# Increasing chance of previously record-breaking UK average September temperatures

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# Document history

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## Introduction

Following the Met Office attribution protocol, and methodology similar to that set out by Pirret et al. (2023), this note documents a rapid attribution study using HadGEM3-A (Ciavarella et al., 2018) to assess the changing chance of observing the UK mean September temperature recorded in 2023. The 2023 UK average value of 15.2˚C equalled the previous record from 2006. This attribution study is supplemented with a qualitative assessment of projected September mean temperature over the UK using the UK Climate Projections (UKCP; Murphy et al., 2018), which provides a guide to expected future changes in September UK temperature. To facilitate a rapid study, the attribution study is limited to use of a single climate model, which means that it does not fully explore the uncertainty that would be represented by the use of a range of modelling systems. As well as providing a view of September temperatures in the future, the UKCP study also provides a view of changing chance of hot September temperatures in the UK from a range of models.

Specifically, this aims of this study are to:

a) identify the approximate probability that any September in the present climate would reach or exceed the 2023 September average of the daily mean temperature for the UK (15.2˚C) in the present climate (present climate represented by the years 2016 to 2022),

b) compare this to the chance of a September reaching or exceeding this value in a hypothetical present-day climate that has not been influenced by greenhouse gas emissions (so-called, 'natural' climate),

c) qualify how UK September average temperatures are projected to change in the future by the end of the 21$^{st}$ century under different climate change scenarios.

# Data

For the attribution study, we used simulations from the HadGEM3-A model (Ciavarella et al., 2018), which had been run at a resolution of N216 (giving grid boxes of around 60km over the UK) as part of a previous study. This is an atmosphere-only model constrained by observed sea-ice and sea surface temperatures that are historically observed (Rayner et al., 2003). To represent an ocean without human influence, anthropogenic temperature differences were separately simulated in CMIP5 and subtracted from the observed values (Christidis et al. 2013). CMIP5 is used for consistency with previous studies, and future work may consider inclusion of CMIP6. While 60km is coarser than the scales upon which some extremes are observed, for attribution of temperature extremes averaged over the UK and an entire month this is a reasonable approach (Vautard et al., 2019). Four different experiments were performed and used in this study:

| Experiment Name | Years used | Ensemble size (per year) | Forcing | Purpose |
|---|---|---|---|---|
| historical | 1960-2013 | 15 | Observed | Model evaluation |
| historicalNat | 1960-2013 | 15 | Natural only | Model evaluation |
| ALL (historicalExt) | 2016-2022 | 525 | Observed | Attribution |
| NAT (historicalNatExt) | 2016-2022 | 525 | Natural only | Attribution |

Table 1: HadGEM3-A data summary

Additionally this study relies on the land component of the UK Climate Projections (Murphy et al, 2018) Probabilistic Projections and Global Projections averaged over the UK to illustrate the chance of September average temperatures in the UK exceeding 2023 record of 15.2˚C. These two products were chosen for this study for the following reasons:

- The Probabilistic Projections provide sample realisations for average temperature for multiple alternative future scenarios to 2100. They provide a comprehensive sampling of uncertainty, and are expected to well represent the climate of UK September temperature.
- The global projections provide the ability to study structural model uncertainty, because they include 13 simulations for several global modelling centres (CMIP5-13) alongside an ensemble of 15 variants of a Hadley Centre model (HadGEM3.05) known as a perturbed-parameter ensemble (PPE-15). At approximately 60km resolution, the ability to simulate the climate of September in the UK is expected to be acceptable.

Observed temperatures for the study come from the monthly average of the daily mean temperatures from HadUK-Grid (Hollis et al., 2019) averaged over the UK. This dataset covers the period from 1884 to close to the present day. Taking the period up to September

2023 the record value is 15.2˚C, with 2023 equalling the record set in 2006. Note that since the index considered here is a whole UK average, differences in magnitude between datasets with different resolutions (i.e. 60km simulations vs 1km observations) are considered negligible.

# Method

To calculate the estimates a) and b) described in the introduction (i.e. the approximate present-day, and hypothetical 'natural-climate' chance, of observing the record September UK mean temperature of 15.2˚C) we use the 'extension' runs of the HadGEM3-A system. The data available for these runs covers the period 2016-2022, with 525 members per year, all of which were used in the study. This ensemble is judged sufficiently large to sample natural variability which is important to the estimation of the chance of UK record temperatures, and conversely short enough to be representative of an approximately stationary period of present-day climate. This approach of taking a several-year sample of attribution simulations is sometimes referred to as the unconditional approach (Otto, 2017) in that we do not constrain the estimation of probability to only reflect conditions (sea surface temperatures) from the year in question (which is known as the 'conditional' approach).

To complete the study we begin by calculating an index to represent the quantity we wish to investigate. The index we use in this study is the UK average daily mean temperatures for September. This index is calculated for every year within each of the time series in Table 1, as well the observed dataset.

First, we use the 'historical' simulations for the period 1960 to 2013 compared to observations for model evaluation and bias identification (see Model Evaluation section). Once the bias correction has been applied to them, the 'extension' runs of HadGEM3-A (525 ensemble members; see Table 1) were used to calculate the two probability estimates. The probabilities are calculated by fitting a stationary generalised extreme value (GEV) distributions to each sample, then bootstrapping the samples to calculate uncertainty estimates on the probabilities (Pirret et al, 2023). These results are discussed in the section entitled 'Climate Attribution'. Finally, we calculate this index for two strands of the UK Climate Projections (Probabilistic and Global) and present the results in the Climate Projections section.

# Model Evaluation

The HadGEM3-A system and UKCP Global and Probabilistic projections have been subject to extensive evaluation and use and are deemed suitable for use for statistics such as UK and monthly means values. Since UKCP is only used qualitatively in this study, the existing validation is judged to be sufficient. For HadGEM3-A we build on existing validation and focus on identifying model biases and the processing needed to remove their impact on the results.

In particular evaluation considers the extent to which the HadGEM3-A historical ensemble reproduces the observations in terms of key summary statistics: mean, standard deviation, trend and skew over the historical period (1960-2013). These statistics are calculated using the python scipy.stats functions (Virtanen et al., 2020).

The timeseries in Figure 1 provides a qualitative assessment that the model relatively well captures the observed variability and trend when all forcings are included. There is a small mean bias in the all-forcing 'historical' data over this period of approximately 0.06 °C. This is removed from all of the simulations before further evaluation and estimation.

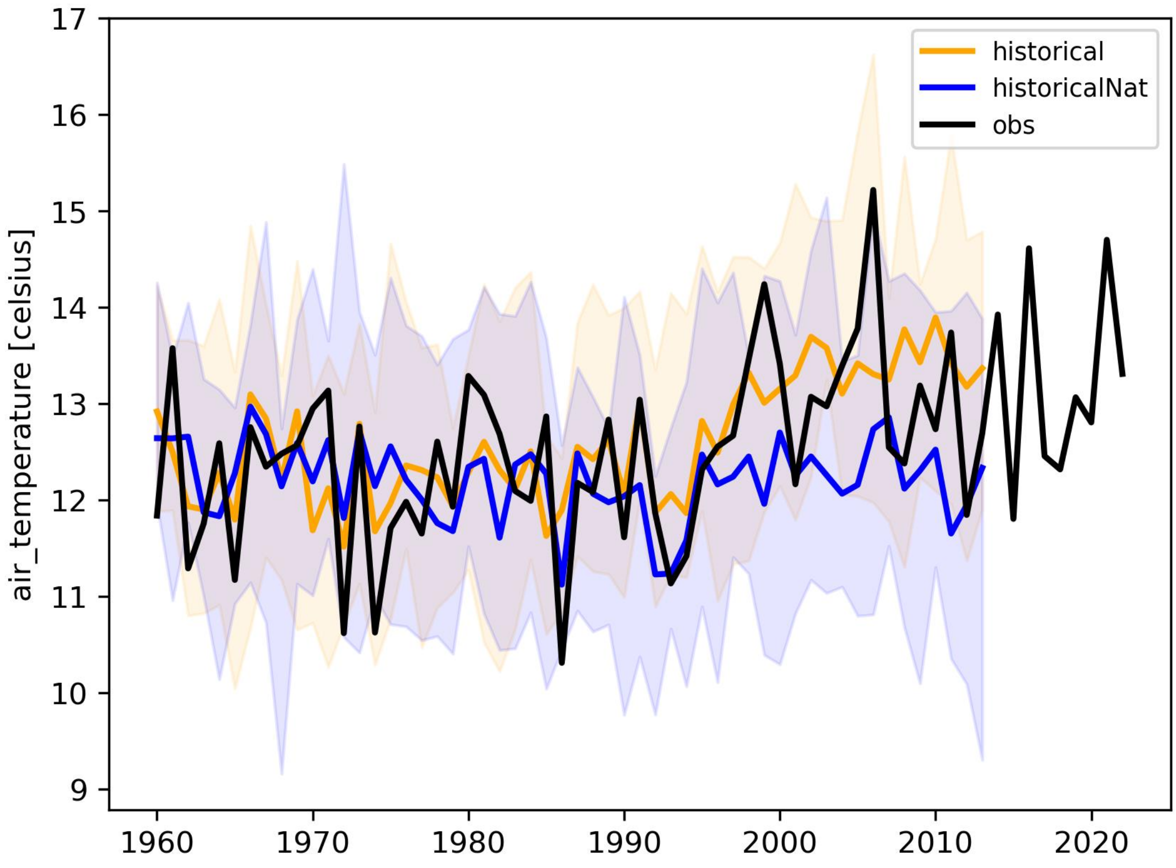


Figure 1: The UK mean September temperatures from HadGEM3-A (historical and historicalNat, see Table 1), with the thick lines showing the ensemble median and the shaded area the full (15 member) ensemble spread. Observations from HadUK-Grid (at N216) are overlaid (obs, black).

Investigation of the summary statistics also indicates that the ‘historical’ simulations capture the relevant features of the observations. This investigation is carried out by comparing the mean, standard deviation and skew of observations to each member of the historical HadGEM3-A ensemble. Where the statistics for the observations sit within the range of the same statistics calculated on the ensemble, this indicates that the simulations reasonably well reproduce the key features of the observations, and supports existing validation.

For each of mean, standard deviation and skew the observations sit between the 5$^{th}$ and 7$^{th}$ (of 15) ensemble members of the historical simulations, indicating that the simulations well capture these aspects of the observations.

For trend the observations are at the upper end of the ensemble (with observations sitting between the 13$^{th}$ and 14$^{th}$ ensemble members). This may be as a result of natural variability, and it is reassuring that the ensemble captures the observations. However, it could indicate a systematic bias in the ability of the model to pick up the real-world response to climate forcings. If this is the case, the change in likelihood of the record-breaking temperatures would represent an under-estimate of the real-world situation.

# Climate Attribution

The data used for the attribution step considers model experiments for the years 2016-2022, and includes a greater number of ensemble members per year (525) than the evaluation period (15). In Figure 2, we compare the observed value of the index to histograms of the values in the bias-adjusted ALL and NAT ensembles. The area to the right of the black vertical line is proportional to the probability of the observed value being equalled or exceeded. This area is clearly much larger in ALL than NAT.

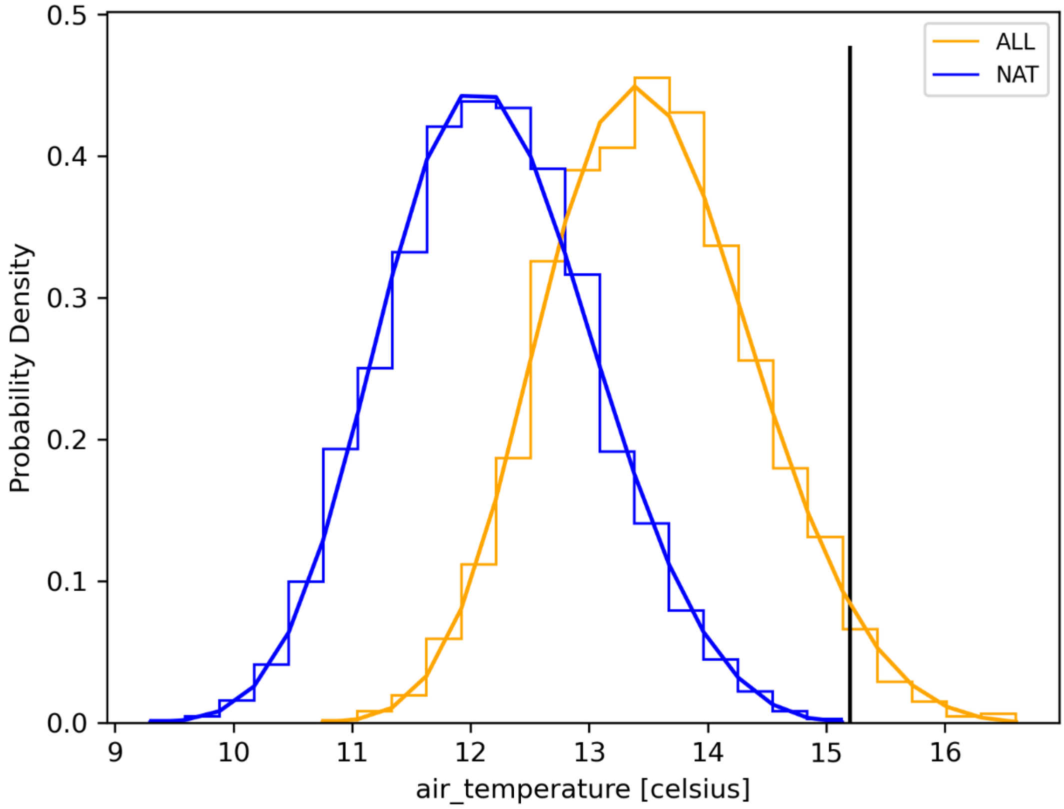


Figure 2: Histogram of UK mean daily mean temperature for September index in the experiments with all forcing (ALL in orange) and with only natural forcing (NAT, blue), with the stepped line showing the values from the model and the smooth line the fit with a generalised extreme value (GEV) distribution. The black vertical line shows the index value in HadUK-Grid observations in 2023 (15.2˚C).

To these histograms, we apply a generalised extreme value distribution, calculated using the python scipy.stats functions (Virtanen et al., 2020) and plotted on Figure 2. From that we calculate the probability of equalling or exceeding the observed value, with the probabilities in the two experiments displayed in the middle column below. To estimate the sampling uncertainty of this result, a bootstrapping methodology is applied to the ensemble members within each of ALL and NAT, shown in the right-hand column.

| Descriptor | Probability | Confidence interval<br>[5th percentile, 95th percentile] |
|---|---|---|
| ALL (historicalExt) | 0.035 | [0.031, 0.038] |
| NAT (historicalNatExt) | 0.00001 | [0.00000001, 0.00007] |

Table 2: Probabilities (calculated from GEV fit) of reaching or exceeding the September average temperature of 15.2 in present-day and natural climate, presented with bootstrapped confidence intervals.

These values imply that with only natural forcing, the chance of getting an index value of 15.2˚C or higher is small. In the present climate, whilst unlikely, it is something that is expected to happen with a probability around 3 to 4% annually (giving a return period of around 1 in 28 years). In the natural climate it would have been practically impossible. The calculated probabilities from the GEV fit are quoted in Table 2 for completeness, however due to the level of extrapolation beyond values seen in the NAT ensemble it is not recommended that the precise numbers are used in interpretation, beyond recognising that they represent a very unlikely event. For the same reason, unlike many attribution studies, we do not present a ratio of the probabilities which is often used to infer how much more or less likely an event is in our present climate compared to the 'natural' climate.

Note that, due to the framing of our study, the calculations are based on a small number of years (2016-2022), so do not sample the full range of boundary conditions (e.g. sea-surface temperatures) and use one model, so do not fully sample model uncertainty. However, the change in likelihood from almost impossible, to something we would expect to occur occasionally, is in line with multi-model studies for other high extreme temperatures (e.g. Pirret et al. 2023, Lowe and Wallace 2023, Zachariah et al. 2022 and Christidis et al. 2020).

Comparing the likelihood of UK September average temperature reaching 15.2˚C in the recent model simulations to the recent observed record, one might note that the simulations contain more occurrences (110) compared to observations (2). This is for two reasons: firstly, the observed world represents a more limited sample (53 years of HadUK-Grid compared to a HadGEM3-A model ensemble of 525 members for 7 years), so the model will have a greater number of these extreme events. Secondly, the current (2023) climate is warmer than any previous time in the observational world and that warming appreciably increases the probability of an event.

Despite these limitations, our results show that climate change has substantially increased the probability of warm Septembers. These results are in line with existing studies showing an expected extension of summer into Autumn (Cotterill et al., 2021), an upward trend in UK average autumn temperatures (Kendon et al., 2023, Figure 11) and that the chance of hot UK temperatures has increased significantly over the 20th century in Europe (e.g. Christidis et al., 2015; McCarthy et al., 2019).

# Climate Projections

The UK Climate Projections (UKCP; Murphy et al., 2018) are here used to illustrate the projected trend in September average temperatures. First, we explore this in the Probabilistic Projections, which combine physical climate models with statistical techniques to provide comprehensive information about the variety of potential future climates. The method results in 3000 realisations, so here we present the data as percentiles. The data are available for different emissions scenarios known as Representative Concentration Pathways (RCPs), with higher RCP numbers related to higher emissions of greenhouse gases.

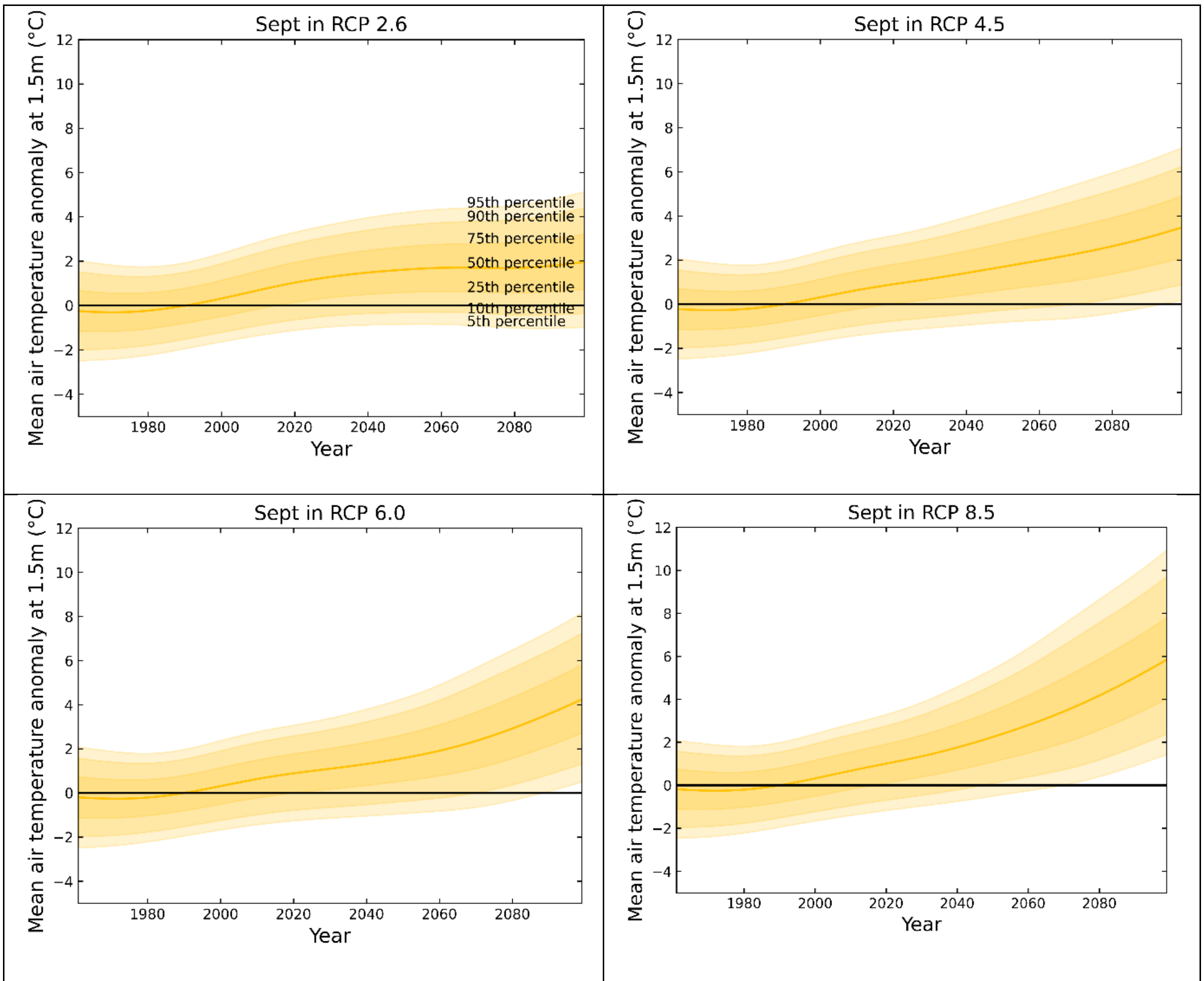


Figure 3: UKCP Probabilistic Projections for September UK mean temperatures, compared to a baseline of 1981-2000, for four RCPs.

Figure 3 shows the September UK mean temperature projections as anomalies, i.e. differences between the projections and the recent climate (1981-2000). This shows that for all RCPs shown here, September UK mean temperature is projected to increase. The anomalies are similar across the different emissions scenarios until around 2050, with the 50th percentiles increasing by around 2˚C. Beyond 2050, the chance of similarly warm Septembers is strongly governed by emission pathway, increasing significantly under RCP8.5 but levelling off under RCP2.6. This describes a picture of warmer September in the UK on average, though there will still be year-to-year variation.

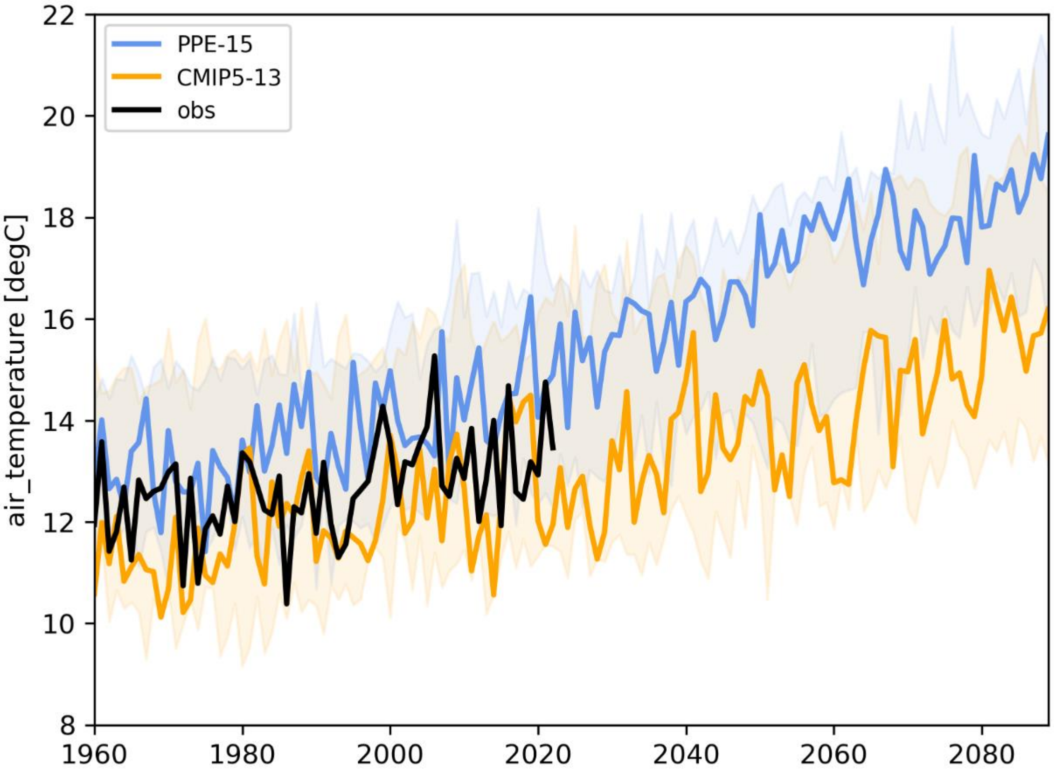


Figure 4: UKCP Global Projections for September UK mean temperatures, for RCP8.5. The PPE-15 refers to the 15 HadGEM3.05 perturbed-parameter ensemble members, and CMIP5-13 refers to the 13-member multi-model ensemble from CMIP5 data. The ensemble range is represented by the coloured area, with one ensemble member picked out as a thicker line. The HadUK-Grid observations to 2022 are shown in black.

The UKCP Global Projections (Figure 4) consist of two ensembles of physical climate models: one consisting of 15 versions of the HadGEM3.05 climate model in a perturbed-parameter ensemble (PPE-15); the other consisting of 13 CMIP5 models in a multi-model ensemble (CMIP5-13). While the trend is broadly upward, the individual ensemble members from each of the PPE-15 and CMIP5-13 clearly show this year-to-year variation. Therefore, in future climate, projections show warmer Septembers on average, with most years warmer than 2023 by the end of the 21st century but some years could still be cooler. Overall, the UKCP indicate that in the UK, Septembers are projected to become warmer.

 

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