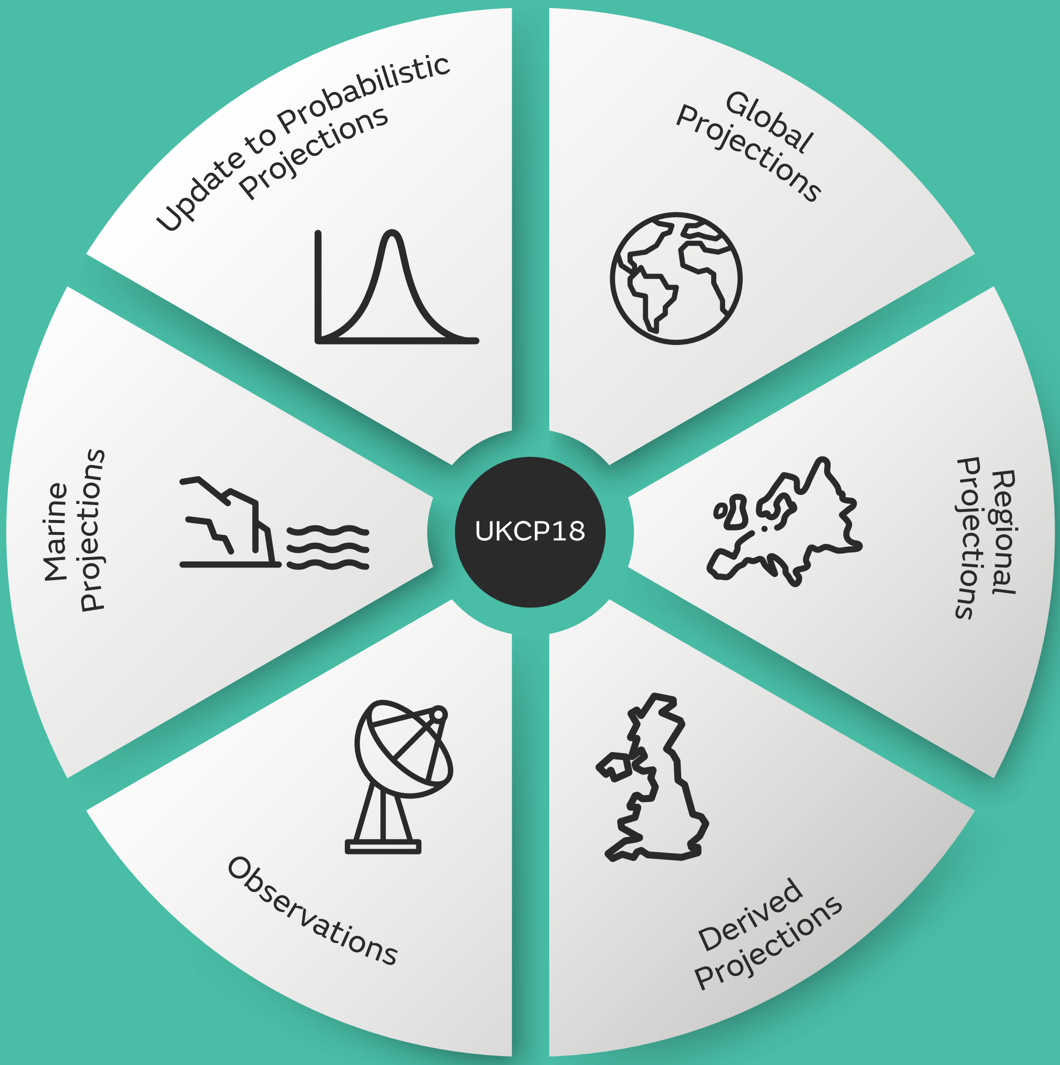
Department for Environment Food & Rural Affairs
Department for Business, Energy & Industrial Strategy
Met Office Hadley Centre
Environment Agency

UKCP18 Science Overview Report

November 2018 (Updated March 2019)



Jason A. Lowe, Dan Bernie, Philip Bett, Lucy Bricheno[1], Simon Brown, Daley Calvert, Robin Clark, Karen Eagle, Tamsin Edwards[2], Giorgia Fosser, Fai Fung, Laila Gohar, Peter Good, Jonathan Gregory, Glen Harris, Tom Howard, Neil Kaye, Elizabeth Kendon, Justin Krijnen, Paul Maisey, Ruth McDonald, Rachel McInnes, Carol McSweeney, John F.B. Mitchell, James Murphy, Matthew Palmer, Chris Roberts, Jon Rostron, David Sexton, Hazel Thornton, Jon Tinker, Simon Tucker, Kuniko Yamazaki, and Stephen Belcher.

[1] National Oceanography Centre, Liverpool, UK [2] King's College, London, UK

Version 2.0

---

www.metoffice.gov.uk

Contents

Summary

UKCP18 provides a new set of climate projections and tools to access climate data. The major innovations in UKCP18 include the use of new observations of weather and climate, inclusion of a more recent generation of climate models from around the world and the results from latest Met Office global and regional climate models. The involvement of users in the design of UKCP18 has been greater than for previous UK climate projections, such as UKCP09.

UKCP18 climate projections consist of: updated probabilistic projections, giving estimates of different future climate outcomes; a new set of global climate model projections, comprising simulations from both the latest Met Office Hadley Centre climate model and global climate models from around the world; and a set of regional climate model projections on a finer scale (12km) for the UK and Europe. The global and regional model projections offer users the ability to better explore climate variability and changes, including retaining spatial coherence and the relationship between different climate metrics. Whilst these are not intended to be used to derive a probability distribution of model response, they will allow users to explore alternative climate futures in more detail than the probabilistic projections. Later we will provide a further set of projections produced with a model of horizontal scale 2.2km, which is better able to represent some small-scale processes seen in the atmosphere, such as those important for large convective storms in the summer. UKCP18 projections for the seas around the UK comprises: new estimates of the time-mean sea level rise around the UK coastline; exploration of the possible changes in future storm surge and tides and new information on the change in sea surface waves. Alongside the projections are new observations of UK climate, which are described in the State of the UK Climate 2017 report (Kendon et al, 2018). These observations and linked attribution studies show that the UK climate has already changed, with evidence that some changes over the UK are at least partly connected to increases in greenhouse gas concentrations in the atmosphere.

Some of the UKCP18 products provide results for a range of future emission scenarios going from a situation where global emissions of greenhouse gases rapidly peak and decline towards the ambitious climate targets in the Paris climate agreement, to a case where increased use of fossil fuels leads to higher greenhouse gas emissions.

The main findings from an initial analysis of UKCP18:

- Observations for the UK show that the most recent decade (2008-2017) has been on average 0.3 °C warmer than the 1981-2010 average and 0.8 °C warmer than 1961-1990. All of the top ten warmest years have occurred since 1990.
- In the past few decades there has been an increase in annual average rainfall over the UK, particularly over Scotland for which the most recent decade (2008–2017) has been on average 11% wetter than 1961–1990 and 4% wetter than 1981-2010. However, natural variations are also seen in the longer observational record. The observations made in the future will be dependent on both long-term climate trends and natural variability.

<u>Projected future changes over land areas:</u>

- Overall the probabilistic projections in UKCP18 show ranges that have a large overlap with those from UKCP09, but with some notable differences in the tails of the projected distributions.

- Over land the projected general trends of climate changes in the 21st century are similar to UKCP09, with a move towards warmer, wetter winters and hotter, drier summers. However, natural variations mean that some cold winters, some dry winters, some cool summers and some wet summers will still occur and users may need to factor this into decision-making.

- In UKCP18, the probabilistic projections provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of average warming between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to 0.7°C to 4.2°C in winter, and 0.9°C to 5.4°C, in summer. For precipitation, corresponding ranges of UK average changes are -1% to +35% for winter, and -47% to +2% for summer, where positive values indicate more precipitation and negative values indicate reduced precipitation.

- Hot summers are expected to become more common. In the recent past (1981-2000) the probability of seeing a summer as hot as 2018 was low (<10%). The probability has already increased due to climate change and is now estimated to be between 10-25%. With future warming, hot summers by mid-century could become even more common (with probabilities of the order of 50% depending on the emissions scenario followed).

- Additionally, UKCP18 simulates sub-seasonal and sub-monthly extremes of climate and their changes, such as daily extreme temperature and rainfall. There is also the potential for future changes in the time spent experiencing different types of weather regimes. These can be examined using the new global and regional projections.

Future changes at the coast and in the sea:

- UK coastal flood risk is expected to increase over the 21st century and beyond under all emission scenarios considered. This means that we can expect to see both an increase in the frequency and magnitude of extreme water levels around the UK coastline. This increased future flood risk will be dominated by the effects of time-mean sea level rise, rather than changes in atmospheric storminess associated with extreme coastal sea level events. There may also be changes in tidal characteristics.

- 21st century projections of time-mean sea level change around the UK vary substantially by emissions change scenario and geographic location. The very likely ranges for UK capital cities at 2100 are summarised below for each scenario included in this report.

	Sea level change at 2100 (m) relative to 1981-2000 average		
	RCP2.6	**RCP4.5**	**RCP8.5**
London	0.29-0.70	0.37-0.83	0.53-1.15
Cardiff	0.27-0.69	0.35-0.81	0.51-1.13
Edinburgh	0.08-0.49	0.15-0.61	0.30-0.90
Belfast	0.11-0.52	0.18-0.64	0.33-0.94

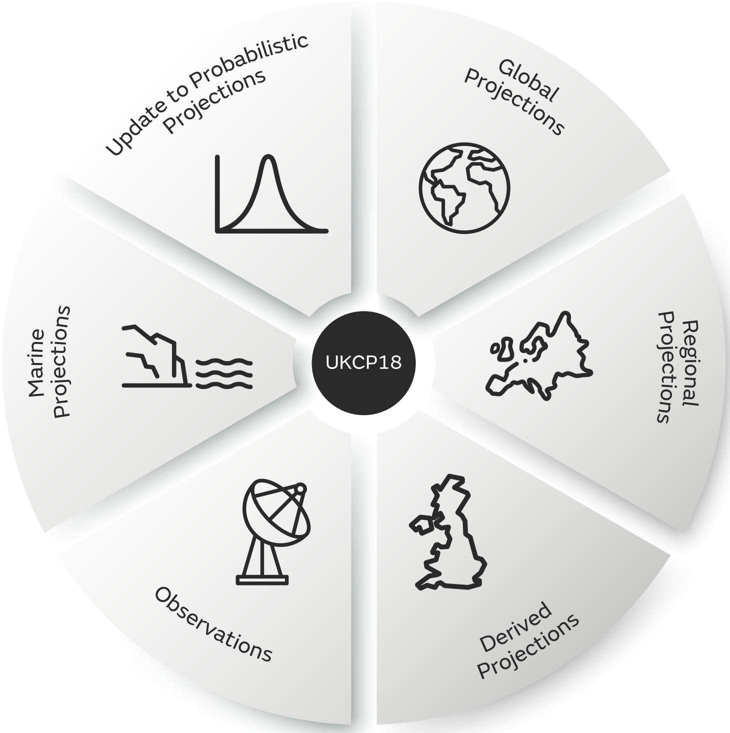
- The risk of coastal flood events will rise with the projections of increase in time-mean sea level. However, based on storm surge modelling work, we suggest a best estimate of no significant additional increase in the statistics of extreme water levels associated with atmospheric storminess change. The largest trend found in our set of surge simulations of this additional component corresponds to a change of approximately 10 cm per century for the 1-year return level, which is considerably less than the time-mean sea level change under the same emission scenario. However, we cannot rule out larger trends in storm surge due to this additional component. The additional component could be either positive (augmenting the mean sea level change) or negative (partially offsetting the mean sea level change).
- 21st century projections of average wave height suggest changes of the order 10-20% and a general tendency towards lower wave heights. Changes in extreme waves are also of order 10-20%, but there is little agreement in the sign of change among the model projections. High resolution wave simulations suggest that the changes in wave climate over the 21st century on exposed coasts will be dominated by the large-scale response to climate change. However, more sheltered coastal regions are likely to remain dominated by local weather variability.
- Exploratory, time-mean sea level projections to 2300 suggest that UK sea levels will continue to rise over the coming centuries under all emission scenarios considered. For London the projection ranges at 2300 are approximately 0.5 - 2.2m and 1.4 - 4.3m for the lowest and highest emission scenarios, respectively. The values for Edinburgh and Belfast are lower. The projections extending beyond 2100 should be considered as illustrative of the potential future changes.

Users of UKCP18 are provided with a number of web-based tools to access the knowledge and data. All users will have access to a website containing high-level statements on future climate, similar to and expanding on those in this summary, alongside guidance notes on different climate metrics and how to use the different UKCP18 products. This website also contains more detailed reports on the land and sea projections, the limitations of the climate information and FAQs. More technical users can choose to access a user interface to interrogate aspects of the UKCP18 data and tailor the outputs to their needs, such as choosing to look at a particular region. The most advanced technical users and the research community can also directly access climate model output, and are recommended to read both the land and marine science reports (Murphy et al, 2018; Palmer et al, 2018).

1. Introduction

UKCP18 provides new projections of how climate might change in the UK over coming decades and covers both land areas and the seas around the UK. The projections are produced using computer models of the atmosphere and oceans, which capture recent understanding of how the climate system works. The projections are accompanied by observations of the state of the UK climate, which is published by the Met Office on an annual basis (Kendon et al, 2018). The study of observations show numerous and consistent changes in the UK climate over recent decades. Several attribution studies have found that some, but not all, changes in the UK climate can already be connected to increases in greenhouse gas concentrations in the atmosphere.

The UKCP18 projections form an update of the UKCP09 products and have been produced because of user demand for new capability and the opportunities for improved simulations provided by the latest generation of climate models and advances in the capacity of supercomputers. The climate information products available in UKCP18 are summarised in the infographic below.



It is not possible to give a precise prediction of how weather and climate will change years into the future so UKCP18 provides ranges that aim to capture a spread of climate response based on current knowledge, and using a particular set of methodologies developed by the Met Office and collaborators. Users can explore the types and magnitudes of climate change that are projected for the future. Depending on the purpose and the level of risk aversion, users may choose to focus on the full range of outcomes or pay particular attention to parts of the projected range such as the largest projected changes. It is important to understand that natural day-to-day, month-to-month and year-to-year variations in weather and climate will occur in the future on top of long-term climate trends.

Thus, whilst the projections show trends towards a greater frequency of warmer weather, there will still be the possibility of cold periods driven by the natural weather variations. The extent of future climate change will be strongly affected by the amount of greenhouse gases that the global population chooses to emit in future years. If society significantly reduces emissions compared to present-day the climate changes will be lower than if it continues to increase emissions of greenhouse gases. Many users might want to compare potential futures with different levels of emissions.

In the near-future (a few years and possibly up to a decade or more, depending on the metric of interest and spatial scale considered) predictions and projections are dominated by natural variations in weather and climate when measured relative to a recent baseline period of 1981-2000. However, as we look further into the future a large body of research has found that the trends of a changing climate becomes more obvious and pronounced. In UKCP18, the projections over land show a trend towards warmer temperatures throughout the century, with more warming in the summer. The warming is expected to be greatest in the southern UK but the difference between southern and northern UK warming may not be particularly large. UKCP18 also projects a trend towards a greater chance of more rainfall in the winter but less rainfall in the summer. For both temperature and rainfall the changes are much larger if greenhouse gas emissions are assumed to continue to increase.

The marine projections show a continuation and likely acceleration of the sea level rise observed around the UK, and even if emissions are significantly reduced this century the sea level rise will continue well beyond year 2100. Alongside the increases in time-mean sea level there will be increases in extreme coastal water levels, driven mainly by the rise in mean sea level rather than changes in storminess. Changes in tidal characteristics and waves may also occur in the seas around the UK, with increases and decreases both possible, depending on location.

Together, the observations and projections can be used as one source of information when planning for the future, or as a communication tool. Whilst the projections represent the latest scientific understanding it is important to keep in mind the caveats and limitations of the projections and methods used. Although the academic community's understanding and ability to simulate the climate is advancing all the time, models are not able to represent all of the features seen in the present-day real climate. This means that users including the climate projections in their decision-making need to consider how best to factor the capabilities and limitations into the choices they make, informed by a thorough understanding of the consequences of different climate outcomes – perhaps including those beyond the ranges of uncertainty presented here. This is not an easy task and some users may need to perform or commission further research to fully understand how climate variability and change will affect them. Some further advice is provided in the user guidance.

Whilst the remit of providing projections for UK climate variability and change was established by Defra, a peer review panel has provided an important input in steering the direction of the research and production of the projections. In particular, the peer review panel has provided advice to the project team to refine scientific decisions, reviewed the scientific outputs of the project and commented on their presentation, for instance at annual workshops and via written reports to the project's Governance Board. This was complemented by the input from two user groups, which included policy-makers, academics, consultancies, utility companies and other users. It is the view of the Met Office that these inputs have improved both the scientific quality of the UKCP18 products and their usability.

Many of the methods are based on existing scientific literature. However there are also new cutting-edge techniques used. Over the coming months and years the science teams responsible for production of the results will be publishing more of the results in the peer reviewed scientific literature. However, we are also keen that the community of users contributes to the evidence base on the quality and utility and the projections by putting their own analyses into the public domain.

2. Climate change over land

UKCP18 provides a number of tools to investigate climate variability and change over the UK land areas. First, it provides a new set of probabilistic projections that combine information from several collections of computer models, including those used to inform the IPCC 5th assessment (IPCC, 2013), with observations using advanced statistical methodologies. The approach involves using many different variants of a particular computer model of the climate (HadCM3) to simulate a wide range of different climate outcomes; this is known as a perturbed parameter ensemble (PPE). A statistical emulator is then set up to estimate climate outcomes for a much greater number of climate model variants. This distribution of outcomes is adjusted (both in the mean and the spread) by taking account of the diversity provided by structurally different climate models feeding into the most recent IPCC climate assessment. Finally, the projected outcomes are weighted by comparing the model simulations of historical climate with observations from the real world, so that some model variants are down-weighted and others given more weight. This is achieved within a well-defined formal Bayesian statistical framework. These estimates of the ranges of future climate are available for several alternative future scenarios of emissions, including RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Unlike UKCP09, which focused on 30-year mean probabilistic projections, the new UKCP18 projections are available for each month and season for each future year and so take better account of year-to-year variability in climate, which can be very important for decision-making. This broadens the probability estimates.

The significant advances of UKCP18 over previous probabilistic projections provided in UKCP09 are: the inclusion of simulated natural interannual variability; the inclusion of models from the most recently completed IPCC assessment report (the so called CMIP5 models, compared to CMIP3 models used in UKCP09); a more comprehensive sampling of Earth System modelling uncertainty; and more up-to-date observational constraints (including new metrics that account for the ocean heat uptake and atmospheric carbon dioxide concentrations). UKCP18 also includes improvements to the detailed methodological approach, including the statistical aspects of the methodology.

The second component of UKCP18 is a new set of global climate model projections that allows users to look at spatially coherent changes of the future at scales down to around 60km and a greater number of climate metrics than the probabilistic projections. There are 28 projections of future climate for the RCP8.5 emissions scenario, comprised of a set of 15 projections from the new Met Office Hadley Centre climate model (HadGEM3-GC3.05) plus a set of 13 projections from models that informed the IPCC 5th assessment (CMIP5). Together, the two sources of model projection provide a greater span of outcomes than either set of models could alone. The GC3.05 simulations were produced by generating a perturbed parameter ensemble (PPE) to yield different but plausible variants of the model. This set was filtered using comparisons with observations, the scientific literature and expert judgement to leave models that give plausible simulations of climate from 1900 to present, whilst maximising diversity of the spread in the future projections. The CMIP5 model projections were also filtered to retain only the most plausible models. The GC3.05 set is noticeably warmer in the future global average than the CMIP5 set. However, both sets are compatible with the statements made by the IPCC in the 5th assessment report about ranges of future warming for the RCP8.5 emission scenario. The spatial scale of the underlying models varies from around 150km for the coarsest CMIP5 model projections down to 60km for the GC3.05 model projections, but for the convenience of users the results have all been placed on the same 60km grid. A set of global projections was not provided as part of UKCP09 and this new product was requested by users to allow the investigation of international impacts, including those that then affect the UK, such as through international food availability or price.

The inclusion of GC3.05 is also a major step forward because it produces a better representation of many aspects of European weather compared with earlier models, including a better representation of storm tracks and UK precipitation variability. However, this improved performance needs to be balanced by the fact that in the model versions used here the simulation of the second half of the 20th century is towards the colder end of the range covered by the CMIP5 models, whilst the rate of future warming is towards and above the higher end of CMIP5 models. When considering the global mean climate warming response near the surface it is important to recognise that whilst this is a common metric for comparing climate models, and is used extensively in discussions of mitigation of emissions, it is only a crude indicator of climate model performance. The global climate model simulations of the recent and historic period have been evaluated against observations for a wide range of metrics in the land science report (Murphy et al, 2018).

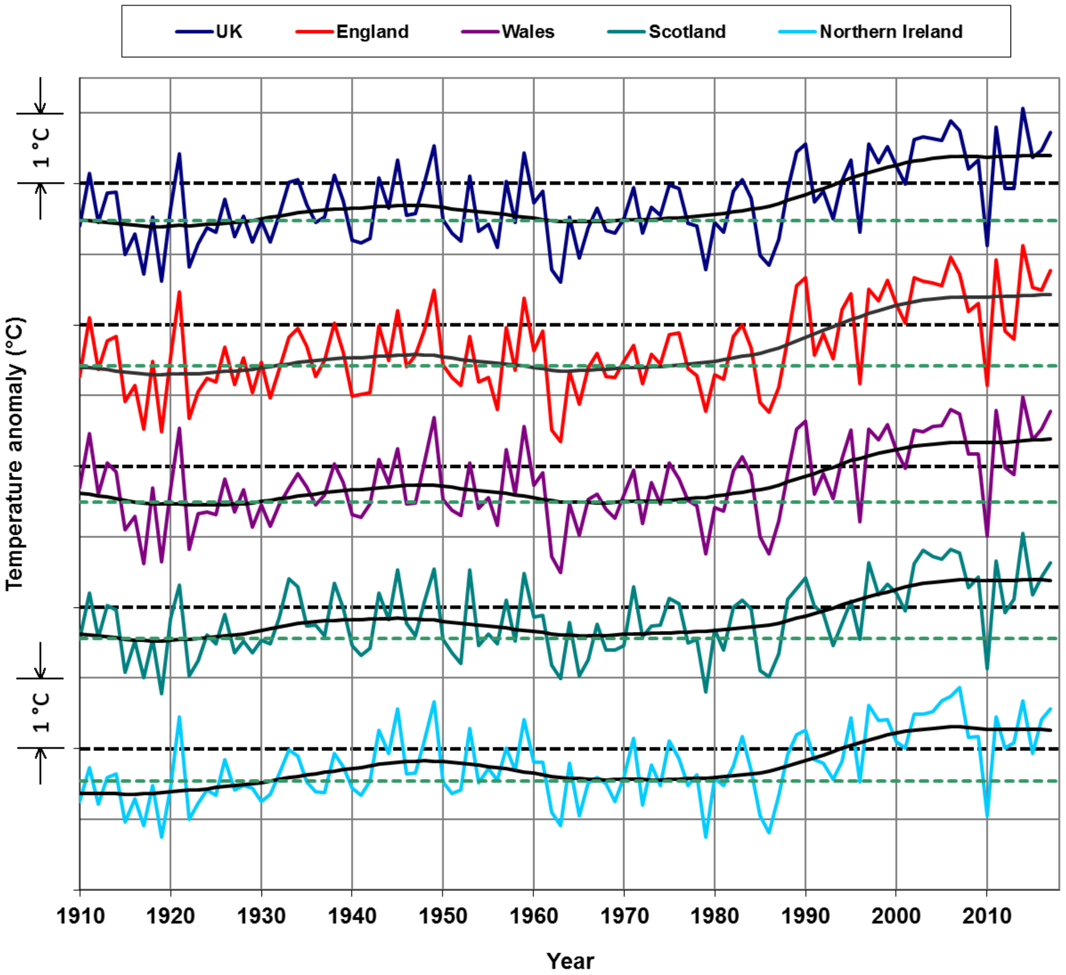
The third component of UKCP18 are a set of regional climate model projections. Initially we have released twelve projections at 12km spatial resolution over Europe. This set has greater spatial detail than the 25km model used in UKCP09 and benefits from a range of model improvements, described in detail in the land science report. There is also a major benefit that the regional model is driven at its boundaries by the GC3.05 global model, which leads to improvements in the information entering the regional domain. However, this must be set against the disadvantage that GC3.05 only samples the warmer end of the range of global outcomes. This means that the set of regional simulations will not cover the full range of outcomes simulated by the 28 global climate projections for the RCP8.5 scenario. At a later stage we will also release additional simulations for the UK at a finer scale of 2.2km, which is near to that used for weather forecasts and can explicitly simulate convective storm events in the atmosphere and sub-daily weather information. Evaluation information on the regional models is also documented in the land science report (Murphy et al, 2018).

2.1. Observed climate change over the UK

Examining observations of the climate allows us to place the modelled climate into context. There is a comprehensive set of observations of weather and climate covering the UK, with some of the records now extending back for more than 150 years. The Central England Temperature series provides evidence that the early 21st century has been warmer than the previous three centuries. Attribution analysis of this temperature record shows a significant contribution to the warming coming from human driven emissions of greenhouse gases (e.g. Karoly and Stott, 2006). The State of the UK Climate 2017 (Kendon et al, 2018) provides the most recent annual update and interpretation of UK observations.

The majority of the State of the UK Climate 2017 report is based on observations of temperature, precipitation, sunshine and wind speed from the UK land weather station network managed by the Met Office and a number of key partners and co-operating volunteers. The observations conform to current best practice observational standards as defined by the World Meteorological Organization (WMO). The observations also pass through a range of quality assurance procedures at the Met Office before application for climate monitoring. In addition to the atmospheric measurements, time series of near-coast sea-surface temperature and sea level rise are also considered. Details of how to access observational data are provided on the UKCP18 website.

The most recent decade (2008-2017) has been on average 0.3 °C warmer than the 1981-2010 average and 0.8 °C warmer than 1961-1990. Nine of the ten warmest years for the UK have occurred since 2002 and all the top ten warmest years have occurred since 1990. Year 2017 was the fifth warmest for the UK in a series from 1910, and eighth warmest for Central England in a series from 1659. Additionally, the most recent decade (2008-2017) has had 5% fewer days of air frost and 9% fewer days of ground frost compared to the 1981-2010 average, and 15% / 14% compared to 1961-1990 (Figure 2.2).

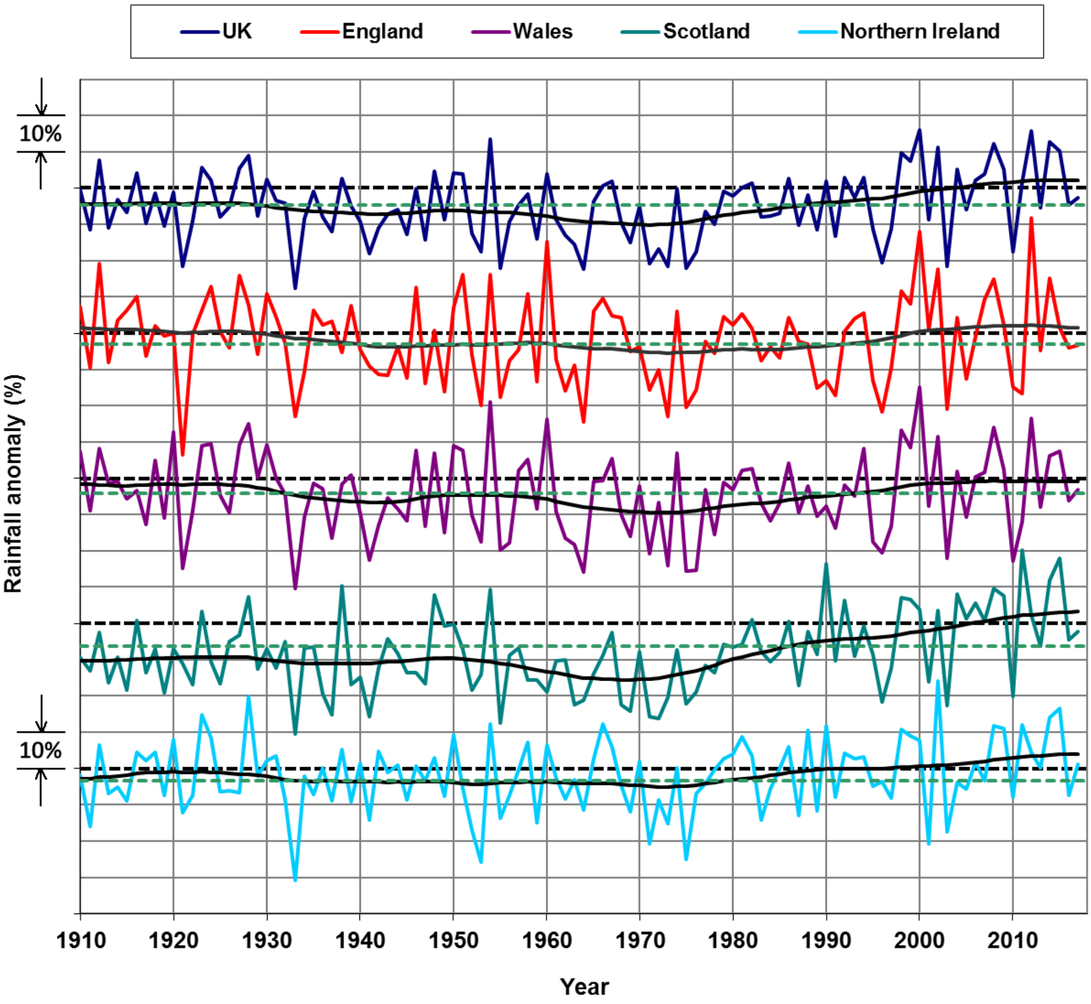


Area	1961-1990 average	1981-2010 average	2008-2017 average	2017
UK	8.3	8.8	9.1	9.6
England	9.1	9.7	10.0	10.4
Wales	8.6	9.1	9.4	9.9
Scotland	7.0	7.4	7.7	8.0
Northern Ireland	8.4	8.9	9.1	9.5

Figure 2.2. Annual mean temperature for the UK and countries, 1910–2017, expressed as anomalies relative to the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of±1ºC. The table provides average. The plot shows several different areas which are offset for clarity and ease of comparison; the offsets do not reflect absolute differences between the time-series. Smoothed trend lines were calculated using a weighted kernel filter as described in Kendon et al, 2018.

In the past few decades there has been an increase in annual average rainfall over the UK, particularly over Scotland for which the most recent decade (2008–2017) has been on average 11% wetter than 1961–1990 and 4% wetter than 1981-2010 (Figure 2.3). Rainfall in 2017 for the UK overall was 97% of the 1981-2010 average but seven of the ten wettest years for the UK have occurred since 1998.

Focusing on the seasonal changes, the two recent winters of 2013-2014 and 2015-2016 stand out as the highest in the dataset, each with over 150% of the 1981-2010 average UK rainfall overall. Also of note is the run of recent wet summers; of the last ten summers from 2008 to 2017, only summer 2013 has seen a UK rainfall total below the 1981-2010 average. Thus, UK summers for the most recent decade (2008 to 2017) have been on average 20% wetter than 1961-1990 and 17% wetter than 1981-2010. Long time-scale natural variations are also seen in the observational record.



Area	1961-1990 average	1981-2010 average	2008-2017 average	2017
UK	1101	1154	1185	1124
England	828	855	874	827
Wales	1400	1460	1453	1416
Scotland	1472	1571	1628	1534
Northern Ireland	1099	1136	1200	1150

Figure 2.3. Annual rainfall, 1910–2017, expressed as a percentage of the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±10%. The table provides average values (mm).

The most recent decade (2008–2017) has had for the UK on average 6% more hours of bright sunshine than the 1961–1990 averages and 3% more than the 1981-2010 average. These trends are particularly evident in winter and spring with 14% and 11% more sunshine than the 1961-1990 average respectively. There are no compelling trends in storminess as determined by maximum gust speeds from the UK wind network over the last four decades.

A supplementary report to the State of the UK Climate was produced summarising observed changes in climate extremes over the period 1961-2017. (Met Office, 2018). That report provides a collection of standardised indices relating to climate extremes derived from observations of UK temperature and rainfall. The World Climate Research Programme (WCRP) and World Meteorological Organization (WMO) expert team on climate change detection and indices (ETCCDI1) coordinate, organise and collaborate on climate extremes, indices and climate change detection. This team have defined a set of 27 core indices.

The hottest day of the year for the most recent decade (2008-2017) has been on average 0.8 °C above the 1961-1990 reference. The warm spell duration index in the most recent decade (2008-2017, 13.2 days) is more than double that of the 1961-1990 reference (5.3 days). The lowest temperature of the year has increased by 1.7 °C when comparing the most recent decade (2008-2017) with the 1961-1990 average. A much larger increase than the equivalent change in the mean temperature of the UK.

The amount of rain from extremely wet days has increased by 17% when comparing 2008-2017 with the 1961-1990 period. Changes are largest for Scotland and not significant for most of southern and eastern areas of England. Other extreme rainfall indices exhibit large inter-annual variability but are broadly consistent with increased rainfall over the UK.

2.2. Probabilistic projections of future UK climate

The probabilistic projections in UKCP18 are an update of those produced for UKCP09. The probabilities presented can be interpreted as being an indication of how much the evidence from climate models and observations taken together in our methodology support a particular future climate outcome. The median can be considered the level for which as much evidence points to a lower outcome as a higher one. There is much stronger evidence that an outcome will be in the 5th to 95th percentile range than in either the upper or lower tails of the distribution.

There has been discussion in the scientific literature about whether model uncertainty estimates are reliable indicators of the real world, and whether or not they should be used in decision-making. The UKCP18 team acknowledges that the estimated ranges for future climate are conditioned on a set of modelling, statistical, and dataset choice assumptions with expert judgement playing a role in the various methodological and data choices. As the science evolves some of these preferred choices will also change, which will lead to new estimates of uncertainty. There are also some aspects of climate and climate change that are not yet represented well in any climate model. The team commissioned to produce UKCP18 believe that based on current knowledge the UKCP18 outputs best capture the range of potential future climate outcomes. UKCP18 can provide an important ingredient to future adaptation planning but users are always encouraged to think of the appropriate decision framework for their particular problem, with its unique consequences of choosing particular actions and particular acceptable risk levels. For instance, it may be desirable to perform sensitivity checks looking at the consequences of changes beyond those used from the probabilistic projections. Some users are also already recognising that some adaptions can follow more flexible approaches to decision making, acknowledging that not all decisions or components of decisions need to be taken immediately.

The future change in climate over the UK will depend strongly on future emissions of greenhouse gases (see Box on greenhouse gas consistent scenarios). For any given scenario of future emissions and climate metric we project a spread in modelled outcomes, which is affected by both our current understanding of climate and how we represent it in our models, and by natural climate variations. For a given time horizon the relative importance of these terms varies with the particular metric considered and the spatial scale considered – typically with more impact from natural variability on smaller spatial scales. The results account for uncertainties in both physical and carbon cycle feedbacks.

Temperature is a very important climate metric. Many other climate metrics scale with temperature change, and temperature is associated with a range of potential impacts such as heat stress on humans and an increased need for cooling. Extremes of temperature can have major impacts on infrastructure, including transportation. Changes in precipitation (rainfall and snowfall) can also have many impacts including flooding and drought, which may have consequences on human health, infrastructure and the natural capital of the UK. UKCP18 projected temperature and precipitation changes meaned over the UK region are shown below in Tables 2.1 and 2.2 for the mid and late 21st century, with changes measured relative to a 1981-2000 baseline. The evolution over time of the uncertainty range is shown in Figure 2.4. The SRES A1B emission scenario was used in UKCP09 and is retained here for continuity, although we recommend new users focus on the newer RCP scenarios.

Future emissions of greenhouse gases

The future change in climate projected by models in UKCP18 is strongly dependent on global greenhouse gas emissions in the future.

UKCP09 used a set of three alternative views of future greenhouse gas emissions drawn from a set called SRES. The middle scenario, used in many studies that applied UKCP09, was called SRES A1B. The Special Report on Emission Scenarios (SRES) scenarios did not consider recent developments in climate change mitigation and many of their assumptions on the evolution of technologies, such as renewable energy generation, are now out of date. UKCP18 uses scenarios for future greenhouse gases called the representative concentration pathways (RCPs) which were designed to cover a more up to date range of assumptions around future population, economic development and to explicitly include the possibility of mitigation of greenhouse gas emissions towards international targets (Moss et al, 2010).

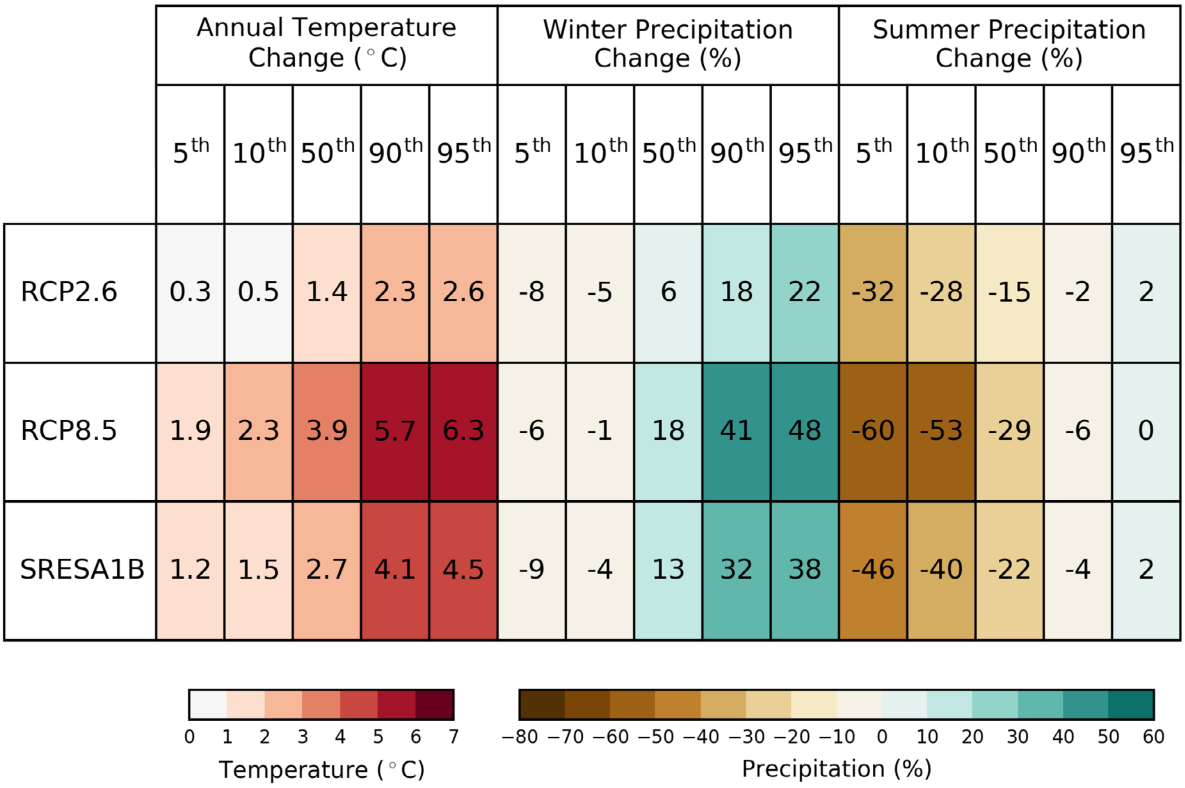
The RCPs are expressed for future radiative forcing targets in 2100 of 2.6, 4.5, 6.0 and 8.5 watts per square metre (W m-2), and these targets are incorporated into the names of the RCPs; RCP2.6, RCP4.5, RCP6.0 and RCP8.5 pathways. Each pathway drives a different range of projected global mean temperature increases over the 21st century, taking account of uncertainty in aspects such as the transient climate response and rate of ocean heat uptake. The RCP pathways lead to a broad range of climate outcomes but are neither forecasts nor policy recommendations.

RCP2.6 represents a future in which the world aims for and is able to implement sizeable reductions in emissions of greenhouse gases. Many studies show that following this scenario gives a sizeable chance of limiting global average warming to near 2°C above pre-industrial levels, which is also (at the time of writing this document in 2018) consistent with the long-term target specified in the UK Climate Change Act. Some simulations in the published literature also suggest the RCP2.6 scenario could produce a response as low as the more ambitious target in the Paris climate agreement, which includes provision to aim for limiting warming to below 1.5°C.

RCP8.5 represents a world in which global greenhouse gas emissions continue to rise. It is a potential future where the nations of the world choose not to switch to a low-carbon future. The temperature increases associated with this are much higher than RCP2.6.

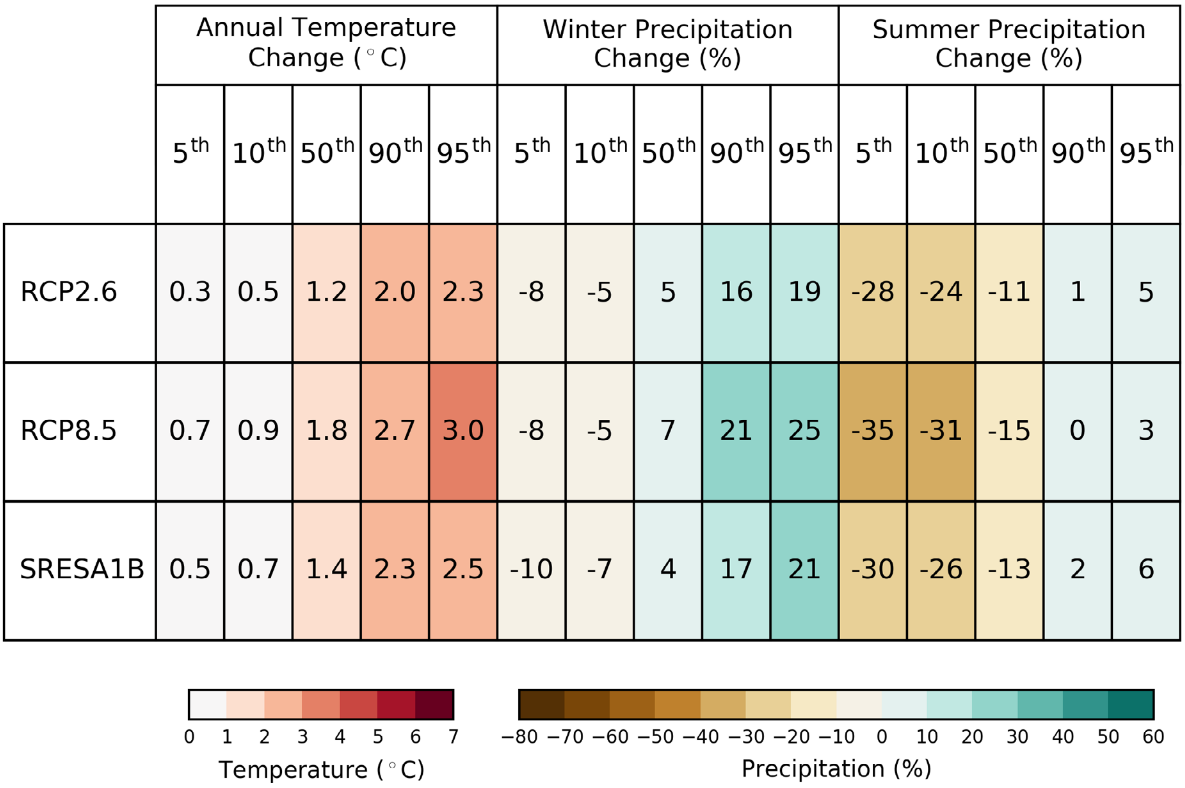
The Paris climate agreement, signed by many of the world's greenhouse emitting nations beginning in 2015, includes pledges to reduce emissions. In most cases the emission pledges, which have not yet been fully implemented, extended to year 2030. The eventual global average temperature rise by 2100 will be dependent on whether the pledges are implemented and perhaps tightened, and what the emissions are between 2030 and 2100. Therefore, UKCP18 includes two additional scenarios between the RCP2.6 and RCP8.5 scenarios called RCP4.5 and RCP6.0. If, after 2030, no further emission reductions are achieved but emissions do not rise then a number of studies suggest the temperature outcome of RCP4.5 may be the most likely. However, RCP6.0 allows for some further increase in emissions.

The four RCPs considered in UKCP18 attempt to capture a range of potential alternative futures, spanning a range of outcomes. However, due to methodological limitations not all scenarios are available for every UKCP18 product. Furthermore, the real world may follow a different emissions pathway altogether. Users wishing to consider their vulnerability to future weather and climate may wish to consider all of the scenarios available, with adaptation to the climate response of an RCP8.5 future representing a more precautionary view of future for future emissions. The scientific community can not reliably place probabilities on alternative scenarios, and so can not say which scenario of greenhouse gas emission is most likely.



	Annual Temperature Change (°C)					Winter Precipitation Change (%)					Summer Precipitation Change (%)				
	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th
RCP2.6	0.3	0.5	1.4	2.3	2.6	-8	-5	6	18	22	-32	-28	-15	-2	2
RCP8.5	1.9	2.3	3.9	5.7	6.3	-6	-1	18	41	48	-60	-53	-29	-6	0
SRESA1B	1.2	1.5	2.7	4.1	4.5	-9	-4	13	32	38	-46	-40	-22	-4	2

Table 2.1. Projected change in temperature and precipitations for the UK region from 1981-2000 to 2080-2099 using the probabilistic projections.



	Annual Temperature Change (°C)					Winter Precipitation Change (%)					Summer Precipitation Change (%)				
	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th	5th	10th	50th	90th	95th
RCP2.6	0.3	0.5	1.2	2.0	2.3	-8	-5	5	16	19	-28	-24	-11	1	5
RCP8.5	0.7	0.9	1.8	2.7	3.0	-8	-5	7	21	25	-35	-31	-15	0	3
SRESA1B	0.5	0.7	1.4	2.3	2.5	-10	-7	4	17	21	-30	-26	-13	2	6

Table 2.2. Projected change in temperature and precipitations for the UK region from 1981-2000 to 2041-2060 using the probabilistic projections.

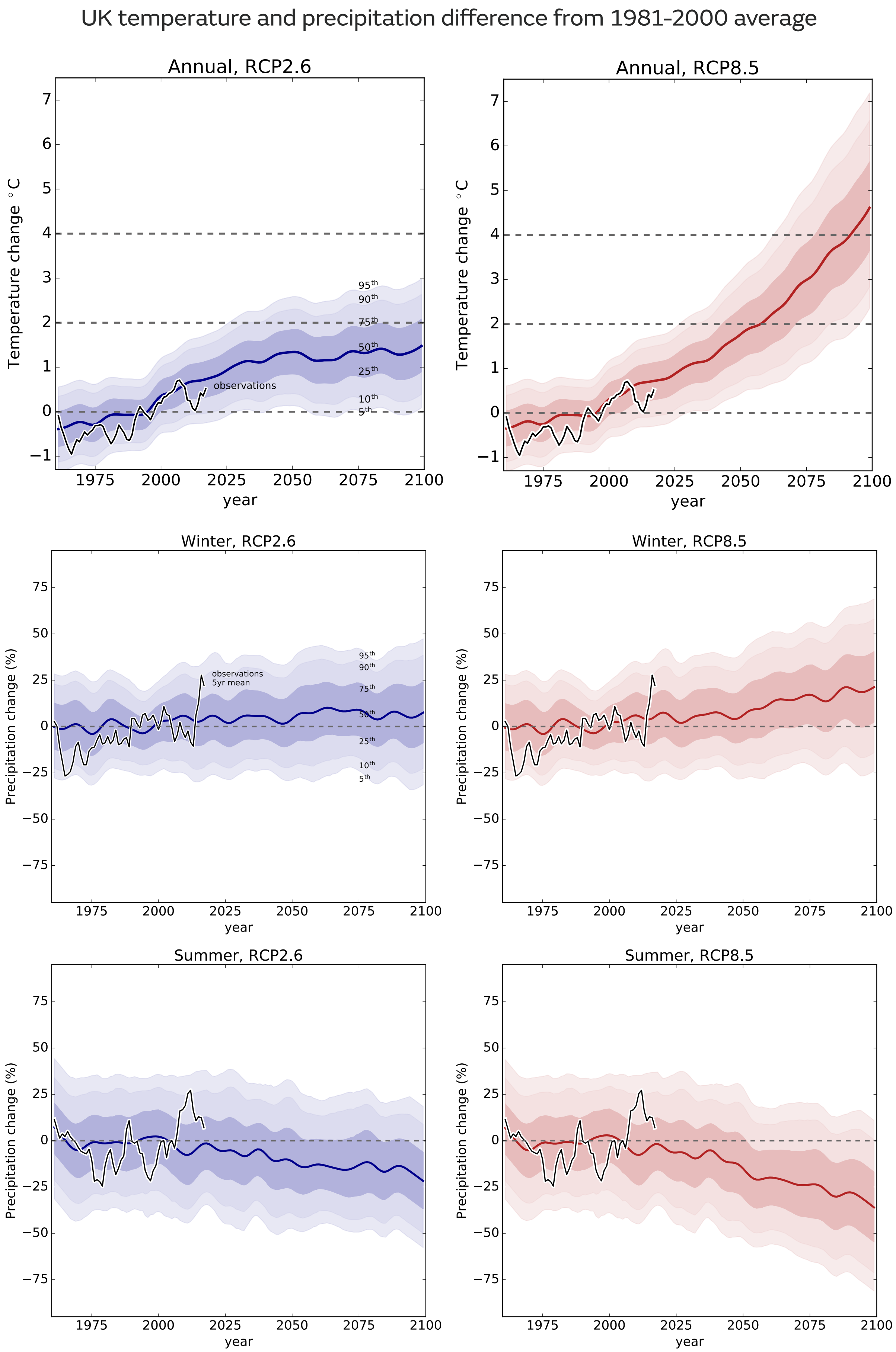


Figure 2.4. UKCP18 UK area mean temperature (top row) and percentage precipitation changes (lower two rows) for the lowest emission scenario (RCP2.6, blue) and highest emission scenario (RCP8.5, red). The shading boundaries show the 5th, 10th, 25th, 50th (median, central solid line), 75th, 90th, and 95th percentiles. NCIC observations (https://www.metoffice.gov.uk/climate) are shown as a black line for the historical part of the curves. Values are expressed relative to the 1981-2000 baseline used in UKCP18 projections.

For many users, climate at the mid-21st century may be more important to consider. For temperature, and for scenarios with emissions that remain high throughout the century these are typically much lower than the end of century values. For the RCP2.6 scenario, in which emissions rapidly reduce after present-day, the difference between mid and late 21st century warming is much less.

It is possible to estimate and present changes for the UK mean climate change in several different ways. Tables 2.1, 2.2 and Figure 2.4 first calculate the mean change over the UK for the different climate metrics then estimate the probabilistic spread in these UK mean quantities. An alternative is to use the gridded probabilistic results to calculate spatial means of particular local percentiles, such as the 10th, 50th and 90th percentiles. For the latter approach we draw directly from the land science report for the 2061-2080 period and the RCP8.5 scenario. There is a range of warming of 0.7°C to 4.2°C in winter, and 0.9°C to 5.4°C, in summer. For precipitation, corresponding ranges of UK average changes are -1% to +35% for winter, and -47% to +2% for summer, where positive values indicate more precipitation and negative values indicate reduced precipitation. The ranges in this example correspond to the 10th to 90th percentile spread.

Many users may be most interested in the spatial variation of projected climate changes over the UK regions. Ranges are shown in Figure 2.5 to 2.10 for several metrics temperature and precipitation metrics. These results do not retain the spatial coherence, meaning that, for instance, the 90th percentile for one location might not occur at the same time as the 90th percentile at another location.

The seasonal mean temperature maps show the strong emissions scenario dependency seen earlier in the UK area mean results. When compared to the pattern of response earlier in the century it is again clear that the separation of scenario responses becomes more pronounced during the second half of the 21st century. The warming amount is different in the summer and winter, with more warming in the summer leading to a greater amplitude in the seasonal cycle of temperature than at present. Some regional variations in warming can also be seen and are most evident in the summer and at higher percentile results. The pattern manifests as a north-south warming gradient, with greater warming in the south. In the winter the regional variations in warming are less clear but there is some evidence of enhanced warming over parts of Scotland in some scenarios and at some percentile levels.

The increase in the 50th percentile result for the summer mean of the daily maximum temperatures is slightly greater than for corresponding daily mean temperatures. For each emissions scenario the spread of the results is also greater for the maximum temperature than for the daily mean. Changes in the winter mean of daily minimum temperatures are on a par with the change in the mean daily temperatures but the spread of results appears larger.

Patterns of change in winter precipitation appear less emissions scenario dependent for the 10th and median outcomes but for the 90th percentile, which represents a rainfall increase, the scenario dependence is clearer and changes are larger for the higher emission scenario. There are some notable features in the patterns, particularly the smaller increase in rainfall in the 90th percentile over Scotland, and some evidence of larger increases in the South of England.

Spatial variations of summer precipitation changes show a more pronounced emissions scenario dependence and spatial pattern. The reduction in summer rainfall in the 10th percentile is greatest in the highest emissions scenario and shows a strong north-south gradient, with more reductions in rainfall in the south. The small increases in summer rainfall in the 90th percentile are largest in the lower emissions scenarios, and there is again evidence of a north-south gradient with lower increases to the north.

Although the results are presented for individual 25km areas it is recommended that users applying any of the UKCP18 projections need to consider several 25km model grid boxes when using the results. Ideally, users need to compare their particular location with the wider context provided by looking at the broader scale.

Overall, the projections show a trend towards a higher frequency of warmer and wetter winters. Cold winters and drier winters will still occur as a result of natural variations in the climate system but we expect them to be less frequent. In summer, the trend is towards a greater frequency of hotter and drier summers, but again with some colder summers and some wet summers. These trends are broadly consistent with UKCP09, which may partially reflect that we have improved the methods used to generate the probabilistic scenarios rather than producing a completely new approach. We have only shown a small subset of the results here. Users can reproduce these types of plots for their own preferred variables, future periods and present-day baselines using the web-based tools available as part of UKCP18.

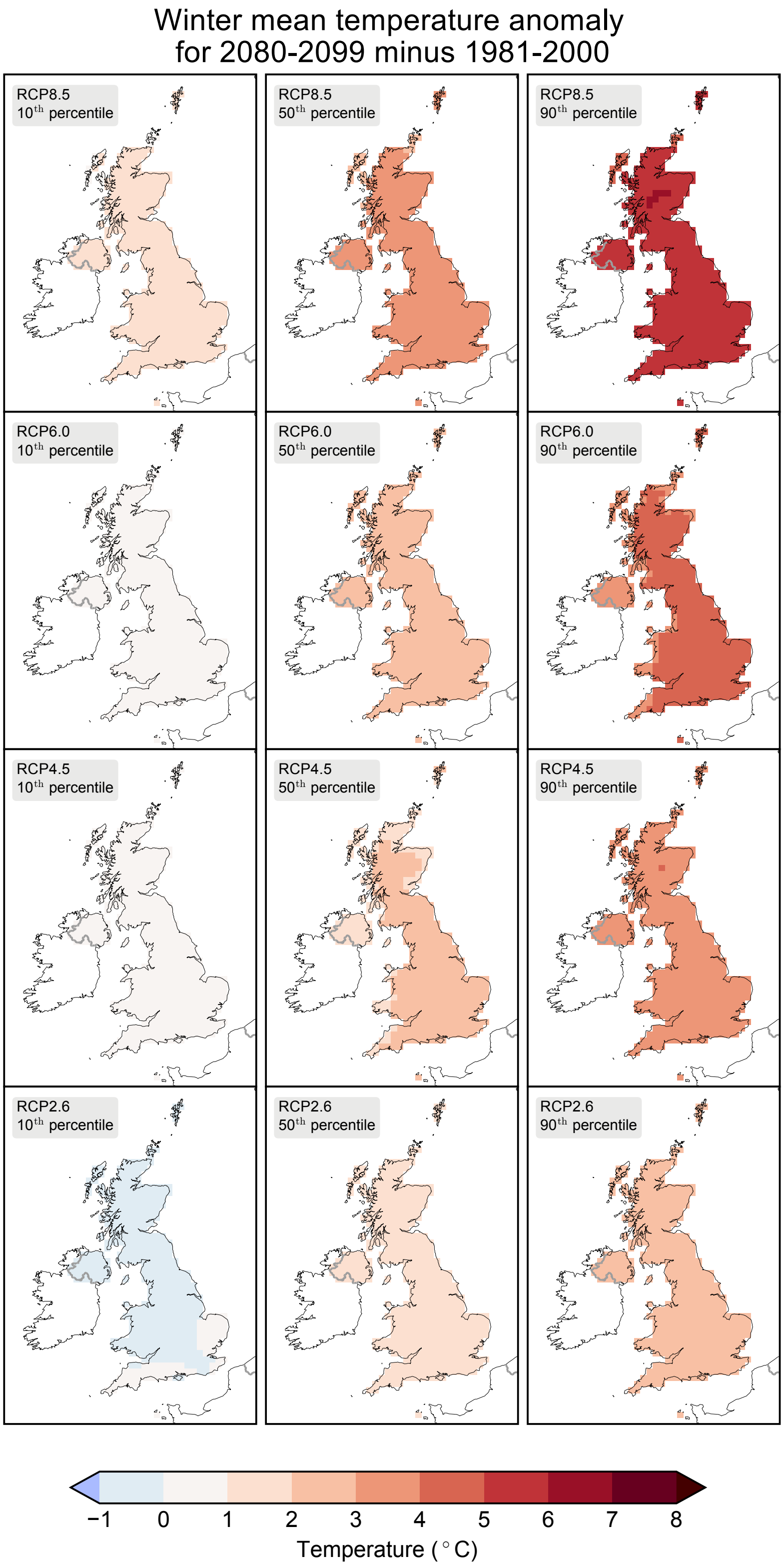


Figure 2.5. Changes in 20-year mean winter temperature for 4 emissions scenarios using in UKCP18 (from top, RCP8.5, RCP6.0, RCP4.5 and RCP2.6) in °C. Results are shown for the 10th (left column), 50th (middle column) and 90th (right column) percentile outcomes. They cover the period 2080 to 2099 relative to a 1981-2000 baseline.

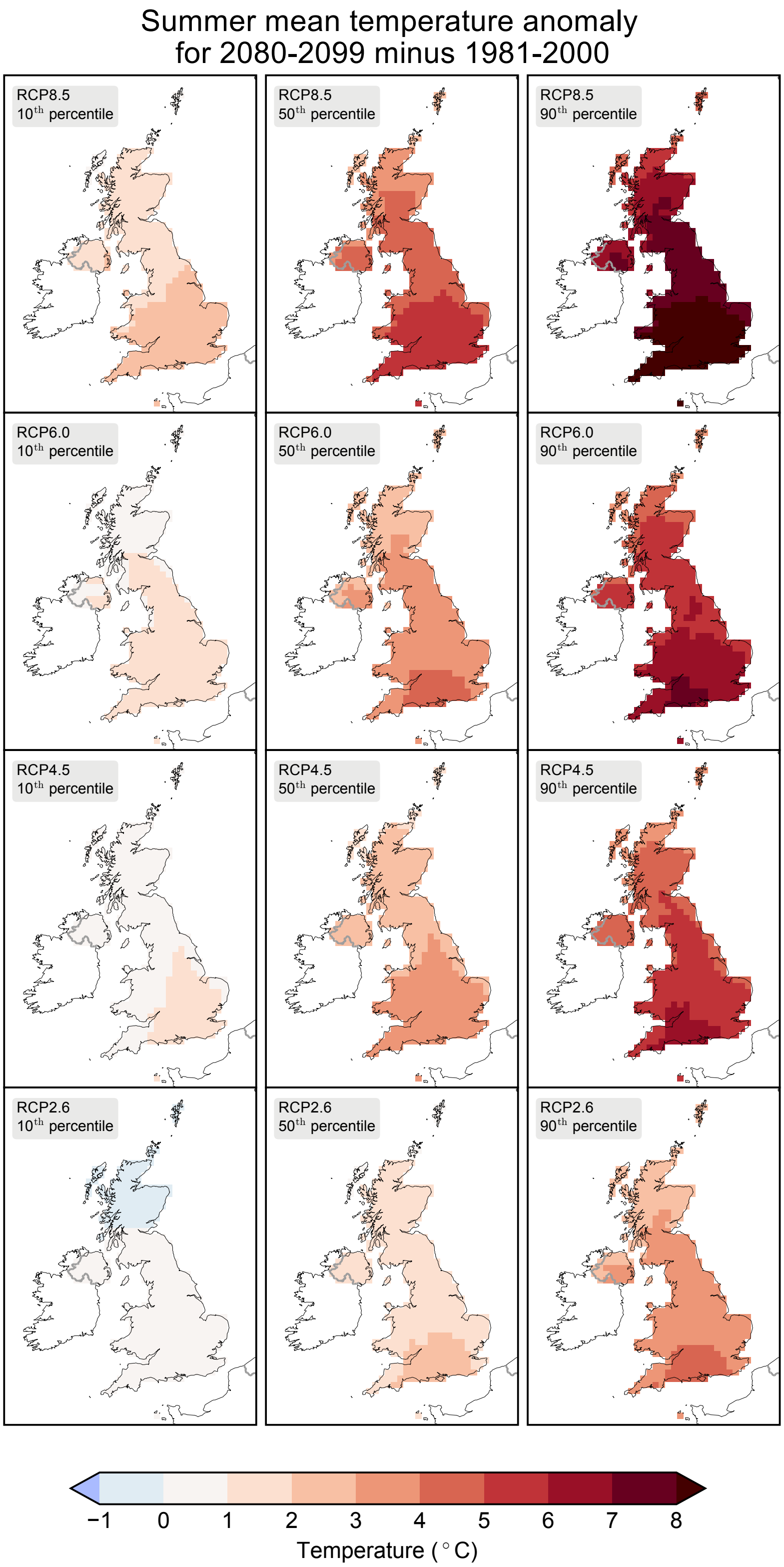


Figure 2.6. As 2.5, but for summer.

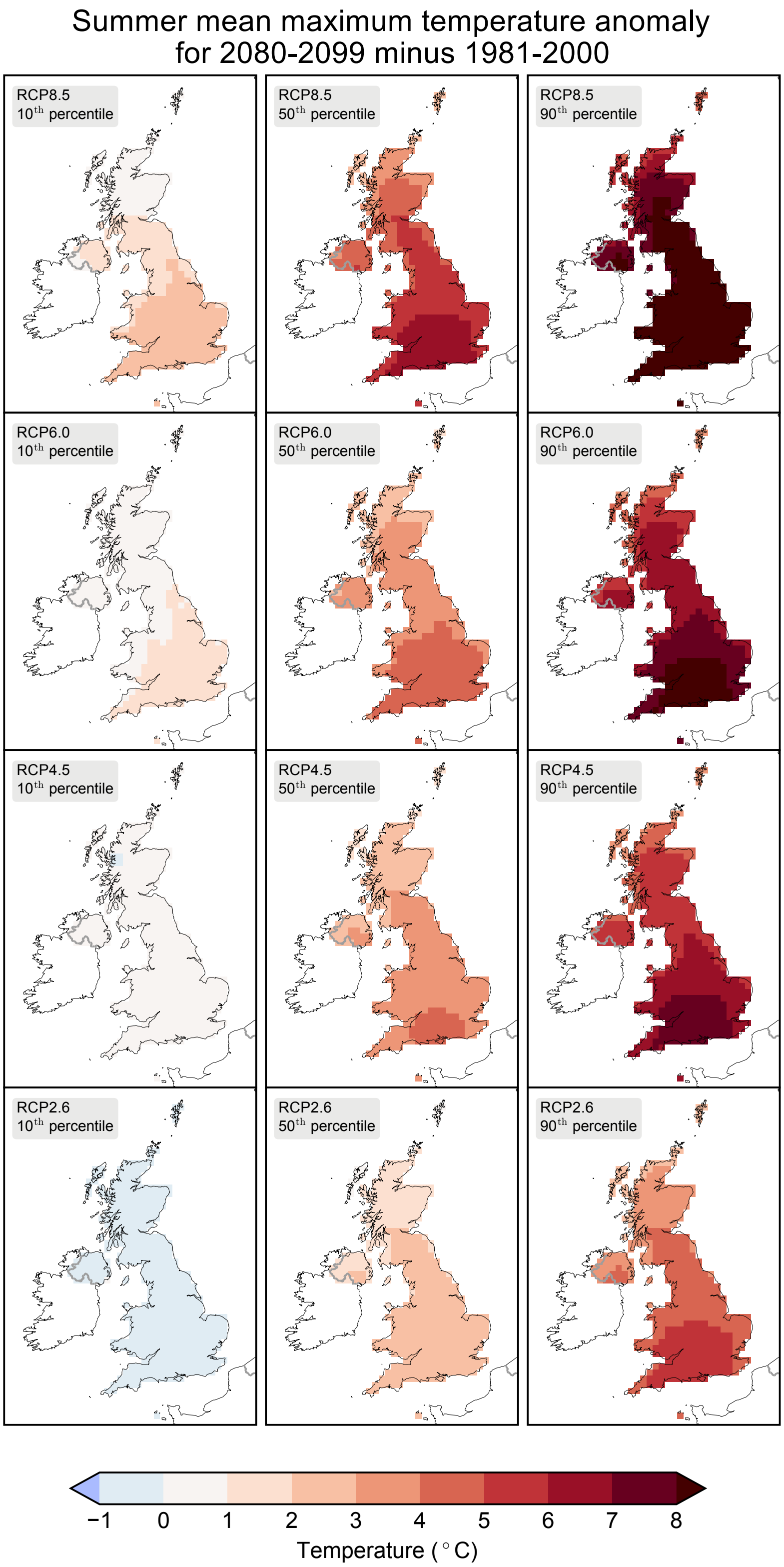


Figure 2.7. As 2.5, but for changes in the 20-year mean of summer daily maximum temperatures.

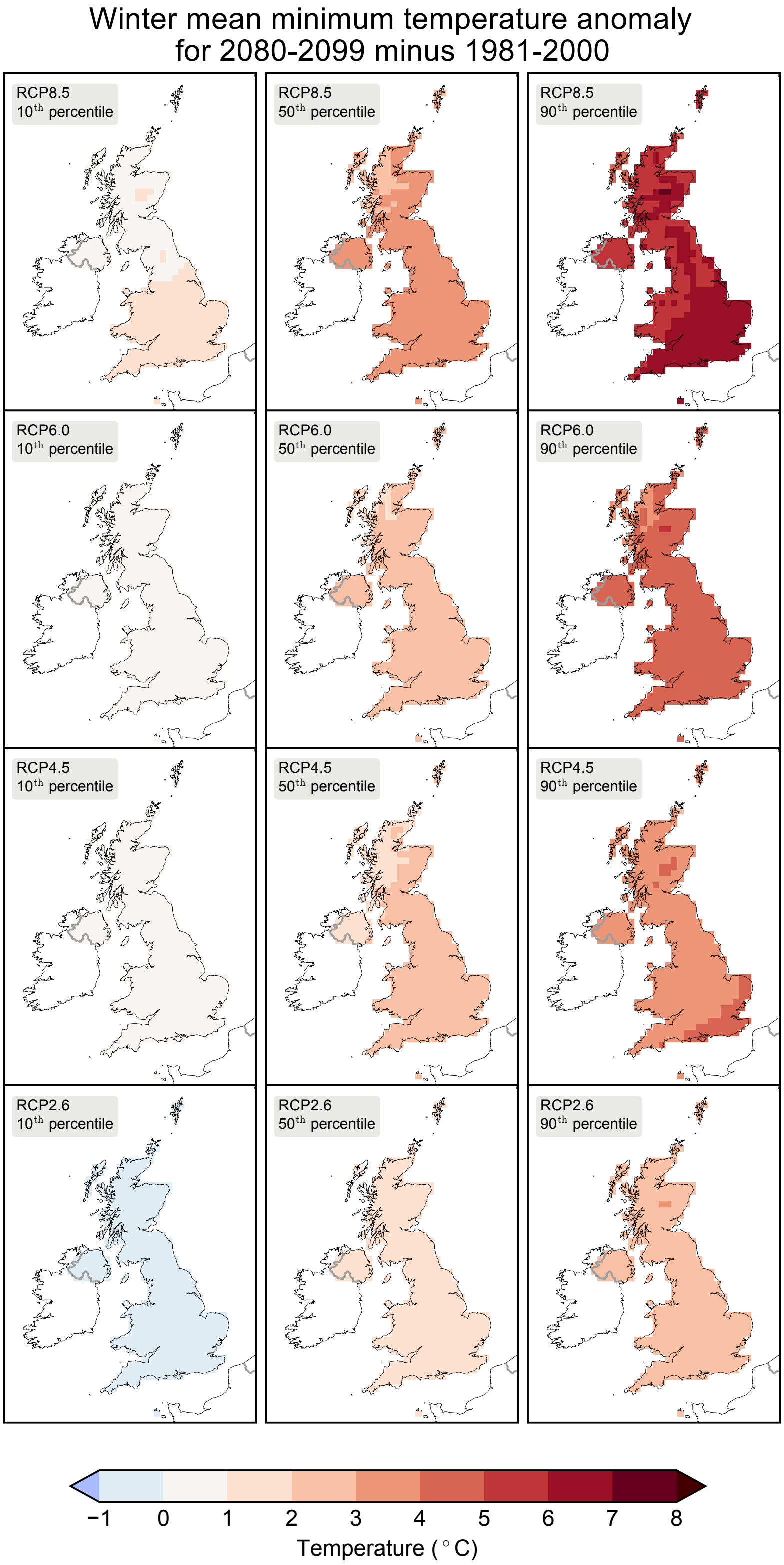


Figure 2.8. As 2.5, but for changes in the 20-year seasonal mean of winter daily minimum temperatures.

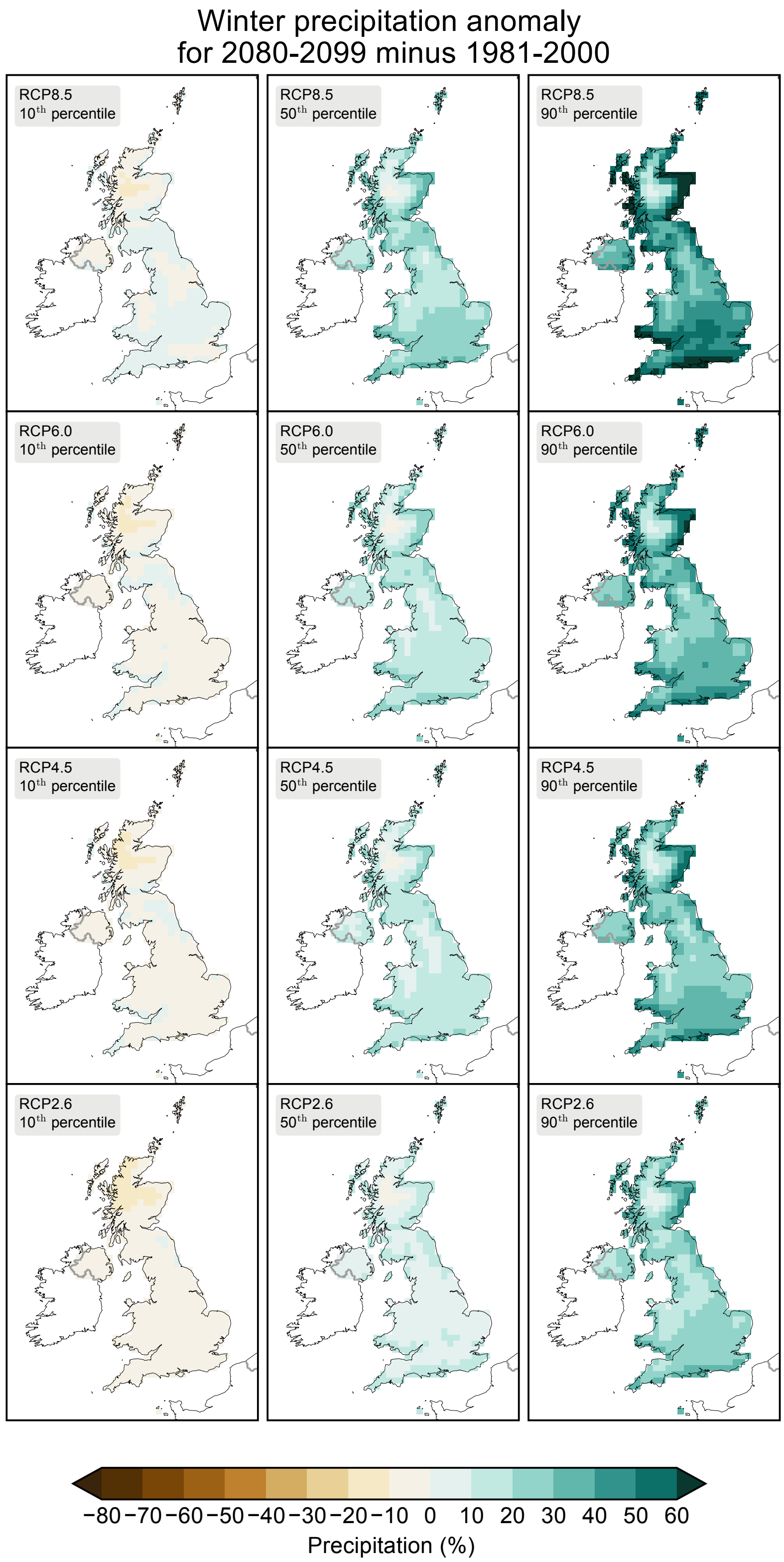


Figure 2.9. As for 2.5 but for changes in the 20-year seasonal mean of winter seasonal mean precipitation (%).

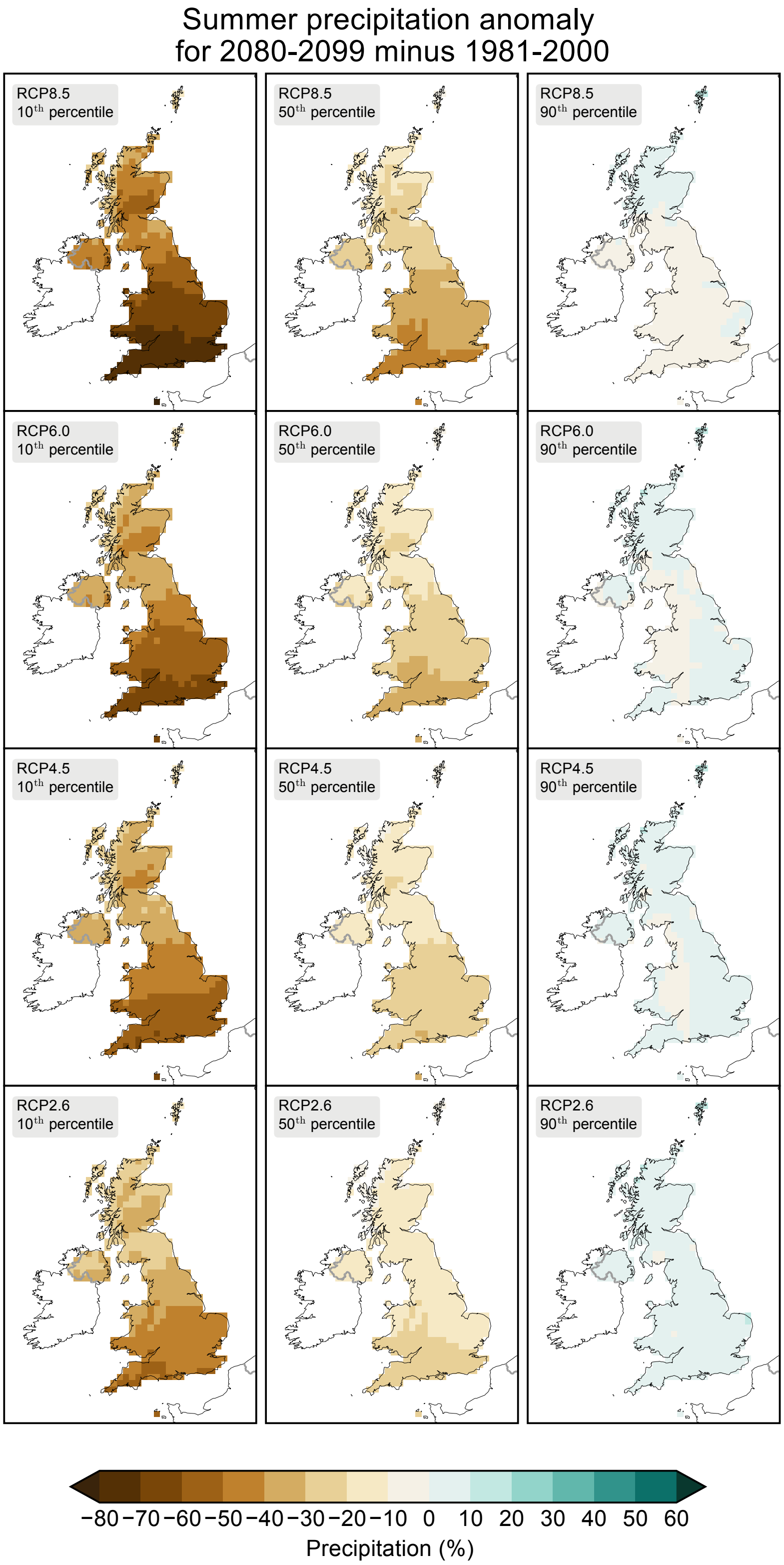


Figure 2.10. As 2.9 but for summer.

As well as looking at changes in long-term climate means it is also helpful for many applications to look at extreme months or seasons using the probabilistic projections. This allows both model uncertainty and natural climate variability to be factored into assessments. Figure 2.11 illustrates this using probability density functions, showing how including the variability from annual values widens the distributions of potential climate outcomes. The fractional contribution from interannual variability is a greater fraction of the total spread early in the century. Later in the century model uncertainty becomes more important for a given emission scenario.

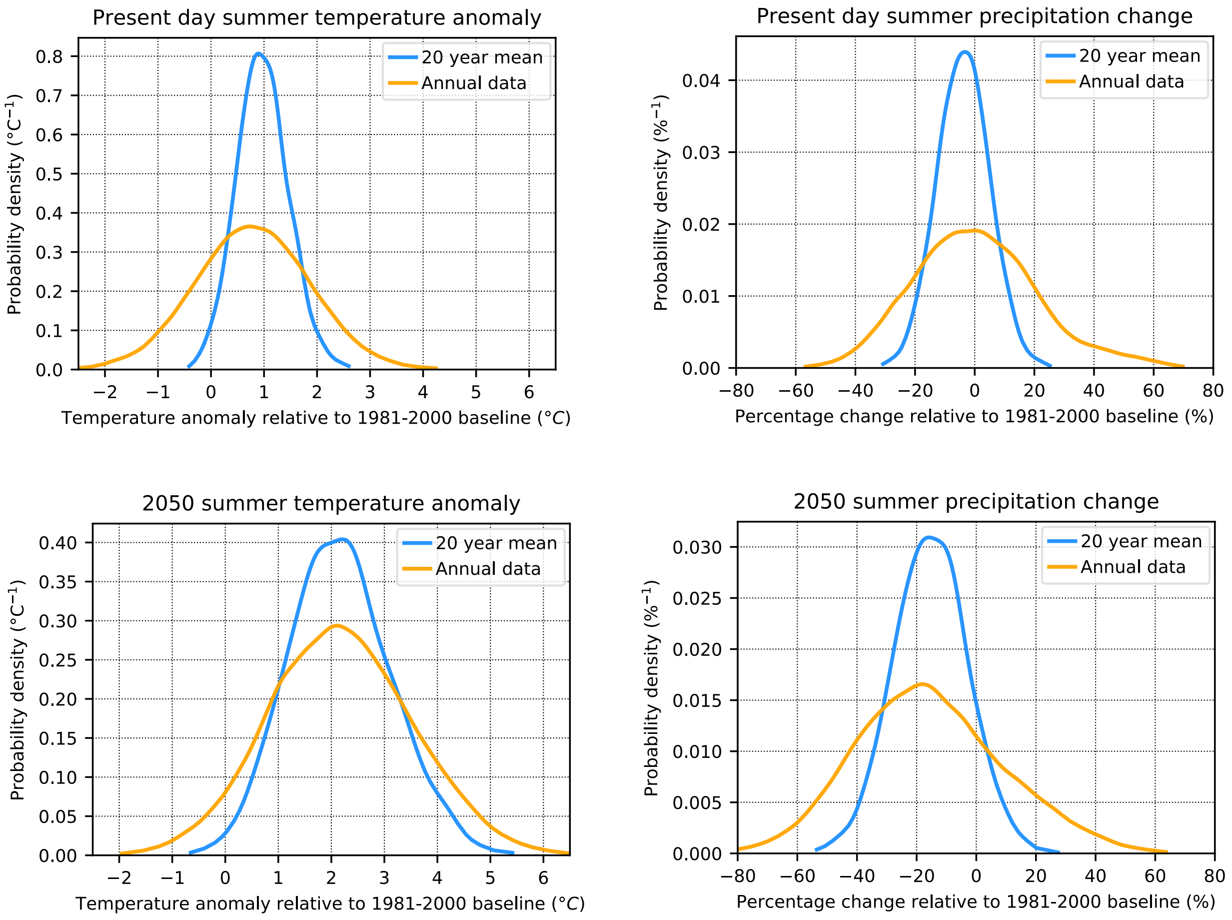


Figure 2.11. Simulated probability density functions for the summer 20 year means and for annual values. The top row shows results for present-day centered on 2018, and the bottom row is for results year 2050 (RCP8.5), with the results expressed relative to the 1981-2000 baseline. The left land panels show change in temperature whilst the right shows change in precipitation. Note, that the curves are not a prediction for the year they are centred on, they are projections in the spread of outcomes by that time.

Figure 2.12 shows cumulative probability distributions for four time periods centred on different years, and also includes interannual variability. An event like or warmer than that observed in summer 1976, which had a similar mean temperature to 2018 over the June, July and August period, had a low probability of less than 5% during the 1981-2000 baseline period. By present-day the probability increases as a result of climate change to between 10 and 25%. By the middle of the century the probability of a summer as warm or warmer than 1976/2018 has a projected probability of the order of 50% (66% for the RCP8.5 scenario and 54% for the RCP2.6 scenario). The probability in the second half of the century depends on the future emission scenario chosen. For RCP8.5 a summer like or warmer than those of 1976 and 2018 may have a probability of greater than 90% by the end of the 21st century. In the lower emission scenario of RCP2.6 the probability remains near to 50% as the end of the century is approached.

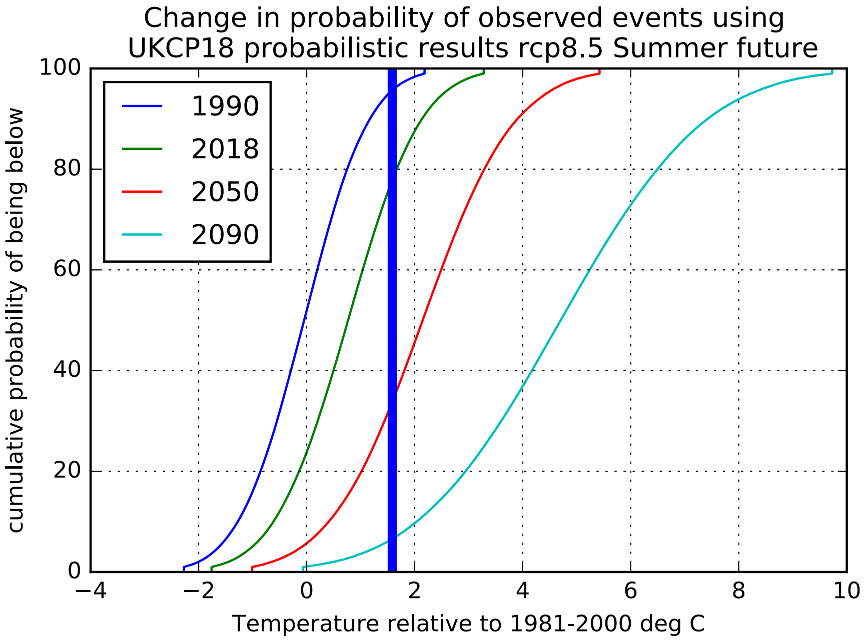


Figure 2.12. Simulated change in the summer temperatures relative to the 1981-2000 baseline using the probabilistic projections centred on 1990 (middle of the baseline period), 2018, 2050 and 2090. These include both model uncertainty and natural variability. The vertical blue line shows an estimate of the warming for summer 1976, which is also similar to that of 2018. Results are for the RCP8.5 scenario.

2.3. Exploring sets of global and regional model projections

The probabilistic projections discussed in the previous section provide context for how the projected future climate might change, including providing information on the range of changes for different future greenhouse gas emission scenarios. Many users have expressed a desire for also having a set of global and regional climate model projections that represent how variability and long-term changes in climate might evolve over the UK (and beyond) over the 21st century. Our design philosophy in UKCP18 has been to use the most recent climate models to provide this evidence. This approach is consistent with a growing interest by users in constructing internally consistent, physically based storylines that help us understand the robustness of those particular futures that would be most relevant to a particular user. There is no single climate projection that can provide this because different users have different interests and weather vulnerabilities. Therefore, the UKCP18 set of global model projections provides 28 plausible but diverse projections from which to choose. The set comprises projections with the GC3.05 model and other CMIP5 models. Many of the global simulations from the GC3.05 model have been downscaled to a 12km scale and will be further downscaled to 2.2km in future. The global and regional model projections are provided for the RCP8.5 scenario.

The global model projections are shown as a time-series and compared to the spread from the probabilistic projections in Figure 2.13 for global mean temperature change. It is clear that the GC3.05 models tend to sample the warmer end of the future response range projected by the probabilistic approach and CMIP5 models sample the mid-range and colder end – with some limited overlap in the middle. This is consistent with recent research into a HADGEM3 model version (GC3.1), to which the UKCP18 GC3.05 versions of the model are closely related, having an equilibrium climate sensitivity above the likely end of the current IPCC range, and higher than the CMIP5 set of models. However, potential users should note that the projected response over the UK has a wider spread in both GC3.05 and CMIP5 projection sets and the degree of overlap of the sets is greater. There is also a greater overlap for some metrics, such as precipitation.

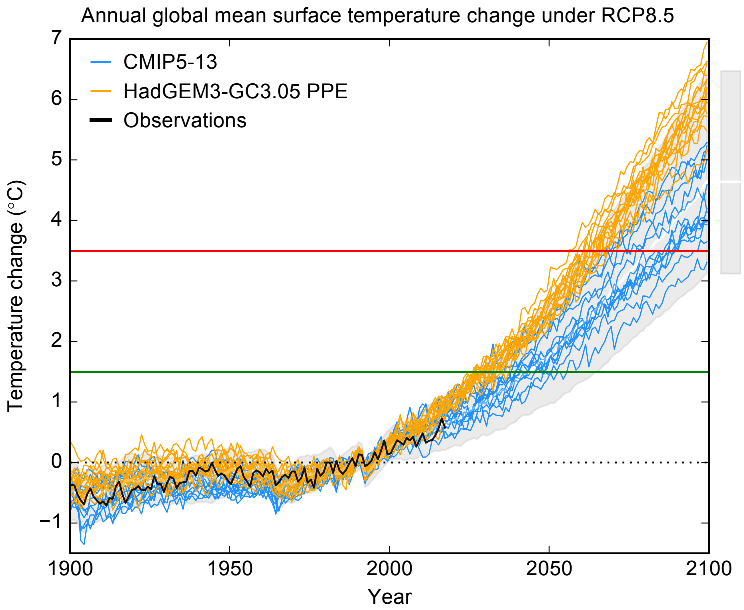


Figure 2.13. Historical and future changes in annual global mean surface temperature (GMST) from 1900-2100, relative to 1981-2000. Future changes are based on the RCP8.5 emissions scenario, applied in the projections beyond 2005. The probabilistic projections are shown as shading and shades of grey cover the 5th to 95th percentile range. The grey bar to the right of the plot shows the spread in 2100, with the white line showing the median. The global climate model projections based on the Met Office model GC-3.05 are shown as orange lines. The light blue lines are CMIP5 projections. The black curve shows observations from Cowtan and Way (2014). These observations are derived from HadCRUT4. The green and red lines show the warming for 2°C and 4°C above pre-industrial levels (taken as 1850-1900).

The different types of climate projection products available over land areas in UKCP18 are summarised in Table 2.3. The global and regional climate model projections have a major advantage over the probabilistic results in that they fully retain the relationship between different locations (have spatial coherence), so that large-scale events affecting multiple locations can be investigated in detail. They also retain the relationship between all of the climate metrics provided, allowing users to examine the covariation of the different metrics, such as temperature, precipitation and wind speed. Additionally, the global and regional sets of projections avoid many of the assumptions used to combine strands of evidence in the probabilistic projections, which for some users may be an important consideration.

Land projection product	Spatial scales	Source of model information	Number of simulations
Probabilistic projections	25km	GC3.05, CMIP5	100+ to produce and 3000 projections per scenario generated from distributions.
Global model projections	60km	GC3.05, CMIP5	28 projections (15 HadGEM3 + 13 CMIP5)
Regional model projections	12km	Limited area configuration of GC3.05 atmosphere model	12 projections
Convection-permitting projections (to come later)	2.2km	Met Office Operational Weather Forecast Model UKV	10+ projections

Table 2.3. Summary of projections and source models for land projection products. The 2.2km projections will be launched later. Note that although global model projections are provided at 60km, the native scale of the GC3.05 model, many of the CMIP5 models used in the global projections were coarser but have been re-gridded to 60km for use here.

Users may choose to look at the set of 28 projections of future climate from the global models, or the 12 regional models. A key choice will concern the relative benefits of the enhanced spatial detail available from the regional simulations, versus the broader sampling of alternative outcomes available from the global projections. Alternatively, users may choose to select a subset of these projections depending on their application. Users are also reminded that the global and regional projections are not intended to provide probability distributions, nor have they been constructed to replicate the probabilistic projections, but they can be placed in the context of the probabilistic results described earlier. Further discussion on the use of the global and regional model projections is provided in the user guidance.

In this section, we show an example of using the probabilistic information from section 2.2 to provide context for and to help select from the set of global model projections available. However, users may also choose to begin with the global and regional projections themselves rather than the probabilistic results, selecting suitable members based on their own criteria.

The UKCP18 land science report (Murphy et al, 2018) includes a detailed assessment of how well the global model projections are able to replicate the spread in the probabilistic projections over the UK for the RCP8.5 emissions scenario. In summary, it finds that for temperature the spread of the global model projections is slightly narrower than the range of the probabilistic projections over the UK, with this especially notable at the lower end of the distribution in summer and winter, and at the higher end of the distribution in winter. The range of precipitation from the global projection set is slightly narrower than the probabilistic projections.

The 12km projections also cover a sizeable part of the probabilistic range but the spread tends to be lower than for the global model projections because the regional simulations are only driven from GC3.05, which means they are not able to sample the lowest levels of warming at a given time in the future. Users are advised to consult the land science report (Murphy et al, 2018), which provides further information of the spread of the global and regional model projections relative to the probabilistic scenarios.

2.3.1. Example exploration of global climate model projections

We present an example of how the different land projection tools might be used together, which also illustrates the types of information available from the global climate model projections.

Consider first the probabilistic projections; users can use the UKCP18 website tools to derive bivariate distributions for warming and precipitation changes over parts of the UK (Figure 2.14). The shading represents the probability levels, so 90% of the distribution sits within the outer circle, and the evidence strands that inform the probabilistic change indicate a low probability of being outside of this. The dots on Figure 2.14 are seasonal mean values estimated for all of the global model projections provided. A mean trend towards warmer but wetter winters, and towards hotter and drier summers is apparent, although the inclusion of year-to-year variability demonstrates there is still a possibility for individual seasons that go against the mean trend. For example, dry winters and wet summers will still occur, although less frequently. The ability of the global model to sample the range of the probabilistic estimates is again evident, and consistent with our previous assessment made by considering the spreads for temperature and precipitation separately. Advanced users may choose to use a variety of methods, including scaling and time-shifting approaches, to enable the global model projections to cover more of the probabilistic distribution if this is relevant to their particular application. However, this should be done with caution and introduces a range of additional uncertainties, caveats and limitations as explained in the land science report (Murphy et al, 2018).

For our example, we progress by selecting two of the global model projections based on the summer projected changes. These are shown in red and dark blue. One of these models is referred to as Model A and is a member of the GC3.05 model set. The second is called Model B and is a member of the CMIP5 model set. We have selected these models for this example, but other users may wish to choose projections to suit their needs and vulnerability to weather and climate change. No special significance should be attached to these two simulations.

It is apparent that for both of these models natural variations over this five-year period cause a significant spread in the seasonal values and mean that we would not necessarily expect to see simple year-on-year monotonic change in temperature and precipitation. It is also apparent that choosing a model based on being amongst the largest of the probabilistic climate changes in summer does not necessarily translate into the same model being in such an extreme position in the winter change results. Insights such as this are one of the benefits of using the global projections, but must be considered in the context of their only being 28 plausible global projections which, for instance, can not simulate all potential realisations of future natural climate variability. We now proceed to look at the global and local changes in these two model simulations.

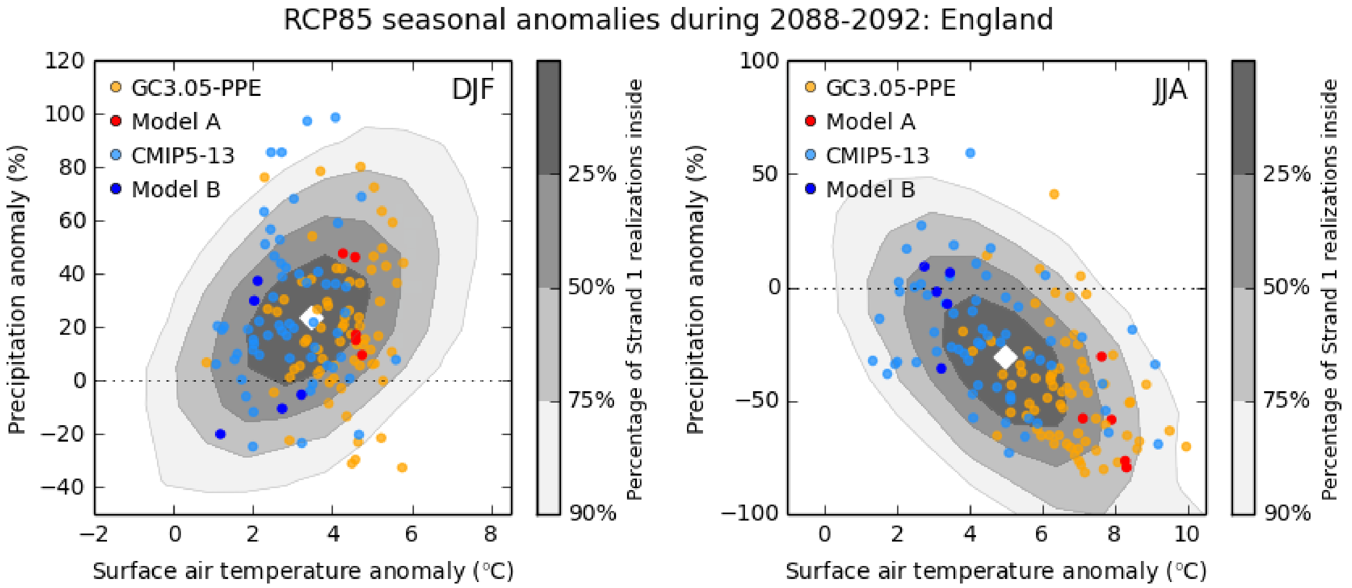


Figure 2.14. Projected temperature (bottom scale, °C) and precipitation (left hand scale, %) changes to the end of the 21st century over England for December to February (left hand panel) and June to August (right hand panel). Shading shows results from the probabilistic projections (% probability, right hand scale). The dots show global projections, there is one dot for each model for each of the 5 years considered, and all results are for RCP8.5. The orange dots and light blue dots represent the sets of GC3.05 and CMIP5 projections respectively. Two example models selected from the set of 28 global projections are shown in red and dark blue.

The global pattern of annual mean 21st century warming is shown in Figure 2.15. The warmer model has a global mean increase of 6.7°C, compared with 3.9°C in the cooler model. Both models exhibit the same well-known features, although the magnitudes of change and fine-scale details are different. The patterns of change show some basic features common to all climate change simulations. These include a land-sea contrast, with the land warming more than the ocean, and accelerated northern high-latitude warming. Some land areas warm faster than others, and in parts of the world this can sometimes be linked to an amplification associated with surface drying and/or snowline retreat. We could use the output of the two projections to look at climate changes other than warming across the globe, including regional precipitation and changes in atmospheric circulation. Additionally, we could use the output from the global climate models to drive a range of impact models in order to look at aspects such as water availability, flooding, drought, agricultural productivity or heat stress on humans.

For our example we will focus in on the UK region. Figure 2.16 shows the variation over time of local warming and the change in near surface wind speed over the UK. In both time-series there is evidence of strong year-to-year variability. Unsurprisingly, the higher global warming in Model A is reflected in higher UK warming too. In these two projections the time-series of wind speed change is more dominated by natural variability and little long-term trend is evident. Users could decide to look at extreme values from these time-series, for instance as maps of annual maxima or they may consider fitting the extremes to an extreme value distribution. Where the results are clearly non-stationery this should be taken into account in any fitted distribution.

An advantage of the global model projections is that they preserve the relationship between all climate metrics simulated. Therefore, we could choose to look at the correlation between the two metrics for each projection in order to better understand if wind increases might be linked to rising temperatures. In practice, users would likely do this not on annual or monthly data but on the higher frequency daily data available. However, users may wish to note that daily extremes may be better simulated in the regional model products.

Figure 2.16 also shows the change in simulated rainfall across the seasonal cycle. Model B has very little change during the 21st century (compare thin and thick lines) whereas the Model A simulation shows more of a change with increases in rainfall in the winter and decreases in the summer. There is little change in March and in October/November.

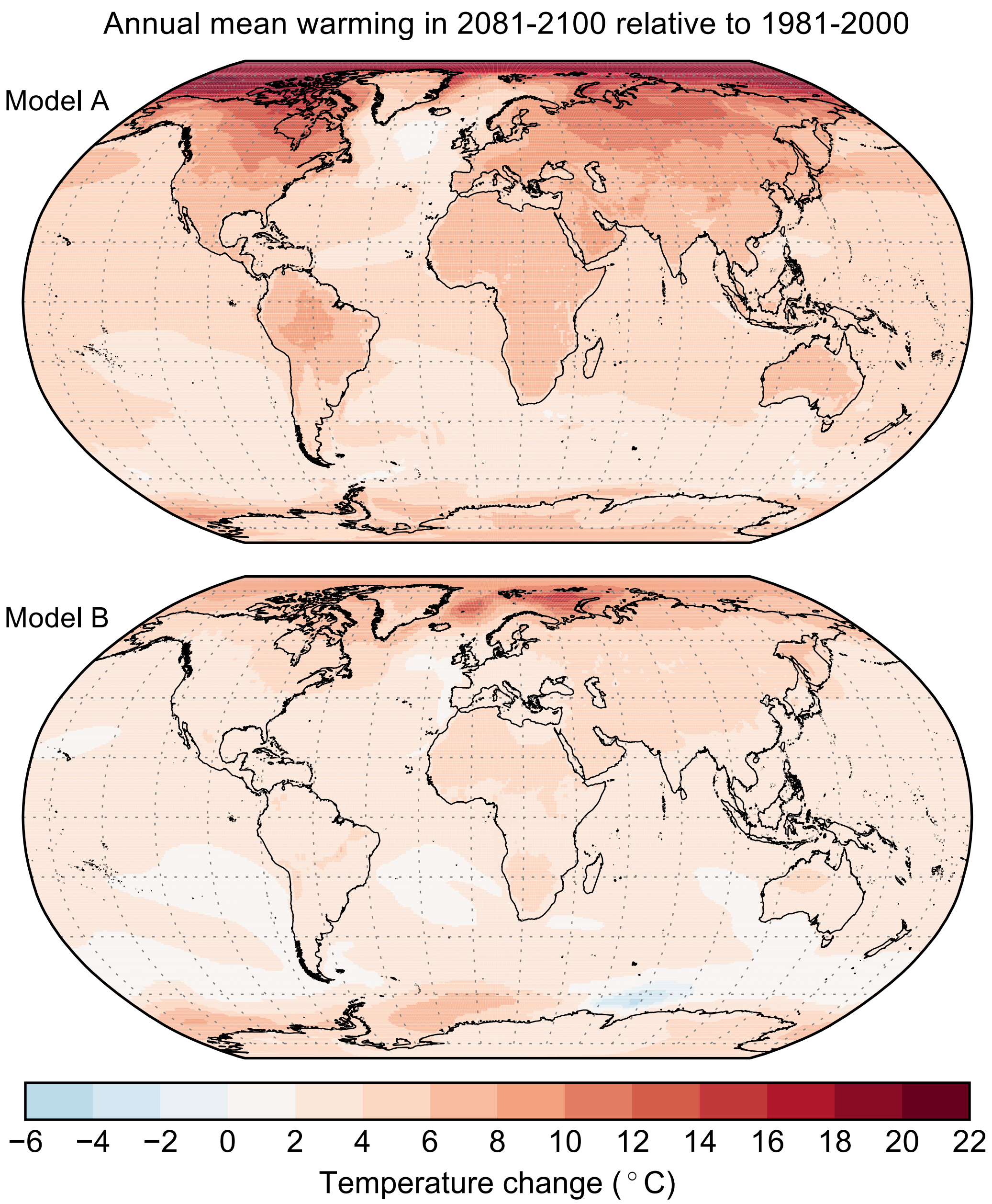


Figure 2.15. Annual mean warming (°C) in each of the two example plausible projections from 1981-2000 to 2080-2099 for scenario RCP8.5. The upper panel is from a Model A with higher climate sensitivity to greenhouse gas increases, and the bottom panel is from a Model B with a lower climate sensitivity.

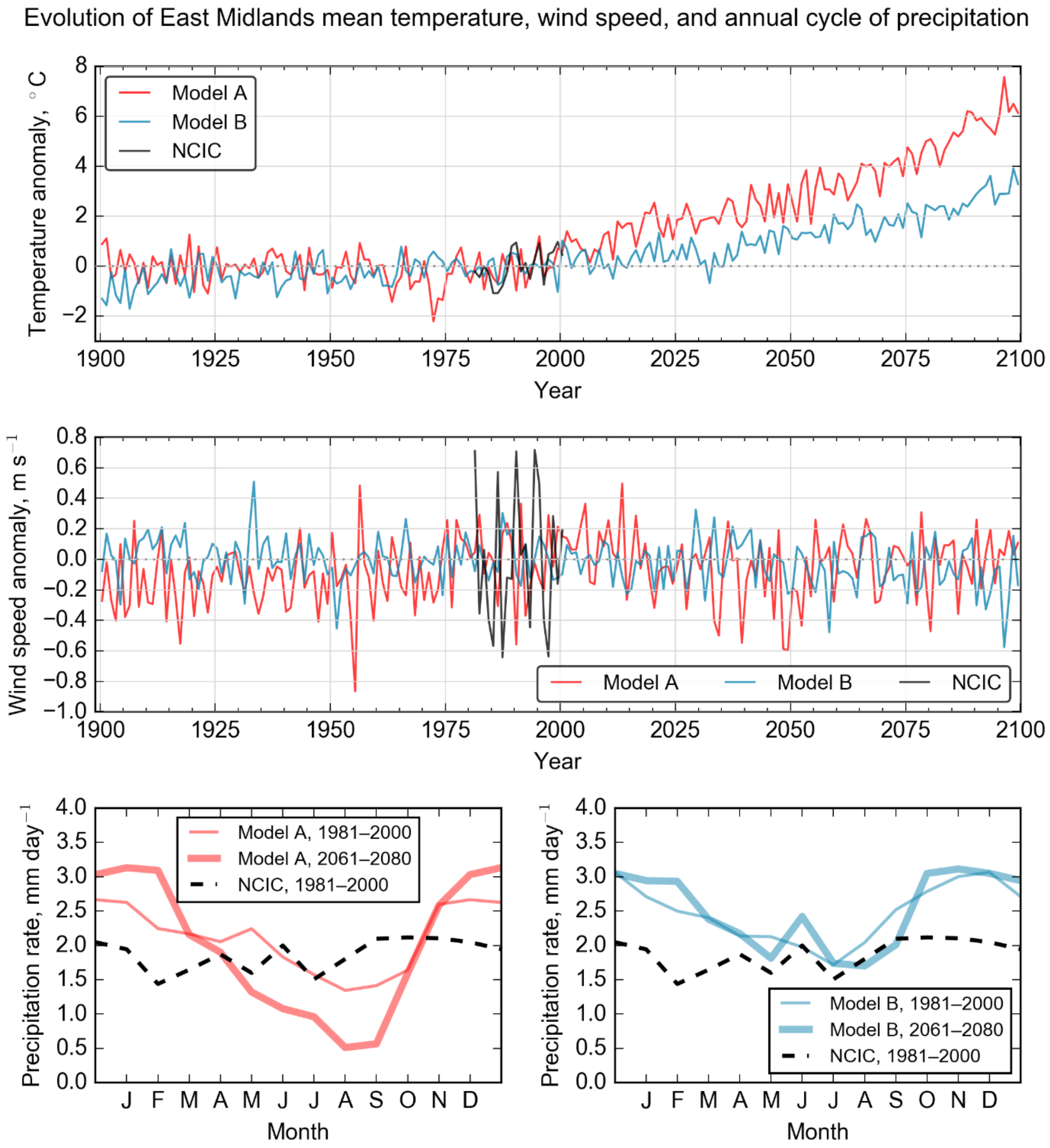


Figure 2.16. Evolution of changes from two global model projections, Model A (red curves) and Model B (blue curves), for the example East Midlands region. Top panel, annual temperature (°C) and middle panel, near surface wind speed (m/s). Results are expressed relative to the 1981-2000 period. Bottom panel, seasonal cycle of precipitation (mm/day). Colours as in top panels. Thin curves are averages over 1961-2000, and the thick curves are averages over 2061 to 2080. The observations (black dashed line) are derived from the NCIC data (https://www.metoffice.gov.uk/climate).

As many users are interested in weather and climate extremes, Figure 2.17 shows the change in the frequency distribution of daily maximum temperatures in the two global model projections. In the Model A projection the distribution can be seen to shift to warmer temperatures and to broaden. However, there are no large changes in the skewness of the distribution. For the projections from Model B the changes are much smaller, although there is some evidence of a positive shift in the distribution. There is also no clear evidence of a broadening in the distribution or a change in the skewness. From an impacts perspective these two projection examples could have very different consequences for human heat stress, or impacts on transport infrastructure, such as railway line buckling.

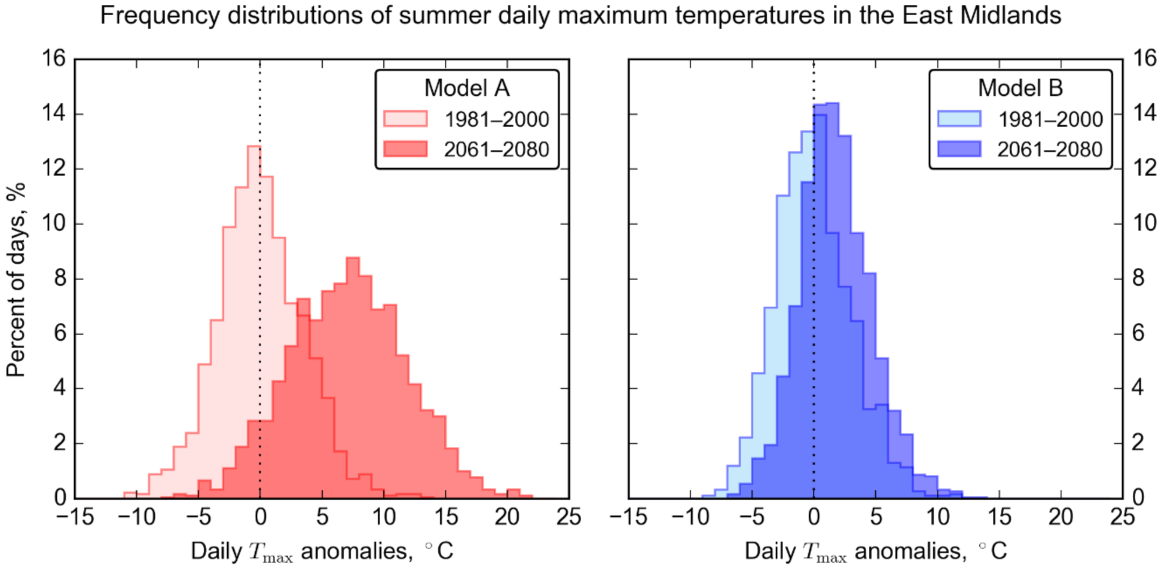


Figure 2.17. Frequency distributions (density of days) for changes in daily maximum temperatures (°C) in summer for the two global model projections (Model A (left hand panel); Model B (right hand panel)). Results are shown for 1981-2000, light shading and the change to 2061-2080, dark shading. For the present-day the results are centred on zero.

Another advantage of the global projections is that they preserve the relationship for a given metric expressed at different locations. This means that users can look at impacts that occur concurrently, which might be important for national or regional planning of the response to weather extremes. This is illustrated for the two projections in Figure 2.18 for daily mean air temperatures and looking at two different parts of the UK, South West England and the North Scotland. Simulated daily temperature differences are seen to exceed 10°C, between these two locations.

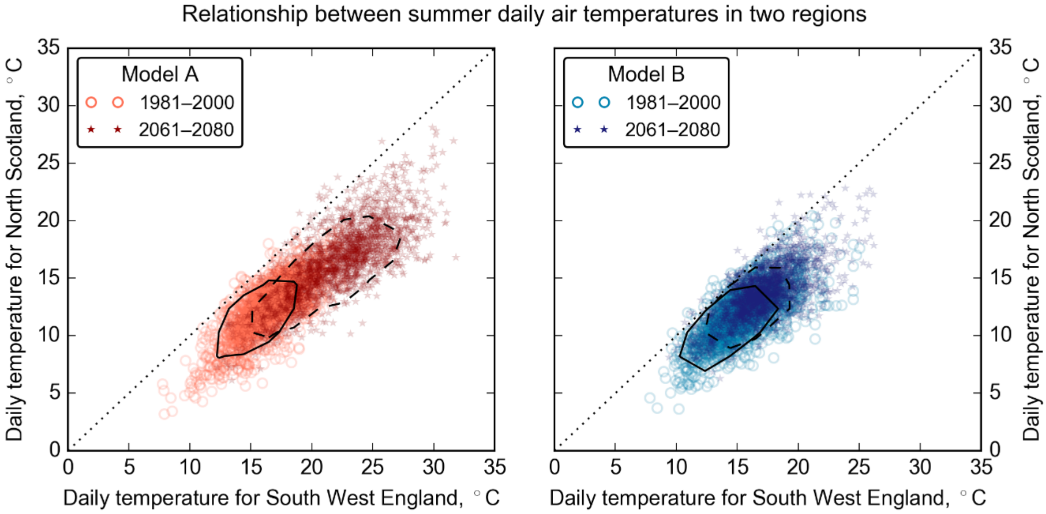


Figure 2.18. Demonstration of the difference in daily summer temperature (°C) between the South West England (bottom scale) and North Scotland (vertical scale) regions for the two global model projections of climate. The solid and dashed lines contain 67% of the projected values for the baseline and future periods respectively. Model A (left panel) and Model B (right panel). Circles, 1981-2000; stars, 2061- 2080. Temperatures are absolute values rather than anomalies.

Some potential users have expressed an interest in understanding the local changes they see in future weather and climate in terms of the larger-scale changes, in which there may be more confidence. A tool to aid this exploration is the use of weather typing, where periods of time are characterised in terms of the dominant prevailing large-scale weather type. For the two global model projections we investigate whether there is a change in the number of days experiencing two particular weather types (called NAO- and NAO+). Figure 2.19 shows how the surface pressure deviations from the long-term mean differ between the two weather types. It also shows how Model B shows little change in the time spent in these two weather types, whereas for Model A there is evidence of a transition to more days in the NAO+ state from the NAO- state towards the end of the century. However, it is unclear if this is due to natural variability or is part of a human driven trend.

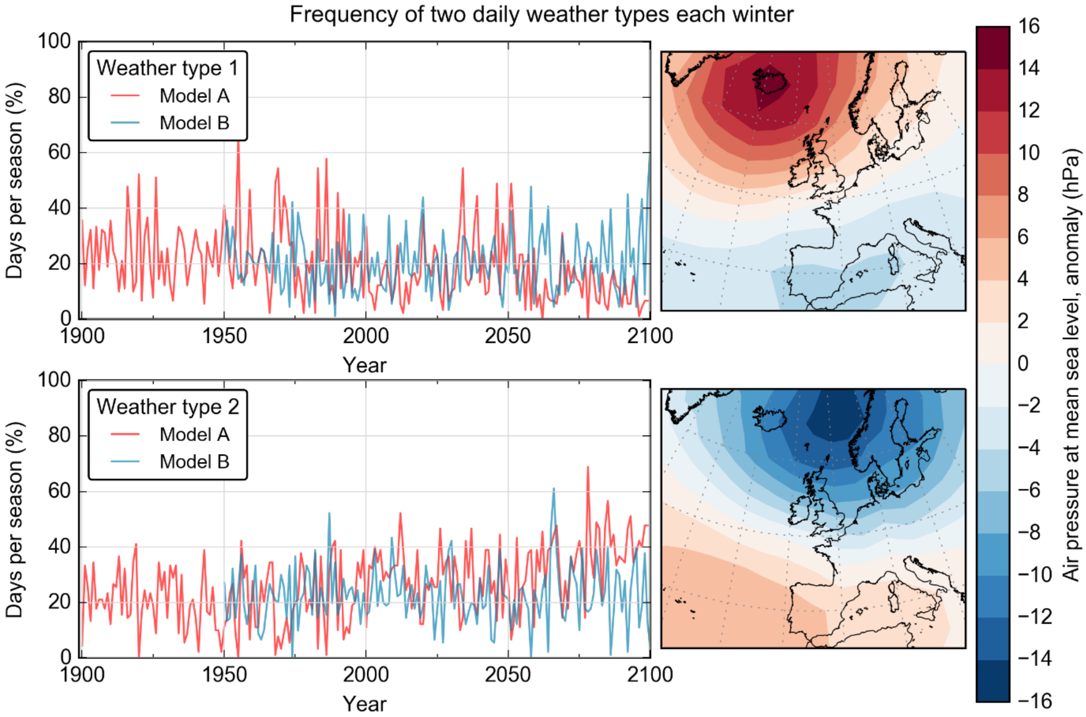


Figure 2.19. The right hand panels show the surface pressure anomaly associated with the two weather types (hPa). The left hand panels show the percentage of days per season associated with each type for two global model projections (red curve, example Model A; blue curve, example Model B).

2.3.2. Exploration of 12 km regional climate projections

One of the global model projections used as an example in section 2.3.1 is from the CMIP5 set of models whilst the other is a GC3.05 model. Twelve of the GC3.05 simulations have been downscaled from the global model scale of 60km to a finer scale using a 12km regional climate model. Figures 2.20 and 2.21 show the spatial patterns of warming and winter precipitation change projected by both the global and regional models. A high degree of consistency can be seen when the models are compared on the scale of the coarser global model, but more spatial detail, associated with aspects such as better simulation of the topography and coastlines is evident when the regional model simulation is considered on its native scale of 12km.

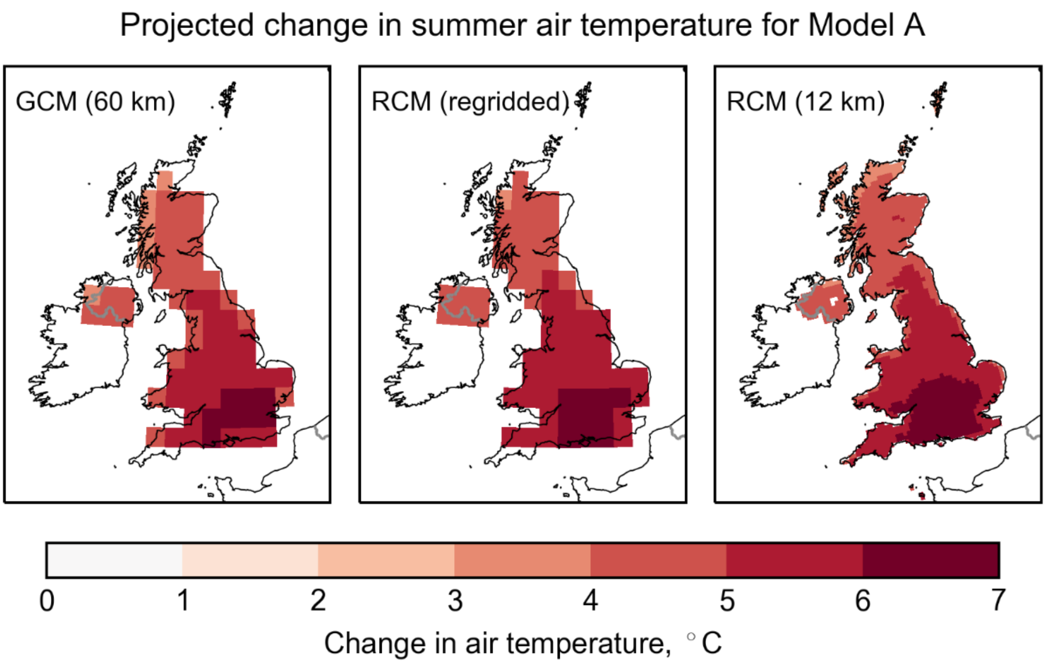


Figure 2.20. Comparison of a single global model projection (example Model A, left hand panel) and the regional climate model it drove (right hand panel) for surface air temperature changes, ºC. The middle panel shows the Regional Climate Model (RCM) response regridded to the Global Climate Model (GCM) grid for a clearer comparison. The demonstration shows the change in air temperature between present-day and the period 2060-2080.

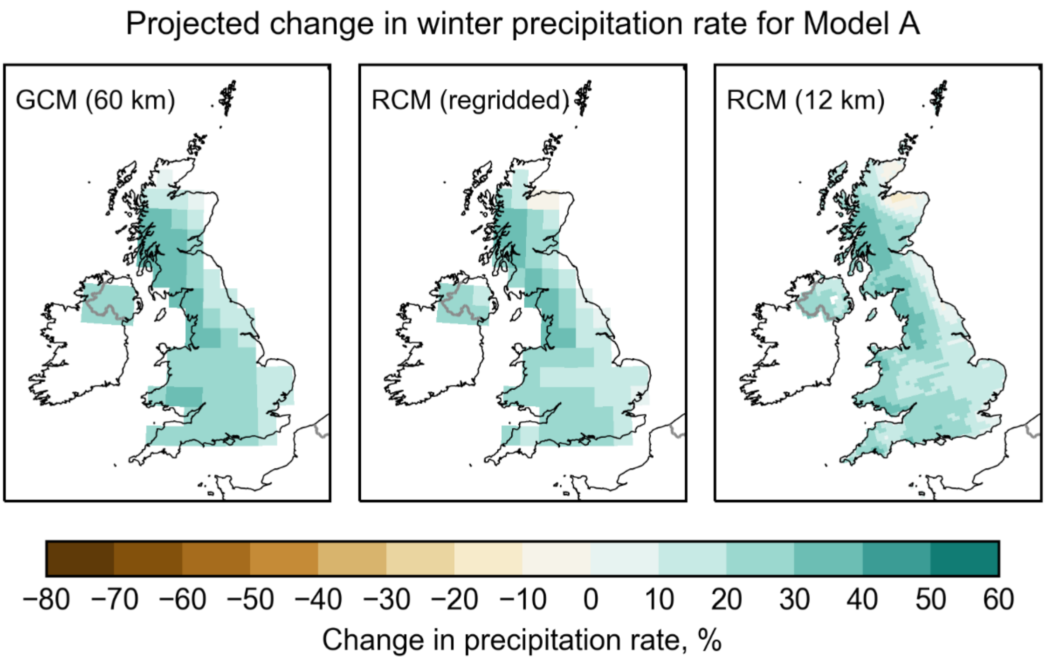


Figure 2.21. As for 2.20 but for winter precipitation (%).

The advantages provided by the regional model over the global model are further demonstrated by comparing the distributions of simulated historic period precipitation rates with those from observations (Figure 2.22). As discussed in more detail in the land science report (Murphy et al, 2018), the 12km regional model is better able to simulate some of the more extreme daily rainfall events, especially in the winter season where the global model underestimates their frequency in the UK region. Later, when the 2.2km regional model data is released it is expected that this will also show improved ability to simulate convective summertime precipitation compared with the 12km model or the global model, which is important for hourly extremes.

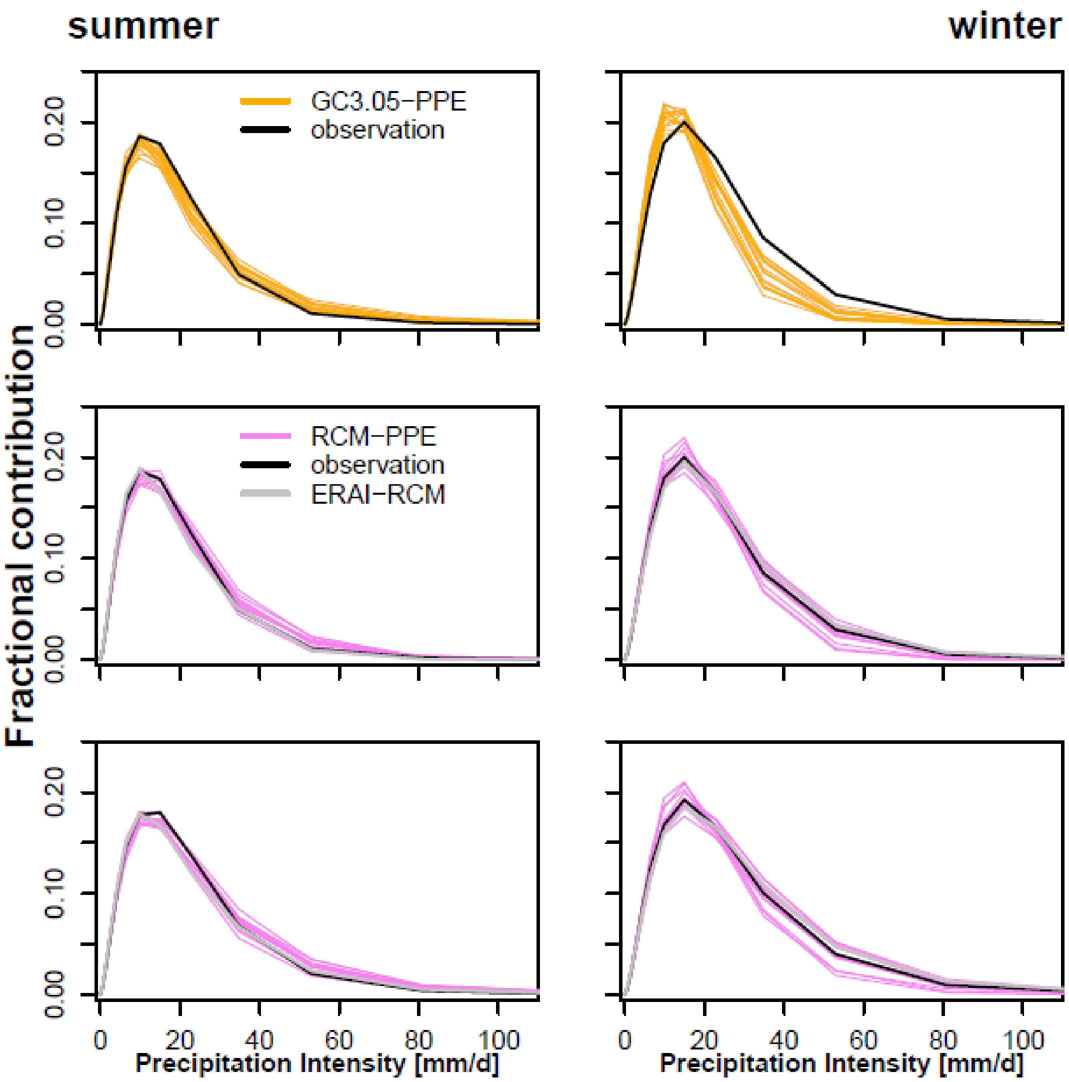


Figure 2.22. Fractional contribution of daily precipitation events within 20 intensity bins to total accumulated UK precipitation in summer (left) and winter (right), during 1981-2000. The contributions are calculated by assigning each day from every UK grid point to the relevant bin, and multiplying the number of counts in each bin by the average intensity. Dry days are assigned to the lowest bin. Results are shown for the GC3.05 global models and the 12km regional climate models. The pink curves show regional climate models driven by the GC3.05 model. The grey line shows a regional climate model driven by reanalysis. The black line shows observations. The bottom two rows both show the regional model data. The middle row shows results regridded onto the global model grid whereas the bottom row shows the regional model data on its own 12km grid.

We proceed to focus on examples of the 12km scale climate projections for seasonal mean precipitation changes (Figure 2.23 and 2.24). Many features associated with local topography are evident. The overall view in this example is an increase in rainfall in the winter and a decrease in the summer. Many users are expected to choose the regional model projections when assessing the impact of climate changes because of the ability to simulate the finer scale features and to provide a better simulation of weather extremes than the global model projections. However, the choice of UKCP18 product depends on the particular application and is a balance between providing the best information on the range of future changes, having global spatially coherent coverage from 1900 to 2100 or improved simulation of regional features over the UK and European region. User guidance is provided on the UKCP18 website.

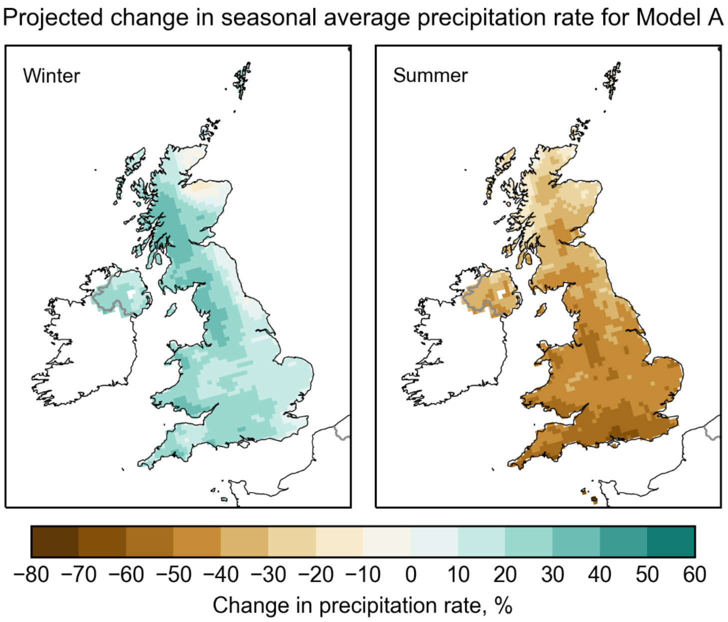


Figure 2.23. A single regional climate model projection showing change in seasonal mean precipitation from 1981-2000 to 2060-2080. A single regional climate model simulation showing change in seasonal mean precipitation (%) from present-day to the period 2060-2080. Left panel, December to January, right panel, June to August.

It is also valuable to provide a demonstration of the regional models ability to simulate extreme events. Figure 2.24 shows the median response across the 12 members of the regional model set for changes in the intensity of extreme wet days (the 99th percentile of daily precipitation) at the native 12km scale and for winter and summer. It is clear that there are increases in the precipitation intensity on wet days in winter across the whole UK and decreases in summer across central and southern UK. This more clearly highlights the spatial detail provided by the 12km RCM – for example, greater increases in winter locally over the west-facing coastal regions and greater decreases in summer along the south coast.

Considering the full set of 12 regional climate model projections, the 99th percentile of daily precipitation in winter, averaged across the UK, is seen to change between the baseline period and 2061-2080 from 25.3-29.9 mm/day to 29.6-33.9 mm/day. In summer the change is from 20.9-25.8 mm/day to 17.4-26.0 mm/day. The 99th percentile of daily temperature in summer, averaged across the UK, changes between the baseline period and 2061-2080 from 18.8-22.6°C to 23.4-27.5°C.

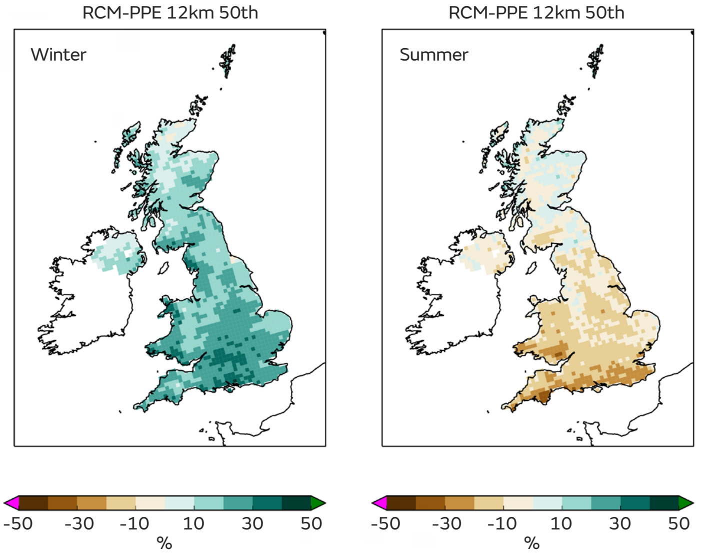


Figure 2.24. Median estimate at each point from the set of 12km model projections of the precipitation intensity of extreme seasonal wet days (%) in winter (left) and summer (right) between 1981-2000 and 2060-2080.

2.4. Global projections for other temperature levels

The computational expense of performing simulations with the global and regional models means that the sets of global model and regional model projections are only currently being provided for the RCP8.5 emission scenario. However, UKCP18 uses pattern-scaling and time-shifting techniques to provide projections for the lower RCP2.6 scenario. This is done for both the GC3.05 and CMIP5 model members, noting some constraints on the CMIP5 data. The approaches used to produce this derived climate model data is described in a separate report (Gohar et al, 2018). The probabilistic projections can be used to provide context for the RCP2.6 scenario, as they did for the global model projections for RCP8.5. Figure 2.25 illustrates the RCP2.6 time-series generated for UK temperature rise using the derived method. The spread is comparable to that from the probabilistic scenarios.

The derived data introduces additional uncertainties and assumptions and should be considered as having a lower confidence than the actual, unscaled, climate model outputs. Users need to be cautious if using the derived daily data to look at the amount of time continuously spent beyond a particular threshold value.

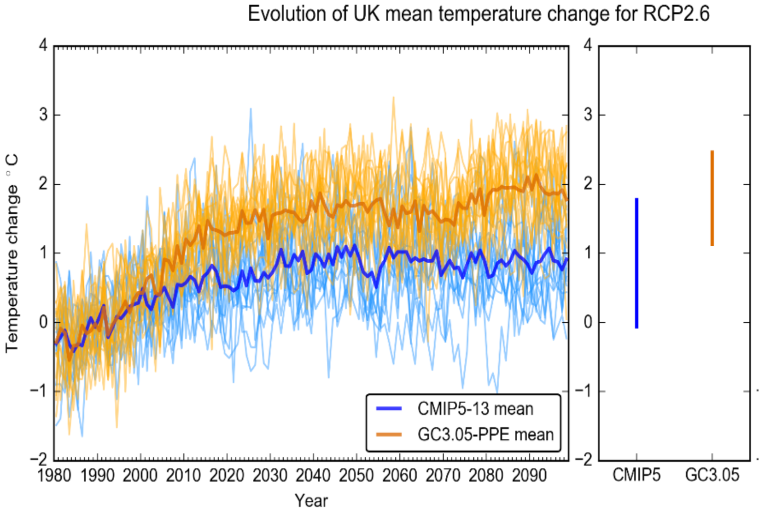


Figure 2.25. Left hand plot shows UK mean temperature changes in RCP2.6 relative to the 1981-2000 baseline. The available CMIP5 projections from the sub-set used by global model projections is in blue and the results from the HadGEM3 GC3.05 projections are in orange. The means for each set are shown as darker thicker lines of the corresponding colours. The middle plot shows the range of 20-year means at 2080-2099 for the CMIP5 and GC3.05 sets.

Increasingly, users are asking for simulations of the climate response over the UK for global temperature increases of 2°C and 4°C above pre-industrial levels. These are sometimes taken as representative of alternative futures in the cases of strong mitigation of greenhouse gas emissions and weak or no mitigation, respectively. The 2°C and 4°C global mean warming levels have been selected because of their importance to mitigation targets in the United Kingdom. The Committee on Climate Change discussed in their first report on targets the benefits of emission reductions that would limit the central estimate of global mean warming to around 2°C above pre-industrial levels and reduce to very low levels (e.g. less than 1%) the possibility of exceeding 4°C (CCC, 2009). This is also similar to, although slightly above the climate targets in the international Paris Climate Agreement, which aims to limit global mean warming to well below 2°C, and to aim for a stricter limit of 1.5°C.

An advantage of the use of fixed warming levels is that it removes the need to consider some of the uncertainty in the global mean magnitude of climate response to the emissions in the RCP scenarios. Thus, models that have higher sensitivity to greenhouse gas forcing can be used alongside those with lower sensitivity when results are presented for fixed warming levels.

For illustration, Figures 2.26 to 2.29 show the projected changes over the UK for global warming levels of 2°C and 4°C, using results derived from both the HadGEM3 and CMIP5 models. The results are presented relative to the same baseline used elsewhere in UKCP18, 1981-2000, but show the changes to the time when the global mean warming reaches 2°C or 4°C above pre-industrial levels. Pre-industrial is defined here as 1851-1900 to match the recent IPCC special report on 1.5C (IPCC, 2018). The maps show exemplar model results that maintain spatial coherence. These were calculated by first looking at the mean UK changes, arranging the models in order of increasing magnitude of change and then selecting the second model, the median model and the penultimate model as exemplar results.

For precipitation, the general trend towards a reduction in the summer and an increase in the winter is evident, especially for the 4°C level of global warming. For 2°C of global warming above pre-industrial levels the magnitude of changes tend to be lower and the role of internal variability in the particular models chosen as exemplars becomes more important.

Results indicate that at the time of 2°C of global mean warming, the largest warming in the UK will be in the southeast, decreasing toward the north and west. Warming patterns are similar in winter and summer but the magnitude is systematically higher in summer. Percentage changes in precipitation are strongly seasonal with wetter winters and drier summers projected. Precipitation changes relative to present-day are typically strongest in the south and west, ranging from a summer drying of up to 50% across much of the south and winters wetter by up to 20% across much of the country.

Changes to UK climate at the time of 4°C of global warming are similar in their spatial pattern to those at 2°C but with larger changes. In particular summers warm more than winters. Precipitation in summer decreases most in the south compared to present-day, with a median reduction of up to 40% across much of the South of England. Conversely winter precipitation increases slightly in the median, by up to 20% across much of the south and west of the country. The results can also be seen to exhibit the same broad scale features as simulated directly in the global climate models for the RCP8.5 case, although with some differences in magnitude.

By presenting results conditioned on particular levels of global warming we have removed the information on when the global warming levels are reached. Recent analysis of CMIP5 model by Gohar et al, (2017) suggest that a global mean warming level of 2°C could be reached from between the late 2020s up to around 2060 for the RCP8.5 emission scenario, and from around the late 2030s onwards for the lower RCP2.6 emission scenario. Without mitigation of climate change, warming of 4°C could be reached from the 2060s onward. Table 2.4 shows dates of global thresholds being exceeded for the 28 global projections.

Model ID	GWL2	GWL4
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 2.4. Timings of exceeding global mean warming levels of 2 °C (GWL2) and 4 °C (GWL4) in RCP8.5 above pre-industrial levels. 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 observations. Timings are based on a centred 25 year running mean. While all simulations pass 2 °C of global mean warming some simulations do not reach global mean warming levels of 4 °C by the end of the century.

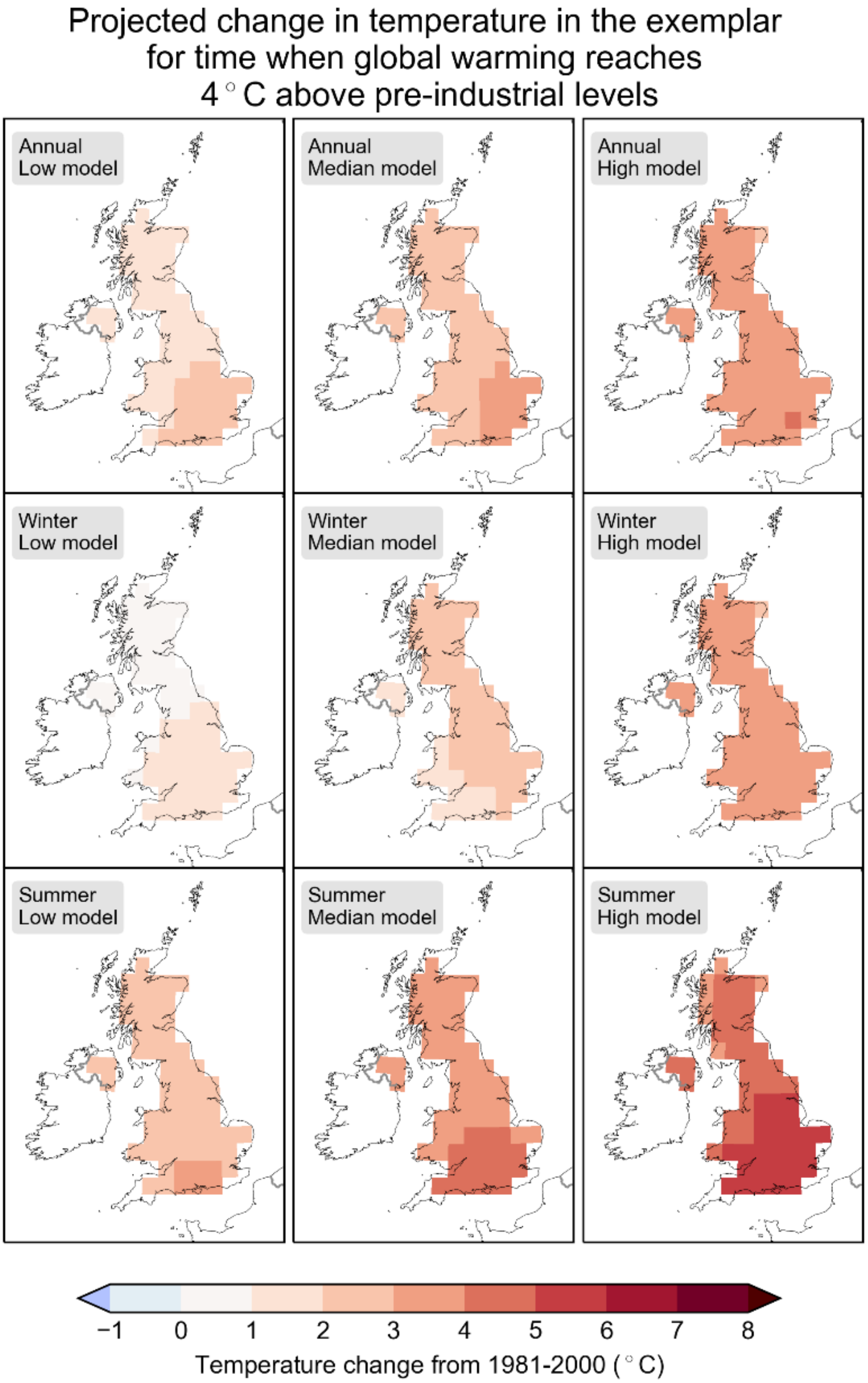


Figure 2.26. Changes in 20-year means of the UK seasonal mean temperatures expressed relative to a 1981-2000 baseline at a global mean warming of 2°C above pre-industrial levels. Rows show annual (top), winter (middle) and summer (bottom) changes. Columns shows maps for the model projection with a UK mean temperature changes which are relatively low (left), high (right) or median (centre).

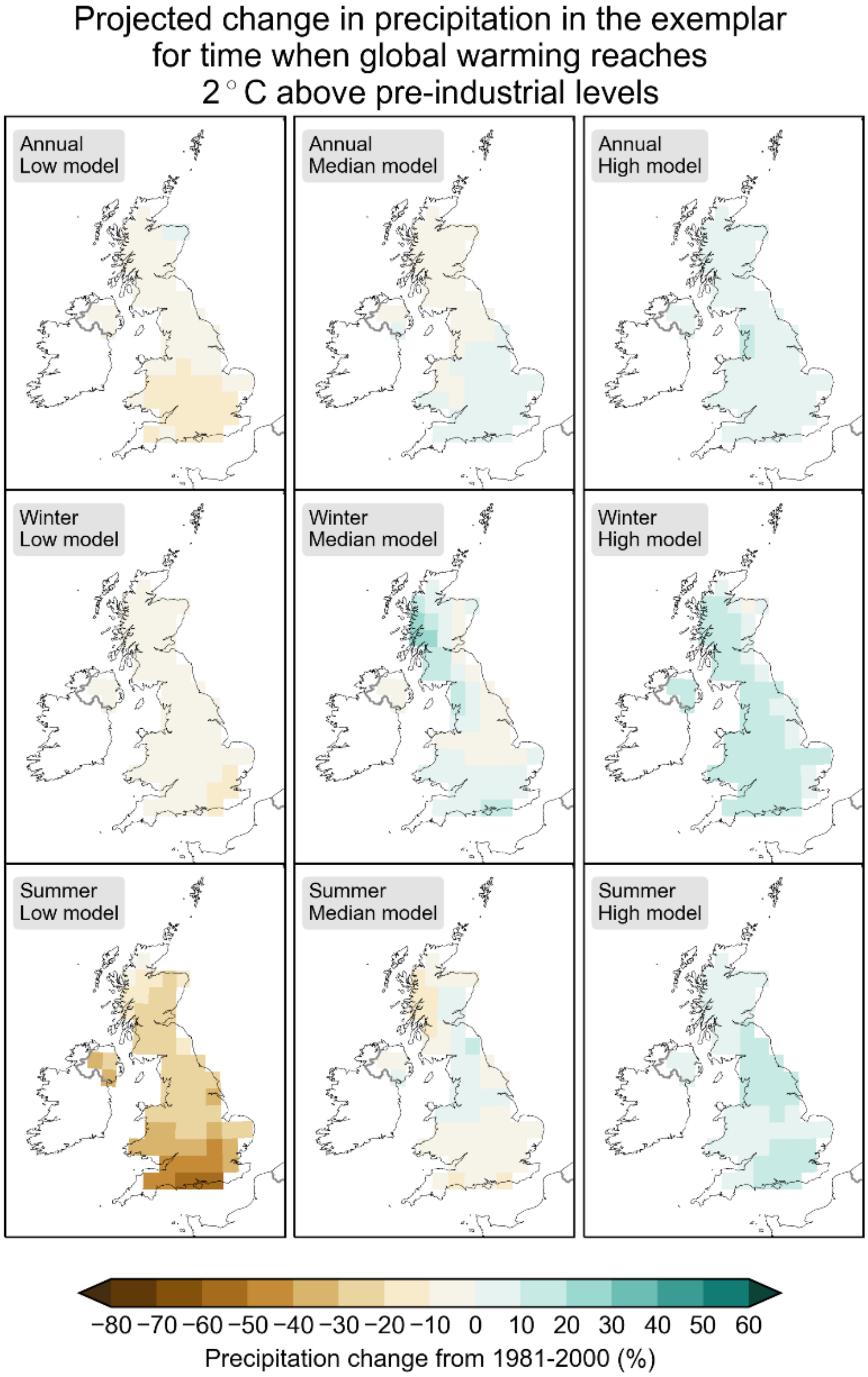


Figure 2.27. As Figure 2.26 but for precipitation.

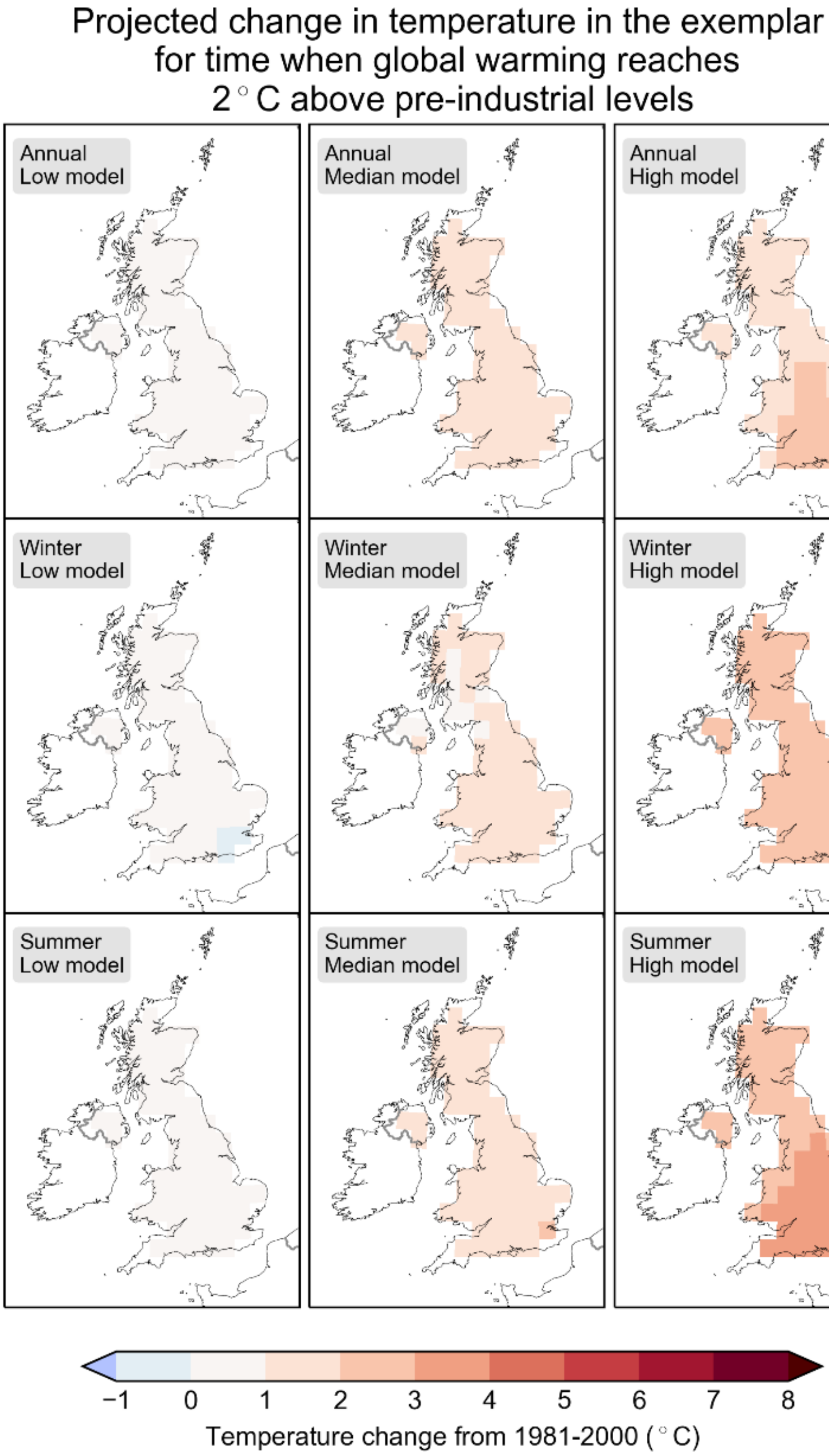


Figure 2.28. As Figure 2.26 but for a global mean warming of 4°C.

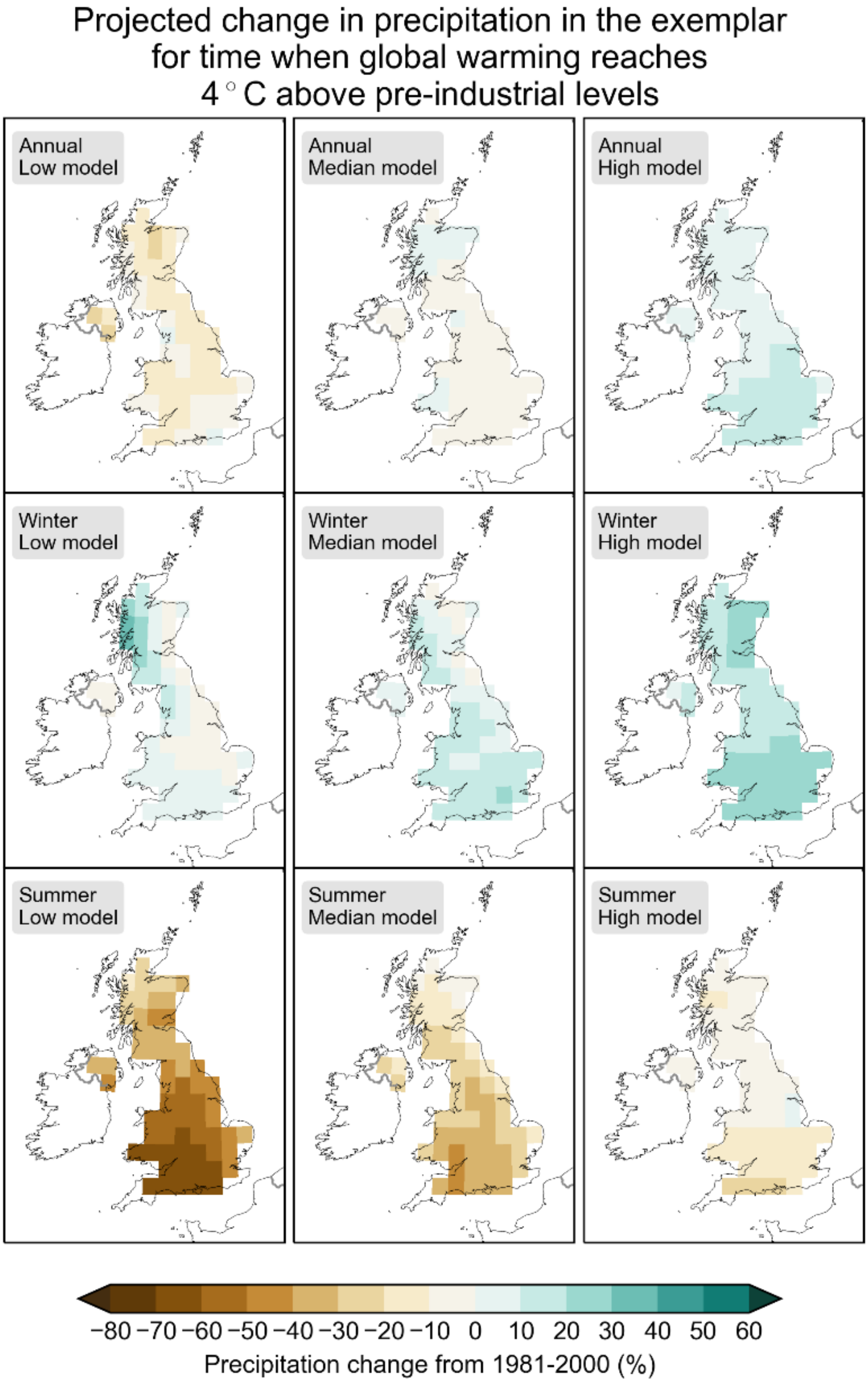


Figure 2.29. As Figure 2.28 but for precipitation.

2.5. How may users choose the appropriate UKCP18 projections?

The land projections provide a range of tools including: new probabilistic projections for four alternative future pathways of greenhouse gas emissions; global climate model projections for the RCP8.5 simulation; and regional climate model projections for the same scenario. It also provides an extra product of derived data derived from the global projections for a future scenario with lower emissions of greenhouse gases and for 2°C and 4°C of global warming. A guidance note is provided to users on selecting the approach or approaches that are most suited to them (Fung et al, 2018). We summarise some of the major considerations in Table 2.5, alongside a reminder of the characteristics of the data products.

The probabilistic projections, global projections and regional projections that comprise the UKCP18 land projections are all derived from climate models, which approximate the real climate system. Hence, there can be systematic differences between climate model results and observations (i.e. biases). In addition, climate scientists do not yet understand some potential influences on future climate well enough to include them in current models. Despite these limitations the combined evidence of UKCP18 covers a broad range of potential future climate pathways. However, it remains possible that real world future changes could lie outside the envelope of these estimates. Future generations of climate models will be developed that reflect improved scientific capabilities and understanding, potentially leading to a requirement to update the UKCP18 projections with new, and potentially different, advice.

The probabilistic projections are designed to provide a primary tool for assessments of the widest range of uncertainties in UKCP18, and generally show broader ranges of future climate than the global and regional climate model projections. They can be an important tool for a variety of different types of risk assessment, including when attempting to be robust against all simulated scenarios, and when used alongside other information such as the global and regional projections of climate and of course, information on vulnerabilities, adaptation options and risk tolerance. They may be especially useful for the avoidance of overconfident decision-making. The probabilistic projections are derived from a statistical framework that supports the formal application of observational constraints, and estimation of the relative likelihood of specific outcomes. We emphasise again, that these are conditional on the knowledge, data, methods and expert choices used to construct them. If a decision is sensitive to relative likelihood or focused heavily on specific probability levels, then we recommend users test the sensitivity of their findings to the UKCP18 results. For instance by exploring the consequences of reasonable variations to the UKCP18 results, including to probability levels.

	Probabilistic projections	Global model projections	Regional model projections
Description	Probabilistic changes in future climate based on assessment of model uncertainties.	A set of 28 projections with detailed data on how climate may evolve in the 21st century.	A set of 12 high-resolution climate projections over Europe downscaled from the global projections.
Period	1961-2100	1900-2100	1981-2080 for 12km
Temporal resolution	Monthly Seasonal Annual	Daily Monthly Seasonal Annual	Daily Monthly Seasonal Annual
Spatial resolution	25km	60km	12km
Geographical extent	UK and regions	UK and regions Global	UK and regions Europe
Emissions scenarios	RCP2.6 RCP4.5 RCP6.0 RCP8.5 SRES A1B	RCP2.6 (UK only)† RCP8.5 2°C world (UK only) † 4°C world (UK only) †	RCP 8.5
Why use it?	▪ The most comprehensive assessment of uncertainties in UKCP18. ▪ Explores emissions scenario uncertainty. ▪ Explores uncertainty in key processes in climate models. ▪ Helps characterise future extremes in risk assessment.	▪ Long time series. ▪ Spatially coherent*. ▪ Direct access to 'raw' climate model data. ▪ Includes results from the Met Office Hadley Centre global climate model. ▪ Includes CMIP5 model results.	▪ Enhanced spatial detail. ▪ Spatially coherent. ▪ Improved extremes. ▪ Direct access to 'raw' climate model data.

Table 2.5. A summary of the key characteristics of each the three strands of information for the UKCP18 land projections.
†Only available for the UKCP18 derived projections. *spatial coherence is important when analysing climate risks at different geographical locations at the same time, e.g. national assessments. ** A smaller set is available for RCP2.6 as some CMIP5 data is unavailable.
***Only available for Met Office Hadley Centre model.

The global and regional model projections provide flexible datasets derived directly from climate model output. This confers full spatial and temporal coherence, and offers consistent information on a wider set of climate metrics and time scales than is available from the probabilistic projections. These projections also avoid many of the assumptions included in producing the probabilistic projections. The global and regional projections provide storylines of plausible futures that can be used to develop case studies, stress-test a system and to develop and consider decision options. The global and regional projections can also be used to build confidence in the use of the data, by providing opportunities to explain the future outcomes that they represent in terms of the climate physics, e.g. the global model provides information on large-scale drivers that affect the patterns of weather that we experience in the UK. However, we recommend that many users may benefit from considering the global and regional projections in the broader uncertainty context of the probabilistic projections, where the information is available.

The downscaled regional model projections offer a greater level of spatial detail, which can improve the simulation of some aspects of weather and climate. Typically, the downscaled simulations are better able to represent observed extremes of temperature and rainfall. However, in UKCP18 the downscaled regional projections of climate are only driven by part of the global model projection set and so may not capture the full range of outcomes produced by the probabilistic projections. Furthermore, the global model simulations may be a more appropriate tool when there is a need to look at the earlier historical context before 1980, for impacts around the world and to look at large-scale physical drivers of future change.

It is important to emphasise again the potential value of combining information from the UKCP18 land products. For example, the probabilistic projections can be used to show sampling limitations of the global and regional projections. Another example might involve use of the global projections to select a case study corresponding to a specific large-scale circulation anomaly, and then using one of the regional projections to derive detailed local information on potential impacts such as flood risk. Users should consult the guidance documents for further information on this.

UKCP09 contained a Weather Generator, which is a tool for providing long synthetic series of daily climate variables. This can be used for risk analysis of impacts that depend upon the sequence of weather conditions (e.g. river flows and plant growth). It also provided a convenient tool for statistical analysis of the joint effects of multiple climate variables. A Weather Generator has not been provided in UKCP18. During development of UKCP18 we examined the actual uses the weather generator was put to in UKCP09 applications. The majority of users appear to have applied the Weather Generator to extract daily data. In UKCP18 global and regional climate model projections provide daily information with a more physically based approach and our view is that these should be used in preference to the Weather Generator. Some users liked the convenience of bias correction included in the Weather Generator but the UKCP18 view is that all users applying daily data need to actively consider the best bias correction approach for their particular needs rather than a single approach. A very limited number of users wanted the weather generator for looking at sub-daily time-scales. The UKCP18 approach is that we would like to encourage users to take these from a physically based modelling system that can be better evaluated against real world observations rather than the statistical approach of the weather generator. Such users are directed to the forthcoming 2.2km regional model projections. However, we accept some UKCP18 users may still want to develop a Weather Generator approach and we hope that the raw climate model data we provide will facilitate this.

As well as assessing which land projection data source(s) are appropriate for their application, users need to consider their preferred channel for receiving and communicating the information. UKCP18 contains data, reports, maps, graphs and key messages and these contain different levels of information that enable users to tackle different challenges. It is recommended that users consider which of these may be most helpful, before starting their analysis.

3. Marine climate projections

Observations show that time-mean sea level around the UK rose by approximately 1.4 mm/yr in the 20th century when corrected for land movement. However, in many cases it is the extremes of coastal water level that are associated with the worst impacts.

UKCP18 provides new projections for the marine environment. In particular, there are updated projections of time-mean sea level rise around the UK coastline and new projections of extreme water levels including storm surges and tides. The UKCP18 global mean sea level rise estimates follow the IPCC 5th assessment approach (IPCC, 2013) for contributions from thermal expansion, glaciers and small ice caps, land storage and some of the ice-sheet contributions. It uses an updated approach to assess an Antarctic ice dynamic contribution to future sea level rise (Levermann et al, 2014), although alternative choices are also explored in the marine science report (Palmer et al, 2018).

Regionalisation of the sea level rise simulations to the UK coastline also broadly follows the approach in the IPCC assessment by taking into account regional changes in ocean circulation and density. The components of global mean sea level rise associated with a mass transfer of water from the land to the ocean are also associated with spatial “fingerprints” of change that are dependent on the geographic distribution of the mass loss from the land. In order to have some representation of the uncertainty in the fingerprint patterns, UKCP18 uses two independent sets of fingerprints. The final component of regional sea level change is associated with glacial isostatic adjustment (GIA), which is sometimes referred to as “post-glacial rebound”. This phenomenon occurs due to the very slow response of Earth’s mantle material to the removal of land ice mass following the last glacial maximum, about 21,000 years ago. A Monte Carlo method, essentially making a large number of random draws from an underlying statistical distribution many times in order to build up a picture of the combined uncertainties, is applied to combine the uncertainties in different sea level terms and provide an overall frequency distribution for the local sea level rise around the UK.

Users need to be aware that there are a variety of additional geophysical processes not included in the UKCP18 regional sea level projections that can affect local sea level change, especially through vertical land movements. These include processes such as sediment compaction or movement, other sources of subsidence, and even tectonic activity. Where vertical land motion data are available (for example, from differential GPS stations or satellite interferometry) this information could be incorporated into site-specific assessments of future sea level change by users, taking care not to double-count the vertical land movement estimates which are already included in the UKCP18 projections.

Simulations of storm surges are made by taking near surface winds and atmospheric pressure from climate models and using them to drive a barotropic storm surge model, CS3. This surge model has a long history of also being used for short term operational forecasting for the UK of surge levels a few hours to a couple of days ahead, and has a spatial scale of around 12km. For UKCP18 the winds and pressure are drawn from existing climate model simulations made as part of the Euro-CORDEX experiment (Jacob et al, 2014) and from CMIP5 experiments. The atmospheric drivers from the former have a greater spatial detail (around 12.5 km) than those from CMIP5. Both sets of surge simulations show a similar relationship between changes of intensity and changes of frequency of extreme events to that relationship seen in the tide-gauge record for any given site, but the CMIP5-driven simulations exhibit a larger spread.

The approach to simulation of surges is similar to that used in UKCP09 except the source of the driving data is different. In both UKCP09 and UKCP18, surge information is extracted by running the surge model with both meteorological forcing and tidal forcing together, then with tidal forcing only. The surge information is calculated from the differences between the simulations. In UKCP18, this process has been repeated with different amounts of time-mean sea level rise added, as this can alter tides and surges, for instance by changing the speed of propagation of a shallow water wave. Alongside the mean sea level rise and surge simulations a small number of simulations were carried out using a global and regional wave model. The wave simulations used winds as driving data from the same experiment sets as the surge simulations as far as practicable.

As with UKCP09, the surge and wave simulations are not designed to comprehensively sample the full range of potential changes but instead to pragmatically provide a number of projections of the future, based on available driving data, that may be used to test the sensitivity in particular applications to plausible future changes.

3.1. Projections of time-mean sea level change

3.1.1. Global mean sea level projections

Although UKCP18 mean sea level rise projections are based on those in the IPCC 5th assessment (IPCC, 2013) there are two major differences. First, we use a baseline period of 1981-2000 rather than 1986-2005; and second we include updated estimates of the contribution from Antarctic ice dynamics. The change of baseline period results in a small +0.01m increase in projected values of global mean sea level. The change in Antarctic ice dynamics brings about a more substantial change to the global mean sea level projections, systematically increasing the projections and in particular raising the upper end of the range of model results. The 2100 values for IPCC 5th assessment and UKCP18 are summarised in Table 3.1.

For the median case for all scenarios considered, the largest component of the global mean sea level rise is thermal expansion. The next largest terms are the contribution from glaciers and small ice caps and from Greenland deglaciation. The smallest terms, which are similar in magnitude, are the Antarctic contribution and the contribution from land storage of water. The relative importance of different sea level change contributions can be quite different for the upper percentiles of the UKCP18 estimates and can vary over time.

Climate scenario	Global mean sea level rise at 2100 (m)	
	UKCP18	IPCC AR5*
RCP2.6	0.29 - 0.66	0.27 - 0.61
RCP4.5	0.38 - 0.79	0.36 - 0.71
RCP8.5	0.56 - 1.12	0.53 - 0.98

Table 3.1. Summary of the projected global sea level change at 2100 for UKCP18 and the IPCC AR5. *Note that the IPCC 5th assessment values have been adjusted to the 1981-2000 baseline used in UKCP18. UKCP18 model ranges represent the model projected 5th to 95th percentile range.

One of the key uncertainties for 21st century sea level projections is the potential for accelerated rise from land-based ice loss associated with Antarctica. An important development since the publication of the IPCC 5th assessment is work to better understand the potential for collapse of the West Antarctic Ice Sheet and consequent acceleration in the rate of global sea level rise. This is a predominantly marine-based ice sheet, where ice mass input to the ocean is governed primarily by ice flow processes rather than the surface mass balance (the difference between snow accumulation on the ice sheet and ice melt) that dominates for the East Antarctic Ice Sheet. Recent satellite and modelling evidence suggests collapse of the West Antarctic Ice Sheet could already be underway, via a positive feedback known as 'Marine Ice Sheet Instability'. Recent studies have also proposed a second potential positive feedback on ice loss from West Antarctica called 'Marine Ice Cliff Instability'. This feedback could be triggered by disintegration of the floating ice shelves around Antarctica, wherever these leave behind coastal ice cliffs taller than around 100m in height. Such cliffs would be structurally unstable, and if they entirely collapsed, leaving behind further unstable cliffs, this could lead to self-sustaining ice losses and associated global sea level rise of order 1m by 2100 if the feedback were rapid and widespread. However, this must be contrasted with other studies published since the IPCC assessment, which suggest maximum rates of about 0.4-0.5m per century for the global sea level rise contribution from Antarctica. This is discussed in more detail in the marine science report (Palmer. et al, 2018), which compares several alternative approaches to simulating the dynamic ice sheet term. The pace of literature in this field is moving extremely rapidly and users are advised to consider the implications of there being likely future updates to this component of sea level rise.

Our summary interpretation of the recent evidence is that the high end scenarios of UKCP09 (referred to as the H++ scenario), which allowed for a low probability future with sea level rise up to around 2m by 2100, can still be considered a useful plausible but unlikely high-end sea level pathway for decision-making. It should not be considered a theoretical maximum rate of sea level rise. The scientific community will further update the potential for higher sea level rise scenarios in the coming months but this is likely to be in a different format to the previous scenario, reflecting an emerging need for tailored high-end scenarios for different users.

3.1.2. Coastal time-mean sea level projections for the UK

The coastal time-mean sea level projections presented in this section are derived from the global mean sea level projections. There are substantial variations in projections of coastal time-mean sea level change around the UK for any given RCP scenario (Figure 3.1).

For the UK average, total sea level rise is slightly lower than for global mean values across all scenarios. For example, under RCP4.5, the UK coastal mean value at 2100 is 89% of the global rise. The pattern of sea level rise across the UK can be broadly characterised by a north-south gradient, with larger sea level rise to the south. The larger sea level rise to the south, which is also seen in observations of past sea level rise, is primarily due to vertical land movement, although other aspects and in particular the spatial fingerprint of ice melt from the Greenland ice sheet are important in future. Some regions of the UK coastline have projections of time-mean sea level rise that are larger than the global average. In addition, the range of UK coastal sea level projections is larger than for the global mean sea level time series, owing to the additional uncertainty associated with regional processes.

Time-mean sea level projections for UK capital cities show the largest sea level rise for London and Cardiff. Edinburgh and Belfast show values for future sea level rise, that are lower than the other two capital cities. The sea level projections for UK capital cities are summarised in Table 3.2 and Figure 3.2.

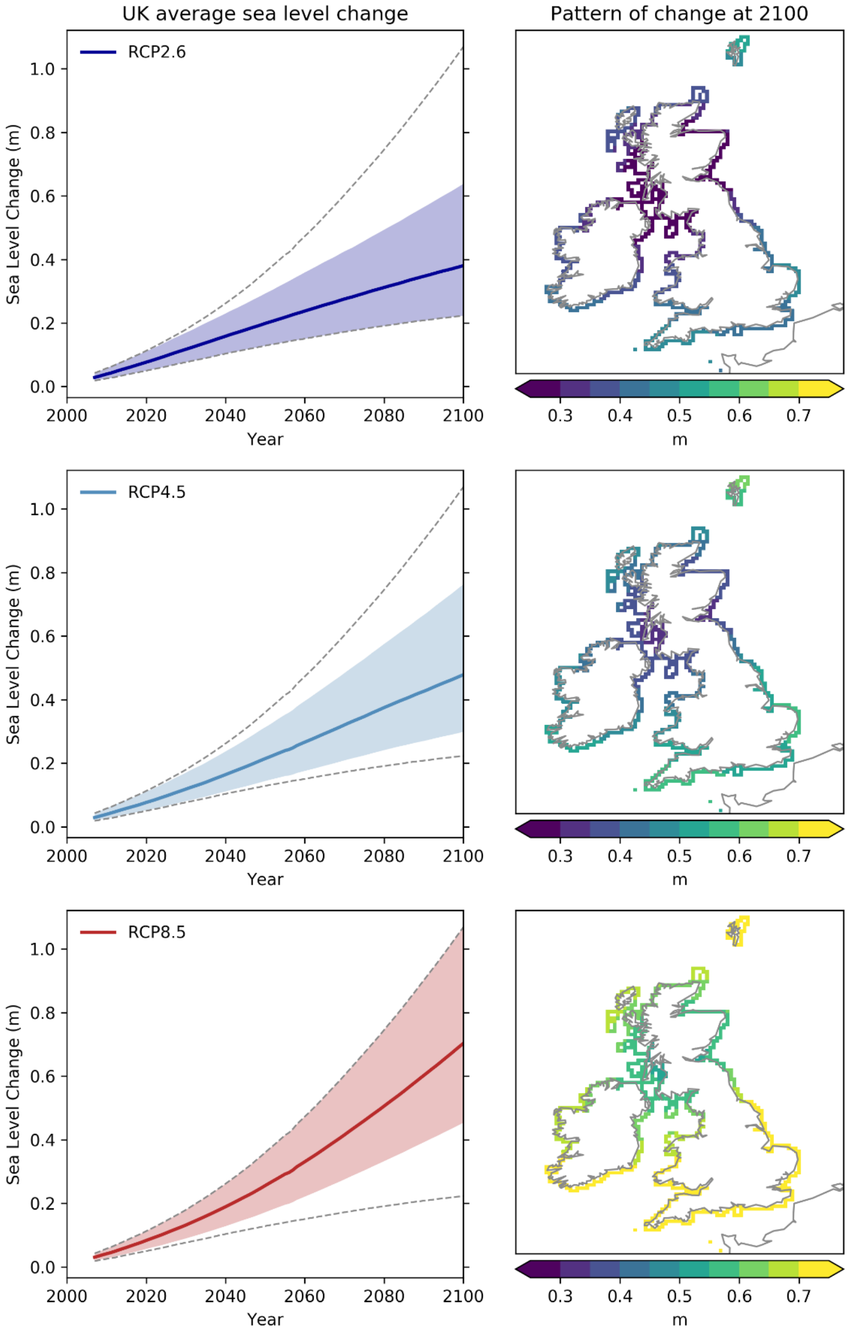


Figure 3.1. Time series of time-mean sea level change based on the average of 49 UK ports (left hand panel). The solid line and shaded regions represent the central estimate and ranges for each RCP scenario as indicated in the legend. The dashed lines indicate the overall range across RCP scenarios. The spatial pattern of change at 2100 associated with the central estimate of each RCP scenario is shown in the right hand panel. All projections are presented relative to a baseline period of 1981-2000. Top row shows RCP2.6, middle row, RCP4.5 and bottom row, RCP8.5.

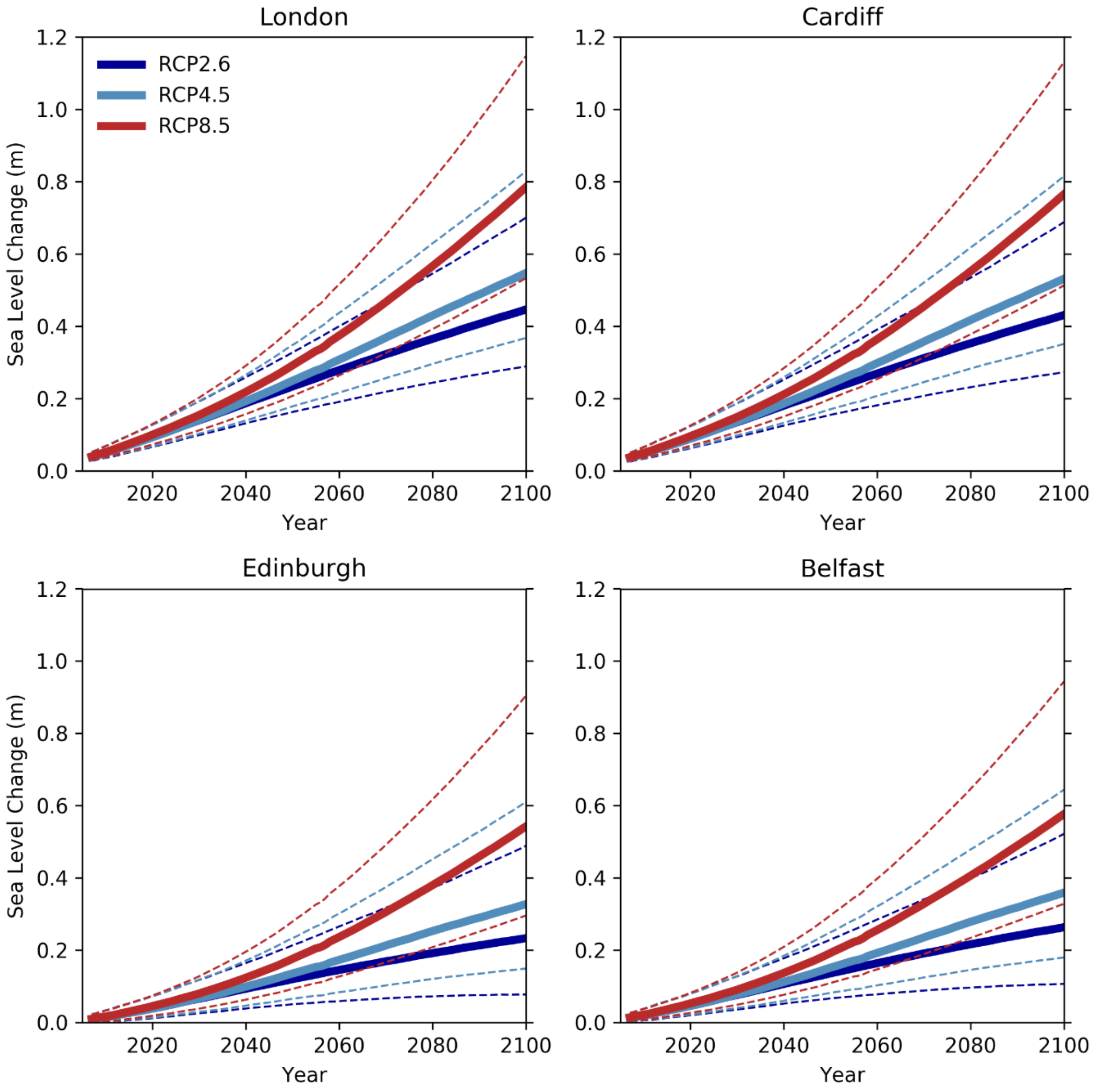


Figure 3.2. 21st century projections of time-mean relative sea level under RCP2.6, RCP4.5 and RCP8.5. The solid lines indicate the central estimate and dashed lines indicate the projection range for each RCP as indicated in the legend. All projections are presented relative to a baseline period of 1981-2000. Clockwise from top left London (Sheerness), Cardiff (Newport), Belfast (Bangor) and Edinburgh (Leith).

	London			Cardiff			Edinburgh			Belfast		
YEAR	**R2.6**	**R4.5**	**R8.5**	**R2.6**	**R4.5**	**R8.5**	**R2.6**	**R4.5**	**R8.5**	**R2.6**	**R4.5**	**R8.5**
2020	0.07 – 0.13	0.07 – 0.13	0.07 – 0.13	0.06 – 0.12	0.06 – 0.12	0.07 – 0.13	0.01 – 0.07	0.01 – 0.07	0.02 – 0.07	0.02 – 0.08	0.02 – 0.08	0.03 – 0.08
2040	0.13 – 0.26	0.14 – 0.27	0.16 – 0.29	0.12 – 0.25	0.13 – 0.26	0.15 – 0.28	0.04 – 0.16	0.05 – 0.17	0.06 – 0.20	0.05 – 0.18	0.06 – 0.18	0.08 – 0.21
2060	0.19 – 0.40	0.22 – 0.44	0.26 – 0.52	0.18 – 0.39	0.21 – 0.43	0.25 – 0.51	0.06 – 0.27	0.08 – 0.30	0.13 – 0.38	0.08 – 0.29	0.10 – 0.32	0.15 – 0.40
2080	0.24 – 0.55	0.30 – 0.63	0.39 – 0.80	0.23 – 0.53	0.28 – 0.62	0.38 – 0.79	0.07 – 0.37	0.12 – 0.45	0.21 – 0.62	0.10 – 0.40	0.15 – 0.48	0.23 – 0.65
2100	0.29 – 0.70	0.37 – 0.83	0.53 – 1.15	0.27 – 0.69	0.35 – 0.81	0.51 – 1.13	0.08 – 0.49	0.15 – 0.61	0.30 – 0.90	0.11 – 0.52	0.18 – 0.64	0.33 – 0.94

Table 3.2. Projected ranges of sea level rise at UK capital cities (in m) under RCP2.6, RCP4.5 and RCP8.5 relative to a baseline period of 1981-2000.

An analysis of sea level rise uncertainty suggests that for stakeholders who are interested in relatively short climatological time horizons, e.g. the 2020s to 2050s, coastal sea level variability is an important consideration. The best information currently available on observed coastal sea level variability comes from the network of tide gauges around the UK (http://www.psmsl.org/). In order to aid the interpretation of the available tide gauge records and give a first-order picture of the magnitude of coastal sea level variability, UKCP18 also examined sea level trends from a 7 km resolution regional ocean model simulation. The model simulations suggest that the largest magnitude sea level changes arising from variability occur on timescales of about 5 years, with 5th and 95th percentile trends in annual mean values that can exceed 6 cm over this period. The simulations also suggest a large degree of spatial coherency in the magnitude of the variability. Therefore, the magnitude of sea level variability observed at a tide gauge site is typically representative of a much longer stretch of coastline. This can be exploited by users.

3.2. Projections of change in storm surge and extreme water levels

Storm surges are temporary excursions in water level above the level of the tide. They are caused by variations in atmospheric surface pressure and winds. To produce projections of the likely component of change in sea level extremes due to 21st century atmospheric storminess change, we used five CMIP5 simulations, downscaled with the SMHI RCA4 regional climate model, to drive the CS3 storm surge model. These five models were chosen based on their ability to simulate a realistic climate over northwest Europe, and they span a range of projected responses over the 21st century.

Three of the simulations show little coherent change around the UK coastline and the pointwise 5th to 95th percentile overlaps zero rate of change for most coastal locations. Two of the five simulations exhibit significant spatially-coherent signals of 21st century change: the HadGEM2-ES-RCA4 simulation, which exhibits a negative signal of change, and the MPI-ESM-LR-RCA4 simulation, which exhibits a positive signal of change (Figure 3.3). For the MPI-ESM-LR-RCA4 simulation the most likely trend (i.e. the most consistent with the simulated extremes) is shown by the red line and the red shading shows the 5th to 95th percentile confidence interval of the trend fitted to that simulation.

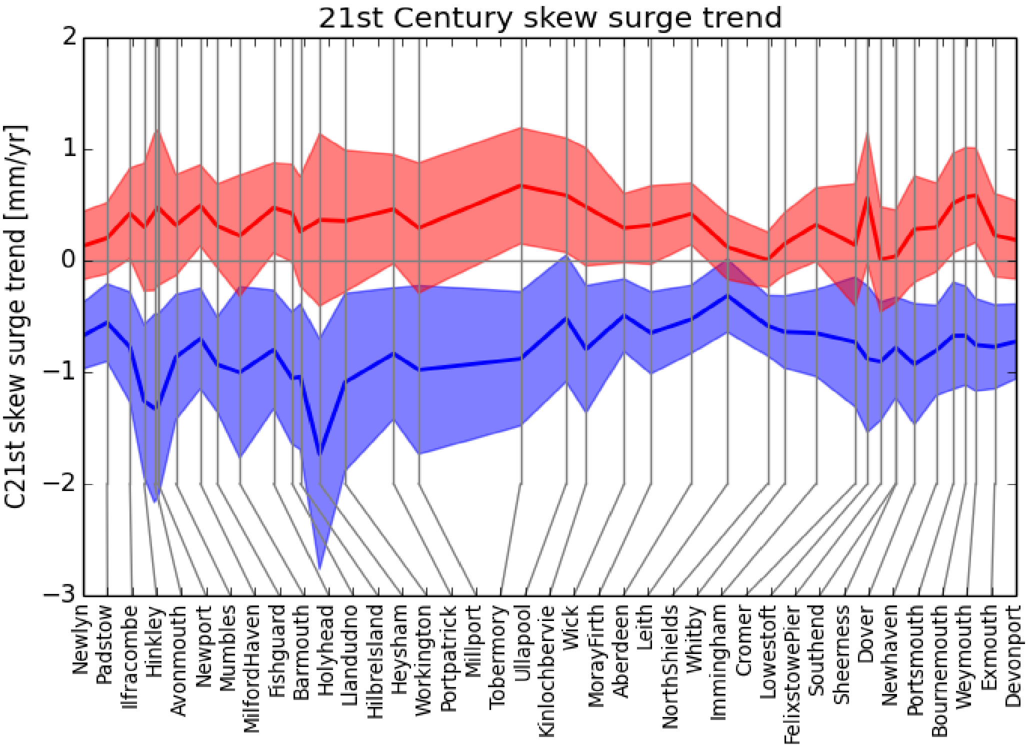


Figure 3.3. Projected 21st century trends in extreme of skew surge for sites of class A tide gauges around the UK mainland, in the MOHC-HadGEM2-ES-RCA4 simulation (blue) and the MPI-ESM-LR-RCA4 simulation (red). This does not include mean sea level change and is due to projected storminess change only. The lines show the central estimates. The shading shows the uncertainty (5th to 95th percentile) in the fitted trend based on a pointwise site-by-site assessment.

The two simulations shown in Figure 3.3 do not agree on the size or even the sign of the change. The other three RCA4-downscaled simulations generally exhibit weaker and less spatially-coherent trends. For comparison, the current observed rate of global mean sea level rise is around 3.2 mm/yr (2.8 to 3.6 mm/yr) and typical projected rates averaged over the 21st century are somewhat larger than this. Thus, we see that even the largest projected changes due to changes in storminess in the RCA4-downscaled simulations are smaller by about an order of magnitude than typical projected changes in mean sea level. We cannot be sure whether any projected changes in surge in Figure 3.3 are a response to greenhouse gas forcing or an expression of long-period internal variability. From a user perspective both could lead to coastal impacts.

Thus, we conclude in UKCP18 that a future 21st century trend of zero remains the best estimate based on the RCA4-downscaled simulations. In this case all of the change in the water level extremes during the 21st century would come from the change in the mean sea level plus any changes in surface waves (section 3.4) and tidal characteristics (section 3.5) and none of the change would come from changes in atmospheric storminess.

However, there is a caveat to the findings – the size of the model set used is relatively small. Ideally, a larger set of models would have been available at the finest spatial resolutions. Some CMIP5 simulations that were not downscaled to a finer scale with RCA4 exhibit larger signals of 21st century change in atmospheric storminess. To produce an illustrative high-end projection of the component of extreme sea level change due to atmospheric storminess changes over the 21st century we used atmospheric data from one such simulation to drive our storm surge model. The results are discussed in detail in the marine science report (Palmer et al, 2018) but in summary, at some locations the size of the resulting projected trend in the 200-year return level is between 2 and 3 mm/yr. This projection sits outside the limited range of the RCA4-downscaled simulations. Projections of the 21st-century trend in 1-year and 200-year still water return level (due to atmospheric storminess change only) from this simulation are included in the marine science report as an illustration for users who have a high level of risk aversion. However, it is not an upper limit to the theoretical storminess-change contribution.

3.3. Projected future coastal return level curves

We can combine projections of regional mean sea level change with the best available estimates of the present-day return levels of extreme still water level at selected tide gauge sites around the UK.
This includes tide and storm surge, but does not include the effect of waves. We include the uncertainties in the projections of regional relative mean sea level change but not the uncertainties in the present-day return levels.

In Figure 3.4 we present indicative return level curves of extreme still water level based on a simple addition of projected regional mean sea level change (for three different times in the 21st century) to the best available estimate of the present-day return level curves from the Environment Agency for four sites around the UK (Coastal Flood Boundary Conditions for the UK, Environment Agency, 2018).

Users can either consider the change in water level for a given return period, or the change in return period for a given water level. At some locations, a water level with a 1000-year return period in the present-day could occur more frequently than every 10 years by 2100, under the most extreme climate change scenario. However, for central estimates of sea level rise and especially for the lower RCP2.6 scenario the reductions in future return period are much lower.

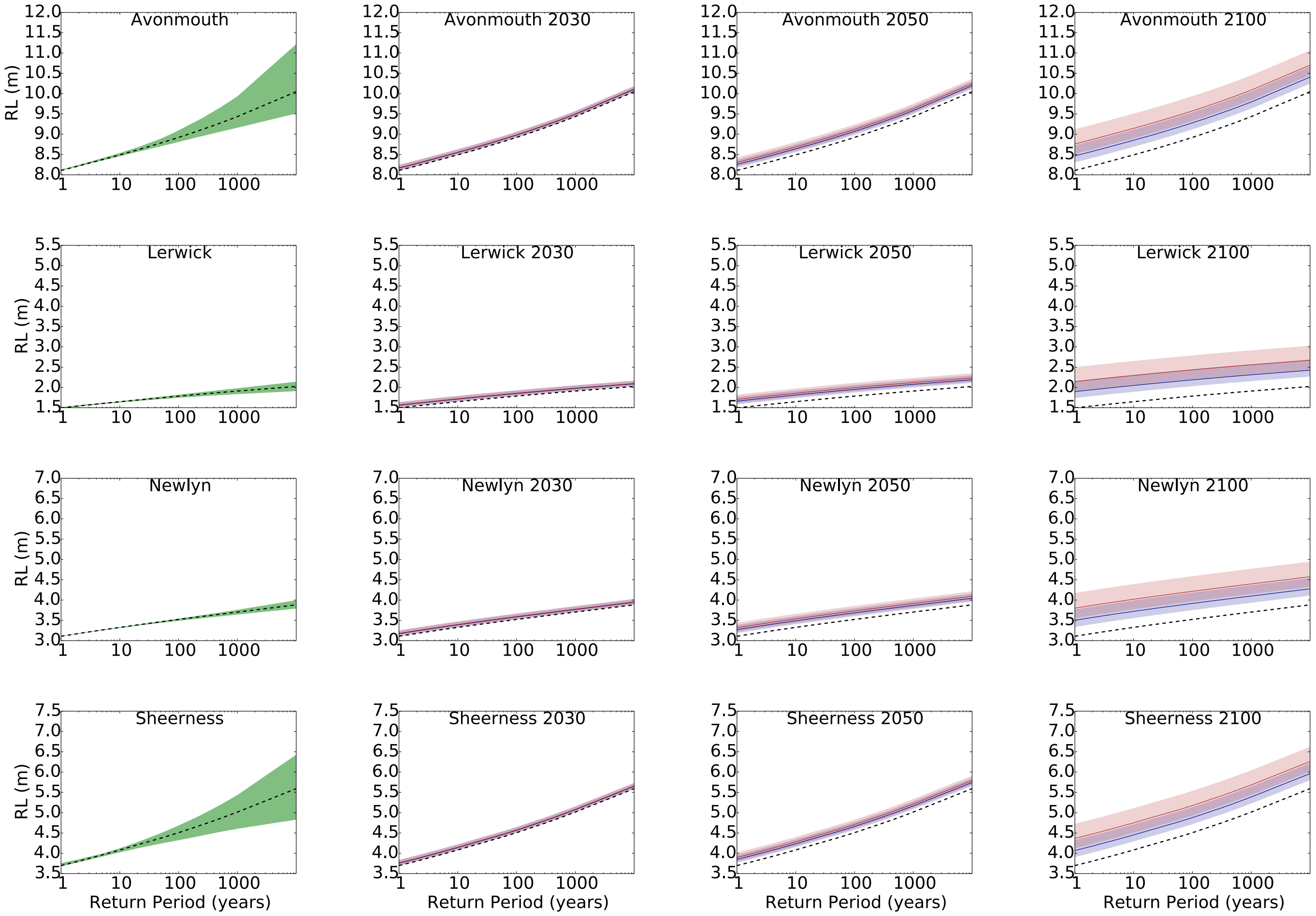


Figure 3.4. Projected future still water Return Level (RL) at Avonmouth, Lerwick, Newlyn and Sheerness. The present-day curve from Environment Agency (2018) is shown by the dashed black line (the lowest dashed line in each panel). Left hand panels also show an estimate of the present-day uncertainty (green shading, showing 5th to 95th percentile). The blue (red) lines show the future return level curve under the central estimate of mean sea level change from the RCP2.6 (RCP8.5) scenario. The blue (red) shading shows the respective 5th to 95th percentile. Uncertainty from the mean sea level projections is included. Uncertainty due to storminess changes is not included. Uncertainty in the present-day return level curves is not included in the projected future curves. The uncertainties shown should be regarded as minimum uncertainties.

3.4. Projections of changes in wave climate

Changes in sea surface waves can have an impact at the coast, causing overtopping of sea defences and contributing to the erosion of the shoreline.

Seven global wave models driven using winds from the CMIP5 global climate models explored potential changes in mean and annual maximum significant wave height under the RCP8.5 emission scenario. These simulations suggest an overall decrease in mean significant wave height around most of the UK coastline of 10-20% over the 21st century. The model projections show changes in annual maximum significant wave height also of up to 10-20%, but the sign of change differs among models and coastal location. It is also important to note that only a subset of the CMIP5 models were used in this part of the assessment limiting the confidence of the findings.

Higher spatial resolution regional wave model projections are presented based on a single CMIP5 model under RCP4.5 and RCP8.5. For this case it was found that there is a high degree of consistency between the global and regional wave model results, which is an important criterion for demonstrating that the regional model is behaving in a physically plausible way. This regional model configuration shows a similar magnitude of change to the global model simulations but provides better treatment of coastal processes and additional insights into the projected changes. The regional projections show more consistent changes across the 21st century and RCPs for the more exposed coastlines, where remote generation of swell waves dominates the significant wave height. For more sheltered sections of coastline, significant wave height changes are determined primarily by locally-generated waves and therefore local weather “noise” seems to dominate over the climate change signal. We note that projected changes in wave climate are inextricably linked to changes in atmospheric circulation and storminess. Given the inherent uncertainty in projections of storm track changes and the limited sample size available, the wave projections presented here should be viewed as indicative of the potential changes with low confidence.

Figure 3.5 shows relative changes in significant wave height at coastal model points. In this plot the modelled UK coastline is ‘unwrapped’ anticlockwise, starting and ending in the Bristol Channel. The first panel shows that the largest waves are seen on western facing coasts, including Cornwall, South West Wales, and North West Scotland. These west-facing coasts are dominated by long swell waves. Swell waves reaching the UK coastline are generated offshore, in the North Atlantic. The long period swells may have an integrative effect, as they build with storms moving across the ocean basins. The lowest wave heights are found in more enclosed seas, which are sheltered from long swells. In these semi-enclosed seas (for instance Irish Sea, North Sea) windsea waves are generated by local winds with a short fetch. In fetch-limited areas, there are short-period waves driven by local storm systems. By partitioning the wave conditions by peak period it could be possible to isolate changes in locally generated windsea and non-local swell waves.

The second and third panels of Figure 3.5 show changes in mean and annual maximum respectively. Four coloured lines are plotted for two time slices each from RCP 4.5 and RCP 8.5. Where the four futures cluster together, and show the same direction of change, we are more confident in an emergent climate signal. The mean significant wave height reduces at most coastal sites, of the order of 10%. The four future projections are coherent in their direction of change, and the largest reduction in coastal mean significant wave height is seen in under RCP8.5 at the end of the 21st century.

The change in annual maximum significant wave height is more spatially complex, and the different time horizons show opposing change signals in some locations. The projections of the annual maximum wave heights tend to agree in direction of change (showing increased significant wave height) on the swell dominated coasts. This is especially clear on the Cornish coast and South West England (also West of Ireland, not shown). The annual maximum wave projections diverge most strongly in the semi-enclosed seas, where wind-sea waves dominate. For example, consider the North Sea region between Hull and Orkney. In the North Sea coastal projections there is no consistent direction of change between the four future time horizons. In the fetch-limited areas where local windsea waves dominate there is no clear direction of change within this single model for future projections in either RCP4.5 or RCP8.5 scenario.

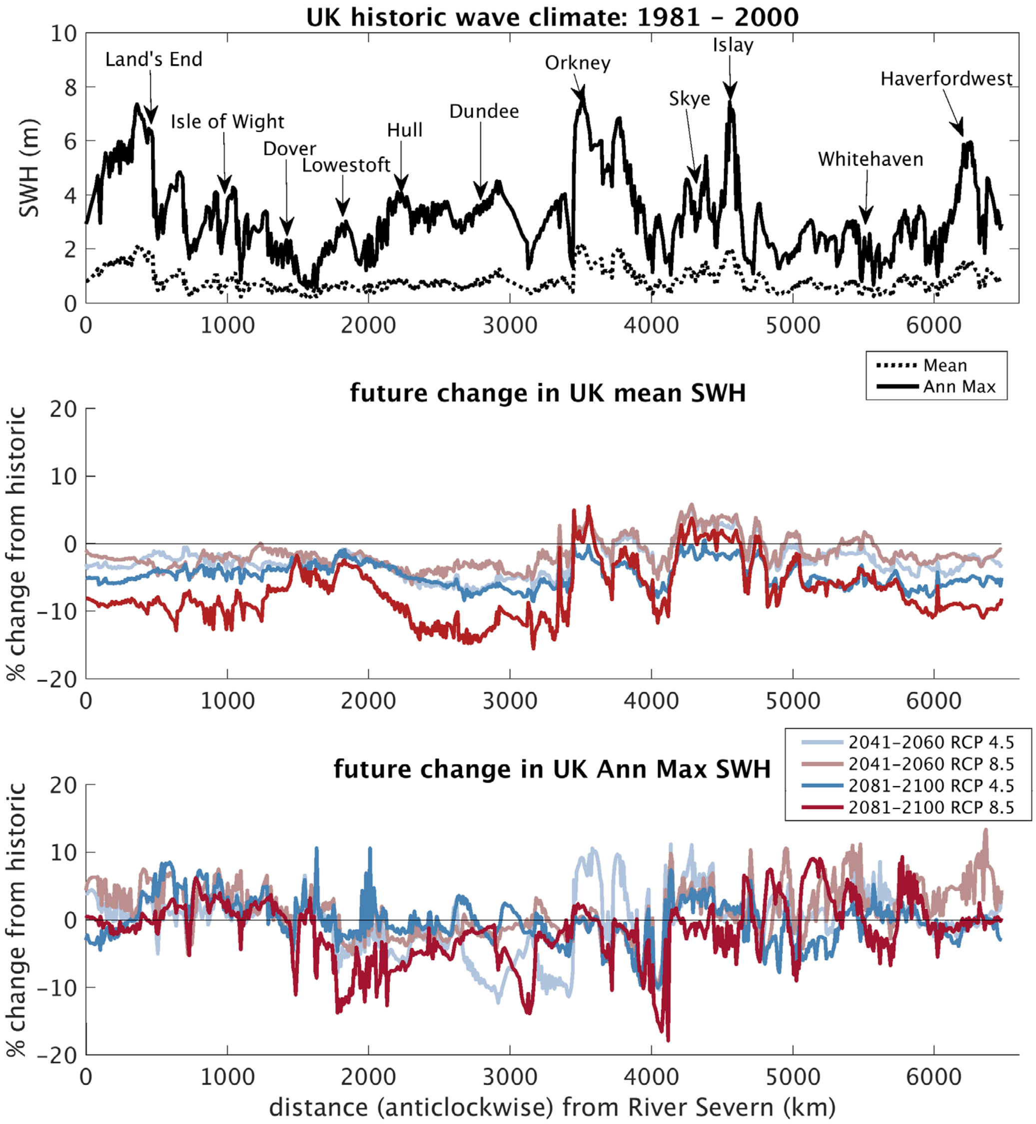


Figure 3.5. Coastal strip plots of historical wave climate and projected future changes for UK mainland. The top panel shows the mean significant wave height (SWH - dotted line) and mean annual maximum wave height (AnnMax - solid line) from the historical simulation. The second and third panels show percentage changes in mean SWH and AnnMax respectively, relative to a 1981-2000 baseline period. The four coloured lines represent "mid-century" (2041-2060) and "end-century" (2081-2100) change signals for RCP4.5 and RCP8.5. The coastal strip plots, involve starting from South West England then looking anticlockwise around the UK through the English Channel, into the North Sea. Proceeding around Scotland, and then South into the Irish Sea, ending with the Welsh coast and back to the Bristol Channel.

3.5. Projected changes in tidal characteristics

Mean sea level rise results in a direct increase in both low and high waters. However, since the propagation of tide and surge is dependent on water depth, there is also a potential for mean sea level change to have a more spatially complex effect on local tidal range and the extent of storm surges above the high tide. Changes to currents might also occur and could affect aspects such as sediment transport. Here we report numerical modelling simulations, made using the tide/surge models used for section 3.2, which give some indication of the potential for changes in tide and surge characteristics under future mean sea level rise.

The spatial pattern of change in tidal range derived here agrees well with that reported by some earlier work. However, modelling studies disagree on the sign of change around the Bristol Channel. The size of the tidal response to imposed sea level change is not proportional to the size of the imposed change at many sites.

3.6. Exploratory post-2100 sea level rise scenarios

Some UKCP18 stakeholders expressed a desire for sea level rise estimates that go beyond year 2100. This is especially important for sea level because there is now a large body of literature that suggests that increasing sea level will likely continue beyond 2100 for a considerable period of time even if global greenhouse gas emissions are restricted. The precise magnitudes of post-2100 projections must be considered of lower confidence than those to 2100 because of both the higher uncertainty in future greenhouse gas emissions and uncertainties in the physical science and our ability to model physical processes, such as those associated with the ice sheets, that might become increasingly important further into the future and for larger sea level rise estimates. However, that with the expectation of continued increase in sea level beyond 2100 is a high confidence result.

The extended projections were made for three future scenarios, which represent extensions of the RCP2.6, RCP4.5 and RCP8.5. These extensions follow idealised assumptions for the emissions rather than having a more direct link to the technologies and actions that produce greenhouse gases. The temperature and thermal expansion were simulated using a simple 2-layer global mean climate model. A major limitation is that this model was previously tuned to more complex models but for a range of climate conditions that did not extend to some of those experienced beyond 2100. Other sea level rise terms were estimated using variants of the method applied to 2100 but taking account of, for instance, the total amount of ice in glaciers. This is discussed in detail in the marine science report (Palmer et al, 2018).

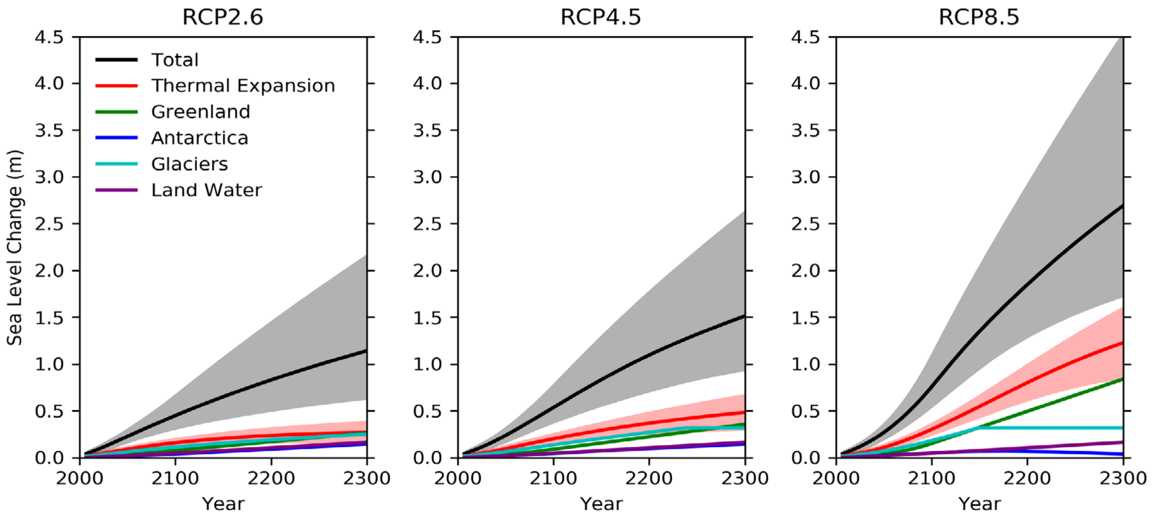


Figure 3.6. Time series of global mean sea level change to 2300 (m) with a baseline period of 1981-2000. Individual components are indicated by the coloured lines. The model projection ranges are indicated by the shaded regions for total and thermal expansion. Black, total change; changes due to thermal expansion, red; changes over Greenland (green) and Antarctica (blue) ; other glaciers over land (cyan); land water (purple).

The exploratory, illustrative, time-mean sea level projections to 2300 replicate an established view that global sea levels will continue to rise over the coming centuries under all RCP climate change scenarios. Of the UK capital cities, London and Cardiff show the largest values of future sea level rise, with projected ranges at 2300 of approximately 0.5 - 2.2 m, 0.8 - 2.6 m and 1.4 - 4.3 m for RCP2.6, RCP4.5 and RCP8.5, respectively. Edinburgh and Belfast show substantially lower values of approximately 0.0 - 1.7 m, 0.2 - 2.1 m and 0.7 - 3.6 m for RCP2.6, RCP4.5 and RCP8.5, respectively. These extended projections show uncertainty increasing with time and have much lower confidence that the 21st century projections; consequently they should be used with caution.

4. Notable differences between UKCP09 and UKCP18

As knowledge of the climate system improves through research, and also as the observed signal of climate change increases compared to natural variability we can expect changes in the projected ranges of future climate. Such change has resulted in UKCP18 being produced and having some differences to UKCP09, although the large overlap of projected ranges between UKCP09 and UKCP18 is evident for many climate metrics.

UKCP18 has many improvements over UKCP09, and provides some additional tools. The previous projections for UKCP09 made use of the SRES B1 ("Low"), SRES A1B ("Medium") and SRES A1FI ("High") scenarios. UKCP18 now provides improved probabilistic projections for five scenarios, including SRES A1B, which allows an inter-comparison of UKCP09 and UKCP18 results. UKCP18 introduces four new emission scenarios: RCP2.6, RCP4.5, RCP6.0 and RCP8.5, which span a greater range of future CO_2 concentrations and associated climate forcings than the SRES scenarios used in UKCP09. Broadly speaking, the older UKCP09 scenarios cover a similar range of future climate change forcings as the RCP4.5 to RCP8.5 scenarios used in UKCP18. The RCP2.6 scenario included in UKCP18 allows users to investigate the effect of significant mitigation of global greenhouse gas emissions.

A comparison of the UKCP09 and UKCP18 probabilistic results for the South East UK is shown in Figure 4.1 for the change over the 21st century. This uses thirty-year baseline and end of century periods for both the UKCP09 and UKCP18 results and is reported for the SRES A1B emission scenario, as this was the only baseline and averaging period available for the earlier dataset and SRES A1B is the only scenario common to both UKCP09 and UKCP18. When using comparable baselines the differences in response come from the changes in scientific methodology and input data.

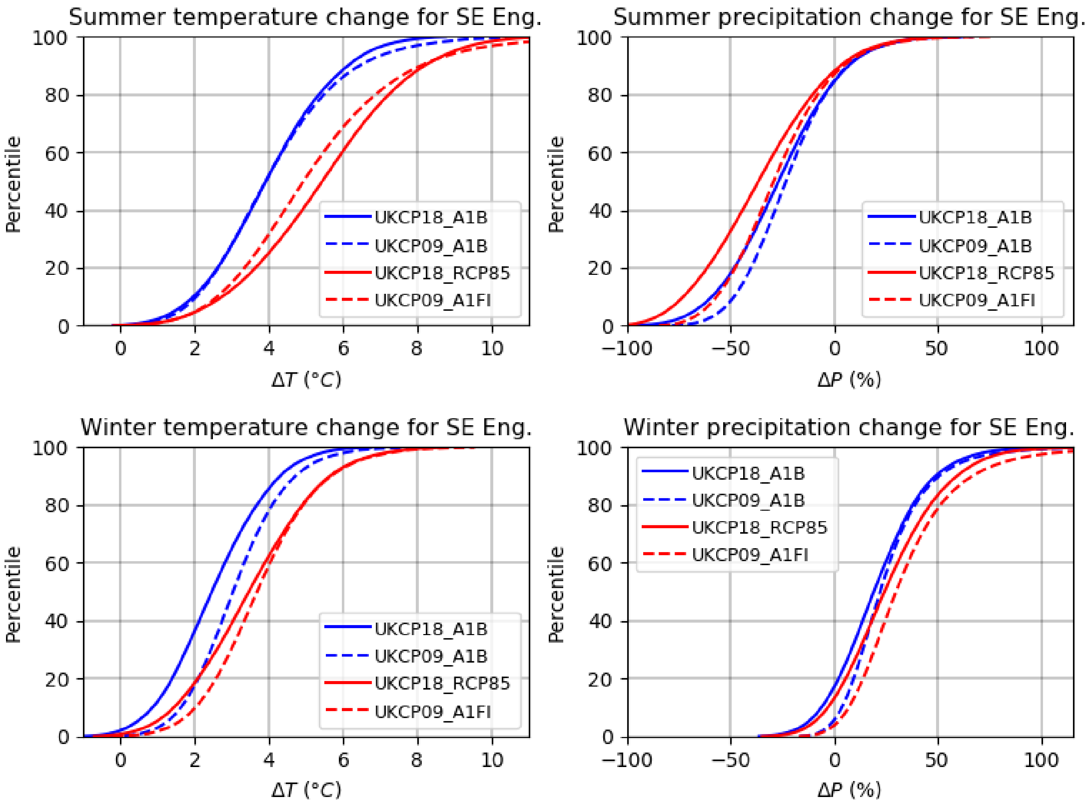


Figure 4.1. Comparison of annual warming and precipitation changes for the UKCP09 and UKCP18 probabilistic projections for the South Eastern UK. Default UKCP09 present-day and future time-periods used (1961-1990 and 2070-2099 respectively). Top panels show summer; bottom panels winter. Left hand column, temperature; right hand column, precipitation. Blue curves SRES A1B scenario, solid for UKCP18 and dashed for UKCP09; Red curves, solid for UKCP18 RCP8.5 and dashed for UKCP09 A1F1.

For temperature, it is clear that the differences in 21st century warming between UKCP09 and UKCP18 are dependent on season, with the largest differences in the winter. UKCP18 has slightly less warming for the same common scenario in winter for South East England. A point relevant to users is that the highest emission scenario in UKCP18, RCP8.5, gives slightly greater warming than the highest emissions scenario in UKCP09, SRES A1FI, for some of the percentile range in summer and slightly less warming in winter.

For precipitation, there are also differences between the UKCP09 and UKCP18 when using the same baselines and emission scenarios. This is most evident at lower percentiles, with UKCP18 showing slightly larger reductions in precipitation or slightly smaller increases in precipitation compared to UKCP09. When comparing the highest emission scenario results for UKCP18 and UKCP09 the former is again shifted towards to either slightly greater reductions in precipitation or slightly smaller increases.

The differences between UKCP18 and UKCP09 do also vary by location and the Northern Scotland location changes are shown in Figure 4.2 for comparison and consideration by users. Many of the differences are qualitatively similar to the South East England location. A notable feature is that in UKCP18 there is less warming than UKCP09 in summer for SRES A1B for Northern Scotland. For the highest emissions scenario the distribution becomes noticeably wider for winter warming in the UKCP18 case compared to UKCP09.

Despite the differences, there is considerable overlap between the two sets of projections over land, with uncertainty ranges being broad in both cases. The differences between UKCP18 and UKCP09 at any particular percentile level appears much smaller than the 5th to the 95th percentile spread for the season and metric being assessed. Users who have previously applied UKCP09 results are recommended to examine the consequences of using UKCP18 in more detail using the tools provided to access UKCP18 data.

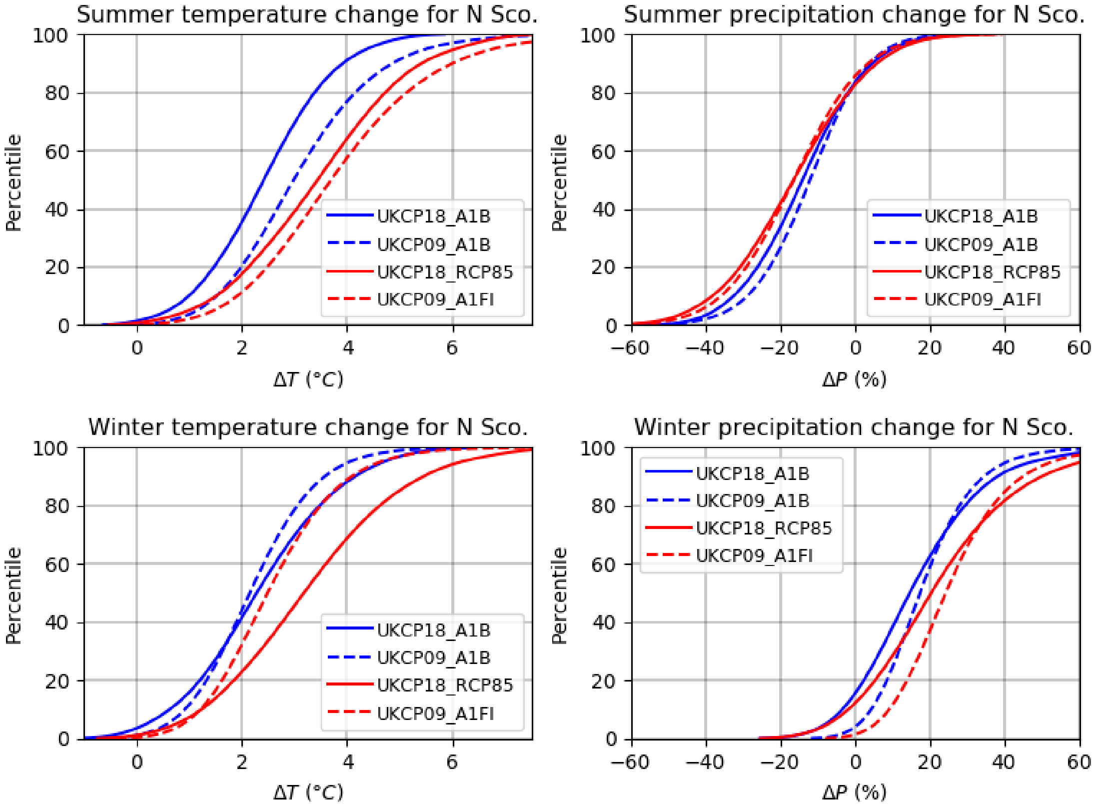


Figure 4.2. As 4.1 but for Northern Scotland.

A major new product introduced for UKCP18 is the provision of a set of global model projections of climate. This offers the capability to look at impacts in the UK and globally but did not have a comparable product in UKCP09. The twenty eight global projections are available with a spatial scale of 60km. UKCP18 also provides twelve new regional climate model simulations from a 12km climate model, compared with the eleven simulations provided from a 25km model in UKCP09. However, the future simulations can not be directly compared because they follow different pathways of future greenhouse gas emissions, with UKCP18 representing a higher emission scenario, RCP8.5 compared to the UKCP09 pathway of SRES A1B. Whilst we can not compare the future climate projections directly we can note that the global climate models used to drive the regional climate models have improvements in many aspects of European climate compared to those used in UKCP09. UKCP18 land projections also provide results from global climate models conditioned on 2°C and 4°C global warming. There was no comparable product in UKCP09. We will also launch a set of 2.2km scenarios in UKCP18, which are able to capture additional physical process such a more credible representation of larger-scale atmospheric convection.

For the marine climate projections, UKCP18 includes projections of mean sea level rise, and changes in storm surges and waves. UKCP18 also contains information on potential changes in tides. However, unlike UKCP09, projected changes in shelf sea temperatures and salinities were not commissioned or produced. Apart from that, the 21st century marine projection components of UKCP09 have all been updated under UKCP18. In addition, UKCP18 provides exploratory extended projections of time-mean sea level change beyond 2100.

The time-mean sea level projections of UKCP18 are based on updated scientific methods and climate change scenarios compared to UKCP09. The most important methodological difference is the inclusion of ice dynamics in UKCP18 projections of future sea level rise, resulting in systematically larger values for the top of the range than presented in UKCP09. The RCP climate change scenarios used in UKCP18 also span a greater range of climate forcing over the 21st century than the SRES scenarios used in UKCP09. While this results in a greater overall spread of regional sea level projections for UKCP18, we find that the modelling uncertainty for a given emission scenario is similar to that reported in UKCP09. Focusing on regional scales, a comparison of the 21st century time-mean sea level projections for London and Edinburgh from UKCP18 and UKCP09 is shown in Figure 4.3.

In both the UKCP09 Marine and Coastal projections and UKCP18 a storm surge model forced by atmospheric data from a set of climate model simulations of the 21st century was used. However, where the UKCP09 storm surge modelling used a set of driving projections based on a single climate model with perturbed atmospheric physics parameters, the UKCP18 storm surge modelling uses atmospheric data from a set of five diverse climate models selected from the CMIP5 projections and downscaled with the RCA4 regional climate model. An additional simulation used one further CMIP5 model not downscaled through a regional climate model. Both UKCP09 and UKCP18 concluded that changes in mean sea level will likely be the dominant driver of changes in future coastal water level extremes.

There is also an important difference in the high-end surge projection. UKCP09 selected a particular CMIP3 model with large projected storm track strengthening over the UK (according to one metric of storminess) and presented a high-end 21st century storm surge change based on two different crude scaling approaches intended to anticipate the result of downscaling that CMIP3 model, in the absence of suitable atmospheric data. UKCP18 selects a particular CMIP5 model with large projected storm track strengthening over the UK (according to the same metric of storminess) and presents “illustrative high-end” 21st century storm surge change results from a simulation driven directly by atmospheric data from that model. This avoids making assumptions about the validity of the scaling relationship used in UKCP09. The resulting storm surge high-end 21st century change in UKCP18 is smaller than that reported in UKCP09.

UKCP09 and UKCP18 both contain illustrative simulations of future waves, but like the storm surge modelling a different philosophy of driving atmospheric data has been chosen. Both approaches show some location dependent changes that merit further investigation by users sensitive to these changes.

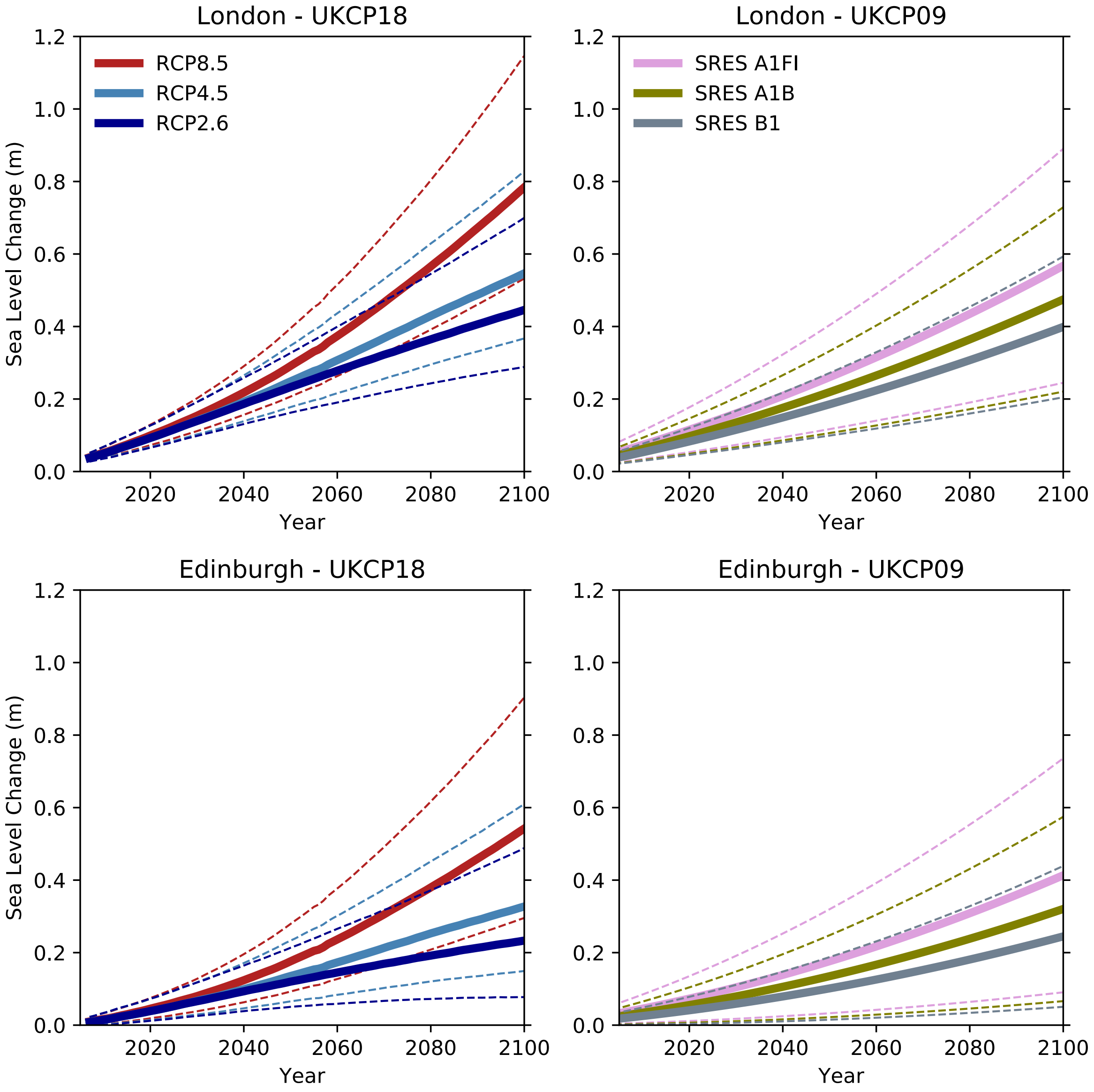


Figure 4.3. Time-mean sea level projections (m) for London (top panels) and Edinburgh (bottom panels). In left column, UKCP18 scenarios (RCP2.6, (dark blue); RCP4.5, (light blue); RCP8.5 ,(red). In right column, UKCP09 scenarios (SRES A1FI, (pink); SRES A1B, (green); and SRES B1, (grey)). The solid lines indicate the central estimate and dashed lines indicate the projection range. SRES A1FI, SRES A1B and SRES B1 correspond to the "High", "Medium" and "Low" climate change scenarios referred to in the UKCP09 Marine Report. UKCP18 results presented relative to a baseline of 1981-2000. UKCP09 results presented relative to a baseline of 1980-1999 (note that the difference in baseline period equates to 1-2 mm).

5. Caveats and limitations of UKCP18

The approaches used in UKCP18 have been subject to a rigorous evaluation. The models used for the future also simulate the present-day and the model results have been compared with observations. The physically based models of the climate used in UKCP18 are based on the well-established laws of physics and the latest understanding of how the climate system operates has been included in the projections. Further, an independent peer review panel of scientific experts has provided guidance on the approaches and influenced how the projections are made and presented. The panel contains many internationally renowned experts chosen to cover the breadth of UKCP18 products. This panel, which has been in place throughout most of the period of the UKCP18 production process, has been expanded for the final review of reports to include additional experts. Their views on UKCP18 are summarised on the user website.

It is important for users to be aware that, although we have confidence that the projections represent a significant improvement on UKCP09, there are still limitations in our ability to project 21st century weather and climate. Furthermore, all simulations of the future are conditioned on both a limited number of scenarios of future greenhouse gas emissions and the particular methodologies we employ in UKCP18. However, the limited number of greenhouse gas scenarios is less of an issue for the next two or three decades than for later in the century. While the global and regional projections of future climate use the latest climate models and are diverse they can not cover all potential future climate outcomes out to 2100 (or beyond in the case of sea level). Users making decisions based on any future climate information need to take this into account in their decision-making frameworks.

The 21st century projections presented in this report are produced for the RCP climate change scenarios. The results are therefore subject to any inherent limitations of the assumed emissions scenarios.

For the climate simulations over land users need to note:

- The probabilistic projections make use of global climate simulations using climate models of many different spatial resolutions and vintages. Like all climate models these replicate many aspects of the observed climate but also show biases compared to observations. Furthermore, they do not explicitly represent smaller-scale processes such as atmospheric convection.
- The probabilistic projections also adopt a particular set of methods including an approach to emulating climate models, treatment of structural uncertainty and use of a particular simple energy balance climate model. The approach also downscales results to the 25km scale using a statistical approach based on a global model-regional model pairing from a single model structure. Each stage of the method has many assumptions and relies on expert judgement.
- The probabilities represent the relative strength of evidence supporting different plausible outcomes for UK climate, based on the climate models, physical insight, observational evidence and statistical methodology used to produce them. However, they may not capture all possible future outcomes, because, for example, some potential influences on future climate are not yet understood well enough to be included in climate models.

- The global climate model projections also rely on global climate models with their inherent abilities and limitations. However, the set includes the latest Met Office climate model (GC3.05) which has a greater spatial detail than many other global models and many improvements to the treatment of atmospheric physics compared to earlier models. This model performs better at replicating many observed aspects of climate than earlier Met Office models, such as that used in producing the probabilistic projections, but does focus more on the higher end of the range of future warming. The set of GC3.05 projections is augmented with additional projections from IPCC CMIP5 models so that a wider range of future global warming is simulated.

- The sets of global and UK future climates has limited sizes and whilst it does cover a range of diverse futures, it can not simulate every possible future climate. This is especially true of the regional climate model set of projections which is not driven by any CMIP5 model simulations.

- Downscaling – the process of generating model data at higher spatial and/or temporal resolution – adds detail but also introduces another level of uncertainty. The additional information content is still valuable for specific applications, but finer model spatial resolution does not necessarily provide greater confidence, unless it has been shown to give a better representation of the underlying physical processes. For instance, the 12 km model better resolves mountains and coastlines and land surface heterogeneities; whilst the forthcoming 2.2 km model additionally better represents atmospheric convection offering projections of changes on local and hourly scales in which we have greater confidence.

- The derived scenario data uses approximate methods to produce an emulation of global climate model projections for other scenarios or fixed global warming levels based on the projections for RCP8.5. This introduces additional uncertainties and part of the method relies on an assumption of linearity in the model which seems reasonable for CMIP5 models based on pattern-scaling studies but has not yet been fully demonstrated for the Met Office global climate model output.

- Global climate models will typically provide greater confidence for long-term climate averages than extreme events or time series of daily or sub-daily values.

For the climate simulations of sea levels, storm surges and waves users should note:

- The UKCP18 21st century time-mean sea level projections are based upon the 5th to 95th percentiles of the underlying model distributions. However, there may be a greater than 10% chance that the real-world response lies outside the 5th to 95th percentile range and this likelihood cannot be accurately quantified. For instance, we cannot rule out substantial additional sea level rise associated primarily with dynamic ice discharge from the West Antarctic Ice Sheet. We recommend that decision makers make use of multiple strands of evidence, including H++ scenarios, where available, when assessing vulnerabilities to future extreme water levels.

- The 21st century projections presented in this report are predicated on the CMIP5 climate models and the RCP climate change scenarios. The results are therefore subject to any inherent limitations of the underlying model ensembles and assumed climate change scenarios.

- The 21st century surge and wave projections are based upon relatively small CMIP5 model ensembles. It is unlikely that these simulations span the full range of CMIP5 model responses under climate change. These projections should be viewed as indicative of the overall magnitude of changes we might see over the 21st century. For both these sets of simulations, we cannot be sure of the relative influence of the climate change signal vs natural variability.

- The extended time-mean sea level projections have much lower confidence than the 21st century projections. These projections can be considered as sensitivity studies and should not be interpreted as showing the full range of post-2100 behaviour, or the most likely behaviour. The potential for additional sea level rise from Antarctic dynamic ice discharge is even more uncertain on these time horizons, with some studies suggesting several additional metres of rise by 2300 under RCP8.5.

- The simulations of changes in tide and surge characteristics make the simple assumption of a fixed coastline under all levels of future sea level rise. However, several global tide model studies (e.g. Pickering et al, 2017) find that tidal changes are very sensitive to coastal management practices. Thus, the findings presented here need to be interpreted as illustrative of potential changes. Further work is needed under more realistic model configurations to make progress in this research avenue.

- One of the limitations of the storm surge and waves projections presented in this report was the availability of high frequency CMIP5 climate model output needed to drive surge and wave model simulations. The storm surge projections (presented in section 3.2) made use of dynamically downscaled data provided as part of the Euro-CORDEX project. Only a handful of Euro-CORDEX simulations had the high frequency surface wind and pressure data required to drive the storm surge model. The wave projections (presented in section 3.4) were limited to existing global and regional wave model simulations that had already been carried out as part the EU RISES-AM and COWCLIP projects. It was not possible to include the GFDL-ESM2M model (which provides our largest increase in the atmospheric drivers of surge) among our wave simulations. This limited the degree of consistency we were able to achieve across the surge and wave modelling components and resulted in model ensembles that are much smaller than for the time-mean sea level projections.

- The primary effect of mean sea level increase on waves is to increase the mean height around which the waves fluctuate, leading to increased over-topping and coastal flooding. An important secondary inshore effect arises as follows. The maximum amplitude of waves before breaking in shallow water is limited by the water depth. Thus, an increase in mean sea level will in general have the secondary effect of moving the surf zone further inshore, increasing the wave energy available at the coast for over-topping and coastal erosion, thereby exacerbating the primary effect. Users should be aware that we do not assess this secondary inshore effect here: our assessment of changes in the wave climate focusses on offshore wave changes.

Finally, all users need to be aware that as our understanding of the climate system and our ability to model it improves, and as computing power increases, it is likely that future projections will be refined. A consequence of these expected improvements is that both the climate model projections and probability distribution for a given outcome are likely to evolve in the future.

References

Committee on climate change, 2008. Building a low-carbon economy - the UK's contribution to tackling climate change. http://archive.theccc.org.uk/archive/pdf/TSO-ClimateChange.pdf

Cowtan K. and Way R.G., 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. Q. J. R. Meteorol. Soc. 140: 1935-1944.

Fung, F, 2018. How to Bias Correct, UKCP18 Guidance, Met Office.

Fung F, Lowe J, Mitchell JFB, Murphy J, Bernie D, Gohar L, Harris G, Howard T, Kendon E, Maisey P, Palmer M and Sexton D, 2018. UKCP18 Guidance: How to use the UKCP18 Land Projections. Met Office Hadley Centre, Exeter.

Fung F, Lowe J, Mitchell JFB, Murphy J, Bernie D, Gohar L, Harris G, Howard T, Kendon E, Maisey P, Palmer M and Sexton D, 2018. UKCP18 Guidance: Caveats and Limitations. Met Office Hadley Centre, Exeter.

Fung F, Palmer M, Howard T, Lowe J, Maisey P and Mitchell JFB, 2018. UKCP18 Factsheet: Sea Level Rise and Storm Surge, Met Office Hadley Centre, Exeter.

Fung F, Bett P, Maisey P, Lowe J, McSweeney C, Mitchell JFB Murphy J, Rostron J, Sexton D and Yamazaki K, 2018. UKCP18 Factsheet: Wind. Met Office Hadley Centre, Exeter.

Maisey P, Fung F, Harris G, Lowe J, McSweeney C, Mitchell JFB, Murphy J,Rostron J, Sexton D and Yamazaki K, 2018. UKCP18 Factsheet: Precipitation. Met Office Hadley Centre, Exeter.

Maisey P, Fung F, Harris G, Lowe J, McSweeney C, Mitchell JFB, Murphy J,Rostron J, Sexton D and Yamazaki K, 2018. UKCP18 Factsheet: Temperature. Met Office Hadley Centre, Exeter.

Maisey P, Thornton H, Fung F, Harris G, Lowe J, McSweeney C, Mitchell JFB, Murphy J, Rostron J, Sexton D and Yamazaki K, 2018. UKCP18 Factsheet: Weather Types. Met Office Hadley Centre, Exeter.

Gohar L., Bernie D., Good P., and Lowe J.A., 2018: UKCP18 Derived Projections of Future Climate over the UK.

Gohar, L. K., Lowe, J. A., Bernie, D., The Impact of Bias Correction and Model Selection on Passing Temperature Thresholds. JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES Volume: 122 Issue: 22 Pages: 12045-12061. 2017.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jacob D., Petersen J., Eggert B., Alias A., Christensen O.B., Bouwer L.M., Braun A., Colette A., Déqué M., and Georgievski G., 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change 14: 563-578.

Karoly D. J., and Stott P. A., Anthropogenic warming of central England temperature. ATMOSPHERIC SCIENCE LETTERS Volume: 7 Issue: 4 Pages: 81-85. 2006.

Kendon, M., McCarthy, M., Jevrejeva, S., Matthews and A., Legg, 2018: State of the UK Climate 2017.

Levermann, A., Winkelmann, R., Nowicki, S., Fastook, J. L., Frieler, K., Greve, R., Hellmer, H. H., Martin, M. A., Meinshausen, M., Mengel, M., Payne, A. J., Pollard, D., Sato, T., Timmermann, R., Wang, W. L., and Bindschadler, R. A., (2014). Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models. Earth System Dynamics, 5, 271-293. https://doi.org/10.5194/esd-5-271-2014

Moss et al, the next generation of scenarios for climate change research and assessment. NATURE Volume: 463 Issue: 7282 Pages: 747-756. 2010.

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.

Palmer M., Howard T., Tinker J., Lowe J.A., Bricheno L., Calvert D., Edwards T., Gregory J., Harris G.R., Krijnen J., and Roberts C., 2018: UKCP18 Marine Report.

Pickering M.D., Horsburgh K.J., Blundell J.R., Hirschi J.J.-M., Nicholls R.J., Verlaan M., Wells N.C., (2017), The impact of future sea-level rise on the global tides, Continental Shelf Research, Vol. 142, pp 50-68. https://eprints.soton.ac.uk/407983/3/1_s2.0_S0278434316304824_main.pdf

Pickering M.D., K.J.Horsburgh, J.R.Blundell, J.J.-M.Hirschi, R.J.Nicholls, M.Verlaane, N.C.Wells. The impact of future sea level rise on the global tides. Continental Shelf Research. Volume 142, 15 June 2017, Pages 50-68. https://doi.org/10.1016/j.csr.2017.02.00.

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), 2013: IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth ssessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324

Version 2: March 2019, updated to account for new methodology for production of UK and regional aggregate information in land strand 1.

Acknowledgement

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 Professor Sybren Drijfhout.

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

Version	Issue Date	Review Date	Reviewer	Change Description
1.0	November 18	November 19	Met Office	Launch version
2.0	March 19	November 19	Met Office	Updated to account for new methodology for production of UK and regional aggregate information in the probabilistic projections