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HS2

High Speed Rail (Crewe – Manchester) Environmental Statement

Volume 5: Appendix CL-001-00000

Climate change

Climate data and information

M71

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Contents

Figures

Tables

1 Introduction

1.1.1 This report is an appendix to the climate change assessment for the Proposed Scheme; it presents an overview of the current climate conditions and projected climate change trends and related information.

1.1.2 This appendix should be read alongside:

- Volume 3, Route-wide effects;
- Volume 4, Off-route effects; and
- Volume 5, Appendix: CL-002-00000 Results of climate change assessments.

1.1.3 The document is informed by the UK Climate Projections 2018 (UKCP18)[1], which are the latest set of climate projections for the UK. The methodology for developing projections is set out in Annex A.

1.1.4 Other data sources, such as findings from published scientific literature, were also considered to build on the evidence available from UKCP18 for those variables where appreciable uncertainty exists. H++ and L-- scenarios[2] are also considered, which represent the plausible lower and higher end of the climate change projections.

1.1.5 This document presents recent historical climate data as a baseline for two study locations, Manchester and Crewe, that lie along the route of the Proposed Scheme see Figure 1. The historical data is obtained from the 12km HadUK-Grid dataset[3] which holds the gridded climate variables derived from the network of UK land surface observations. The locations have been selected to sample typical climatic conditions along the route of the Proposed Scheme. In addition to these two locations, analysis has been undertaken for one location in Scotland related to the off-route works.

1.1.6 Future climate change projections for the two locations are presented using both UKCP18 probabilistic projections and Regional Climate Model (RCM) projections to summarise the projected future changes in climate.

1.1.7 These climate change projections have been used to inform the climate change trends used in the climate change resilience (CCR) and in-combination climate change impacts (ICCI) assessments for the Proposed Scheme (see Volume 5: Appendix CL-002-00000).

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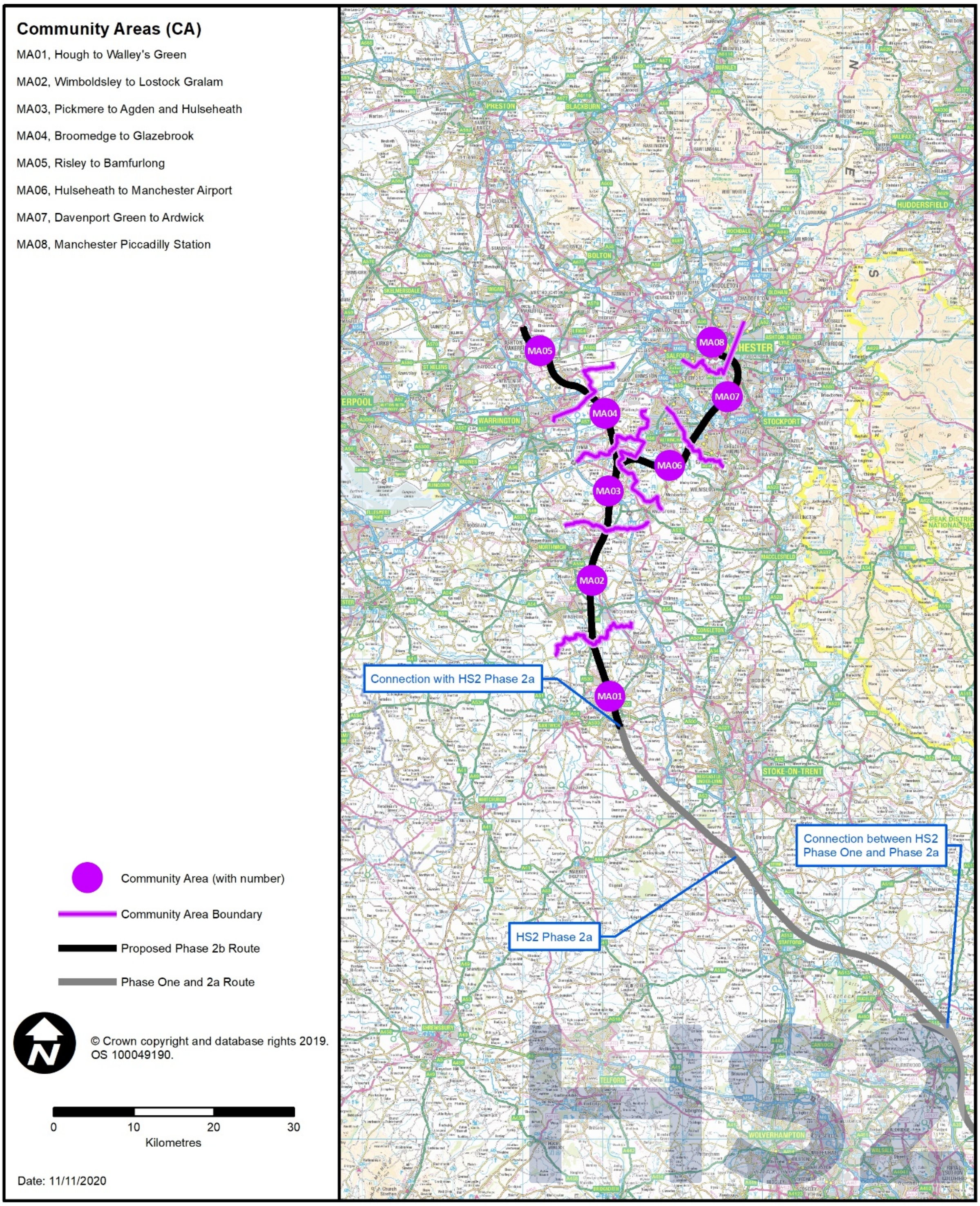
[1] Meteorological Office (2018a), *UK Climate Projections (UKCP).* Available online at: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index.

[2] Wade, S., Sanderson, M. and Golding, N. (2015), *Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snap,* Report to the Adaptation Sub-Committee of the Committee on Climate Change. Available online at: https://www.theccc.org.uk/publication/met-office-for-the-asc-developing-h-climate-change-scenarios/.

[3] Meteorological Office, Hollis, D., McCarthy, M., Kendon, M., Legg, T. and Simpson, I. (2018), *HadUK-Grid gridded and regional average climate observations for the UK,* Centre for Environmental Data Analysis. Available online at: https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb.

Figure 1: The route of the Proposed Scheme and Community Areas



1.2 Purpose of this document

1.2.1 The purpose of this document is to provide evidence to support the projected future climate trends used within the climate change assessments. This document is not intended to provide climate change design values for the Proposed Scheme; for that, a more detailed analysis would be required.

1.2.2 Relevant climate variables have been selected for presentation within this document. A summary of the projected climate trends used in the climate change assessments are presented in Table 1.

Table 1: Projected climate trends informing the climate change assessments for the Proposed Scheme

Projected future climate trend
Increase in mean, maximum and minimum daily temperatures across all seasons
Increased frequency of heatwaves
Decreased frequency of cold weather events (e.g. snow and ice)
Increased frequency of heavy rainfall events
Increased frequency of dry spells
Increased frequency of windstorm events in the second half of the 21st Century
Decrease in relative humidity
Hotter and drier conditions in summer
Warmer and wetter conditions in winter
Changes in temperature and rainfall patterns
Increased frequency of extreme weather events (e.g. dry spells, heavy rainfall events, heatwaves)
Increased frequency of lightning events in the second half of the 21st century
Decreased frequency of fog events in the second half of the 21st century

1.2.3 There are some minor changes in the climate change trends used within the climate change assessments when compared to the trends used for the HS2 Phase 2a route climate change assessments. This is partly due to the differences between the climate projections used for each assessment; the assessment for Phase 2a used UKCP09 data, whereas the assessment for the Proposed Scheme uses UKCP18 data, as this is the most up to date data available. As the knowledge of, and confidence in climate change projections for the UK increases, the likely climate change trends have also been altered slightly.

2 Climate data and information

2.1 Historical climate baseline data

2.1.1 Historical baseline conditions for climate variables have been obtained using Met Office HadUK-Grid gridded observational data at a spatial resolution of 12km to facilitate comparison with UKCP18[3]. This data has been derived from the UK land surface observation network. This dataset was produced to support the UKCP18 project and supersedes the UKCP09 gridded observations.

2.1.2 Table 2 presents the climate baseline data for Crewe and Manchester between 1981 – 2000, the selected baseline period of 1981 – 2000 is in line with the UKCP18 methodology[4].

2.1.3 The climate baseline variables selected for presentation within this document to support the climate change trends identified in Table 1 include: mean annual daily temperature; mean summer daily maximum temperature; mean winter precipitation (seasonal); mean summer precipitation (seasonal); and mean annual relative humidity. Summer months are defined as June, July and August and winter months are December, January and February.

2.1.4 Table 3 presents the data for extreme weather events for the same 1981 – 2000 baseline. The criteria used to define each extreme weather event are included within the definition for each variable. Some extreme weather events occur when one day reaches the required threshold, for example a 'heavy rain' event is defined as one day which receives more than 25mm of rainfall. On the other hand, some extreme weather events require a threshold condition to be reached and maintained for a certain time period in order to be classified as an event, for example a 'dry spell' event denotes at least 10 consecutive days without rain.

2.1.5 The extreme weather indices selected to support the climate change trends in Table 1 include: number of days receiving more than 25mm of rainfall ('heavy rain day'); number of dry spells (at least 10 consecutive days without rain); number of days when maximum temperatures exceed 25°C; number of days when minimum temperatures fall below 0°C ('frost day'); and number of heatwaves (at least 3 consecutive days with maximum temperatures over a given threshold temperature). For Crewe and Manchester, the temperature threshold values for heatwave occurrence are 26°C and 25°C respectively, to reflect the differences in climatology between the two locations[5].

2.1.6 Due to the lack of certainty in the data, historical climate and future projection data for lightning, wind and fog have not been included within the data tables and no data analysis as part of this study has been undertaken. Evidence for trends has instead been inferred from the available literature, as outlined in the future climate baseline section.

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[4] Meteorological Office (2018b), *UKCP18 Land Projections: Science Report*. Available online at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf.

[5] Meteorological Office (2018c), *Heatwaves*. Available online at: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave.

Table 2: Historical mean climate data for Crewe and Manchester (1981 – 2000)

Climate variable	Crewe	Manchester
Mean annual daily temperature [°C]	9.6	10.2
Mean summer daily maximum temperature [°C]	19.9	19.9
Mean winter precipitation [mm/season]	180	228
Mean summer precipitation [mm/season]	177	212
Mean annual relative humidity [%]	81.4	77.6

Table 3: Observed mean historical extreme weather data for Crewe and Manchester (1981 – 2000)

Climate variable	Crewe	Manchester
Annual number of days when daily maximum temperature is greater than 25°C	9.0	9.4
Annual number of days when daily maximum temperature is greater than 25°C	45.8	30.0
Annual number of days when precipitation is greater than 25mm per day ('heavy rain')	1.0	1.4
Annual number of dry spells (10+ consecutive days with no precipitation)	3.9	3.3
Annual number of heatwaves (3+ consecutive days with maximum temperatures over threshold[5])	1.0	1.5

2.2 Future climate baseline

2.2.1 This section presents the projected changes in the selected climate variables outlined in Table 2 and Table 3. Changes in temperature, precipitation and humidity are presented using UKCP18 data for both locations. No numerical data is presented for changes in wind, fog and lightning; future trends in these variables are supported by information available in scientific literature.

UKCP18 data extraction

2.2.2 The UKCP18 is the latest set of climate change projections for the UK. It replaced the previous UKCP09 projections. Rather than emission scenarios, as used in UKCP09, the UKCP18 projections are based on representative concentration pathways (RCP). These represent possible future climate scenarios with varying degrees of mitigation and greenhouse gas emissions.

2.2.3 Four RCP: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 are used in UKCP18, representing the possible range of future greenhouse gas concentrations[6].

[6] Van Vuuren, D.P., et al. (2011), *The representative concentration pathways: an overview*, Climatic Change, 109, 5-31.

2.2.4 Two key UKCP18 products inform the climate change assessment – the probabilistic projections and the RCM projections:

- the probabilistic projections combine information from several collections of computer models, including those used to inform the Intergovernmental Panel on Climate Change (IPCC) 5th assessment[7], to provide a high-quality future climate dataset. These are available at 25km spatial disaggregation up to the year 2100. Probabilistic projections are available for a range of RCPs, though are not spatially coherent, i.e. the 90th percentile for one location might not occur at the same time as the 90th percentile at another location. The probabilistic projections provide estimates of changes to annual, seasonal and monthly climate. They do not provide information for shorter periods and are therefore less useful when considering extreme events where daily or sub-daily data is more relevant; and
- the RCM projections provide future daily data from 12 plausible model runs up until 2080 on a 12km grid over the UK for a range of climate variables. RCM projections have full spatial and temporal coherence; however, they are only available for RCP8.5.

2.2.5 The new UKCP18 'local' projections, which use a convection-permitting model, available at 2.2km spatial disaggregation[8], are not used in this document. These can provide refined insights on localised climate hazards, especially summer rainfall intensity. However, in relation to the Proposed Scheme, the daily regional (12km) projections can be used to investigate the likely general trends in extreme events and are considered to be sufficiently detailed to inform the projected future climate trends.

2.2.6 Projection data for the period 2020 – 2039 is taken to represent the construction period, and the operational period is represented by projections from 2080 – 2099 (for probabilistic projection data) or 2060 – 2079 (for Regional Climate Model data).

2.2.7 It is important to note that the Proposed Scheme has a design life of 120 years, so goes beyond the timeframe of all the climate projections used.

2.2.8 Based on current emission trajectories, it is considered unlikely that RCP2.6 will be met[9]; this pathway denotes strict mitigation to limit warming to 1.6°C by 2100. Consequently, projections for RCP2.6 have not been used within this climate assessment. However, for comparative purposes with other RCPs, RCP2.6 has a peak CO_2 concentration at around 440 parts per million (ppm) in 2050, reducing to around 420ppm by 2100, and continuing to decline to around 360ppm by 2300.

[7] Intergovernmental Panel on Climate Change (2014), *Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of The Intergovernmental Panel on Climate Change*. Available online at: http://ar5-syr.ipcc.ch/topic_summary.php.

[8] Meteorological Office (2018d), *UKCP18 Factsheet: UKCP Local (2.2km) Projections*. Available online at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-factsheet-local-2.2km.pdf.

[9] Intergovernmental Panel on Climate Change (2018), *Special Report - Global warming of 1.5 ° C.* Available online at: https://www.ipcc.ch/sr15/.

2.2.9 RCP4.5 presents an intermediate stabilisation scenario in which CO_2 concentrations are approximately 540ppm by 2100 as a result of emissions mitigation policies[10]. By contrast, RCP8.5 represents a world in which greenhouse gas emissions continue to rise and associated temperature increases are much higher; CO_2 concentrations are approximately 940ppm by 2100[10], rising to around 1,960ppm by 2250 before stabilising.

2.2.10 To present a range of plausible future climate scenarios, that take the uncertainty in future mitigation action into consideration, the data presented within this document for future climate projections covers the range between RCP4.5 and RCP8.5. These RCP are considered to represent a broad range of possible outcomes, with RCP6.0 projections falling between RCP4.5 and RCP8.5 projections by the end of the century, and thus are captured in the presented range.

2.2.11 Changes in mean climate conditions are based on the probabilistic projections. This document presents the 50th percentile results for RCP4.5 and RCP8.5, as well as the 10th to 90th percentile range for each RCP. Thus, the results are considered to capture the uncertainty associated with future global greenhouse gas concentrations, as well as those associated with climate modelling. Fuller detail on the methodology applied can be found in Annex A.

2.2.12 Humidity projections are based on daily data from the UKCP18 RCM projection which are only available for RCP8.5. Given this different source of information (compared to the other mean climate variables) they are not presented in the data tables for each location. Instead the future changes are given in the text for just the 50th percentile projection.

2.2.13 Projected changes in extreme weather events require UKCP18 data on a daily or sub-daily scale, therefore RCM projections have been used as the probabilistic projections are only available down to monthly resolution.

2.2.14 This document presents data on extreme weather using the median of 12 available model realisation outputs. To provide an indication of the uncertainty associated with the RCM projections, the second lowest and second highest of the 12 model realisations are presented as a range (following an approach used in the UKCP18 Science Report[4]). The lowest and highest projections were not selected to avoid the risk of presenting potential outliers.

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[10] Meinshausen, M., et al. (2011), *The RCP greenhouse gas concentrations and their extensions from 1765 to 2300,* Climatic Change, 109, pp. 231-241.

Limitations

2.2.15 Climate change projections are associated with a range of limitations. In addition to the intrinsic limitations and caveats in the UKCP18 data[11], and the Met Office guidance on using the land projections[12], the following specific limitations have been noted:

- a key limitation of the UKCP18 RCM projections is that they are only available for RCP8.5, whereas the probabilistic projections are available for a greater range of plausible future scenarios (i.e. RCP 2.6, 4.5, 6.0 and 8.5);
- the probabilistic projections provide estimates of average changes to annual, seasonal and monthly climate. They are less useful when considering extreme events which require sampling at timesteps suitable for discerning the extreme events themselves. The daily or sub-daily data of the RCM is therefore of more relevance, though constrained to a single RCP, to understanding the possible changes to extreme events;
- the projections do not cover the entire design life of the Proposed Scheme. Data from the probabilistic projections are available up to 2099. Whereas data from the RCM projections are only available up to 2079;
- the RCM model projections do not capture the same range of uncertainty as the probabilistic projections can provide. The probabilistic projections are therefore considered to present a more complete understanding of the uncertainty in future climate change;
- UKCP18 probabilistic projections are not available for all relevant climate variables. For example, probabilistic projections do not present data on relative humidity, whereas the RCM projections do. Data for humidity is therefore only available for RCP8.5 from the RCM data;
- lightning and fog projections are not currently available from UKCP18. The information from UKCP09 technical notes, and other supporting literature, have therefore been used. The sources of this information may not therefore be entirely consistent with the latest UKCP18 data; and
- projected changes in the number of occurrences of extreme events have been added onto the baseline values obtained from the observed baseline gridded data. In a more detailed study where the absolute values are needed (rather than the trend), a more sophisticated analysis of the data would be required in which bias correction techniques are applied to the modelled data (both baseline and future period) such that consistency between baseline observations and modelled output is achieved. Refer to Annex A for more detail on methodology.

[11] Meteorological Office (2018e), *UKCP18 Guidance: Caveats and limitations*. Available online at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---caveats-and-limitations.pdf.

[12] Meteorological Office (2018f), *UKCP18 Guidance: How to use the Land Projections.* Available online at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---how-to-use-the-land-projections.pdf.

Other data sources

2.2.16 Projected changes to wind, fog and lightning are provided via reference to key scientific literature. The references have been cited within this document. The projections are summarised at a route-wide level, as they are not given at spatial scales that allow individual locations to be distinguished.

2.2.17 Reference to the UK Committee on Climate Change Adaptation Sub-Committee Report: Developing H++ Climate Change Scenarios[2] has been made to include consideration of the low probability, high impact climate risks. The H++ and L- - scenarios represent the plausible higher and lower end of climate change projections respectively.

2.3 Summary of projected changes

2.3.1 This section presents the projected changes to climate and extreme weather events for Crewe and Manchester, for both the construction and operation periods. A further location associated with off-route works in Scotland, Annandale depot, is also considered, focused on a specific potential climate change impact which may result in an ICCI. It then summarises projected changes in wind, fog and lightning at the route-wide level. Finally, consideration is given to H++ and L- - scenarios, exploring a wider range of future changes in climate.

Crewe

2.3.2 Climate change projections for a range of climate conditions are presented in Table 4 for the selected RCPs for the construction and operation periods. Table 5 presents the projected change to the occurrence of extreme weather events. The values presented in the text below are based just upon the central (50^{th} percentile) projections from the RCPs analysed (refer to the tables for fuller detail on the probabilistic nature of the projections where the 10^{th} and 90^{th} percentile projections, and 2^{nd} lowest and 2^{nd} highest RCM model realisations are also given in brackets).

Mean climate conditions

2.3.3 Mean temperatures in Crewe are projected to increase across all seasons throughout construction and operation. Mean annual daily temperatures are projected to increase from the observed 1981 – 2000 baseline (9.6°C) by 0.8°C – 0.9°C by 2020 – 2039 and by 2.4°C – 3.9°C by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively. Mean summer daily maximum temperatures are projected to show the largest increase when compared to other seasons; these temperatures are projected to increase from the observed 1981 – 2000 baseline (19.9°C) by 1.1°C – 1.3°C by 2020 – 2039 and by 3.5°C – 5.5°C by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively.

2.3.4 Changes in seasonal precipitation show some variation. Mean winter precipitation is projected to increase from the observed 1981 – 2000 baseline (180mm) by 3.0% – 3.5% by 2020 – 2039 and by 10.3% – 15.9% by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively. Mean summer precipitation is projected to decrease from the observed 1981 – 2000 baseline (177mm) by 6.0% – 7.1% by 2020 – 2039 and by 23.3% – 35.3% by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively.

2.3.5 Mean annual relative humidity in Crewe is projected to decrease from the observed 1981 – 2000 baseline (81.4%) to 80.3% by 2020 – 2039 and to 78.8% by 2060 – 2079 (only RCP8.5 scenario available).

Extreme weather events

2.3.6 Table 5 displays the data on extreme weather events presented as a comparison between the observed 1981 – 2000 baseline number of events and the projected future number of events for the RCP8.5 scenario. Note that projections for extreme weather events are based only on the RCP8.5 scenario, as outlined within the limitations section.

2.3.7 Similar to mean temperature projections, the occurrence of temperatures above 25°C is also projected to increase from the observed 1981 – 2000 baseline (9.0 events/year) to 19.0 events by 2020 – 2039 and to 50.7 events by 2060 – 2079. The frequency of heatwaves is also projected to increase from the observed 1981 – 2000 baseline (1.0 events/year) to 2.3 by 2020 – 2039 and to 8.5 by 2060 – 2079. The annual number of 'frost days' per year is projected to decrease from the observed 1981 – 2000 baseline (45.8 events/year) to 29.0 events by 2020 – 2039 and down to just 13.1 events by 2060 – 2079.

2.3.8 The number of 'heavy rain days' per year (daily rainfall >25mm) is projected to change slightly from the observed 1981 – 2000 baseline average (1.0 event/year) to 1.1 events by 2020 – 2039 and to 1.3 events by 2060 – 2079. The number of dry spell events per year is projected to increase from the observed 1981 – 2000 baseline (3.9 events/year) to 4.1 by 2020 – 2039 and to 4.6 by 2060 – 2079.

Table 4: UKCP18 projected climate change for mean climate conditions in Crewe

Climate variable	Projected trend	Baseline value (1981 – 2000)	Projected change[1]			
			2020 – 2039		2080 – 2099	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
Mean annual daily temperature	↑ (increase)	**9.6**°C	**+0.8** °C (+0.2, +1.4)	**+0.9** °C (+0.3, +1.6)	**+2.4** °C (+0.9, +3.8)	**+3.9** °C (+2.0, +5.9)
Mean summer[2] daily maximum temperature	↑ (increase)	**19.9**°C	**+1.1** °C (+0.1, +2.2)	**+1.3** °C (+0.3, +2.4)	**+3.5** °C (+0.6, +6.4)	**+5.5** °C (+2.1, +9.2)
Mean winter[2] precipitation	↑ (increase)	**180**mm	**+3.0** % (-4.5, +10.5)	**+3.5** % (-4.1, +11.4)	**+10.3** % (-0.7, +22.0)	**+15.9** % (+1.3, +33.1)
Mean summer[2] precipitation	↓ (decrease)	**177**mm	**-6.0** % (-22.0, +10.9)	**-7.1** % (-23.9, +10.6)	**-23.3** % (-45.9, -0.6)	**-35.3** % (-62.8, -5.1)

*[1] Note: 50th percentile value presented in **bold**. 10th to 90th percentile range presented in brackets.*

[2] Summer = June, July, August. Winter = December, January, February.

Table 5: UKCP18 projected occurrence of extreme weather events in Crewe

Climate variable	Projected trend	Observed baseline value (1981 – 2000)	Projected future value[1]	
			2020 – 2039	2060 – 2079
Annual number of days when daily maximum temperature is greater than 25°C	↑ (increase)	**9.0**	**19.0** (13.7, 24.2)	**50.7** (35.5, 63.1)
Annual number of days when daily minimum temperature is 0°C or lower	↓ (decrease)	**45.8**	**29.0** (23.5, 39.5)	**13.1** (1.3, 21.8)
Annual number of days when precipitation is greater than 25mm per day	↑ (increase)	**1.0**	**1.1** (0.8, 1.5)	**1.3** (1.1, 2.2)
Annual number of dry spells (10+ days with no precipitation)	↑ (increase)	**3.9**	**4.1** (3.8, 4.4)	**4.6** (4.3, 5.1)
Annual number of heatwaves (3 days with maximum temperatures over 26°C)	↑ (increase)	**1.0**	**2.3** (1.3, 3.4)	**8.5** (4.7, 11.8)

*[1] Note: median value presented in **bold.** 2nd lowest and 2nd highest RCM model realisations presented in brackets.*

Manchester

2.3.9 Climate change projections for a range of climate conditions are presented in Table 6 for the selected RCPs for the construction and operation periods. Table 7 presents the projected change to the occurrence of extreme weather events. The values presented in the text below are based just upon the central (50^{th} percentile) projections from the RCPs analysed (refer to the tables for fuller detail on the probabilistic nature of the projections where the 10^{th} and 90^{th} percentile projections, and 2^{nd} and penultimate RCM model realisations are also given in brackets).

Mean climate conditions

2.3.10 Mean temperatures in Manchester are projected to increase across all seasons throughout construction and operation. Mean annual daily temperatures are projected to increase from the observed 1981 – 2000 baseline (10.2°C) by 0.8°C – 0.9°C by 2020 – 2039 and by 2.4°C – 3.8°C by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively. Mean summer daily maximum temperatures are projected to show the largest increase when compared to other seasons; these temperatures are projected to increase from the observed 1981 – 2000 baseline (19.9°C) by 1.1°C – 1.2°C by 2020 – 2039 and by 3.4°C – 5.4°C by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively.

2.3.11 Changes in seasonal precipitation show some variation. Mean winter precipitation is projected to increase from the observed 1981 – 2000 baseline (228mm) by 2.2% – 2.8% by 2020 – 2039 and by 10.1% – 15.7% by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively. Mean summer precipitation is projected to decrease from the observed 1981 – 2000 baseline (212mm) by 6.5% – 7.5% by 2020 – 2039 and by 23.0% – 34.9% by 2080 – 2099, for RCP4.5 and RCP8.5 scenarios respectively.

2.3.12 Mean annual relative humidity in Manchester is projected to decrease from the observed baseline (77.6%) to 76.5% by 2020 – 2039 and to 75.3% by 2060 – 2079 (only RCP8.5 scenario available).

Extreme weather events

2.3.13 Table 7 displays the data on extreme weather events presented as a comparison between the observed 1981 – 2000 baseline number of events and the projected future number of events for the RCP8.5 scenario. Note that projections for extreme weather events are based only on the RCP8.5 scenario, as outlined within the limitations section.

2.3.14 Similar to mean temperature projections, the occurrence of temperatures above 25°C is also projected to increase from the observed baseline (9.4 events/year) to 16.7 events by 2020 – 2039 and to 42.5 events by 2060 – 2079. The frequency of heatwaves is also projected to increase from the modelled baseline (1.5 events/year) to 2.8 by 2020 – 2039 and increases further to 9.1 by 2060 – 2079. The annual number of 'frost days' per year is projected to decrease from the modelled baseline (30 events/year) to 11.8 events by 2020 – 2039 and to <0.1 events by 2060 – 2079.

2.3.15 The number of 'heavy rain days' per year (daily rainfall >25mm) is projected to increase from the observed 1981 – 2000 baseline average (1.4 events/year) to 2.6 events by 2020 – 2039 and to 3.9 events by 2060 – 2079. The number of dry spell occurrences per year is projected to increase slightly from the observed 1981 – 2000 baseline (3.3 events/year) to 3.5 by 2020 – 2039 and to 4.0 by 2060 – 2079.

Table 6: UKCP18 projected climate change for mean climate conditions in Manchester

Climate variable	Projected trend	Baseline value (1981 – 2000)	Projected change[1]			
			2020 – 2039		2080 – 2099	
			RCP4.5	RCP8.5	RCP4.5	RCP8.5
Mean annual daily temperature	↑ (increase)	**10.2**°C	**+0.8** °C (+0.2, +1.4)	**+0.9** °C (+0.3, +1.6)	**+2.4** °C (+0.9, +3.8)	**+3.8** °C (+1.9, +5.9)
Mean summer[2] daily maximum temperature	↑ (increase)	**19.9**°C	**+1.1** °C (+0.1, +2.1)	**+1.2** °C (+0.2, +2.3)	**+3.4** °C (+0.5, +6.3)	**+5.4** °C (+2.0, +9.1)
Mean winter[2] precipitation	↑ (increase)	**228**mm	**+2.2** % (-5.2, +10.0)	**+2.8** % (-4.9, +10.8)	**+10.1** % (-1.7, +23.1)	**+15.7** % (+0.7, +33.2)
Mean summer[2] precipitation	↓ (decrease)	**212**mm	**-6.5** % (-23.1, +11.1)	**-7.5** % (-24.8, +11.0)	**-23.0** % (-45.7, -0.2)	**-34.9** % (-62.6, -4.7)

[1] *Note: 50th percentile value presented in **bold**. 10th to 90th percentile range presented in brackets.*

[2] *Summer = June, July, August. Winter = December, January, February.*

Table 7: UKCP18 projected occurrence of extreme weather events in Manchester

Climate variable	Projected trend	Observed baseline value (1981 – 2000)	Projected future value[1]	
			2020 – 2039	2069 – 2079
Annual number of days when daily maximum temperature is greater than 25°C	↑ (increase)	**9.4**	**16.7** (13.3, 21.5)	**42.5** (30.6, 53.7)
Annual number of days when daily minimum temperature is 0°C or lower	↓ (decrease)	**30.0**	**11.8** (4.8, 23.0)	**0** (0, 3.4)
Annual number of days when precipitation is greater than 25mm per day	↑ (increase)	**1.4**	**2.6** (1.2, 3.0)	**3.9** (2.5, 5.0)
Annual number of dry spells (10+ days with no precipitation)	↑ (increase)	**3.3**	**3.5** (3.0, 3.8)	**4.0** (3.6, 4.4)
Annual number of heatwaves (3 days with maximum temperatures over 25°C)	↑ (increase)	**1.5**	**2.8** (1.9, 3.9)	**9.1** (5.9, 12.7)

[1] *Note: median value presented in **bold.** 2nd lowest and 2nd highest RCM model realisations presented in brackets.*

Off-route works

2.3.16 In addition to the route of the Proposed Scheme, consideration is given to the potential climate change trends related to locations of off-route works. This is only directly relevant to those locations that have identified a potential ICCI associated with the off-route works. As part of the assessment of off-route works, it is noted that Annandale depot, located in southwest Scotland, would have a wastewater discharge to a small watercourse. A significant operational effect on the water environment has been identified related to concerns about insufficient dilution of the treated waste discharged to the small watercourse. The climate trend related to changes in stream baseflow has therefore been investigated to support the evaluation of climate impacts at this location.

2.3.17 For the location of Annandale Depot, the UKCP18 probabilistic approach has been used, based on 25km grid square data for both RCP 4.5 and RCP8.5. The time horizons considered are 2020 – 2039 and 2080 – 2099, consistent with the analysis for the route of the Proposed Scheme. Monthly rainfall provides an appropriate indicator of changes to river flow on a monthly and seasonal basis, so monthly percentage change values, compared to the 1981 – 2000 baseline, have been abstracted for the 10th, 50th and 90th percentiles, for the 25km grid square that covers Annandale. For both RCPs and both time horizons, the trend for the 50th percentile is clear that summer rainfall (June to August) is projected to decrease. In the time horizon for 2080 – 2099, the reduction in summer rainfall extends to the period from May to September. This analysis confirms that the climate trend related to drier summers, resulting in lower river flows, as identified for the main route, is also valid for the Annandale Depot location.

Wind

2.3.18 Future changes in European wind speeds are relatively poorly studied when compared to temperature and precipitation[13]. According to the available literature presenting results from both General Circulation Models (GCM) driven by global boundary conditions, and RCM evaluations, slight increases in the frequency of windstorm events in the UK and Northern Europe, particularly during winter months, could occur in the second half of the 21st century[14]. This includes an increased frequency of storm days and increased wind speeds

[13] Gonzalez, P.L.M., Brayshaw, D. J. and Zappa, G. (2019), *The contribution of North Atlantic atmospheric circulation shifts to future wind speed projections for wind power over Europe,* Climate Dynamics, 53 (7-8), pp. 4095-4113.

[14] Rockel and Woth (2007), *Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations,* Climatic Change, 81 (1), pp. 267-280. Available online at: http://prudence.dmi.dk/public/publications/PSICC/Rockel&Woth.pdf.

during storm events[15]. However, there is no compelling trend in maximum gust speeds from the UK wind network over the last five decades[16].

2.3.19 Projected increases in average wind speeds for the end of the 21st century are estimated to remain between ±15-30% of observed historical values[17, 18, 19]. It is recognised that the frequency and intensity of UK and European windstorms is dominated by natural and complex spatial and temporal variability[20], and all conclusions on projections for changes in wind speeds are strongly caveated due to the uncertainty in the model outputs.

2.3.20 The complex variability in wind conditions and relationships with other climatic systems such as the North Atlantic Oscillation[21], preclude the ability to make robust statements on the likely changes in wind conditions that will occur over the 21st century.

2.3.21 The H++ scenario projects the number of days per year with strong winds to increase between 50 – 80% greater than a 1975 – 2005 baseline (strong winds defined here as UK-averaged daily mean wind speeds over the 99th percentile of historical simulations, at 850 hectopascals (hPa)). This scenario alongside the available literature therefore present a justification towards the use of a precautionary climate change trend for increased wind speeds in the latter parts of the 21st century.

Fog

2.3.22 UKCP18 does not supply projections for fog. UKCP09 provided technical papers[22] regarding fog projections which forecast a decrease in the frequency of fog events in the second half of the 21st century in all seasons (from a 1961 – 1990 baseline). The largest anomaly from the baseline was in the winter season, which could be as high as a 50% reduction. These projections are based on the medium emissions scenario for UKCP09.

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[15] Donat, M.G., et al. (2011), *Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multi-model simulations,* Natural Hazards and Earth System Sciences, 11, 1351-1370.

[16] Royal Meteorological Society (2019), *State of the UK Climate 2018*, International Journal of Climatology, 39(S1). Available online at: https://doi.org/10.1002/joc.6213.

[17] Pryor and Barthelmie (2015), *Climate change impacts on wind energy: a review*, Renewable and Sustainable Energy Reviews, 14(1), 430-437.

[18] Tobin, I., et al. (2015), *Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections,* Climatic Change, 128(1-2), 99-112.

[19] Carvalho, D., et al. (2017), *Potential impacts of climate change on European wind energy resource under CMIP5 future climate projections,* Renewable Energy, 101, 29-40.

[20] Robinson, E., et al. (2017), *UK Windstorms and Climate Change, An update to ABI Research Paper No. 19 (2009).* Available online at: https://www.abi.org.uk/globalassets/files/publications/public/property/2017/abi_final_report.pdf.

[21] Pryor, S.C., et al. (2012), *Analyses of possible changes in intense and extreme wind speeds over Northern Europe under climate change scenarios*, Climate Dynamics, 38 (1-2), 189-208.

[22] Boorman, P., et al. (2010a), *Future changes in fog frequency from the UKCP09 ensemble of regional climate model projections - Technical Note*. Available online at: http://cedadocs.ceda.ac.uk/1338/1/tech_note_on_fog_projections_from_11_member_RCM.pdf.

Lightning

2.3.23 Future changes in lightning frequency have not been released for UKCP18, and only limited other work has been reported on lightning changes expected as a result of future climate change. However, lightning projections for the 2080s (against a 1961 – 1990 baseline) have been presented in UKCP09 technical papers[23]. These projections use Convective Available Potential Energy (CAPE) in J/kg to infer lightning flash frequency (flashes/min) in future climates, under the medium emissions scenario. CAPE projections suggest that by the 2080s, there will be an increased number of lightning days for all seasons, with the largest increase from the baseline in summer months. There is a distinct north–south gradient of change, increases in the north of the UK are projected to be greater than 30%.

H++ and L- - Scenarios

2.3.24 As previously mentioned, H++ and L-- scenarios represent the plausible higher and lower end of climate change projections. They assess very low probability, high impact risks and use UKCP09 as one of the sources for information. H++ projections have not been updated for UKCP18 data at the time of writing, therefore the UK Committee on Climate Change Adaptation Sub-Committee Report Developing H++ Climate Change Scenarios[2] has been used as the key reference for this section, unless otherwise referenced.

2.3.25 Information from the H++ and L-- scenarios presented in this section aims to provide a broader range of changes, reflecting the extremities of the climate change probabilistic distributions of plausible change.

High temperature

2.3.26 The H++ scenario for mean summer maximum temperatures exceeds 30°C over much of the UK, and potentially up to 34°C over some of central and southern England. The hottest summer days could exceed 40°C, and even 48°C in extreme cases.

Low temperature

2.3.27 Although the frequency of cold weather events is projected to decrease, UKCP18 advises that cold winters are still possible even with an underlying warming trend due to natural variability, and should be factored into decision making. In the H++ report, cold snaps are discussed within the L-- scenario (which presents the opposite end to H++ scenario of extreme warmer temperatures). The L-- scenario projects UK average winter temperatures to be 0.3°C in the 2020s and to decrease further to -4°C in the 2080s. The minimum winter temperature for the 2020s is projected to be -7°C and decreases further for the 2080s to -11°C. This L-- scenario is considered extremely unlikely, and there is low confidence in the

[23] Boorman, P., Jenkins, G., Murphy, J. and Burgess, K. (2010b), *Future changes in lightning from the UKCP09 ensemble of regional climate model projections – Technical Note.* Available online at: http://cedadocs.ceda.ac.uk/1340/1/tech_note_on_projections_of_lightning_from_11_member_RCM.pdf.

evidence that supports these future trends. However, extreme cold weather events have been considered as part of the climate change assessments to ensure that potential future climate impacts are adequately assessed.

High precipitation

2.3.28 The H++ scenario for high precipitation projects a 70 – 100% increase in winter rainfall (December to February), from a 1961 – 1990 baseline. The H++ scenario also projects up to a five-fold increase in the frequency of daily and sub-daily heavy precipitation events in both summer and winter.

Low precipitation

2.3.29 The H++ scenario for low precipitation projects significant increases in 6-month summer droughts (a precipitation deficit up to 60% less than the long-term average 1900 – 1999), with no notable change in winter droughts. However, longer and drier periods (a precipitation deficit of up to 20% less than the long-term 1900 – 1999 average) lasting between 3 to 5 years are considered possible.

Wind

2.3.30 The H++ scenario projects the number of days per year with strong winds to increase by between 50 – 80% compared to a 1975 – 2005 baseline (strong winds defined here as UK-averaged daily mean wind speeds over the 99th percentile of historical simulations, at 850hPa).

3 Summary

3.1.1 This report provides an overview of the current climate conditions and projected climate change trends and related information used to inform the CCR and ICCI assessments for the Proposed Scheme.

3.1.2 Historical and future baselines are presented for two study locations along the route of the Proposed Scheme for a range of climate change scenarios. In addition to these study locations, a further location associated with off-route works in Scotland is also considered.

3.1.3 The historical mean climate and frequency of extreme conditions are similar for the two primary locations during the observed baseline period (1981 – 2000).

3.1.4 Future temperatures are projected to increase across all seasons through to the end of the century, with more pronounced increases anticipated for summer months.

3.1.5 Future projections of seasonal precipitation show increases during the winter, and decreases during the summer. The magnitude of change projected for summer precipitation is more marked than the magnitude of change projected for winter precipitation.

3.1.6 For the location of the off-route works for which a potential ICCI has been identified, the analysis confirms that the climate trend related to drier summers, resulting in lower river flows, as identified for the main route, is also valid.

3.1.7 Mean annual relative humidity and the frequency of fog events are anticipated to decrease in future climate projections. By contrast, the frequency of lightning events and wind speeds are projected to increase, though the confidence in the wind projections is relatively low compared to other climatic variable (e.g. temperature and precipitation).

3.1.8 Future projections for extreme weather events show a general trend towards more frequent heatwaves, dry spells, and heavy precipitation events, particularly for the operational phase (as indicated by data for 2060 – 2079). Cold weather events are projected to decrease in frequency in the future. With the exception of daily minimum temperatures, future climate conditions are anticipated to become more extreme.

Annex A: Methodology

1 Projections and locations

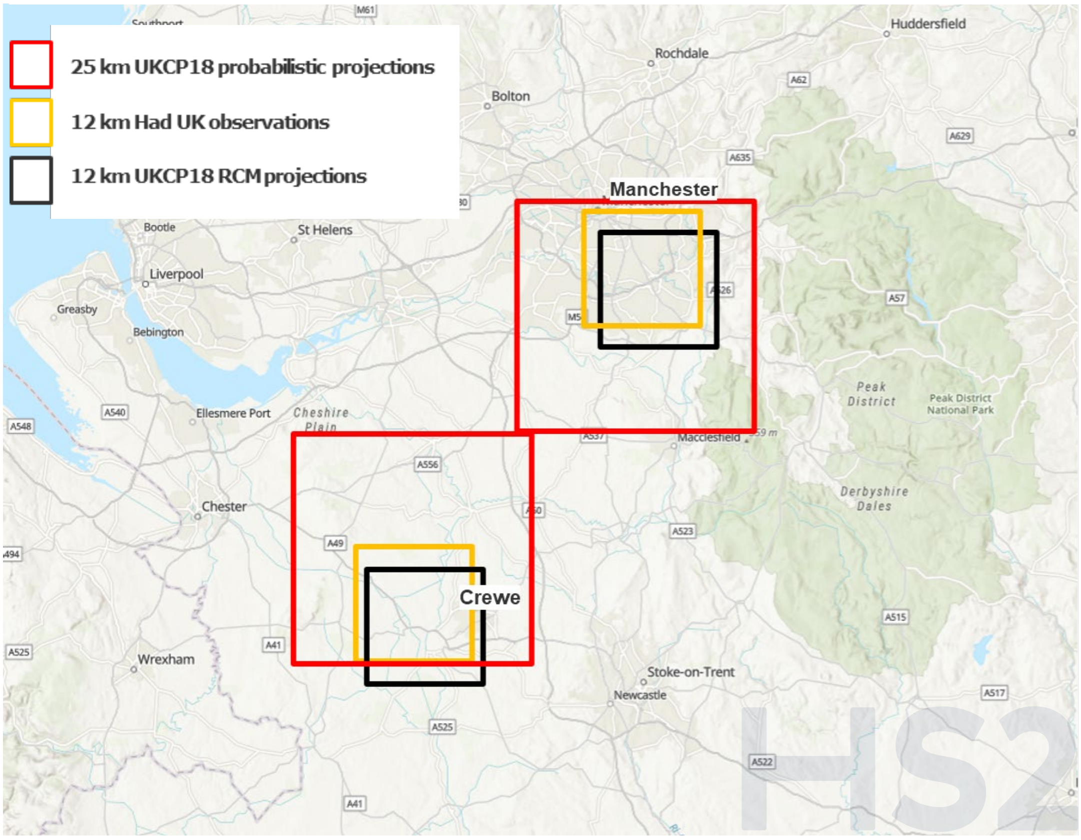
As outlined in the historical climate baseline, this climate assessment used observed baseline values for the period 1981 – 2000 for each climate variable at a spatial resolution of 12km, obtained from the HadUK-Grid gridded observational data. Variables chosen for presentation help to support the climate trends used in the climate assessments.

The locations of the grid squares used for both the observed data and climate change projections are presented below. Figure A 1 displays the grid square locations extracted for each location and data set along the route of the Proposed Scheme.

Table A 1: Coordinates used to extract UKCP18 data for Crewe and Manchester

Location	Coordinate (Easting, Northing)
Crewe	370515, 355405
Manchester	386140, 395311

Figure A 1: Grid square locations for Crewe and Manchester



Climate change probabilistic projection data (25km spatial resolution) was extracted from the UKCP18 User Interface[24] at each location for RCP4.5 and RCP8.5 pathways. For both pathways, the 10th, 50th and 90th percentiles were presented for each climate variable in order to provide an indication of the range of possible futures i.e. providing an indication of the uncertainty associated with the projection. Change values have been presented, as extracted directly from the UKCP18 User Interface.

Probabilistic projections were used to determine the projected change in future mean climate conditions up to the year 2100, over two periods: 2020 – 2039 and 2080 – 2099. For climate variables such as mean annual temperature and mean winter rainfall.

[24] Meteorological Office (2018g), *UKCP User Interface*. Available online at: https://ukclimateprojections-ui.metoffice.gov.uk/.

2 Comparison of observed and modelled baselines for extreme weather events

The baseline values presented within this document are from observed weather conditions during the 1981 – 2000 baseline period. Baseline values for both observed and modelled data are presented here in Table A 2 to enable a comparison between the modelled and actual weather data. For some variables this shows that the modelled values are biased (i.e. differ to what observations of that period give), however the modelled change in the number of occurrences still provides a valid indication of the projected trend[25].

In a more detailed study where the absolute values are needed (rather than just the trend), a more sophisticated analysis of the data would be required in which bias correction techniques are applied to the modelled data (both baseline and future period) such that consistency between baseline observations and modelled output is achieved.

Table A 2: Comparison of observed and modelled baseline data for extreme weather events

	Crewe		Manchester	
Climate variable	**Observed baseline value (1981 – 2000)**	**Modelled baseline value (1981 – 2000)**	**Observed baseline value (1981 – 2000)**	**Modelled baseline value (1981 – 2000)**
Annual number of days when daily maximum temperature is greater than 25°C	9.0	3.8	9.4	2.8
Annual number of days when daily minimum temperature is 0°C or lower	45.8	42.4	30.0	47.1
Annual number of days when precipitation is greater than 25mm per day	1.0	1.3	1.4	4.7
Annual number of dry spells (10+ days with no precipitation)	3.9	0.8	3.3	0.7
Annual number of heatwaves (3 days with maximum temperatures over 26°C)	1.0	0.3	1.5	0.3

[25] Meteorological Office (2018h), *UKCP18 Guidance: Bias correction*. Available online at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---how-to-bias-correct.pdf.

3 Threshold analysis

Regional Climate Model (RCM) projections of future daily data at 12km grid resolution for the selected grid squares, as shown in Figure A 1, were used to determine the projected change in annual occurrence of future extreme events for two periods: 2020 – 2039, and 2060 – 2079. Projected changes in the number of occurrences from the 1981 – 2000 baseline period (derived from the RCM outputs using percentiles of the anomalies) have been added onto the baseline values obtained from the observed baseline gridded data, to determine the projected change values as displayed in the data tables for each location.

To give confidence in the trends selected for use in the climate change assessments, additional thresholds for key extreme weather events such as high and low temperatures and intense precipitation were selected for further threshold frequency analysis to assess if similar trends are likely to occur at different thresholds. The outputs of these additional frequency analyses are presented in Table A 3 and Table A 4.

By reviewing the data in Table A 3 and Table A 4, the following summary statements have been made and can be applied at both study locations.

- results of the maximum temperature threshold analysis show a trend towards increased occurrence of higher temperatures in the future; for example, temperatures of 40°C and above are only projected to occur during 2060 – 2079;
- results of the minimum temperature threshold analysis show a trend towards decreased occurrence of lower temperatures in the future; for example, temperatures of -5°C or less are projected to almost cease entirely by 2060 – 2079; and
- results of the maximum precipitation threshold analysis are not as pronounced as temperature projections, however these do show that precipitation is projected to slightly increase in the future; for example, the occurrence of precipitation of 35mm per day is projected to increase slightly between each time period.

The data in Table A 3 and Table A 4 is based on the direct analysis of the RCM outputs, without adjustment to observed baseline and is therefore different to the data entries within Section 2.3.

The threshold analysis supports the underlying trends that have been selected for use to underpin the scientific basis of the climate change assessments. The results of this analysis predominantly support the climate change trends used in the climate change assessment, where there are discrepancies these are not considered to materially impact the trends selected.

Table A 3: Threshold exceedance analysis for daily maximum and minimum temperatures and daily precipitation, for Crewe. Data presented as the average number of days per year that the threshold value is projected to be exceeded per year

	Time period		
Daily maximum temperature °C	1981 – 2000	2020 – 2039	2060 – 2079
25	3.8	15.0	48.7
30	0.3	1.6	10.9
35	0	0.1	1.7
40	0	0	0.2
	Time period		
Daily minimum temperature °C	**1981 – 2000**	**2020 – 2039**	**2060 – 2079**
-5	4.5	1.2	0.1
0	42.4	29.3	10.0
+5	154.5	124.9	82.9
	Time period		
Daily precipitation mm	**1981 – 2000**	**2020 – 2039**	**2060 – 2079**
25	1.3	1.6	1.6
35	0.4	0.5	0.6
45	0.1	0.2	0.2

Table A 4: Threshold exceedance analysis for daily maximum and minimum temperatures and daily precipitation, for Manchester. Data presented as the average number of days per year that the threshold value is projected to be exceeded per year

	Time period		
Daily maximum temperature °C	**1981 – 2000**	**2020 – 2039**	**2060 – 2079**
25	2.8	10.1	38.1
30	0.1	0.9	6.7
35	0	0.1	0.7
40	0	0	0.1
	Time period		
Daily minimum temperature °C	**1981 – 2000**	**2020 – 2039**	**2060 – 2079**
-5	7.6	1.9	0.2
0	47.1	32.8	11.3
+5	159.9	130	88.8
	Time period		
Daily precipitation mm	**1981 – 2000**	**2020 – 2039**	**2060 - 2079**
25	4.7	5.5	7.1
35	1.2	1.5	2.3
45	0.3	0.4	0.8

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