Department
for Environment
Food & Rural Affairs

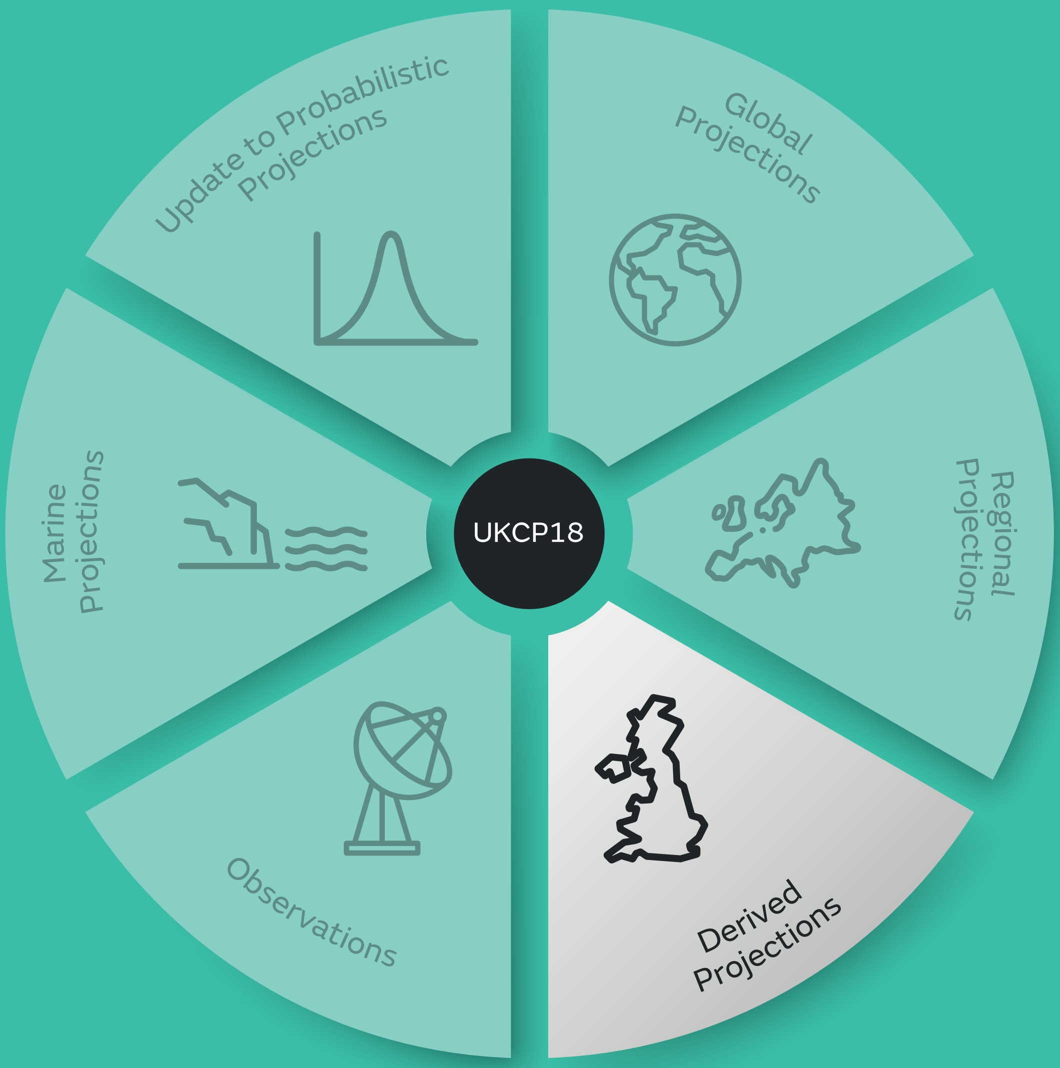
Department for
Business, Energy
& Industrial Strategy

Met Office
Hadley Centre

Environment
Agency

UKCP18 Derived Projections of Future Climate over the UK

November 2018



Laila Gohar, Dan Bernie, Peter Good and Jason A Lowe

www.metoffice.gov.uk

Contents

Summary

The global model projections of UKCP18 provide a set of projections for the RCP8.5 scenario of greenhouse gas emissions and concentrations. This report details methodologies for using the RCP8.5 data to derive two 50-year simulations at global mean warming levels of 2°C and 4°C above pre-industrial, and for an alternative scenario RCP2.6, which corresponds to a lower level of warming than RCP8.5.

The approach is built on a combination of time-shifting and pattern scaling techniques, in combination with some simplifying assumptions about global mean temperature change and natural variability. The output is intended to be used in the same way as climate model output, but with some additional caveats on top of the usual caveats associated with climate model projections. As a derived product, it should be noted that there is less confidence in the time slice data than the global model projections for RCP8.5. Similarly there is less confidence in the RCP2.6 derived data than the 2°C and 4°C time slices, as the derived RCP2.6 data is based on more assumptions than the time slices.

Results indicate that at 2°C of global mean warming, the largest warming in the UK will be in the South East where summer temperatures may increase another 3 to 4°C relative to present day, while median increases throughout the year are at least 1 to 2°C across the whole country. Percentage changes in precipitation vary seasonal with slightly wetter winters and drier summers. Precipitation increases are small in winter and broadly similar across the country. In summer precipitation decreases show of more drying toward the south.

Changes to UK climate at 4°C of global warming are similar in their spatial pattern to those at 2°C but with larger changes. All seasons warm, but summers warmer than winters, with summer temperature rising by another 4 to 5°C in the south of England and 3 to 4°C elsewhere in the country. Median summer precipitation decreases most in the south compared to present day, with a median reduction of up to 20 to 30% across much of the England and Wales. Conversely, winter precipitation increases slightly in the median by up to 20% across most of the country.

At 2°C of global warming the temperature of the warmest and coolest days in the UK increases in both summer and winter. In winter cool days warm slightly more than hot days, while in summer hot and cools days warm by similar amounts. Changes to daily precipitation show a slight increase in precipitation in winter across the country, while in summer there is a small drying over the south of the country.

At 4°C of global warming the changes to daily temperatures and precipitation are more pronounced. The temperature of cool and hot days increases in winter, slightly more for cool days, with increases of 2.5 to 3°C across the country. Summers show a pronounced drying with the wettest summer days drying by up to 40%. Daily precipitation changes indicate that winter days become wetter, with changes across the west of the UK experiencing the largest increases. In summer both wet and dry days become drier, with precipitation on dry days decreasing by up to 50% across much of Southern England and Wales, and smaller percentage reductions elsewhere. The wettest summer days are also dry, with 40% reductions in parts of the south.

Whilst the derived RCP2.6 data is of lower confidence than the time slice data, global mean warming in the last 20 years of RCP2.6 (2081-2100) is close to 2°C. As such the outputs from derived projections for RCP2.6 between 2081 and 2100 are similar to those for the 2°C time slice.

What data is provided?

Derived data is available for the lower forcing scenario RCP2.6 and is analogous to the global model projections of RCP8.5 in that it consists of 28 projections, but differs in that the data is only available for the UK land region while model projections of RCP8.5 have global coverage. Of these 28 derived projections, 15 are derived from RCP8.5 projections of the UK Met Office's HadGEM3-GC3.05 perturbed physics ensemble (GC3.05-PPE from herein) and 9 are taken directly from the projections run as part of CMIP5. Four other models from CMIP5 used in the global model projections either did not perform RCP2.6 or else had no data available. For these CMIP5 models with no RCP2.6 projection data available, derived data is produced from their RCP8.5 projection in the same way as for GC3.05-PPE.

Owing to issues with data availability for the 13 CMIP5 models used in UKCP18, the two 50-year time-slices for global mean warming levels of 2°C and 4°C above pre-industrial are provided for the 15 simulations of the GC3.05-PPE along with only those models in the CMIP5 subset which pass the global mean warming level in question. In some cases the CMIP5 models did not report all the variables examined in this study and so the actual number of simulations available may be further reduced for some variables.

For both the time-slices and RCP2.6, continuous monthly data is available for temperature, precipitation, relative humidity, net downward shortwave radiation and surface wind. Continuous daily data is also provided for temperature and precipitation. This data can be obtained from https://ukclimateprojections-ui.metoffice.gov.uk/

How should the derived data be used?

The derived simulations presented here are intended to be treated as estimates of what the global model projections would produce if run for the three scenarios presented. This was not done due to computer resource limitations although this may be possible in future.

The RCP2.6 data is intended to be used alongside the global model projections in order to explore uncertainty for a lower emissions scenario. The two time-slices are a different presentation of information than transient projections of RCPs. They provide information about the UK climate over a sustained period at different levels of global mean warming. This is more useful for some applications where stationarity of the mean climate is important to build statistical analysis of UK impacts at a given level of global climate change.

Both the transient and time-slice data can be used in the same way as standard climate model output, providing a limited set of plausible realisations capable of supporting a wide range of impact studies and development of narratives, but with some additional caveats (detailed in section 4).

A key caution around the use of the time-slice data is that the set of projections on which they are based includes a slightly smaller sample from CMIP5 so the structural uncertainty sampled is also smaller than in the global model projections. As such the time-slices should be interpreted as providing a minimum spread for the two different levels of global mean warming. The RCP2.6 data is based on the combined GC3.05-PPE and subset of CMIP5 defined in developing the global model projections, so it takes more account of structural uncertainties, but this 'full' set is itself not a complete picture. The probabilistic projections should be used where consideration of a broader range of potential uncertainties is required.

A consequence of the methodology used to derive data in this study is that the temporal consistency cannot be ensured between months in the daily data. As such, caution should be used for duration based metrics of climate variability and in these instances the global model projections should be considered instead.

If climate models were run for these scenarios, how might the UK output differ from the data provided here?

Differences would arise from two main sources: natural internal climate variability and errors in the approximate methods used here:

- **Internal climate variability.** The natural variability of the climate means that even two different runs of the same climate model, but with different initial conditions, will give partly different results. For the same reason, any future simulation of RCP2.6 will inevitably give partly different results to the estimates provided here. This is not due to any error in the approximate methods used. At the UK scale natural internal variability can be large, so the differences between any future simulations and the estimates provided here could be large simply from natural internal variability.

- **Errors in the approximate methods used.** Potential limitations of the methods used are described in more detail in section 4. The results for the 2°C and 4°C global mean warming levels are to be considered the more reliable than those for RCP2.6 as they involve fewer assumptions. Detailed evaluation of the methodology has been performed (Appendix A) using the data from CMIP5 for which simulations of RCP2.6 exist for evaluation of the method. Results from this suggests that for the variables examined and provided in this study, errors in the methods appear to be small compared to the inevitable and unavoidable effects of internal variability. However, there are limitations in the extent to which this can be tested. First, it is fundamentally only possible to test this for CMIP5 where projections of RCP2.6 exist (RCP2.6 projections do not for the GC3.05-PPE). If GC3.05-PPE behaves sufficiently differently from the CMIP5 models, the errors in the approximation methods may be larger than indicated in our tests. For example, early results from GC3.05-PPE suggest that the derived methods in this report may overestimate the climate change signal for RCP2.6 (but not for the 2°C and 4°C time-slices). Secondly, while the methodology has been designed to maintain the physical consistency between variables and their spatial coherence, it is impossible to test all the potential applications of these data. The errors in variables produced from the combination of climate variables and/or non climate data (e.g. exposure or wind power generation) could theoretically be larger (or smaller) than the errors evaluated in the key variables provided because of either compensation or compounding of errors between variables.

  There is also some literature to suggest that the different time scales of response within the climate system may alter the characteristics of climate change at a given level of warming. Differences occur depending on the pathway of climate forcing and timing of reaching a given level of warming (Ceppi et al, 2018), which may introduce some additional errors to the methodology used here.

1. Introduction

It is important that UKCP18 take into account the uncertainty regarding the amount of greenhouse gas emissions emitted into the atmosphere in the future. In the probabilistic projections of UKCP18 this is addressed by using several emission pathways, ranging from RCP2.6 (strong global mitigation policy with falling emissions) to RCP8.5 (minimal mitigation policy with rising emissions with increasing global wealth and population).

In the global model projections simulations are provided for an ensemble consisting of 15 Perturbed Physics Ensemble (PPE) realisations of the UK Met Office's HadGEM3-GC3.05 global model run from "1901-2100" (hereafter GC3.05-PPE), plus 13 realisations of selected CMIP5 coupled ocean-atmosphere models (hereafter CMIP5-13). The CMIP5-13 simulations were added to increase the diversity of global and regional changes sampled in the realisations (see Murphy et al, 2018 for full details). Only one emission scenario, RCP8.5, was considered due to the very large amount of supercomputer resource required for performing a GC3.05-PPE. RCP8.5 was considered the best option to use to allow users to test their vulnerability to a plausible but high future emission case.

Following feedback from UKCP18 users the decision was taken to include a second future emissions pathway, the strong mitigation RCP2.6, using an approximation approach based on the GC3.05-PPE RCP8.5 simulations and the CMIP5-13 simulations of RCP2.6. The current report focuses on the methodology, evaluation and characterization of the output of this derived data. The approach used for production and evaluation of monthly data was largely developed in a previous report of the Hadley Centre Climate Program (Good and Lowe, 2017), so while an overview of this is given here, more attention is paid to the extensions of this earlier work including consideration of daily as well as monthly data.

The derived data developed and described in this report and provided for users consists of UK-wide 60km resolution time series for an ensemble of RCP2.6 as well as 50-year time-slices characteristic of the climate when global mean temperatures rise to either 2°C or 4°C above pre-industrial levels. Following the approach of the IPCC special report on 1.5°C we take the 51 year period of 1850 to 1900 inclusive to be representative of pre-industrial. Time series include internal variability and are available at monthly frequency for precipitation, temperature, relative humidity, solar radiation, surface wind and also at a daily frequency for temperature and precipitation. The decision over which variables to provide was based on the outcomes from webinars and discussions with key users from which the Met Office produced a list of prioritized climate metrics for the derived scenarios and time-slices. It was also informed by the time available and a number of scientific reasons detailed in the main text of this report. There is scope to increase the availability of variables at monthly and daily frequencies at a later stage depending on user demand and resources, providing that evaluation tests for any new variables are successful. The tiers of data provided by this study are shown in Table 1.

Highest priority	Moderate priority
1. Daily precipitation	6. Monthly humidity
2. Daily temperature	7. Monthly solar radiation
3. Monthly precipitation	8. Monthly wind direction
4. Monthly temperature	
5. Monthly wind speed	

Table 1. Priority variables provided by this study. Solar radiation is provided as net downward short wave at the surface, whilst surface wind is supplied as eastward and northward components.

2. Methodology

Overview

The method used to produce the derived monthly and daily data relies on a combination of approaches commonly referred to as "time shifting" and "pattern scaling" along with some statistical assumptions.

The time-shifting methodology (Herger et al, 2015; Schleussner et al, 2016), posits that it is possible to use a time period early in a transient high forcing simulation, such as RCP8.5, to represent a climate sample for a lower forcing scenario, such as for RCP2.6, later in the century. The underlying assumption is that different scenarios with the same global-mean temperature have the same regional climate changes.

An advantage of time shifting is that it does not assume linearity and so it is not biased by non-linear mechanisms which can cause the regional climate change per degree of global warming to be different at different levels of global mean temperatures. However, parts of the climate system that depend on the history of climate forcing (due to different response times from global warming), or on the balance of different climate forcing agents (which changes over time differently in different scenarios), may cause the response of, e.g. a 2°C world early in an RCP8.5 simulation to differ from a 2°C world late in an RCP2.6 simulation. There is also some recent work by Ceppi et al, (2018) who show that there are different time scales of circulation response, with a poleward shift of the midlatitude jets and Hadley cell edge occurring within "5–10" years of changes in forcing, when less than half the warming response has been realised. The results imply that shifts in midlatitude circulation generally scale with the radiative forcing, rather than with global-mean temperature. This a relevant finding for the future climate of the UK but one which we have not assessed the impact of in this work.

While there are potential issues with time shifting, Herger et al's, (2015) assessment of this approach globally over land and sea found that, overall, the error introduced by using time-shifting was small compared to other sources of uncertainty, such as ensemble spread. Further more a previous assessment of pattern scaling (Mitchell 2003) for temperature and precipitation showed time-shifting to have a similar skill to pattern scaling when considering temperature and precipitation over the UK (Good and Lowe 2017).

When the present study extended this comparison of methods for all other variables in Table 1, time-shifting was shown to produce slightly better results than pattern scaling when considering the wider selection of variables. For brevity, this additional analysis is not included in this report but will be submitted for publication in the peer-reviewed literature.

As well as time-shifting, the methodology used in this study also draws on aspects of pattern scaling to estimate the monthly internal variability from RCP8.5. This approach assumes that local changes in a given climate variable changes linearly with respect to global mean temperatures.

Data used and provided by this study

The global model projections consist of the 15 member GC3.05-PPE, designed to sample uncertainty in the underlying parameter space (Murphy et al, 2018), and a subset of CMIP5 simulations to better sample structural uncertainty in the projections. The subset of CMIP5 RCP8.5 simulations were selected from 42 available on the basis of sufficient availability of data (for RCP8.5) and then further screened using a combination of global and regional performance criteria. Those passing the screening stage were clustered into groups of models sharing similar error characteristics, and 13 selected models chosen by picking the best-performing model(s) in each "group" (CMIP5-13 from herein). Murphy et al, (2018) describe and discuss the rational for this selection procedure in detail. The combination of this CMIP5-13 and GC3.05-PPE data gives a total of 28 global model projections. The 13 CMIP5 models used are listed in Appendix B. The approach of combining CMIP5-13 with GC3.05-PPE has been followed for the derived data where possible.

Derived RCP2.6 data is added to CMIP5-13 simulations, however as use of RCP2.6 was not envisaged by the global model projections when developing its criteria for selecting a CMIP5 subset, some of the CMIP5-13 models did not perform simulations for RCP2.6. Of the 13 CMIP5 models selected only 9 have projections data available for RCP2.6. Three are not available because no simulations were performed, and one is not because the data is not available on the Earth System Grid Federation which distributes the data. For the 4 CMIP5-13 models where RCP2.6 data is not available we apply the same technique as for GC3.05-PPE to produce it (section 2.2). So the 'full' set of simulations is 28 members as per the global model "projections" (Appendix B).

As detailed in the following section, the 50-year time-slices at 2°C and 4°C of global warming rely on the original RCP8.5 simulations having passed these global warming levels by the late 2080s. While all the GC3.05-PPE simulations of RCP8.5 pass 4°C, not all the CMIP5-13 pass this threshold. Therefore, this reduces the number of CMIP5-13 derived simulations for the 4°C of global warming set and therefore their contribution to structural uncertainty and uncertainty in the models response to forcing. This is, however, less of an issue for the time slices as they are presenting information at warming levels, so uncertainty in model response to forcing, or different scenarios, is manifest in the timing of reaching warming levels. Indication of the timing of global mean temperatures passing 2°C and 4°C in CMIP5 simulations is provided at the end of in Section 3.1 (Table 2, Table 3).

The following sections give technical details the implementation of this methodology for the production of monthly and daily data for the derived time-slices at global mean warming levels of 2°C and 4°C and RCP2.6.

2.1 Fifty year time-slices at global mean warming levels of 2°C and 4°C

A schematic outlining the approach for the time slices is shown in Figure 1 and elaborated on below.

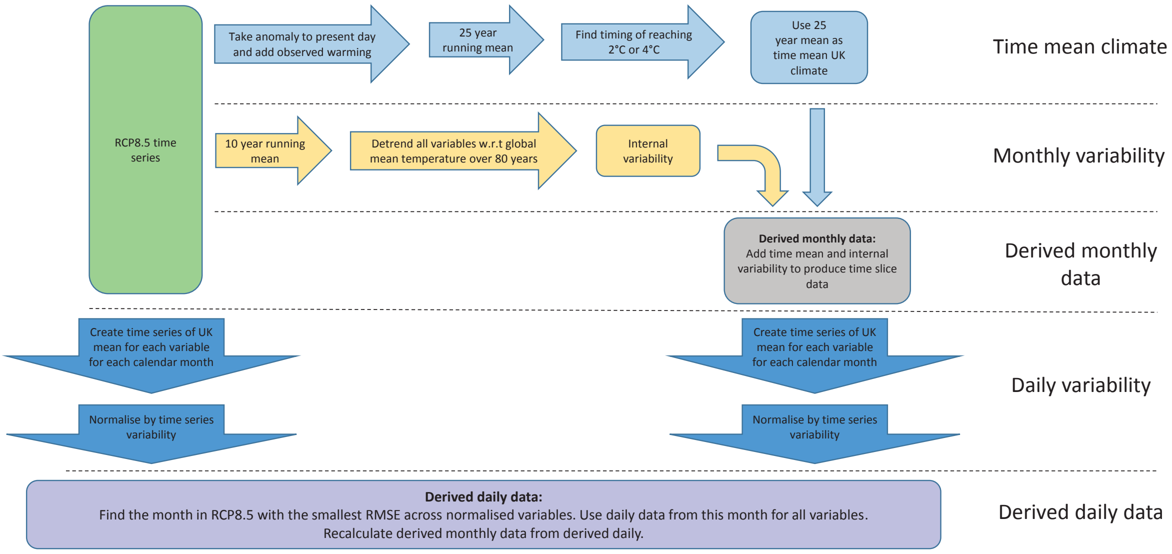


Figure 1. Schematic of the steps involved in producing data for the two time slices for derived monthly data (grey box) and derived daily data (lilac box) from the original RCP8.5 simulations (green box).

Mean climate

The spatial patterns of climate variables at each level of global warming were calculated using time-shifting of each RCP8.5 projection. A centred 25-year running mean of global annual mean warming was used to select the 25-year period from each projection with a global mean warming closest to the target level. Time-slices were based on the mean of a 25-year period. This length was a pragmatic choice, commonly used in climate change literature. It is sufficiently long to reduce internal variability usefully, while not being so long as to cause other issues. Averaging periods much longer than 25 years would lead to the earlier intervals (at lower temperatures) including historical periods with high aerosol forcing – which could be unrepresentative of future climates when reductions in aerosol forcing are widely anticipated.

To calculate the timing of reaching warming levels we add a projections temperature anomaly from present day onto the observed warming from pre-industrial to present day. This reduces the spread in future temperatures but ensures consistency with the historical record. Throughout this report, we define “pre-industrial” as the mean “1850-1900” climate, in line with IPCC’s 2018 special report on 1.5°C. “Present day” is defined as the mean “1981–2000” climate. The observed warming between pre-industrial and present day is taken from HadCRUT4 (Morice et al, 2012), and has a value of 0.51°C.

Monthly variability data

Climate variability needs to be added to the time-mean climate to produce the time-slice. We base this on a time series from detrended transient climate projections. As the length of the time-slices has been fixed at 50-years, this length of variability time series are extracted from the RCP8.5 simulations by first using the 80-year period “2007-2086” to estimate a multi-decadal linear climate trend, which is subtracted from the original time series, leaving a detrended time-series of variability. Fitting to this 80-year period only, rather than a longer period, reduces influence from aerosol or nonlinear mechanisms.

This assumption that a regional climate variable, Y, is an approximately linear function of global-mean temperature over this 80-year period is effectively pattern scaling. This approach is implemented here by first applying a 10-year running mean to the global-mean temperature time-series. Then a linear regression is applied to build a statistical model of Y as a function of global mean temperature (Tg): $Y = m \cdot Tg + c$. Using 80 years, instead of a 50-year length that we need for the variability time series, preserves more multi-decadal variability in the resulting detrended time series. From the resulting detrended time series of variability, years "2015-2064" are used to estimate the variability of both time-slices.

Users should be aware that by using the same variability for time slices at 2°C and 4°C there is autocorrelation between the two time slices derived from the same model and that any trend over time in internal variability of the transient simulations will not be evident between the 2°C and 4°C time slices.

It should be noted that the derivation of daily data produces slightly different monthly means and for consistency between frequencies of data the monthly means have been recalculated from the derived daily data for temperature and precipitation.

Daily data

It is not possible to use the detrended variability time series, derived in the previous section, as detrending doesn't work for daily precipitation. With a physical lower bound of zero the implied values at the lower end of the detrended data would be negative and therefore unphysical. Some attempts have been made in other applications using a change of variables, but this introduces some unphysical, variable-dependent (and probably location-dependent) assumptions, and there is no clear way of doing this that preserves model-generated physical relationships between different variables.

Instead, the methodology for deriving monthly data is adapted to derive daily time series which are temporally consistent on short time scales (sub-monthly), that are spatially coherent, and which have physical consistency between different climate variables. This makes it appropriate daily data for many types of impact assessments.

To estimate daily data for a given month of the time slice, to find the month in that particular model's RCP8.5 projection which most closely matches the time slice's UK monthly mean climate. This month's daily data is then used for all variables for which daily data is required to retain physical consistency between variables. To retain the seasonality this is done by finding the closest match only within data for the same calendar month. This produces a product that preserves the climate-model-simulated spatial patterns and physical relationships between different variables at sub-monthly time scales as it is taken directly from the model projection. The same approach is used to produce daily data for RCP2.6 projections.

For each month of the time series this is implemented by:

1. Calculating UK regional mean for each monthly variable for the time slice and RCP8.5. This is done rather than using individual grid points so we have the same date chosen for the whole of the UK and the coherence is preserved.
2. Normalising each UK mean monthly variable (for both RCP8.5 and time-slice) by the standard deviation of internal variability, calculated from the detrended RCP8.5 monthly time series for the calendar month in question (e.g. for all Januarys as a time series). This converts variability of each variable into non-dimensional units of standard deviation, so different variables may be inter-compared.

3. For each year (e.g. Januarys in each year) in RCP8.5, calculate the difference between the normalised variables for that year and the same variables for the chosen year in the time-slice. Then take the root mean square (RMS) across the different variables. This gives one RMS 'error' value for each year of a calendar month.
4. Choose the year in RCP8.5 with the smallest RMS 'error' and use daily data for all locations and all variables from this year (and calendar month) of RCP8.5 as the 30-day time-series for the chosen year of the time-slice.

As the daily data is chosen from the closest matches to the time-slice in RCP8.5, the monthly mean of the daily data will not precisely match the previously derived monthly means from the time-slice. To preserve consistency between data at different frequencies, the monthly means for those variables which also report daily data are recalculated using the monthly mean of the derived daily data.

The outlined approach for derived daily data preserves the sub-monthly temporal coherence but users with an interest in beyond intra-monthly correlation in daily data, changing variability or duration based metrics based on daily data, may wish to consider using parts of the underlying model simulations. Table 2, section 3.1 provides the timings of when individual simulations reach the two global warming levels, based on a centred 25 year running mean. This can be used to guide the extraction of transient model data centred on these levels of warming.

2.2 RCP2.6 time series

Mean climate

While some projections of RCP2.6 exist for CMIP5-13, no projections of RCP2.6 are available for the GC3.05-PPE so an estimate of the global mean annual warming must first be made before applying the methodology described in section 2.1 to include internal variability.

Previous work examining CMIP5 projections has found that the ratio of warming between two scenarios over time is similar across different models (Good et al, 2012, their figure 9). Here we assume that this relationship in CMIP5 holds for the GC3.05-PPE. We further assume that the warming ratio between RCP8.5 and RCP2.6 over time for each GC3.05-PPE simulation is the same as for the CMIP5-13 mean, and use this to derive a time series of global mean RCP2.6 temperatures from the GC3.05-PPE projections of RCP8.5.

The assumption that the ratio between scenarios for each member of the GC3.05-PPE ensemble is the same as for the CMIP5 mean cannot be tested as the runs needed do not exist. Errors in this assumption may introduce a bias in the RCP2.6 data produced. However, some preliminary work (not shown) has been done examining the temperature response of GC3.05-PPE compared to estimates based on a "step response model" (Good et al, 2011). The step response model uses a climate model's warming response to forcing in 4xCO_2 experiments to simulate a models response in alternative forcing scenarios. It does this by superimposing a warming profile (a direct scaling of the 4xCO_2 response) for each annual increase in forcing as a sum of annual forcing changes. This approach has been shown to produce useful results and is used extensively by IPCC (e.g. Collins et al, 2013).

Comparison of the step model for GC3.05-PPE suggests some non-linearity in the global response to RCP8.5, with it diverging from the step model response once CO_2 concentrations have roughly doubled (Tim Andrews, pers. comm.). CMIP5 projections for RCP8.5 do not show this behaviour, with the implication being that using the ratio between scenarios from CMIP5 may lead to an underestimate of warming in RCP2.6. For this reason, there is more confidence in the results for the 2°C and 4°C global warming levels than those for the derived RCP2.6, as they do not make any about warming ratios between scenarios.

Having produced a global mean annual time series for RCP2.6, the spatial pattern of a climate variable (as absolute values) used for a given year is produced using the time-shifting approach, based on RCP8.5. This is done in the same manner as for the time-slices in section 2.1. A 25-year running mean of the RCP8.5 global mean warming is first produced for each simulation and this is used to select the 25-year period with a global mean warming closest to that of the derived RCP2.6 global mean time series derived from the scenario scaling from CMIP5.

Monthly variability is then calculated in the same way as for the "time slices" (section 2.1) and added to the derived time series. The only difference is that the 50-year period "2015-2064", used for variability in the time-slices, is repeated to produce data up to 2100.

Daily data is then calculated in the same way as for the time-slices (section 2.1). As before the monthly mean data recalculated from the daily data, where this is produced, to ensure consistency between products at the two data frequencies.

Note that as no RCP2.6 data was available for 4 of the CMIP5-13 models, the same approach was used to produce derived data for these 4 models (Appendix B for model names) in the same way as for GC3.05-PPE. This produces a set of 28 simulation for RCP2.6 which is directly comparable to the global model projections of RCP8.5.

3. Results

This section characterizes the changes to UK climate in the time-slices at Global mean Warming Levels of 2°C and 4°C (GWL2 and GWL4 from herein) and RCP2.6.

Evaluation of the methodology described in section 2 has been carried out using simulations of RCP8.5 from CMIP5 to derive data for RCP2.6. Based on a set of predefined assessment metrics its performance was found to be acceptable. Results from this evaluation can be found in appendix A and in Good and Lowe (2017).

For RCP2.6 the global mean warming in the last 20 years of this century (2081-2100) in GC3.05-PPE is very close to 2°C above pre-industrial (1850-1900). As initial analysis also showed very similar patterns of UK climate change at the end of RCP2.6 and in the 2°C time-slice, the focus here is on the two time-slices, GWL2 and GWL4.

3.1 Changes to UK climate in 2°C and 4°C worlds from the HadGEM3.05 model

Throughout this section all climate changes are presented as relative to present day ("1981-2000"). The maps presented show changes to UK climate in two ways.

The first type of maps show the changes from individual projections which are from the high and low end of UK mean projected changes. To do this the projections are arranged in order based on their UK mean change and the second highest and second lowest changes taken to represent high and low end changes. The model nearest the median UK mean changes it taken for the median. These exemplar simulations give spatially coherent patterns of change associated with relatively high or low simulated changes in the UK mean. These aid a storyline approach to future risk assessment. The UK mean cumulative frequency distributions for some variables are also provided in this report and online, with simulations numbered, to help users select other simulations on interest based on the UK mean of changes.

The second type of maps shown are to illustrate the range across the set of simulations at different locations. A similar approach is taken to choosing the exemplar, but instead this is calculated on a grid cell by grid cell basis, taking the difference between the projection with the second highest change in that grid cell, and that with the second lowest. This more robustly illustrates the diversity across the time slices from different models, but do not show spatially coherent results.

All maps are shown as annual means as well as winter (December to February) and summer (June to August) means.

UK climate changes at 2°C of global mean warming

Relative to present day, at 2°C of global mean warming there is little spatial variation in the median annual mean warming, with a uniform warming of 1 to 2°C across the country. Warming is slightly larger in summer than winter, with summers warming more in the south east, by up to 4°C, decreasing toward the north and west. Percentage precipitation changes vary seasonally with some indication of drier summers and slightly wetter winters.

The exemplar models at the low, median and high end of the spread of the UK mean warming from present day are shown in Figure 2 for a global mean warming level of 2°C, for summer, winter and annual means. For low end warming in annual mean, summers and winters, warming is limited to under 1°C across the country. Median exemplar warming is almost uniformly 1 to 2°C in winter, summer and annual means. High end exemplars show more spatial variation and differences between seasons. The annual mean changes in Scotland and Wales are between 1 and 2°C and between 2 and 3°C warmer in England. In winter the high end warming is smaller than in summer, with a uniform warming across the country of between 2 and 3°C. In summer the warming is strongest in the south east at 3 to 4°C and decreases to the north and west to under 3°C.

The differences in spatial pattern of warming between seasons seen in Figure 2 is a consequence of using a single simulation. When the warming based on the grid cell levels range of warming is examined (not shown) the results are broadly comparable with Figure 2 but the patterns of change are more consistent across seasons and across different levels of UK warming for a global warming of 2°C. Care should be taken in interpreting patterns of changes from the exemplar as definitive patterns of change.

To illustrate the spread in temperature change across all simulations at 2°C of global warming, Figure 3 shows the difference between the high and low end of projected warming for annual, summer and winter means at 2°C of global warming, calculated on a grid cell by grid cell approach. Using the high and low end values rather than the minimum and maximums avoids results being overly influenced by outliers. The spread in winter is between 1 and 2°C with slightly larger spread in a band from North West to South East England. The spread in summer warming is again between 1 and 2°C but with a bigger spread, 2 to 3°C, in Southern England.

So that users may be able to select particular simulations for a storyline approach to analysis we also include the cumulative distribution of frequency (CDF) for the UK mean temperature changes, with each ensemble member labelled (Figure 4). CDFs for GWL2 and GWL4 are available online.

Precipitation changes for exemplar simulations at GWL2 (Figure 5) exhibit different changes across seasons, with suggestion of more drying in the summer and more wetting in the winter, although both seasons produce predominantly drier conditions at the low end, and wetter conditions in the high end exemplar, relative to present day.

For the low end exemplar, the summer drying is strongest over the South of England and Wales with a precipitation reduction of 40 to 60% in some places, albeit with a relatively small absolute rainfall in this season. This drying gradually reduces toward the north to smaller than -20% in the North of Scotland. In the median exemplar changes are less than 20% except in a few regions in the West of Scotland where there is a slightly larger increase in precipitation. In the wet exemplars there is an increase of up 0 to 20% across the country.

Conversely to the changes in summer, in winter the low exemplar is only slightly drier than present day. The median in winter shows close to zero change, as with summer, but this time indicating a slight tendency toward wetting. The high end in winter indicates increase in precipitation of 0 to 20% across the country.

The range between the high and low warming at GWL2 are shown in Figure 6. The ranges in the projections vary between seasons with larger ranges in summer than winter. Also evident is regional variation in the spread of projected changes at 2°C of global warming. The range of changes is small (0 to 10%) across most of the country in the annual mean, with some areas of a 10 to 20% range in the south east. Seasonally the range of projected changes are stronger. The range in winter is broadly around 0 to 10% across the country with a slightly larger range in Scotland, while in summer the spread is much larger than in winter with the biggest ranges in the south up to 50%.

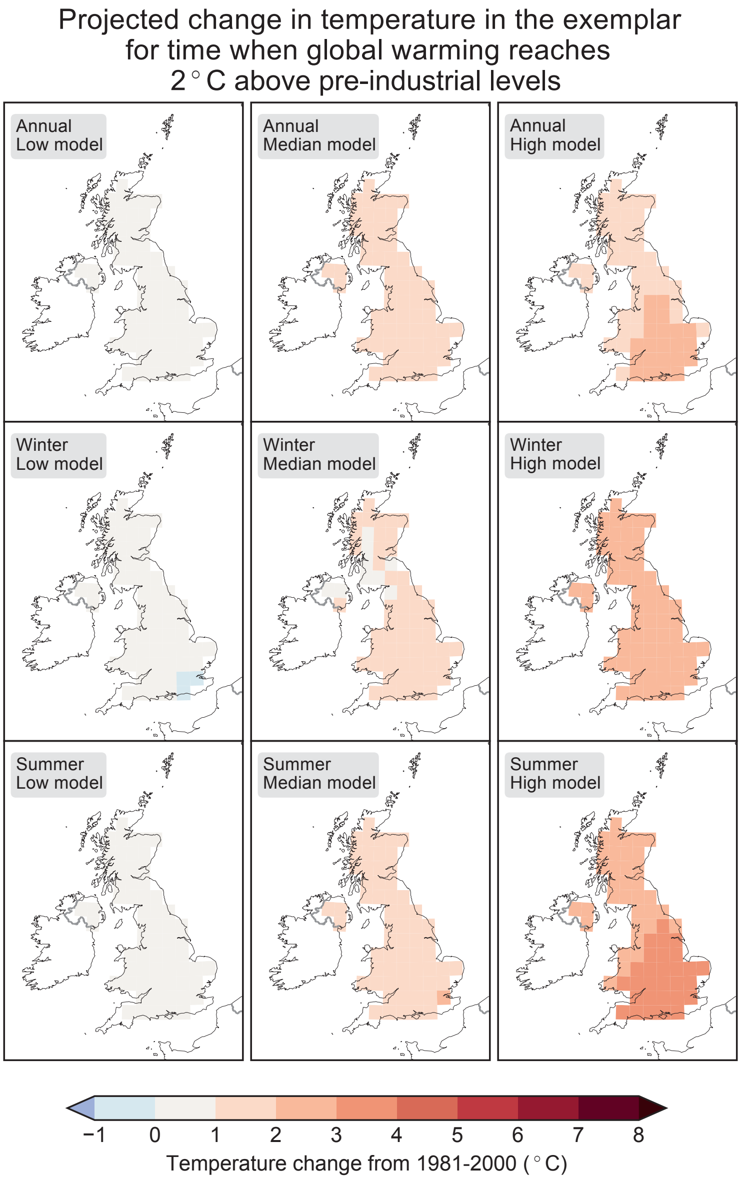


Figure 2. Exemplar projection changes in UK temperatures at a global mean warming of 2°C (GWL2) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean temperature changes which are relatively low (left), high (right) or median (centre).

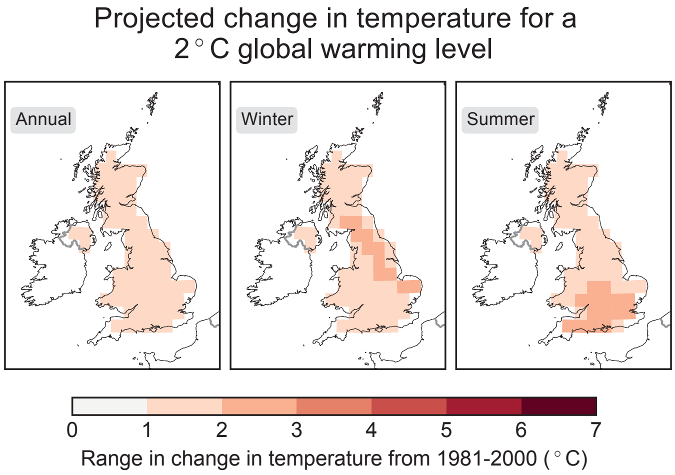


Figure 3. The range between the high and low end temperature changes at each grid cell at a 2°C global mean warming.

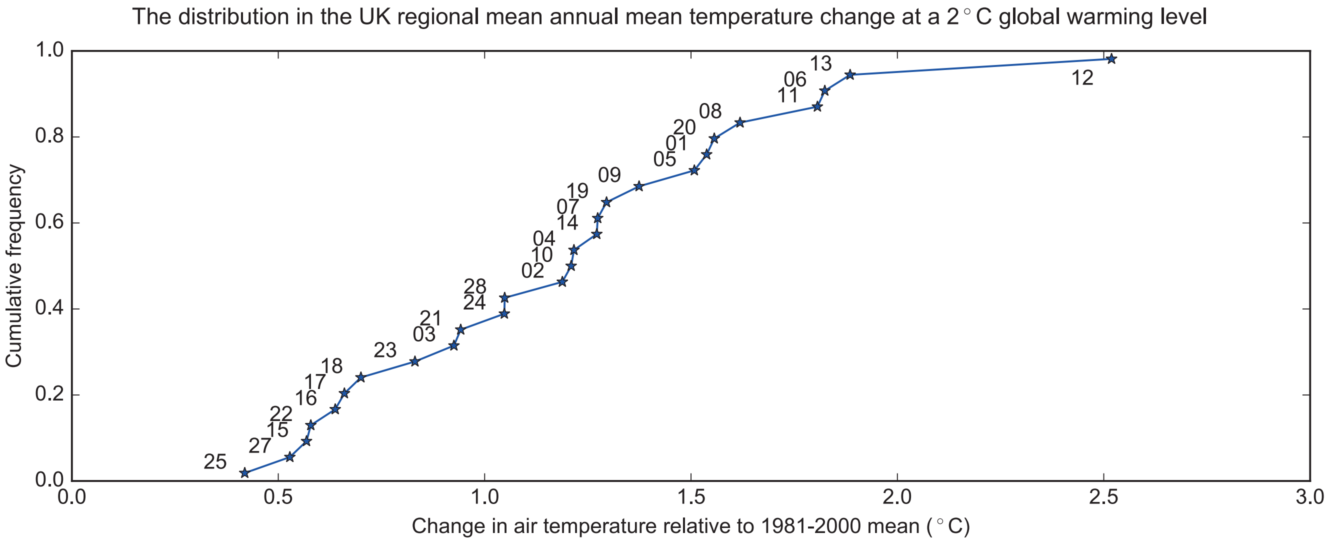


Figure 4. Cumulative frequency distribution of UK mean temperature at global mean warming level of 2°C. Each realisation is numbered to aid selection of individual simulations for use in a storyline approach to analysis.

As relative humidity is a function of surface air temperature as well as water vapour content, changes in relative humidity will be related to changes in surface air temperature. The exemplar changes in relative humidity (Figure 7) can often be interpreted in this context. For example in winter the high end relative humidity changes are a country wide increase of under 2% which, as temperatures increases are nearly uniform in their increase (Figure 2), can be attributed to the winter wetting seen in Figure 5 and the associated increase in water vapour. In summer, the general drying combined with the increasing temperatures leads to decreasing relative humidity across exemplars with a spatial pattern of the strongest decreases in the south east, 4 to 6% for the median, which decreases toward the north with slightly positive changes in Scotland for the high end exemplar.

Annual mean changes to surface wind speed in the exemplars (Figure 8) are close to zero across the country except for the low end in England where it reaches a decrease of up to 0.4ms^{-1}. Winter changes are again close to zero in the median, but show signs of a small increase of up to 0.4ms^{-1} in parts of Wales, northeast England and the Scottish boarders. The low end changes show stronger changes with a decrease in the west of up to 0.6ms^{-1}, reducing to under 0.2ms^{-1} in the east. In summer the high end changes are close to zero, but with signs of decrease in the south each for the median exemplar, and a more extensive decrease of up to 0.4ms^{-1} across England and Wales in the low end exemplar.

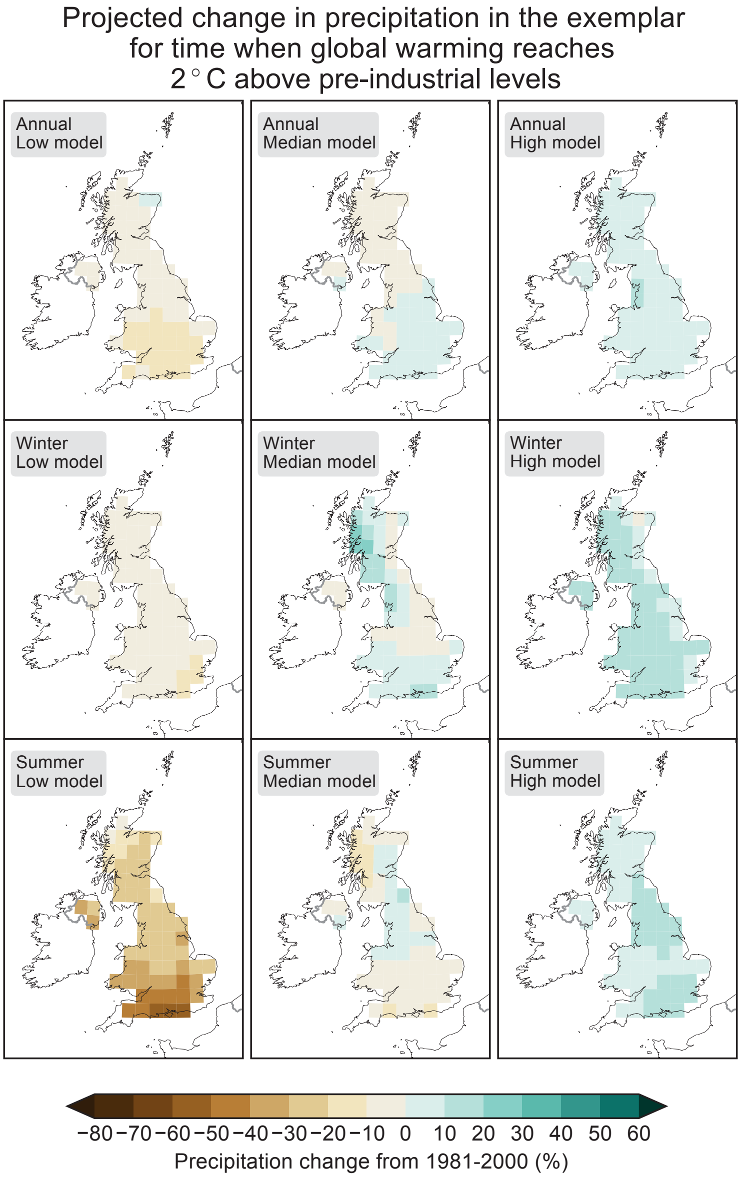


Figure 5. Exemplar projection changes in UK precipitation at a global mean warming of 2°C (GWL2) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean precipitation changes which are relatively low (left), high (right) or median (centre).

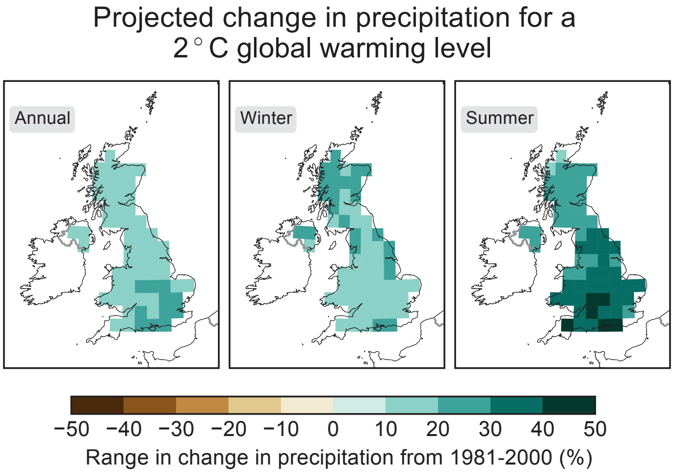


Figure 6. The range between the high and low end precipitation changes at each grid cell at a 2°C global mean warming.

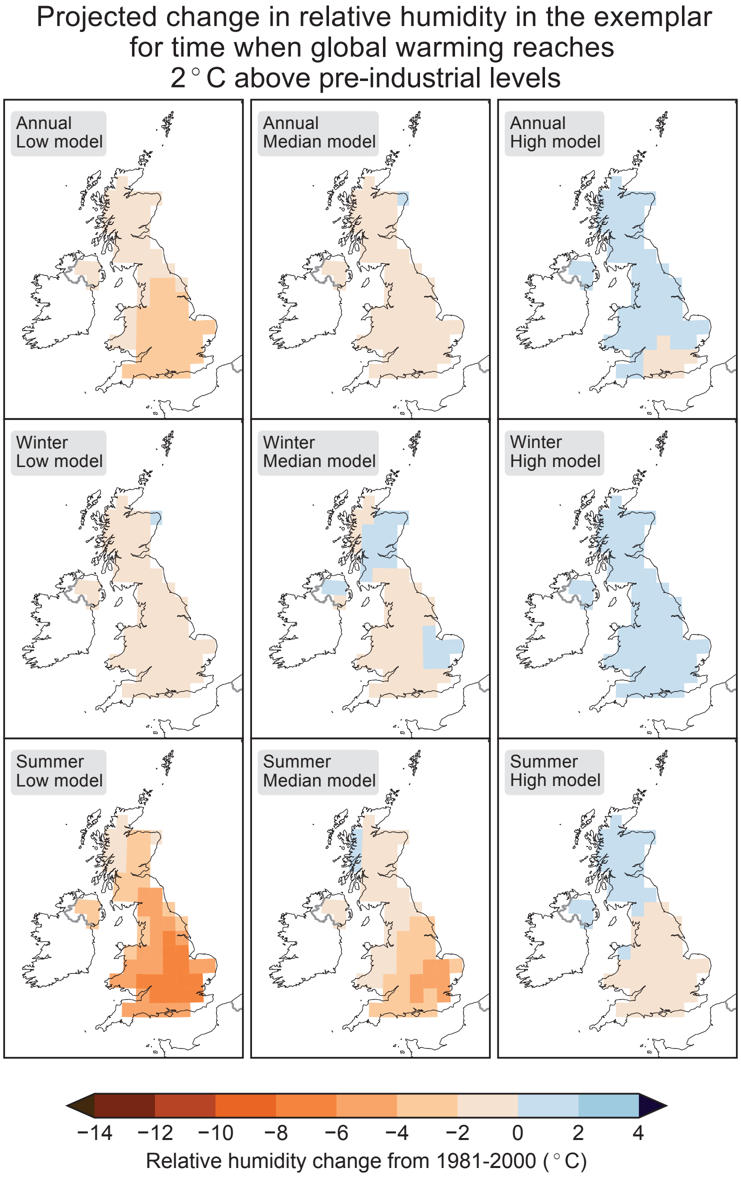


Figure 7. Exemplar projection changes in UK relative humidity at a global mean warming of 2°C (GWL2) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean relative humidity changes which are relatively low (left), high (right) or median (centre).

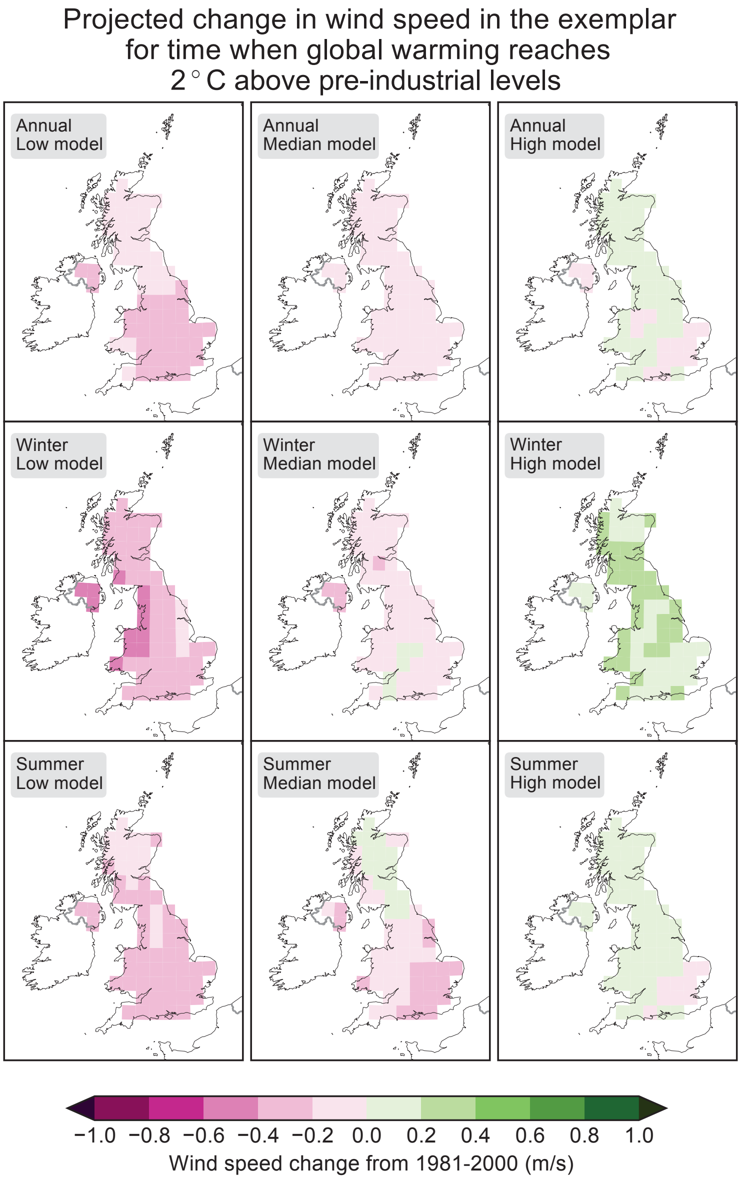


Figure 8. Exemplar projection changes in UK wind speed at a global mean warming of 2°C (GWL2) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean wind speed changes which are relatively low (left), high (right) or median (centre).

UK climate changes at 4°C of global mean warming

Changes to UK climate at a global mean temperature increase of 4°C include summers warming more than winters, but that the uncertainty in winter "warming" is larger. Summer warming is largest in the south with median temperature increases of up to 5°C. Warming in winter is more uniform across the country and is limited to under 4°C. Precipitation changes indicate wetter winters and drier summers with summer drying largest in the south with median reductions of 40 to 60% possible across England and Wales.

At GWL4, changes to UK temperatures at annual, winter and summer means exhibit spatial patterns in the exemplars which are broadly in line with those seen at GWL2 but with larger increases (Figure 9). The exemplar median annual mean warming in the south east is 3 to 4°C, decreasing to 2 to 3°C in the rest of the country. Similar patterns are seen in the low and high end warming exemplars for GWL4, but with the south east warming limited to under 3°C in the low and up to 5°C above present day temperatures in the high.

As with GWL2, the seasonal changes to temperature in GWL4 are larger in the summer than winter. In summer the spatial pattern of warming in the exemplars are similar to the annual means, with the warming in the south east up to 6°C in the high exemplar, reducing to under 4°C in Northern Scotland. In the median this range is 4 to 5°C in the south east 3 to 4°C elsewhere. The low exemplar for summer warms by 3 to 4°C in parts of the south east but 2 to 3°C in the rest of the country.

In winter the exemplar warming for the median is 2 to 3°C across the country except the south west which is cooler. This difference in spatial pattern has been investigated and found to be an artefact of using the exemplar approach. The projections as a whole indicate a larger warming in the south east (not shown). The low end warming shows a north/south split of under 1°C in the north and over 1°C in the south, while the high end warming exemplar is uniformly 3 to 4°C across the country.

The range across simulations calculated at a grid cell level indicates that although the warming in winter is smaller, the range of projected warming is larger than in summer (Figure 10). The range in the annual mean is between 1 and 2°C across the country. In winter it is 2 to 3°C across most of the country, and in summer the range is 2 to 3°C in the south east but under 2°C elsewhere.

A cumulative frequency distribution for UK mean temperatures at global mean warming of 4°C is provided in Figure 11, showing a larger spread in the lower half of the distribution than the upper half.

Changes in UK precipitation at GWL4 are, as with those at GWL2, highly seasonal (Figure 12). In the exemplar simulations winters are generally wetter and summers drier across the country. In winter the high, or wet exemplar at GWL4 has increases of 20 to 30% for Wales and Southern and Central England, and also in East Scotland. The rest of the country has increases of under 20%. The low, or dry exemplar shows a weak tendency toward wetting in the west and drying in the east, while the median indicates a slight wetting across most of the country with most in the south and west.

Changes in summer are dominated by drying. In the low exemplar decreases in precipitation reach 70% in Southern England and Wales. This drying decreases toward the north reaching 20% to 30% in Scotland. It should be noted however that absolute rainfall is lowest at this time of year. Similar patterns are seen in the median and high end exemplar but with smaller percentage changes. The south to north range is a drying of 50% to 0% in the median and generally less than a 20% reduction in the high exemplar.

The only major difference between the exemplar and the maps based on individual grid cell spread (not shown) are a smaller drying in the south for the summer low exemplar, and a slightly stronger wetting in the winter high exemplar.

The spread in the projected precipitation changes at the grid cell level are shown in Figure 13. In the annual, summer and winter the ranges have a similar spatial pattern, with larger ranges in the south east which decrease to the north and west. The range is largest in the summer with a range of 40 to 50% in the south east decreasing to 20 to 30% in Scotland. In winter the range is 30 to 40% in small parts of the south east and 10 to 20% in the west and Wales.

Changes in relative humidity at GWL4 (Figure 14) differ in their spatial patterns from those of GWL2 on account of the changing relative influence of changes in water vapour content and surface air temperature. Annual mean exemplar changes show a decrease which is largest in the southeast, 4 to 6% relative to present day, in line with the temperature changes seen in Figure 9. This reduces toward the north to near zero change in the north of Scotland. The same pattern is evident in the median and high exemplars but with a weaker change in the south east but a similar gradient toward the north.

During the winter there is little spatial pattern in the changes to relative humidity, being near uniformly between a 0 and 2% reduction in the low and a 0 and 2% increase in the high. The median is close to zero change across England and Wales but with a small decrease up to 4% in small parts of North Scotland.

In summer the largest signals are again in the south east associated with the drying and warming in this region. In the low exemplar this can reach a 10 to 12% reduction while in the high it is limited to under 8% in most places.

Surface wind speed changes at GWL4 compared to present day are shown in Figure 15. As with results from GWL2 there are only limited changes in wind speed. Annual averages in the high exemplar indicate little change across the country. The median shows a near uniform minor decrease of up to 0.2ms^{-1}, while the low a uniform reduction of up to 0.4ms^{-1}.

During summer the low exemplar shows more spatial patterns of change, with speeds in the south decreasing by up to 0.8ms^{-1} but generally by 0.4 to 0.6ms^{-1} across Southern England and Wales, and under 0.4ms^{-1} in the rest of the country. Median winter changes are near zero across the country while the high end indicates a 0.2 to 0.4ms^{-1} increase across the country.

In summer the high end exemplar changes are around zero, and in the median are a slight decrease with some suggestion of a stronger decrease, up to 0.4ms^{-1} in the far south. The low changes are a decrease of between 0.2 and 0.4ms^{-1} across the country except the North of England which decreases by up to 0.6ms^{-1}.

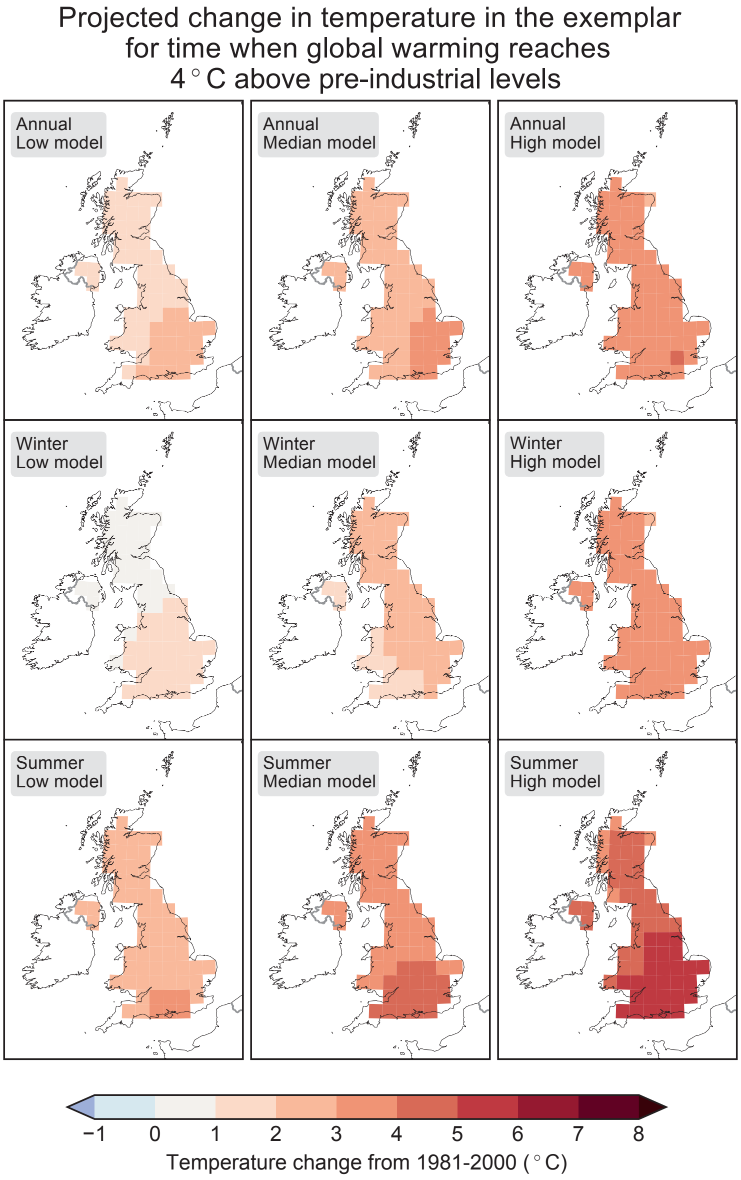


Figure 9. Exemplar projection changes in UK temperatures at a global mean warming of 4°C (GWL4) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean temperature changes which are relatively low (left), high (right) or median (centre).

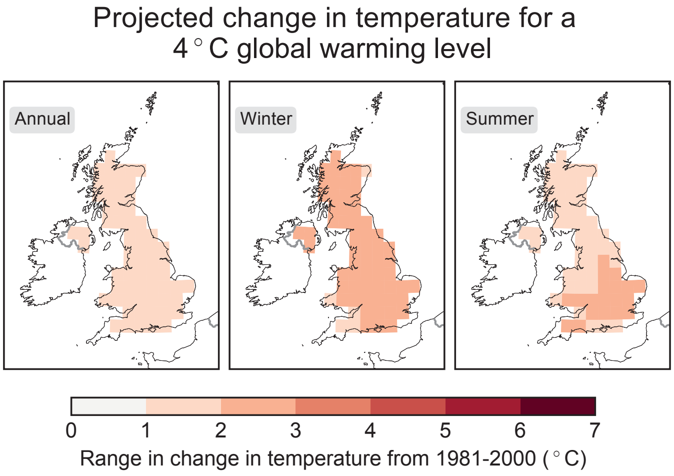


Figure 10. The range between the high and low end temperature changes at each grid cell at a 4°C global mean warming.

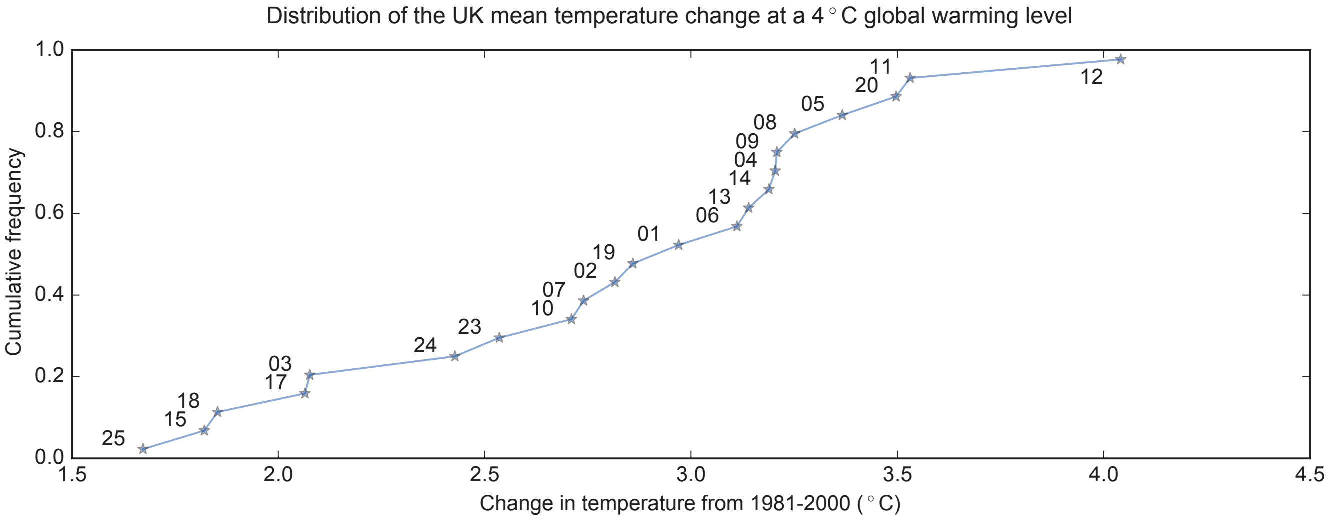


Figure 11. Cumulative frequency distribution of UK mean temperature at global mean warming level of 4°C. Each realisation is numbered to aid selection of individual simulations for use in a storyline approach to analysis.

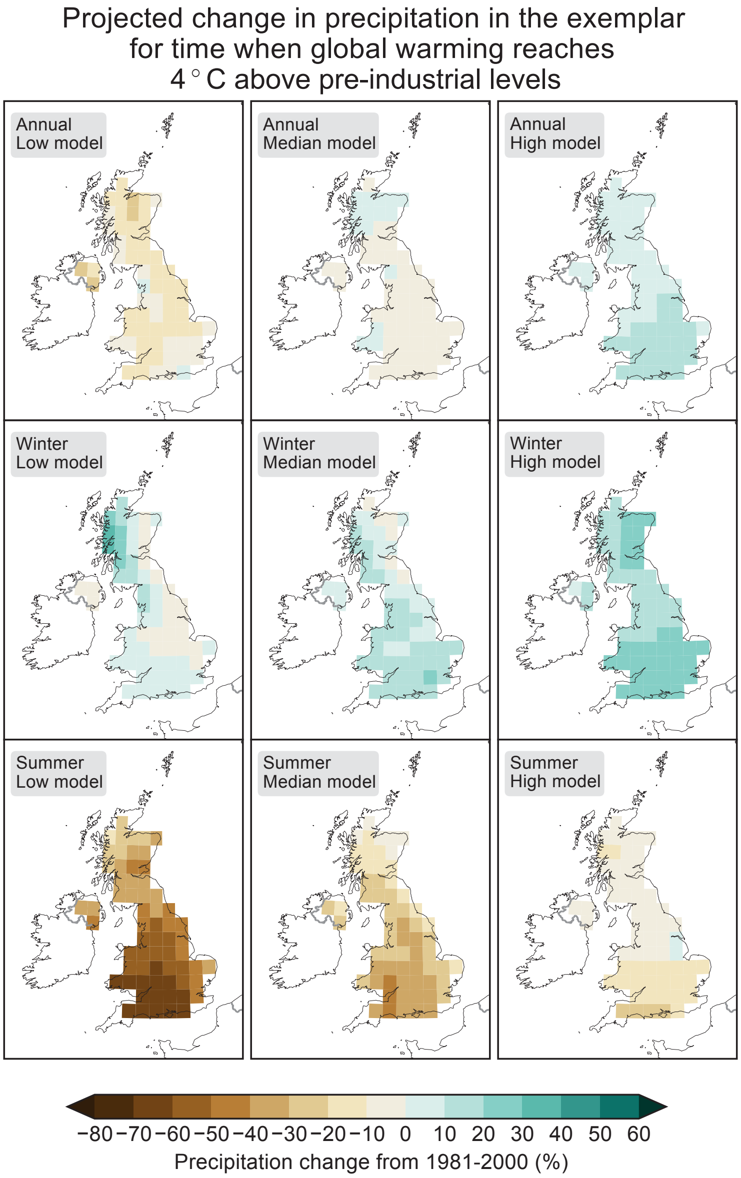


Figure 12. Exemplar projection changes in UK precipitation at a global mean warming of 4°C (GWL4) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean precipitation changes which are relatively low (left), high (right) or median (centre).

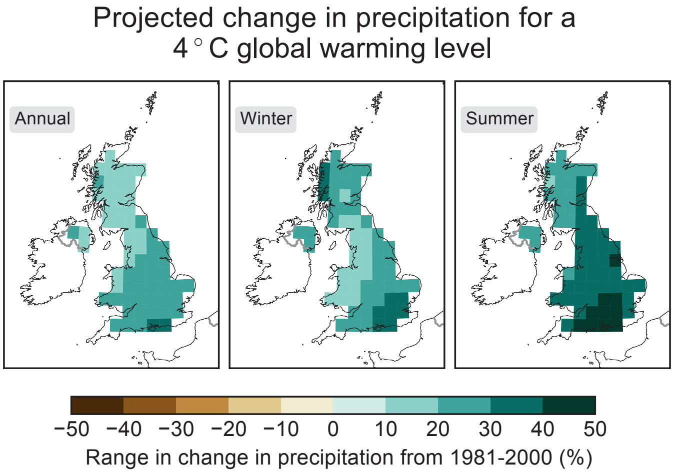


Figure 13. The range between the high and low end precipitation changes at each grid cell at a 4°C global mean warming.

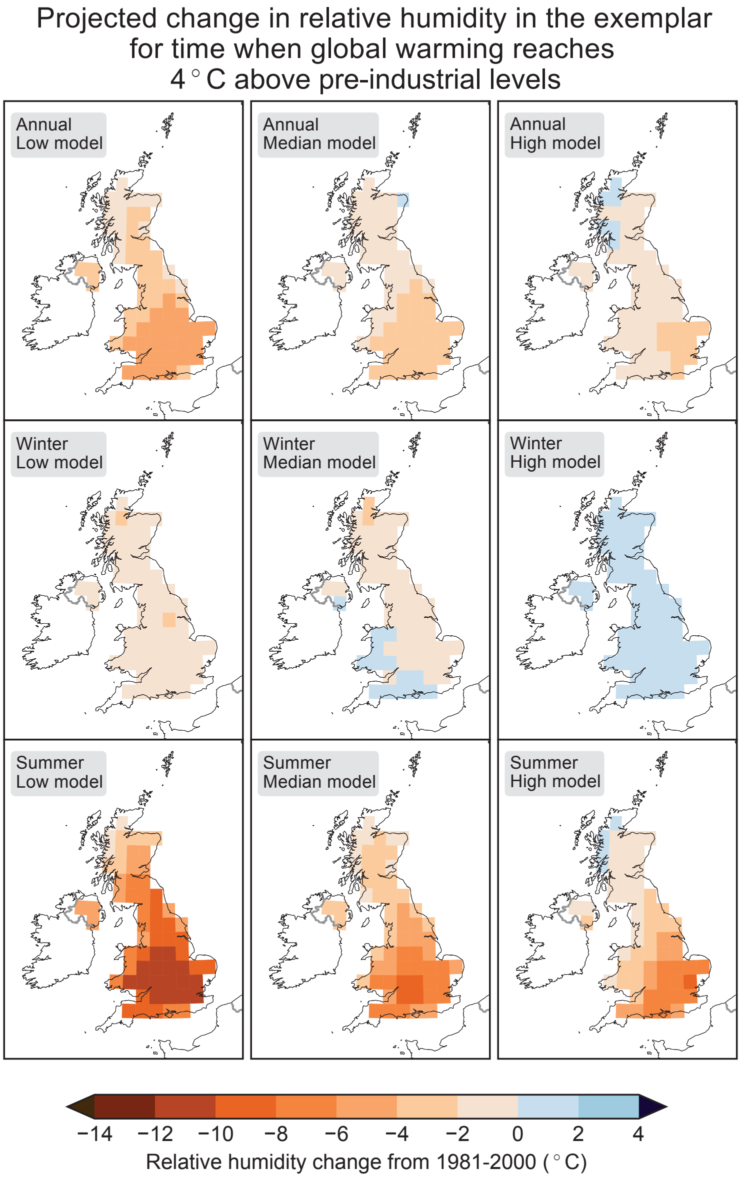


Figure 14. Exemplar projection changes in UK relative humidity at a global mean warming of 4°C (GWL4) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model relative humidity with a UK mean temperature changes which are relatively low (left), high (right) or median (centre).

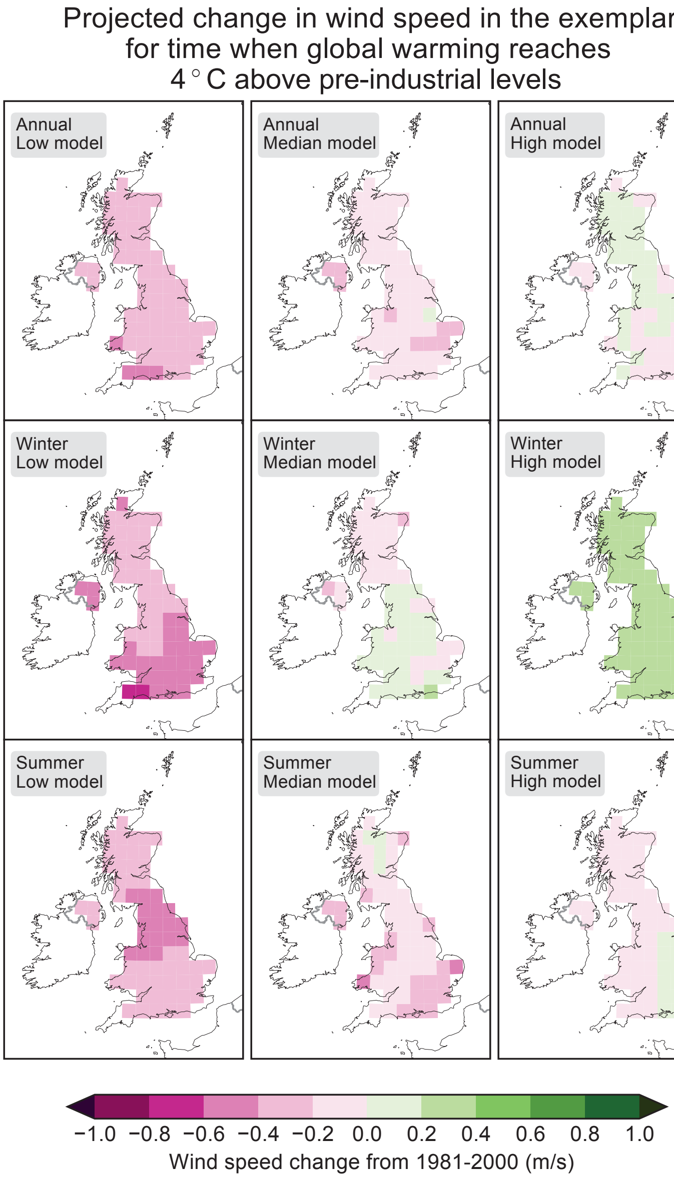


Figure 15. Exemplar projection changes in UK wind speed at a global mean warming of 4°C (GWL4) above pre-industrial (1850-1900). Changes are shown relative to present day (1981-2000). Rows show annual (top), winter (December-February; middle) and summer (June-August; bottom) changes. Columns shows maps for the model projection with a UK mean wind speed changes which are relatively low (left), high (right) or median (centre).

Daily temperature distributions at a global mean warming of 2°C and 4°C

As described in section 2.1, some daily data is also produced for the RCP2.6 time series and the two 50-year time-slices at GWL2 and GWL4. Owing to resource considerations only surface air temperature and precipitation changes have been produced for this study and here we examine some of their characteristics. We use the 10th and 90th percentiles of the distribution of daily mean temperature and precipitation to characterise the low and high end of the distribution of daily values. This is done separately for summer or winter, through the entire 50-years of the GWL2 and GWL4 time series. Presented below are the mean from all models of the change in 10th and 90th percentiles relative to present day ("1981-2000"). Temperature values are reported as changes in °C while precipitation changes are reported as percentages. From herein, the changes to the low and high ends of the distributions of daily temperatures will simply be referred to as low and high, cool and hot, or dry and wet as appropriate.

Figure 16 shows the mean of low and high end changes for daily temperature at GWL2. Winter changes in daily mean temperatures show that cool days warm by 1 to 1.5°C across the country, whilst warmer winter days warm less with increase of under 1°C. During summer there is a more distinct spatial pattern of change, which is similar for hot and cool days and is also similar to the pattern of mean warming seen in GWL2, with hot and cool days warming most in the southeast than elsewhere. Both hot and cool days warm by 1 to 1.5°C across Scotland and 1.5 to 2°C across England. In summer there is some suggestion of larger warming of hot days in the south east.

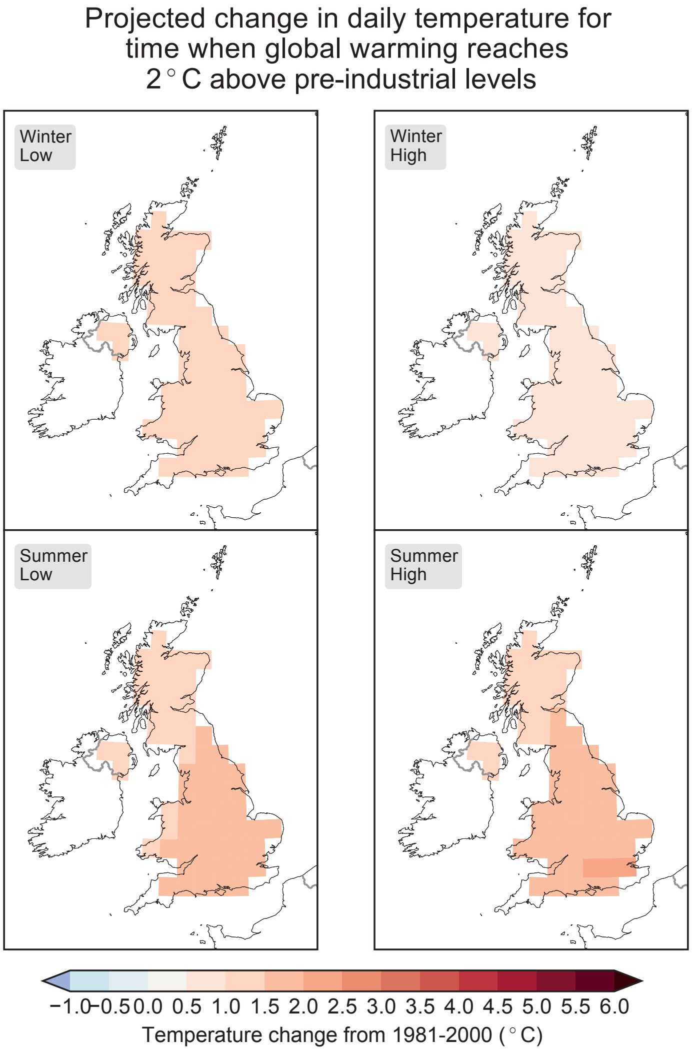


Figure 16. Temperature changes on cool and hot days, relative to present day (1981-2000), at a global mean warming level of 2°C. The mean change from all models is shown. Changes in winter are averages over December, January and February. Changes in summer are averages over June, July and August.

Changes to daily mean precipitation are shown in Figure 17. Changes to daily winter precipitation are small and less than 10% across the country. The small changes that are present indicate an increase in precipitation for the whole country except the far North of Scotland which is less than 10% drier on both wet and dry days. Changes to summer daily precipitation are rather different. A pronounced drying is seen to dry summer days with reductions of up to 30% in parts of the south west and a reduction of 10 to 20% across Southern England and Wales. Reduction in Northern England and Scotland are less than 10%. Note this these are relative changes to the driest days in the driest part of the year so absolute changes may be relatively small but nevertheless important in terms of their impacts. Changes in the wettest summer days also show a drying, reducing by up to 20% across the most of the country and 10 to 20% in some parts of Southern England.

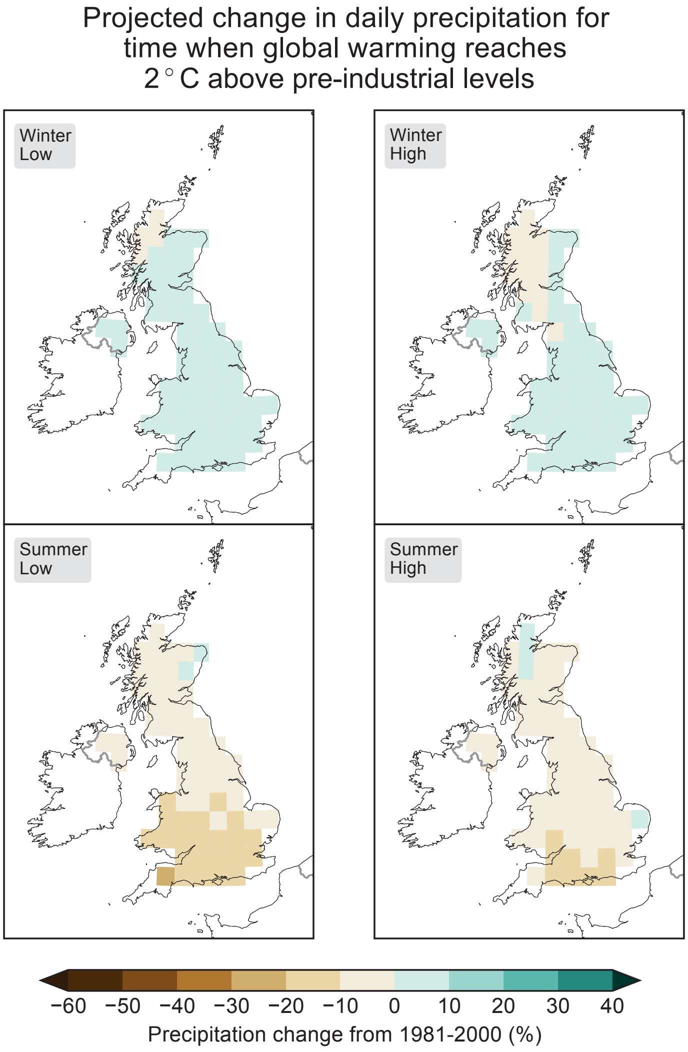


Figure 17. Precipitation changes on wet and dry days, relative to present day (1981-2000), at a global mean warming level of 2°C. The mean change from all models is shown. Changes in winter are averages over December, January and February. Changes in summer are averages over June, July and August.

At GWL4 we see an amplification of the changes seen at GWL2 with similar spatial patterns for cool and warm days. Cool winter days warm by more than hot days, increasing by 2.5 to 3°C across the country (Figure 18). Hot winter days warm by 2.5 to 3°C in England but by 2 to 2.5°C in Wales and Scotland. Change to the temperatures of hot and cool days are larger in summer, with hot summer days warming more than cool days. Warming is largest in the south east and decreases toward the north and west for both hot and cool days, giving a similar spatial pattern to the increase in the seasonal mean temperatures (Figure 9). Cooler summer days warm by 4 to 4.5°C across England, possibly up to 5°C in the south east, but with increases reducing to under 3°C in the far North West of Scotland. Hot summer days warm by 4.5 to 5°C compared to present day, across much of Southern England, possibly exceeding 5°C in some locations, again with this increase reducing toward the north and west, being limited to under 3°C in the North of Scotland.

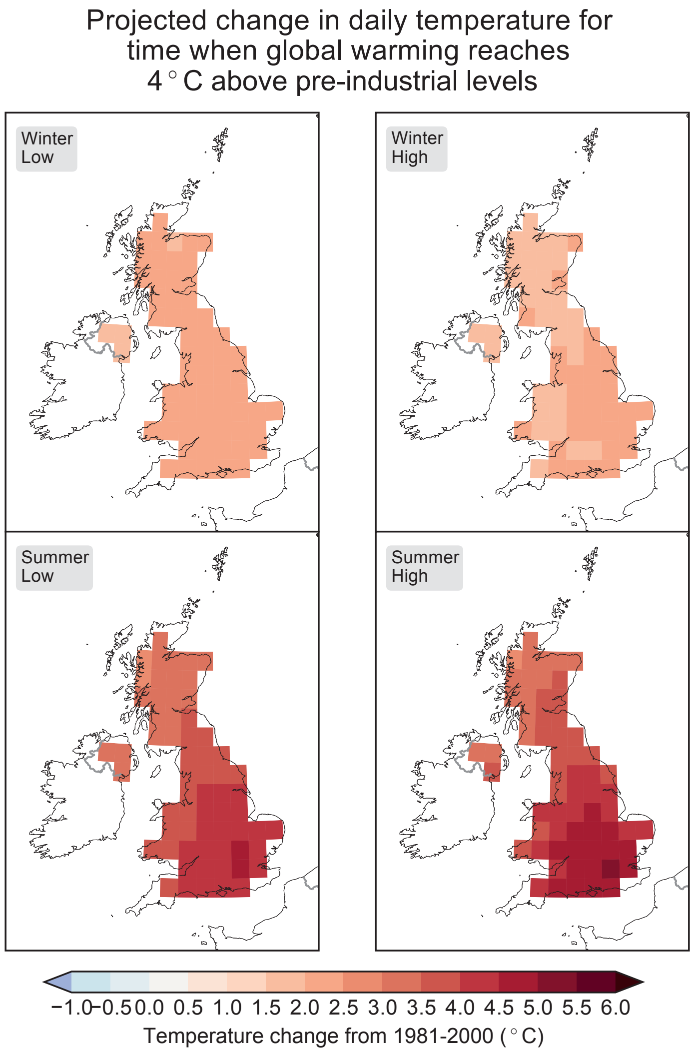


Figure 18. Temperature changes on cool and hot days, relative to present day (1981-2000), at a global mean warming level of 4°C. The mean change from all models is shown. Changes in winter are averages over December, January and February. Changes in summer are averages over June, July and August.

Changes to daily precipitation at GWL4 show some larger changes than GWL2. Summer precipitation, which decreases in the seasonal mean (Figure 12), shows large percentage drops in daily precipitation for both dry and wet days. Dry days decrease in precipitation most, by up to 50% in summer across much of Southern Wales and England, with this drying reducing toward the north to under 20% in Northern Scotland. The wettest summer days dry less but with a similar pattern, with precipitation reductions of up to 40% on limited parts of the south coast and again decreasing toward the north. Drying is limited to 0 to 10% reductions in the far north.

The combined picture from the changes to seasonal means and the daily mean temperature distributions is that the changes seen at GWL2 are amplifed at GWL4. Daily summer temperatures warm by more than those in winter, both for hot and cool days. Daily precipitation in summer decreases most on the south coast and the driest days become drier by a larger percentage than the drying of wet summer days (although in absolute terms the differences may be smaller). Conversely winter daily precipitation increases slightly for both wet and dry days.

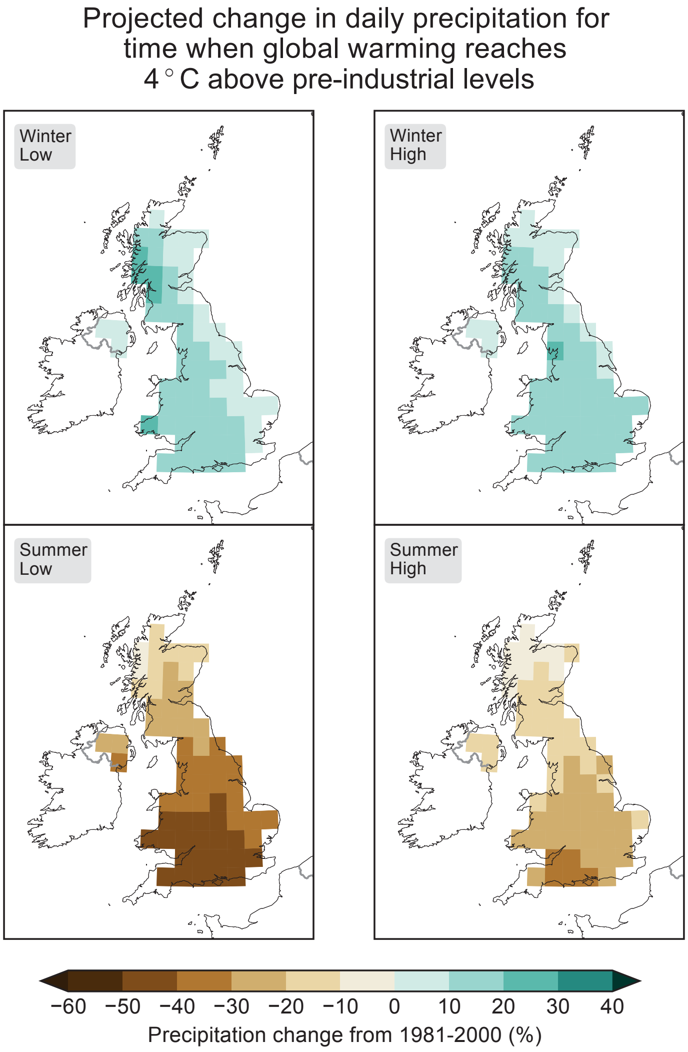


Figure 19. Precipitation changes on wet and dry days, relative to present day (1981-2000), at a global mean warming level of 2°C. The mean change from all models is shown. Changes in winter are averages over December, January and February. Changes in summer are averages over June, July and August.

Timing of reaching 2°C and 4°C of global mean temperature increase

The assumption underlying the time-shifting approach is that the changes to the climate at a given level of global mean warming are independent of the time at which that level is reached. This assumption translates uncertainty in model response to forcing, or in their response to different scenarios, into uncertainty around the timing of reaching the warming levels of interest.

Table 2 shows the timing of when each global model projection passes 2 and 4°C of global mean warming, the warming from present day has been added to the observed warming from pre-industrial to present day. This is the same approach used to diagnose the timing of reach 2 and 4°C in section 2.1. This approach, also used in the IPCC's recent special report on 1.5°C, reduces the spread in timing of reaching warming levels but ensures that present day warming is in line with observations. If these dates are used to extract data from the global model projections around these warming levels, users should take care to calculate anomalies relative to present day and add these onto observational changes from pre-industrial to present day before using the data.

Analysis of CMIP5 by Gohar et al, (2017) examined the timing of reach different levels of global warming in multiple sets of models and scenarios. Their approach has been applied to the RCP8.5 projections used in this study (Table 3). As this does not use projected anomalies to present day data added onto an observational record, there is a wider range of possible dates than the likely underestimate in Table 2.

Model ID	Global 2˚C earliest passing	Global 4˚C earliest passing
1	2030	2063
2	2027	2061
3	2030	2060
4	2027	2060
5	2032	2066
6	2029	2064
7	2031	2064
8	2032	2070
9	2028	2057
10	2032	2067
11	2029	2064
12	2035	2067
13	2029	2063
14	2031	2063
15	2033	2068
16	2045	
17	2040	2084
18	2042	2087
19	2031	2071
20	2041	2078
21	2045	
22	2044	
23	2038	2078
24	2030	2068
25	2036	2071
26	2045	
27	2050	
28	2055	

Table 2. Timings of exceeding global mean warming levels of 2 (GWL2) and 4 °C (GWL4) in RCP8.5. The global warming levels are derived from the model simulated global annual mean anomaly relative to 1981-2000 baseline plus the observed warming from 1850-1900 mean to 1981-2000 mean based on HadCRUT4 (Morice et al, 2012) and so differ from the results in Table 3. Timings are based on a centred 25 year running mean. While all simulations pass 2 °C of global mean warming some simulations to no reach global mean warming levels of 4 °C by the end of the century.

Ensemble	Scenario	Global 2°C earliest passing	Global 2°C latest passing	Global 4°C earliest passing	Global 4°C latest passing
GC3.05-PPE	RCP 2.6$^{\$}$	2038	2090*		
CMIP5	RCP 2.6	2042	2087		
CMIP5-13	RCP 2.6	2045	2071		
GC3.05-PPE	RCP 8.5	2029	2045	2061	2074
CMIP5	RCP 8.5	2029	2058	2068	2090*
CMIP5-13	RCP 8.5	2029	2058	2069	2090*

Table 3. Timing of passing 2°C and 4°C of global mean temperature. Where no value is reported no simulations reach that warming level. *Following Gohar et al, (2017) a 20 year running mean is used to calculate this values and so 2090 is the last year that can be diagnosed up to 2100 when these runs end. Other simulations may (or may not) have passed the warming levels later had the runs been extended further. $Data from GC3.05-PPE for RCP2.6 is a derived product rather than directly simulated by a climate model.

From the raw model output (Table 3) the timing of reaching global mean warming level of 2°C could as soon as the late 2020's, while 4°C could be reached from the mid 2040's in GC3.05-PPE and or the late 2050s based on CMIP5.

3.2 RCP2.6 projections

As noted previously, projections for the end of the century from the GC3.05-PPE of RCP2.6 are similar to those from the 50-year time-slice at a global mean warming level of 2°C. Given this, we do not show a detailed characterisation of climate changes over the UK for RCP2.6, but instead look at brief comparisons between the RCP2.6 data produced in this study and the simulations from the CMIP5-13 subset of CMIP5 used for the global model projections (Murphy et al, 2018).

As the selection of CMIP5-13 for the global model projections did not anticipate the future inclusion of data from RCP2.6, the sub-set of CMIP5 models in CMIP5-13 includes 4 that did not perform simulations of RCP2.6. To ensure consistency with the 28 member ensemble used in land strand 2 (15 from GC3.05-PPE and 13 from CMIP5-13), we apply the time-shifting approach to GC3.05-PPE to the 4 models in CMIP5-13 with no data available for RCP2.6. Temperature projections globally (Figure 20), and over the UK (Figure 21), from GC3.05-PPE are generally higher than those in CMIP5-13 for RCP2.6. The same is true for RCP8.5 (Murphy et al, 2018) where the mean is clearly towards the upper end of CMIP5 projections.

Changes to UK mean precipitation exhibit a large degree of temporal variability. The trend in the means from CMIP5-13 and GC3.05-PPE are similar in winter, both showing a slight increase, while in summer CMIP5-13 show a negligible signal while GC3.05-PPE produces a slight decrease. Annual mean trends in both (not shown) are for a slight increase.

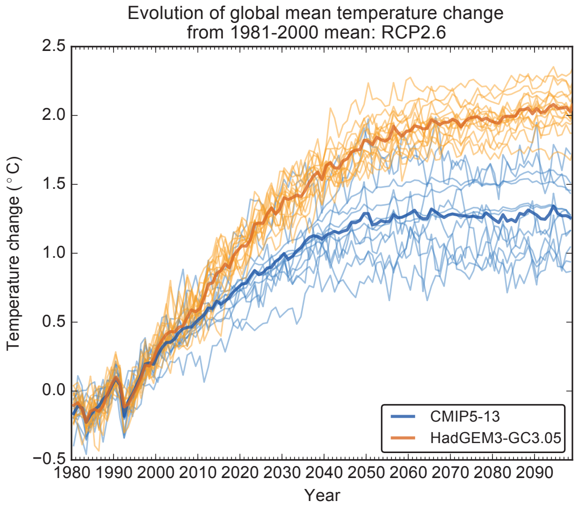


Figure 20. Global annual mean temperature relative to 1981-2000 mean for RCP2.6. CMIP5 is shown (in blue) with the mean as a thicker, darker line. Results from GC3.05-PPE are shown (in orange) with the mean in thicker, darker line. Note the kinks in the early 1980s and 1990s are due to volcanic eruptions of El Chichon and Mt. Pinatubo respectively. The simulated cooling is stronger that was observed but this is a well known feature CMIP5 models and GC3.05-PPE.

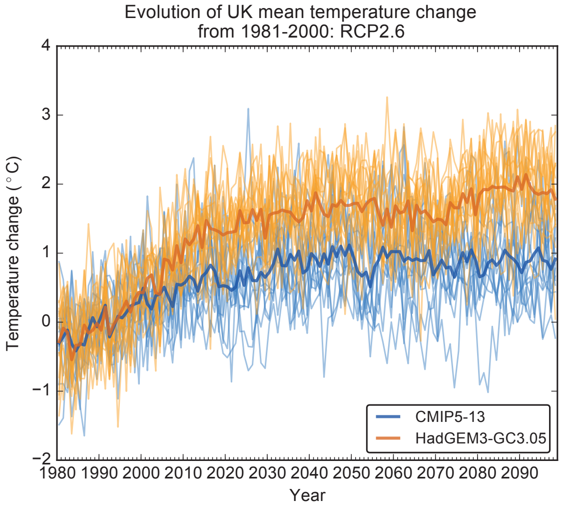


Figure 21. UK mean temperature changes in RCP2.6 relative to the 1981-2000 mean. The available CMIP5 data from the sub-set used by land strand 2 (Murphy et al, 2018 and appendix B) is in blue and the results from GC3.05-PPE are in orange. The multi-model means are shown as darker thicker lines of the corresponding colours.

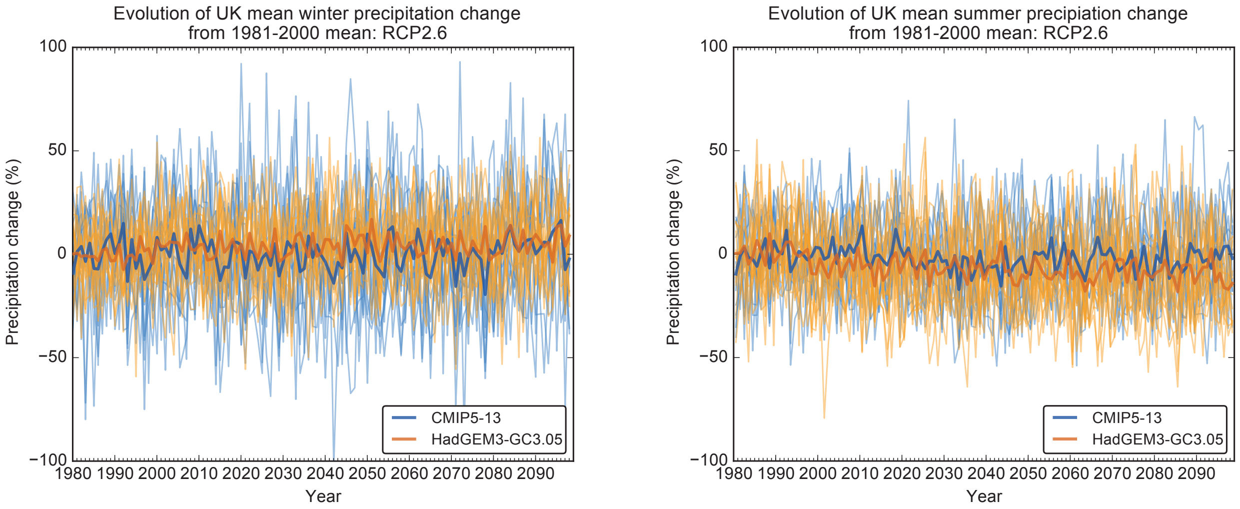


Figure 22. UK mean summer and winter precipitation changes in RCP2.6 relative to the 1981-2000 mean. The available CMIP5 data from the sub-set used by land strand (Murphy et al, 2018 and appendix B) is in blue and the results from GC3.05-PPE are in orange. The multi model means are shown as darker thicker lines of the corresponding colours.

4. Discussion and limitations

The global model projections of RCP8.5 have been used to produce a derived set of equivalent data for RCP2.6. Where possible, for each projection two 50-year time-slices at 2°C and 4°C of global mean warming have also been produced. The methodology is based on a combination of approaches: using a method built on the approach of time-shifting to produce time-mean climate changes; a method related to pattern scaling to extract time series of variability; and assumptions about the relative warming of particular models between scenarios. Where possible data is produced at monthly frequencies for surface air temperature and precipitation, near surface relative humidity, surface wind speed in northward and eastward wind components, and net downward shortwave radiation. Daily data was also produced for surface air temperature and precipitation.

While presented as relative to present day in this report, compared to pre-industrial the climate changes in the time-slices are roughly linear between global warming levels of 2 and 4°C. Changes to UK climate at 4°C of global mean warming are approximately double that at 2°C. This is not an artefact of the methodology as the time-shifting approach used to estimate the mean climate does not assume linearity between regional climate responses and global mean temperatures.

Compared to present day conditions the main trends seen are a warming which is highest in the south and decreases towards the north, and which is stronger in summer than winter. Small precipitation increases are seen in winter which is largest in the south and a summer drying which is also largest in the south. The summer precipitation decrease has a larger relative magnitude than the wetting in winter.

Results have been presented primarily as exemplars, simulations from the full set which are toward the low, middle or high end of the set of projections, based on the UK mean of the variables in question. While this produces spatially coherent patterns of change there are instances where exemplars can give potentially misleading impression of regional changes, especially for temperature and precipitation. We advise some caution in this regard if using regional time series based on individual projections.

There are also a number of limitations and potential issues with the methodology as presented here;

Considerations for both time-slices and RCP2.6

As with any product derived from climate model data, these projections are conditional on the set(s) of simulations from which they are derived. The projections exhibit a range of historical biases and projected changes that depend on the design choices made in construction of individual models. Where feasible, users should compare against alternative projections (e.g. the probabilistic projections from UKCP18), in order to understand how the results may depend on different choices of climate modelling information. In addition, some simulation errors may be common to all climate models, implying limitations in knowledge and capability whose effects will not be represented in projections from current models.

Another limitation to consider is that the resolution of the global models on which the derived data is based is of the order of 60km. At such resolutions, convective precipitation is entirely parameterised and previous work by Kendon et al, (2014) has shown that convection permitting models (grid spacing of the order of 1km) give a better representation of rainfall in the UK summer.

While the evaluation has demonstrated skill in synthesizing data from CMIP5 models (Appendix A), it was not possible to demonstrate that the approach works well specifically for GC3.05-PPE as no RCP2.6 simulations were available for evaluation.

Not all possible utilizations of the derived data have been considered in the evaluation carried out for this study. There may be characteristics of the derived time series which expose unanticipated problems with the methodology, but without a systematic testing of every conceivable exploitation of the data this would be hard to avoid. Users should keep this in mind while designing applications, for example if using a duration based measure for events which may last longer than a month when using the derived daily data where intra-month temporal coherency has not be preserved.

There is however consistency between the data at monthly and daily frequencies of a given variable. Our choice of attaining this by recalculating the monthly means from the daily data (where produced) may reduce the coherence between variables for monthly data that have been produced from daily data and those monthly variables that have been produced directly. The level of this potential impact has not been thoroughly investigated.

Users should also be aware that as the same monthly variability derived from RCP8.5 is used for RCP2.6 and the time-slices, there is a correlation between the variability in the corresponding ensemble members in all these products. The potential impact of this should be considered by users when planning further analysis.

Finally, no bias correction has been applied to these products so users may wish to consider their requirements in this regard. The 60km resolution of GC3.05-PPE may be a contributing factor to localised biases in some climate variables such as precipitation and surface wind speed which users may need to consider.

Various additional limitations of GC3.05-PPE are discussed in detail in Murphy et al, (2018).

Issues effecting only time-slices at 2°C and 4°C of global warming

The analysis of the global model projections used a set of 28 projections which combined the GC3.05-PPE with a subset of CMIP5 to a better sample structural uncertainties in climate projections. There were a number of issues influencing whether this combination of data sources is appropriate for producing the derived data .

For the 50-year time-slices at global mean warming levels of 2 and 4°C, the use of the same 28 projections would be possible for 2°C as all 28 pass 2°C. However, not all the CMIP5-13 models reach 4°C by the end of the simulation so those cannot be used for the 4°C time-slice. The alternatives for dealing with this would be to include only those models passing 4°C in the warmer time-slice, but all 28 in the lower time-slice. Alternatively, consistency between the time-slices could be ensured by using only those models passing 4°C for the two time-slices. In this case, both would include a different subset of CMIP5-13 to global model projections.

The decision was made to provide analysis in this report based on as much data as possible for each time slice and so all models passing either 2 or 4°C are used, although it should be noted that this will introduce an inconsistency between the number of models contributing to the content of the two time-slices.

That the 'warmer' GC3.05-PPE may reach specific warming levels sooner than CMIP5-13 is relatively unimportant for the time-slices given the time shifting assumptions used in this work: that climate changes at a given level of global mean warming are similar regardless of when they occur.

Another consideration when using time-slices data is the extent to which uncertainties are captured by GC3.05-PPE. Murphy et al, 2018 compares the uncertainty in UK climate response from the probabilistic projections, the global model projections, and the regional model projections from UKCP18. This suggests that data based on GC3.05-PPE, compared to the 28 projections from global model projections, may slightly over estimate summer temperature response over the UK and overestimate the summer drying over England. This is a result that should be considered when making use of the time slice data alongside the global model projections.

Issues effecting only RCP2.6

The assumption that the ratio of warming between scenarios (specifically between the RCPs) from Good et al, (2011) was used to produce a global time series of annual mean temperatures for RCP2.6 from each projection. However some preliminary analysis of the linearity of the response of GC3.05-PPE to forcing suggests that it may warm above a linear response calculated from the step-response model of Good et al, (2011), whilst the CMIP5 models are a better fitted by the step model (Tim Andrews, pers. Comm.). There is preliminary evidence that at least some of this non-linear behaviour may be driven by the prescription of Ozone used in GC3.05-PPE, however the extent to which this drives the apparent non-linearity is as yet unclear. Whatever the cause, the implication is that our approximation of the RCP2.6 warming may be too warm towards the end of the simulations depending on when any apparent non-linearity actually becomes evident.

Related to the previous point, the assumption that the warming ratio between scenarios is the same for each of the projections from GC3.05-PPE has also not been verified. This is compounded by the fact that each member ran with a different CO_2 concentration time series to represent different carbon cycle responses in an emissions-driven system (Murphy et al, 2018) while CMIP5 all prescribed the same CO_2 for the RCPs. As such the ratios between RCP8.5 in the ensemble and other scenarios may vary across the GC3.05-PPE, suggesting that the spread in annual mean temperature time series in RCP2.6 data from this study may be underestimated.

Potential improvements

The multivariate root mean square (RMS) error approach for selecting daily data from RCP8.5 could be improved. At present it uses the UK mean time series, when it could use the time series of each UK grid cell and select daily data based on minimizing the sum of the RMS across all grid cells. How much impact such an approach would make has not been investigated.

Processing for the daily data could be expanded to include other variables. This would mean recalculating the daily for temperature and precipitation as any new variables will be included in the multivariate RMS method for selecting representative daily data from RCP8.5. It will also mean recalculating the monthly data for those variables from the daily data to ensure consistency of the data between different frequencies of data. This arises from the multivariate RMS approach not giving exact matches for all variables in all cases.

Finally, the global warming projections used for the RCP2.6 simulations could potentially be improved, to account for non-linear behaviour, based on the new UKCP18 model simulations. An estimate of climate response to aerosol forcing could potentially be made to improve the time-shifting methodology.

5. References

Ceppi, P., Zappa, G., Shepherd, T. G., and Gregory, J. M., (2018). Fast and slow components of the extratropical atmospheric circulation response to CO_2 forcing. Journal of Climate, 31(3), 1091–1105. https://doi.org/10.1175/JCLI-D-17-0323.1

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P. Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver A. J., and Wehner M., (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G. K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Good, P., Gregory, J. M., and Lowe, J. A., (2011). A step-response simple climate model to reconstruct and interpret AOGCM projections. Geophysical Research Letters, 38(1), 1–5. https://doi.org/10.1029/2010GL045208

Good, P., Ingram, W., Lambert, F. H., Lowe, J. A., Gregory, J. M., Webb, M. J., Ringer, M. A., and Wu, P., (2012). A step-response approach for predicting and understanding non-linear precipitation changes., Climate Dynamics, 39(12), 2789–2803. https://doi.org/10.1007/s00382-012-1571-1

Good, P., and Lowe, J., (2017). Assessment of the use of scaling and time-shifting methods to produce climate scenarios at or around 20C above pre-industrial levels. Met Office HCCP deliverable.

Herger, N., Sanderson, B. M., and Knutti, R., (2015). Improved pattern scaling approaches for the use in climate impact studies. Geophysical Research Letters, 42(9), 3486–3494. https://doi.org/10.1002/2015GL063569

Kendon, E. J., Roberts, N., Fowler, H., Roberts, M., Chan, S., and Senior, C., (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. Nature Climate Change. 4. 570-576. 10.1038/nclimate2258.

Mitchell, T. D. (2003). Pattern scaling - An examination of the accuracy of the technique for describing future climates. Climatic Change, 60, 217-242.

Morice, C. P., Kennedy, J. J., Rayner N .A., and Jones, P. D., (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset, J. Geophys. Res., 117, D08101, doi:10.1029/2011JD017187.

Murphy, J. M., Harris, G. R., Sexton, D. M. H., Kendon, E. J., Bett, P. E., Brown, S. J., Clark, R. T., Eagle, K., Fosser, G., Fung, F., Lowe, J. A., McDonald, R. E., McInnes, R. N., McSweeney, C. F., Mitchell, J. F. B., Rostron, J., Thornton, H. E., Tucker, S. and Yamazaki, K., 2018: UKCP18 Land Projections: Science Report.

Schleussner, C. F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Chiders, K., Schewe, J., Frieler, K., Mengal, M., Hare, W., Schaeffer, M., (2016). Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c. Earth System Dynamics, 7(2), 327–351. https://doi.org/10.5194/esd-7-327-2016

Appendix A: Evaluation of methodology using CMIP5

The methodology for validating the derived RCP2.6 data is to, in the first instance, produce data from the RCP8.5 projection of CMIP5 rather than GC3.05-PPE. The rational for this that model output is available for both scenarios for CMIP5 and so the production errors can be assessed. The evaluation of monthly data used here is an extension of that from Good and Lowe (2017) with a new approach used for the evaluation of daily data. No explicit evaluation of the time-slices is performed for two reasons. Firstly the process is the same as for the RCP2.6 without the additional assumptions about scaling of scenario results and so if the process is acceptable for RCP2.6 then we assume it holds for the time-slices. Secondly there are no model runs with constant global mean warming of 2°C or 4°C against which to perform any evaluation.

The main aim of the evaluation of monthly data was to assess if the 'projection errors' (the RMS difference between derived data and a climate model simulation of RCP2.6) are comparable to or smaller than those expected from internal variability. This is because an set of projections of RCP2.6 would only be better than our derived approach if the internal uncertainty from long-period internal variability was smaller than the prediction errors.

Internal variability between two 25-year periods in RCP2.6 is estimated by taking the final 50-years of each RCP2.6 run and splitting into odd and even years (giving two 25-year samples with almost identical time-mean climate, but differing internal variability). These two 25-year samples were compared with each other, using the same statistics used to assess prediction errors below. Results using this approach are denoted 'variability samples' below.

Differences, between the derived and actual RCP2.6 CMIP5 projections, have some uncertainty due to internal variability, and due to the finite sample of models. 2-sigma confidence intervals for each statistic are estimated by bootstrap resampling with replacement, sampling randomly from the ensemble of models. This assumes the available sample (here, the sample of CMIP5 climate projections) is representative of the underlying population (in this case all possible climate projections given the uncertainties in modelling these projections). Unlike parametric methods, bootstrap resampling does not require any assumption about the underlying statistical distribution, treating the available sample as if it was the underlying population. The bootstrap resampling is used to generate 1000 alternative random samples of CMIP5 models and calculate the RMS prediction error for which confidence intervals may be estimated.

Results from the main evaluation are shown in Figure 23 for the period 2075-2099 in which the mean difference from the time-shifting methodology across all projections is shown in blue. In general there is little evidence of significant mean, regional-mean bias in the estimated time-mean climate for temperature, precipitation, relative humidity ("hurs"), net downward short wave radiation and both components of surface wind (eastward "uas" and northward "vas") as well as total surface wind speed ("SfcWind"). With the exception of wind speed in October, the confidence intervals of the mean prediction errors overlap zero (i.e. the mean errors are not significantly different from zero). Further, the scatter in the prediction errors around zero is comparable with that from the variability samples from RCP2.6 (black). Given the potential, albeit apparently minor, shortcoming with the surface total wind speed we have decided to provide wind speed as component parts which do not show the same issue. The period 2050-2074 was also examined with similar results (not shown).

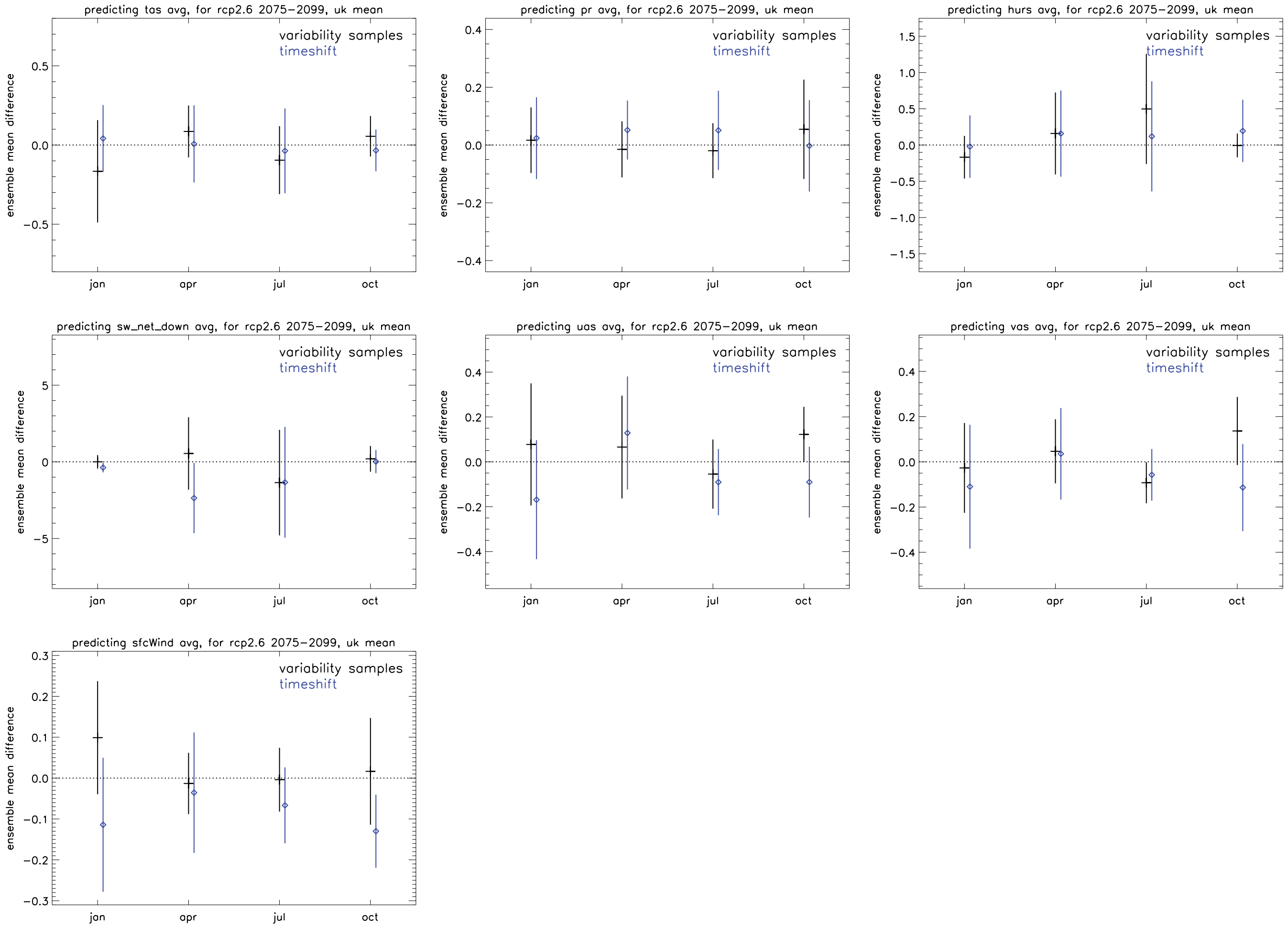


Figure 23. Testing for regional-mean multi-model mean bias. Results are regional-mean, multi–model mean differences between each prediction and RCP2.6 (blue), for predicting years 2075-2099 in RCP2.6. For comparison, differences are also shown for the variability samples (see text) from RCP2.6 (black). The 2-sigma confidence intervals are estimated using bootstrap resampling (see text). The same analysis of the period 2050-2074 was also examined with similar results (not shown).

To give extra context, prediction errors are also compared against the multi-model mean differences between RCP8.5 and RCP2.6 emissions scenarios at the end of the century. Using a comparator that comprises more than natural variability is a pragmatic choice equivalent to asking if the approximation approaches add an additional error that is small compared to other key uncertainties in future climate (squares in Figure 24). It is clear that for temperature both the natural variability and the RMS error from the approximation methods are much smaller than the RMS differences between different emission scenarios. For precipitation, this is also true for summer and winter but not in spring and autumn. This is presumably because the signal of change in this period is smaller and comparable to natural variability. Results for humidity, net downward short wave and total wind speed are qualitatively similar to precipitation in that for some months natural variability and the RMS error from the approximation methods are much smaller than the RMS differences between different emission scenarios, but in others, the signal of change in this period is smaller and comparable to natural variability. For the two components of wind speed the RMS error is comparable to that from scenario uncertainty, emphasizing the large degree of natural variability compared to any scenario dependent signal.

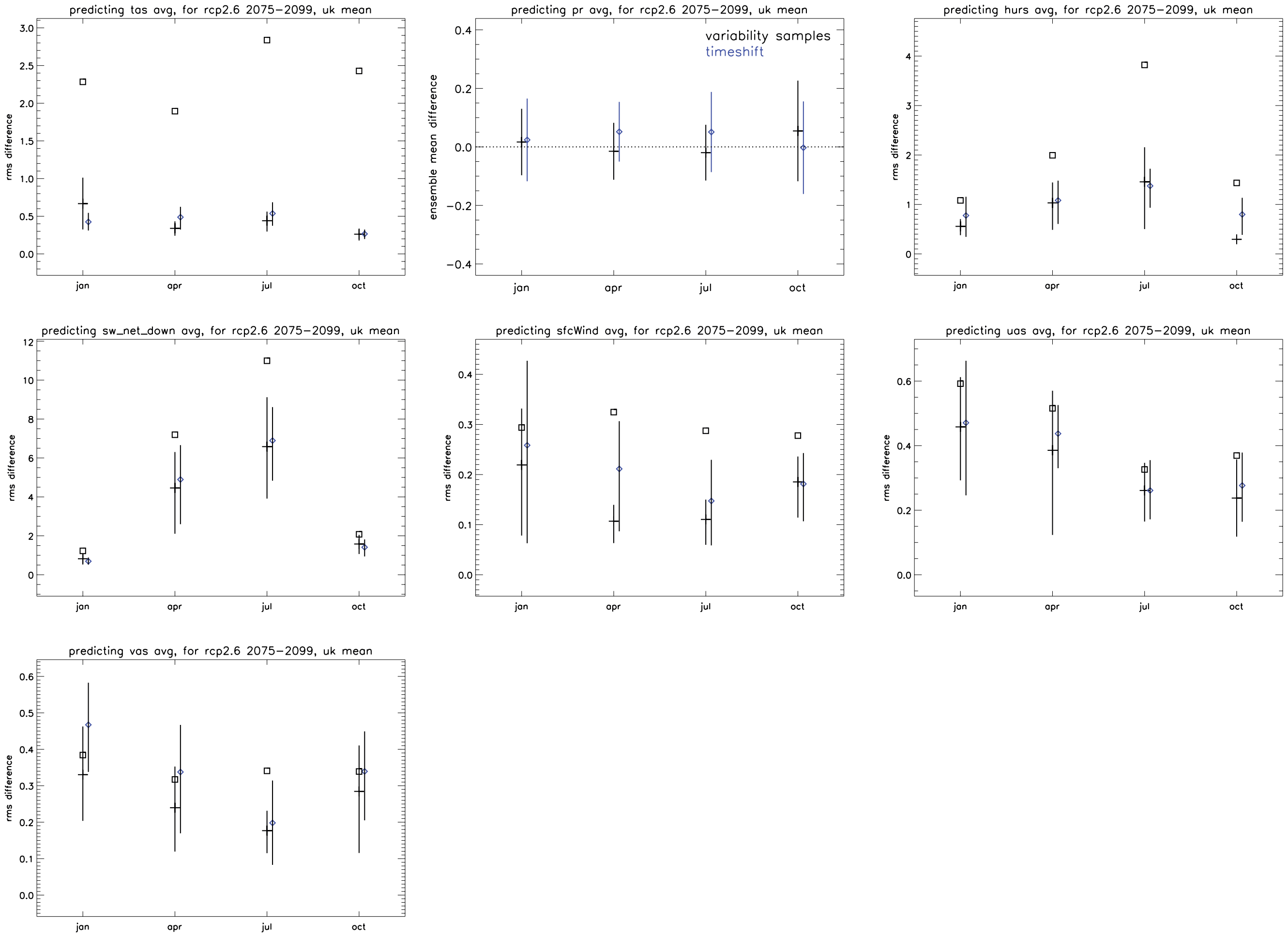


Figure 24. As Figure 23, but showing RMS differences instead of ensemble mean differences. Derived data blue; black: variability samples. In addition, RMS differences between RCP8.5 and RCP2.6 shown by squares.

The performance of estimated wind direction cannot be evaluated in the same way as for other variables (taking a time-mean wind direction does not make sense since, for example, wind angles of 359 and 0 degrees correspond to almost identical wind directions) so we perform two evaluations relevant to wind direction. First, the northward and eastward wind components have been evaluated separately by the standard method and are included in all subsequent evaluation. Secondly, differences in direction of the time-mean wind vector (between predictions and RCP2.6 and between the two variability samples) have been evaluated (Figure 25). This shows that the statistical distributions of differences in direction of the time-mean wind vector between the predictions and RCP2.6 (red and blue curves) are no larger in magnitude than expected from internal variability (black curves).

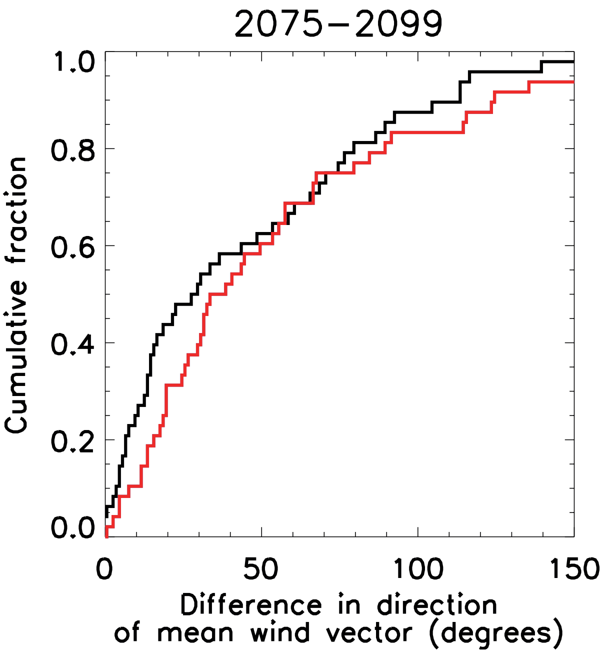
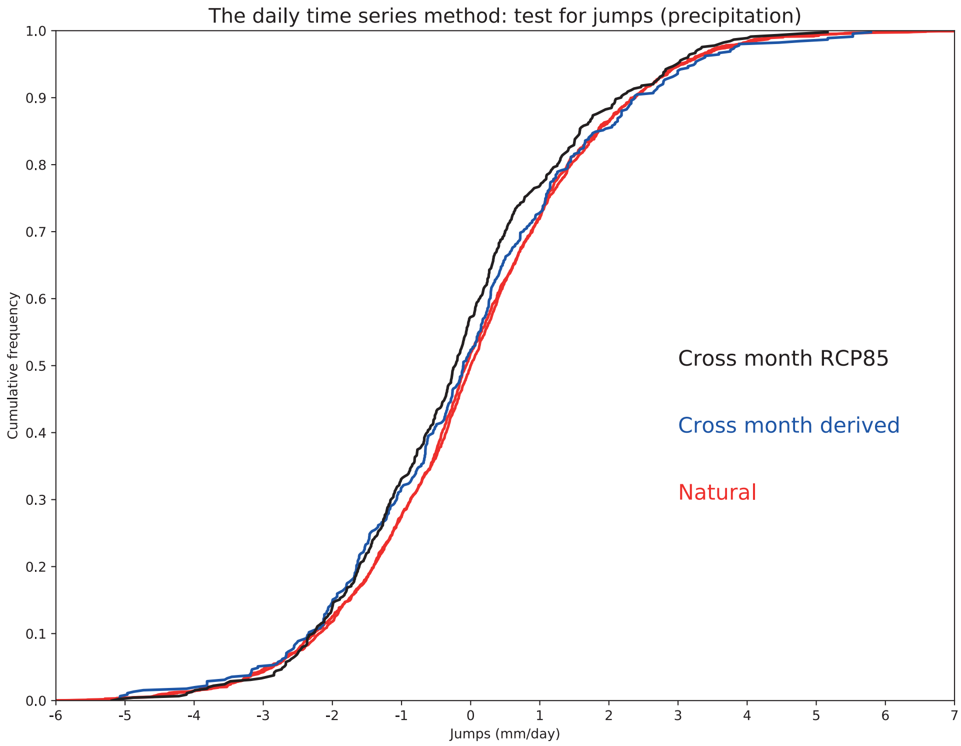


Figure 25. Cumulative distribution functions for the difference in direction of the time-mean wind vectors for (black) the two variability samples and the RCP2.6 data produced in this study (red). Results for the four months (Jan, Apr, Jul, Oct) from CMIP5.

The approach for constructing daily time series for the ensembles of time-slices at global mean warming levels of 2°C and 4°C, as well as the derived RCP2.6, involves a multivariate assessment of the monthly mean to select months from the RCP8.5 time series to use for daily data. This multivariate assessment preserves the consistency between variables in the daily data, but there is potential for there to be unrealistic jumps between months as different parts of the RCP8.5 daily data are joined together. To assess whether end of month jumps are statistically affected in the daily data produced, we look at the size of jumps between 5 day averages, building cumulative frequency distributions, and ask whether these are more different than expected from internal variability. In Figure 26 the distribution from 5 day blocks throughout all periods are shown (red) which includes the jumps between 5 day blocks within months. This is compared to the distribution of jumps between 5 days blocks at the end and beginning of consecutive months. Black shows the distribution from RCP8.5 and blue for the derived RCP2.6 daily data which would differ from that of RCP8.5 if the methodology for producing the daily data had introduced any bias at the transition between months. The good match between these two indicates that jumps are not an issue here statistically. However if a user application may be sensitive to such jumps we recommend further assessment of this issues with relation to the application.



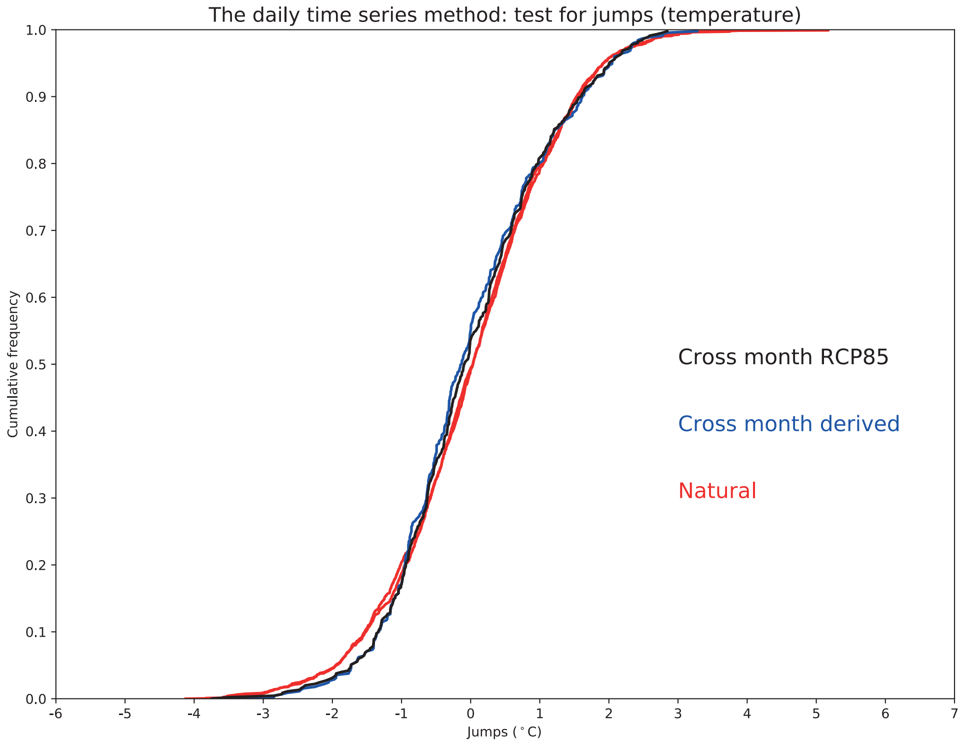


Figure 26. Cumulative frequency distribution of the jumps in precipitation (top) and temperature (bottom) between 5 days means of each variable. A distribution through all times of all months is shown in red, while one based only on 5 days means either side of a transition between months from RCP8.5 is shown in black. A similar distribution of the jumps at month transitions for the RCP2.6 data is shown in blue.

Consistancy between monthly means from daily and monthly methodology

As the daily data is taken from the RCP8.5 ensemble based on a multivaritate match to the monthly data, the daily data preserves the spatial coherence of each variable and the consistancy between daily data of different variables. However as even the best match of the monthly data will not be an exact match, the monthly means of the daily data will not match exactly with the monthly means which were calculated directly. This inconsistancy between data frequencies can be is dealt with in a number of ways which have different benefits and problems.

1). This could be ignored and users could simply be made aware of the differences between the daily and monthly mean data. This places the responsibility on the user to develop a solution.

2). The monthly data could be recalculated from the daily data. The would ensure consistancy between different frequencies of data available to users, but it would reduce the coherence between variables at the monthly level.

3). The daily data could be scaled to conserve the monthly mean values. This would retain the coherence between variables in the monthly data, but at the cost of changing the daily data, potentially intoducing less realistic daily variability.

To retain consistancy between frequencies of data and reduce user effort we have chosen to follow apporach 2) and recalculate the monthly mean data provided from the daily data for temperature and precipitation.

Appendix B: CMIP5 models included in analysis

Of the 42 CMIP5 models used to provide concentration-driven simulations under the RCP8.5 scenario, eleven were not considered, due to insufficient availability of daily data for a core set of impacts-relevant variables. The remaining 31 models were screened using a combination of global and regional performance criteria. Those passing the screening stage were clustered into groups of models sharing similar error characteristics, and the 13 selected models were then chosen by picking the best-performing model(s) in each group. Murphy et al, (2018) describe the selection procedure in detail. A list of the remaining models included in analysis in this report is given in Table 4.

Modelling group	Group acronym	Model designation
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CM*
Beijing Climate Centre, China Meteorological Administration	BCC	BCC-CSM1.1
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
This differes to LS2 approach of including the structural uncertainty from	CSIRO-BOM	ACCESS1-3*
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1-BGC*
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
EC-EARTH consortium	ICHEM	EC-EARTH**
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G
Met Office Hadley Centre	MOHC	HadGEM2-ES
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-MR
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR
Meteorological Research Institute	MRI	MRI-CGCM3
National Center for Atmospheric Research	NCAR	CCSM4

Table 4. The 13 CMIP5 models selected to contribute realisations of future climate. *No simulations of RCP2.6 performed. Derived data produced as per GC3.05. **No RCP2.6 data available through the Earth System Grid Federation (ESGF). Derived data produced as per GC3.05.

Acknowledgment

We thank the UKCP18 Peer Review Panel, chaired by Sir Professor Brian Hoskins, for their continued valuable input during the project, and specifically in reviewing and commenting on the final reports. The Peer Review Panel consisted Professor Mat Collins, Professor Jim Hall, Dr Ed Hawkins, Professor Gabi Hegerl, Dr Erik Kjellström, Professor Christoph Schär, Professor Ted Shepherd, Dr Claudia Tebaldi, Professor Dr Bart Van Den Hurk and Prof Sybren Drijfhout.

The UKCP18 Project is part of the Met Office Hadley Centre Climate Programme funded by BEIS and Defra.