high, setting a new UK  
325 record for highest overnight minimum temperature of 26.8 °C in Oxfordshire. These high temperatures and  
326 drought caused widespread damage to crops and water resources and extensive wildfires across Europe  
327 (Tripathy and Mishra, 2023) as well as high excess heat-related deaths (Ballester *et al.*, 2023).



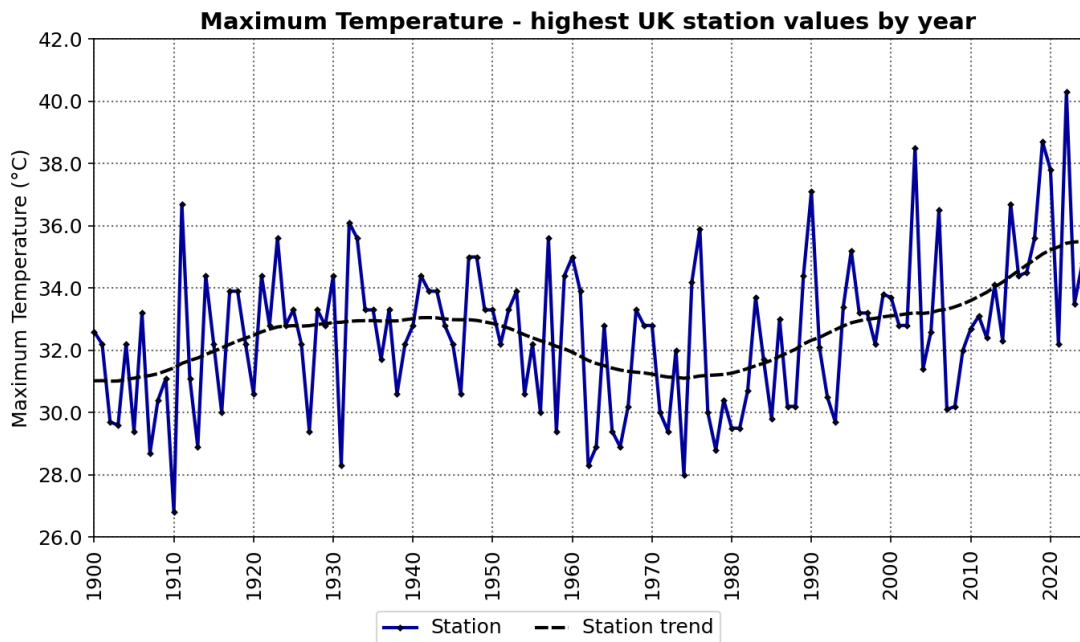
328

329 *Figure 1.4: Time series of UK daily maximum temperature during summer 2022.*

330 The July 2022 event was also remarkable for the heatwave's extent. The maximum temperature of 40.3 °C was  
 331 recorded at Coningsby (Lincolnshire), but six more stations recorded temperatures exceeding 40 °C in a band  
 332 from London to Nottinghamshire (Kendon, 2022). Moreover, 30 stations exceeded 39 °C, and some 46 stations  
 333 broke the previous national temperature record of 38.7 °C. New national temperature records were set in Wales  
 334 (37.1 °C at Hawarden Airport on 18<sup>th</sup> July) and Scotland (34.8 °C at Charterhall on 19<sup>th</sup> July). The England  
 335 temperature record was broken by 1.6 °C, while both Wales and Scotland broke their records by 1.9 °C. Many  
 336 long-running temperature stations in the UK network recorded their hottest day on record by extraordinary  
 337 margins, including Durham (maximum temperature: 36.9 °C, exceeding the previous record by: +4.0 °C, in a 155  
 338 year dataset), Sheffield (39.4 °C, +3.8 °C, 138 years), Bradford (37.9 °C, +4.0 °C, 134 years).

339 The temperature during extreme heat events in the UK is rising faster than average temperatures, as shown in  
 340 Figure 1.5. This may partly be due to changes in wind patterns, which some climate models don't fully capture  
 341 (Vautard *et al.*, 2023). UK heatwaves often occur when high pressure over Scandinavia and low pressure over  
 342 the Atlantic bring hot air from the south and are therefore coupled with heatwave events affecting continental  
 343 Europe more widely.

344 Climate change is increasing the likelihood of extreme temperatures, such as during summer 2022. Heat  
 345 extremes are more severe than in the past for comparable large-scale weather patterns, and heatwaves are  
 346 projected to continue to become more frequent and more severe in the future.



347

348 *Figure 1.5: Station observations, showing UK maximum temperature (in °C) for each year from 1910 to 2024. The UK*  
 349 *national maximum recorded temperature through time increases from 36.7 °C in 1911, 37.1 °C in 1990, 38.5 °C in 2003, 38.7*  
 350 *°C in 2019, and 40.3 °C in 2022.*

351 **Future change**

352 Hot summers are expected to continue to become more frequent in the UK, with an increasing chance of hotter,  
 353 drier summers (Lowe *et al.*, 2018). Heatwave-drought events with a 1% chance of occurring in the current  
 354 climate are estimated to become five times more frequent by the 2040s in a high emissions scenario (Kendon *et al.*,  
 355 2023), which would be equivalent to a 2.5 °C GWL.

356 In summer, greater increases in maximum temperatures are projected over the southern UK where the most  
 357 extreme high temperatures are generally experienced now. The frequency and intensity of heatwaves are also  
 358 expected to increase. For example, heatwaves producing 40 °C temperatures in the UK could occur every few  
 359 years by 2100 for a 4 °C GWL (Christidis *et al.*, 2020).

360 The rising temperatures will increase heat-related hazards. Tropical nights, where temperatures do not fall  
 361 below 20 °C, are currently rare in the UK climate, but are expected to become more common. High  
 362 temperatures overnight can be a hazard to health, making it hard to cool buildings, especially in urban areas.  
 363 Climate models indicate multiple occurrences annually in the London area under a 2 °C GWL and more widely  
 364 across England at 4 °C GWL (Hanlon *et al.*, 2021).

365 **1.3.1.2 Fire**

## Headlines

1. The number of UK fire weather days has increased due to climate change, with hotter, drier conditions exacerbating wildfire risks, but it is uncertain whether climate change is increasing wildfire incidence in the UK (**Medium confidence**).
2. Climate models indicate a doubling of high fire weather days for a GWL of 2 °C, with a longer wildfire season into the late summer. Higher temperatures and lower humidity are the key drivers of increased wildfire risks (**Medium confidence**).
3. Wildfire is an emerging risk for the UK. So far, events have not produced widespread major impacts, aside from degraded air quality from peatland fires, but this may change. There is a large increase in wildfire hazard between GWLs of 2 °C and 4 °C (**Medium confidence**).
4. In addition to direct climate changes affecting fire weather days, fire risk depends on ignition risk, which relates to fuel availability. It is uncertain how climate change will change vegetation types and human activity relevant to wildfire risks.

366

367 This section considers hazards relating to wildfire in the UK. The table below identifies which risks this hazard is  
368 particularly (but not exclusively) relevant to.

Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment	Infrastructure
N1, N5, N6, N8	E2, E6, E7,	H1, H2, H3	BE1, 5, 6, 8	I1, I3, I4, I5, I6, I8

## 369 Introduction

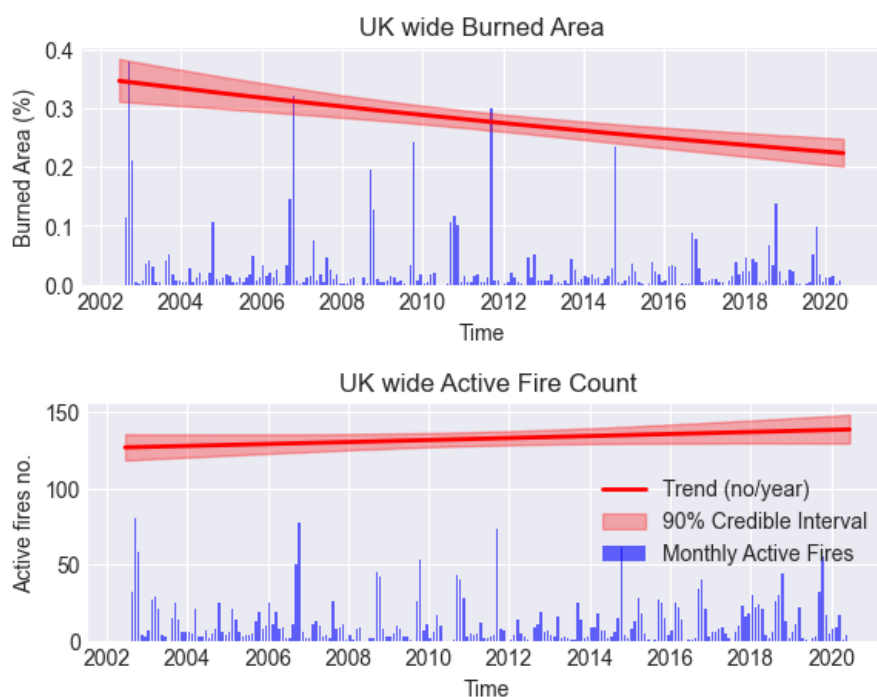
370 High risk fire weather occurs on days with high temperatures, low humidity, and strong winds, creating dry  
371 conditions that promote ignition and fire spreading. In the UK, wildfire is defined as 'any uncontrolled vegetation  
372 fire which requires a decision, or action, regarding suppression' (*Fire and Rescue Service: wildfire operational  
373 guidance*, 2013). Currently, UK fire frequency peaks in April with a secondary peak in summer. In spring, the  
374 ground is still largely covered by dry plant matter from the previous growing season. If dry air and winds prevail,  
375 this creates ideal conditions for fires to spread following accidental ignitions from springtime influxes of visitors  
376 to the countryside. Later in the summer, new plant growth can dry out in warm weather, becoming more  
377 flammable. UK wildfires primarily affect grasslands, broadleaved woodlands, and heathlands, especially near to  
378 the rural-urban interface where human activity frequently ignites wildfires. Larger wildfires occur in moorlands  
379 and peatlands, where fuel accumulation and slower reporting of wildfires contribute to their spread.

380 Weather, vegetation, and land management shape UK wildfire risk. High fire risk weather quantifies the  
381 contribution to the hazard from the meteorological conditions. Wildfire hazard is also affected by land  
382 management and human activity (e.g., escaped fires).

## 383 Observed Change

384 The number of fire weather days in the UK has increased due to climate change, with hotter, drier conditions  
385 exacerbating wildfire risks (UNEP, 2022). In 2022 there was a significant increase in fire activity, with 185,437 fire  
386 incidents in the UK, a 28% rise from the previous year. This increase is attributed to the hot dry summer that

387 year (Home Office, 2022). While long-term wildfire data is limited, recent trends suggest important changes,  
 388 shown in Figure 1.6. Since 2002, the total UK area burned by wildfires has generally declined, but the number of  
 389 fires has increased, and fire seasons are becoming longer. This shift points to more frequent but smaller fires,  
 390 with trends potentially influenced by land management changes as well as by climate change. However, extreme  
 391 fire events, with large impacts on people and property, are now occurring. The 2022 heatwave, when  
 392 temperatures exceeded 40 °C, produced an unprecedented number of fires. Research suggests that climate  
 393 change made fires six times more likely in 2022 (Burton et al., 2024). This evidence highlights the growing risks  
 394 from wildfire in a warming UK.



395

396

397 *Figure 1.6: Annual UK burned area from the Global Fire Emissions Database, <https://www.globalfiredata.org/index.html> (GFED5, top) and*  
 398 *GFED500 active fire counts (bottom) for 2002 onwards. While the total burned area has generally declined, the number of active fires has*  
 399 *increased, suggesting a shift toward more frequent but smaller fires.*

#### 400 **Case Study: The Saddleworth Moor Fires (2018)**

401 In June 2018, the Saddleworth Moor fire in Greater Manchester became one of the UK's largest wildfires,  
 402 burning for several weeks. Triggered by human activity, the fire was worsened by a prolonged dry spell and  
 403 extreme high temperatures. The fire spread rapidly, burning large areas of peat and heather, emitting an  
 404 estimated 24,000 tonnes of carbon (Baker et al., 2025). The fire was particularly difficult to control due to  
 405 smouldering peat fires that burned underground.

406 During the fire, PM2.5 levels – fine particulate matter that can harm human health – were four to five-and-a-half  
 407 times higher than normal in the Greater Manchester area, significantly increasing the risk of respiratory  
 408 problems and excess mortality. The health impact was considerable, with an estimated 4.5 million people  
 409 exposed to levels of PM2.5 higher than health-based guidelines for at least one day and a rise in hospital  
 410 admissions for respiratory issues (UKHSA, 2023). The fire caused major financial losses, estimated at £21 million  
 411 (UKHSA, 2023), including the cost of firefighting, damages to the environment, and disruption to local  
 412 communities.

## 413 Future Change

414 Climate projections suggest the UK is likely to experience warmer, wetter winters and hotter, drier summers,  
415 increasing the risk of wildfires (UKCP18; UKHSA, 2023; Perry et al., 2022). Spring and autumn are also expected  
416 to become warmer, potentially extending the fire season beyond its usual spring peak (Belcher et al., 2021). At a  
417 GWL of 2 °C, the number of days with "very high" fire danger could double, and increase fivefold at a GWL of 4  
418 °C (Perry et al., 2022). Spring fire risk is also likely to rise, with a 1.5 times increase in England at a GWL of 2 °C  
419 and a doubling at a GWL of 4 °C (Perry et al. 2022). This suggests a potential extension of the wildfire season,  
420 particularly in late summer and early autumn, depending on fuel availability. Regions in the south and east will  
421 experience the greatest increase in fire risks from increased conditions conducive to wildfire, with the average  
422 number of high-fire-risk days rising 3-4 times by the 2080s (Arnell et al. 2021). Fire risks will also increase in the  
423 north of the UK. Warmer summers may also increase the risk of human ignitions from increases in outdoor  
424 recreational activities (Belcher et al., 2021).

425 As housing developments near to wildfire-prone areas increase, exposure to wildfires and potential ignitions  
426 may also increase (UKHSA, 2023). New work from Hetzer et al., (2024) shows that fire weather in Europe,  
427 including the UK, will likely become more severe this century under high emissions scenarios, with projections  
428 showing an increase of 25% in climate conditions conducive to wildfire in temperate regions by the end of the  
429 21<sup>st</sup> century, relative to 1996-2016 (Senande-Rivera et al., 2022).

### 430 1.3.1.3 Cold Events

#### Headlines

1. Despite the warming climate, extreme cold events still occur due to climate variability. However, decreases in the frequency, duration, and intensity of cold events over recent decades have been attributed to human-induced warming of the climate (**High confidence**).
2. Cold winters and extreme low temperatures are expected to continue to become less frequent and less severe (**High confidence**).
3. Improved climate model simulations of snowfall and lying snow indicate their continued decline under future warming (**Moderate confidence**).
4. There is still uncertainty in current climate model simulations of winter trends in North Atlantic atmospheric circulation. This may affect projections of how events conducive to cold conditions in the UK are influenced by climate change.

431

432 This section considers hazards relating to winter mean temperature, cold snaps, cold extremes, snow and ice.  
433 The table below identifies which risks this hazard is particularly (but not exclusively) relevant to:

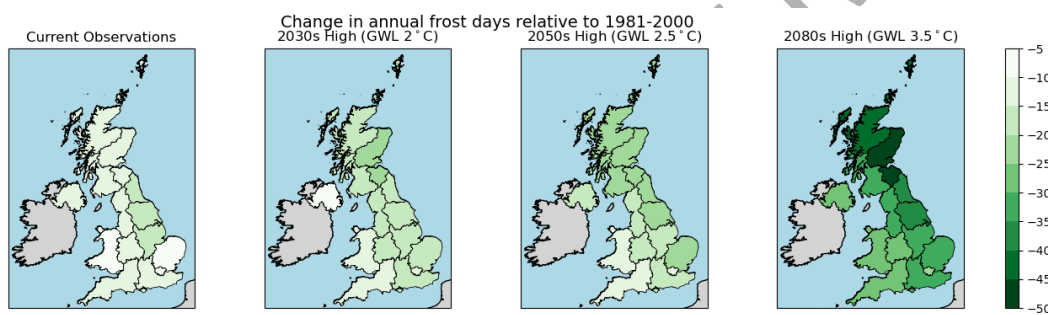
Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment	Infrastructure
N6, N8, N9, N10	E1, E3, E7	H2, H4, H6, H7	BE8, BE9	I1, I2, I3, I4, I5, I6, I7, I9

434

435 *Table 1.3: Number of frost days annually for current and future scenarios.*

		2005-2024	2030s		2050s		2070s		
Metric	Region	Recent Past	Central	High	Central	High	Central	High	
	GWL:		1.0 °C	1.5 °C	2.0 °C	2.0 °C	2.5 °C	2.5 °C	3.5 °C
Frost Days	Average number of days per year with a minimum temperature below 0 °C.								
	London	45.5	34	36.5	27	38.5	25	27.5	
	Belfast	47.5	36	46	33	42	26	33.5	
	Edinburgh	82	70	78.5	59	71	52	57.5	
	Cardiff	45	36.5	40	28.5	39	25.5	29	

436



437

438 *Figure 1.7: Maps showing current (2005-2024) and future changes in frost days relative to a 1981-2000 baseline. Panels are*  
 439 *provided for the CCRA4 high scenarios for UK administrative regions. [Note that the metrics tables and maps within the State*  
 440 *of the Climate chapter may be subject to minor amendments following Community Review. These will not materially impact*  
 441 *any of the conclusions of the chapter.]*

442 **Introduction**

443 Globally, the frequency and intensity of cold extremes have decreased since 1950, with human-induced  
 444 greenhouse gas forcing the main driver (Seneviratne et al. 2021).

445 UK winter mean temperature has increased significantly: the Central England Temperature winter mean  
 446 temperature for the most recent decade (2015-2024) is 1.7 °C higher than the 1850-1900 baseline. Cold spells in  
 447 Europe, and the UK, are caused by high pressure systems with winds from the north or east. The frequency of  
 448 these weather patterns is strongly influenced by the North Atlantic Oscillation (NAO), which varies from year-to-  
 449 year and decade-to-decade.

450 Cold days, cold spells and snowfall constitute a significant climate hazard for the UK. Table 1.3 and Figure 1.7  
 451 summarise changes in frost days for various GWL scenarios. Reductions are projected across the country, with  
 452 the largest reductions in northern and eastern regions, for example Edinburgh, which has an average of 82 frost  
 453 days in the current climate

---

## 454 Observed Change

455 In recent decades, UK winters have become warmer and wetter. The frequency of air frosts and ground frosts  
456 have reduced annually by more than 14 and 30 days respectively, when compared to a 1961-1990 baseline.

457 The number of Heating Degree Days (HDD), days where heating of buildings is required for comfortable indoor  
458 temperatures, has reduced by 14% relative to the 1961-1990 baseline. Conversely, Growing Degree Days, with  
459 conditions suitable for plant growth, have increased by 21% (Kendon, 2025).

460 Extreme cold temperatures have reduced in both frequency and severity. The top ten coldest months, seasons,  
461 and years recorded in UK regions predominantly occurred in the late 19<sup>th</sup> and early 20<sup>th</sup> centuries. In contrast,  
462 the top ten warmest months, seasons, and years are predominantly within the most recent decade.

463 Although widespread and substantial cold and snow events occurred in 2022, 2021, 2018, 2013, 2010 and 2009,  
464 their frequency and severity has generally declined since the 1960s. The cold winter of 2009/2010 and the cold  
465 spring of 2013 were particularly extreme for the recent climate and consequently high impact events. Human-  
466 induced climate change has halved the likelihood of a 2010 winter (Christidis and Stott, 2012).

467 Hazards co-occurring with cold weather include strong winds, snowfall and blizzards, snow drifts, and icy  
468 surfaces. Snow-covered surfaces reflect more sunlight and insulate the air from the Earth's surface, a negative  
469 feedback which can further reduce air temperatures, particularly during extended cold spells normally  
470 associated with high pressure systems.

471 The winter of 1963 is the only year, in a series from 1884, with a winter (December to February) mean  
472 temperature below zero ( $-0.27^{\circ}\text{C}$ ). The exceptional cold affected much of mainland Europe, and resulted in  
473 huge negative impacts on people, society and infrastructure, including transport disruption, power outages, and  
474 shortages of food and fuel. If similar weather patterns to the extreme cold winter of 1963 were to occur today, it  
475 would still lead to an extreme cold anomaly. This would be more severe than recent cold winters such as 2010,  
476 or the 'beast from the east' cold event in 2018. Although a winter as severe as 1963 is still physically possible in  
477 Europe, it is very unlikely (Sippel et al., 2024). However, if preparedness and adaptation to cold extremes reduce  
478 in response to a warming climate this may cause less severe future cold waves to be more impactful than past  
479 events (Pinto et al., 2024).

## 480 Future Change

481 The UKCP18 regional climate models indicate that the number of frost days (daily minimum temperature below  
482  $0^{\circ}\text{C}$ ), icing days (daily maximum temperature below  $0^{\circ}\text{C}$ ) and Heating Degree Days are all projected to decrease  
483 across the UK. The largest reductions are in Scotland (Hanlon et al. 2021). Intense cold spells, where the local  
484 daily average surface temperature is less than  $-2^{\circ}\text{C}$  for two or more days, are also expected to become less  
485 frequent, but will still occur (Kendon et al., 2021). Decreases in the amount of snowfall and snow cover are  
486 expected across the UK, especially in mountainous regions; in low-lying areas snowfall is already more  
487 intermittent (Pirret et al., 2021).

## 488 1.3.2 Water-dominated Hazards

### 489 1.3.2.1 Rainfall, flooding and further hydrological hazards

## Headlines

1. The UK climate is getting wetter, particularly in winter (**High confidence**). There is evidence of increasing rainfall extremes at daily scales, but for short-duration (1-3hr) rainfall extremes, trends are difficult to detect above natural variability (**Medium confidence**).
2. Rainfall is expected to become more intense which could lead to an increase in severe flooding (high confidence). Increases in mean winter rainfall will also drive increases in antecedent moisture, exacerbating flood risk (**Medium confidence**).
3. There is improved understanding of the drivers of extreme rainfall, and how changes will emerge over the coming years and decades. The latest projections indicate greater increases in peak river flows (**Medium confidence**).
4. Observations of sub-daily rainfall remain sparse and observations of surface water flooding are poor. Standard flood risk assessment approaches based on simple uplift approaches may underestimate future flood hazard. Uncertainty remains on the role of changes in large-scale circulation patterns in future extreme rainfall change, and how accurately these are represented in climate models.

490

491 This section looks at how extreme rainfall in the UK affects flooding. It covers both short bursts of heavy rain  
 492 that cause surface flooding and longer events that lead to river flooding. The table below identifies which risks  
 493 this hazard is particularly (but not exclusively) relevant to.

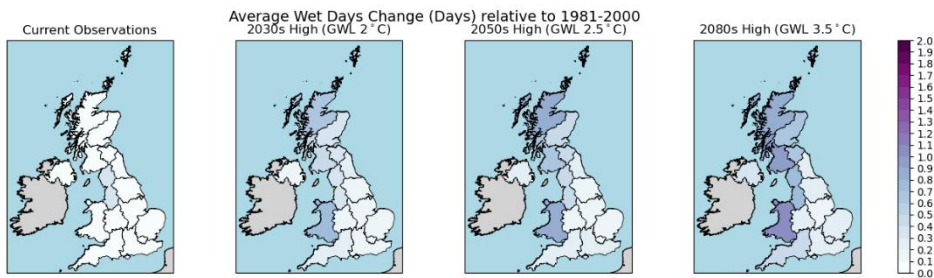
Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment	Infrastructure
N1, N2, N4, N6, N8	E1, E2, E3, E4, E7	H2, H6	BE2, BE4, BE6, BE7, BE8	I1, I2, I3, I4, I5, I6, I9

494 Table 1.4: Number of heavy rainfall days annually for current and future scenarios.

Metric	Region	2005-2024	2030s		2050s		2070s	
		Recent Past	Central	High	Central	High	Central	High
<b>Summer Wet Days</b>	Average of the maximum 1-day rainfall (mm) in June, July and August.							
	London	33.3	33.7	38.8	32.7	36.5	32.1	42.1
	Belfast	34.1	31.2	38.8	31.5	36	31.4	39.3
	Edinburgh	34	35.5	42.3	35.1	46.3	37.6	50.5
	Cardiff	38.4	34.3	39.7	32	45.8	33.5	41
<b>Winter wet spells (mm)</b>	Average of the maximum 5-day precipitation accumulation (mm) in December, January, and February.							
	London	44	48.6	55.9	47.4	64.4	49.1	59.6
	Belfast	54.4	57.3	68.8	58.9	74	61	69.2
	Edinburgh	67.9	59.9	70.9	60.4	68.5	59.4	76.7

	<b>Cardiff</b>	<b>79.1</b>	<b>87.8</b>	<b>104.4</b>	<b>89.3</b>	<b>108.5</b>	<b>89.9</b>	<b>120</b>
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495



496

497 *Figure 1.8: Maps showing current (2005-2024) and future changes in heavy rain days, relative to a 1981-2000 baseline.*  
 498 *Panels are provided for the CCRA4 high scenarios for UK administrative regions. [Note that the metrics tables and maps*  
 499 *within the State of the Climate chapter may be subject to minor amendments following Community Review. These will not*  
 500 *materially impact any of the conclusions of the chapter.]*

## 501 Introduction

502 Although rainfall in the UK varies greatly from day to day and year to year, there is strong evidence that the  
 503 climate is becoming wetter overall, particularly during the winter-half year (October to March). Several recent  
 504 record-breaking rainfall events have been linked to climate change, and evidence suggests that rainfall extremes  
 505 are becoming more frequent and intense. Climate projections indicate a general shift toward wetter winters and  
 506 drier summers, but with heavier bursts of summer rainfall. New high-resolution climate model projections  
 507 available since CCRA3 have produced new findings that are reported here.

## 508 Observed Change

509 Observations show that both annual average rainfall and the frequency of heavy rainfall events in the UK have  
 510 increased. Between 2015 and 2024, the UK was 10% wetter than during 1961-1990, with winters 21% wetter  
 511 and smaller changes in other seasons (Kendon et al. 2025). Five of the ten wettest years on record have occurred  
 512 this century, while none of the 10 driest years (since records began in 1836) have occurred during this period.  
 513 The likelihood of wet winters has increased by at least 1.5 times compared to a climate without human-induced  
 514 climate change (Christidis et al., 2018), while extreme winter daily precipitation is now 1.4 to 2.6 times more  
 515 likely than without human-induced climate change (Cotterill et al., 2024).

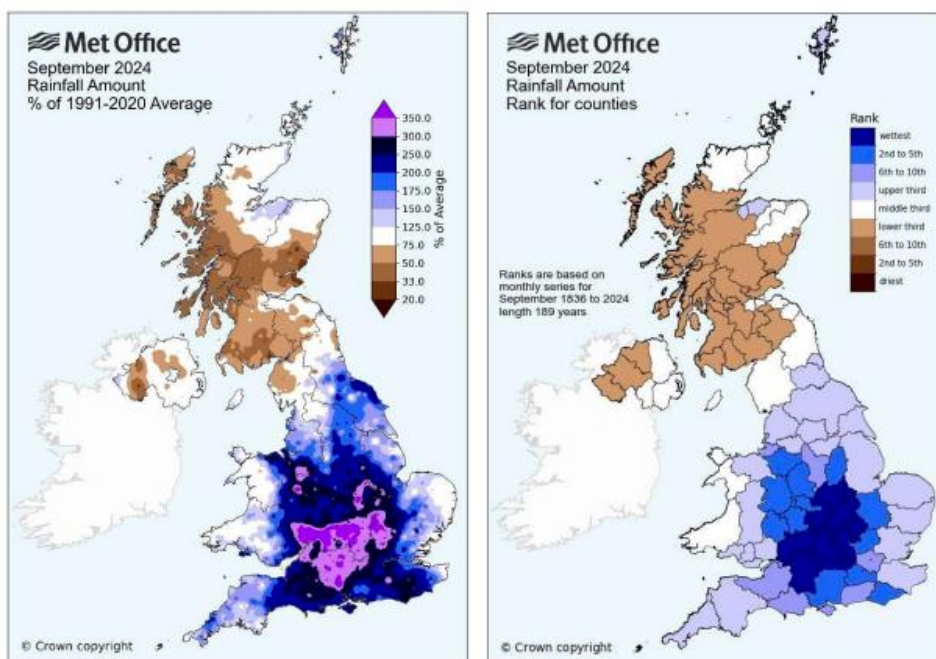
516 There is growing evidence that rainfall extremes are changing (Hawkins et al., 2020) and human-induced climate  
 517 change has increased the likelihood of several recent record-breaking rainfall events. These include the record  
 518 wet February 2020 (Davies et al., 2021), extreme daily rainfall in October 2020 (Christidis et al., 2021), and heavy  
 519 rainfall leading to the record wet winter in 2023/24 (Kew et al., 2024). However, detecting trends in sub-daily  
 520 rainfall (e.g., rainfall measured over minutes to hours rather than days) remain challenging. This is due to sparse  
 521 and short sub-daily rainfall observations as well as significant decadal variability in the UK's climate (Kendon et  
 522 al., 2018). Recent studies have made use of new km-scale climate model projections to explore convective  
 523 rainfall events (e.g., Tett et al. 2023) but attribution studies are limited by small ensemble sizes. Overall,  
 524 attributing trends in rainfall at regional to local scales is difficult, as natural variability plays a major role in  
 525 driving extremes.

526 Attribution studies now extend beyond rainfall to include hazards such as flooding, revealing that human-  
527 induced climate change has increased the severity of several recent UK floods. This includes the winter 2023/24  
528 floods, where England and Wales experienced their highest winter flows on record (Chan et al., 2025), estimated  
529 as 13.5% higher than analogue periods back to the 1850s.

### 530 **Extreme wet month – September 2024**

531 A sequence of storms in the last ten days of September 2024 brought 150 to 200 mm of rain to parts of the  
532 Midlands, almost a quarter of the expected annual rainfall for the region. Oxfordshire and Bedfordshire had  
533 their wettest calendar month on record in a series from 1836. Oxford recorded its wettest calendar month for  
534 250 years, and the two-day rainfall total from 22 to 23 September was 118.9 mm, breaking the previous record  
535 of 98.1 mm from 9 to 10 July 1968. Some locations received more than 400% monthly average rainfall from 21-  
536 30 September.

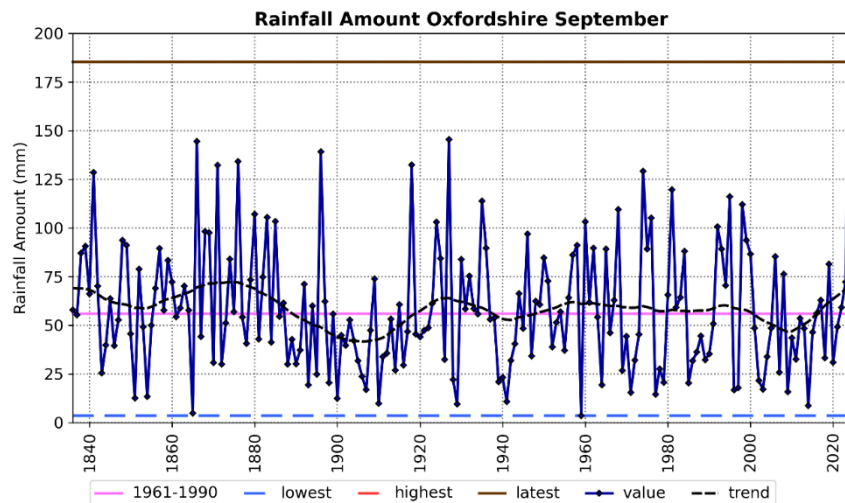
537 Figure 1.9 shows rainfall totals and rankings (by county) for September 2024. A large region in central England  
538 exceeded 300% of average monthly rainfall. Gloucestershire, Wiltshire, Oxfordshire, Berkshire, Warwickshire,  
539 Leicestershire, Northamptonshire, Buckinghamshire, Bedfordshire, and Rutland recorded their wettest  
540 September on record (shown in dark blue on the right-hand panel).



541  
542 *Figure 1.9: (left) September 2024 rainfall as a percentage of the 1991-2020 monthly average. (right) Ranking of September 2024 rainfall*  
543 *within the monthly series from 1836-2024.*

544 Torrential downpours from thunderstorms caused disruption and damages to transport and infrastructure.  
545 Surface water flooding closed roads in the west Midlands including a section of the M5 motorway, and flooded  
546 sections of the rail network.

547 For Oxfordshire this was a record-shattering event (see Figure 1.10). The 185.2 mm recorded was 27% wetter  
548 than the previous wettest September (1927, with 145.5mm). Some of the same areas also recorded their  
549 wettest February in 2024, experiencing two record wet months in the same year.



550

551 *Figure 1.10: Time series of Oxfordshire September monthly rainfall amounts. The solid brown line indicates the September 2024 total*  
 552 *rainfall, far outside the range of other September monthly totals in a series from 1836.*

## 553 Future Change

554 Rainfall intensity is projected to increase with further warming, mainly due to the capacity of the warmer  
 555 atmosphere to hold more moisture. According to the UKCP Local projections, by 2070 under a high emissions  
 556 scenario (equivalent to roughly a 4 °C Global Warming Level), the number of events exceeding 20 mm per hour,  
 557 enough to trigger a flash flood, could increase 4-fold (Kendon et al., 2023). Similarly, the number of autumn days  
 558 exceeding 50mm could increase by 85% (Cotterill et al., 2021). Using the same projections, events with a 3%  
 559 annual likelihood are expected to become 30% more intense for hourly extremes and 20% more intense for daily  
 560 extremes (Chan et al., 2023b). Overall, for every degree of regional warming, the intensity of heavy downpours  
 561 is expected to rise by 5-15% (Kendon et al., 2023), meaning significant changes are likely even under lower  
 562 global warming levels. Short-duration summertime rainfall extremes are projected to increase most strongly in  
 563 northern parts of the UK and for the most extreme events (Kendon et al., 2021). The largest increases in hourly  
 564 extremes are expected in autumn, with projected rises of 30% in the southern UK and 50% in the northwest UK  
 565 by the 2070s (Kendon et al. 2021). This is consistent with an extension of the season for intense summer  
 566 downpours.

567 Changes in hourly rainfall extremes may not occur gradually (Kendon et al., 2023). Instead, there may be rapid  
 568 shifts from year-to-year, and high regional differences, reflecting the combined effects of natural variability and  
 569 climate change. Record-breaking events are projected to increase substantially for both seasonal rainfall and  
 570 local rainfall extremes (Kendon et al., 2023).

571 Other aspects of rainfall change are also important for understanding future impacts. Slow-moving storms,  
 572 which produce high rainfall amounts and flooding, are projected to be around 14 times more frequent across  
 573 Europe by 2100 (Kahraman et al., 2021). The risk of large intense thunderstorms capable of producing heavy  
 574 rainfall that lasts for several hours is also increasing (Chan et al., 2023a). However, these changes depend on  
 575 large-scale dynamics, and are more uncertain, varying across models.

576 Increases in rainfall intensity may lead to increases in flooding (Rudd et al., 2019; Rudd et al., 2023) but other  
 577 factors such as catchment characteristics, changes in land surface and pre-event soil moisture conditions also  
 578 control flood characteristics.

579 Hydrological models indicate decreases in low river flows and increases in high flows across the UK by the end of  
 580 the century (or GWL above 4 °C) (Kay et al., 2021b; Smith et al., 2024; Hannaford et al., 2023; Arnell et al., 2021;  
 581 Hughes et al., 2021; Lane et al., 2022; Parry et al., 2023b). Increases to flood peaks are typically higher in the  
 582 west and the rate of change may accelerate for some southern regions for global warming levels over 2.5 °C  
 583 (Rudd et al., 2023). The frequency of widespread flood events in winter is expected to increase significantly,  
 584 while these show a reduction in spatial scale in summer (Griffin et al., 2024). For Northern Ireland, we expect  
 585 increases in mean winter river flows but decreases in mean flows in other seasons (Kay et al., 2021a).

### 586 1.3.2.2 Drought in the UK

#### Headlines

1. There is some evidence for more severe river flow and soil moisture droughts in parts of the UK. Hydrological trends remain hard to detect due to large variability and the impacts of water management.
2. Hot, dry summers are expected to occur more often, reducing river flows and worsening droughts. Drier soils may prolong heatwaves and worsen droughts.
3. Widespread summer droughts will become more likely with warming, but low river flows and groundwater levels may coincide less. Socio-economic factors such as increasing water demand for energy production, may worsen droughts.
4. Changes in atmospheric circulation in response to warming, including climate drivers of multi-year droughts, remain uncertain. Further research is needed to ensure hydrological models accurately capture key drought processes.

587

588 This section considers hazards related to low rainfall, river flows, soil moisture and groundwater levels. The table  
 589 below identifies which risks this hazard is particularly (but not exclusively) related to.

Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment and Communities	Infrastructure
N1, N2, N4, N5, N6, N8	E1, E2, E3, E4, E6, E7	H2, H4, H5	BE4, BE6, BE8	I1, I2, I5, I6, I9

#### 590 Introduction

591 Drought is defined as a prolonged lack of water in the environment due to low rainfall (meteorological drought)  
 592 leading to drying of soils (soil moisture drought) and low river flows or groundwater levels (hydrological drought)  
 593 (Environment Agency, 2023).

594 Periods of low rainfall in the UK often happen when high-pressure weather systems block the usual path of  
 595 Atlantic storms. These systems push the jet stream north or south, keeping wet weather away from the UK  
 596 (Shaffrey, 2023). Dry winters are also linked to a weaker jet stream, bringing fewer storms to the UK. Large-scale  
 597 ocean patterns like La Niña can also contribute to drier conditions (Folland *et al.*, 2015). Additionally, slow  
 598 changes in sea surface temperatures over decades can cause prolonged periods of more frequent or less  
 599 frequent droughts (Sutton and Dong, 2012).

---

600 Drought affects the hydrological cycle at different timescales. Changes in river flows and groundwater levels  
601 depend on climatic factors but are also influenced by physical properties of river catchments (such as soil types  
602 and subsurface water storage) and water management (such as abstractions or streamflow support). Soil  
603 moisture deficits are additionally controlled by water loss due to evaporation, transpiration by plants and  
604 subsurface drainage.

605 Droughts in the UK impact public water supplies, water quality, agricultural productivity and ecosystems. The  
606 effects of drought are worse when they coincide with other climate extremes like heatwaves and wildfire.

## 607 Observed Change

608 UK winter rainfall is increasing, while no clear trends are evident for other seasons. A clear reduction in summer  
609 rainfall has not yet been observed (Ossó *et al.*, 2022). These rainfall changes are reflected in river flows, with  
610 increasing winter river flows in Scotland and northwest England. In summer, some rivers in southern UK show  
611 decreasing trends but these are not often statistically significant (Hannaford *et al.*, 2024). Since the 1960s, some  
612 rivers in the south and east show worsening droughts, while those in the north and west show less severe  
613 droughts (Hannaford *et al.*, 2024). Observed trends in groundwater levels are mixed, with increases in northern  
614 England and some reductions in central England (Di Nunno and Granata, 2024). Historically, the southeast UK  
615 has experienced more spatially extensive and longer droughts than the northwest. When the southeast is under  
616 severe drought, it is rare for the northwest to also be in severe drought (Tanguy *et al.*, 2021).

617 There is low confidence in identifying the main drivers of recent trends in river flows and groundwater levels,  
618 particularly in determining if climate or human influences have had the greatest influence. Urbanisation,  
619 reservoir management and wastewater discharge all affect river flows and groundwater levels and can  
620 exacerbate hydrological droughts (Wendt *et al.*, 2020; Van Loon *et al.*, 2022; Salwey *et al.*, 2023; Coxon *et al.*,  
621 2024). Land use change also drives river flow changes in some Scottish catchments (Wray *et al.*, 2024).

622 Modelled estimates of soil moisture show wetting trends in October and December and drying trends in April in  
623 most UK regions (Almendra-Martín *et al.*, 2022; Bevacqua *et al.*, 2024). Rising temperatures and related  
624 increases in evaporation since the 1960s have increased the frequency of springtime flash droughts, rapid-onset  
625 events that can last weeks to months (Noguera, Hannaford and Tanguy, 2024).

626 The 2022 drought had widespread impacts on agriculture, wildlife and water supplies (Barker *et al.*, 2024).  
627 Summer river flows in parts of southern and eastern England were among the lowest ever recorded and it  
628 caused the most spatially-extensive soil moisture drought for the past 60 years across western and central  
629 Europe (Schumacher *et al.*, 2024). Several water companies in south, east and west England imposed water use  
630 restrictions, affecting 19 million people.

631 The likelihood of severe combined heatwave and drought has increased (Baker, Shaffrey and Hawkins, 2021),  
632 with events like the 2022 drought both hotter and drier than similar droughts in the pre-industrial climate  
633 (Faranda, Pascale and Bulut, 2023). Soil moisture droughts like 2022 have become more likely across western-  
634 central Europe and are projected to become twice as likely at 2 °C GWL relative to 1850-1900 (Bevacqua *et al.*,  
635 2024; Schumacher *et al.*, 2024). Drier soils may also lead to atmosphere circulation changes that prolong these  
636 hot and dry extremes (Dirmeyer *et al.*, 2021).

## 637 Future Change

638 The UKCP18 projections indicate wetter winters and drier summers in the UK. Compound hot, dry extremes are  
639 expected to increase with warming (Bevacqua *et al.*, 2022). Meteorological drought coupled with increased  
640 evaporation is projected to be more than three times more frequent at a GWL of 4 °C (Reyniers *et al.*, 2023).

641 Nine-month rainfall deficits similar to the severe 1976 drought are expected to occur five times more frequently  
642 from the 2040s under the RCP8.5 emission scenario (roughly comparable to a GWL of 3 °C) relative to present-  
643 day (Kendon *et al.*, 2023).

644 River flow droughts are projected to become more frequent and severe across the UK based on the UKCP18  
645 projections. Most catchments are expected to experience reduced river flows, especially the south and east in  
646 summer (Lane and Kay, 2021; Parry *et al.*, 2023). The north and west of the UK is expected to see an increase in  
647 shorter seasonal droughts (Parry *et al.*, 2023). For Northern Ireland, river flows are expected to decrease in all  
648 seasons apart from winter (Kay *et al.*, 2021).

649 Projections for groundwater droughts are more uncertain, some boreholes may show modest declines but  
650 others show increases as wetter winters enhance groundwater recharge (Parry *et al.*, 2023). Widespread  
651 summer droughts are more likely to affect multiple UK regions simultaneously (Dobson *et al.*, 2020; Tanguy *et*  
652 *al.*, 2023), although in the southeast, river flow droughts are less likely to occur simultaneously with  
653 groundwater droughts (Tanguy *et al.*, 2023). This has important implications for water transfers and strategies  
654 for optimizing conjunctive use of surface and groundwater sources (Murgatroyd and Hall, 2020; Murgatroyd *et*  
655 *al.*, 2022).

656 Soil moisture droughts are also projected to increase in spatial extent, frequency and severity across the UK  
657 (Arnell and Freeman, 2021; Kay, Lane and Bell, 2022). Extreme soil moisture droughts that had about a 6%  
658 chance of occurring in a 1981-2000 climate are projected to become much more likely, with an 18% chance of  
659 occurring for a GWL of 2 °C, and a 33% chance at a GWL of 4 °C, with months between June and October being at  
660 especially high risk of soil moisture drought in the far future (Szczykulska *et al.*, 2024).

### 661 1.3.3 Wind-dominated Hazards

#### 662 1.3.3.1 Strong winds from Extra-Tropical Cyclones and Low Wind events

##### Headlines

1. There is no clear long-term trend in severe storms (extra tropical cyclones) affecting the UK, with decadal and year to year variation in storm activity. In the more recent past, the stormiest period was in the 1990s; since the early 2000s, damaging windstorms in Europe have become less common (**High confidence**).
2. Future changes are driven by natural and anthropogenic causes. The combined impact is uncertain. Biases in global climate models lead to over- and underestimates of the persistence and frequency of weather patterns important for storms in the North Atlantic (**Medium confidence**).
3. Newly available high-resolution climate model simulations (kilometre scale) give improved insight into the details of severe extra tropical cyclones, revealing a tendency to stormier conditions, and increased frequency of sting jets, in the future warmer climate (**Medium confidence**).
4. There is a lack of understanding of which factors will be most important in changing storm characteristics in the future.

663

664 This section considers the hazard of surface windstorms and wind drought. The table below identifies which risks  
 665 those two hazards are particularly (but not exclusively) relevant to.

Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment and Communities	Infrastructure
N1, N6, N8	E2, E4, E6, E7	H2, H6	BE4, BE6, BE7, BE8	I1, I2, I3, I4, I5, I6, I7, I8, I9

666 *Table 1.6: Summary of winter windy days (>98<sup>th</sup> percentile) for recent past (2005-2024) and under GWL central  
 667 and high scenario.*

		2005-2024	2030s		2050s		2070s	
Metric	Region	Recent Past	Central	High	Central	High	Central	High
Winter windy Days	Number of days in December, January and February, where winds exceed the 98 <sup>th</sup> percentile of the baseline (1 °C GWL)							
	London	3	3	4.5	3	4.5	4	6
	Belfast	3	2.9	4	3	4.5	3	4.7
	Edinburgh	3	3.9	5	3	5.8	4	4.9
	Cardiff	3	3	4	3	4.5	3	4.5

668

## 669 Introduction

670 Severe extra-tropical cyclones (also called *low pressure systems*) produce windstorms that cause significant  
 671 damages to public and private property and regularly lead to fatalities. Extra-tropical cyclones usually form over  
 672 the western North Atlantic over several days. Their development and strengthening are driven by complex  
 673 interactions between weather patterns high in the atmosphere (cf. e.g., Uccellini and Johnson 1979; Hoskins and  
 674 Valdes, 1990; Pinto et al., 2009), exchanges between the ocean and the air (e.g., Nelson et al., 2014), and the  
 675 release of heat from condensation (e.g., Fink et al., 2012).

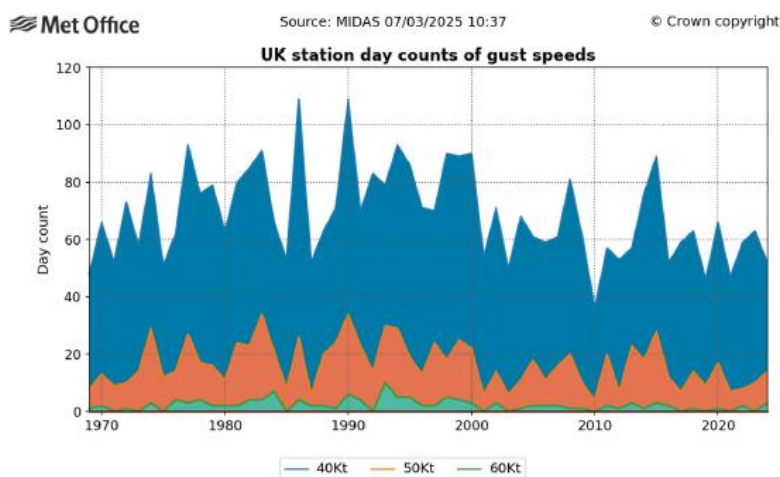
676 Surface low-pressure systems form due to interactions between atmospheric waves and the temperature  
 677 difference between the north and south of the mid-latitudes. These strong temperature contrasts create fast-  
 678 moving air currents called the Polar-Front Jetstream, at about 10-12 km altitude, with wind speeds reaching over  
 679 300 km/h (cf. e.g., Woollings, 2019; Stendel et al., 2021).

680 At the surface, strong winds in extra-tropical cyclones occur along cold and warm fronts (cf. e.g., Shapiro and  
 681 Keyser, 1990), and in ‘sting jets’, narrow streams of air that descend rapidly from high altitudes to the ground  
 682 (e.g., Browning, 2004; Hart et al., 2017; Eisenstein et al., 2020). Although sting jets are hard to detect, they have  
 683 been linked to severe damage in storms such as the Great Storm of 1987 (e.g., Baker, 2009; Clark & Gray, 2018).

684 Extreme low wind speeds also present a hazard for specific applications, such as the generation of electricity  
 685 from wind (kinetic) energy, for example March 2021 in the UK (Staffell et al., 2021, 2022). Persistent, low wind  
 686 episodes are mostly caused by atmospheric blocking, where a strong surface high-pressure system blocks the  
 687 prevailing westerly flow. These blocks are part of the natural variability of the UK climate and a consequence of  
 688 the waviness of the atmospheric flow in the mid-latitudes.

## 689 Observed Change

690 Analysis of observed and reconstructed storms activity over the past century shows no clear long-term trend in  
691 severe storms across Europe, including the UK (e.g., Feser et al., 2015). There is substantial year-to-year and  
692 multi-decadal variability (e.g., Alexander et al., 2005, Matulla et al., 2008), with the stormiest period occurring in  
693 the 1990s (Alexandersson et al., 1998; 2000; Alexander et al., 2005). Since the early 2000s, the number of  
694 damaging European windstorms has declined (Dawkins et al., 2016; cf. Fig. 1.13). This variability is closely linked  
695 to phases of the North Atlantic Oscillation (NAO, cf. section 1.3 of this report) (Dawkins et al., 2016), but, so far,  
696 there is no clear evidence that changes in windstorm activity can be directly attributed to human-induced  
697 climate change (IPCC, 2021).



698

699 Fig. 1.11: The number of days each year when maximum gust speeds  $\geq 40, 50$  and  $60$  Kt (46, 58, 69 mph; 74, 93, 111 kph)  
700 are recorded by at least 20 or more UK stations, from 1969 to 2024. Stations more than 500 m above sea level are excluded.  
701 The counts for 2024 are 52 (40 Kt), 14 (50 Kt) and 3 (60 Kt). The three days in 2024 in which at least 20 stations recorded  
702 gusts  $\geq 60$  Kt were 21 and 22 January (Storm Isha) and 7 December (Storm Darragh). Source: Kendon et al. (2025, their Fig.  
703 34).

704 Atmospheric blocking and related low wind events occur over the UK about 5-10 times each season, lasting for  
705 variable lengths of time (Lupo, 2021). Across the Northern Hemisphere, these events have become more  
706 frequent over the past 60 years, increasing from around 30 to 40 events per year (Lupo, 2021; Lupo et al., 2019).  
707 In observations, sustained periods of low wind power generation (duration of 14 days) have a return period of  
708 five years, while the longest observed event (about 26 days) is expected to occur about once every 100 years  
709 (Potisomporn et al., 2025).

## 710 Future Change

711 Climate models suggest a possible increase in extreme extra-tropical cyclones and windstorms over the North-  
712 east Atlantic (e.g., Carnell et al., 1996; Lambert and Fyfe, 2006; Leckebusch & Ulbrich, 2004; Leckebusch et al.,  
713 2006; Zappa et al., 2013, Little et al., 2023). However, the last two IPCC assessment reports (IPCC 2013, 2021)  
714 concluded that projections of future storminess remain uncertain. Most current models show a northward  
715 extension of the North Atlantic storm track, which could lead to increased frequency of windstorms over  
716 western Europe (e.g., Harvey et al., 2020), with larger increases at higher global warming levels (e.g., Feser et al.,  
717 2015). Higher resolution ocean models also project greater increases in east Atlantic storminess (Grist et al.,  
718 2021; SSP5-8.5 scenario to 2050; roughly equivalent to a GWL of  $2.5^{\circ}\text{C}$  at 2050). Recent research indicates that  
719 UK storm severity could increase by around 30% by 2080 (under SSP5-8.5 scenarios comparable to a GWL of  $3.5$

---

720 °C), mainly due to storms covering larger areas (Priestly et al., 2024). However, few studies focus on changes in  
721 storminess at mid-century (Little et al., 2023) as large natural variability makes it difficult to detect clear trends  
722 in storminess.

### 723 *Climate Change from UKCP18 Simulations*

- 724 • A summary of UKCP18 simulations is presented in Figure 1.12, showing the number of storm days per  
725 winter and their future change.
- 726 • Storm days are defined as days with wind speeds above a damage-relevant threshold (> 98<sup>th</sup> percentile,  
727 based on Klawa & Ulbrich 2003; Leckebusch et al., 2008).
- 728 • The UK currently experiences about 2.5 storm days per winter across all regions. No change is identified  
729 from UKCP18 for the central GWLs: results for England, Wales and Northern Ireland are very similar, and  
730 for Scotland a slight decrease is simulated.
- 731 • At higher global warming levels, towards the end of the century, Scotland shows the largest increase in  
732 storm days, with an additional 1.2 storm days per winter. For England, Northern Ireland, and Wales this  
733 change is smaller, about one day or less per winter.

### 734 *Increased resolution and CPM simulations*

735 Recent advances in computing power have made it possible to run more detailed simulations of extreme  
736 windstorms. Manning et al. (2022; 2023) used a high-resolution convection-permitting model (CPM, 2.2 km grid  
737 spacing) to examine how UK windstorms might change in the future. They found that global climate models  
738 (CMIP5 and CMIP6 ensembles) tend to underestimate storm strength, whereas the finer-scale CPM results show  
739 a clear increase in the frequency of extreme windstorms by 2100. This rise is mainly due to increases in warm-  
740 core storms that contain "sting jets" (climate forcing similar to a GWL of 3.5 °C, high end for 2080). However,  
741 large-scale circulation changes could also play a role. A recent kilometre-scale global model study suggests that  
742 future storms may shift further north, potentially reducing their impact on the UK (Gentile et al., 2025).

### 743 *Why is there uncertainty about future storminess?*

744 Uncertainty in future storminess is mainly due to competing effects in the atmosphere. With human-induced  
745 climate change, the lower atmosphere is warming faster at the poles, reducing the temperature difference  
746 between north and south, which could lead to fewer storms. However, higher in the atmosphere, this  
747 temperature contrast may increase, potentially leading to stronger storms (e.g., Shaw et al., 2016; IPCC, 2021) as  
748 it alters wave activity in the atmosphere and the jet stream. Also, warmer air can hold increased moisture: this  
749 may make storms more intense and bring heavier rainfall (e.g., Booth et al., 2013; see also section 1.3.2.1 on  
750 precipitation).

751 Yet, using several climate models indicates intensification of the North Atlantic jet stream in most considered  
752 storylines at GWLs of 2 °C and 4°C (Harvey et al. 2023). Storm frequency increases across northern and central  
753 Europe (Little et al. 2023), with storm severity more than doubled at GWLs of 2.5-3.5 °C in 2080. Under lower  
754 emissions scenarios, the projected increase in storm risk is lower.

### 755 *What do we know about future storm damages and loss?*

756 Future storm damages in the UK and western central Europe are expected to increase, although estimates vary  
757 (e.g., Leckebusch et al., 2007; Pinto et al., 2007; Donat et al., 2010). One study estimates a 23% rise in annual  
758 windstorm losses with 2.5 °C global warming (Ranson et al., 2014). More recently, Severino et al. (2024) found  
759 that rare damaging storms could happen every 28 years instead of every 100 under a high-emissions scenario

760 (SSP5-8.5, roughly comparable to a GWL of 3.5 °C). However, there remain large uncertainties in these projected  
 761 changes, mainly due to differences between climate models.

762 *The future of blocking and wind droughts*

763 Our understanding of changes to high-pressure blocking systems and related low winds (‘wind droughts’) is  
 764 characterised by three main aspects:

- 765 • Bias: Climate models systematically underestimate the occurrence of blocking situations (cf. i.a.  
 766 Woollings et al., 2018), thus hindering the clear understanding of dynamical causes of blocking  
 767 occurrence and how these might change.
- 768 • Frequency of blocking events: Global climate models show an overall decline in the hemispheric mean  
 769 mid-latitude blocking occurrence (Kautz et al., 2022), but these projected changes are smaller in  
 770 magnitude than model biases and natural decadal variability in blocking frequency (Woollings et al.,  
 771 2018), so highly uncertain.
- 772 • Duration of wind droughts: In a recent study, Qu et al. (2025) found an increasing trend in wind drought  
 773 duration (including the UK) in CMIP6 models, with an increase in the duration of the 25-year event of  
 774 20% to 40%, depending on GWL and time horizon.

775 **1.3.3.2 Severe Thunderstorms, Lightning and Hail**

**Headlines**

1. Severe convective storms are rare, but their impacts are large. Localised events like lightning strikes, hailstorms, tornadoes, and wind gusts cause severe damage to infrastructure, disrupt transport networks, and threaten lives. There is no evidence of observed trends due to lack of data and modelling studies (**Low confidence**).
2. Lightning frequency is expected to increase. While hailstorms are expected to decrease in frequency, the largest hailstones could increase in size. Little is known about future changes to tornadoes or convectively-driven wind gusts (**Low confidence**).
3. There is now a better understanding of these hazards, their impacts, and their future changes compared to CCRA3 (**Medium confidence**).
4. Both observations and models need to be improved with respect to clear identification of hazards such as hail and tornados. Increased model resolution will help in particular with simulation of hazards such as convective gusts.

776

777 This section considers hazards relating to convective (thunder)storms: tornadoes, (large) hail, lightning,  
 778 damaging wind gusts and heavy rainfall leading to flash floods. The latter is detailed in section 1.3.2.1. The table  
 779 below identifies which risks this hazard is particularly (but not exclusively) relevant to.

Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment and Communities	Infrastructure
N1, N6, N8	E2, E4, E7	H2, H6	BE2, BE4, BE6, BE7	I1, I2, I3, I4, I5, I6, I7, I8, I9

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## 780 Introduction

781 Severe thunderstorms leading to lightning strikes, intense precipitation, hail or even tornadoes are common in  
782 the midlatitudes. In the UK, thunderstorms occur less frequently than in continental Europe (Enno et al. 2020),  
783 but their impacts are significant and affect public safety, disrupt transport and energy systems, and damage  
784 agriculture and critical infrastructure.

## 785 Observed Change

786 Data limitations in observations and short-term forecasts hinder our ability to fully understand and prepare for  
787 hazards from convective storms. These events are short-lived, and localised in nature, which makes them difficult  
788 to monitor with existing systems. Volunteers are relied upon to report hail and tornadoes, which leaves gaps in  
789 the data. Radar often misses small tornadoes near the ground. Over the past 30 years, thunderstorm activity has  
790 slightly decreased in southern England but slightly increased in the north, in each region by about 0.25 days per  
791 year (Stone et al. 2022).

792 There is no clear long-term trend for hail frequency in the UK. More tornadoes have been reported since the  
793 1990s, likely due to better awareness and reporting (Wells et al., 2024). Because the incidence of tornadoes  
794 varies a lot from year to year and records are short, it is difficult to identify trends (Mulder and Schultz 2015).  
795 Despite their impacts, research on convective wind gusts in the UK is limited. Long-term observational trends in  
796 wind gusts related to convective activity are unknown, although there is an overall decline in high wind gust days  
797 over the UK (cf. Fig. 1.13 above).

## 798 Future Change

799 Convection-permitting climate models, such as UKCP Local, better represent thunderstorm processes and  
800 hazards (Kahraman et al., 2022). Studies with these models suggest UK lightning frequency could increase  
801 significantly under high-emission scenarios (Kahraman et al., 2022). By 2100, the number of lightning strikes in  
802 summer could double due to more unstable air stratification and extra moisture in a warmer climate (Kahraman  
803 et al., 2022). Lightning is also expected to increase over the North Sea in winter, which could threaten offshore  
804 wind farms and other marine infrastructure (Kahraman et al., 2022).

805 Severe hailstorms are expected to become less common in the UK by 2100 (Sanderson et al., 2015, Kahraman et  
806 al., 2025). Sanderson et al. (2015) find the number of thunderstorms producing damaging hailstones (diameter  
807 greater than 15 mm) reduce by a factor of two by 2070 for a high emissions scenario. Kahraman et al. (2025)  
808 show an increase in the number of thunderstorms with high amounts of small hailstones. However, they suggest  
809 severe hailstorms will increase by 20% in 2040s, but decrease by 64% by 2100 for a high emissions scenario.

810 This is because multiple factors for large hail growth change in a much warmer climate. These include increases  
811 in vertical wind shear due to a weaker large-scale circulation, and stronger updrafts in the hail growth layer. It is  
812 notable that the frequency of hailstorms in the UK is much lower than other parts of Europe in all simulations,  
813 and uncertainty in e.g., wind shear changes could dramatically affect these results. However, isolated instances  
814 of very large hailstones are expected to become more common (Kahraman et al., 2025).

815 There is little research on how tornadoes or strong winds from thunderstorms might change in the UK, as  
816 current climate models cannot simulate these events well. This also applies to convection-related wind gusts.

## Headlines

1. Near coastal UK ocean temperatures are steadily rising (**high confidence**) and has increased the frequency of extreme high-water events (**Very high confidence**).
2. Marine temperatures will continue to rise (**High confidence**). Sea level will continue to rise, further increasing the frequency of high-water events (**Very high confidence**). Significant changes in UK water circulation are expected (**Low confidence**).
3. June 2023 experienced record-breaking sea surface temperatures in UK waters. Such events are likely to be commonplace by mid-century (**Confident**). Sea level rise is accelerating (**High confidence**).
4. There are a lack of tide gauges along the UK coastline (only 10 tide gauges in 2024) leading to large uncertainties in estimates of local and regional sea level changes and extreme water levels, increasing the risk of coastal inundation in coastal areas (**High confidence**). Future ice mass loss from ice sheets remains the largest uncertainty for future sea level rise (**Low confidence**), leading to substantial risk of inundation in coastal areas. Changes in extreme sea levels and their link to changes in storms in the Atlantic and Arctic remain uncertain (**Low confidence**). Knowledge of the future regime of current circulation in UK waters (**Low confidence**).

818

819 This section considers hazards relating to sea surface temperatures, waves, storms and sea level rise. The table  
820 below identifies which risks this hazard is particularly (but not exclusively) relevant to.

**Risks affected per Sectoral Impact Category**

Land, Nature and Food	Economy	Health and Wellbeing	Built Environment and Communities	Infrastructure
N1, N3, N7, N9	E2, E3, E4, E6	H1, H2	BE3, BE6, BE8	I2, I3, I4, I7

821 *Table 1.7: Sea level projections from the Met Office Projecting Future Sea Level (ProFSea) tool (Perks & Weeks,*  
822 *2023) for coastal locations are provided. This follows the methodology laid out in UKCP18 to provide sea level*  
823 *projections for future emissions scenarios. Sea level projections are not well suited to the GWL approach adopted*  
824 *for other climate indices, so here are presented projections for a middle scenario (RCP4.5) and a high-end emissions*  
825 *scenario (RCP8.5). The table includes the central estimate only and users requiring more information about the*  
826 *underpinning science and uncertainty ranges should review Perks (2023) and the ProFSea tool.*

Region	2030s		2050s		2080s	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
<i>Time-mean sea-level rise projections relative to 1981-2000 (m)</i>						
<i>London</i>	<i>0.15</i>	<i>0.17</i>	<i>0.26</i>	<i>0.30</i>	<i>0.44</i>	<i>0.58</i>
<i>Belfast</i>	<i>0.09</i>	<i>0.10</i>	<i>0.16</i>	<i>0.20</i>	<i>0.29</i>	<i>0.42</i>
<i>Edinburgh</i>	<i>0.08</i>	<i>0.09</i>	<i>0.15</i>	<i>0.19</i>	<i>0.26</i>	<i>0.39</i>
<i>Cardiff</i>	<i>0.15</i>	<i>0.16</i>	<i>0.25</i>	<i>0.29</i>	<i>0.43</i>	<i>0.56</i>

---

## 827 Introduction

828 The marine environment faces threats from ocean warming, marine heatwaves, acidification, changes in ocean  
829 currents, and alterations in carbon storage. These changes affect marine life and human activities. Wave  
830 conditions around the UK are influenced by local winds and incoming swell waves from the Atlantic and Arctic  
831 Oceans. Extreme waves occur during intense storms and are closely linked to storm track.

832 Climate risks in the UK often manifest as multi-hazards at the coast. Extreme sea level events are driven by  
833 various mechanisms, spanning a wide range of time scales. Extreme sea levels can be generated by storms (often  
834 termed storm surges). Their heights and potential impacts are controlled by the intensity, speed, and path of the  
835 storm and its timing relative to the tide. Temporary, but potentially very damaging, individual occurrences of sea  
836 level extremes are called 'event-scale' extreme sea levels. These occur due to a combination of factors such as  
837 storm surges, waves, and astronomical tides. Extreme sea levels cause coastal flooding and erosion. These risks  
838 impact various sectors, including food and water security, renewable energy, and shipping.

839 Global sea-level rise is driven mainly by the expansion of seawater as it warms, and the melting of land ice, due  
840 to warming temperatures. The rate of global sea-level rise is increasing, with significant contributions from  
841 melting glaciers and ice sheets. Since 1900, average sea levels in the UK have risen by 19.5 cm, with two-thirds  
842 (13.4 cm) of this rise happening in just the last three decades (Kendon et al., 2025). This rate of change is higher  
843 than the global estimate of 10.6 cm calculated from satellite altimetry, suggesting UK sea level is rising faster  
844 than the global average.

## 845 Observed Change

846 The rate of ocean warming has increased consistently over the past six decades, with record warming in 2023.  
847 Near-coast sea-surface temperatures around the UK from 2014-2023 were 0.3 °C warmer than the 1991-2020  
848 average and 0.9 °C warmer than 1961-1990 (Kendon et al., 2024). Warmer oceans are contributing to marine  
849 heatwaves, and in June 2023, an intense 2-week marine heatwave caused ocean temperatures to be 5 °C  
850 warmer than average for that time of year (Jacobs et al., 2024).

851 With respect to wave heights, overall, a 0.1 m reduction in average wave height has been observed, leading to  
852 calmer seas. However, the height of the most extreme waves has increased by 0.5 m in some areas, associated  
853 with increasing storminess (Bricheno et al., 2023, Bricheno and Wolf, 2018). Cyclone tracks have been shifting  
854 northward since the 1990s. Historical records show the northeast UK is most impacted by long and high storm  
855 surges, while the English Channel experiences shorter and smaller events (Camus et al., 2024). There is no firm  
856 evidence linking climate change to observed trends in UK storms and waves.

857 Observational data provides confirmation of the accelerating rate of sea level rise. The tide gauge at Newlyn  
858 recorded the highest sea level on record in 2023 (Kendon et al., 2024). Sea level rise is not uniform around the  
859 coastline of the UK. From 1991 to 2020 the rate of sea level rise at locations around the UK ranged from 3.0 to  
860 5.2 mm per year, with the highest rates of change recorded in the Scottish Outer Hebrides and at the southeast  
861 England coast, with the lowest rates along the coast of northeast England (Kendon et al., 2022). However, the  
862 low density of tide gauges around the UK coastline means there are large uncertainties in both the rate of sea-  
863 level rise and the impacts of storms on local extreme sea levels.

## 864 Future Change

865 *Future Marine Conditions*

---

866 In the northwest European shelf seas, sea surface temperatures are projected to increase by about 3 °C by the  
867 2100, with a related reduction in salinity (by 1 practical salinity unit) under a high emissions scenario. Marine  
868 heatwaves are expected to become more common by the mid-21<sup>st</sup> century (Berthou et al., 2024, Jacobs et al.,  
869 2024).

870 Changes in air temperature will alter ocean density stratification, areas where lighter (warmer or fresher) water  
871 sits on top of denser (colder or saltier) water. There will be an increase in the strength and duration of summer  
872 stratification. Additionally, more rainfall and runoff from the land could increase stratification in coastal seas, in  
873 particular the North Sea (Holt et al., 2018). Increased stratification reduces the mixing of nutrients from deeper  
874 waters and affects the distribution of oxygen, impacting marine ecosystems and fisheries. It also affects the  
875 regulation of sea surface temperatures, which can lead to changes in weather patterns. Decreased ocean  
876 circulation strength could also affect regional climate, especially in western Europe (Tinker et al., 2024).

### 877 *Future Sea-Level Rise*

878 Centuries of rising sea levels are already committed due to past emissions, but the rate and amount of future  
879 sea-level rise depend on greenhouse gas emissions (Naughten et al., 2023, Fox-Kemper et al., 2023). By 2100,  
880 global sea levels could rise by 0.28 to 0.55 m under low emissions and by 0.63 to 1.02 m under high emissions  
881 scenarios (Fox-Kemper et al., 2023). By 2300, UK capital cities could experience 1 to 4 m of sea-level rise (Palmer  
882 et al. 2024). Future rates of ice loss, particularly from Antarctica and Greenland, remain uncertain, potentially  
883 leading to higher sea levels than currently predicted. High-impact, low-likelihood scenarios, providing a plausible  
884 worst-case, could lead to an additional 1 m of global mean sea level rise by 2100 (Fox-Kemper et al., 2023, van  
885 de Wal et al., 2022) and between 8 to 17 m by 2300 under a high emissions scenario (Fox-Kemper et al., 2023).

886 By 2100, the winter storm track over the UK could intensify (medium confidence, cf. section 1.3.3.1), increasing  
887 the severity of waves (Morim et al., 2019, Wolf et al., 2020). Severe storms during autumn may become more  
888 frequent if tropical cyclones intensify and their region of origin expands northwards (Bricheno et al., 2023; cf.  
889 section 1.3.2). Rising sea levels will allow waves to travel in deeper water, increasing flood and erosion risks  
890 (Environment Agency, 2020). The spatial pattern of high waters around the UK depends on maximum wave  
891 height, storm surges, tidal range, and sea-level change. Southern England will experience the greatest amount of  
892 sea-level rise, raising the risk of extreme water levels (Rulent et al., 2021). Retreating sea-ice will increase the  
893 height of waves from the north. Under a high emissions scenario, 1-in-100-year coastal floods are expected to  
894 occur at least once a year along most European coastlines before 2050 (Vousdoukas et al., 2018).

895 Since CCRA3, Palmer et al. (2024) have developed a sea level storyline framework that more completely  
896 represents future uncertainties, including poorly understood ice sheet instability processes, and provides a  
897 comprehensive set of possible outcomes to inform coastal decision makers. Projected sea-level rise at 2300 for  
898 the UK, under three storylines based upon IPCC AR6 likely ranges, shows a marked spatial pattern in the  
899 magnitude of sea-level rise experienced across the UK. The largest sea level rise is projected for the south and  
900 southwest of the UK.

901 **1.3.5 Compound Hazards**

**Headlines**

1. Multi-hazard storm sequences in winter and impactful hot-dry periods in summer have become more common (**Low confidence**).
2. The likelihood of very severe hot-dry summers and wet-windy winters with multiple, linked, high-intensity events (e.g., heatwaves or storms) will increase. Cold multi-hazard events will be less prevalent (**High confidence**).
3. Co-occurring hazards in the UK were not explicitly considered in CCRA3, but are now widely recognised as a first-order factor in dictating the severity of risks (**High confidence**).
4. With a few key exceptions the extent to which multiple hazards co-occur and how this relates to larger-scale circulation patterns is poorly researched, both for the present-day and within climate models representing the future.

902

903 This section considers how and when hazards co-occur or compound, focussing on the link through to impacts.  
 904 The table below identifies which risks this hazard is particularly (but not exclusively) relevant to.

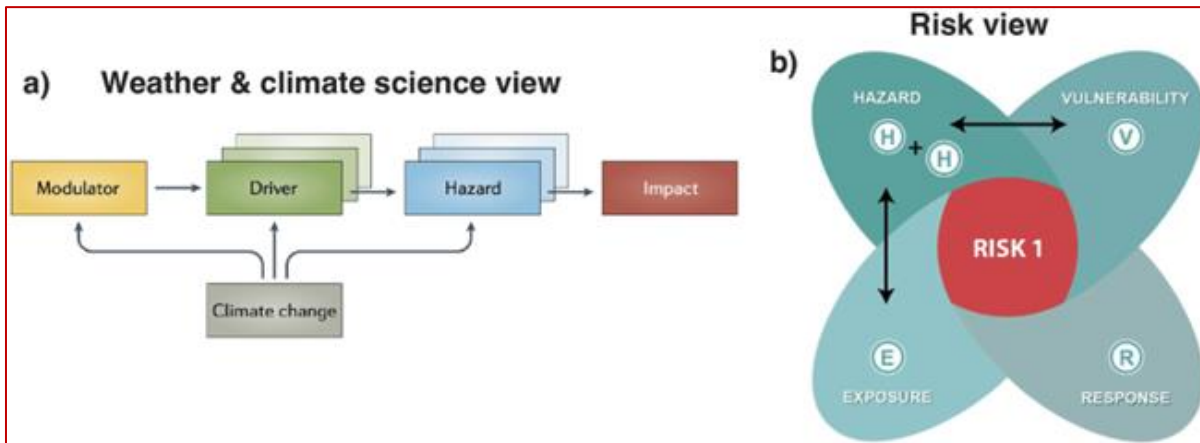
Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment and Communities	Infrastructure
N1, N2, N6, N8, N11	E1, E2, E3, E4, E6, E7	H1, H2, H6	BE1, BE2, BE4, BE6, BE7, BE8	I1, I2, I3, I4, I5, I6, I7, I8, I9

905 **Introduction**

906 Extreme weather phenomena often do not occur in isolation. When hazards co-occur or compound, linked by  
 907 various atmospheric processes, impacts may be amplified (e.g., Hillier et al., 2015; Zscheischler et al., 2020) and  
 908 potential impacts can be larger than from individual hazards separately. Consequently, understanding the  
 909 processes leading to compound events is necessary to fully quantify their overall risks.

910 Risk from multiple natural hazards, or *multi-hazard risk*, has been long recognised (e.g., Hewitt and Burton,  
 911 1971; UNEP, 1992; Kappes *et al.*, 2012). Recently, this has evolved into the broader concept of *compound risk*,  
 912 which refers to the combination of multiple drivers and/or hazards that together contribute to societal or  
 913 environmental impacts (Leonard et al., 2014; Zscheischler et al., 2018; Hillier et al. 2020, cf. Fig 1.14a). Simpson  
 914 et al. (2021) further expanded this framework by focussing on linkages, such as shared vulnerabilities or  
 915 interdependent systems, that create complex climate risks (Fig 1.14b). They identified 10 types of risk  
 916 interdependency, including cascading effects (de Ruiter *et al.*, 2019).

917



918

919  
920  
921

Fig. 1.12: Weather and climate risks often arise due to multiple, interacting factors. a) A compound event, climate-based perspective where hazards might have common modulators (e.g., storms, El Niño) and/or a related driver (e.g., wind, rain) (Zscheischler et al., 2020). b) Linkages between determinants of complex risk – modified from Simpson et al. (2021).

Four characteristics usefully categorise **compound hazards** (Zscheischler et al., 2020, Bevacqua, 2021):

**Preconditioned:** hazards manifest due to previous environmental events or pre-existing conditions e.g., hydro-meteorological events as extensive rain over a longer period affecting soil moisture.

**Multivariate:** involves multiple climate drivers and/or hazards, even if not individually extreme.

**Temporally compounding:** hazards occurring clustered in a limited time window.

**Spatially compounding:** hazards affecting a specified geographic region.

922

923 The term *co-occurring* (Hillier et al., 2015) is increasingly used (De Luca et al., 2017; Dodd et al., 2021; Pradhan et  
924 al., 2022; Bloomfield et al., 2023). It is valued for its simplicity, as it deliberately avoids implying any underlying  
925 process. Instead, it only describes an *episode* (Hillier et al., 2025) in which two or more events occur within the  
926 same region (e.g., a country or a city) and within a defined timeframe (e.g., an hour, a week, a year).

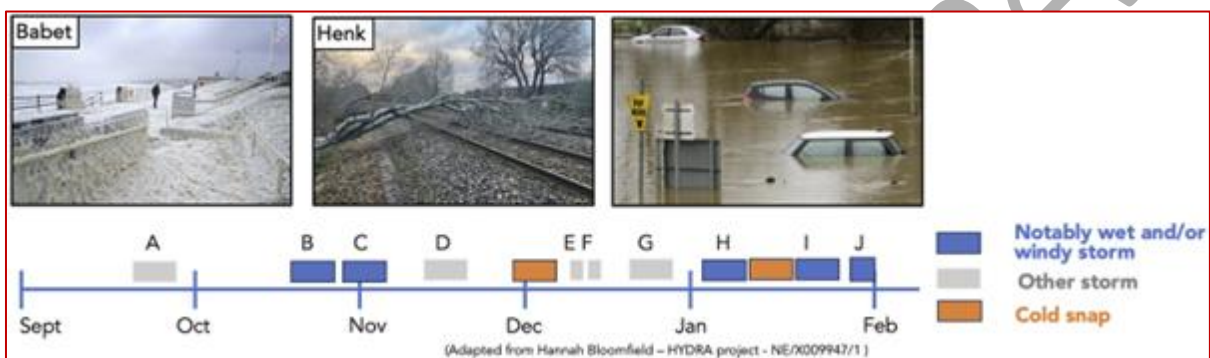
## 927 Observed Change

928 Between 16 and 21 February 2022 the storm sequence ‘Dudley’, ‘Eunice’ and ‘Franklin’ caused several hydro-  
929 meteorological hazards (snow, landslides, flooding, extreme winds) at locations across the UK and Northwest  
930 Europe (Kendon, 2022a; Mühr et al., 2022). Then, in July 2022, there was widespread drought, extreme heat  
931 (>40°C) and wildfires. These are recent examples of co-occurring extremes within a single year. However,  
932 detecting a trend from the past to current climate in these co-occurring extremes needs a longer historical  
933 record than is required when looking at one hazard alone, and recent occurrences constitute weak evidence.

934 CCRA3 did not explicitly consider impactful compound events (e.g., Sherwood et al., 2024; Wood et al., 2023),  
935 compounding, or co-occurring hazards except to suggest that plausible storylines and scenarios (Shepherd et al.,  
936 2018) might be useful in developing appropriate stress tests. It noted, separately, the roles of a large-scale

937 atmospheric pattern called the North Atlantic Oscillation (NAO). Winters with a positive NAO phase (NAO+) are  
938 dominated by storms and so are warmer, wetter and windier in the UK (Murphy et al., 2018), while NAO+  
939 summers are characterised by high pressure favouring hotter and dryer conditions (Folland et al., 2009).

940 During winter, inland flooding and extreme winds are the two primary hazards impacting the UK, and evidence is  
941 increasingly robust that they systematically co-occur for timescales from daily to seasonally, driven by cyclonic  
942 storms (Bloomfield et al., 2023). This co-occurrence is greatest in NAO+ winters and for the most severe events,  
943 perhaps controlled by the jet stream via its influence on storm formation and evolution (Hillier et al., 2020;  
944 Hillier and Dixon, 2020; Manning et al., 2024). Successive storms, like in winter 2013/14 (cf. Wild et al., 2014) can  
945 cause very wet antecedent conditions that can lead to prolonged or extreme flooding (e.g., Bloomfield et al.,  
946 2023; Fig. 1.15). Importantly, wintertime storms can also cause sequences of storm surges and high waves  
947 (Jenkins et al., 2023), and landslides impacting roads and railways (Klaver et al., 2024; Palamakumbura et al.,  
948 2021). Likewise, snowmelt can amplify flooding (e.g., Storm Bert) and damaging wintertime tornadoes and hail  
949 are also possible (e.g., Jersey in storm Ciarán) (Wells et al., 2024b, a).



950  
951 *Fig. 1.13: Timeline of a very active storm season in the UK and Ireland, winter 2023/24. Letters are the first letters of named storms (Met*  
952 *Office, 2024), e.g., 'B' is Babet.*

953 During summer, hot-dry conditions in the UK are typically linked to stable high-pressure and an NAO+ state (e.g.,  
954 Kautz et al., 2022), enhancing the chance of drought, shrink-swell subsidence (one of the UK's most costly  
955 geohazards at £3 billion over the past decade (Jones et al., 2020)), and dangerous heatwaves if hot air is drawn  
956 north to the UK (e.g., Felsche et al., 2024). Airflow from the south, often at the end of heatwaves, can also bring  
957 severe convective thunderstorms and accompanying multiple hazards (Gray and Marshall, 1998), e.g., hail (Wells  
958 et al., 2024a), tornadoes (Clark and Smart, 2015) and intense rainfall with the potential to cause flash flooding  
959 (Gray and Marshall, 1998; Sauter et al., 2023). This combination, except tornadoes, was exemplified in the  
960 unprecedented July 18-19<sup>th</sup> heatwave in 2022, which was an NAO+ summer (Kendon, 2022b; Kendon et al.,  
961 2023).

## 962 Future Change

963 Climate projections suggest the need to be prepared for more combined heatwave-drought summers,  
964 comparable to 1976 (Baker et al., 2021; Kendon et al., 2024), and for more winters with both extreme winds and  
965 flooding (Bloomfield et al., 2023; Hillier et al., 2025). Aside from these studies the extent to which multiple  
966 hazards co-occur and how this relates to larger-scale circulation patterns is poorly known, both at present and in  
967 climate models representing the future.

968 This section presents a 'what if' (Sherwood et al., 2024) or storyline (Shepherd et al., 2018) approach. It takes  
969 the idea of a persistent seasonal state (Bloomfield et al., 2023; Hillier et al., 2020) – a hot-dry summer or wet-  
970 windy winter – and combines this with an extremely intense episode of multi-hazard events.

### **A plausible compound high-impact wet-windy winter scenario:**

A plausible high-impact wet-windy winter scenario could bring 15-20 major storms, each causing flooding, strong winds, landslides, or coastal flooding. Together, these could seriously weaken the UK's ability to cope.

Given the increasing likelihood of hazard co-occurrence (e.g., Bloomfield et al., 2023; Hillier et al., 2025), this scenario follows the Bank of England in its stress tests (Bank of England, 2022; Hadzilicos et al., 2021) by including three high magnitude events within 1-2 weeks:

1. A severe windstorm akin to the infamous 15th October 1987 storm (87J), exacerbated by an increased likelihood of sting jets (Manning et al., 2022), with a southern UK storm track.
2. Extreme, widespread flooding exceeding Desmond or Babet levels given a wetter future climate (DeLuca, 2017; Matthews, 2018; Manning et al. 2024).
3. A major storm surge like that of Xaver (2013) but with a 0.6 m higher sea level, leading to coastal flooding exceeding the impact of the 1953 event in the National Risk Register (Bulgin et al., 2023; Perks et al., 2023).

This scenario is realistic because ongoing climate changes make it more likely that multiple extreme events could happen at the same time.

971

972

### **A plausible compound high-impact hot-dry summer scenario**

Such a scenario would resemble the events of the extreme hot and dry summer 1976, a benchmark drought in the National Risk Register (HM Government, 2023).

1. As climate change progresses, such a scenario increases in likelihood.
2. Extreme heat exceeding 40 °C for multiple days and prolonged days with high wildfire risk could be five times more frequent (Kennedy-Asser et al., 2021; Perry et al., 2022).
3. In this scenario many sustained and large wildfires in the UK are plausible due to abundant fuel and low levels of familiarity with this hazard.
4. Shrink-swell subsidence could affect 10% of properties (Harrison et al., 2020).
5. Following this, convective thunderstorms, akin to those in present-day central Europe, could bring widespread damage from large hailstones and surface-water flooding.

973

974 Flooding and saturated soils can readily follow prolonged drought and heatwaves, such as the hot-dry summer  
975 of 2022 leading into the very wet winter of 2023 (Fig. 1.15), in the NAO+ conditions historically typical of such  
976 rapid transitions in the UK (Parry et al., 2023). Desiccated earth structures, such as reservoir dams and railway  
977 embankments, can be severely weakened by prolonged dryness, only to be further stressed by saturation and  
978 heavy rainfall (Holmes et al., 2022). This type of high-impact extreme weather pattern transition is considered  
979 plausible (Arnell et al., 2025) and highlights the potentially surprising nature of climate-related hazards.

---

980 **1.3.6 Climate Change and Air Quality in the UK**

981 Both climate change and air quality issues are caused by anthropogenic emissions into the atmosphere (Pinho-  
982 Gomes et al., 2023). They have important implications for human health and the environment, with health  
983 effects of air pollution occurring rapidly, whereas effects of climate change occur over longer timescales (Akasha  
984 et al., 2021).

985 Climate change causes increased temperatures, altered precipitation, and shifts in atmospheric circulation, all of  
986 which influence the dispersion and chemistry of air pollution. For example, warmer conditions accelerate the  
987 formation of ground-level ozone, while increased atmospheric stagnation can trap pollutants. Several air  
988 pollutants are also climate forcing agents, such as particulate matter and ozone, hence air pollution can affect  
989 climate change both positively and negatively depending on whether they act as greenhouse gases or reflect  
990 radiation from the Earth. For example, a recent study (Samset et al., 2025) showed that the East Asian aerosol  
991 cleanup has likely contributed to the recent acceleration in global warming.

992 Since 2020, evidence has strengthened that climate change is already affecting air quality in the UK. For  
993 example, in recent hot summers, such as 2018 and 2022, ozone limits were exceeded, with increased health  
994 risks, particularly during heatwaves. Observed and modelled increases in stagnation events suggest a higher  
995 likelihood of pollution build-up under future climates (Horton et al., 2014). Wildfires are an increasingly  
996 important source of air pollution as they increase with climate change, both from UK fires due to hotter, drier  
997 summers and via long-range transport from Europe and North America (Burke et al., 2023).

998 Climate projections suggest the frequency and severity of air pollution episodes will increase, particularly for  
999 ozone (Tran et al., 2023). Future air pollution levels will depend strongly on emissions policy and technological  
1000 change. Multi-hazard air pollution and heat stress events are likely to become increasingly common (Sillman et  
1001 al., 2021), which will amplify health burdens.

1002

---

## 1.4 Global Climate and Anthropogenic Climate Change

While the focus of this chapter is on the UK, here we discuss several aspects of global climate. Firstly, this covers the large-scale drivers of UK climate to understand how they might change in future. Secondly, extremes of climate and climate change being experienced globally are discussed. In some cases, these might have a direct impact on the UK, for instance through supply chains affecting food or goods. In other cases, these can provide a pointer to what we might expect in the UK as warming continues. Thirdly, we discuss earth system tipping points, which are very large-scale, often abrupt or irreversible changes in regional climate that, if they were to occur, would produce further consequences for UK climate.

### 1.4.1 Large-scale drivers of UK climate variability and change

#### Headlines

1. Recent evidence finds slightly higher surface windspeeds in the wider northern hemisphere in the winter, and a strengthening of the winter jet stream. However, it is unclear whether this is a consequence of climate change or long-term natural climate variability (**Medium confidence**).
2. Projections of future North Atlantic conditions show an overall tendency towards more frequent wet and windy winters in the UK. However, climate models differ in the details of changes in frequency and persistence (**Medium confidence**).
3. Under continued global warming, large-scale conditions will continue to cause an increase in the frequency and severity of UK heat extremes and a decrease in the frequency and severity of winter cold spells (**High confidence**).
4. An important gap remains in our understanding of the main causes for future changes of the North Atlantic jet stream. Further evidence gaps stem from discrepancies between observed and modelled past circulation changes and discrepancies between different models on future circulation changes and how these impact weather and climate extremes.

#### Introduction

Direct warming from increases in the concentration of greenhouse gases is an important factor in UK climate change. This is often referred to as the “thermodynamic component”. We have also described how large-scale changes in “atmospheric circulation”, which we experience as weather, will be important.

The UK’s weather and climate are shaped by interactions between the ocean, atmosphere, and ice in the North Atlantic. These combine to drive the North Atlantic jet stream, a band of enhanced westerly winds over the North Atlantic region. The strength and positioning of the jet, in turn, has a major impact on the type of weather the UK experiences.

---

1023 Several factors play a role in determining the characteristics of the jet and the weather the UK experiences,  
1024 including:

- 1025 • Sea surface temperatures in the North Atlantic. Warm seas warm the air above them. As warm, moist air  
1026 rises above the sea, this can cause clouds to form, and if enough energy is transferred from the sea to  
1027 the air, storms can develop.
- 1028 • Spatial differences in sea surface temperature. The sea surface is not uniform in temperature; there are  
1029 warmer and colder areas. More energy is transferred to the atmosphere above the warmer regions. This  
1030 affects the weather. North Atlantic sea surface temperatures are also influenced by the 'Atlantic  
1031 Multidecadal Oscillation', which is a natural cycle between warmer and cooler phases of the North  
1032 Atlantic Ocean, each lasting 20-40 years (Sutton and Dong, 2012).
- 1033 • Arctic temperatures and sea ice cover (Barnes and Screen, 2015), as this influences the amount and  
1034 position of cold air north of the jet stream.
- 1035 • The behaviour of winds circulating high up in the stratosphere (the stratospheric polar vortex), up to 30  
1036 miles (50 km) above the earth (Baldwin and Dunkerton, 2001). A strong polar vortex favours a strong jet  
1037 stream, which potentially leads to shorter-lived, but more intense weather systems over the UK.
- 1038 • Convection causing warm air to rise over the tropical regions affects weather patterns and influences jet  
1039 stream shape in the mid-latitudes.
- 1040 • A simplified description of typical atmospheric flow pattern is often framed in terms of the North  
1041 Atlantic Oscillation (NAO) and the East Atlantic (EA) patterns, which are the dominant patterns for  
1042 weather and climate in the UK. The NAO describes how wind patterns over the North Atlantic change  
1043 between linear west-east (zonal) flow and wavier (meridional) flow. The EA pattern is centred just west  
1044 of the UK and is most active in winter. When the EA is in a positive phase, it often brings high pressure  
1045 over the UK, which usually leads to colder and drier weather in winter.

1046 On top of those North Atlantic regional aspects, atmospheric signals in one part of the world communicate to  
1047 other regions via the propagation of atmospheric waves (e.g., Hoskins and Karoly, 1981). Prominent examples  
1048 are the influence of the El Niño Southern Oscillation (ENSO; Brönnimann, 2007) or the Quasi Biennial Oscillation  
1049 (e.g., Gray et al., 2018) from the tropics on weather in the UK. For example, ENSO can influence the NAO pattern  
1050 and is ultimately responsible for colder and drier winters in northern Europe and wetter weather in southern  
1051 Europe in a positive ENSO phase (during El Niño years).

1052 Beyond those global- to continental-scale influencing factors, the interaction of physical processes at regional to  
1053 local scales are also important for the UK. For example, Fink et al. (2004) showed that local to regional moisture  
1054 deficits enhance temperature maxima, which again reduce available moisture, thus producing a positive  
1055 feedback loop. In the UK, spring 2025 was extremely dry (up to 50% less than average rainfall), contributing to  
1056 the very warm summer in 2025 (top 5%, according to UK Met Office (2025)).

1057 Further important phenomena are so-called climate (or weather) whiplash events (Swain et al., 2018): as a  
1058 warmer atmosphere can absorb more moisture, e.g., by evaporation from the soil, the soils get drier while the  
1059 amount of moisture in the atmosphere may increase significantly. Once the atmosphere becomes unstable,  
1060 rapid changes with extreme rainfall amounts could be observed. Thus, a rapid shift between extreme dry  
1061 conditions and heavy rainfall with potential flood events may occur. These weather whiplash events are also  
1062 connected to significant and abrupt changes in the atmospheric circulation over the North Atlantic and the UK  
1063 (Francis et al., 2023).

## 1064 **Observed Changes**

1065 *Atmospheric thermodynamic changes*

---

1066 Between 2011 and 2020, the Earth was 1.1 °C warmer than in pre-industrial times (1850-1900), mainly due to  
1067 human activities (IPCC AR6, 2021). This warming has caused an increase in heat extremes in most regions,  
1068 including the UK and Europe (Seneviratne et al., 2021) Cold spells in the UK happen less often and are not as  
1069 severe (Kendon et al., 2024), which is also true in other parts of the world (Seneviratne et al. 2021).

1070 Over the last 40 years, the Arctic has warmed about four times faster than the global average (Rantanen et al.,  
1071 2022). This is known as ‘Arctic Amplification’, and its causes are well known. Sea ice reflects sunlight, radiating  
1072 energy from the sun back into space. Melting sea ice reflects less sunlight, allowing more heat to be absorbed by  
1073 the ocean. Clouds also play a role by affecting how much heat enters and leaves the Arctic, which adds to the  
1074 warming (Forster et al., 2021).

#### 1075 *Atmospheric circulation changes*

1076 CCRA3 concluded that while theories had been proposed for how climate change could affect the North Atlantic  
1077 jet stream and thus weather and climate over the UK, so far there was little observational evidence to support a  
1078 climate change signal was emerging. Since CCRA3, new evidence updates this view.

1079 Atmospheric reconstructions using a blend of observational data and weather models (so-called reanalyses)  
1080 show a recent strengthening of the winter jet stream (averaged around the entire Northern hemisphere) at  
1081 altitudes of 8-12 km above the surface (Woollings et al., 2023). In consequence, these datasets also show winter  
1082 lower tropospheric winds over the North Atlantic have strengthened since 1950 (Blackport and Fyfe, 2022).  
1083 However, it is unclear whether this is a consequence of climate change or slowly varying natural climate  
1084 variability.

### 1085 **Future Changes**

1086 Global climate models are core tools to understand and to project future climate changes. Since CCRA3 there  
1087 have been advances in understanding model limitations in simulating North Atlantic atmospheric circulation.  
1088 Global climate models driven by historical forcings struggle to reproduce the observed strengthening of the  
1089 winter North Atlantic jet stream (Blackport and Fyfe 2022). Several hypotheses have been proposed to explain  
1090 the discrepancy, including:

- 1091 • Climate models underestimate multidecadal variability in the winter North Atlantic atmospheric  
1092 circulation (Simpson et al., 2018)
- 1093 • Climate models struggle to capture observed sea surface temperature trends in the equatorial Pacific  
1094 (Wills et al., 2021) which influence the North Atlantic jet stream through teleconnections (Cheung et al.,  
1095 2022)
- 1096 • Climate models may underestimate the jet stream response to external climate forcings (Smith et al.,  
1097 2025)

1098 There is currently no consensus on these mechanisms, and they are challenging to test given the relatively short  
1099 instrumental record. These limitations may impact on our ability to explain in detail how climate change will  
1100 influence all relevant climatic factors over the North Atlantic and the UK.

1101 Climate models also appear to underestimate observed trends in northwest European summer heat extremes  
1102 (Patterson, 2023; Vautard et al. 2023), in part because they underestimate the observed trend in summer-time  
1103 North Atlantic atmospheric circulation towards a ‘wavier’ state (e.g., Coumou et al., 2015). It is unclear whether  
1104 these summer circulation trends are a signal of climate change or due to internal climate variability. Circulation-

---

1105 driven heatwaves may also be amplified by local ‘thermodynamic’ factors such as long-term drying trends in soil  
1106 moisture (cf. section 1.3.1.1. on heat hazard).

1107 The models used for seasonal-to-decadal forecasting, which are similar to those used for climate projections,  
1108 underestimate the potential quality of multi-annual North Atlantic and UK climate forecasts in winter due to  
1109 signal-to-noise errors (Eade et al., 2014; Smith et al., 2021). The reasons remain under investigation but include  
1110 a poor representation of teleconnections (Williams et al., 2023; O’Reilly et al., 2025). This could mean  
1111 simulations of future climate conditions need to be carefully analysed for biases, and corrected or calibrated if  
1112 needed. Nevertheless, Degenhardt et al. (2023 & 2024) show that seasonal forecasting models can now provide  
1113 skilful predictions of extreme windstorm frequency and intensity ahead of the winter season in the UK.

1114 *Atmospheric thermodynamic changes*

1115 There is high confidence that all future greenhouse gas emissions scenarios considered by IPCC AR6 WGI (2021)  
1116 result in increased global warming over the near-term (2021-2040), mainly due to increased cumulative CO<sub>2</sub>  
1117 emissions in nearly all considered GWLs. There is a projected increase in the frequency and severity of  
1118 heatwaves across many regions, including the UK and western Europe (Seneviratne et al., 2021). Atmospheric  
1119 moisture is projected to increase with warming (IPCC, 2023) due to an enhanced capacity of the atmosphere to  
1120 contain water vapour with higher temperatures. This will lead to further intensification of the global water cycle,  
1121 including its variability and extremes.

1122 Climate models robustly show stronger warming over land than sea under future climate change scenarios (Lee  
1123 et al., 2021), including for the UK and Europe. This corresponds to larger warming trends where people live than  
1124 for the global mean trend.

1125 Di Chen et al. (2022) identified the global change in frequency of significant precipitation ‘whiplash’ events by  
1126 means of an 80-member multi-model ensemble for a high GWL at the 2070-time horizon. They find an increasing  
1127 frequency of those events mainly in several semi-arid regions of the globe, but also for the UK. For the latter,  
1128 changes of about 20-30% are identified. While thermodynamical factors are mainly responsible, in specific  
1129 regions circulation related factors are also present.

1130 *Atmospheric circulation changes*

1131 As introduced in section 1.3.3.1 changes in high atmosphere waves and the way they interact with the jet stream  
1132 play a major role in shaping weather patterns over the UK. At times when the waves interact with the jet stream  
1133 such that the ridges of the waves are enhanced, the usual west-east flow of wind can be obstructed for days or  
1134 even weeks, a process referred to as ‘blocking’ (cf. section 1.3.3).

1135 When this happens, weather systems can get ‘stuck’ in place, leading to prolonged periods of hot, dry weather  
1136 (in summer) or cold spells (in winter) under the block, and flooding either side of the block. This has caused  
1137 many examples of high impact weather events, such as winter cold spells like the “Beast from the East”  
1138 (February 2018), and summer heatwaves like the UK’s first recorded 40 °C day (July 2022). On the other hand,  
1139 fast travelling (so-called transient) waves may occur, which lead to an increased succession of low pressure  
1140 systems over the UK, like in winter 2013/14. Those upper-tropospheric waves normally have a wavelength of 50-  
1141 70 longitudinal degrees (at 50N, roughly 3,500-5,000 km) and need to be simulated correctly in any climate  
1142 model to realistically simulate changes in related weather circulation patterns at the surface. It is noted that  
1143 CMIP6 models, for example, show improved blocking locations in comparison to CMIP5 models but still suffer  
1144 from biases in persistence and frequency (IPCC, 2021). Notably, during winter transient flow regimes, CMIP6  
1145 models still show a too-zonal pathway for those transient waves (IPCC, 2021).

1146 On average, the CMIP6 models show weak near-term changes (2021-2040) in Northern hemisphere midlatitude  
 1147 circulation patterns, in all seasons and under all greenhouse gas scenarios considered in Lee et al. (2021). By the  
 1148 end of this century, CMIP6 models show a tendency to a more positive NAO-like flow pattern (thus more zonal,  
 1149 with transient waves) in all seasons except summer (Lee et al., 2021; Fabiano et al., 2021; Dorrington et al.,  
 1150 2022; Rousi et al., 2020; Pope et al., 2021; Davini et al., 2020).

1151 Such changes imply more frequent wet and windy winters in the UK. However, climate models differ in their  
 1152 quantitative details of changes in frequency and persistence (Dorrington et al., 2022), meaning uncertainty  
 1153 remains in the future likelihood of regimes associated with extreme weather events. In summer, climate models  
 1154 project an increase in anticyclonic (high pressure) circulation west of the UK in August, relevant for western and  
 1155 central European drought (Rousi et al., 2021), leading to more frequent dry and hot conditions also in the UK.

1156 Francis et al. (2023) conclude that weather whiplash events in the North Atlantic/European region, including the  
 1157 UK, are likely to increase in frequency by the end of the century under a high greenhouse gas emission scenario  
 1158 equivalent to a global warming level of 3.0 °C.

1159 **1.4.2 Global Climate Changes with relevance to the UK**

**Headlines**

1. There have been global increases in the intensity and frequency of heavy rainfall, heatwave and drought events, and in the intensity of tropical cyclone windspeeds (**Very high confidence**).
2. The above trends are expected to continue, alongside increased risks of intense floods (**High confidence**).
3. Capacity for rapid attribution of observed events to anthropogenic climate change, large observational datasets, and development of higher resolution simulations have built confidence in the above (**High confidence**).
4. Large-scale circulation patterns influence global rainfall patterns and regional weather, driving uncertainties in some regional hazards. Higher resolution simulations improve representation of processes such as heavy rainfall and tropical cyclones, but improvements to land models are still needed.

1160  
 1161 This section has two parts. First it looks at climate change beyond the UK which might impact indirectly on the  
 1162 UK, for instance through the impact on global food production. Second it looks at events in the global climate  
 1163 outside the UK that might provide analogues of what we might need to prepare for in the UK in future.

1164 **1.4.2.1 Large-scale climate changes that might impact the UK**

1165 This section considers the hazards relating to global changes in precipitation, temperature and wind. For the  
 1166 latter, the focus here is on tropical cyclones; for European windstorms see Section 1.3.3.1. The table below  
 1167 identifies which risks this hazard is particularly (but not exclusively) relevant to.

Risks affected per Sectoral Impact Category				
Land, Nature and Food	Economy	Health and Wellbeing	Built Environment and Communities	Infrastructure

N10	E1, E2, E3, E5, E7	H4, H5	I1, I2, I4, I7
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## 1168 Introduction

1169 Severe internationally occurring events such as floods, droughts, heatwaves and extreme storms may impact UK  
 1170 risks via a variety of pathways, including food availability (Ercin et al., 2021), trade and shipping (Freeman et al.,  
 1171 2024), disease transmission (Semenza & Paz, 2021), and displacement of people and humanitarian emergencies  
 1172 (Hermans & McLeman, 2021). This section summarises some changes in global climate hazards that may act as  
 1173 shocks to the UK's economy and security, with attention to some key regions, e.g., East Asia for manufacturing,  
 1174 Europe and Africa for food imports. For further detail, see the IPCC reports.

## 1175 Observed Change

1176 By combining large datasets and improving methods, it is now faster to diagnose any link between recent  
 1177 weather events and human-caused climate change.

1178 **Heavy rainfall:** Studies indicate an increasing risk of heavy rainfall events, driven by anthropogenic climate  
 1179 change. Events such as the heavy rainfall affecting Spain in October 2024 are estimated to have doubled in  
 1180 likelihood and increased in intensity by 12% (World Weather Attribution, 2024). The peak intensity of short-  
 1181 duration (e.g., hourly) precipitation is increasing at the fastest rates (e.g., Fowler et al., 2021).

1182 **Flooding:** In regions where soils are drying, e.g., Southern Europe, flood magnitudes have decreased; where soil  
 1183 moisture is increasing, e.g., Northern Europe, flood magnitudes have increased (Wasko et al., 2021). Very heavy  
 1184 rainfall is driving increases in the rarest, strongest floods regardless of soil moisture (Bertola et al., 2021; Wasko  
 1185 et al., 2021).

1186 **Drought:** Summertime drought intensity has increased in Western North America, Australia, Southern Europe,  
 1187 Eastern, Central and Southern Africa and parts of South America (Vicente-Serrano et al., 2022). There is  
 1188 agreement that changes result from warming over land, which drives increased evaporation, with land-use also  
 1189 playing a role in some regions. Drought-related European cereal losses are estimated to have increased at 3%/yr  
 1190 over the past 50 years (Brás et al., 2021).

1191 **Heat:** Most regions on the globe show a significant increase in extreme heat (IPCC, 2023). Observations and  
 1192 models indicate that heatwaves can coincide in important regions to global food supply due to connections in  
 1193 atmospheric patterns (Meehl et al., 2022). The frequency of drought-heatwave events is increasing globally, with  
 1194 the fastest increases seen in low-income regions including Africa and East Asia (Zhang et al., 2024), driving  
 1195 humanitarian and agricultural risks.

1196 **Wind:** Observations and model simulations show decreasing tropical cyclone frequency but increased  
 1197 windspeed intensity and intensification rates (e.g., Camargo et al., 2023), and a shift poleward (Studholme et al.,  
 1198 2022) and towards coastal regions (Wang & Toumi, 2021). The latter implies increased risk to populous regions.  
 1199 Recent work suggests that intense tropical cyclones are occurring earlier in the year, which may increase  
 1200 likelihood of events coinciding with other types of heavy rainfall events (Shan et al., 2023).

## 1201 Future Change

1202 Temperature and rainfall are expected to change as the planet warms. The Arctic will warm the most (cf. i.a.  
 1203 Tebaldi et al., 2021) and some areas, like the tropical Pacific and Arabian sea, will get wetter. Other areas, like  
 1204 subtropical regions, the Mediterranean and southern Europe, may get drier. This leads to a potential food  
 1205 production risk for the UK. Stronger tropical storms are also expected. At a GWL of 2.0 °C for the late 21<sup>st</sup>

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1206 century, tropical cyclone lifetime maximum windspeeds are expected to increase by 5% (range 1-10%), with an  
1207 additional 13% of storms reaching very intense levels (Knutson et al., 2020).

1208 A major advance since CCRA3 has been the production of a growing number of global and regional ‘convection-  
1209 permitting’ model simulations with resolutions of less than 10 km, made possible through improved  
1210 supercomputer power. These simulations resolve small-scale processes such as convection, reducing model  
1211 uncertainties.

1212 **Heavy rainfall:** High-intensity events are expected to increase in many regions, with reduced moderate and light  
1213 rainfall, such that future climates support increases in both flood and drought (Fowler et al., 2021). Convection-  
1214 permitting simulations over Western Europe indicate that the most extreme short duration events increase at  
1215 approximately 10-14%/ °C, (e.g., 20-24% at a GWL of 2 °C, i.e., 2050s for central scenario) likely leading to  
1216 increased flood risk (Lenderink et al., 2021).

1217 **Flooding:** Floods that historically occurred every 50 years are expected to occur with increasing frequency, e.g.,  
1218 every 36 years at a GWL of 1.5 °C (i.e., 2030s for central scenario), and even more frequently for warmer  
1219 climates. These affect regions of UK sensitivity for food production, e.g., Northern Europe, and  
1220 manufacturing/trade, e.g., China (Huang et al., 2024). Flood return periods are shorter for the same global  
1221 warming level achieved under higher emissions scenarios.

1222 **Drought:** Studies agree on an increased likelihood of drought over much of South and Central America, the  
1223 Middle East and North Africa, southern Europe, and southern Australia, with severity and duration increasing  
1224 with global mean temperature (Douvillle & et al., 2023). Economic impacts of drought, e.g., on crop production,  
1225 are projected to worsen in a warmer climate (Naumann et al., 2021).

1226 **Heat:** Global projections indicate a further increase in the frequency and intensity of extreme heat (IPCC, 2023).  
1227 Dangerous levels of heat that are extremely rare today will become possible across several regions across the  
1228 tropics. Estimates suggest the global population exposed to severe heat stress annually would increase to 20% at  
1229 a GWL of 1.5 °C (2030s central scenario), 30% at a GWL of 2 °C (2050s central, 2030s high scenario), and over  
1230 50% at a GWL of 3 °C (2080s high scenario) (Freychet et al., 2022). The frequency and intensity of crop growing  
1231 season heatwaves increases in models, particularly at a GWL of 2 °C, with Asia, North America and Europe most  
1232 affected (Chen et al., 2024).

1233 **Wind:** Poleward shifts of tropical cyclone regions are expected (Li & Zhou, 2024). The speed with which tropical  
1234 cyclone storm systems move from one place to another is projected to decrease, leading to longer exposure of  
1235 locations to wind and rain (Camargo et al., 2023). Future changes in how often tropical cyclones occur are  
1236 uncertain. The intensity of tropical cyclone windspeed is expected to increase in a warming climate (Camargo et  
1237 al., 2023). Increased tropical cyclone intensity is projected to drive increased storm surges affecting a larger  
1238 coastal area, including key manufacturing and shipping regions in East and Southeast Asia (Muis et al., 2023;  
1239 Wood et al., 2023).

#### 1240 **1.4.2.2 Extreme climate events around the world that might provide** 1241 **analogues of future UK events**

1242 Recently, since CCRA3, significant and devastating extreme weather events have occurred across the world. In  
1243 this section, we discuss three unprecedented extreme events which did not directly impact the UK but are  
1244 examples of extreme weather now possible in our warmer climate, which is already significantly influenced by  
1245 climate change. Studies support the notion that they are harbingers of extreme weather in future climates

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1246 (known at least since e.g., Schär et al., 2004, Fink et al., 2004), given futures of medium to high-end GWLs to the  
1247 end or the mid of this century, respectively.

1248 These extreme events cannot be transferred one-to-one to the weather and climate of the UK. As we have  
1249 discussed above, the weather and its variability in the UK are highly variable for multiple reasons. Nearly all of  
1250 them will be influenced by climate change. But we can use the study of those events to inform about potential  
1251 magnitudes of events to come to inform necessary and important disaster risk and reduction efforts, before or  
1252 in the aftermath of such extreme events. With increasing evidence of climate change impacts being realised in  
1253 the present day, we cannot exclude the occurrence of respectively equivalent events with comparable  
1254 magnitude for the UK.

Draft for Community Review

### The Pacific-Northwest Heatwave, June 2021

This heatwave began in late June 2021, in response to a strong high-pressure system and advection and large-scale sinking of airmasses originating from the tropics (White et al., 2023). Temperatures broke all-time maximum temperature records by more than 5 °C, and reached 49.6 °C, an all-time Canadian record, measured in the town of Lytton. Warnings of extreme heat events being possible originated both from sub-seasonal forecasts and weather forecasts. Nevertheless, due to its extreme magnitude, the heatwave caused severe consequences. It led to hundreds of attributable deaths across the Pacific Northwest, caused spikes in hospital visits and caused severe impacts on marine life (Fleishman et al. 2025). It also led to a wildfire which burnt down the town of Lytton shortly after this town broke the Canadian temperature record. As this event was clearly a “record-shattering” event (Fischer et al., 2021: an event that breaks records by large margins), the event was so unprecedented that it was not anticipated as physically possible if estimating return periods of annual maximum daily maximum temperature using a General Extreme Value distribution (e.g., Bartusek et al., 2022). A rapid attribution analysis supports this view and concluded that this event was virtually impossible without human influences (Philip et al., 2022). Events of such severe magnitude have the potential to surprise populations and over-challenge adaptation as it far exceeds previous records.

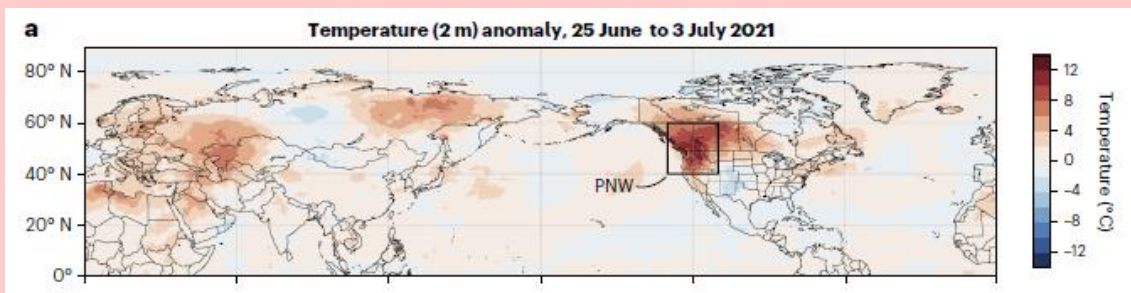


Fig. 3.3.1: Timing, location and magnitude of the PNW heatwave in 2021. Figure from Bartusek et al. (2021; their figure 1a)

Fischer et al. (2021) demonstrate that the probability of occurrence of those “record-shattering” events for future climate states depends on warming rate, rather than global warming level, and is thus pathway-dependent. They also highlight the role of a disturbed and abnormal atmospheric circulation. They found that slow- and fast-moving components of the atmospheric circulation interacted, along with regional soil moisture deficiency, to trigger this extraordinary heat event (five times larger than the standard deviation).

Thompson et al. (2024) conclude that many regions could see events that break records by large margins which could cause severe consequences there as well. A storyline hindcast analysis highlights that this was a very rare event, with the unusual circulation explaining most of the extreme temperatures, which would have been about 1 °C less extreme without anthropogenic warming.

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### Ahr-floods in Germany, July 2021

From 12<sup>th</sup>-15<sup>th</sup> of July, severe rain occurred over Western Europe due to the slow-moving low pressure system *Bernd*, falling on already wet soils. Between 12 and 19 July 2021, the low-pressure system resulted in extreme rainfall of more than 150 mm in 72 hrs (Mohr et al., 2023), about five times the observed daily maximum average in July (e.g., Tradowsky et al., 2023). According to Kreibich et al. (2022) and Rhein & Kreibich (2025), this led to unprecedented flash floods, killing 184 people in Germany (134 in the Ahr valley; Roggenkamp et al., 2024) in addition to extensive damage to buildings, long term power outages and economic losses of around 33 billion EUR (Kron et al., 2022; Munich Re, 2022). The German association of insurance industry (GDV) estimates insured losses worth about 8.4 billion EUR (GDV, 2023). Several days before storm *Bernd* hit western Europe, the European Flood Awareness System (EFAS) accurately predicted severe risk of flooding and issued a notification to the German authorities (Tradowsky et al., 2023). This triggered a flood warning for major rivers but small rivers like the Ahr were not sufficiently considered. Tradowsky et al. (2023) conclude “not all exposed authorities and people received the warnings and when they did, the warnings were not always understood and acted upon”. This case illustrates that warning alone is not sufficient, but the warning needs to reach decisionmakers and population in time to get out of harm’s way.

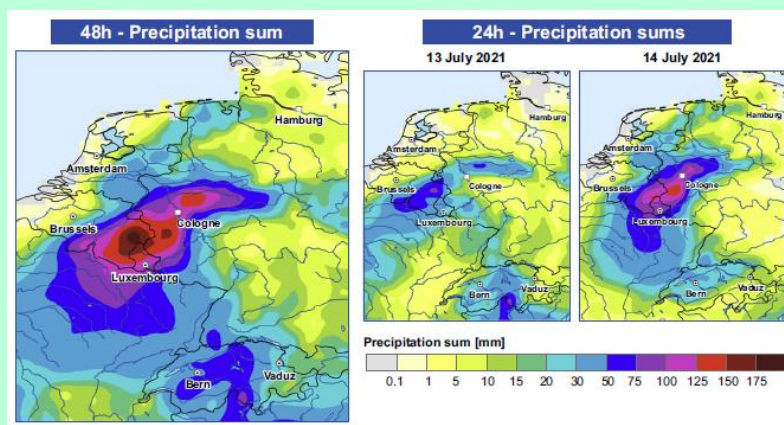


Figure 3.3.3: Accumulated precipitation over 48 h (left) and accumulated over each of the individual days of the extreme precipitation event (middle and right). Data source: Extended E-OBS dataset. Copyright of Fig.: DWD. Figure taken from Tradowsky et al. (2023, their figure 2).

Based on rainfall data, a probabilistic event attribution conducted by World Weather attribution indicates that rainfall accumulations in the Ahr, Erft and Meuse catchment exceeded previous observed records, as did discharge levels of the rivers. However, the small spatial scale and estimate far outside previous records challenges robust event attribution based on observed extreme events. Thus, World Weather Attribution focused on rainfall over a larger Western European area that encompasses the river catchments (Tradowsky et al., 2023). The analysis estimated the observed rainfall event to have about a 400-year return period, and that compared to preindustrial conditions (1.2 °C lower global mean temperature) a 1-day extreme rainfall event intensity has already increased by 3-19%, thus substantially enhancing the probability of a severe wet event. The likelihood of such an event occurring today compared to a 1.2 °C cooler climate was estimated to be enhanced between 1.2-9 times, depending on analysis method and considering uncertainties. This is in line with a warmer atmosphere raining out more moisture under suitable conditions. However, comparing the observed flood levels in the Ahr valley to earlier periods, Roggenkamp et al. (2024) estimate that floods of similar magnitude occurred before, most similarly in 1804, emphasizing the value of considering past extreme events. This example highlights the risk from a combination of factors exacerbating flood levels, from saturated soils to very extreme rainfall combined with lack of preparedness and insufficient response which needs to be considered for adaptation to intensifying extreme events.

### Valencia-Flood in Spain, October 2024

The province of Valencia in Spain was hit by unprecedented rainfall amounts in autumn 2024. According to Faranda et al. (2024), within 24 hours on the 29<sup>th</sup> of October, 630 mm of rain (equivalent to 630 litres per square metre) were recorded in Turis. In Chiva, some 10 km north, 491 mm rain fell in just eight hours. At many locations across the province intense rainfall exceeding 300 mm within 24 hours was reported by AEMET (Spanish Meteorological Agency; e.g., Amiri et al., 2025), which caused widespread flooding. To give context to these rainfall amounts, the previous maximum daily rainfall at Valencia airport was recorded on 6<sup>th</sup> Oct 1971 at 186.9 mm, according to AEMET. Using rainfall observations from approximately 225 personal weather stations (low-cost commercial devices primarily operated by citizens) Rombeek et al. (2025) identified two bursts of extreme rainfall leading to a first flood wave in the Margo catchment triggered by about 180 mm of rain in a few hours. While this flood wave propagated downstream, a second extreme rainfall event amplified the overall event and likely contributed to the devastating consequences. Related flash floods killed over 200 people and interrupted the water and electricity supply for hundreds of thousands in the provinces of Valencia and Castellón, as well as in Málaga (Andalusia) and Albacete (Castilla-La Mancha).

In the western Mediterranean, severe rainfall and flooding events are often triggered by so-called cut-off lows, pockets of cold air aloft in consequence of the meandering mid-latitude wave pattern. This cold air aloft, together with warm and moist air over the western Mediterranean closer to the surface, destabilises the atmosphere and allows large amounts of rain to be triggered. In the context of climate change, it is important to note that a warmer atmosphere can hold more moisture and by every degree of temperature increase, the amount of moisture saturated air to hold increases by ca. 7%. Faranda et al. (2025) conclude that cut-off lows that cause floods in southeastern Spain are up to 7 mm/day (an increase of up to 15%) wetter over the Mediterranean coast of Spain in the present than they would have been in the past without human influences on climate.

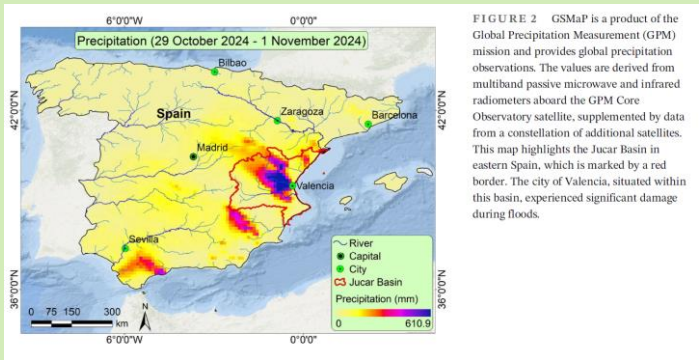


FIGURE 2 GSMP is a product of the Global Precipitation Measurement (GPM) mission and provides global precipitation observations. The values are derived from multiband passive microwave and infrared radiometers aboard the GPM Core Observatory satellite, supplemented by data from a constellation of additional satellites. This map highlights the Jucar Basin in eastern Spain, which is marked by a red border. The city of Valencia, situated within this basin, experienced significant damage during floods.

Figure 3.3.5: Rainfall over Spain, 29.10-1.11.2024; from Amiri et al., (2025); their Figure 2.

World Weather Attribution (WWA) published a rapid assessment in the aftermath of the event (WWA, 2024). This is not making full use of climate model simulations formally used to quantify the anthropogenic climate influence of specific events; their results are based on observations only. By analysing three observational, long-term rainfall datasets, they conclude that “heavy 1-day rainfall events, as intense as the one observed, are about 12% more intense and about twice as likely in today’s climate, that is 1.3 °C warmer than it would have been in the cooler preindustrial climate without human-caused warming.” Resulting estimates of probabilities for the amount of river discharges as observed during this event are highly uncertain, but include e.g., the Rambla de Poyo catchment at 1 in 900 years. WWA (2024) further states that “over the past ~75 years, daily rainfall extremes in the September–December season in central and southeastern Spain have increased significantly with global warming, approximately doubling in likelihood and equivalently increasing in intensity by 12%.”

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## 1.4.3 Tipping Points in the Global Climate System

### Headlines

1. With global warming breaching 1.5 °C and 2 °C above pre-industrial levels, the risk of crossing tipping points increases (**Medium confidence**).
2. Crossing some tipping points would impact the UK directly, through changes in climate or accelerating sea level rise, while others could impact on global food systems and migration with indirect impacts on the UK (**Low confidence**).
3. Since CCRA3, this risk has increased, due to increased global warming. At the same time, new research on tipping points becomes available (**Low confidence**).
4. Confidence in risk of tipping points and the warming level at which they become more likely remains low due to limitations in process understanding and inconsistencies in evidence from past climates and different climate modelling approaches.

This section considers tipping points of the global climate system. Tipping points could cause changes that occur faster than the pace of global warming or are irreversible on human timescales. The table below identifies which risks this hazard is particularly (but not exclusively) relevant to.

### Introduction

Tipping points are defined as critical thresholds beyond which the climate system reorganizes, often abruptly and/or irreversibly (Lenton et al., 2008; Chen et al., 2021), on global or large regional scales. Examples include changes in ocean circulation, accelerated ice sheet collapse, or collapse or substantial shift in forest systems. While the concept of tipping points is intuitive, its definition is vague, hence some consider it not useful (Kopp et al., 2024). A clearer definition would specify traits of tipping dynamics, such as changes that, once triggered, are sustained or self-amplifying, and/or irreversible and/or rapid compared to the pace of global warming and the timescale at which a system changes normally. It is also important to quantify the timescales of tipping. Once a critical threshold has been crossed, the resulting committed climate change may take years, decades, or even centuries to fully materialize.

Past climates have shown that tipping events such as rapid changes in ocean circulation are possible, yet there is large uncertainty at what warming levels and rates of warming tipping dynamics may be triggered in the future. The capability of climate models to capture processes involved in tipping is also highly uncertain, as it requires interactions that are not well resolved or represented in models (for example, input of freshwater from interactively melting ice, or vegetation dieback and fire caused by drought and heat). Despite this, the latest generation of earth system models can provide useful insight into tipping points involving the ocean, such as changes in circulation and sea ice, and the land surface, such as changes in forests. Where the models do not yet include the necessary processes, insight can be gained by driving other, so-called offline models, for instance for ice sheet changes and permafrost carbon release.

Recent review papers highlight that the risk of tipping events can be best avoided by limiting warming to below 1.5 °C (Armstrong McKay et al., 2022; see also table), although the high uncertainty in tipping points makes it difficult to aim mitigation efforts specifically to address them (Kopp et al., 2025). Recent literature also highlights the need for improved process understanding and monitoring (e.g., Wang et al., 2024). Despite their high uncertainty, tipping points are discussed here due to their ability to cause severe impacts.

1290 Some tipping points could affect the UK directly, such as a shutdown or severe reduction of the Atlantic  
 1291 Meridional Overturning Circulation (AMOC) or Sub Polar Gyre (SPG) circulation, which would cool the UK relative  
 1292 to the rest of the world. Tipping points in ice sheets, particularly in Antarctica, could cause a faster rise in sea  
 1293 level than projected otherwise. Triggering tipping dynamics could also cause global impacts that could affect the  
 1294 UK indirectly, for example through changes in livelihoods of fishing communities following collapse of  
 1295 warmwater coral ecosystems, or of land abandonment due to sea level rise (cf. overview in Table 1.7).

1296 *Table 1.7: Examples of tipping elements with near-term tipping potential. Global warming level estimates and examples are*  
 1297 *taken from (Armstrong McKay et al. 2022; and Ritchie et al., 2025) and are based on expert assessment, hence true*  
 1298 *uncertainties may be under- or overestimated as scientific understanding evolves and recent work has revised some estimates.*  
 1299 *Note also that some examples from Armstrong McKay are not included here either due to 1) uncertainty if they are affected by*  
 1300 *tipping dynamics, 2) estimates that likelihood of triggering them is low for warming levels near Paris targets, or 3) due to unclear*  
 1301 *links to the UK.*

Tipping element	Central estimate and minimum/maximum estimate of global warming trigger level; confidence	Potential Impact on UK	Timing of impacts relative to committed tipping
AMOC collapse	4 °C [1.4 to 8] Low	Direct impact on seasonal climate in UK projected, including colder winters relative to global warming (van Westen et al., 2025) and precipitation changes with impacts on agriculture (Ritchie et al. Nature Food 2020)	Depending on forcing level and freshwater forcing estimated after later half of 21 <sup>st</sup> century. Full AMOC reduction would likely occur over at least a few decades after the TP is crossed (Jackson & Wood Clim Dyn 2018)
SPG collapse	1.8 °C [1.1-3.8 ] High	Linked to AMOC collapse with similar, but lower amplitude potential impacts (Swingedouw et al. Proc NY Acad Sci 2021, Menary et al GRL 2025)	5yrs to several decades
West Antarctic Ice Sheet collapse	1.5 °C [1 to 3.0] High	Increased sea level rise	Long (multi-century to thousands of years) timeline even after tipping dynamics has started
Greenland ice sheet collapse	1.5 °C [0.8 to 3.0]	Increased sea level rise largely counteracted by effect of gravity; changes in atmospheric circulation	Long (thousands of years), high uncertainty even after tipping dynamics has started
Alpine glaciers	2 °C [1.5 to 3] Medium	Indirect impacts through impact on water availability / flooding for billions of people	Changes from high runoff while glaciers melt to reduced availability after – decades to centuries

Warm-Water coral Reefs	1.2 °C [1.0-1.5]	Indirect impacts through impacts on local livelihoods and on global biodiversity	Estimated around a decade; severe bleaching events are occurring
Amazon rainforest	3.5 °C [2 to 6] Low Note: earlier when considering deforestation and climate change together]	impact through carbon budget; possibly also on water availability in other tropical regions affecting food production and biodiversity	50 years to centuries
Boreal Permafrost collapse	4 °C [3 to 6] Low Note: that the local trigger temperature may be reached at different times at different locations.	Impact through global carbon budget by increase in greenhouse gases; uncertain magnitude	Some carbon is already released, but release of permafrost carbon can take centuries and beyond
Boreal forest Southward retraction, Northward advance	4 °C [1.4to 5]4 Low	Impact on carbon budget and feedback on warming; fire emissions	Highly uncertain, some changes may be already underway

1302 Examples of tipping points are shown in figure 1.16 below and discussed in several recent review papers  
1303 (Armstrong McKay 2022; Lenton et al., 2023; Wang et al., 2023).

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- Collapse of the ocean currents of the Atlantic Meridional overturning circulation (AMOC), and a related collapse of the Sub Polar Gyre: AMOC collapse would cool the North Atlantic sector relative to the rest of the planet and change global weather patterns. A collapse or shift of the AMOC has been observed in past climates and occurs in climate models when large amounts of fresh water interrupt the sinking of very saline water, but how much fresh water is required for this collapse varies between lines of evidence and between climate models. Current (CMIP6) climate models suggest weakening but collapse of the AMOC is considered unlikely in the 21<sup>st</sup> century (IPCC WG1 2021). A recent study (Baker et al. Nature 2025) identifies physical mechanisms that underly that stability. However another recent study of CMIP6 models (Drijfhout et al. 2025) shows that on longer timescales (2300) the AMOC could reach very weak values. A severe reduction or collapse of the AMOC would affect the UK, as it is in relatively close proximity to the North Atlantic and close to the most intense cooling area associated with an AMOC shutdown or severe reduction. The detailed impacts would depend on the background level of global warming at the time of the weakening; this topic is currently under-researched but several studies are in progress. AMOC collapse would also change the pattern of sea level rise compared to scenarios without it; and affect weather patterns including rainfall.
  - Collapse of the Amazon rainforest, or its transition to a seasonally dry or less forested state, driven by a combination of enhanced drought stress and deforestation: Amazon collapse would reduce carbon uptake by forest and with it the carbon budget, and could also change how water is cycled back to the atmosphere. This could change rain availability downstream with possible consequences for tropic-wide rainfall patterns with possible impacts on food production across the tropics.
  - More rapid collapse of major ice sheets, both in Greenland and Antarctica by tipping dynamics in ice sheets: The most significant effect across the UK would occur in response to Antarctic ice sheet tipping, for example significant loss of the West Antarctic ice sheet (Bamber and Riva, 2020) due to gravitational pull effects. The resulting sea-level rise over coming centuries would be considerably higher than without the accelerated loss of the ice sheets, although the full effect would still take centuries or more to be realised.

- Shifts in the boreal forest (Wang et al., 2023) could impact how much solar radiation the Earth absorbs, while permafrost thaw could have consequences for regional water cycles and the global carbon budget if this causes significant methane release.

Many changes associated with tipping points can be of global or at least subcontinental significance (see Armstrong McKay et al., 2022). However, even regional tipping points could cause impacts that affect the UK, e.g., through disruptions of food systems or agriculture which could contribute to political instability and migration, although these links are poorly understood. Once tipping points have been crossed, changes are not reversible, at least not under the same forcing conditions that triggered them, and some aspects, including the impact of the tipping point, may take significantly longer to recover than the time it took to reach them (Lenton et al., 2023). It is also possible that overshoots over climate targets may be short enough to avoid triggering some tipping points (e.g., Richie et al., 2023), a topic where there is substantial uncertainty and ongoing research at present.

Lastly, triggering tipping dynamics may cause cascading effects into the climate system, potentially destabilizing other regions prone to tipping, but those connections are highly uncertain. For instance, a collapse in the AMOC may increase the risk to parts of the Amazon forest if the rainbelt moves southward, although new model simulations have raised questions about this. The likelihood of Amazon collapse increases if considering deforestation (see e.g., Flores et al., 2024). Many ideas and concepts around tipping points are being explored in ongoing climate model experiments (see Winkelmann et al., 2025).

The topic of tipping points has been received significant attention since CCRA3, with multiple reviews published and underway. Tipping points need to be considered to anticipate high impact outcomes from climate change, even if their probability is presently difficult to estimate, and although some of them are more likely to occur far in the future.

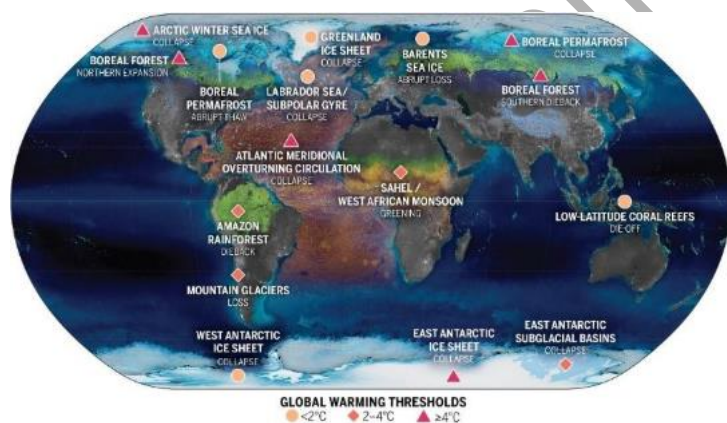


Figure 1.14: The location of climate tipping elements in the cryosphere (blue), biosphere (green), and ocean/atmosphere (orange; figure from Armstrong McKay, 2022). There is also an estimate of global warming levels at which these tipping points have been hypothesized to occur with pins coloured light orange where this may occur below 2 °C; between 2 and 4 °C, i.e., accessible with current policies (orange, diamonds); and at or above 4 °C (red, triangles).

## Observed Change

Observations support concerns about global tipping elements, and there is evidence that tipping dynamics occurred in past climates. Some studies have used proxy indicators of past AMOC change, along with simple dynamical systems ideas, to suggest that the AMOC may be getting closer to a tipping point (Boers Nat CC 2021,

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1362 Ditlevsen and Ditlevsen Nat Comms 2023). However, uncertainties in both the proxies and the dynamical  
1363 warning indicators mean that any predictions of tipping time are subject to huge uncertainty (e.g., Ben Yami et  
1364 al. Sci Adv 2024). While the Amazon rainforest is not yet severely vulnerable to climate change alone (Armstrong  
1365 McKay et al., 2022), analysis of the resilience of its forest ecosystem highlights its degraded state due to  
1366 increased drought and increasing deforestation. Coral ecosystems have been increasingly frequently bleached  
1367 during marine heatwaves (see review in Romanou et al., 2024). Mountain glaciers in many regions are in strong  
1368 retreat (Fox-Kempner et al., 2021) and are already affecting flood risk and water availability for large populations  
1369 depending on them.

1370 Observations show severe and accelerating loss of sea ice that is expected to be substantial in the 21<sup>st</sup> century.  
1371 While sea ice change is reversible when global warming reduces (Wang et al., 2023), impacts on Arctic  
1372 ecosystems may not be. There is also a scientific debate to what extent regional sea ice loss could have  
1373 substantial impacts on weather patterns and with that, affect the UK weather and weather hazards.

## 1374 **Future Change**

1375 As global warming continues, the likelihood of crossing tipping points increases, although only a few are  
1376 estimated to be in the 'possible' range at present warming levels, while there are concerning signals in  
1377 observations as discussed above. As the threshold forcing (e.g., warming level) is approached, tipping can be  
1378 induced by internal climate variability, even before the theoretical threshold has been reached, meaning that  
1379 prediction of the timing of tipping can be particularly challenging (Romanou et al 2023, Gu et al. 2024). The rate  
1380 of future warming is also important, as some research suggests that rapid warming can trigger tipping dynamics  
1381 even in the absence of instability (Ashwin et al., 2012).

1382 Estimates vary strongly in the literature as to at which global warming levels tipping dynamics may be triggered.  
1383 Resolving these uncertainties will take time, as climate models miss processes that simulate key mechanisms. In  
1384 some cases (e.g., AMOC) the impacts of the tipping event may be strongly dependent on the background global  
1385 warming level. There are large uncertainties and contradictory estimates in the scientific literature on if and at  
1386 what global warming levels tipping may occur. It is possible that some tipping points may be already close to  
1387 tipping or have been crossed during the 21<sup>st</sup> Century, leading to committed changes that play out over the  
1388 following decades or centuries (Drijfhout et al. 2025, Chandler et al., 2025). Scientific evidence suggests, that  
1389 triggering tipping dynamics increases the impacts of climate change and makes adaptation more difficult.

## 1.5 Research Advances, Gaps and Looking ahead to CCRA5

Since CCRA3 climate research has made significant advances globally and provides new and better insight into key aspects of the weather and climate of the UK. Research advances have focussed on addressing a number of key known limitations and uncertainties in understanding UK climate change. For UK climate change, this has particularly seen improved representation of high impact weather and climate extremes. This has been achieved through improved resolution of the models, allowing for more adequate representation of the meteorology and physical processes that underly a number of key climate hazards, such as intense rainfall. Alongside these modelling improvements advances have been made in methodologies for analysis, such as development of storyline approaches which have supported impact relevant assessments of climate hazards. In this section a number of key advances since CCRA3 are summarised, as are the remaining key capability gaps in climate science to be further developed looking toward CCRA5. Table 1.8 below goes on to summarise current climate modelling capabilities and limitations.

### Key advances since CCRA3:

- The UK Climate Projections service UKCP Local has improved representation of local scale high-impact weather events, such as intense rainfall, through a set of high-resolution simulations.
- UKCP Local now has simulations that run from the year 1981 through to 2080 continuously. The continuous 100-year data sets offer new insights about how variable local climates can be (Kendon et al., 2023) and also allow UKCP Local to be used in a Global Warming Level (GWL) framework.
- Additional model simulations in UKCP now allow assessment of a range of possible outcomes. This has improved understanding of uncertainties in climate projections, and permits evaluation of present and future climate hazards
- Application of the UNSEEN methodology and Extreme Event Attribution have furthered our assessment of extremes for the UK including rate of change in extreme temperatures (Kay et al. 2025) and storm hazards (Kew et al. 2024).
- Development of storyline approaches for assessing risks from climate extremes has improved our understanding of potential consequences of climate change (Shepherd et al. 2018, Harvey et al., 2023, Arnell, 2024; Palmer et al., 2024).
- Further improvements of historical observational datasets of the UK through the digitisation of archive collections, particularly for 19<sup>th</sup> century rainfall.
- Large ensemble international modelling efforts are targeting uncertainties around individual climate forcings (Large Ensemble Single Forcing Model Intercomparison, LESFMIP, Smith et al. 2022) and representing internal climate variability and extremes (Single Model Initial-condition Large Ensemble, SMILE, Maher et al. 2021).
- Regional Environmental Prediction modelling (Lewis et al. 2019) moves toward integrated environmental prediction at km-scale and has, for example, demonstrated the role of marine heatwaves on UK climate (Berthou et al. 2024).

**Key climate science and capability gaps:**

- AI and Machine Learning have advanced weather forecasting since CCRA3, but more research is needed to apply these tools to climate projections.
- Tipping points are hard to model accurately because key processes (like vegetation-fire interactions) are missing. Better observations, such as monitoring of ice sheets, vegetation, and ocean circulation, are essential.
- High-resolution weather models improve the understanding of changes to extreme rainfall and tropical storms, but often overestimate rainfall intensity. Improving how they simulate surface water flow is needed.
- UK climate is shaped by both global and local factors. While there is high confidence that warming will bring more heatwaves, fewer cold spells and more intense rainfall extremes, predicting changes to storms and other rainfall characteristics is still uncertain.
- Large-scale circulation and storm projections are still not robust. More focus is needed on understanding the North Atlantic climate system and the role of natural cycles.
- Current climate models struggle to simulate key processes like jet stream shifts and storm development. Higher resolutions and better process representations are needed.
- Standard flood risk estimation methods may underestimate future hazards by ignoring changes in rainfall patterns and storm clustering. New methods are needed.
- Future risk assessments will need updated UK climate scenarios that reflect a wider range of emission pathways and use the latest high-resolution models.
- Large ensembles are required to accurately estimate risks of extremes far in the tail of the distribution and ‘black swan’ events.
- Uncertainties remain in Earth-system processes, such as carbon-cycle feedbacks and their impact on global and regional climate change.
- The UK currently lacks a single point of access to data on the entire range of climate risk indicators.

1408 Table 1.8: Climate models, their features, uses and limitations.

Model Type	Resolution	Key Features	Main Uses	Limitations
Global Climate Models (GCMs)	~50-100 km	Simulate the full Earth system (atmosphere, ocean, land, ice)	Long-term global climate projections, IPCC assessments	Too coarse to capture local detail or extremes; simplified representation of small-scale processes

<b>Regional Climate Models (RCMs)</b>	~10-25 km	Focus on specific regions; use GCM outputs as input	Detailed regional projections, impact studies	Still rely on GCM boundary conditions; limited in capturing very local extremes
<b>Convection-Permitting Models (CPMs)</b>	~1-4 km	High-resolution; simulate storms and rainfall explicitly	Local extremes (e.g., flash floods, intense storms), urban climate studies	Computationally expensive; typically run for short time periods or small areas
<b>Coupled CPMs</b>	~1-4 km	High-resolution; examples include ICON (Icosahedral Non-hydrostatic Model), and the Met Office UKV model	Global to local extremes, coupling allows for a more realistic simulation of complex feedback processes	Computational very expensive; global coupled CPM typically run for less than two months
<b>Earth System Models (ESMs)</b>	~50-100 km	Include biogeochemical cycles (carbon, nitrogen, etc.)	Climate-carbon feedbacks, ecosystem-climate interactions	High complexity increases uncertainty; still limited in spatial resolution
<b>Simple Climate Models (SCMs)</b>	No spatial resolution	Use simplified equations; fast to run	Policy analysis, scenario testing, global temperature projections	Cannot simulate regional impacts or extremes; oversimplified physical processes
<b>Spatial and time emulator models</b>		Statistical tools that emulate the local responses of complex Earth System Models (ESMs)	Quick and efficient regional assessments for impact analysis	Build on complex ESMs, calibrated for each individual ESM;
<b>Paleoclimate Models</b>	Varies	Simulate past climates using proxy data	Understanding past climate variability and model validation	Limited by quality of proxy data

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## 1.6 References

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Draft for Community Review