EHTF Weather and Climate Change Report: March 2023

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Executive Summary

Following the unprecedented heat of 18/19 July 2022 and its impacts on Network Rail's infrastructure and operations, this report has been commissioned to consider the climatological context of this event; to summarise the alerts and forecasts around this event and to recommend any improvements; and to assess the likelihood of such events in the coming years and decades as climate change progresses.

There is no doubt that heatwaves are becoming increasingly common in the UK in summer as temperatures rise due to the effects of global warming. However, the extreme nature of the temperatures in July 2022 was due to a combination of factors that led to a 'perfect storm' of extreme heat. Antecedent dry conditions across south-west Europe and the UK, combined with an unusually disturbed northern hemisphere circulation, led to extreme hot and dry air from as far away as North Africa being channelled over the UK. The end result was unprecedented heat across the UK, exacerbated by background warming from climate change.

This event was well forecast and warnings of the risk of extreme heat were issued at least one week in advance. The Met Office issued its first ever Red Severe Weather Warning on 15 July, which proved to be very accurate. Network Rail was well served by its forecast provider, MetDesk, and following the Weather Advisory Task Force (WATF) report of 2021, it had the necessary links with experts in the Met Office to support its decisions. With the developments already ongoing from the WATF recommendations, the future provision of extreme heat-related forecasts is in good shape.

It is important that Network Rail has access to the latest information on how climate change will affect its operations and infrastructure so that it can develop appropriate adaptation and resilience plans. This report commissioned the Met Office to produce a new, in-depth analysis of how extreme temperatures and heatwaves may change decade-by-decade through the 21st century, based on its state-of-the-art kilometre-scale simulations. The following key conclusions from this study include:

- Summer mean temperatures will increase by a further 0.5^{o} to 1^{o}C by 2040 compared with today, regardless of emission scenario. Due to a range of positive feedback mechanisms discussed in this report, extreme temperatures will increase by more than the average temperature change.
- SE England is particularly prone to extreme temperatures, due to its drier summers and its proximity to continental Europe where increasing heat and dryness will become a significant issue.
- Over SE England, days with 25^{o}C and above are likely to double by the 2040s; by the 2070s under a high emission scenario, all summer days could be above 25^{o}C.
- Days above 30^{o}C and 35^{o}C will increase systematically through the century across England and Wales. Scotland is unlikely to see any days above 35^{o}C by the end of the century, but there is a 5% risk of several days a year above 30^{o}C.
- The risk of experiencing extreme temperatures of 40^{o}C and above remains low through the century because of the moderating effects of the North Atlantic on UK climate. Nevertheless, there is a 5% chance of experiencing at least one day per year of 40^{o}C or above, over England and Wales by 2070.
- The frequency and duration of heatwaves will also increase, particularly in SE England. By the 2040s, heatwaves in excess of 30^{o}C, could last on average 4-5 days and with a maximum length of 10 days or more.
- So far, there is no evidence that the frequency of specific weather patterns that favour high summer temperatures will change in the future. The 'perfect storm' of July 2022 is no more or no less likely as climate change progresses.

In summary, extreme temperatures and heatwaves will become an increasing feature of UK summers as global warming progresses. However, the extreme heat of July 2022 is likely to remain a rare event.

1. Introduction

On 18/19 July 2022 Network Rail experienced multiple failures across southern and eastern England as the result of extreme heat and unprecedented temperatures that exceeded 40^{o}C for the first time. These temperatures transcended the tolerance levels of several aspects of Network Rail's infrastructure, such as overhead lines, and, in addition, resulted in knock-on effects, such as wildfires, falling trees and failure of clay earthworks, due to widespread dessication of the countryside. As a result, Network Rail recognises the urgent need to review its exposure and vulnerability to extreme heat, and to ensure that future infrastructure and operations are resilient to increasing levels of risk in the face of the changing climate.

Network Rail therefore commissioned the Extreme Heat Task Force to produce a set of reports, one of which focuses on extreme heat in the context of weather forecasting and climate change. In this report the following topics will be covered:

- Setting the scene – current climatology of heatwaves, extreme temperatures, and their basic drivers
- Case study of July 2022 record-breaking temperatures.
- Forecasting extreme temperatures and heatwaves for various lead times, using July 2022 as an example.
- Climate change and future frequency of extreme temperatures and heatwave characteristics across the network, decade by decade from 2021 to 2080. This includes assessment of potential changes in significant drivers of future heat.
- Recommendations on future actions to ensure the Network Rail has access to weather and climate change information and advice, through improved early warnings, and in-depth knowledge of future climate change.

2. Setting the Scene

2.1. Definition and characteristics of heatwaves.

The definition of a heatwave is dependent on its location. In the UK a heatwave threshold is met when a location records a period of at least three consecutive days with daily maximum temperatures meeting or exceeding the heatwave temperature threshold. The thresholds have been determined based on the 90th percentile of the July daily maximum temperature for a 1991–2020 climatological reference period The threshold varies by UK county reflecting the fact that potential impacts may occur at lower temperatures in the climatologically cooler parts of the country (https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave).

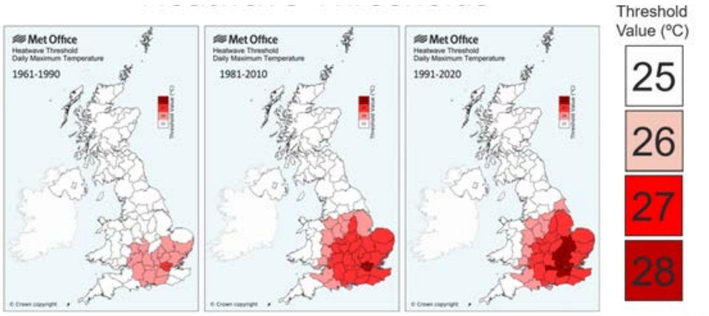


Figure 2.1 Heatwave threshold temperatures (°C) across the UK as updated in January 2022 and based on the most recent 30-year climatology. (Source: Met Office)

As part of the UK's Severe Weather Warning Service, an Extreme Heat Warning may be issued when temperatures are expected to exceed, significantly, those for a heatwave. This is an impact-based warning designed to highlight the potential impacts of extreme heat to protect lives and property, helping people make better decisions to stay safe. In the case of the rail network, rail buckling, overheating of location cabinets controlling signalling, sagging of overhead lines are just some of the impacts of extreme heat which can have serious impacts on performance. Extreme heat also exposes staff and passengers to heat stress as outlined in Table 1, noting that these can be more severe if humidity is high. In Summer 2022 the Met Office issued its first ever red warning for extreme heat reflecting the potential health risks to the public.

UTCI (°C)	*Thermal heat stress category*	*Protection measures*
>46	Extreme heat stress	Temporary body cooling. No physical activity. Drinking $>0.5Lh^{-1}$ water necessary.
38 to 46	Very strong heat stress	Temporary use of air conditioning. Shaded places necessary. Reduce physical activity. Drinking $>0.5Lh^{-1}$ water.
32 to 38	Strong heat stress	Shaded places. Drinking $>0.25Lh^{-1}$ water. Temporarily reduce physical activity.
26 to 32	Moderate heat stress	Drinking $>0.25Lh^{-1}$.

Table 1 Universal Thermal Climate Index (UCTI) heat stress scale and recommended protection measures, adapted from Di Napoli et al. (2019)[1].

In contrast to some types of extreme weather that can be very localised (e.g. intense rainfall), the spatial extent of heatwaves can be quite extensive, often covering more than one route region (Figure 2.2). This is due to the meteorological situation in which heatwaves form. They are typically associated with high pressure systems (anti-cyclones) that are slow moving and can persist over an area for an extended period of time, such as days or even weeks, resulting in prolonged dry, settled and often increasingly warm weather.

[1] Di Napoli, C., Pappenberger, F., Cloke, H. (2019) Verification of heat stress thresholds for a health-based heatwave definition. Journal of Applied Meteorology and Climatology, 58 (6). pp. 1177-1194.ISSN: 1558-8432 | doi: https://dx.doi.org/10.1175/JAMC-D-18-0246.1

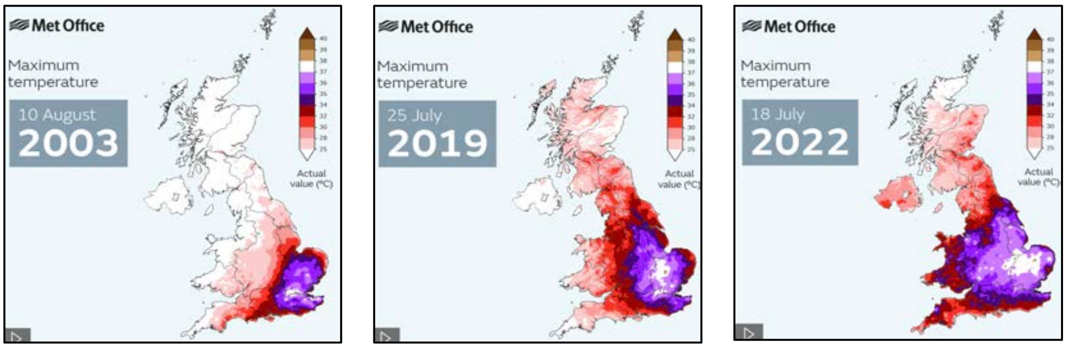


Figure 2.2 Examples of extreme high temperature events showing the spatial scale of the event. (Source: Met Office)

Figure 2.3 gives examples of the duration and frequency of heatwaves for the UK's major metropolitan areas. Durations in excess of 1 week are quite common and those in excess of 2 weeks can account for around 10% of all heatwaves. This may have serious implications for the rail network, including multiple failures across the network and the potential for cascading and indirect impacts.

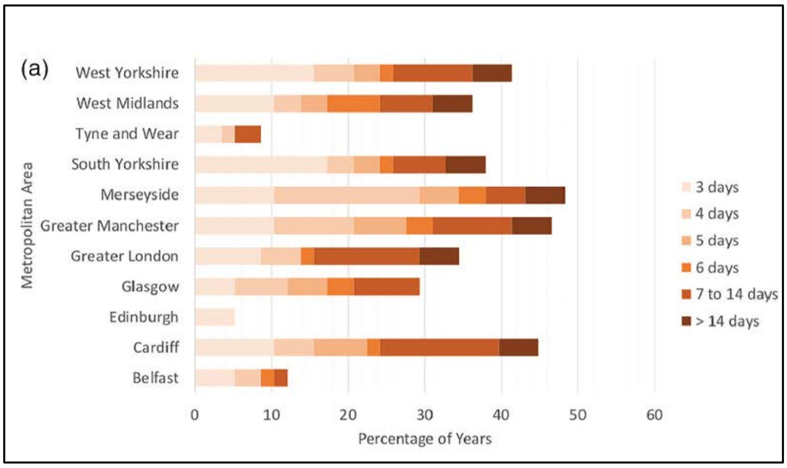


Figure 2.3 Heatwave duration presented as the proportion of years since 1961 with the listed number of heatwave days by Metropolitan Area. (Source: McCarthy et al. 2019[2])

The current definitions of heatwaves are very general and reflect the diversity of impacts across sectors and on human beings. Network Rail may wish to define its own metrics based on infrastructure performance, passenger comfort and staff safety, drawing from recent experience and the other components of the EHTF Report. Working with the Met Office these can then be used within the seamless forecasting suite to provide sector-specific alerts.

2.2 Climatological context of heatwaves

Heatwaves are becoming increasingly common in the UK in summer as temperatures increase, due to the effects of global warming, with 2022 being the first year where the maximum temperature exceeded 40C (Figure 2.4, upper panel). It was also the warmest year on record and the first year over 10°C (Figure 2.4, lower panel). A Met Office scientific study of the summer 2018 heatwave showed that the likelihood of the UK experiencing a summer as hot or hotter than 2018 is a little over 1 in 10. It is 30 times more likely to occur now than before the industrial revolution because of the higher concentration of carbon dioxide in the atmosphere.

[2] McCarthy, M., Armstrong, L. and Armstrong, N. (2019). A new heatwave definition for the UK. Weather, 74 (11), 382-387. https://doi.org/10.1002/wea.3629

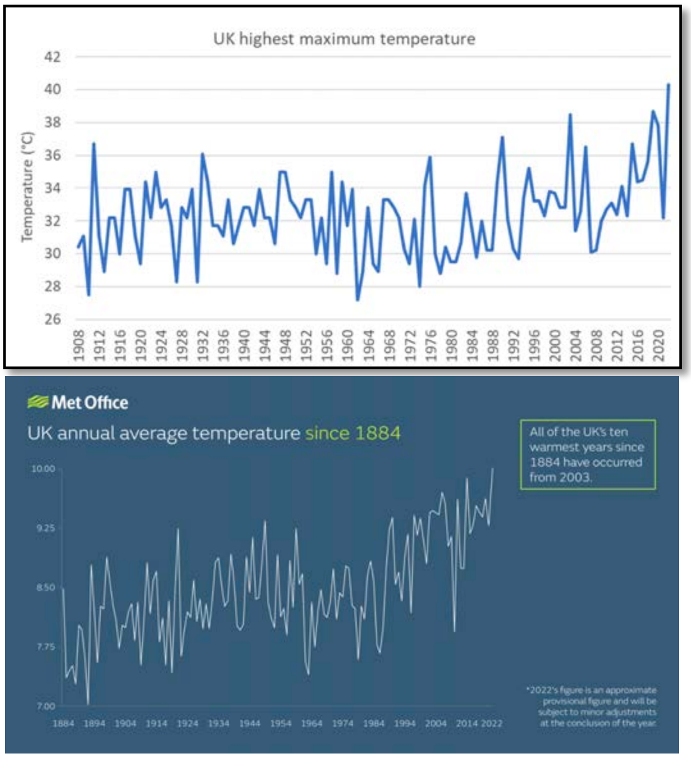


Figure 2.4 Timeseries of the UK's highest maximum temperature (°C) from 1908 to 2022 (upper figure), and the UK annual temperature since 1884 (lower figure). (Source: Met Office)

As Figure 2.4 indicates, the increase in maximum temperatures is much greater than the background global warming, suggesting that other factors may be playing a role in amplifying the intensity of extreme high temperature events. One of these is the soil wetness at the beginning of, and during summer. A notable feature of some extreme temperature events has been the lack of rainfall in the preceding winter and/or spring, extending into summer. Examples include 1976, and especially in 2022 (Figure 2.5, left panels). There has also been prevalence for increasing sunshine in spring in recent years, often associated with persistent high-pressure events, which also drives higher evaporation rates (Figure 2.5, right panel). These two factors can lead to more depleted levels of moisture in the soil during summer months. This means that surface evaporation falls, and just like humans, if the land cannot 'sweat' efficiently then the temperature rises to compensate.

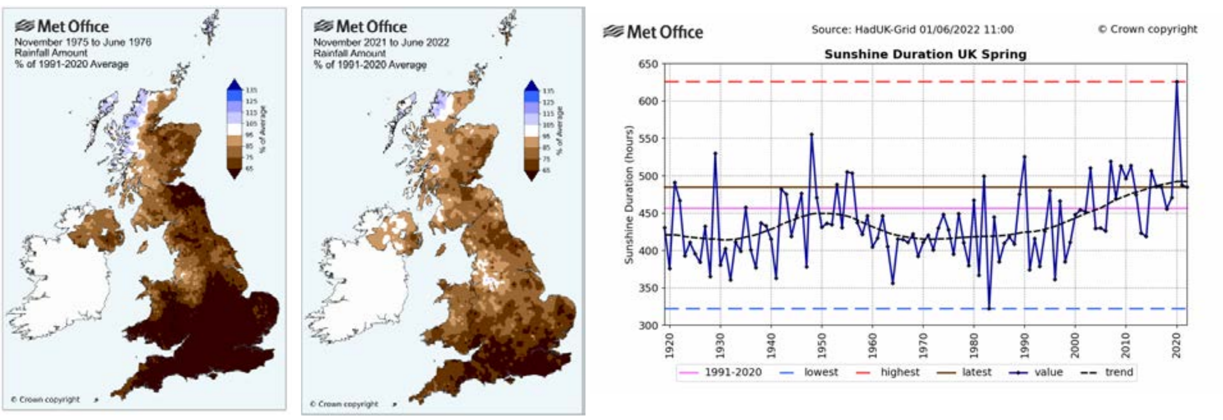


Figure 2.5 Examples of potential precursors for extreme summer heat. Left panels: Rainfall accumulations in the preceding winter and spring for 1976 and 2022. Right panel: Time series of UK sunshine hours during spring. (Source: Met Office)

The seeds of UK heatwaves are not always home grown. Most of the record extreme temperatures tend to occur over the south-east quadrant of the UK (Figure 2.2), reflecting the influence of continental Europe. Like the UK, south-western Europe has been warming systematically, and even though there is no detectable trend in rainfall, higher temperatures have acted to deplete soil moisture and reduce the relative humidity (Figure 2.6, left panels). These hydrological changes have been reflected in an increasing frequency of meteorological droughts (Figure 2.6, right panel). Consequently, climate trends in south-western Europe are important players in the potential risk to the UK of heatwaves and extreme temperatures.

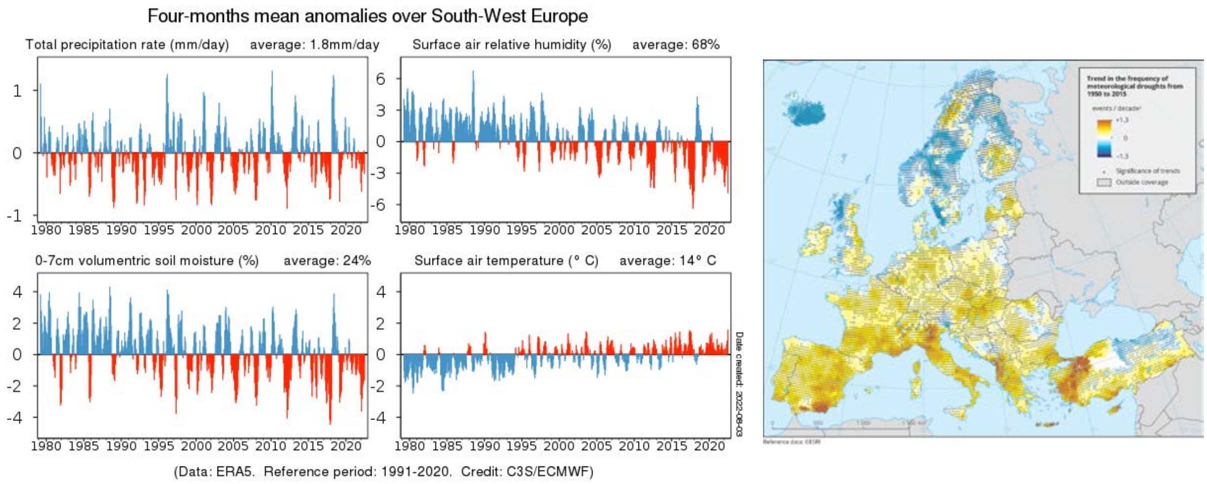


Figure 2.6 Changing climate of south-west Europe with respect to the reference period, 1991-2020. Left panels show the 4-month running mean of anomalies in total precipitation, 0-7cm volumetric soil moisture, surface air relative humidity and surface air temperature. The right panel shows the trend in meteorological droughts from 1950 to 2015, where the dots indicate that the trend is significant. (Source: Copernicus Climate Change Service (C3S) - https://climate.copernicus.eu/esotc/2021)

Heatwaves and heat extremes are also associated with particular weather regimes, especially those involving high pressure over the UK. The positioning of the high pressure is important. When it brings southerly flow from western Europe, sometimes from as far away as North Africa, the air mass can be very warm and dry, exacerbating the risk of wildfires.

The record-breaking heat wave in Lytton, Canada in 2021 highlighted the potential for the atmospheric circulation to amplify the severity of the heat wave considerably (Figure 2.7). A wave in the jet stream, known as an 'Omega Block', was created in which high pressure builds. If this wave becomes stationary, high pressure persists, and a phenomenon known as a 'heat dome' can form. Warm air underneath is trapped - rather like a lid on a pot - becoming hotter and hotter, and creating a heat dome. Hot air, being less dense, rises into the atmosphere, but the high pressure acts as a lid, forcing the air to subside or sink. As the air sinks it warms by compression and the heat builds. The descending air also drives way any clouds; the ground heats up under the clear skies, losing even more moisture until it can no longer 'sweat' effectively, and temperatures rise even further. The heat dome only breaks down when the weather pattern changes and the wave in the jet stream breaks down or migrates away.

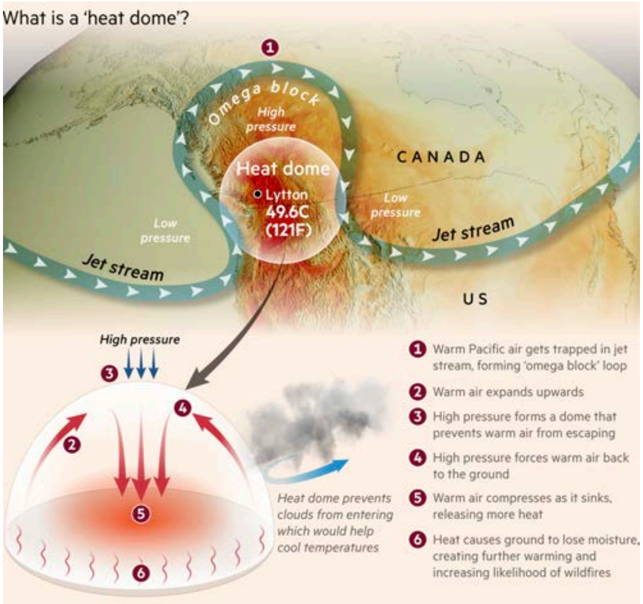


Figure 2.7 Schematic of a heat dome that formed over Lytton in 2021 showing the various components that lead to intensification of the heatwave. (Source: NOAA)

Long-lived heat waves, and especially those in which a heat dome can form, are particularly dangerous for rail infrastructure. Infrastructure is under prolonged heat stress and the extreme high temperatures associated with the heat dome may lead to sudden failures. The spatial scale of the heat dome is such that large parts of the network may be under stress at the same time, leading to multiple failures.

Local factors can also come into play, alongside large-scale systems such as heat domes, and these can act to exacerbate the impact on the rail network. Examples include heat bursts and the local effect of hills and valleys e.g. Foehn effect.

A heat burst is a rare atmospheric phenomenon characterized by a sudden, localized increase in air temperature near the Earth's surface. Heat bursts typically occur during night-time and are associated with decaying thunderstorms (Figure 2.8). The precipitation falling from the decaying storm evaporates in the dry, cold downdraft generated by the storm system, cooling the air even further and producing rapid descent of the dense downdraft. As the downdraft descends, it is warmed by compression, leading to a pulse of very high temperatures at the surface. An example of a heat burst occurred in Lincolnshire and Nottinghamshire during the evening of 25 July 2019, when temperatures surged by more than 10ºC, to 32ºC, in less than an hour. Heat bursts are also characterized by extremely dry air and are sometimes associated with very strong, even damaging, winds.

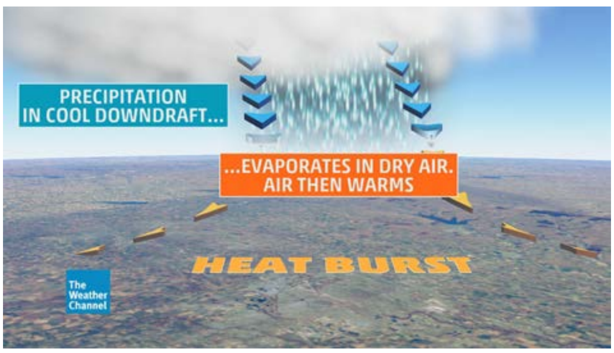
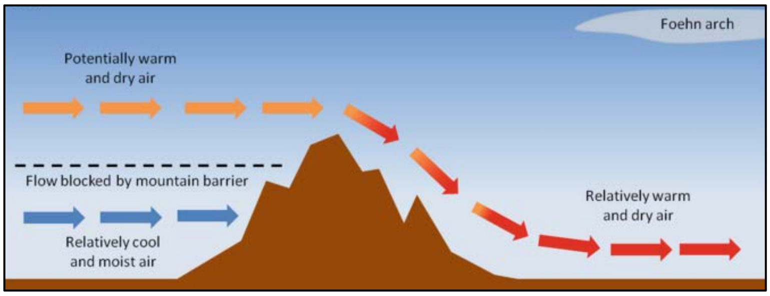


Figure 2.8 Schematic of a heat burst showing the various components that lead to targeted intensification of heat and strong winds. (Source: https://weather.com/science/weather-explainers/news/heat-bursts-thunderstorms-explained)

The Foehn effect also causes warming and drying, in this case of air on the lee side of cross-mountain winds. When winds are insufficiently strong to propel the low-level air up and over the mountain barrier, the air is said to be 'blocked' by the mountain and only air higher up, near mountain-top level, is able to pass over and down the lee slopes as Foehn winds. These higher source regions provide air that becomes warmer and drier on the leeside after it is compressed with descent due to the increase in pressure towards the surface (Figure 2.9).



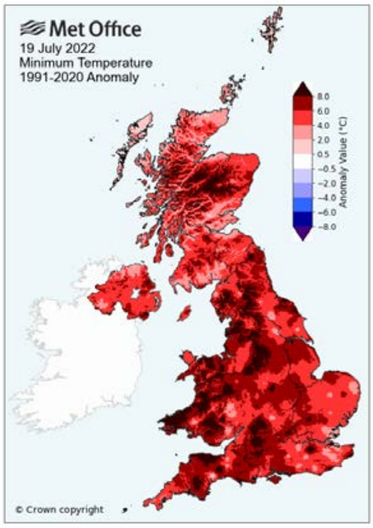


Figure 2.9 Schematic showing the causes of the Foehn effect in the lee of mountains where localised heat spots can be caused by dry air being forced over hills and then adiabatically warmed on the lee side (left panel), and an example of the Foehn effect on night-time minimum temperatures on 18/19 July 2022 (right panel). (Source: Met Office)

The Foehn effect was prevalent during summer 2022 heatwave with record-breaking overnight temperatures to the lee of hills across Wales and NW England, and to the lee and north of Exmoor. For example, Aberporth recorded its highest minima temperature of 24.5°C on the night 18 to 19 July 2022.

In summary, heatwaves and temperature extremes are associated with particular weather regimes, especially those involving high pressure over the UK, and preconditioned by depleted soil moisture. The specific risks from long-lived heat waves have been highlighted, especially those in which a heat dome can form. These are particularly dangerous for rail infrastructure. Infrastructure is under prolonged heat stress, and the extreme high temperatures associated with the heat dome may lead to sudden failures. The spatial scale of the heat dome is such that large parts of the network may be under stress at the same time, leading to multiple failures.

3 Case Study of summer 2022 heat extremes and potential causal factors

July 2022 went down in UK climate history as the first time the UK exceeded temperatures of 40°C. On 19 July, during an intense heatwave, UK saw its new record high temperature of 40.3°C at Coningsby, Lincolnshire. Wales also recorded its highest temperature with 37.1°C at Hawarden, and Scotland followed suit with a record high figure of 34.8°C at Charterhall. For England, 2022 was its joint hottest summer in a series which runs from 1884. This means that four of the five warmest summers on record for England have occurred since 2003.

In addition to extreme daytime temperatures, nights were also exceptionally warm. A new highest daily minimum temperature record of 26.8°C was recorded at Shirburn Model Farm in Oxfordshire on the night of 19 July 2022, meaning that the temperature never got below 26.8°C for an entire 24-hour period. This has surpassed the previous record, exceeding the August 1990 record of 23.9°C by nearly three degrees. In all respects, the heatwave of July 2022 was exceptional, with widespread impacts across the country.

3.1 Role of antecedent and concurrent drought

Very simply, land surface temperatures are controlled by the balance between net radiative heating (heating from the sun and from the downwelling infrared radiation from the atmosphere, cooling by the surface emission of infrared radiation), and cooling by surface evaporation and the turbulent flux of dry (sensible) heat. But surface evaporation depends on soil moisture. When the soil is damp, then evaporation takes place at its full potential and the land is able to 'sweat' readily to remain cool. However, when soils dry out, evaporation declines substantially, and the surface energy budget can only be balanced by increasing the dry turbulent (sensible) heat flux and the outgoing flux of surface infrared radiation. Both these fluxes can only increase if the surface temperature increases. This is why aridity is potentially a major factor in intensifying heat waves, as well as increasing the probability of their occurrence.

It is clear that the intense heat of 2022 was pre-conditioned by unusually dry conditions across the UK in the preceding spring, so soil moisture was already depleted. This continued into the summer with the period from 1 June to late July being exceptionally dry (Figure 3.1).

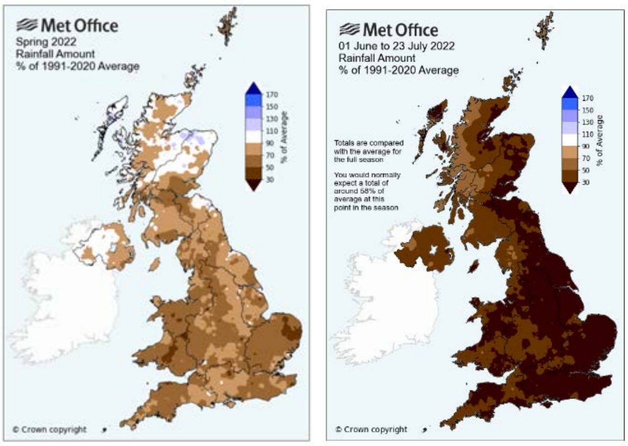


Figure 3.1 Rainfall expressed as a % of the 30-year climatology for Spring 2022 (left) and from1 June to 23 July 2022 (right). (Source: Met Office)

Overall, the UK saw just 56% (46.3mm) of its average rainfall for July, making it the driest July in over 20 years (with 1999 recording 46.1 mm). England had just 35% (23.1mm) of its average rainfall for the month, Wales 53% (52mm), Northern Ireland 51% (45.8mm) and Scotland topped the billing with 81% (83.6mm). Regions in the south and east were especially dry, with southern England reporting its driest July on record in a series that goes back to 1836, with 10.5mm of rain, which is just 17% of its average rainfall. In addition, 13 counties across southern and eastern England reported their driest July on record,

For England, 2022 was the 6th driest summer on record (103mm), and driest since 1995 (66mm), in a series from 1836. For the UK overall, it was the 10th driest summer (156mm) and driest since 1995 (106mm). The summer was also sunnier than normal, which drives higher surface evaporation and exacerbates existing soil dryness.

3.2 The role of the jet stream and weather regimes

A major factor for in the heat of July 2022 was a high-pressure pattern that dominated the UK for much of July, pushing any Atlantic influence, and therefore much of the rain away from the UK. The source of this pattern can be traced back to the tropical Pacific where a strong La Nina event was taking place (Figure 3.2), characterised by colder than normal ocean temperatures along the coast of Peru and spreading across the equatorial East Pacific. This has the effect of confining the warmest ocean waters to the West Pacific Ocean and Indonesian region where these high sea surface temperatures act to drive stronger than normal rainfall from deep cumulonimbus clouds. In turn, the deep heating and outflow within these deep clouds interacts with the jet stream and sets off a series of large-scale (Rossby) waves that propagate along the jet stream and spread the influence of La Nina (and El Nino) around the globe.

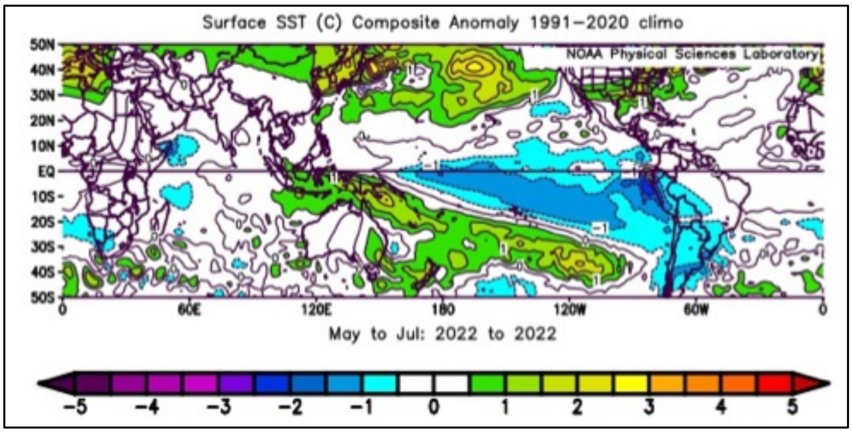


Figure 3.2 Sea surface temperatures anomalies (°C) for the 3 months (May – July 2022) preceding the July heatwave showing colder than normal water in the East Pacific, typical of La Nina conditions. (Source: NOAA)

Figure 3.2 also shows an arc of warmer than normal ocean temperatures to the north and south of the cold water of La Nina. The impact of this pattern on the actual sea surface temperatures in the West Pacific is shown in Figure 3.3. In the tropics, intense convection is typically confined to regions where the sea surface temperature exceeds 28°C; in the West Pacific and Indian Ocean, this isotherm defines what is known as the Indo-Pacific Warm Pool. As Figure 3.3 (left panel) demonstrates, in 2022 the Warm Pool contained temperatures in excess of 30°C (dark red), warmer than the climatology (right panel). This means that the Warm Pool was already primed for more vigorous convection. Potentially more important, however, is the extension of the Warm Pool (28°C isotherm – orange) northwards towards Japan in 2022. This facilitates stronger interactions between deep tropical cumulonimbus clouds and the Jetstream with the potential to excite stronger than normal waves along the Jetstream.

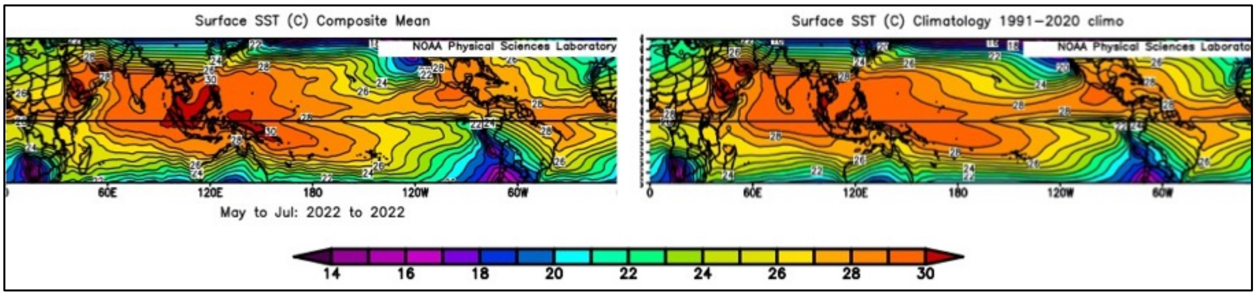


Figure 3.3 Sea surface temperatures (°C) for the 3 months (May – July 2022) preceding the July heatwave (upper panel) and the climatological sea surface temperatures for May to July based on the 30-year average, 1991-2020. (Source: NOAA)

In summary, these two factors – (i) La Nina, and (ii) northward expansion of the Warm Pool – meant that 2022 was primed for strong perturbations to the jet stream and the scene was set for extreme weather conditions in mid-latitudes. In early July 2022, strong pulses of heavy rainfall in the tropical West Pacific triggered some major changes to the jet stream. Climatologically, the summer jet stream is quite weak and zonal (Figure 3.4, left panel), but in 2022 the jet stream was substantially disrupted (Figure 3.4, right panel). The effect of this was to create a pronounced ridge over the UK, as part of a circum-global pattern that created a number of extreme weather events around the northern hemisphere.

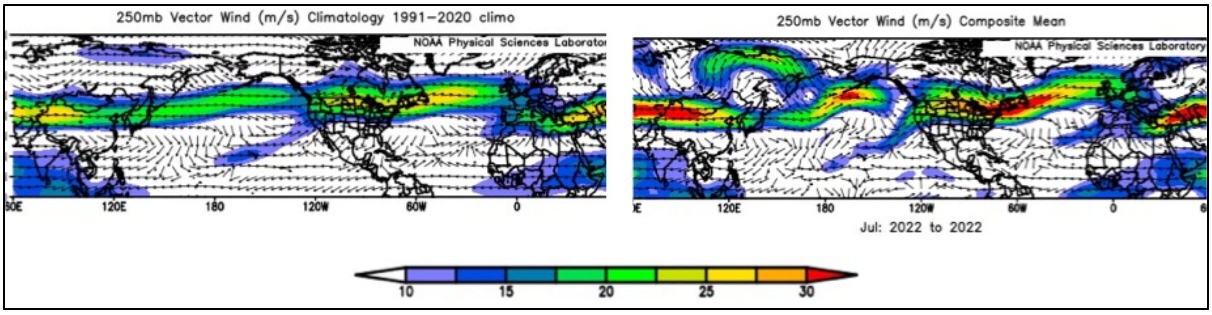


Figure 3.4 Upper tropospheric winds showing the northern hemisphere jet stream (characterised by the strongest winds shown in colour) for July from climatology (left panel) and for 2022 (right panel). (Source: NOAA)

The effect of this disruption to the jet stream was to create a pronounced ridge over the UK, as part of a naturally occurring, circum-global teleconnection (CGT) pattern (Figure 3.5 (upper panel)), characterised by a series highs and lows around the northern hemisphere, typically 5 of each. This pattern of high and lows created a number of extreme weather events around the northern hemisphere (Figure 3.5 (right panel)), in particular a series of warm regions, associated with the chain of five high-pressure regions. The CGT pattern often accompanies heatwaves in the mid-latitudes and was the reason for a number of concurrent heat waves around the world during the summer of 2022, from the US to China.

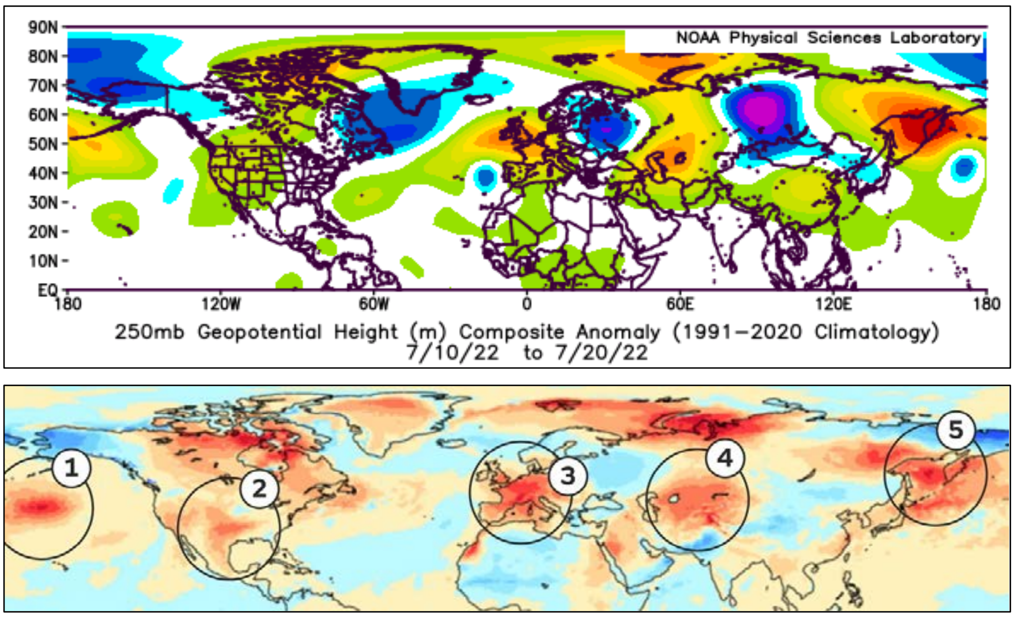
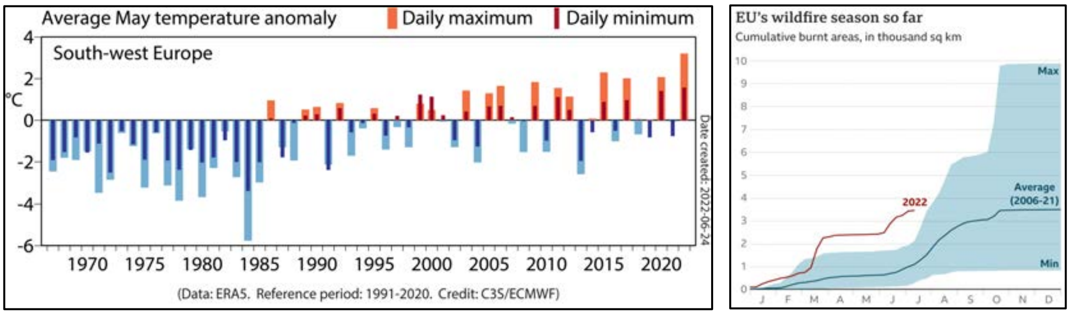


Figure 3.5 Anomalous atmospheric circulation patterns in the 2 weeks leading up to the UK heatwave, showing a series of high and lows circling the northern hemisphere (upper panel). These can be directly linked to high surface temperatures events during the week commencing 18 July, including marine heatwaves (lower panel). (Source: NOAA, Met Office)

3.3 Influence of western Europe

As has already been noted, the UK often comes under the influence of continental air masses which in summer are typically warm and dry. As with the UK, dry conditions in spring can exacerbate summer heat and this was particularly the case for Europe in 2022. Intense heat in May and June broke existing records in several countries. South-west Europe experienced its highest daily maximum and minimum temperatures since records began (Figure 3.6, top left), and the beginning of the wildfire season was exceptionally early (Figure 3.6, top right). By July, soil moisture was substantially depleted across much of southern Europe and the UK (Figure 3.6, bottom left).



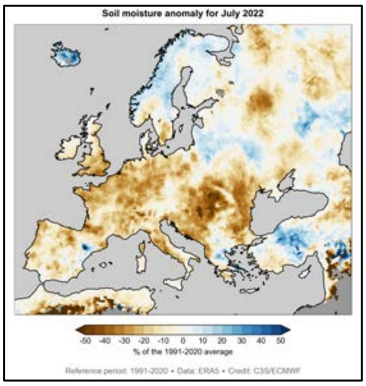


Figure 3.6 Antecedent conditions over south-western Europe. Top left panel: Times series of May average maximum and minimum temperatures showing the trend to much warmer late springs. Top right panel: Seasonal evolution of the EU's wildfire season in recent years, showing the abnormally early start in 2022. Bottom left panel: Map of soil moisture anomalies (%) for July 2022 showing large deficits across south-west Europe and the UK. (Source: Copernicus Climate Change Service (C3S) - https://climate.copernicus.eu/esotc/2021)

Europe continued to swelter in July with a larger number of days with temperatures above 30°C, 35°C and 40°C than a typical July. While the heatwave was very intense in terms of daily temperature extremes, it was mainly the longevity of the period with daily maximum temperatures between 35°C and 40°C that characterised July, particularly in south-western Europe. Europe experienced dry conditions during most of July, with much of the continent seeing rainfall well below average. For the 12 months to July 2022, it was drier than average across all hydrological indicators over much of western and southern Europe, with consequently fire risk being extreme in many areas by July (Figure 3.7).

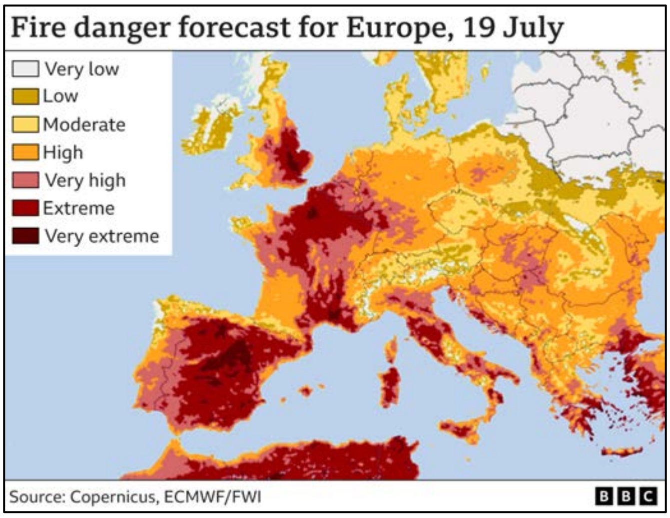


Figure 3.7 Fire danger forecast for 19 July 2022 showing that much of south-western Europe extending into south-east England was under extreme or very extreme risk of wildfires. (Source: ECMWF)

There is no doubt that the extreme conditions over south-western Europe played a critical role in the severity of the UK's extreme temperatures in July 2022. Combined with the trends in European climate, noted in Figure 2.6, the southeast of the UK is particularly vulnerable to what happens in Europe as climate changes.

It is also clear that the atmospheric circulation was a major player in the severity of the heatwave. Just as for Canada in the previous year (Figure 2.7), an omega block in the jet stream formed over the UK, which helped to establish a heat dome and to bring hot, dry air from south-west Europe over the UK (Figure 3.8). The formation of a cyclonic vortex to the south-west of the UK – a so-called Rex Vortex or cut-off low – tightened up the pressure gradient on the western flank of the omega block, accelerating the southerly flow and bringing very hot, dry air from as far south as the Sahara (Figure 3.6). The dessicated conditions over Spain and France meant that this desert air reached the UK with very little modification; indeed, hot and dry air was present from the surface up to near 5000m in the atmosphere.

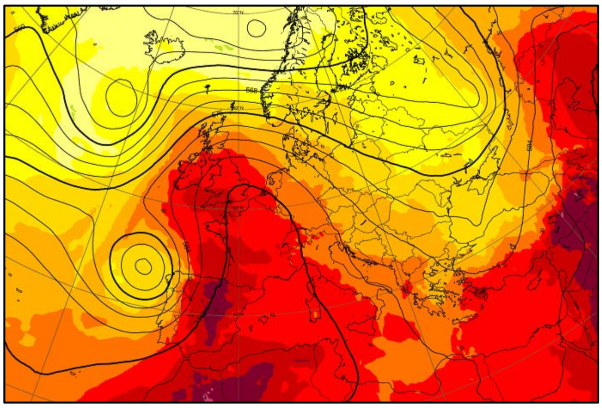


Figure 3.8 Circulation pattern (contours) and air temperatures (colours) in the lower troposphere on 19 July. (Source: ECMWF).

In summary, it is fair to say that the extreme nature of the 2022 heatwave was due to a combination of factors that led to a 'perfect storm'. Antecedent dry conditions across south-west Europe and the UK, combined with an unusually disturbed northern hemisphere circulation, driven by the warmer than average tropical West Pacific, led to the establishment of blocked conditions over the UK and the formation of a Rex vortex to the south-west of the UK. The Rex vortex was particularly effective in tightening up the pressure gradient over Spain and France, channelling extreme hot and dry air from as far away as North Africa over the UK. The end result was unprecedented heat across the UK.

4 Operational forecasting of heatwaves and related hazards

The range of forecasts that are now available to Network Rail, has been discussed extensively in the WATF Report with the focus on rainfall. Much of that discussion is also relevant to forecasting heatwaves and extreme temperatures. Figure 4.1 provides a summary for this report with the focus on temperature (see also Figure 6.3 from WATF Report). It is worth reiterating that the predictability of local heat-related events is generally higher than for rainfall because of the more homogeneous space and time scales for heat.

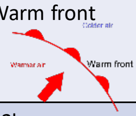
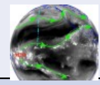
Definition	Nowcast	Very Short	Short	Medium	Extended	Long range
Leadtime	0 to 2 hrs	2 to 12 hrs	12 to 72 hrs	3 to 10 days	10 to 30 days	30 days +
Scale Met Feature	1km Heat Burst 	10km Foehn / Urban 	50km Warm front 	100km Heat Dome 	500km Airmass 	1000km CGT 
Lifetime	10 min	1 hr	12hr	1 day	3 days	5 days
Predictability	30 min	3 hr	36 hr	2 days	7 days	10 days

Figure 4.1 Schematic showing the differing lead times and scales of forecasts available to Network Rail to enable better preparedness ahead of the event. (Source: Met Office)

4.1 Case study of extreme heat forecasting across timescales in Summer 2022

July 2022 is a helpful case study to show the 'art of the possible' in forecasting across a range of lead times and how the information can be used to prepare the public and key service providers. How far ahead is a user-sensitive heatwave event predictable to a level where the forecast information is valuable enough to take action?

First, different users have different requirements on the forecast quality needed to take actions, and these requirements may be different for different lead times; and second, different types of weather have different levels of predictability and for similar types of events, this can vary with season and location. Here one needs to understand the underlying predictability mechanisms for weather and how best to translate this insight for customer decision benefit.

Figure 4.2 provides a summary timeline for the two weeks before the extreme heat of 19 July. It shows a period of heightened activity, from initial identification of potential for extremes, initial communication with customers and eventual escalation of warnings, through to the peak of the heat on Monday 18th and Tuesday 19th July. In the following sections, the forecasts available for decision makers from a season to a few hours ahead will be presented as examples of the type of information that Network Rail can expect to receive.

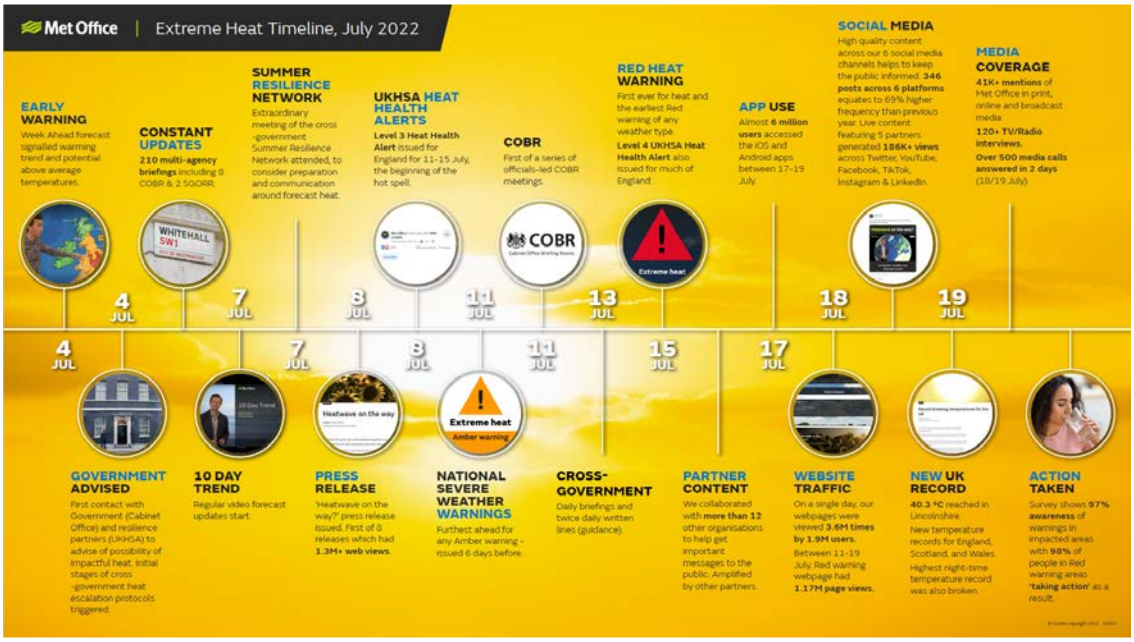


Figure 4.2 Extreme heat timeline for July 2022 showing the different activities beginning more than 2 weeks ahead of the event to prepare government, infrastructure providers and the public. (Source: Met Office)

4.1.1 Looking a season ahead – Seasonal Outlook

In May, the Met Office anticipated a higher chance of a hot summer compared to normal, with impacts from heatwaves more likely than usual, along with a reduction in the chance of a wet summer compared to normal.

Figure 4.3 shows the official probabilistic forecast for June-July-August, based on a 50-member ensemble initialised in May. By their nature, forecasts with these lead times have a large degree of uncertainty, as the spread of the individual forecasts demonstrates in Figure 4.3. This spread can be compared with the spread of the observations over the last 30 years, and allowing for recent climate change, the most recent 10 years. Sometimes the forecasts need to be adjusted to allow for model biases, but not in this case.

The temperature forecast shows a significant shift to higher values compared with the spread of the observations, which is why an elevated risk of a hot summer was predicted. The actual outcome is shown by the blue star, and this lies within the spread of the predictions but above the median value shown by the blue circle. In fact, the ensemble spread shows that 6 members predicted a summer hotter than the hottest so far observed. This could be interpreted as a 10% risk of unprecedented heat and, overall, an elevated risk of damaging heat for Network Rail. What was not well-captured by the forecast was the extreme dryness of the summer which was a contributory factor to the extreme heat and related risks such as wildfires.

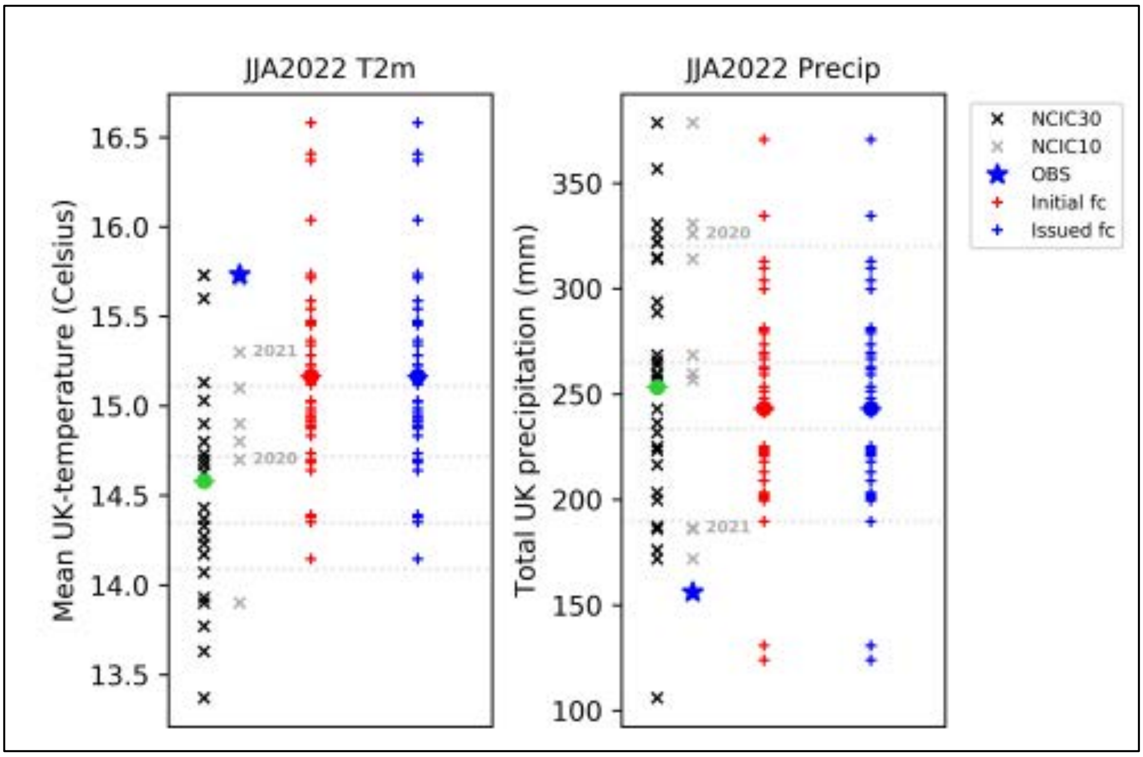
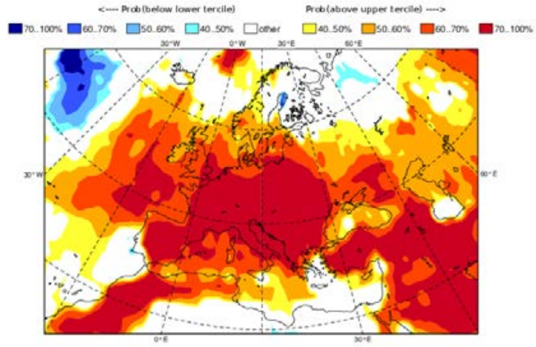
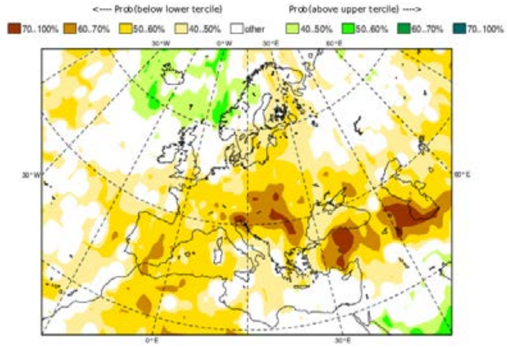


Figure 4.3 Seasonal forecast for UK temperature and precipitation, issued in May 2022 for the 3-month period, June – August based on a 50-member ensemble of forecasts. The black crosses indicate the observations for the last 30 years and the blue crosses give the individual forecasts. The blue star is what actually occurred. (Source: Met Office)

When the Met Office issues its seasonal forecast, it takes account of the forecasts produced by other leading centres, particularly the European Centre for Medium-range Weather Forecasts (ECMWF). Its forecasts also highlighted an elevated risk of a hot summer, but like the Met Office did not capture the extreme dryness (Figure 4.4). What is evident though is that the heat and drought over Europe was anticipated, elevating the risk of high temperatures in the UK, especially over the south-east.





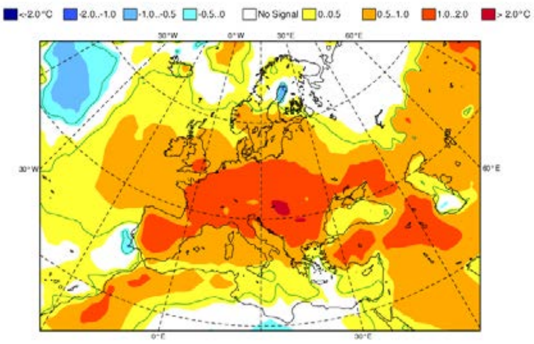


Figure 4.4 Seasonal forecasts of temperature and precipitation for June-August 2022. Upper panels show the probabilities of being in the upper or lower terciles for temperature and precipitation. The dark red areas for temperature indicate a 70% or higher probability of a warm summer, and the yellow areas for precipitation indicate around 50% probability of a dry summer. Lower left panel shows the ensemble mean temperature anomaly indicating, on average, that summer temperatures will be 1 to 2°C above normal for much of Europe and the south-east of the UK. (Source: ECMWF)

Much more could be done with these seasonal to monthly forecasts to make the outputs more relevant to Network Rail's vulnerability and exposure to high temperatures. There is undoubted value in these extended range predictions, but it will be necessary for Network Rail to work together with Met Office scientists to extract the relevant information and to understand how to use it most effectively.

In future, these probabilistic seasonal forecasts could be customised for Network Rail based on its vulnerabilities, so that more specific assessments of risk could be provided to assist forward planning. It is recommended that Network Rail explores with the Met Office, the potential for more user specific risk assessments in the months and weeks leading up to summer.

4.1.2 Looking a week or so ahead

As figure 4.2 demonstrated, the potential for extreme heat was anticipated at least 2 weeks ahead. The WATF Report introduced the Decider Tool as an important indicator of forthcoming weather regimes that might predispose the UK's weather to be wet, windy, cold, hot or dry. Decider uses the 30 weather regimes that characterise UK weather (see Figure 7.1 in WATF Report), derived from 150 years of observations (Neal et al. 2016[3]), to categorise the probabilities of specific regimes in the forecast. The WATF discussed the value of Decider for anticipating wet conditions; here Figure 4.5 gives an example of its use in anticipating high temperatures.

In this example, Decider presents the probabilities of being in a northerly or southerly flow regime for the period 13 to 27 July using the ensemble forecasts initialised on 8 to 13 July. Figure 4.5 shows that over a week ahead the probability of being in a southerly flow regime was high to very high, and the consistency between the forecasts was also very robust. Even 5 days ahead (13 July) the forecasts

[3] Neal, R., D. Fereday, R. Crocker and R. E. Comer, 2016: A flexible approach to defining weather patterns and their application in weather forecasting over Europe. *Meteorological Applications*, 23, 389–400. DOI: 10.1002/met.1563

were very confident that the UK would be influenced by southerly flow on 17/18 July. Bearing in mind the extreme heat and dryness already happening over Europe then southerly flow is a strong indicator for a heatwave and extreme temperatures. On 11 July, the Met Office issued an amber warning for extreme heat in the coming days.

	Wed 13 Jul	Thu 14 Jul	Fri 15 Jul	Sat 16 Jul	Sun 17 Jul	Mon 18 Jul	Tue 19 Jul	Wed 20 Jul	Thu 21 Jul	Fri 22 Jul	Sat 23 Jul	Sun 24 Jul	Mon 25 Jul	Tue 26 Jul	Wed 27 Jul
09:00 UTC blend time on Wed 13 Jul (Latest)	100%	56%	60%	83%	92%	90%	56%	40%	47%	53%	44%	48%	40%	43%	50%
03:00 UTC blend time on Wed 13 Jul (Run -1)	100%	61%	60%	86%	95%	94%	41%	48%	44%	44%	50%	52%	48%	45%	38%
21:00 UTC blend time on Tue 12 Jul (Run -2)	100%	58%	64%	92%	96%	86%	38%	45%	40%	47%	45%	50%	44%	45%	43%
15:00 UTC blend time on Tue 12 Jul (Run -3)	100%	63%	70%	86%	84%	74%	43%	42%	46%	43%	40%	41%	44%	40%	48%
09:00 UTC blend time on Tue 12 Jul (Run -4)	99%	70%	79%	90%	82%	79%	45%	46%	38%	40%	43%	43%	44%	44%	48%
03:00 UTC blend time on Tue 12 Jul (Run -5)	97%	64%	88%	95%	95%	66%	35%	42%	43%	39%	40%	43%	45%	44%	44%
21:00 UTC blend time on Mon 11 Jul (Run -6)	96%	64%	88%	95%	96%	58%	49%	48%	40%	37%	42%	46%	44%	42%	41%
15:00 UTC blend time on Mon 11 Jul (Run -7)	90%	59%	89%	95%	87%	42%	46%	50%	37%	41%	47%	54%	49%	45%	35%
09:00 UTC blend time on Mon 11 Jul (Run -8)	87%	59%	97%	98%	90%	50%	38%	38%	41%	38%	44%	57%	43%	44%	35%
03:00 UTC blend time on Mon 11 Jul (Run -9)	92%	65%	93%	98%	96%	59%	40%	46%	40%	46%	44%	49%	45%	41%	38%
21:00 UTC blend time on Sun 10 Jul (Run -10)	87%	71%	90%	97%	94%	54%	39%	46%	44%	41%	50%	51%	43%	41%	38%
15:00 UTC blend time on Sun 10 Jul (Run -11)	89%	69%	86%	90%	67%	36%	55%	48%	47%	49%	42%	48%	40%	43%	38%
09:00 UTC blend time on Sun 10 Jul (Run -12)	82%	60%	82%	83%	62%	37%	51%	62%	56%	44%	48%	56%	45%	43%	38%
03:00 UTC blend time on Sun 10 Jul (Run -13)	84%	52%	83%	87%	66%	46%	55%	48%	39%	38%	47%	47%	51%	43%	43%
21:00 UTC blend time on Sat 9 Jul (Run -14)	88%	56%	81%	84%	65%	40%	58%	46%	38%	39%	44%	42%	39%	43%	43%
15:00 UTC blend time on Sat 9 Jul (Run -15)	86%	61%	80%	80%	62%	42%	48%	41%	40%	41%	49%	50%	47%	43%	43%
09:00 UTC blend time on Sat 9 Jul (Run -16)	76%	53%	79%	89%	65%	39%	51%	52%	41%	44%	45%	53%	47%	43%	43%
03:00 UTC blend time on Sat 9 Jul (Run -17)	57%	69%	86%	87%	69%	40%	43%	43%	34%	40%	40%	46%	40%	36%	41%
21:00 UTC blend time on Fri 8 Jul (Run -18)	61%	58%	79%	78%	68%	39%	46%	39%	38%	40%	42%	44%	40%	36%	41%
15:00 UTC blend time on Fri 8 Jul (Run -19)	63%	47%	59%	68%	56%	39%	40%	37%	36%	38%	40%	42%	40%	36%	41%
09:00 UTC blend time on Fri 8 Jul (Run -20)	56%	44%	62%	74%	59%	44%	38%	35%	36%	36%	35%	42%	40%	36%	41%

Weather patterns typically associated with a **southerly flow** over the UK are most likely
Weather patterns typically associated with **no meridional bias** over the UK are most likely
Weather patterns typically associated with a **northerly flow** over the UK are most likely

Figure 4.5 Example of the Decider tool applied to the forecasts from 8 July to 13 July, covering the extreme heat of 18/19 July. In this case, the weather is categorised the direction of the flow over the UK, with southerly flow typically bringing hot, dry conditions from the near continent. (Source: Met Office)

This example shows two things, firstly the confidence of the forecast, from the oldest to the newest forecasts, for southerly flow peaking around 17/18 July, and secondly, the likely rapid breakdown of the heatwave subsequently, indicating a window for recovery from any impacts.

4.1.3 Looking a few days ahead

As discussed in the WATF, the Met Office uses a combination of global and regional forecasting systems to provide a seamless capability from a few days to a few hours ahead. The WATF focused on the importance of the kilometre-scale UK forecast for capturing localised precipitation extremes; here its value in capturing extreme temperatures is also demonstrated.

The global forecast ensemble proved to be very skilful in capturing the development of the heatwave and the high temperatures on 19 July (Figure 4.6), where the potential for exceeding a daily maximum of 35^{o}C was already picked up on the forecast from 12 July. In the subsequent days, the forecast became more and more confident so that by 15 July the forecasts were indicating an 80-90% likelihood of exceeding 35^{o}C across eastern England. Confidence in the forecasts for extreme heat over neighbouring France can also be seen.

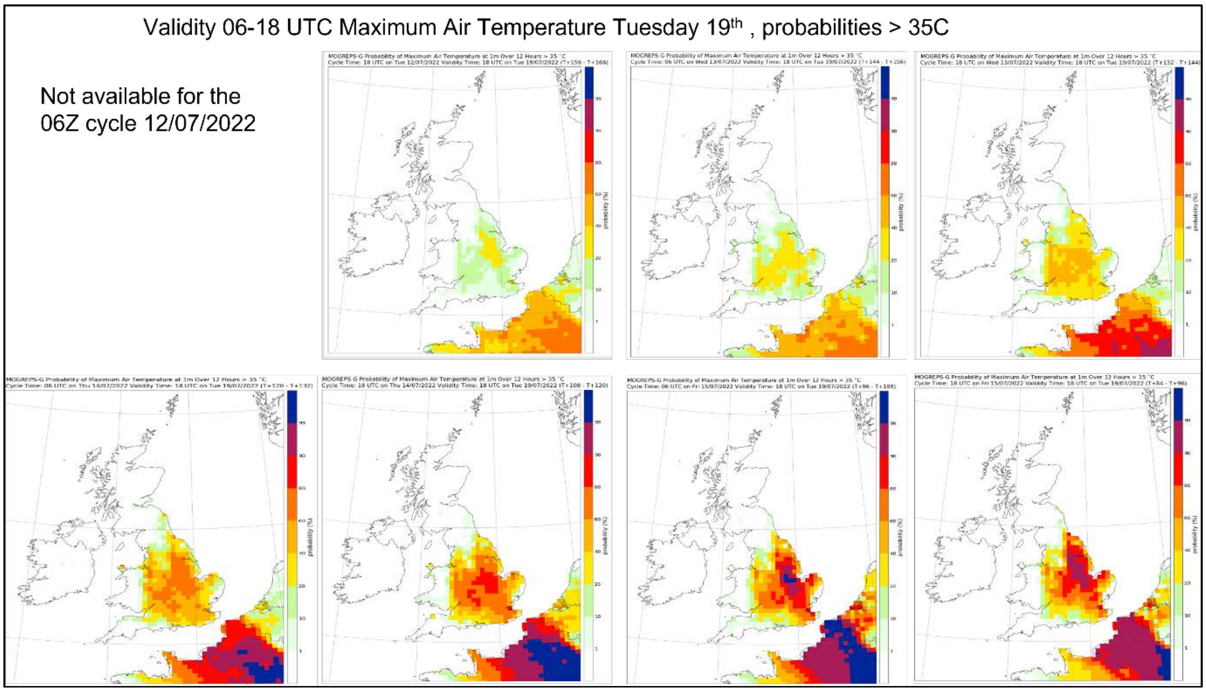


Figure 4.6 Sequence of forecasts from 12 to 15 July, using the Met Office global ensemble system, showing the probabilities of exceeding 35^{o}C on 19 July. (Source: Met Office)

However, the km-scale UK forecast was needed to pick up the localised extreme temperatures that could cause substantial damage. Although the global model successfully predicted maximum temperatures above 35^{o}C, its granularity is too coarse to capture the extreme temperatures of 40^{o}C that were observed (Figure 4.7, top right panel). Instead, the km-scale is needed to forecast these local hotspots (Figure 4.7, lower panels). The likelihood of exceeding 40^{o}C somewhere in eastern England on 19 July was successfully predicted up to 4 days ahead.

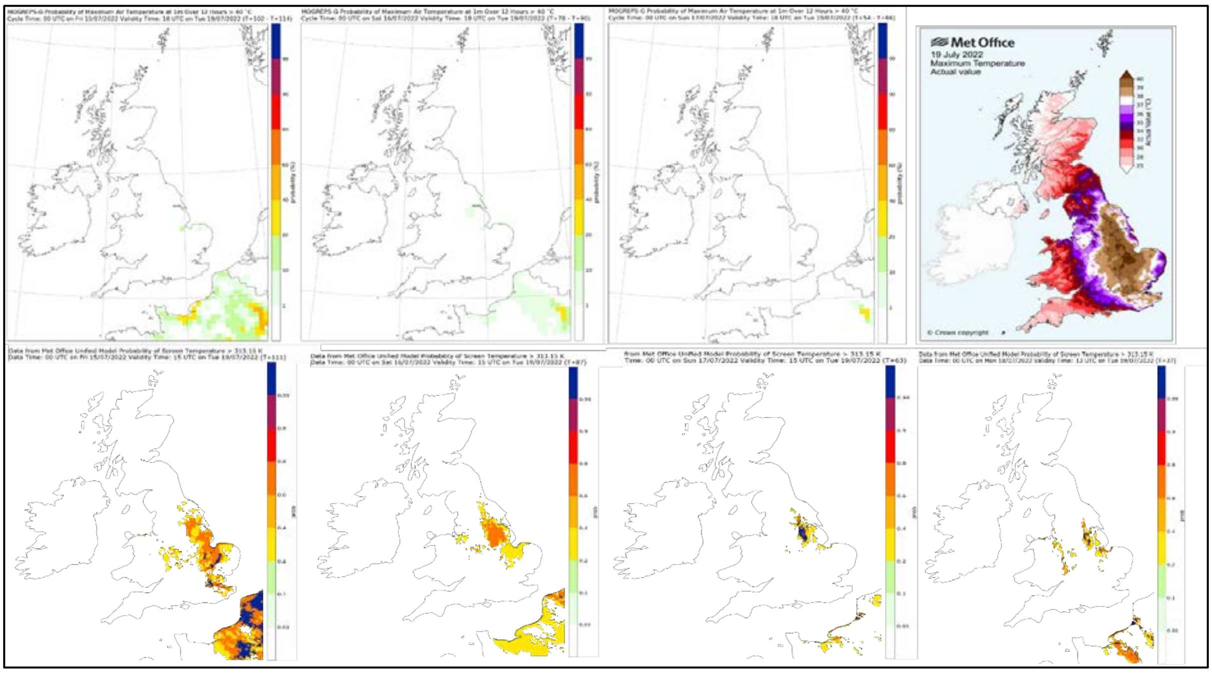


Figure 4.7 Comparison of forecasts made from 15 to 18 July of the probability of exceeding 40^{o}C on 19 July from the global ensemble system (upper row) and the UK kilometre-scale ensemble system (lower row). The upper right panel shows the verification, confirming that the UK forecast successfully captured the most likely locations for extreme heat over eastern England even in the 2-day forecast. (Source: Met Office)

On the basis of these forecasts, the Met Office issued an Amber Severe Weather Warning and its first ever Red Severe Weather Warning for extreme heat on 15 July (Figure 4.8). It was bold, but very accurate, when the area of the Red Warning is compared with the observed maximum temperatures on 19 July (Figure 4.7, top right panel). Along with the high likelihood of unprecedented temperatures, the warnings also highlighted the potential impacts to the public and the mitigation actions they should take.

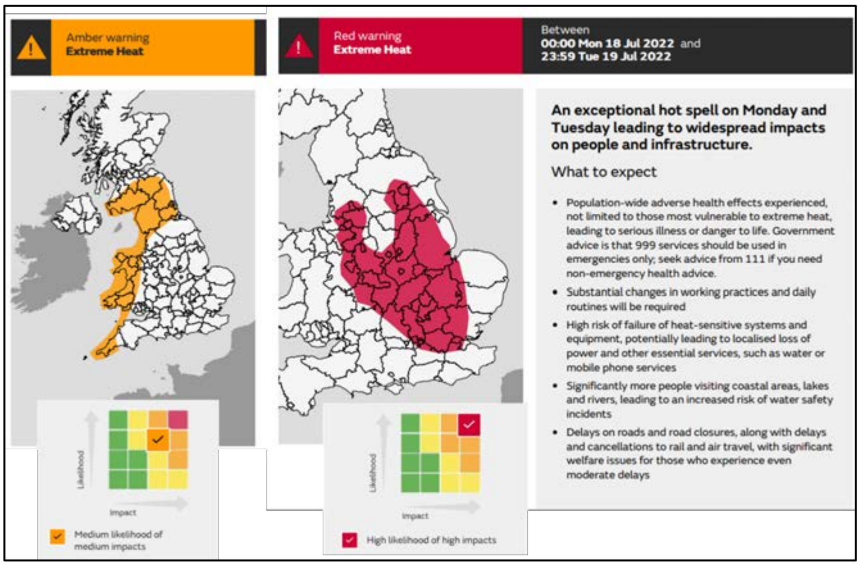


Figure 4.8 Severe weather warnings issued by the Met Office on 15 July. (Source: Met Office)

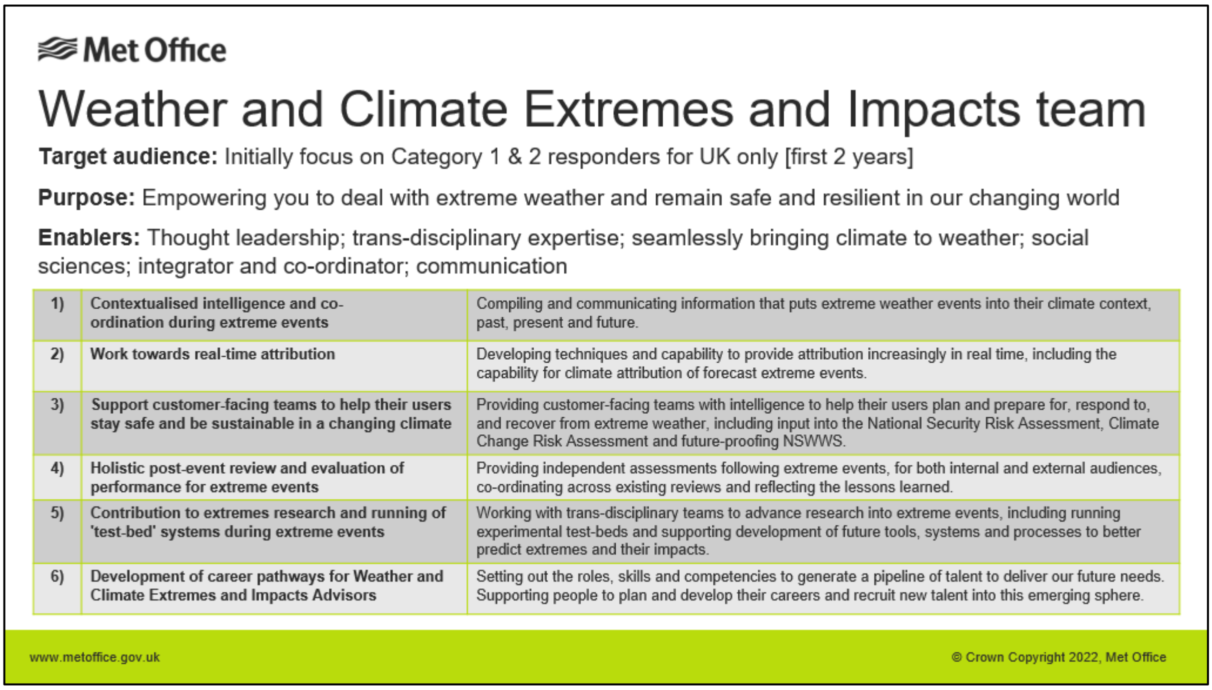
4.2 Other potential factors for future consideration

Beyond just extreme heat, the July 2022 event highlighted other factors for consideration in the future. The first is around the compounding and cascading nature of hazardous weather. Each region faces unique hazard combinations. For example, drought-enhanced wildfires produce mountainside burn scars, which often enhance debris flows from flooding. As noted in the US National Climate Assessment (2017, https://www.globalchange.gov/nca4), "*The physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high, sub-hourly rainfall precipitation on top of hard, baked ground) can be greater than the sum of the parts*".

Dealing with extremes is a very different to managing business-as-usual weather. It requires transdisciplinary methods to co-design, co-develop new capabilities, insights and services that are currently not available. How do we extract an extreme signal from ensembles, how do we communicate a fast-evolving extreme in a way that ensures appropriate actions are taken to safeguard rail passengers and protect critical infrastructure? How does social / behavioural science play into this – and should it?

The Met Office has recognised this need in its recent creation of a new Weather and Climate Impacts Team (Figure 4.9) whose focus is on advancing the capabilities of specific sectors, specifically Category 1 &2 providers, to anticipate and manage the impacts of extreme events, including their compounding and cascading effects.

Besides the direct impacts of extreme temperatures on the railway infrastructure, related hazards include line-side wildfires, dessication of earthworks, particularly clay, and falling trees. In 2022, all these related hazards caused Network Rail some problems, above and beyond failure of infrastructure, such as sagging and fracture of overline cables.



Met Office

Weather and Climate Extremes and Impacts team

Target audience: Initially focus on Category 1 & 2 responders for UK only [first 2 years]

Purpose: Empowering you to deal with extreme weather and remain safe and resilient in our changing world

Enablers: Thought leadership; trans-disciplinary expertise; seamlessly bringing climate to weather; social sciences; integrator and co-ordinator; communication

1)	**Contextualised intelligence and co-ordination during extreme events**	Compiling and communicating information that puts extreme weather events into their climate context, past, present and future.
2)	**Work towards real-time attribution**	Developing techniques and capability to provide attribution increasingly in real time, including the capability for climate attribution of forecast extreme events.
3)	**Support customer-facing teams to help their users stay safe and be sustainable in a changing climate**	Providing customer-facing teams with intelligence to help their users plan and prepare for, respond to, and recover from extreme weather, including input into the National Security Risk Assessment, Climate Change Risk Assessment and future-proofing NSWWS.
4)	**Holistic post-event review and evaluation of performance for extreme events**	Providing independent assessments following extreme events, for both internal and external audiences, co-ordinating across existing reviews and reflecting the lessons learned.
5)	**Contribution to extremes research and running of 'test-bed' systems during extreme events**	Working with trans-disciplinary teams to advance research into extreme events, including running experimental test-beds and supporting development of future tools, systems and processes to better predict extremes and their impacts.
6)	**Development of career pathways for Weather and Climate Extremes and Impacts Advisors**	Setting out the roles, skills and competencies to generate a pipeline of talent to deliver our future needs. Supporting people to plan and develop their careers and recruit new talent into this emerging sphere.

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Figure 4.9 New Met Office team with a focus on managing the impacts of weather and climate extremes in the context of user needs. (Source: Met Office)

It is recommended that Network Rail invest in an R&D and services programme that can interface with this new Met Office team to ensure that it has the best possible intelligence for managing its operations before, during and after extreme events. It is further recommended that elements of these advances are included in the Academy curriculum.

In summary, with the range of forecasts and tools now becoming available to Network Rail, as a result of the WATF recommendations, it should be possible to anticipate episodes of extreme heat and plan for their potential impacts. The Weather Risk Task Force (WRTF) should integrate heatwave and extreme temperature prediction and its impacts into the ongoing work on extreme rainfall and its impacts.

5 Future scenarios for UK heatwaves

The latest UNEP Emissions Gap Report (2022: https://www.unep.org/resources/emissions-gap-report-2022) highlights that, globally, current emission plans are likely to produce a median warming of around 2.5-3°C. Accounting for climate uncertainty and the possibility of emission pledges not being honoured, this could be several °C higher. Limiting global warming to below 1.5°C is almost impossible without some overshoot to higher temperatures and would require big reductions in global emissions.

That the UK will experience rising summer temperatures in the coming decades is therefore without question, regardless of what happens to carbon and other greenhouse gas emissions (Figure 5.1). The lifetime of CO_2 is a century or longer, so the world is already committed to future warming from CO_2 that has already accumulated in the atmosphere. As Figure 5.1 shows, the projected level of warming out to at least 2040 is approximately the same regardless of emission scenario, so Network Rail needs to plan now for these levels of committed warming. Beyond 2050, longer term risks will be much more dependent on whether Net Zero can be achieved. Infrastructure investments which have potential lifetimes into the late 21st century will need to decide what level of risk is appropriate, taking account of worst-case scenarios.

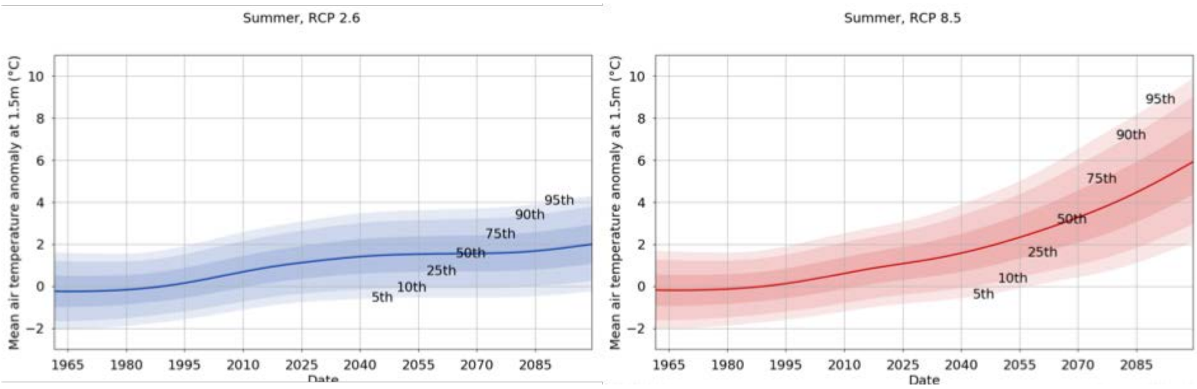


Figure 5.1 Projected changes in the 20-year running mean of the summer average UK surface temperature for a low emission scenario, RCP2.6 (left) and a high emission scenario, RCP8.5 (right). The shaded boundaries show the 5th, 10th, 25th, 50th (median), 75th, 90th and 95th percentiles. Values are expressed relative to the 1981-2000 baseline. Source: Met Office

Against this background of overall warming, this report focuses on what this means for future heatwaves and extreme high temperatures across the rail network. This will be based on the latest UK Climate Projections (UKCP18) which utilise a combination of global and UK regional models to explore a range of possible futures dependent on the emission scenarios used in the IPCC 6th Assessment Report (AR6; Ref). An innovative component of UKCP18 was the implementation of a new 2.2km convective permitting model (CPM) for the UK, similar to that used operationally in weather forecasting (see WATF Report). This was a world-first and provided unprecedented local detail on changes in local weather and extremes.

Multiple realisations for each scenario were created to provide estimates of uncertainty associated with natural climate variability and model parameter uncertainty. These ensembles allow probabilities of specific outcomes to be estimated. These ensemble projections were used extensively in the UK's 3rd Climate Change Risk Assessment (CCRA3 - https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/) in which Chapter 1 focuses on the scientific evidence. This showed that the CPM, combined with the improved global driving model, HadGEM3, produced substantially warmer and drier summers than in previous assessments (Figure 5.2).

As Figure 5.2 shows, HadGEM3 projects hotter and drier summers than in previous assessments (e.g. IPCC AR5, UKCP09), a signal that is carried through into the 12km Regional Climate Model (RCM) and the 2.2km Convective Permitting Model (CPM) results. For England, there is a very strong signal for much reduced rainfall in summer, which in itself, will also act to elevate summer temperatures. This is an important change for Network Rail in managing its future summer climate risks, so it is worth outlining why these should be taken seriously. Firstly, the high warming in HadGEM3, although at the upper range of the IPCC AR6 results, cannot be excluded by observations and is, in any case, useful for stress testing. Second, HadGEM3 performs better than most other IPCC models for many metrics, especially those related to circulation.

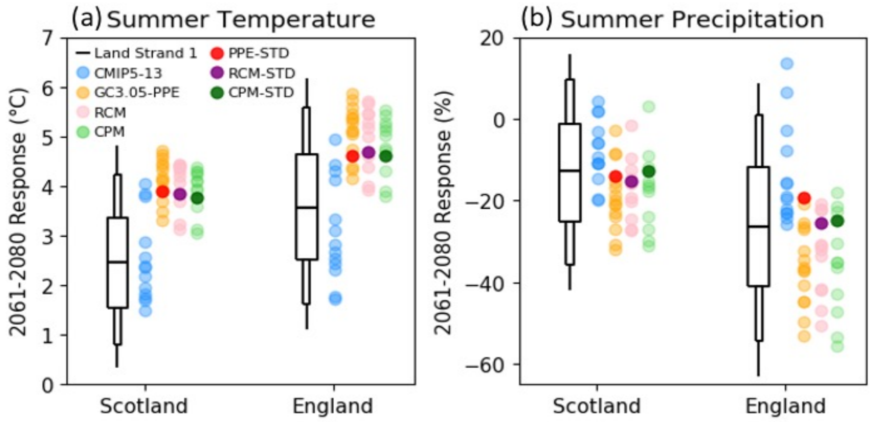


Figure 5.2 Comparison of summer (June, July and August) mean changes in surface air temperature (°C) and precipitation (%) across the different UKCP18 products and components, using projected changes with RCP8.5 scenarios, for 2061-2080 relative to 1981-2000, for Scotland and England. Box and whiskers denote the probabilistic projections based on all available evidence; orange and blue dots denote the HadGEM3 (GC3.05-PPE) and earlier CMIP5 (CMIP5-13 from IPCC AR5) projections respectively. The pink and green dots show the 12km regional model (RCM) and 2.2km convective permitting model (CPM) projections which use HadGEM3 boundary conditions. The solid dots correspond to the 'standard' HadGEM3 simulation within the full ensemble. The probabilistic projections, GC3.05, RCM and CPM all use the RCP8.5 emissions scenario and a range of CO_2 concentration pathways accounting for uncertainties in carbon cycle feedbacks. (Source: Met Office)

UK summers are affected by the population of specific weather regimes, and extreme summer heat (as experienced in 2018, for example) is often associated with a strongly positive summer North Atlantic Oscillation pattern (SNAO; e.g. Folland et al., 2009[4]). The SNAO is characterised by a high-pressure anomaly over and to the north-east of the UK, and in its positive phase, the SNAO corresponds to anomalous easterly winds, which bring warm, and often dry, air from continental Europe, as well as more local solar radiation and surface heating. These effects reinforce the temperature response over the UK, resulting in the SNAO being an important control on UK summer heat.

In addition to influencing summer heat, the SNAO is also an important driver of summer rainfall anomalies. Folland et al. (2009) showed that there is a strong, negative correlation between the SNAO and England-Wales precipitation, with a positive SNAO favouring low summer rainfall and potential drought. HadGEM3 is notable for being able to capture this relationship, unlike earlier models, and thus projections based on HadGEM3 are therefore considered more reliable than earlier models.

Analysis of the future behavior of the SNAO in the HadGEM3 projections shows a trend towards more positive phases under a warming climate, compared with earlier models, especially CMPI5 which underpinned IPCC AR5 (Figure 5.3). This would indicate an increased prevalence of high temperatures

[4] Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S. and Hurrell, J.W. (2009). The Summer North Atlantic Oscillation: Past, Present, and Future. *J. Climate, 22,* 1082 – 1103. https://doi.org/10.1175/2008JCLI2459.1

and drought in the future than in previous assessments and is thus an important consideration for Network Rail. Nevertheless, more research still needs to be done to investigate potential changes in the population of particular weather regimes in a warming world, but these preliminary results suggest elevated risks of summer heat.

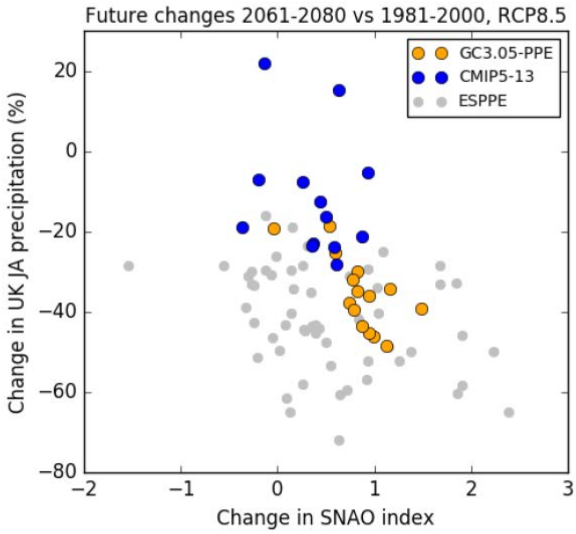


Figure 5.3 Relationship between projected changes in the SNAO and UK high summer rainfall from the CMIP5-13 ensemble with the standard RCP8.5 concentrations (blue) and HadGEM3 GC3.05 ensemble with RCP8.5 emissions (orange). The grey dots refer to a larger ensemble of from a lower-resolution Earth System model using RCP8.5 emissions. Reproduced from UKCP18 Land Report, Murphy et al. (2018)[5].

Based on these new results from HadGEM3 and the UK CPM which suggest warmer and drier summers than in earlier assessments, the Met Office has been commissioned to undertake a bespoke analysis for this report, focusing on the rail network and its future risks from heat waves and extreme high temperatures.

In UKCP18, the 2.2km CPM projections were only available for three 20-year time-slices – 1981-2000 (baseline climatology), 2021-2040 (near-term/committed climate change), 2061-2080 (long-term/emission-dependent climate change) due to availability of computing resources. The other 20-year periods (2001 – 2020, 2041 – 2060) have recently been filled in so that there is now a continuous ensemble of projections for the whole period. Each time-slice consists of an ensemble of 12 projections. This allows us to assess the changing envelop of risk, decade by decade across the UK rail network out to 2080.

Due to limitations in the availability of compute power, the CPM projections only cover the RCP8.5 high emission scenario. This is not an issue out to 2040 or so, due to committed levels of warming; beyond 2050 the results should be used as worst-case scenarios in the event that Net Zero ambitions are not realized through backtracking on existing emission pledges and policies, and/or the climate is more sensitive to greenhouse gas emissions than currently estimated.

5.1 Validation of the UK CPM performance for the current climate

Testing the validity of any climate model for making projections of future climate change is an essential first step, so that any climate change signal can be placed in the context of the model bias. In this study, the performance of the UK CPM in terms of its representation of maximum temperatures has been assessed by comparing its present-day simulation against the gridded UK climatology from observations (HadUK-Grid, Hollis et al. 2018[6] – see

[5] Murphy, J.M., Harris, G.R., Sexton, D.M.H., Kendon, E.J., Bett, P.E., Clark, R.T. et al. (2018). UKCP18 Land Report. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/sciencereports/UKCP18-Land-report.pdf

[6] Hollis, D., M. McCarthy, M. Kendon, T. Legg and I. Simpson, 2019: HadUK-Grid—A new UK dataset of gridded climate observations. *Geoscience Data Journal*, Royal Meteorological Society, 6 (2): 151 – 159. https://doi.org/10.1002/gdj3.78

http://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb). For this purpose, the UK CPM data were re-gridded to 5km to enable direct comparison with the HadUK-Grid data which are at 5 km resolution.

Figure 5.4 shows the mean model biases, using all the data from the 12-member ensemble, for the annual daily maximum temperature (left panel), and for the average daily maximum temperature for the peak summer months (June, July, August – JJA; right panel). These were calculated using 240 'years' from the re-gridded 12-member CPM ensemble versus 20 years of the observations from HadUK-Grid.

On average, there are warm biases in the south versus cold biases in the north, for both the annual maximum temperature and for the average summer maximum temperature. In the south, the biases in the annual maximum temperature are less than 2°C, and in the peak summer months the average daily maximum is within 1°C of the observations. These are considered to be acceptable biases for this initial study, but further work is being undertaken to investigate the impact of bias correction on the climate change scenarios.

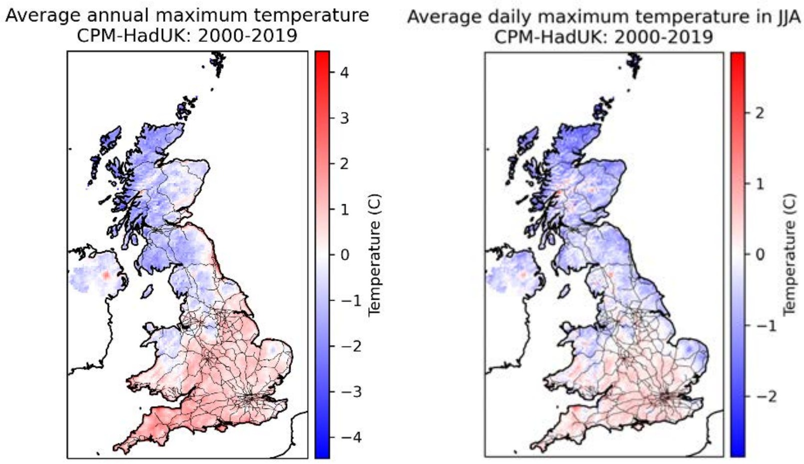


Figure 5.4 Mean bias (°C) in ensemble mean annual maximum temperature (left), and in the ensemble mean of the average daily maximum for the summer months of June, July and August (right) for the current climate. These biases are calculated using 240 'years' from the re-gridded 12-member CPM ensemble versus 20 years of observations from HadUK-Grid at 5km resolution.

A more challenging test of the model is to consider the number of days per year above specific temperature thresholds (Figure 5.5). The table on the right of Figure 5.5 provides the relevant statistics from the HadUK-Grid climatology and provides some context in which to assess the spatial variability in the model biases.

Overall, the validation results suggest that the CPM is an appropriate tool to use in the assessment of future risks to the railway from heatwaves and extreme high temperatures. However, Network Rail should note that all the following results have not been bias-corrected. Although this is unlikely to change the overall message, some specific details might change if bias-correction was included. It is recommended that Network Rail continue to work with the Met Office Hadley Centre as they investigate the possible effects of bias correction.

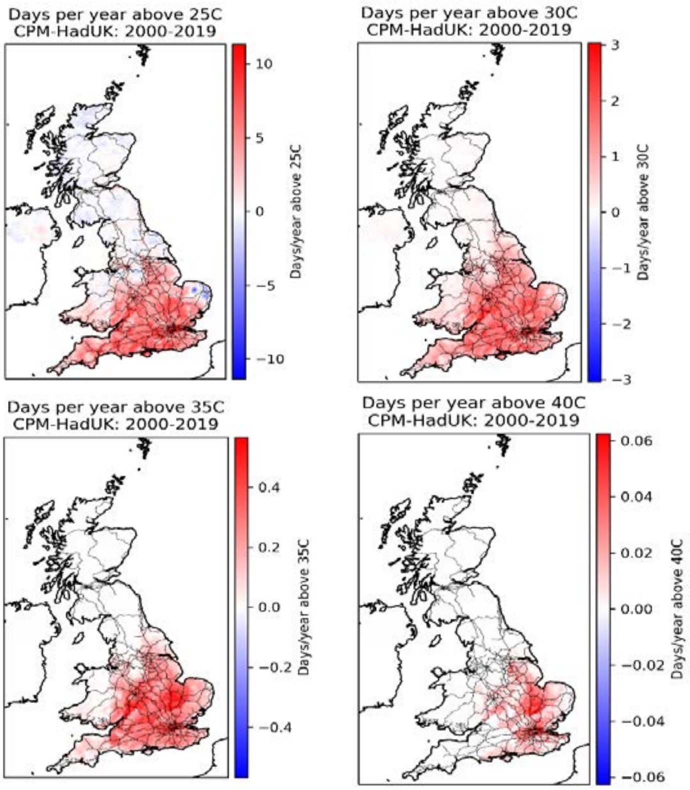


Figure 5.5 Mean biases, against HadUK-Grid observations, in the number of days per year exceeding daily maximum temperatures of 25°, 30°, 35° and 40°C for the current climate. The table puts these biases in context by showing the statistics from observations of the mean, 99th percentile and the maximum days per year.

Days per year above thresholds in HadUK-Grid			
Threshold	**Days per year above threshold**		
	Mean	Q99	Max
25	6.4	22.5	27.95
30	0.47	2.95	4.55
35	0.01	0.15	0.3
40	0	0	0

5.2 Analysis of ensemble mean daily maximum temperature predictions across the rail network

Using all the data from the CPM ensemble, the decade-by-decade changes in daily maximum temperatures have been computed across the UK. Here all the ensemble members are pooled so that for each decade there are 120 'years' of data with which to analyse the plausible decadal mean changes in the UK climate.

Figure 5.6 shows the decadal mean of the annual daily maximum (left panel) alongside the mean of the average maximum temperature in the summer months (JJA; right panel). As expected, the results show that decade by decade there is warming across the whole network. The annual daily maximum is projected to exceed 35°C over much of the southeast rail network by the second half of the century; likewise, by 2050, much of the network is projected to experience summer average maximum temperatures in excess of 25°C.

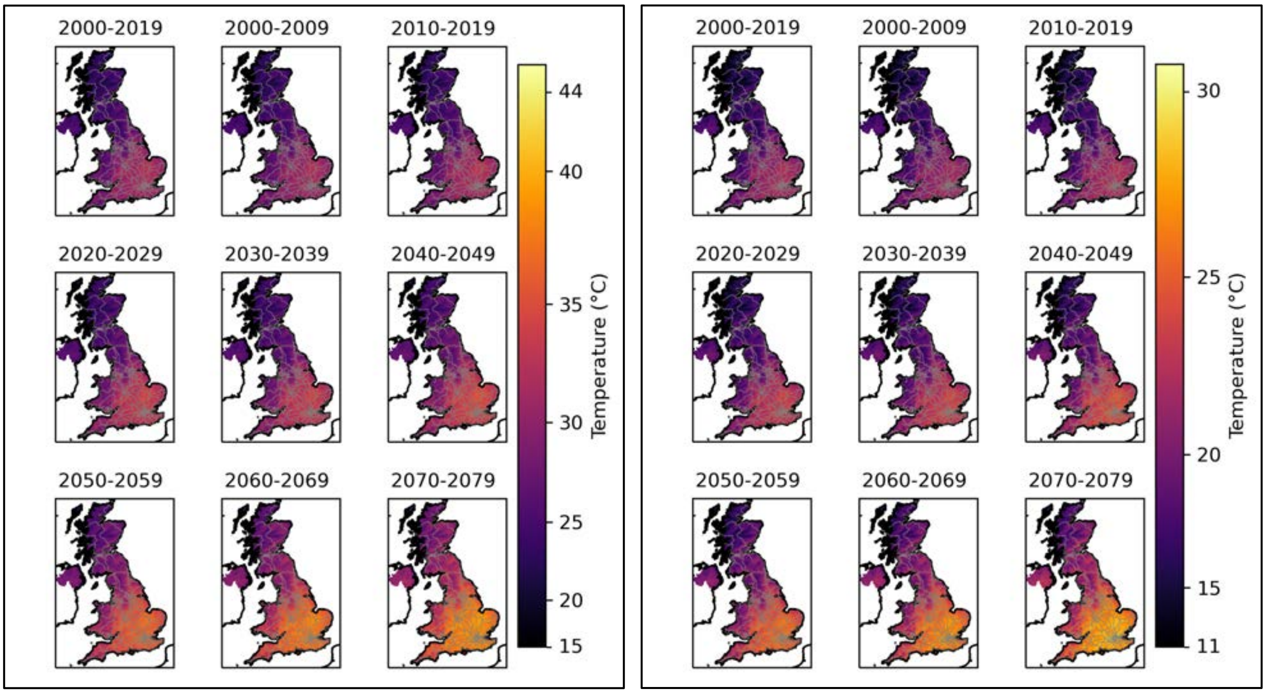
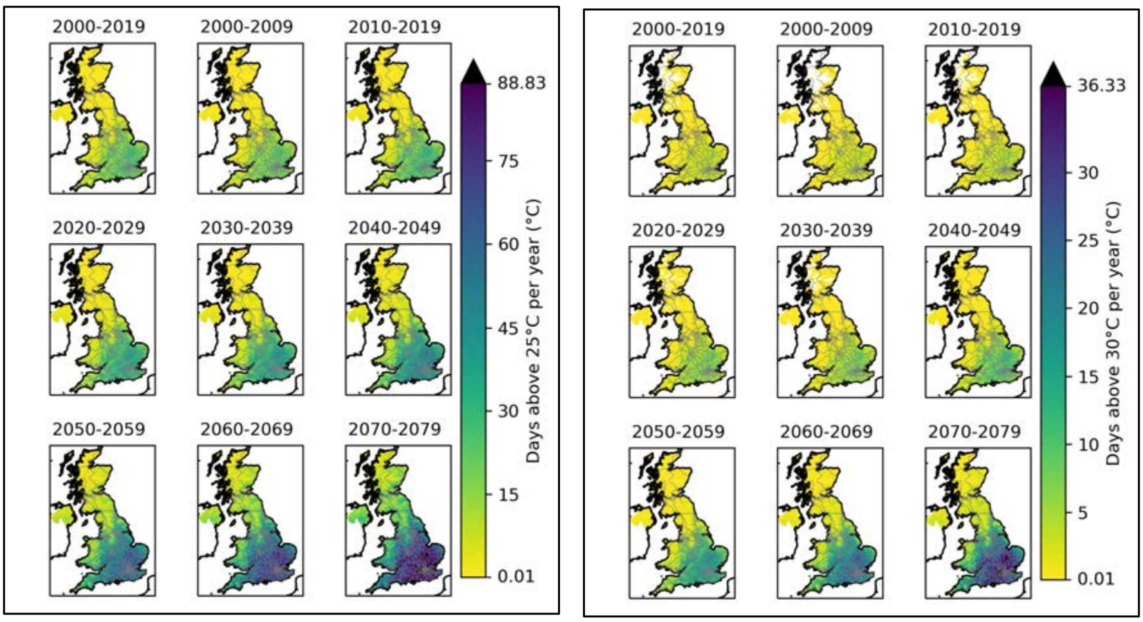


Figure 5.6 Decadal ensemble means in the annual daily temperature maxima (left panels) and in the summer average daily maximum temperatures (right panels) using 120 'years' of CPM data for each decade.

Another way of expressing this is to analyse the average frequency of exceeding particular temperature thresholds. Figure 5.7 shows an example of the decade-by-decade changes in the number of days per year where the maximum daily temperature exceeds 25°, 30°C, 35°C and 40°C. The results show that more than 100 days per year (i.e. the whole summer and beyond) are projected to have maximum temperatures above 25°C, over some parts of the network by the 2070s. The south-east rail network is projected to experience multiple days above 35°C per year by the 2050s.



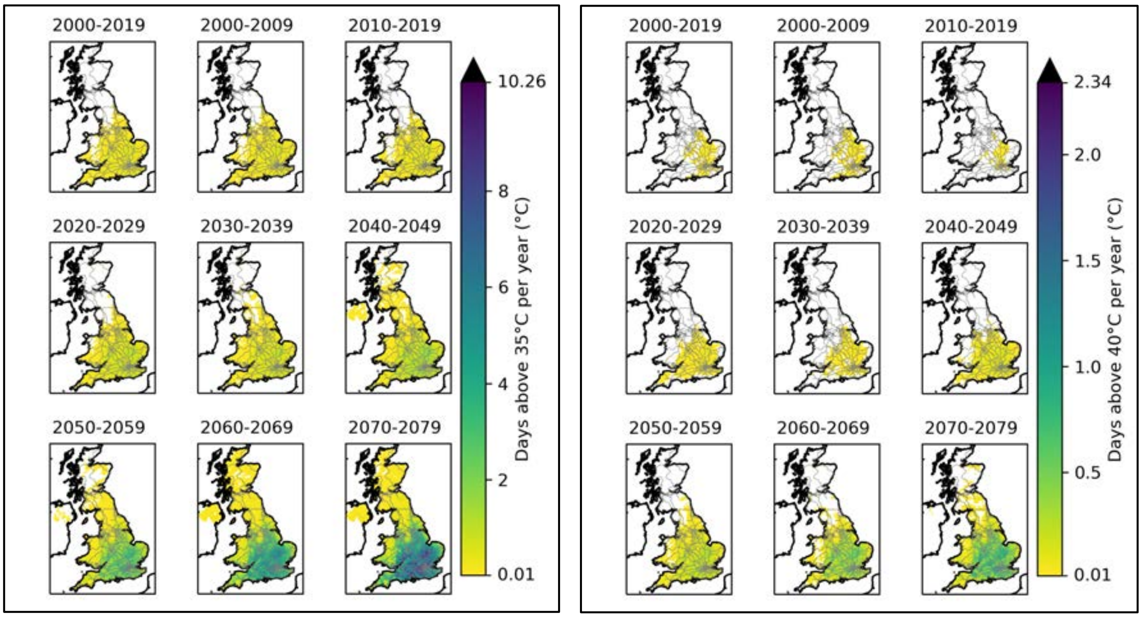


Figure 5.7 Decadal projections of the average number of days per year where the maximum temperature exceeds 25°C (top left), 30°C (top right), 35°C (bottom left) and 40°C (bottom right). White areas have zero days above the maximum temperature threshold.

5.4 Probability analysis of daily maximum temperature predictions

The results shown in Section 5.3 are for the ensemble mean and do not tell us anything about the spread in the data and the potential for low probability, but high impact, extreme temperatures. When Network Rail considers the future risks to their existing assets, and what level of risk they are prepared to take when investing in new assets, it is important to know the probability of particular outcomes. This is an important part of the whole risk matrix that aligns the probability of a hazard with the exposure and vulnerability of the rail network to that hazard.

In this report, the presentation of the distribution of probabilities follows the schematic shown in Figure 5.8 in which the median and percentiles are used to describe the distribution. The median is given by the horizontal bar, and the vertical box covers the 25^{th} to 75^{th} percentiles. The bars and whiskers show the range of the outer 5^{th} and 95^{th} percentile range; anything more extreme than these outer percentiles are represented by individual black circles. This approach has many similarities with the application of probabilistic weather forecasting as discussed in the WATF Report.

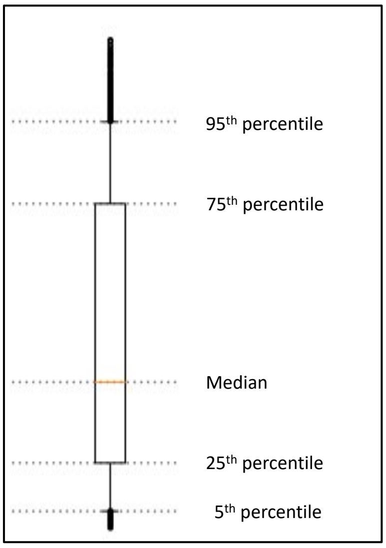


Figure 5.8 Schematic of how the probabilities are presented.

Figure 5.9 provides an example of how the spread in the 120 'years' from the CPM ensemble for each decade can be used to assess the probabilities of a particular event, in this case the annual exceedance rate for specific temperature thresholds for the whole UK. The upper panel of Figure 5.9 is based on the whole UK, while the lower panel uses only those data points from the location of the rail network.

This is an important point. The exact location of an extreme event is essentially chaotic, and it means that by just sampling the rail network, the frequency of extremes may be misrepresented; an extreme could be just slightly shifted by chance and therefore missed. For temperature, which is quite homogenous in space (except for the most exceptional values – see Figure 4.7), this is not as much of an issue as say for precipitation which is highly heterogeneous in space. The lower panel in Figure 5.9 shows that the probability of exceeding specific temperature thresholds is barely changed by sampling just the rail network data points. Where there are differences (such as for 25°C exceedances) this reflects the greater density of the current rail network in the warmer south-east part of the UK.

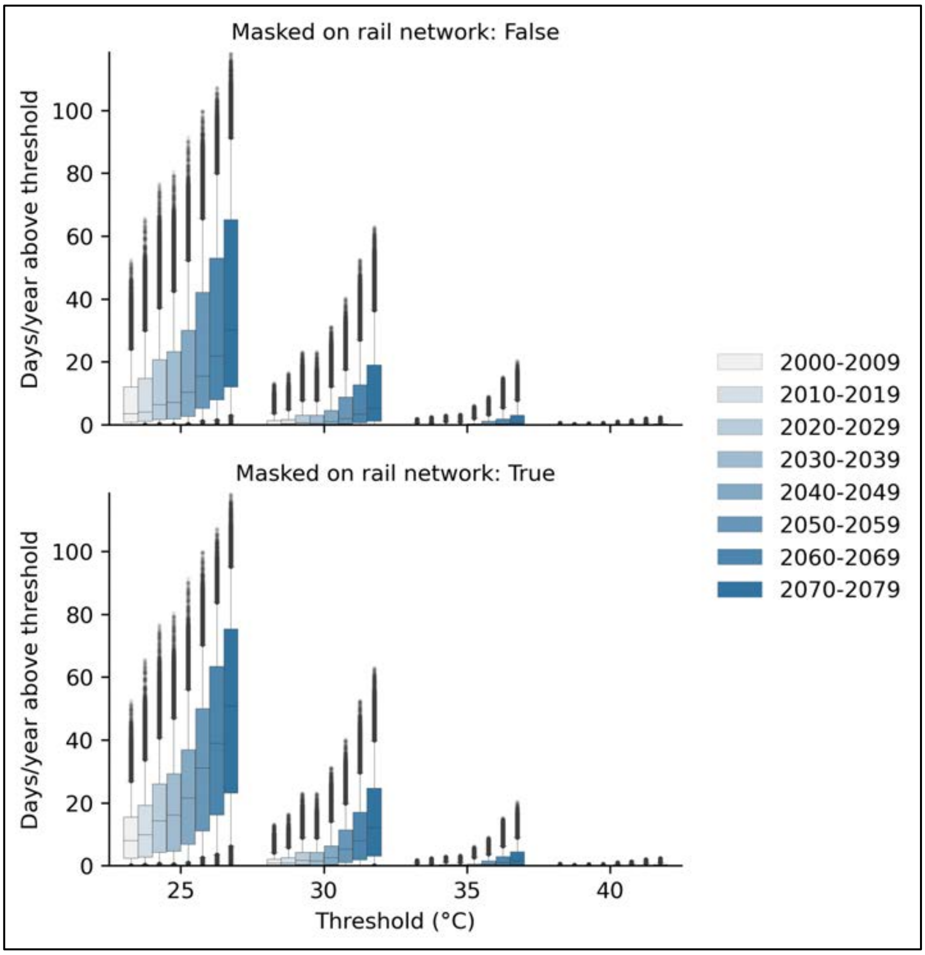


Figure 5.9 Probability distributions of the number of days per year that maximum daily temperatures exceed specific thresholds, decade by decade for the UK. Upper panel is based on all data points for the UK, and the lower panel just uses the data points for the current rail network. The coloured bars show the 25th to 75th percentile range of the number of exceedance days for each decade and for each temperature threshold, with the middle line being the median value. The bars and whiskers show the outer 5% and 95% range.

Figure 5.9 shows that the number of days above 25°C and 30°C increase in magnitude and spread through the 21st century. For a threshold of 25°, the number of days may exceed the length of summer, indicating a continuation of high temperatures into September. The more rapid increase in the number of exceedance days after 2050 reflects the increasing rate of global warming associated with the RCP8.5 scenario (see Figure 5.1). The increase in spread is more interesting; the reasons are not clear although they may reflect the increasing importance of drivers of high temperatures, such as dry conditions and changing weather regimes.

Network Rail is particularly exposed to extreme temperatures above 35°C. To explore these in more detail, Figure 5.9 has been redrawn using a logarithmic scale for the number of days (Figure 5.10). As discussed earlier, for these rare events it is important to sample all data points and not just those for the rail network. Figure 5.10 shows that the frequency of extreme high temperatures increases with time, but nevertheless, they still remain rare events. For example, even in the 2070s, there is only a 5% risk that the temperature may exceed 40°C one day in any year.

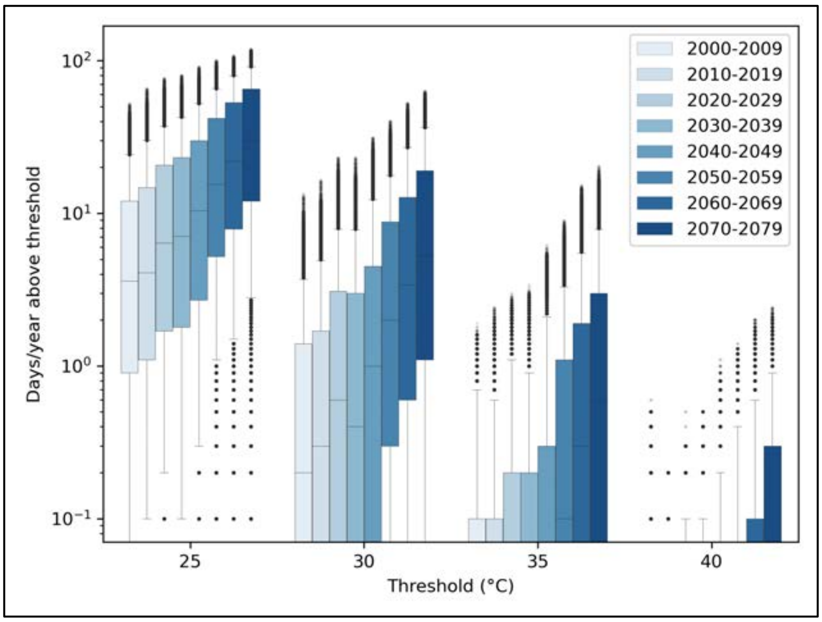


Figure 5.10 As Figure 5.9 (upper panel) but using a logarithmic scale for the number of days per year to highlight the rare extreme temperature events.

The data are also available to drill down to the individual routes and regions and to analyse their specific probability distributions. Figure 5.11 gives an example of the differences across the rail network, in this case for the Southern and for the Wales and Western regions. Again, the statistics are done without the network mask. It demonstrates the differences across the network, reflecting the varying weather conditions and other impacts of climate change. A full set of figures for all routes and regions is provided in the Annex.

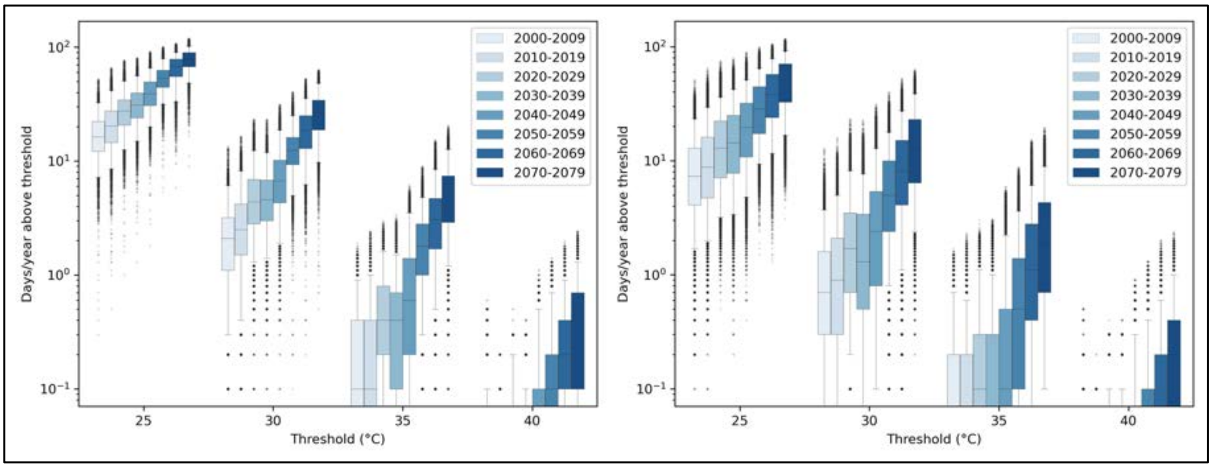


Figure 5.11 As Figure 5.10 but for the Southern (left panel) and Wales and Western (right panel).

The results for extreme high temperatures in Figures 5.10 and 5.11 are consistent with the results presented in CCRA3 - that there is a very small chance of exceeding 40°C by 2040, but that by 2080 (under the high-end scenario, RCP8.5) the frequency of exceeding 40°C is similar to the frequency of exceeding 32°C today. As CCRA3 reports, the median likelihood of exceeding 40°C by 2080 is three times higher in London than across the whole of the UK.

In a related study Christidis et al. (2020)[7] used the UKCP18 land scenarios to explore the return times (in years) for specific maximum temperatures. They considered what might be possible depending on natural variability alone, and then how these return times are changing due to global warming. Figure 5.12 provides a useful summary that emphasizes the large regional differences in return times (or frequencies) across the UK.

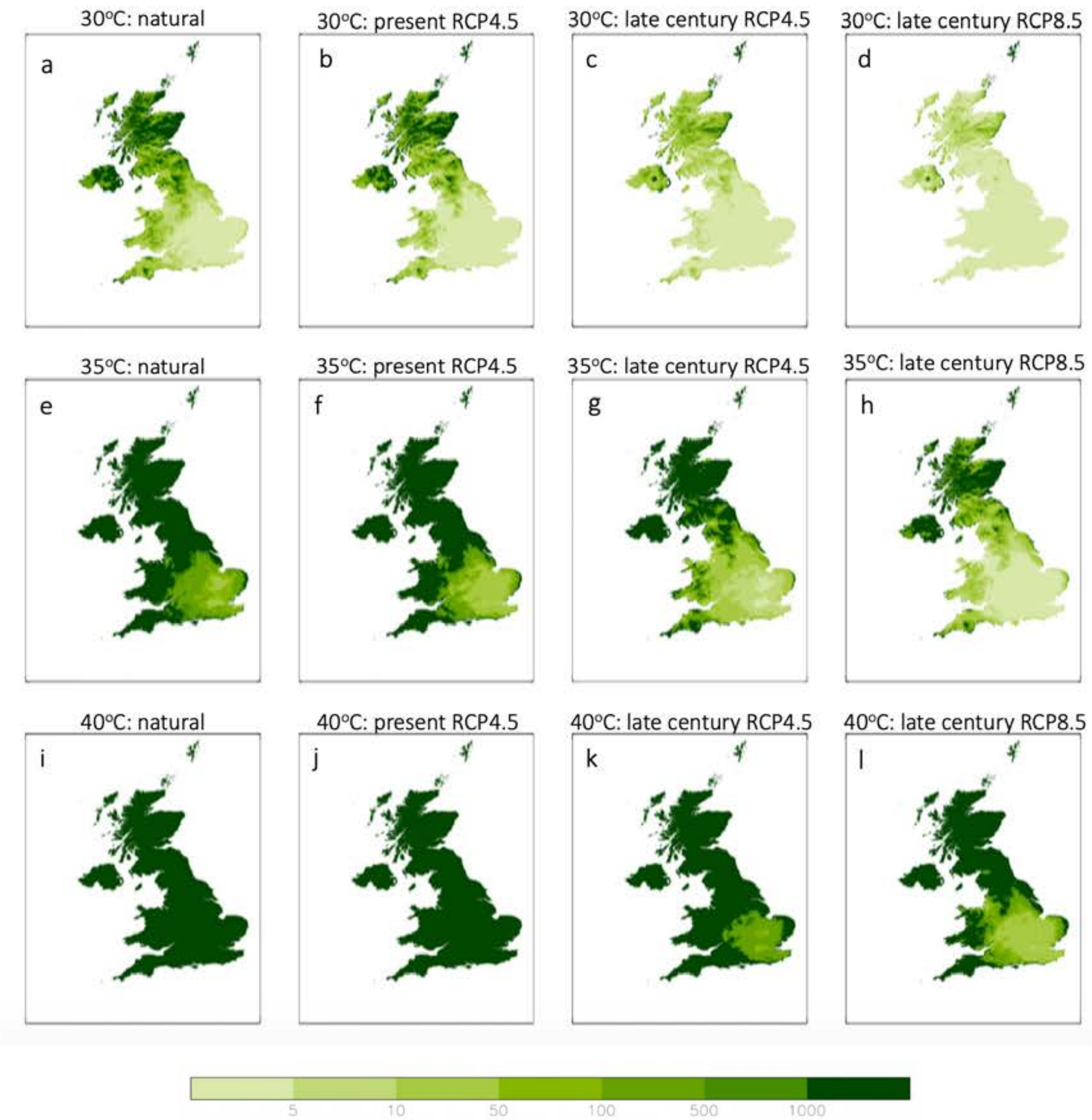


Figure 5.12 Maps of the return time (years) for the warmest daytime temperature going above 30°C (panels a–d), 35°C (e–h) and 40°C (i–l) in the natural climate (panels a, e, i), the present climate (b, f, j), and the climate of the late twenty-first century simulated with the RCP 4.5 (c, g, k) and RCP 8.5 scenarios (d, h, l). Reproduced from Christidis et al. (2020).

[7] Christidis, N., M. McCarthy and P. A. Stott, 2020: The increasing likelihood of temperatures above 30 to 40 °C in the United Kingdom. *Nature Communications* 11:3093 https://doi.org/10.1038/s41467-020-16834-0

Across the whole of the UK the likelihood, locally, of exceeding 30°C, and even 35°C, increases with time. By 2100 many areas in the north are likely to exceed 30°C at least once per decade. In the south-east, temperatures above 35°C become increasingly common, and temperatures exceeding 40°C also become possible. Summers that experience days above 40°C somewhere in the UK have a return time of 100-300 years at present, but this could decrease to 3.5 years by 2100 under future high-end scenarios. Under natural variability alone, Christidis et al. (2020) suggest that temperatures above 40°C are virtually impossible without greenhouse gas warming. In accordance with Figure 5.11, Figure 5.12 emphasises that there are large geographical variations in the probabilities of exceeding specific temperature thresholds and in the potential for rare, extreme high temperatures.

5.5 Analysis of changes in frequency and duration of heatwaves

Alongside short-lived, very extreme temperatures, Network Rail is vulnerable to heatwaves, which can also affect the railway if they last for several days. A key question is therefore whether the frequency and duration of heatwaves will increase in the future. Will there be prolonged periods of high temperatures?

Using all the data from the CPM ensemble, the decade-by-decade changes in frequency of heatwaves per year have been analysed. Heatwaves are defined as a period of at least three consecutive days with daily maximum temperatures meeting or exceeding a specific temperature threshold, as in the current definition (see Figure 2.1).

Figure 5.13 summarises the results for temperature thresholds of 25°, 30°, 35° and 40°C, and shows that the number of heatwave events increases with time, particularly in south-east. For example, by the 2040s more than 4 heatwaves per year above 25°C are predicted, and potentially 1 heatwave per year over 30°C. For the higher temperature thresholds, the likelihood of a heatwave in any year is smaller. For example, by mid-century there is around a 25% chance per year of a heatwave above 35°C. By the 2070s, in any year the chance of a heatwave above 40°C is less than 10%.

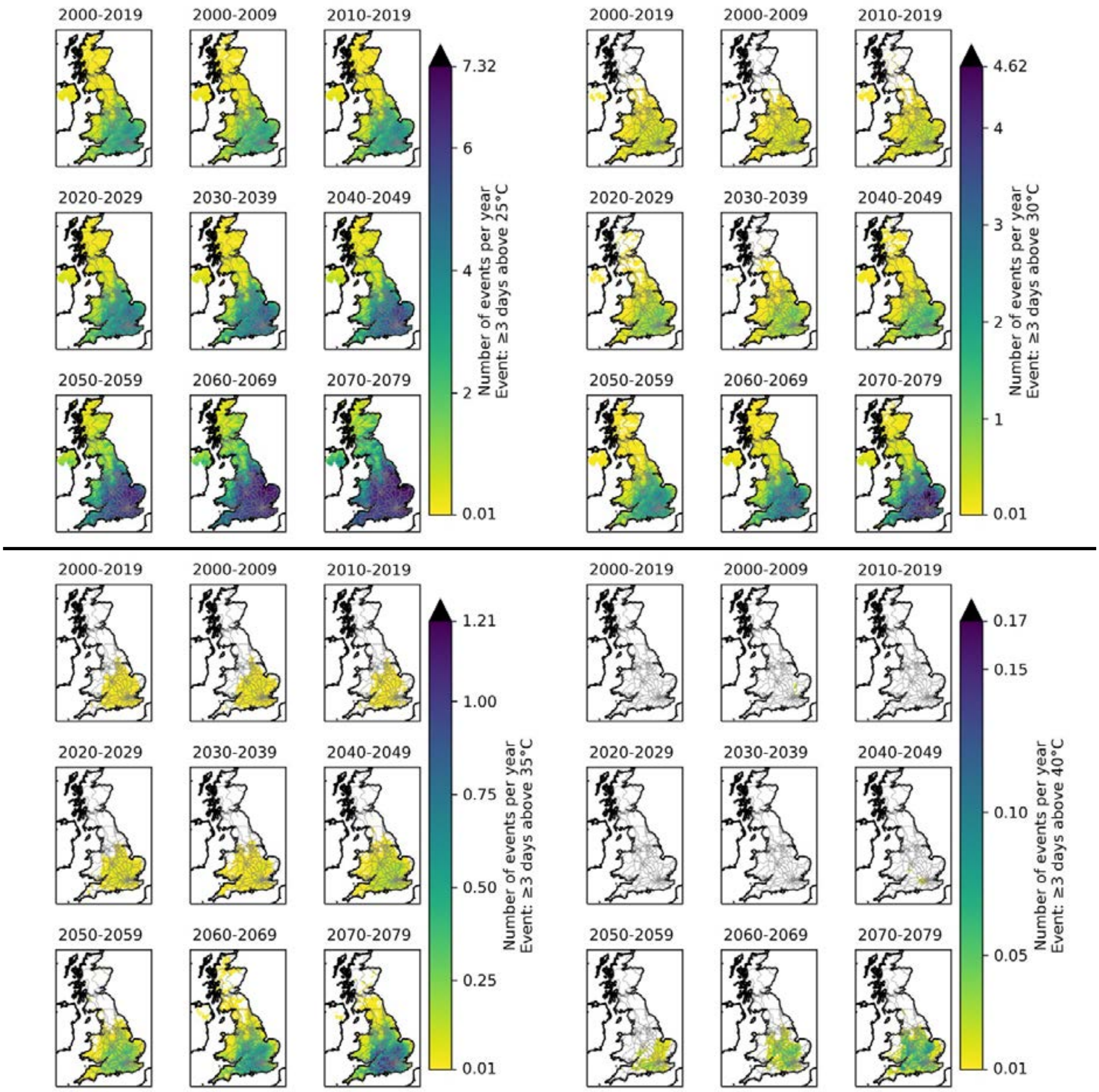


Figure 5.13 Decade by decade maps of the frequency of heatwaves, defined as 3 or more consecutive days above 25° (top left), 30° (top right), 35°C (bottom left) and 40°C (bottom right). White areas indicate no heatwaves.

The frequency of heatwaves, as shown in Figure 5.13, is not the whole story, however. Prolonged heat is also challenging even if it is not extreme. Figure 5.14 provides statistics of the mean length (left panels) and the maximum length (right panels) for heatwaves above 25°C, 30°C and 35°C. Along with the increased frequency of heatwaves, their duration is also projected to increase with time. By the second half of the century, the mean length of a heatwave above 25°C exceeds 10 days (Figure 5.14 top left panel), and the maximum length of a heatwave exceeding 25°C can be very long (Figure 5.14, top right panel) and in excess of 50 days by the 2070s, consistent with the expected rise in summertime temperatures. Even by mid-century, heatwaves in excess of 30°C may have a maximum duration of at least a week, and above 35°C, they may have a duration of several days over SE England.

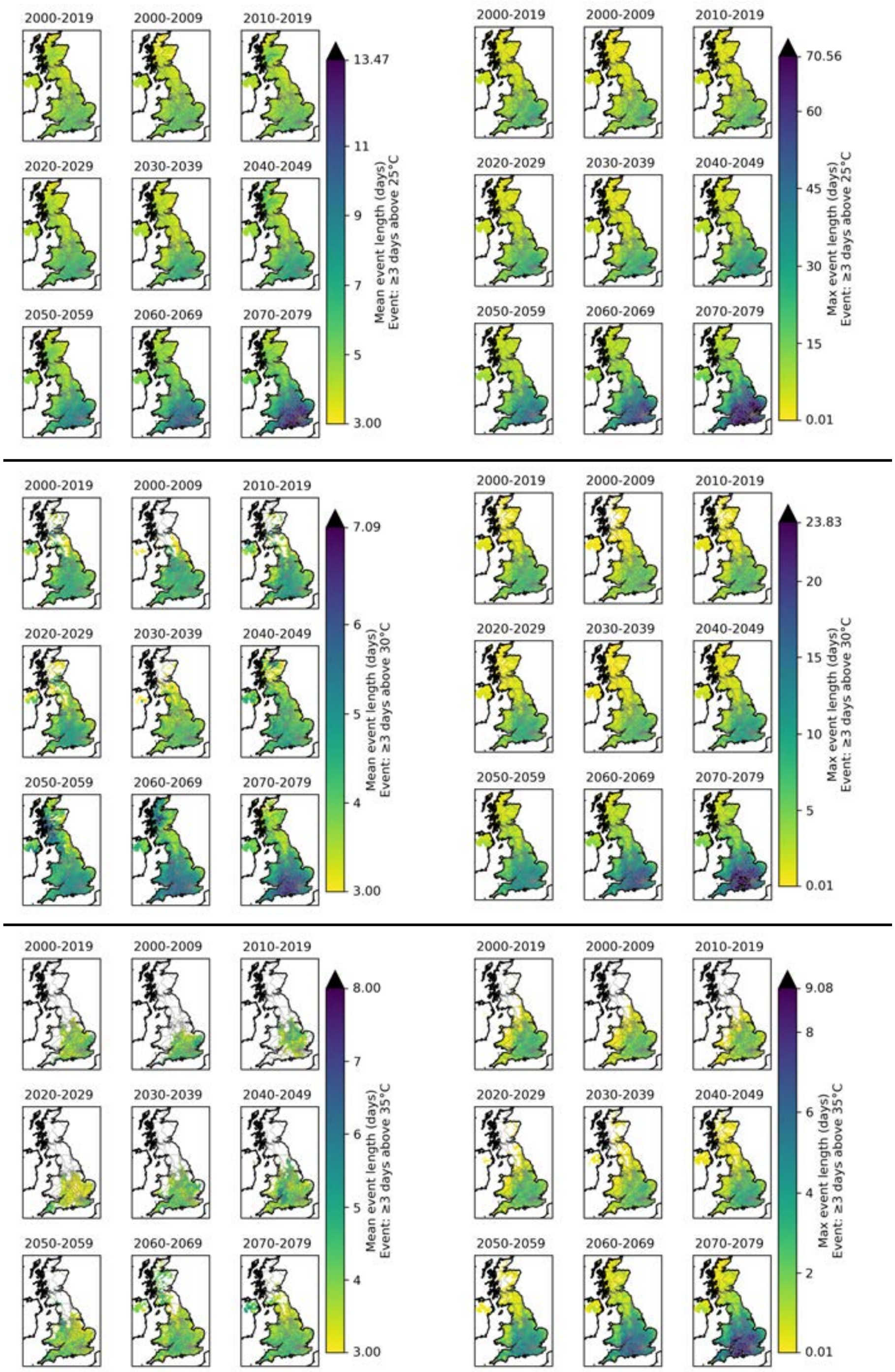


Figure 5.14 Statistics of future heatwaves in terms mean (left panels) and maximum length (right panels) of consecutive days above which the temperature exceeds 25°C (top row), 30°C (middle row) and 35°C (bottom row). White areas indicate no heatwaves.

5.6 Changes in significant drivers of extreme temperatures and heatwaves

Sections 2 and 3 discussed several potential drivers of extreme heat, including antecedent dryness, weather regimes and the influence of western Europe. In this section, these are discussed briefly drawing on published results and new analysis by the Met Office Hadley Centre.

5.6.1 Analysis of future trends in UK dryness during spring (March – May) and summer (June – August).

As discussed in Section 3.1, spring dryness may predispose the following summer to a higher risk of heatwaves and extreme temperatures. Likewise, lower than normal rainfall in summer will likely play a role in the severity of heat waves. This was certainly the case in 2022 and the question is whether climate change will increase the likelihood of spring and/or summer dryness. Figure 5.15 shows the probabilistic projections of spring and summer rainfall from the UKCP18, for low and high emission scenarios. There is no evidence that spring rainfall is likely to change in the future, but both scenarios show a substantial reduction in summer rainfall, which will likely elevate the risk of heatwaves and high temperatures over and above that from just warming alone.

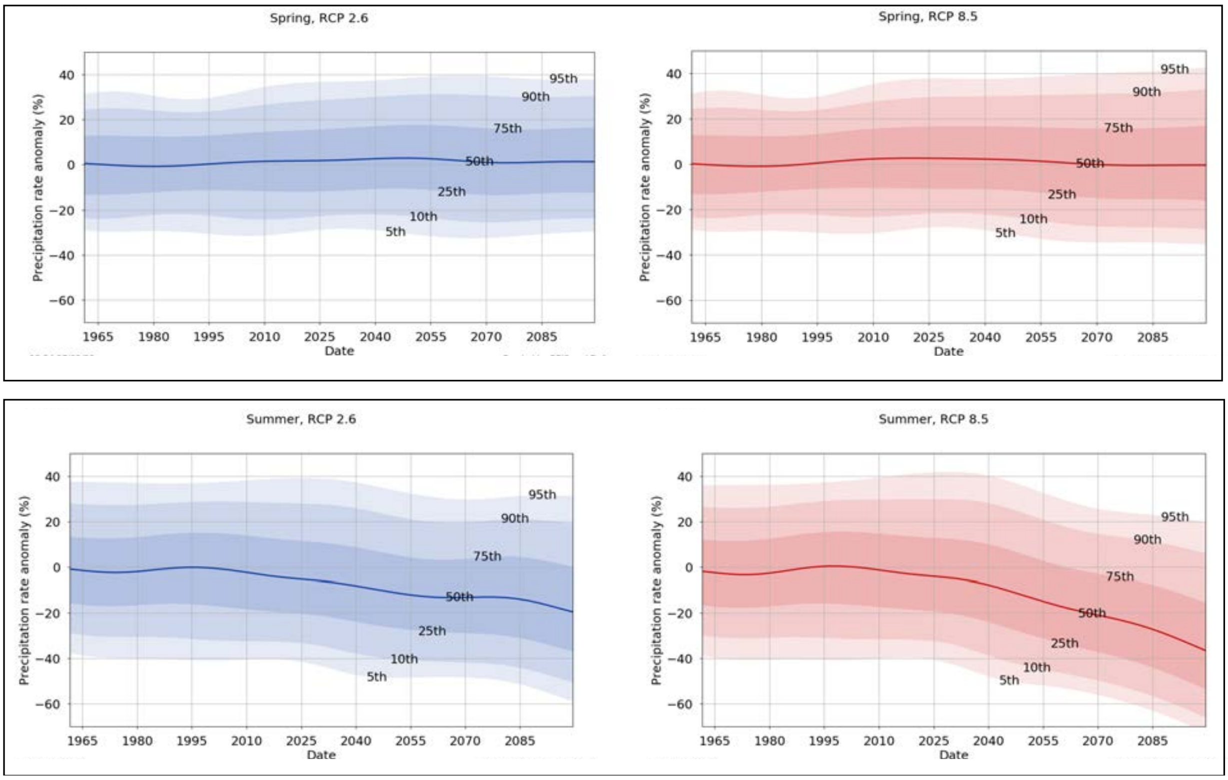


Figure 5.15 Projected changes in the 20-year running mean of the average UK rainfall for spring (upper panels; March, April, May) and summer (lower panels; June, July, August) for a low emission scenario, RCP2.6 (left) and a high scenario, RCP8.5 (right). The results are expressed as % differences from the average rainfall for 1981-2000. The shaded boundaries show the 5^{th}, 10^{th}, 25^{th}, 50^{th} (median), 75^{th}, 90^{th} and 95^{th} percentiles. Values are expressed relative to the 1981-2000 baseline. (Source: Met Office)

Figure 5.16 shows the regional distribution of rainfall changes by the 2070s for spring and summer from the UK CPM projections using the RCP8.5 scenario. In spring, the changes are almost uniform across the country, but in summer, reductions in rainfall tend to be higher in the south. This is important for Network Rail since it means that the denser rail network in that region will be subject to an increased risk of dry conditions and its accompanying impacts.

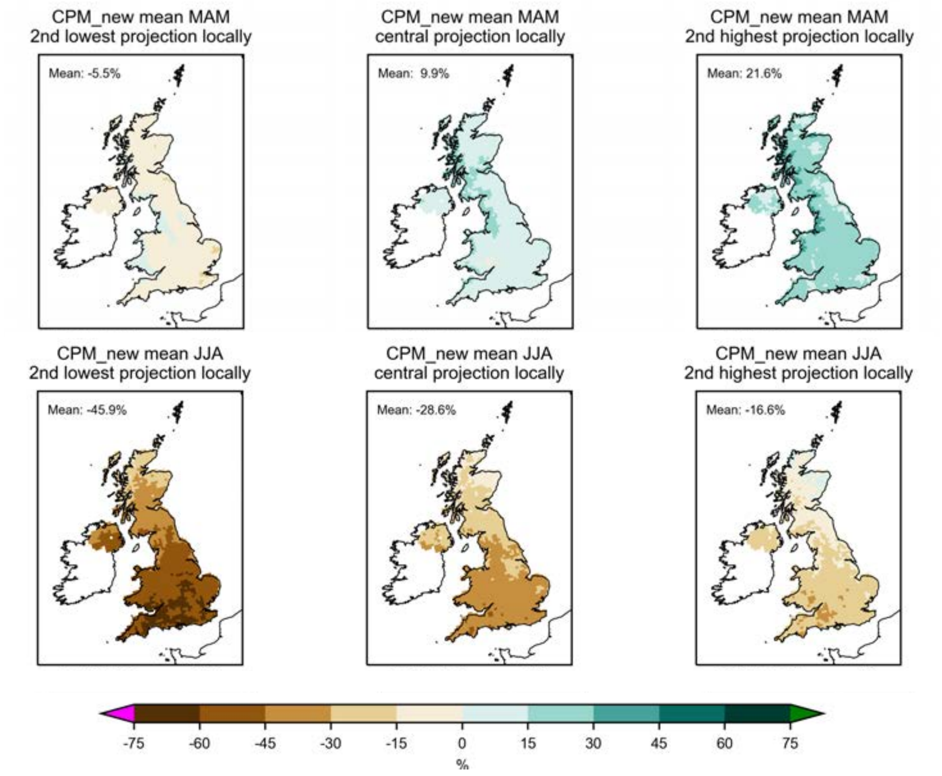


Figure 5.16 Projected future changes in spring (upper panels) and summer (lower panels) mean precipitation (%) for 2061-2080 from the 1981-2000 baseline from the UK CPM ensemble for the RCP8.5 emissions scenario. Changes are shown for 2nd lowest (left), central (centre) and 2nd highest (right) member locally. (Source: Met Office)

5.6.2 Potential changes in the frequency or nature of weather regimes associated with high temperatures

A major factor in the severity of the 2022 heatwaves and extreme temperatures was the prevailing weather pattern. A key, unresolved question in regional climate change is whether global warming will alter weather patterns and/or their frequency of occurrence. For UK climate change, the behaviour of the jet stream will be a critical determining factor, as was the case for 2022 (see Section 3.2), but uncertainties still exist in our understanding of what will happen to the jet stream, and so the results presented in this section should be treated with caution.

Based on the Decider Tool (see Section 4.1.2), the 8 dominant weather regimes associated with high temperatures have been used to explore whether future changes in the frequency of these weather patterns may potentially increase the frequency and/or intensity of heat waves and extreme temperatures over and above that due to anthropogenic warming alone. Figure 5.17 (upper panel) shows the frequency of occurrence of the various weather types for the current climate and for the 2070s, whenever a specific temperature threshold is exceeded. The lower box in Figure 5.17 summarises the 8 weather types in terms of their potential to increase the risk of high temperatures. The results show that there are preferred weather types, especially the negative phase of the North Atlantic Oscillation and the Scandinavian High. However, although there are variations in their relative importance in the future, no clear signal emerges to suggest that the frequency of weather regimes will be a major factor in elevating the risk of heatwaves and high temperatures.

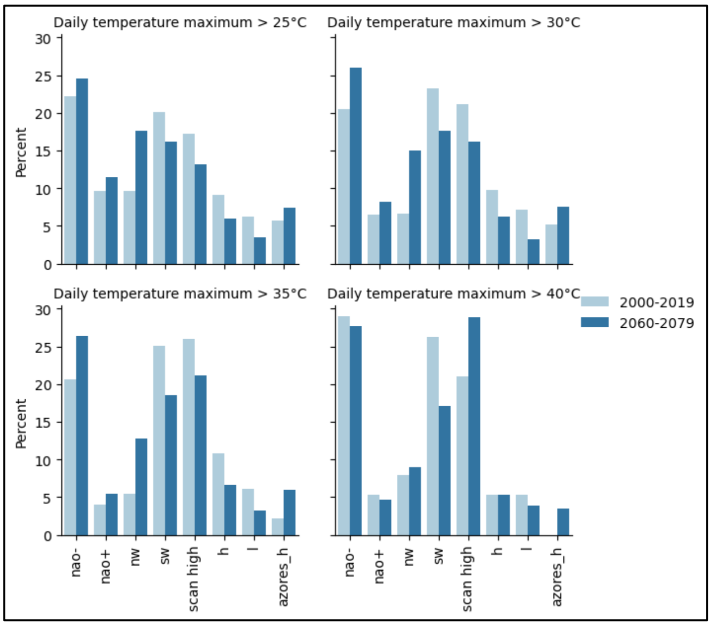


Figure 5.17 Comparison of the frequency of occurrence of 8 dominant weather patterns for the current climate (pale blue) and for the 2070s (dark blue), associated with days above temperature thresholds of 25°, 30°, 35° and 40°C. An interpretation of the 8 weather types is provided in the box below.

nao-	Negative North Atlantic Oscillation – hot and dry conditions
nao+	Positive North Atlantic Oscillation – wet and windy
nw	North-westerly weather type - cool
sw	South-westerly weather type – predisposes to heat
scan high	Scandinavian high – predisposes to continental air masses and heat
h	High pressure weather type – predisposes to hot and dry conditions
l	Low pressure weather type - unsettled
azores_h	Azores High – settled weather and predisposes to warm conditions

This is confirmed in Figure 5.18 which offers a different perspective on the relationship between future heat and weather patterns. This shows the range of maximum temperatures for each weather type for the current climate and for the 2070s under the RCP8.5 scenario. It demonstrates that whatever the weather type, there is a similar increase in maximum temperatures suggesting that global warming is the dominant factor in the increased risk of high temperatures. It is notable that the highest projected maximum temperatures occur under the expected weather regimes, as they do today.

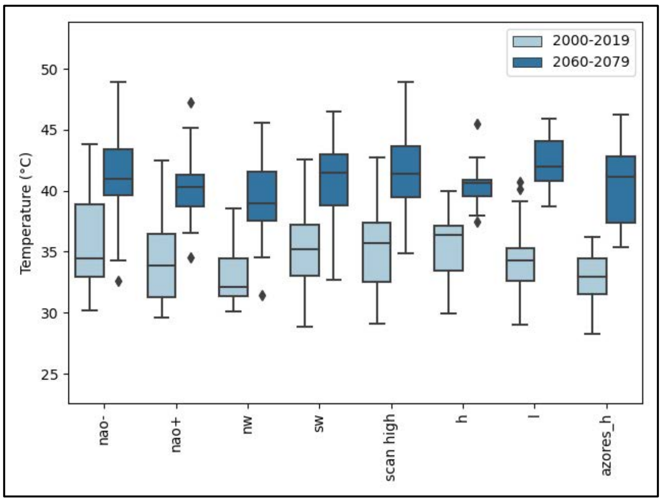


Figure 5.18 Probability distributions of the annual maximum daily temperatures for each weather type as described in Figure 5.17. The distributions are compared for the current climate and for the 2070s based on the RCP8.5 scenario.

5.6.3 Wider perspectives – Influence of changes in European droughts and heatwaves.

As discussed in Section 3.3, conditions over Europe were a significant factor in the severity of the heat in 2022. Trends towards hotter and drier spring and summer conditions are already emerging over south-west Europe (see Section 2.6) and these are likely to continue as global warming progresses (Figure 5.19). As expected, annual temperatures will rise across the whole of Europe. While annual precipitation is projected to increase over much of Europe, there are notable decreases across the Mediterranean and Spain, in particular.

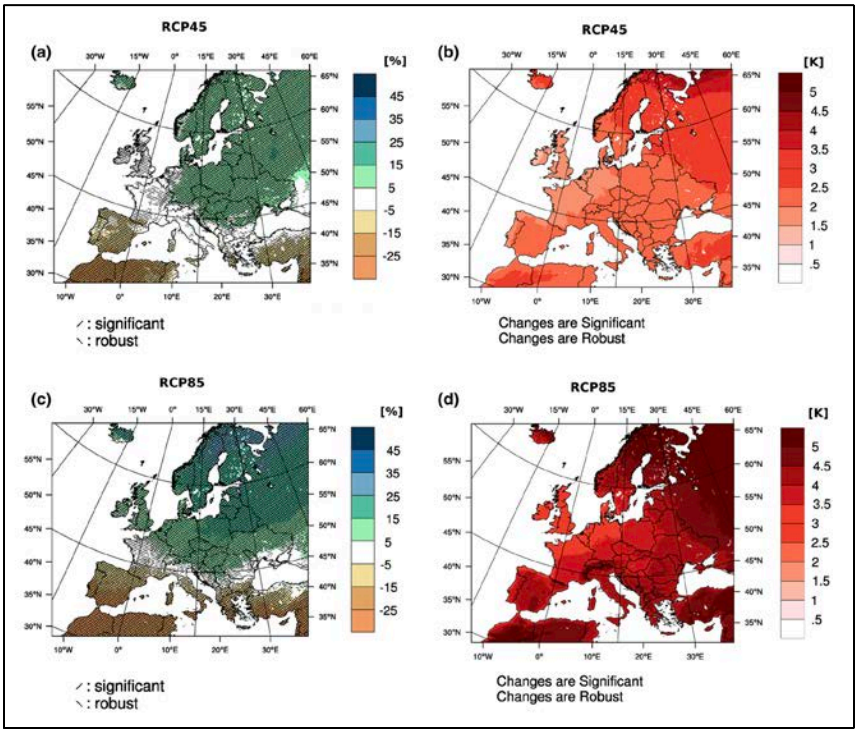


Figure 5.19 Projected changes in total annual precipitation (%) (left) and annual mean temperature [K] (right) for 2071–2100 compared to 1971–2000, for RCP4.5 (a, b) and RCP8.5 (c, d) scenarios. Changes are robust and significant across the entire European continent for temperature. For precipitation, hatched areas indicate regions with robust and/or statistical significance. (Source: Jacob et al. 2014[8])

The combination of higher temperatures and reduced rainfall over southern Europe increases the likelihood of heatwaves and extended dry spells (Figure 5.20), which in turn increases the risks of extreme temperatures and wildfires of the type experienced in 2022. This means that the UK could be exposed to more extreme summer heat from continental Europe with implications for record-breaking temperatures, especially in the south-east.

[8] Jacob, D. et al. 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change, 14, 563-578. https://doi.org/10.1007/s10113-013-0499-2

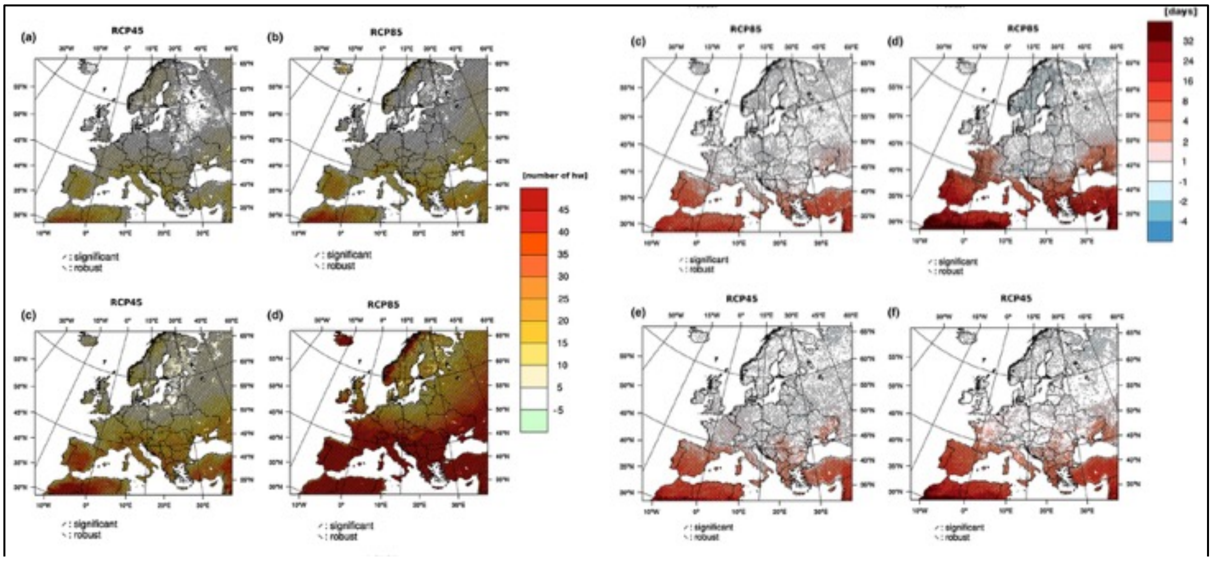
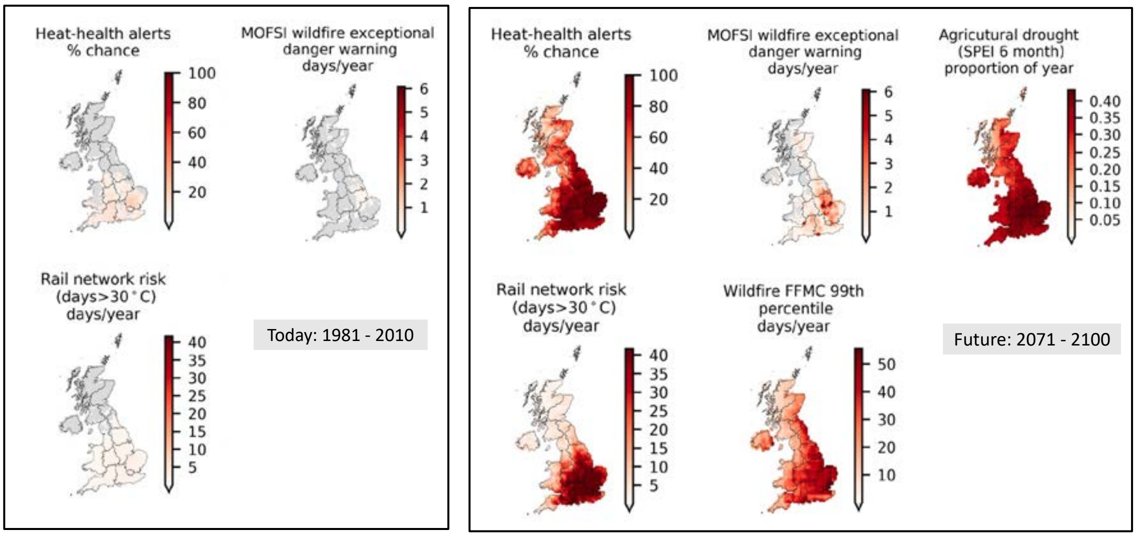


Figure 5.20 Projected changes in the mean number of heat waves (left panels) and in the 95th percentile of the length of dry spells (days; right panels) occurring in the months May–September for 2021–2050 compared to 1971–2000 (upper panels), and for 2071–2100 compared to 1971–2000 (lower panels). Heat waves are defined as periods of more than 3 consecutive days exceeding the 99th percentile of the daily maximum temperature of the May to September season for the control period (1971–2000). The results are based on the RCP4.5 and RCP8.5 scenarios. Hatched areas indicate regions with robust and/or statistically significant change. (Source: Jacob et al. 2014)

5.7 Broader implications of future changes in heatwaves and extreme temperatures

Beyond the risk to infrastructure from extreme heat, there are other impacts that Network Rail will need to consider. These include the human health consequences, the frequency of wildfires, and the effects of drought on lines and earthworks. Drawing on the recent multi-sectoral analysis of changing climate risk across the UK by Arnell et al. (2021)[9], some indicators of relevance to Network Rail have been considered (Figure 5.21). These are based on UKCP18 data and reflect the potential changes under the RCP8.5 scenario.



[9] Arnell, N.W., Kay, A.L., Freeman, A., Rudd, A.C. and Lowe. J.A. (2021). Changing climate risk in the UK: A multi-sectoral analysis using policy-relevant indicators. Climate Risk Management, 31, 100265. https://doi.org/10.1016/j.crm.2020.100265

Figure 5.21 Potential changes in human heat stress, wildfire risk and agricultural drought by the end of the century under the RCP8.5 scenario. (Source: Arnell et al. 2021[7]).

Consistent with the changes discussed in previous sections, heat stress will become an increasing risk, especially for those working outside on rail infrastructure. This will be the case particularly in the south-east where there could be 30-40 days above 30°C by the end of the century.

The Met Office Fire Severity System (MOFSI) suggests that there could be as many as 3 to 6 days per year where wildfires could be exceptionally dangerous. A similar metric, from the Fine Fuel Moisture Code (FFMC), which is regarded as a better measure of wildfire risk, shows widespread levels of risk from wildfires across the UK in the future. Finally, agricultural drought is a good measure of soil drying, which would exacerbate the risk of soil cutting failures. Figure 5.21 shows that the proportion of the year under drought could be as high as 40%. This will be due to enhanced evaporation under a much warmer climate, as well as rainfall changes.

The results in Figure 5.21 are at the extreme end of potential climate change risks, but provide a helpful sense of the challenges that Network Rail may face. These could be explored in more depth using the UK CPM projections for the coming decades to provide an evolving view of these complementary risks.

5.8 Summary of the effects of climate change on extreme temperatures and heatwaves

The analysis presented in this report is the first, in-depth study of how extreme temperatures and heatwaves may change decade-by-decade through the 21st century, based on state-of-the-art kilometre-scale simulations. The results supersede earlier assessments, for example the 3rd Climate Change Risk Assessment (CCRA3: https://www.ukclimaterisk.org/about-the-ccra/uk-climate-risk-independent-assessment-ccra3/). The following key conclusions from this study include:

- Summer mean temperatures will increase by a further 0.5° to 1°C by 2040 compared with today, regardless of emission scenario. Due to a range of positive feedback mechanisms discussed in this report, extreme temperatures will increase by more than the average temperature change.
- SE England is particularly prone to extreme temperatures, due to its drier summers and its proximity to continental Europe where increasing heat and dryness will become a significant issue.
- Over SE England, days with 25°C and above are likely to double by the 2040s; by the 2070s under a high emission scenario, all summer days could be above 25°C.
- Days above 30°C and 35°C will increase systematically through the century across England and Wales. Scotland is unlikely to see any days above 35°C by the end of the century, but there is a 5% risk of several days a year above 30°C.
- The risk of experiencing extreme temperatures of 40°C and above remains low through the century because of the moderating effects of the North Atlantic on UK climate. Nevertheless, there is a 5% chance of experiencing at least one day per year of 40°C or above, over England and Wales by 2070.
- The frequency and duration of heatwaves will also increase, particularly in SE England. By the 2040s, heatwaves in excess of 30°C could last on average 4-5 days and with a maximum length of 10 days or more.
- So far, there is no evidence that the frequency of specific weather patterns that favour high summer temperatures will change in the future. The 'perfect storm' of July 2022 is no more or no less likely as climate change progresses.

In summary, extreme temperatures and heatwaves will become an increasing feature of UK summers as global warming progresses. However, the extreme heat of July 2022 is likely to remains a rare event. There are two caveats to that statement. The first is that the model data have not been bias-corrected and this may affect the details of the statistics particularly at higher and rarer temperatures. The Met Office is undertaking a study on the effect of the model biases. The second is the ongoing lack of understanding around the future behaviour of the North Atlantic Jetstream – will there be more waves and blocking of the type seen in 2022? We just don't know!

6. Recommendations and Concluding Remarks

The links between the WATF and EHTF reports are clear and underscore the importance of an integrated and seamless approach to managing the impacts of extreme weather from whatever meteorological driver, by drawing on the range of forecast products now available to Network Rail from hours to a week or more ahead. With the range of forecasts and tools now becoming available to Network Rail, as a result of the WATF recommendations, it should be possible to anticipate episodes of extreme heat and plan for their potential impacts.

Beyond the WATF recommendations, this report has made some specific further recommendations which Network Rail may wish to consider:

1. The current definitions of heatwaves are very general and reflect the diversity of impacts across sectors and on human beings. Network Rail may wish to define its own metrics based on infrastructure performance, passenger comfort and staff safety, drawing from recent experience and the other components of the EHTF Report. Working with the Met Office, these can then be used within the seamless forecasting suite to provide sector-specific alerts and warnings

2. The specific risks from long-lived heat waves have been highlighted, especially those in which a heat dome can form. These are particularly dangerous for rail infrastructure. Infrastructure is under prolonged heat stress, and the extreme high temperatures associated with the heat dome may lead to sudden failures. The spatial scale of the heat dome is such that large parts of the network may be under stress at the same time, leading to multiple failures. Network Rail will need to plan for large scale disruption and cascading impacts as a result.

3. The extreme nature of the 2022 heatwave was due to an unprecedented combination of factors that led to a 'perfect storm'. It took us into uncharted territory, beyond living experience, and highlighted how unprepared Network Rail is for such an event. The Met Office has recognised this need in its recent creation of a new Weather and Climate Impacts Team whose focus is on advancing the capabilities of specific sectors, specifically Category 1 &2 providers, to anticipate and manage the impacts of extreme events, including their compounding and cascading effects.

   It is recommended that Network Rail invest in an R&D and services programme that can interface with this new Met Office team to ensure that it has the best possible intelligence for managing its operations before, during and after extreme events. It is further recommended that elements of these advances are included in the Academy curriculum.

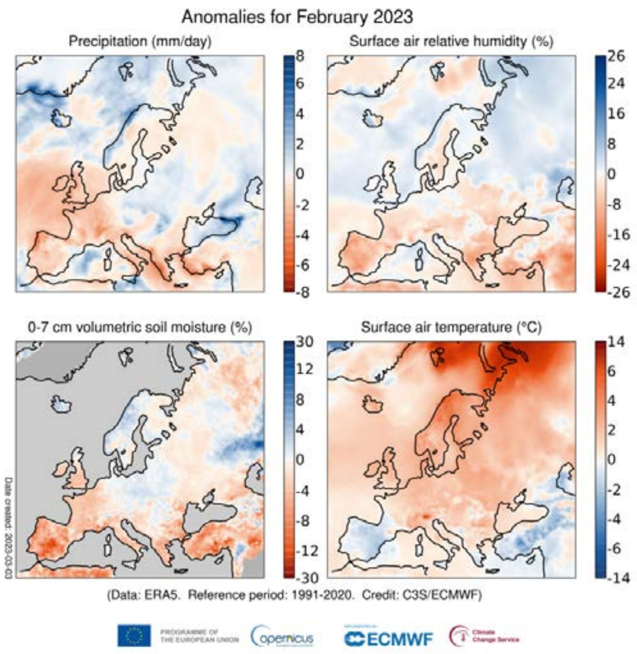
4. The extreme heat of 2022 was well forecast and warnings of the risk of extreme heat were issued at least one week in advance. With the developments already ongoing from the WATF recommendations, the future provision of extreme heat-related forecasts is in good shape. However, more could be done to manage potential risks by exploiting the Met Office seasonal forecast capability. In future, these probabilistic seasonal forecasts could be customised for Network Rail based on its vulnerabilities, so that more specific assessments of risk could be provided to assist forward planning. It is recommended that Network Rail explores with the Met Office, the potential for more user specific risk assessments in the months and weeks leading up to summer.

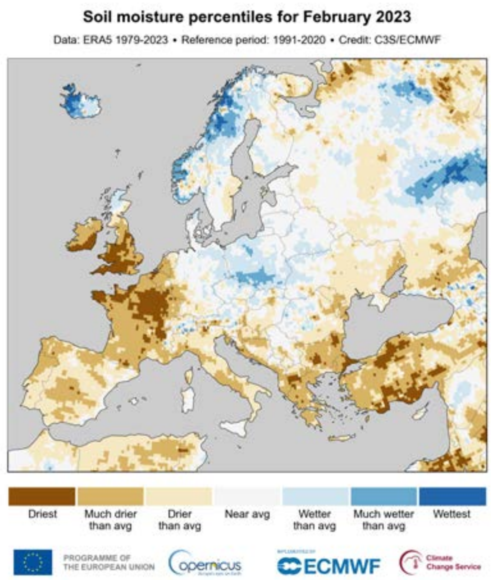
5. It is important that Network Rail has access to the latest information on how climate change will affect its operations and infrastructure so that it can develop appropriate adaptation and resilience plans. A key element of this report is a new, in-depth analysis of how extreme temperatures and heatwaves may change decade-by-decade through the 21st century, based on its state-of-the-art kilometre-scale simulations. The results show the range of possible outcomes that Network Rail can use within in a risk-based framework. It is recommended that similar in-depth reports are commissioned for other natural hazards, such as extreme rainfall, so that Network Rail can plan its adaptive pathways and set priorities for future investments.

In conclusion, the unprecedented nature of summer 2022 was a 'wake-up call' for Network Rail with respect to its resilience to extreme heat. Although the event was well forecast more than a week ahead and well-communicated to Network Rail, the vulnerability of its infrastructure to such extreme temperatures and prolonged heat was not fully appreciated, and not all mitigating actions were in place – see other elements of the EHTF Report. Global warming was undoubtedly a factor in the severity of the event and highlighted that Network Rail needs to plan now for ongoing changes in its exposure to high temperatures. These plans need to be informed by the best climate change information which has been specifically tailored to Network Rail's exposure and vulnerabilities.

Postscript: Potential risks of high temperatures for the coming summer, 2023.

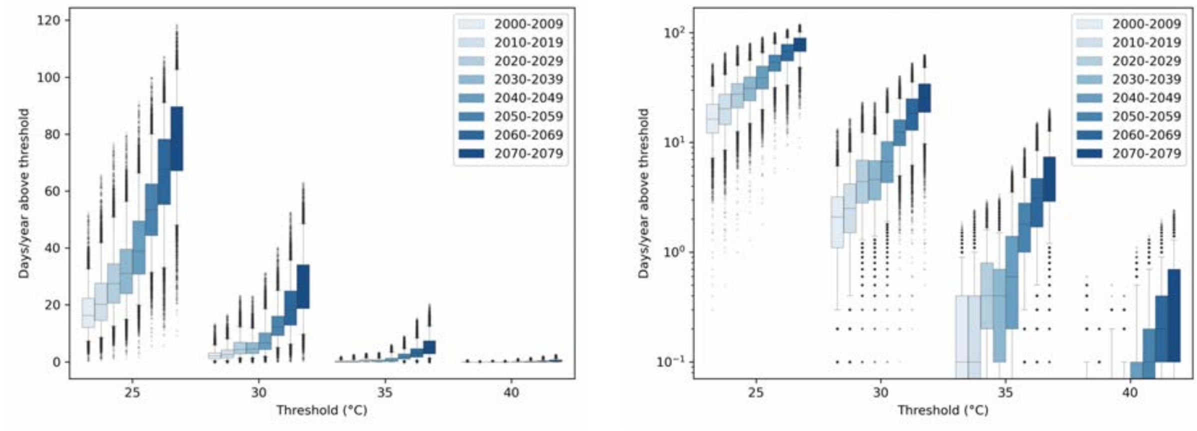
As of March 2023, the latest observations of conditions over Europe, which might indicate a predisposition to drought and therefore the potential for higher summer temperatures, are shown below. Much of western Europe experienced a very dry February, including the UK which received less than half its normal rainfall. Following a fairly dry winter, parts of western Europe are already predisposed to drought.



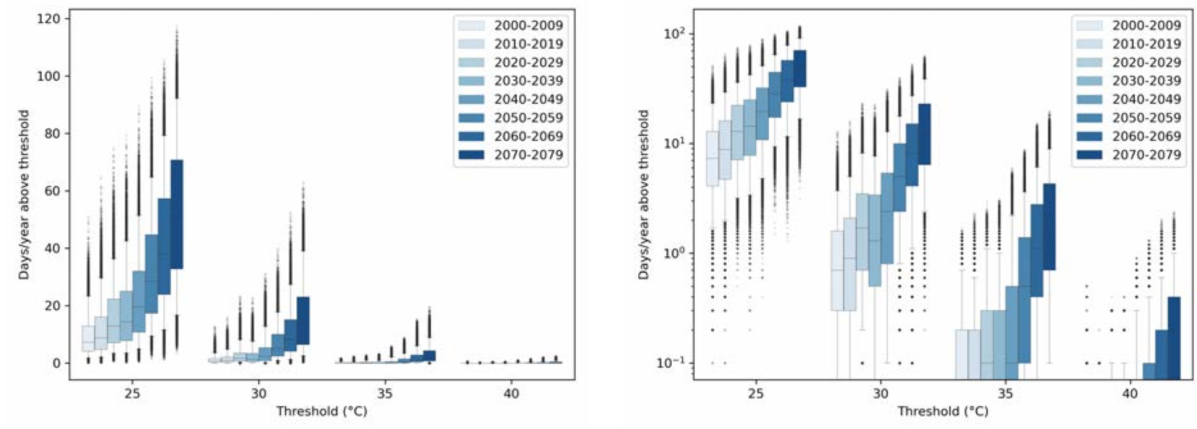


ANNEX: Results for Routes and Regions

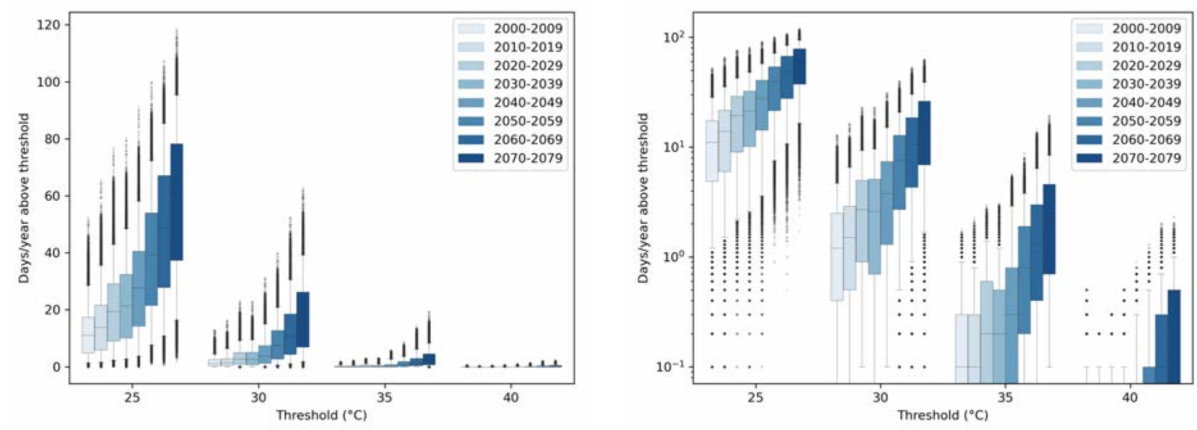
SOUTHERN



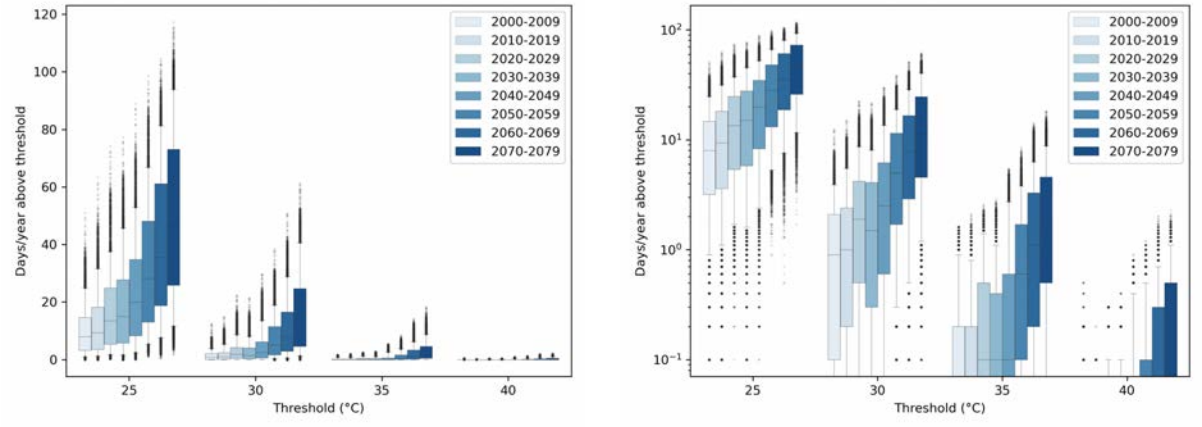
WALES & WESTERN



EASTERN



NORTH WEST & CENTRAL



SCOTLAND