Box 1.1: Climate and climate change projections; some definitions

It is useful at this stage to define some of the terms that we will be using extensively in this report, using definitions broadly in line with those given in IPCC AR4, but adapted to be relevant to UKCP09. The term **climate** is usually defined as the statistical description in terms of the mean and variability of relevant weather variables over a period of time, which in this report is taken as 30 yr (the period adopted by the World Meteorological Organisation).

A **climate change projection** is a projection of the response of the climate system to a given emissions or atmospheric concentration scenario, expressed as a change relative to a baseline climate (taken as 1961–1990 in UKCP09). Both the projection and baseline climate are simulations by a climate model.

A **climate projection** is a projection of the response of the climate system to a given emissions or atmospheric concentration scenario. In UKCP09 climate projections are generated from model climate change projections added to a baseline observational climate.

Climate models are often used to make a single projection of climate change, for a given emissions scenario, which reveals nothing about uncertainty. Using an **ensemble** of a large number of model projections, **probabilistic projections** can be generated, allowing the uncertainty in projections to be quantified by giving the relative probability of different climate change outcomes.

A **variable** is a climate-related quantity such as mean temperature or precipitation.

A **time period** is a 30-yr period over which changes in variables are averaged.

Changes are **spatially averaged** over four areas: a 25 km grid square, an administrative region, a river basin or a marine region. Changes are **temporally averaged** over a month, a season or a year. So, as an example, projections of change in mean daily maximum temperature for the summer season (temporal average) might also be averaged over Wales (spatial average) and for the 2080s (time period).

An **emission scenario** is a plausible future pathway of emissions of greenhouse gases and other pollutants which can affect climate.

In this report we emphasise the assumptions in the UKCP09 methodology, and test the sensitivity of our results to reasonable variations in these, where possible. This is done for reasons of scientific integrity, but the need for such assumptions is an inevitable consequence of the nature of the climate projection problem, and is not unique to the particular approach adopted in UKCP09. Highlighting these assumptions could lead the reader to question the value of the projections, but it is important to put this in the context of their use in adaptation. Planners and decision makers use projections of change in many factors; not just climate itself but also demography, economics, technologies, etc. All of these are uncertain, and subject to assumptions and limitations of their own. We believe that our probabilistic climate projections, despite their limitations, are likely to provide information on climate change and its uncertainty which is at least as robust as the quality of information available for other planning factors.

1.2 What information do the UKCP09 projections provide? A summary

The UKCP09 projections cover changes in a number of atmospheric variables, with different temporal and spatial averaging, by several future time periods, under three future emissions scenarios. Box 1.1 defines these terms. Changes over land areas of the UK include more variables, and at a higher resolution, than those over marine regions.

1.2.1 Climate change over land areas

Variables. The variables for which changes are given over land areas are shown in Table 1.1 (overleaf), broadly similar to those in UKCIP02. Some additional information is given in Box 1.2 (overleaf).

Temporal averaging. For most variables changes are given as averages over three periods: month, season and year, except as shown in the last column of Table 1.1 (overleaf).

Spatial averaging. The resolution of the projections is 25 km over the land area of the UK, including islands large enough to be seen at this resolution (Figure 1.2(a)). Due to the probabilistic nature of the projections, it is not possible for probabilities of change over several individual grid squares to be simply averaged by the user in order to obtain probabilities of change over the total area of the grid squares. For this reason, we also provide probabilities of change for two different sets of aggregated areas over land, each decided upon following consultation.

The first of these aggregated areas (Figure 1.2(b)) encompasses the 16 regions made up of:

- the nine administrative regions of England
- Wales
- Northern Ireland
- Scotland, subdivided into its three climatological regions
- the Isle of Man
- the Channel Islands (represented by a single 25 km grid square)

For simplicity, these are all referred to as *administrative regions*.

Box 1.2: Some additional information on climate variables

Temperatures

Mean daily temperature (often referred to as simply *mean temperature*) is the average of the daily maximum and daily minimum temperatures.

Mean daily maximum temperature (sometime shortened in this report to just *maximum temperature*) is the average of the daily maximum temperatures over the temporal averaging period (for example, a season).

Mean daily minimum temperature (sometime shortened in this report to just *minimum temperature*) is the average of the daily maximum temperatures over the temporal averaging period.

Precipitation

Precipitation is given as a rate, in millimetres per day; however, when discussing monthly, seasonal or annual average changes to this we refer to it for convenience as simply *precipitation*. Note also that it is a total of precipitation of all types — rain, snow and hail.

Relative humidity (RH) and cloud

Just as a change in precipitation from 50 to 60 mm/day would represent a proportional increase of 20%, so a change of RH from 50% in the baseline climate to 60% in the future climate represents a proportional increase of 20% (rather than 10%). The same comment applies to changes in total cloud.

Extremes of temperatures and precipitation

These refer to changes in the 1st and 99th percentiles of the daily distribution of that particular variable during a season, over the complete 30-yr period (that is, about 2700 days). However, because a season has roughly 100 days, changes in the 1st and 99th percentiles of the distribution can be thought of as roughly equivalent to changes in the extreme value of the season, giving a more user-friendly name. Thus the change in the 99th percentile of the daily maximum temperature of the summer season can be thought of as the change in temperature of the *warmest day of the summer* and will be referred to as such in this report. The change in the 1st percentile of daily maximum temperature will be referred to as that of the *coolest day of the season*. The change in the 99th percentile of minimum temperature will be referred to as that of the *warmest night of the season*, that in the 1st percentile as that of the *coldest night of the season* — whilst recognising that the daily minimum temperature does not always occur at night. The change in the 99th percentile of daily precipitation will be referred to as the change in the *wettest day of the season*.

Variable	Unit	Change	Temporal averaging
Mean daily temperature	°C	°C	Month, season, year
Mean daily maximum temperature	°C	°C	Month, season, year
Mean daily minimum temperature	°C	°C	Month, season, year
99th percentile of daily maximum temperature	°C	°C	Season
1st percentile of daily maximum temperature	°C	°C	Season
99th percentile of daily minimum temperature	°C	°C	Season
1st percentile of daily minimum temperature	°C	°C	Season
Precipitation rate	mm/day	%	Month, season, year
99th percentile of daily precipitation rate	mm/day	%	Season
Specific humidity	g/kg	%	Month, season, year
Relative humidity	%	% (of %)	Month, season, year
Total cloud	fraction	%	Month, season, year
Net surface long wave flux	Wm^{-2}	Wm^{-2}	Month, season, year
Net surface short wave flux	Wm^{-2}	Wm^{-2}	Month, season, year
Total downward short wave flux	Wm^{-2}	Wm^{-2}	Month, season, year
Mean sea level pressure	hPa	hPa	Month, season, year

Table 1.1: The climate variables available over land as probabilistic projections of change in UKCP.

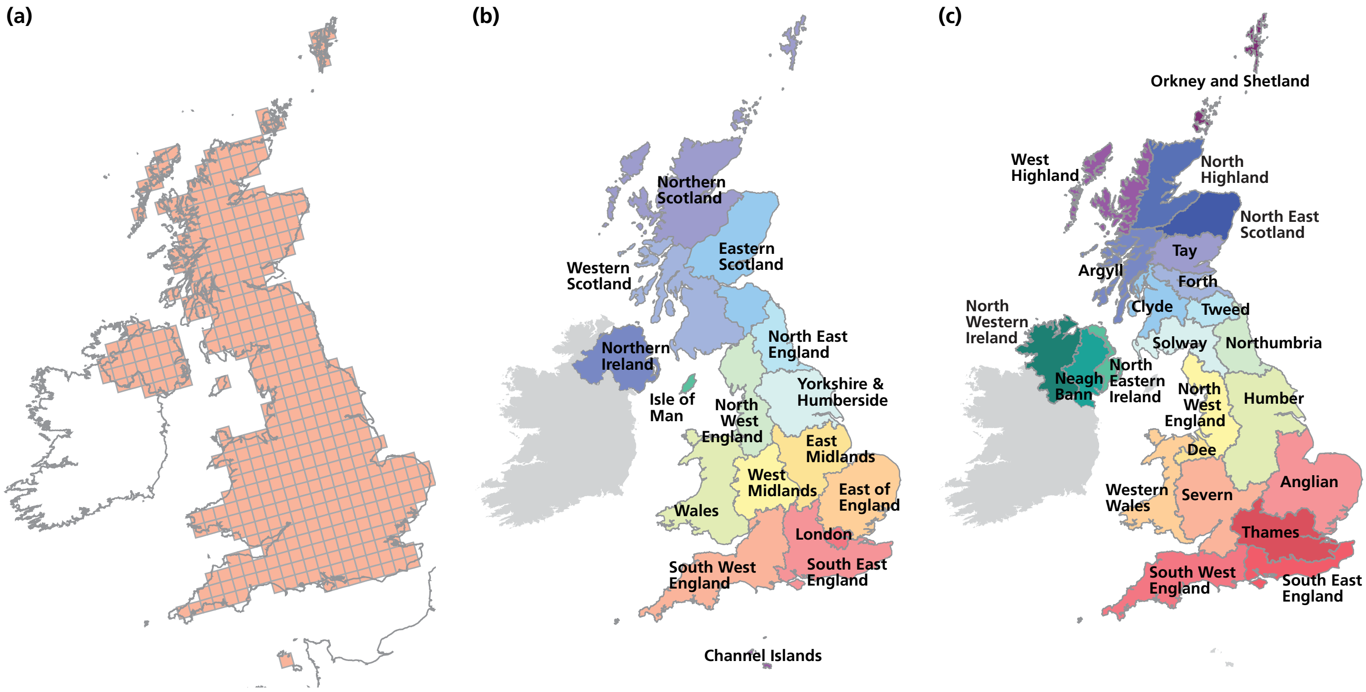


Figure 1.2: (a) Areas over which probabilistic projections are available: (a) the 25 km grid, (b) the 16 administrative regions and (c) 23 river-basin regions.

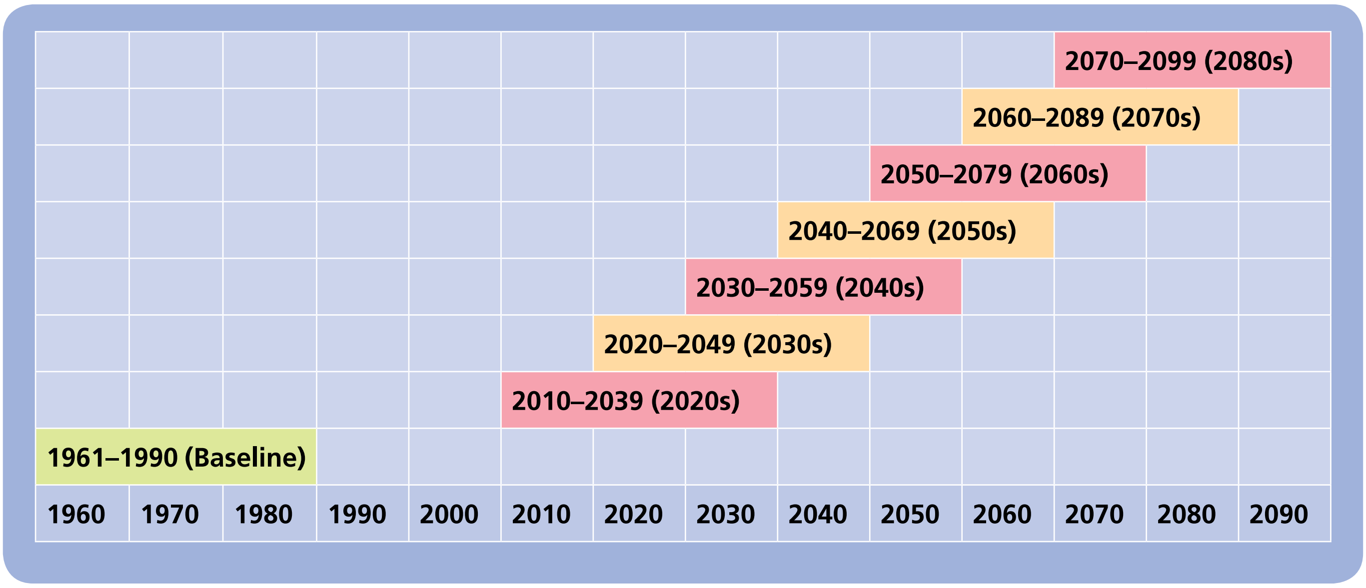


Figure 1.3: The seven 30-yr future time periods over which projections are averaged, relative to the baseline period.

Variable	Unit	Change	Temporal averaging
Mean daily air temperature	°C	°C	Month, season, year
Precipitation rate	mm/day	%	Month, season, year
Mean sea level pressure	hPa	hPa	Month, season, year
Total cloud	fraction	%	Month, season, year

Table 1.2: The climate variables available as probabilistic projections of change over marine regions in UKCP09. Note that the first variable is termed *air temperature* to avoid possible confusion with sea-surface temperature, projections of which are given in the UKCP09 Marine and coastal projections report.

The second set of aggregated areas are river basins, shown in Figure 1.2(c). These are based on the 13 Water Framework Directive River Basin Districts in England, Wales and Northern Ireland. In Scotland, these are based on the 10 Advisory Group Boundaries.

Time periods. Changes are given averaged over each of seven future overlapping 30-yr time periods, stepped forward by a decade, starting with 2010–2039 (specifically 1 December 2009 to 30 November 2039). These future time periods are referred to for simplicity by their middle decade, starting from the 2020s (2010–2039) and ending with the 2080s (2070–2099).

User surveys showed overwhelming support for retaining the same baseline period as used in UKCIP02, and hence all changes are expressed relative to a modelled baseline 30-yr period of 1961–1990 (specifically 1 December 1960 to 30 November 1990). The future time periods are illustrated in Figure 1.3.

Emission scenarios. Changes are given corresponding to three future emissions scenarios — Low, Medium and High.

In the case of mean sea-level pressure, precipitation, relative humidity, temperature (mean, maximum and minimum) and cloud amount, UKCP09 also makes available probabilistic projections over land of future climate in addition to those of the change in climate. This is done by combining probabilistic projections of climate change with the corresponding baseline (1961–1990) climate taken from observations. This is preferable to directly taking the climate model output for future years as it reduces the effect of biases in the model's simulation of the baseline climate, but obviously cannot account for any errors in the projected climate change response.

1.2.2 Climate change over marine regions

The four variables for which changes are given over marine regions are shown in Table 1.2. Changes are given as temporal averages over three periods: month, season and year, and as spatial averages over nine marine regions shown in Figure 1.4; the latter were selected by user consultation and are based on the UK *Charting Progress* areas, with extended natural boundaries where possible.

As with projections over land, changes are given averaged over each of seven future overlapping 30-yr time periods, stepped forward by a decade, from 2010–2039 (*2020s*) to 2070–2099 (*2080s*), and changes are expressed relative to a modelled baseline period of 1961–1990. Changes are given corresponding to three future emissions scenarios — Low, Medium and High.

Marine projections are provided only as changes. Projections of absolute future values are not given.

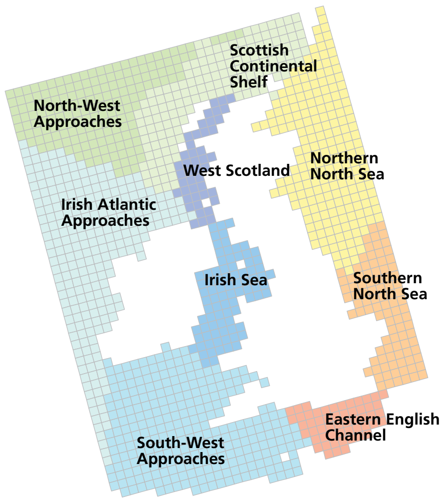


Figure 1.4 (above): The nine marine regions over which changes in climate variables have been projected. The names for these regions have been chosen specifically for the convenience of this report and hence may not be geographically or politically correct.

1.3 Uncertainty

Uncertainty in climate change projections is a major problem for those planning to adapt to a changing climate. Adapting to a smaller change than that which actually occurs (or one of the wrong sign) could result in costly impacts and endanger lives, yet adapting to too large a change (or, again, one of the wrong sign), could waste money. In addition there is the risk of maladaptation – adapting to climate change in a way that prevents or inhibits future adaptation. The 2008 projections are the first from UKCIP to be designed to treat uncertainties explicitly, by generating projections of change that are given, where justified, as estimated probabilities of different outcomes (see Box 1.3 for interpretation of probabilities in UKCP09) rather than giving a single realisation of possible changes from one model or a small sample of possible changes from several models. This means that probabilities are attached to different climate change outcomes, giving more information to planners and decision makers.

Uncertainty in projections of future climate change arises from three principal causes:

- natural climate variability, both internal and external;
- incomplete understanding of Earth System processes and their imperfect representation in climate models (which we term *modelling uncertainty*); and
- uncertainty in future emissions.

The effect of modelling uncertainty manifests itself in the different projections from different climate models, both globally and, to an even greater extent, at local or regional scales where information is critically needed. For the first time in UKCIP, we are able to estimate the size of this uncertainty by providing the user with *probabilistic projections* of climate change for certain key climate variables, where the estimated probabilities can be shown to be robust to the main assumptions in our methodology. This provides information on the estimated relative likelihood of different future outcomes, in the form of a *probability density function* or PDF (see Box 1.3). The PDF takes into account both the modelling uncertainty and that due to natural internal variability, but is not able to include the uncertainty due to future emissions, which is why separate PDFs are given for each of three emissions scenarios.

The reason why different climate models give different projections is because they use different, but plausible, representations of climate processes. Hence, we generate probability distributions using projections from a very large number of variants of the Met Office Hadley Centre model, each representing climate processes in a different way within their structure. We also incorporate projections from twelve other international models which have different structures and which have participated in international intercomparisons such as that for IPCC AR4; this allows us to sample the effects of modelling errors which cannot be incorporated by varying the representations in the Met Office model alone. (Obviously errors due to processes missing from all models cannot be sampled by any technique.) The use of alternative climate models also fulfils one of the main user requests identified from a review of UKCIP,* that the projections should not be based solely on the Met Office model.

The progression to probabilistic projections based on large ensembles has meant that not all of the properties and characteristics of the UKCIP02 scenarios could be carried across to UKCP09 — the direct provision of daily time series from climate model output, for example. Thus the new projections are not a "drop in" replacement or straightforward update of UKCIP02.

* http://randd.defra.gov.uk/Document.aspx?Document=GA01070_3619_FRP.pdf

Box 1.3: How are probabilistic projections presented? Explaining PDFs and CDFs

The provision of probabilistic projections is the major improvement which the UKCP09 brings to users. However, to utilise these appropriately, it is essential that users have a good understanding of what they mean and how they are communicated.

Probabilistic projections assign a probability to different possible climate change outcomes, recognising that (a) we cannot give a single answer and (b) giving a range of possible climate change outcomes is better, and can help with making robust adaptation decisions, but would be of limited use if we could not say which outcomes are more or less likely than others.

Within any given range of plausible climate changes, we cannot talk about the absolute probability of climate changing by some exact value — for example a temperature rise of exactly 6.0ºC. Instead we talk about the probability of climate change being less than or greater than a certain value, using the Cumulative Distribution Function (CDF). This is defined as the probability* of a climate change being less than a given amount. The climate change at the 50% probability level is that which is as likely as not to be exceeded; it is properly known as the median, but in UKCP09 we refer to it by the more user-friendly name of *central estimate*. Thus in Figure 1.5 (top panel), the CDF (a hypothetical example at a certain location, by a certain future time period, for a given month of the year, under a particular emissions scenario) shows that there is a 10% probability of temperature change being less than about 2.3ºC and a 90% probability of temperature change being less than about 3.6ºC. These statements conventionally concern the probability of change being less than a given threshold, but of course we can turn them around to give the probability of exceeding that threshold. Thus the CDF in Figure 1.5 (top panel) also shows that there is a 90% probability of temperature change exceeding about 2.3ºC and a 10% probability of temperature change exceeding about 3.6ºC.

The CDF would be useful for those who want to know the probability of climate change being less than some threshold where an impact of interest starts to occur. However, the CDF is not useful for understanding the relative probability of different specific outcomes. The Probability Density Function (PDF, Figure 1.5, bottom panel) is an alternative representation of the same distribution which is a useful visualisation of the relative likelihood of different climate outcomes. For a given value of climate change, the CDF is the area under the PDF to the left of that value of climate change. As the CDF has a maximum value of 100%, the area under the PDF curve cannot be more than 100%.

As probability is represented by the area under a PDF curve, the *y*-axis in Figure 1.5(b) is referred to as a probability density, with units of "per ºC". However, the PDF can be thought of more simply in relative terms by comparing the ratios of probability density for different outcomes. For instance, as the probability density at 2.9ºC is about 0.7 (per ºC) and the probability density 3.8ºC is about 0.2 (per ºC) , then a temperature change of 2.9ºC is about 3.5 times more likely than one of 3.8ºC. Hence, for simplicity, PDF graphs from the User Interface are all labelled *relative probability* rather than *probability density (per ºC)*.

* Probabilities in CDFs are conventionally taken to range between 0 and 1, although we refer to them here as percentages between 1 and 100.

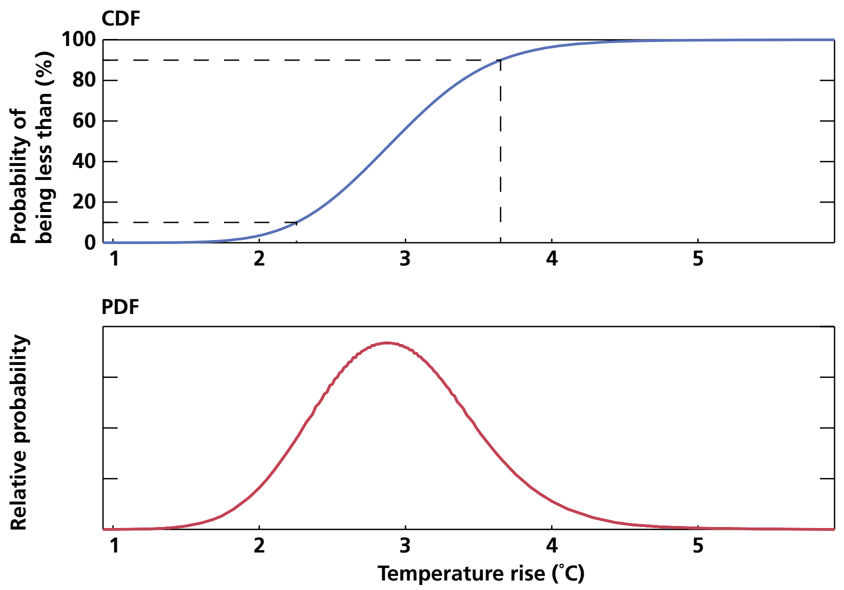


Figure 1.5: Top panel, Cumulative distribution function of temperature change for a hypothetical choice of emission scenario, location, time period and month. Bottom panel, Corresponding probability density function for this hypothetical case.

The hypothetical distribution shown in Figure 1.5 (bottom panel) is smooth and almost symmetrical; in practice the UKCP09 distributions vary in shape, dependent on how the effects of uncertain climate system processes combine to produce different projections for different variables, time periods and locations.

It is very important to understand what a probability means in UKCP09. The interpretation of probability generally falls into two broad categories. The first type of probability relates to the expected frequency of occurrence of some outcome, over a large number of independent trials carried out under the same conditions: for example the chance of getting a 5 (or any other number) when rolling a dice is 1 in 6, that is, a probability of about 17%. This is not the meaning of the probabilities supplied in UKCP09, as there can only be one pathway of future climate. In UKCP09, we use the second type (called *Bayesian probability*) where probability is a measure of the degree to which a particular level of future climate change is consistent with the information used in the analysis, that is, the evidence. In UKCP09, this information comes from observations and outputs from a number of climate models, all with their associated uncertainties. The methodology which allows us to generate probabilities is based on large numbers (*ensembles*) of climate model simulations, but adjusted according to how well different simulations fit historical climate observations in order to make them relevant to the real world. The user can give more consideration to climate change outcomes that are more consistent with the evidence, as measured by the probabilities. Hence, Figure 1.5 (top panel) does not say that the temperature rise will be less than 2.3°C in 10% of future climates, because there will be only one future climate; rather it says that we are 10% certain (based on data, current understanding and chosen methodology) that the temperature rise will be less than 2.3°C. One important consequence of the definition of probability used in UKCP09 is that the probabilistic projections are themselves uncertain, because they are dependent on the information used and how the methodology is formulated. Section 2.6 discusses the uncertainty in the probabilistic projections in more detail and Annex 2 explores their robustness to changes in evidence and methodology.

As mentioned earlier, UKCP09 probabilistic projections also take into account the uncertainties due to natural internal climate variability (sometimes called the *chaotic* behaviour of the earth's climate system), but not the effect of uncertainties in future emissions. The latter, though small over the next two or three decades mainly because of climate system inertia, will be substantial in the second half of the century, but there is currently no accepted method of assigning relative likelihoods to alternative future emissions pathways. We therefore present separate probabilistic projections of future climate change for three scenarios of future emissions. These were selected, after consultation with users, from three scenarios developed by IPCC in its Special Report on Emission Scenarios (SRES) in 2000. In UKCP09 they are labelled High emissions, Medium emissions and Low emissions, and correspond to the A1FI, A1B and B1 scenarios in SRES. Annex 1 gives further detail on these emission scenarios.

1.4 Projections at a daily resolution over land

Changes in daily climate, such as the frequency of hot or very wet days, are likely to be more significant for many climate impacts than changes in monthly or seasonal averages. Whilst we are not able to project changes in storm tracks and anticyclones with confidence, we can project how the characteristics of daily time series could be affected by changes in the more basic aspects of future climate, such as monthly mean temperature and precipitation and other aspects of their distributions, which we have more confidence in projecting.

Our approach, therefore, is to provide a tool known as a weather generator, capable of providing plausible realisations of how future daily time series of several variables could look, consistent with changes in the characteristics of monthly-average climate sampled from the probability distributions. It does not provide a weather forecast for a particular day in the future; it gives statistically credible representations of what may occur given a particular future climate. Despite their limitations (for example, they assume that relationships between different variables remain unchanged in a future climate), we recognised the inevitability of (possibly different varieties of) weather generators being employed by many users, and the advantages for consistency between impact studies that a single weather generator would bring. The UKCP09 weather generator was developed by the Universities of Newcastle and East Anglia, based on a previous version in use by the Environment Agency.

The UKCP09 Weather Generator provides synthetic daily time series of temperature (mean, maximum and minimum), precipitation, relative humidity, vapour pressure, potential evapotranspiration (PET) and sunshine (from which we also estimate diffuse and direct downward solar radiation) at a resolution of 5 km, for each of the three emission scenarios and each of the future 30-yr time periods — 2020s, 2030s, etc. It provides data over land but not for marine regions. The weather generator does not add any additional climate change information over that which is present in the 25 km probabilistic projections. However it does add local topographical information (e.g. hills, valleys) at the 5 km scale, as it is based on observed data which is representative of this scale. The Weather Generator is also able to construct synthetic hourly time series for precipitation, temperature, vapour pressure, relative humidity and sunshine for future time periods. This is a disaggregation of daily data and, again, does not provide any new climate change information at this level. The *UK Climate Projections science report: Projections of future daily climate for the UK from the weather generator* describes the weather generator in detail, with examples of its output, and also considers its limitations.

An entirely different type of projections at a daily resolution (again, not weather forecasts for the future) is also available from an ensemble of transient experiments (that is, run continuously from 1950 to 2099) of the 25 km resolution Met Office regional climate model; the daily time series are spatially coherent and physically consistent across the whole UK and surrounding seas. However, because they are not completely compatible with the probabilistic projections, they are not part of UKCP09, but are available from the Climate Impacts LINK project website, also funded by Defra. Chapter 5 gives more details.

Note that guidance on the application of these projections, including discussion of their limitations, and also some examples of how they could be used, is discussed in a separate publication: UKCP09 User Guidance.

Box 1.4: Confidence in climate projections

There is a cascade of confidence in climate projections. There is very high confidence in the occurrence of global warming due to human emissions of greenhouse gases. There is moderate confidence in aspects of continental scale climate change projections. 25 km scale climate change information is indicative to the extent that it reflects the large-scale changes modified by local conditions. There is no climate change information in the 5 km data beyond that at 25 km. All that can be produced is a range of examples of local climates consistent with current larger-scale model projections. The confidence in the climate change information also depends strongly on the variable under discussion. For example, we have more confidence in projections of mean temperature than we do in those of mean precipitation. The probabilities provided in UKCP09 quantify the degree of confidence in projections of each variable, accounting for uncertainties in both large scale and regional processes as represented in the current generation of climate models. However, the probabilities cannot represent uncertainties arising from deficiencies common to all models, such as a limited ability to represent European blocking. The fact that the UKCP09 projections are presented at a high resolution for the UK should not obscure this, and users should understand that future improvements in global climate modelling may alter the projections, as common deficiencies are steadily resolved.

2 Why do we need probabilistic information? Uncertainties in climate change projections

This chapter describes the uncertainties in projections of climate change and how they arise. It goes into some detail on how climate models are structured, and the reasons why different models give different projections of change. This provides the background to a simplified description of the methodology which has been developed to provide the probabilistic projections for UKCP09. Next, it outlines some of the limitations of these projections. Finally, it describes the three scenarios of future emissions which underlie the projections.

2.1 Background

The development of climate change information over the last two decades has broadly paralleled that in climate science and climate modelling. Planners and decision makers have become increasingly demanding in their requirements over the last decade as the potential severity of impacts is realised, and as UKCIP and others have successfully persuaded more and more stakeholders to bring climate change into the mainstream of their long-term planning process. Successive improvements in models and the way they are used mean that climate scientists are able to come closer to meeting these requirements, but large uncertainties remain which are outlined in this chapter, together with a simplified description of how we are taking account of them in UKCP09. It is the continuing existence of these uncertainties that has largely driven the move away from single projections and towards probabilistic ones.

As outlined in Chapter 1, there are three major sources of uncertainties in estimating future climate change: (i) that due to natural variability, (ii) that due to incomplete understanding of climate system processes and their imperfect representations in models (which we term modelling uncertainty) and (iii) that due to uncertainty in future emissions; these are discussed below in turn. Previous UKCIP climate change scenarios have taken account of some of these uncertainties in different ways (see review by Hulme and Dessai, 2008). UKCIP98 (Hulme and Jenkins, 1998) presented four climate change scenarios, corresponding to four combinations of emissions scenario and global climate sensitivity; the latter was used to scale patterns of change from a single Met Office 300 km resolution global climate projection as an attempt to include model uncertainty. UKCIP02 (Hulme *et al*. 2002) again provided four climate change scenarios, differing only in the emissions scenarios which were again used to scale a single 50 km resolution pattern from the Met Office Hadley Centre regional climate model; no account was taken of model uncertainty as there were no credible techniques then available to do this. Dessai and Hulme (2008) have shown that recent trends in observed UK climate fall broadly within the range of projections of UKCIP (and earlier) scenarios, the greatest ambiguity occurring for summer precipitation.

2.2 Natural variability

Climate, at a global scale and even more at a local scale, can vary substantially from one period (for example, a decade or more) to the next, even in the absence of any human influences. This natural variability of the earth's climate has two causes. The first, natural internal variability, arises from the chaotic nature of the climate system, ranging from individual storms which affect our regional weather to large scale variations over periods of seasons to years. Variability of the latter type results mainly from interactions between ocean and atmosphere, resulting in phenomena such as El Niño. Natural internal variability will continue in future, and be superimposed on longer-term changes due to man's activities. If in a specific future period internal variability happens to act in the same direction as man-made change then the overall change will be that much bigger; if it acts in the opposite direction, the overall change will be that much smaller. Climate models provide realistic simulations of a number of key aspects of natural internal variability in the observed climate (see Annex 3). By running the climate model many times with different initial conditions (a so-called initial condition ensemble) we can estimate the statistical nature of this natural variability on a range of space and time scales, and hence quantify the consequent uncertainty in projections.

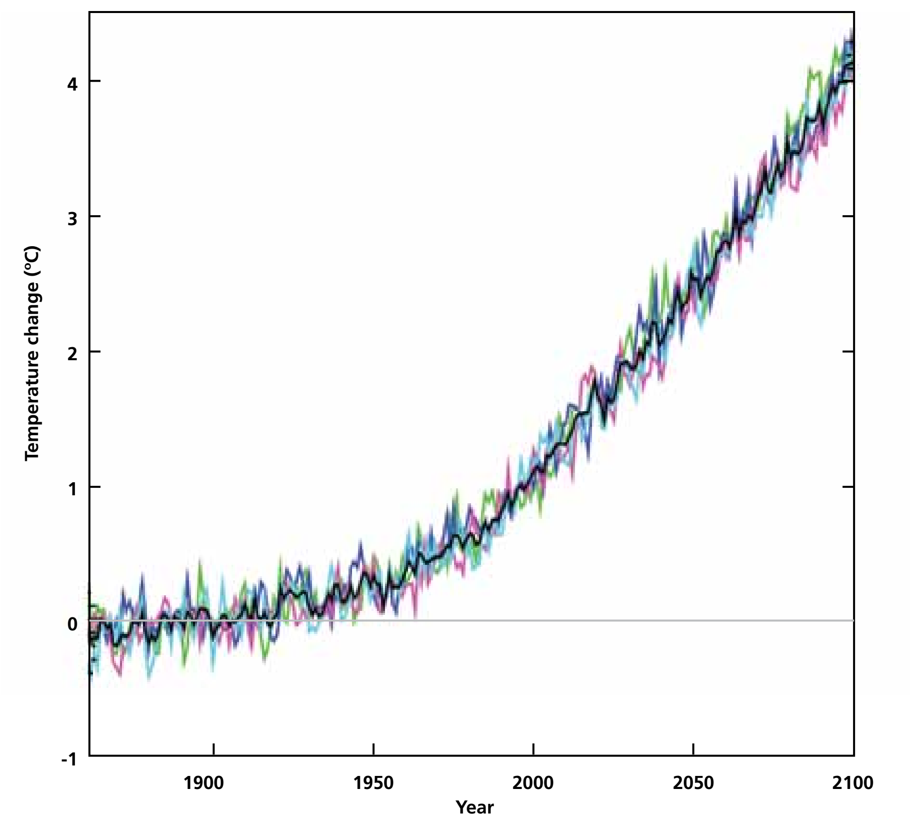


Figure 2.1: Simulations of change in global average temperature for the period 1860–2100 from three experiments with the HadCM3 climate model, shown in the three colours. Each experiment was driven with the UKCIP02 Medium High Emissions scenario but was started with different initial conditions. The black line shows the mean of the three simulations. (Note that influences of changes in solar or volcanic effects are not included.)

Global temperatures projected from a three-member initial condition ensemble, all using the same emissions scenario, are shown in Figure 2.1. It can be seen that, although each experiment shows the same general warming, individual years can be quite different, due to the effect of natural internal variability. If we look at changes at a smaller scale, for example those of winter precipitation over England and Wales (Figure 2.2) we see that, although the three projections show similar upward trends of about 20% through the century, they are very different from year to year and even decade to decade. A common way of reducing the effect of uncertainty due to natural variability on the projections is to average changes over a 30-yr period, as we did in the UKCIP02 scenarios (and do again in UKCP09). But even this still allows large differences in patterns of change, as can be seen from Figure 2.3; for example over Birmingham where two of the model experiments project approximately 30% increases, but the other projects just over 10%. The uncertainty due to projected natural internal variability is included in the overall uncertainty quantified in UKCP09.

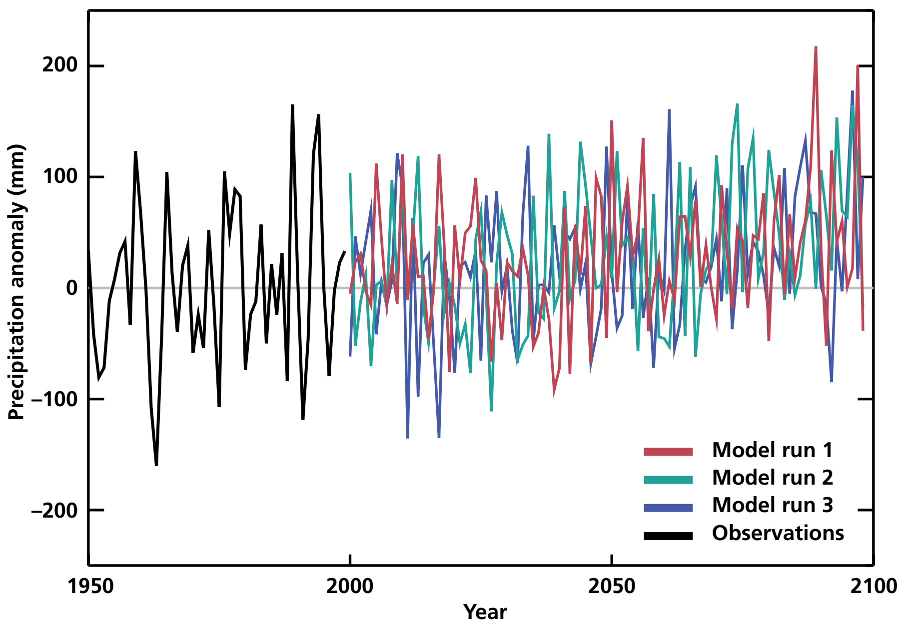


Figure 2.2: The back line shows the observed England and Wales winter precipitation anomaly from 1950–2000, relative to the 1961–1990 average. The three coloured lines show projections of the same variable, from three experiments using the HadCM3 global model. Each experiment was driven with the same (UKCIP02 Medium-High) emissions scenario, but was started with different initial conditions. The differences between the three simulations are due to natural internal variability.

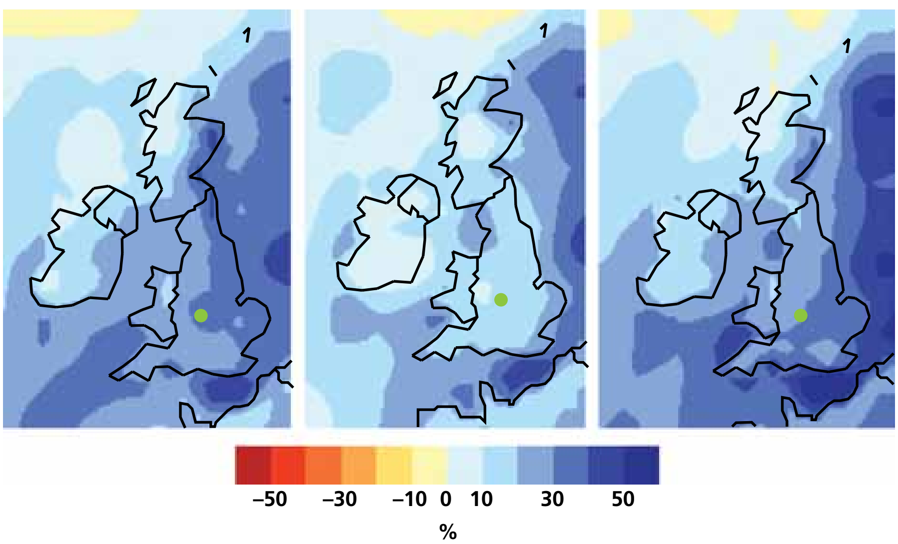


Figure 2.3: Maps of the change in winter precipitation averaged over the period 2071–2100, relative to 1961–1990, taken from the same three model experiments used in Figure 2.2 and described in the caption.

There are some exciting new developments in forecasting natural internal changes in climate over the next decade, suggesting that some details of natural variability may be predictable over the next 30 yr with some skill (Smith *et al.* 2007; Keenlyside *et al.* 2008). (We use the term skill to mean that such techniques, in which observations are used to further determine the initial state of the climate model, produce a narrower range of uncertainty than one would get in the absence of using the observations). Such techniques are still experimental, showing some promise up to a decade or so ahead with predictability beyond that yet to be tested; hence they are not used in UKCP09.

Climate can also vary due to natural external factors (that is, external to the climate system), the main ones being changes in solar radiation and in aerosol (small particles) from volcanoes. The sun is the driving force for the earth's climate so any change in it has the potential to change climate, and indeed we estimate that the rise in global temperatures in the early part of the 20th century may have been partly due to a rise in the amount of energy reaching us from the sun over that period (Stott *et al*. 2003). However, because solar radiation has been relatively constant over the past few decades (apart from changes on the regular 11-yr cycle which are relatively small and are largely smoothed by the inertia of the climate system) we do not attribute recent climate change over this recent period to this factor. Because we cannot forecast with any useable accuracy how the solar radiation will vary in the future, we cannot formally build any changes due to this factor in the projections of future climate; this remains as an uncertainty. However, Stott *et al*. (2003) have estimated that solar radiation changes over the 20th century could have caused between 0.16°C and 0.49°C rise in global temperatures. On the assumption that solar radiation changes over the coming century will be no greater than those in the last, although they could be in either direction, then changes in global temperature due to this factor are unlikely to be greater than ± 0.5°C. (Gareth Jones, pers comm.)

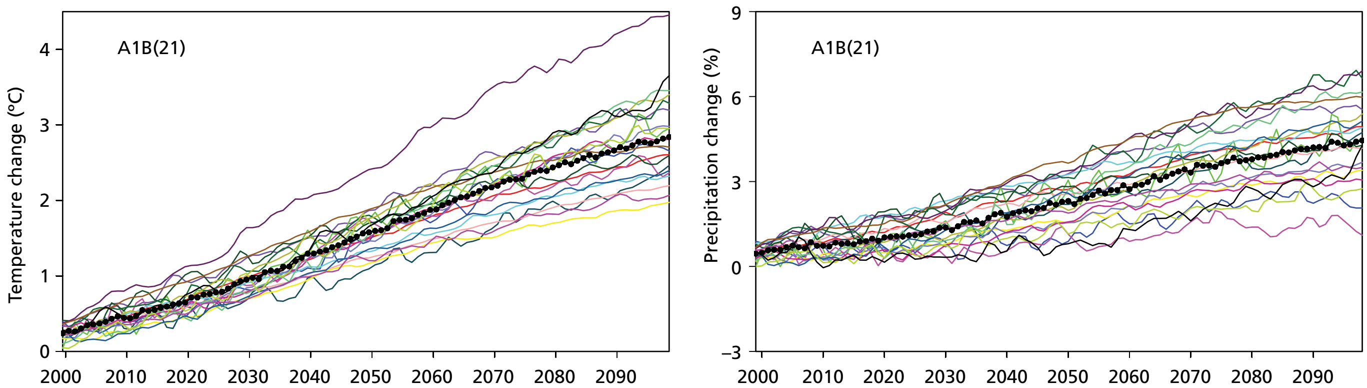
If volcanoes are energetic enough to inject gas into the stratosphere, then the resulting aerosol can remain there for a few years and gradually spread across the globe. Because solar radiation will be reflected back from this aerosol before it can warm the earth, it will have a cooling effect on climate at the surface. The eruption of Mt Pinatubo in the Philippines in 1991 caused global temperatures to drop by about 0.3°C over the following year or two, taking 3–4 yr to recover — and this observed effect has been quite well replicated by climate models (Hansen *et al*. 1996). More energetic volcanoes have an even greater cooling effect. Again, because we do not know the future course of volcanic activity, we have no meaningful way of predicting their effects on climate — apart from being aware that cooling events lasting a few years could occur at any time.

2.3 Uncertainty due to climate models

The second main source of uncertainty in climate projections is modelling uncertainty. This arises from our incomplete knowledge of the climate system and our inability to model it perfectly. As explained in Box 2.1, climate models allow us to calculate the change in climate consequent on a given pathway of future emissions due to human activities. Models provide a mathematical representation of many of the processes in the climate system (atmosphere, land surface, cryosphere and ocean), and allow these processes to interact, hence producing many types of feedback, both positive and negative. The net effect of these will determine how climate evolves in response to changes in greenhouse gases.

These representations are based on a mixture of theory, observations and experimentation, and are inevitably uncertain. All modelling groups seek to represent climate processes in the best possible way in their models and, because this is to an extent a subjective judgement, this leads to different groups adopting different representations. Not surprisingly, this leads to different strengths (and even, in the case of clouds, directions) of feedbacks in the models, and hence different projections of future changes – even when the same pathway of future emissions is assumed. This can be seen from Figure 2.4, which shows changes in global temperature and precipitation from 21 climate models used in IPCC AR4, all under the same emissions scenario. Models with a stronger net positive feedback exhibit a more rapid warming that those with a weaker net feedback; indeed there is a factor of two difference between the highest and lowest projected rates of global warming (Figure 2.4, left panel). Similar comments apply to projected rates of change of global mean precipitation (Figure 2.4, right panel).

Figure 2.4: Smoothed time series of annual change in global temperature (left) and global precipitation, relative to the 1980–1999 average, from 21 global models (including HadCM3, lime green), each driven with the SRES A1B emissions scenario. The mean time series is shown by black dots. The results are not labelled here by model name, but this can be seen in IPCC AR4-WG1. © IPCC AR4-WG1.



Box 2.1: Climate models and how their limitations lead to uncertainties in projections

The climate model

The only way we can calculate how climate will change due to human activities is to use a mathematical model of the earth's climate system, known simply as a global climate model (GCM). This describes the behaviour of the components of the climate and interactions between them. Firstly, the atmosphere; the way it moves horizontally and vertically, plus physical processes that occur in it, such as the formation of clouds and precipitation, and the passage of terrestrial and solar radiation through it. Secondly the ocean, because there is a continual exchange of heat, momentum and water vapour between the ocean and atmosphere and because within it there are large currents which transport heat, water and salt. Thirdly the land, because it affects the flow of air over it, and is important in the hydrological cycle — not just the land surface but soils beneath it — and changes in the land surface (both natural and human-made) affect the climate. Lastly the cryosphere; ice on land (snow, glaciers and ice sheets) and on sea. All of these components of the climate system interact to produce the feedbacks which play a large role in determining how climate will change.