

CLIMATE CHANGE AND GEOHAZARDS IN SOUTH-WEST ENGLAND: PROJECTIONS, PROGRESS AND CHALLENGES

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The Earth's climate has varied naturally throughout geological time, but there is very strong evidence that anthropogenic activity since the Industrial Revolution has superimposed a further climate change component onto the background of this natural climate variability and change. In this paper, the causes of climate change - both natural and anthropogenic - are summarised. The models which are used to simulate the climate, and to make projections of future climate change, are described, and the sources of uncertainty in these projections are also discussed. Recent projections of changes in temperature, precipitation and sea level are outlined, at global, UK and South-West England scales. Finally, some potential links between climate phenomena and geological/geomorphological hazards in South-West England are investigated, highlighting a selection of the current challenges in climate impacts research and the science of climate risk.

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INTRODUCTION

Climate change is a cross-cutting societal issue, with potential implications for everyone. Climate scientists develop the underpinning science and computer modelling capability, which together permit the simulation of the climate system, thereby furthering our understanding of the climate and allowing projections of future climate change to be made. Politicians and policy-makers, informed by these projections, are typically then involved with coordinating a policy response to climate change at a variety of administrative levels (international, national, local, etc.). Finally, either directly in response to projected changes, or indirectly in response to policies, stakeholders - such as industry and the general public - can then consider how they might manage the potential impacts of climate change on their day-to-day activities and lives.

One of the most well-known organisations with respect to climate change is the Intergovernmental Panel on Climate Change (IPCC), whose Fourth Assessment Report ('AR4') was published in 2007. This was the most recent in a series of assessment reports synthesising the state of scientific understanding of climate change. The first volume (Working Group I, 'AR4 WG1' (IPCC, 2007b)) described the physical science basis for climate change. Whilst it is clearly not possible to discuss all the findings of AR4 WG1 in this paper, amongst the conclusions was that "*warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level*".

Climate change per se is not unusual; from a geological perspective, it is known that the climate has varied in the past. In AR4 WG1, evidence from various palaeoclimatic proxies

(including isotope ratios in sediments and seawater) was examined, and from this it was concluded that "*pre-Quaternary climates prior to 2.6 Ma were mostly warmer than today*" (Jansen *et al.*, 2007). More recent palaeoclimatic proxy data, from ice cores, resolve the several glacial-interglacial cycles which have occurred over the past ~700 ka (Solomon *et al.*, 2007). However, considering the (geologically) very recent past, the climate change that has occurred is considered unusual. AR4 WG1 notes that "*palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years [...] Average Northern Hemisphere temperatures during the second half of the 20th century were very likely (>90% probability)¹ higher than during any other 50-year period in the last 500 years and likely (>66% probability)¹ the highest in at least the past 1300 years*" (Solomon *et al.*, 2007). Although there has been natural variation of the climate in the geological past, there is very strong evidence that human activity has been a driver of climate change since the Industrial Revolution.

This paper begins with an overview of the major natural and anthropogenic (human-induced) causes of climate change. Next, the computer models used to produce climate change projections are described and the major sources of uncertainty in those projections are examined. Following this, examples from the most recent set of climate change projections for the UK, and South-West England in particular, are discussed. Approaches to acting upon projected changes to the climate are also considered. Finally, some of the current challenges associated with climate modelling and climate impacts research are explored, using case studies of past events in South-West England, and linking climate change with other geological/geomorphological hazards.

THE CLIMATE SYSTEM AND NATURAL CAUSES OF CLIMATE CHANGE

The climate system consists of the atmosphere, ocean, biosphere, cryosphere (ice and snow) and geosphere (rock and soil). The internal interactions and feedbacks between these components, plus factors external to the system, result in variations in climate over many different timescales and length scales, even without any anthropogenic influence. Below we consider the internal variability of the climate, together with the three major natural external causes of climate change: variation in (a) the Earth's orbit around the sun, (b) solar output, and (c) atmospheric aerosol from volcanoes.

Internal climate variability

The internal variability of the climate results from the chaotic nature of the climate system, characterised by the 'butterfly effect' (Lorenz, 1963) embodied by the idea of "*the flap of a butterfly's wings in Brazil setting off a tornado in Texas*"², which describes the sensitivity of the climate system's behaviour to the initial conditions - that is, a small change at one location in a non-linear system can result in large differences to a later state of the system. Implicit in this analogy is the spanning of many different scales in space and time, and indeed such variability is evident in weather and climate phenomena: from individual, relatively short-lived and small-scale storms to large-scale, self-organising modes of climate variability. Examples of the latter include (i) the El Niño-Southern Oscillation, a major climatic oscillation with a period of 2-7 years resulting from ocean-atmosphere coupling in the tropical Pacific, which affects the climate of many parts of the globe, and (ii) the North Atlantic Oscillation, a variation in pressure patterns in the North Atlantic which chiefly affects the climate of Europe (Solomon *et al.*, 2007).

In the presence of a climate change 'signal', the 'noise' of internal variability could either reinforce or oppose the signal in a given place at a given time. Internal variability is one reason why, for example, the occurrence of one cold winter does not signify the cessation of global warming. It is also important to note that climate change could itself also alter the characteristics of internal variability.

External climate variability

Orbital variations: Over the period of many thousands of years, the Earth's orbit around the sun changes in a quasi-periodic manner. There are three principal cycles, called 'Milankovitch cycles' after the Serbian mathematician who first described them in mathematical detail (Milanković, 1941)³, which describe the variation in the shape (eccentricity) of the orbit, and in the axial tilt (obliquity) and axial precession. Here, we restrict the discussion to these principal variations, but note that others do exist. The periods of the principal variations are approximately 100 ka, 41 ka, and 19-23 ka respectively (Solomon *et al.*, 2007). These cycles affect the total amount of solar radiation incident upon the Earth's upper atmosphere ('total solar irradiance'), and also the extent of seasonal and latitudinal variations in solar irradiance ('insolation'). Hays *et al.* (1976) were the first authors to demonstrate a correlation between climatic oscillations (specifically between glacial and interglacial periods) and Milankovitch cycles; there is considerable evidence in the form of palaeoclimatic analysis of Antarctic ice cores, which also show strong cyclic (glacial/interglacial) variations over the last few hundreds of thousands of years (e.g. Petit *et al.*, 1999; EPICA community members, 2004).

Solar output: In recent decades it has been possible to use satellites to measure the radiation output by the Sun, which revealed slight variations in solar output (Le Treut *et al.*, 2007). This, in addition to the orbital variations described above, is another factor influencing total solar irradiance. The data

thus observed show a well-established cycle with a period of approximately 11 years; other cycles with longer periods have also been postulated to exist. The main known cause of present-day irradiance variability is the presence of sunspots and faculae on the Sun's disc: respectively, dark regions with locally depleted radiation, and bright regions with locally enhanced radiation (Solomon *et al.*, 2007). Larger numbers of sunspots correspond with higher irradiance, and vice versa.

Although solar variability in the satellite era is well-characterised, reconstruction of solar irradiance before this period requires the use of proxies including historical records of sunspot numbers and cosmogenic isotope measurements; such reconstructions are prone to greater uncertainty. For example, the historical record of sunspots extends back over 2000 years (Wittmann and Xu, 1987), but only over the last four centuries (Vaquero, 2007), since the invention of the telescope, have there been sufficient data to serve as a reliable proxy. A major feature of the record since this time is the 'Maunder minimum', a period of low solar activity (and hence comparatively few sunspots), between 1672 and 1699 (Le Treut *et al.*, 2007). This time corresponds to part of the climatic period known as the 'Little Ice Age' (LIA), when some regions of the world are thought to have sustained temperatures notably cooler than the rest of the last millennium, but the issue of any causal relationship between solar activity and temperatures during this period is still a matter of debate, as is the extent to which any recently-observed changes in climate could be related to solar activity.

Some examples relevant to 20th Century climate include the study by Scafetta and West (2006) which stated that solar variability has a significant effect on climate forcing, and that the Sun might have contributed up to 45-50% of the 1900-2000 global warming, and 25-35% of the 1980-2000 global warming. Another study using satellite observations concluded that recent solar variations are too small to have contributed appreciably to the warming which has been observed over the last three decades (Foukal *et al.*, 2006). In addition, a review by Lockwood and Fröhlich (2007) found that "*over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures*". It should be noted that solar radiation effects are further complicated by variations across the spectrum, i.e. not just the gross radiation, in any effects on climate. For example, a link has been postulated between ultraviolet irradiance variability and the winter climate of the Northern Hemisphere (Ineson *et al.*, 2011). Solar influence on the climate continues to be an area of active research.

Atmospheric aerosol from volcanoes: The term 'aerosol' refers to any particulate matter suspended in the atmosphere and includes natural and anthropogenic contributions (the latter are discussed below). Through a variety of mechanisms (Forster *et al.*, 2007)⁴, some better understood than others, aerosols reduce the amount of solar radiation arriving at the Earth's surface, thereby exerting a net surface cooling effect. In the context of external climate variability, large volcanic eruptions are one contributor to the natural atmospheric aerosol burden. The eruption of Mount Pinatubo in 1991, for example, allowed scientists to assess the climatic impact of a major eruption. Around a year after the eruption, reductions in global mean air temperature of around 0.5°C were observed at the surface (Parker *et al.*, 1996).

There are other natural atmospheric aerosols, including dust, for example from deserts⁵, dimethylsulphide (DMS) produced chiefly by marine algae, and salt, especially in the marine atmosphere. However, although these are natural in origin, here they are not considered together with volcanic aerosol because while volcanoes are driven by processes outside the climate system, and as such contribute to external climate variability, this is not the case for the remaining natural aerosols.

ANTHROPOGENIC CAUSES OF CLIMATE CHANGE

Despite the fact that the Earth's climate has always varied naturally, there is strong evidence that anthropogenic influence on the climate system is also affecting the climate. This is demonstrated in two key points from AR4 WG1 (IPCC, 2007c):

- 1) *"Most of the observed increase in global average temperatures since the mid-20th century is very likely (>90% probability)¹ due to the observed increase in anthropogenic greenhouse gas concentrations"*.
- 2) *"It is likely (>66% probability)¹ that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place"*.

These two statements also make reference to the two major anthropogenic causes of climate change, which are (a) anthropogenic greenhouse gases and (b) anthropogenic atmospheric aerosol.

Anthropogenic greenhouse gases

Greenhouse gases (GHGs) are those gases which, due to their molecular structure, absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the atmosphere, the Earth's surface, and clouds (IPCC, 2007b). The greenhouse effect, by which heat is 'trapped' in the lower atmosphere as a result of the presence of these gases, is a natural effect, without which the Earth's surface would be around 33°C cooler (Le Treut *et al.*, 2007) and hence far less conducive to sustaining life. However, the anthropogenic increase in GHGs since the Industrial Revolution, from processes such as land-use change and burning fossil fuels, is resulting in an enhancement of the greenhouse effect - in addition to the effect which would be experienced in the absence of human influence - and it is this anthropogenic enhancement that is contributing to unusual changes in the climate.

The principal anthropogenic GHGs are carbon dioxide CO₂, methane CH₄ and nitrous oxide N₂O. Water vapour is a major GHG, but it is not listed here, because anthropogenic activity does not have a large effect on water vapour concentrations in the atmosphere. The main role of water vapour in connection with anthropogenic GHGs is to respond to and amplify their effects through water vapour feedback. Increased concentrations of the anthropogenic GHGs lead to a warmer atmosphere, which in turn can hold more water vapour per unit volume (according to the Clausius-Clapeyron relation). Since water vapour behaves as a GHG, this results in further warming, and hence a positive feedback occurs (Le Treut *et al.*, 2007).

Anthropogenic atmospheric aerosol

There are also anthropogenic sources of aerosol. These include black carbon aerosol, from sources such as biomass burning; chemical aerosol such as sulphates and nitrates, from industrial sources; and the desert dust derived from human-induced desertification⁵. The climatic effects of anthropogenic aerosol are similar to those of natural aerosol, though there is variation in the geographic distribution of the proportion of aerosol derived from natural and anthropogenic sources.

The net radiative forcing⁶ due to atmospheric aerosol (both natural and anthropogenic) is most likely negative. Positive radiative forcing leads to a global mean surface warming, while negative radiative forcing leads to a global mean surface cooling (Forster *et al.*, 2007). The likely negative radiative forcing of atmospheric aerosol has led to its consideration as a geoengineering solution, i.e. for use in deliberate manipulation of the climate in order to try to offset the effects of warming.

In this case the aerosol would be deliberately injected into the atmosphere at appropriate locations and heights. However, a major study into geoengineering the climate (Royal Society, 2009) recommended caution with respect to the potential implementation of this and many other geoengineering proposals, since they are not well-understood in terms of their impacts, efficacy and cost. The study also noted explicitly that geoengineering should not divert policy away from other strategies for managing future climate change. The two main classes of such strategies will be briefly discussed later in this paper.

CLIMATE MODELS

In order to produce projections of future climate, scientists use climate models. These are mathematical models which encapsulate within a set of equations the essential physics of the climate system. These equations are solved, at an appropriate resolution, in space and time. As with most types of computer simulation, early climate models were relatively primitive and had coarse resolution. Nowadays, improvements to our understanding of physical processes affecting the climate, coupled with huge increases in computational capacity, have resulted in present-day climate models which can be both scientifically complex and also have comparatively fine spatial and/or temporal resolution (Le Treut *et al.*, 2007). That said, while increasing complexity and/or resolution is generally considered advantageous for many purposes, simpler models still have a role to play. Indeed, the 'hierarchy of models' is considered to be a useful mechanism in linking theoretical concepts through to the increasing 'realism' of the more complex models (Held, 2005). As time progresses, climate models become ever more sophisticated, and their developers continually assess their performance. Typically this is achieved by examining how well the models are able to reproduce key elements of past climate and past climate change, when driven by observed historical forcings.

Climate models are not perfect predictors and our understanding of the climate system is not perfect. There are processes which are known but not well-represented in models, and it is also likely that there are aspects of the climate system of which we are currently not aware, and which are hence not represented at all in models. As well as these factors, there are other assumptions made regarding climate model input, as discussed below. Therefore, although very significant scientific progress in the area of climate modelling has been made in recent years, there is still much to be done, and many uncertainties to tease out (Hawkins and Sutton, 2009).

UNCERTAINTY IN CLIMATE CHANGE PROJECTIONS

Climate change projections are subject to a range of inherent uncertainties originating from a variety of sources. The main types of uncertainty are (a) natural variability, (b) forcing uncertainty, and (c) uncertainty in the response of the climate system (often termed 'modelling uncertainty'). These terms, together with some of the approaches used to try to manage and/or understand the uncertainty in projections, are discussed below. The term 'ensemble' will be used frequently in the discussion. It denotes a group of parallel model simulations used to produce climate projections, with different types of ensemble being relevant for different applications.

Natural variability

The uncertainty due to natural variability is handled in different ways depending on the scientific question being addressed. For long-term projections (e.g. out to the latter half of the 21st Century), we are typically interested in the 'signal' due to climate change, and want to separate out the 'noise' of natural variability. Indeed, we cannot reliably predict whether

a given year will be warmer or cooler than average at such far time horizons. Hence, to examine the climate change 'signal', we can calculate the climate parameters of interest over relatively long timescales, thereby smoothing out the inter-annual 'noise'. Often, 30-year time periods are used for both the baseline⁷ and future climate. Using several different future periods and potentially more than one baseline period is also common. However, this does not account for the possibility that longer-term variations are in operation. There are aspects of the climate that are known to vary on decadal or multidecadal timescales, which may not be adequately addressed by using 30-year periods.

With some modifications, climate models can also be used to make nearer-term projections, such as those for the next decade or so. In that case, we are actually interested in the variability - that is, whether a particular year might be warmer or cooler than average. The climate change trend, although present, is relatively small compared to the variability. We can therefore run a climate model many times with slightly different initial conditions (an initial condition ensemble, ICE), enabling us to estimate the spatial and temporal importance of the component of the uncertainty which arises from natural variability. The Met Office's decadal prediction system, DePreSys (Smith *et al.*, 2007), uses this approach. A version of the climate model is initialised with observed data for the ocean and atmosphere, as well as plausible changes in other drivers of the climate discussed above, and a range of different start dates is used, thereby forming the ensemble. Analogous runs without assimilation of the observed data are also performed. Comparing these sets of runs has shown that the assimilation improves the forecast skill of globally-averaged surface temperature throughout the decade (Smith *et al.*, 2007). Improving the resolution and skill of forecasts at these timescales is a major research activity.

Forcing uncertainty

In order to produce climate projections, an estimate of the future amounts of GHGs in the climate system is required as input to climate models. However, we obviously cannot know for certain what our real future GHG emissions pathway will be. This issue has typically been addressed by producing climate change projections under a range of emissions scenarios (e.g. Nakićenović *et al.*, 2000). These are plausible future pathways which GHG emissions might follow, depending on factors such as population, energy mix, technological advances, scales of international cooperation, etc. In addition, the relationship between GHG emissions and GHG concentrations in the atmosphere is climate model-dependent (for example, CO₂ partitioning between different parts of the climate system depends on the representation of the carbon cycle in the climate model).

Uncertainty in the response of the climate system (often termed 'modelling uncertainty')

Although all climate models are based on the same real-world physics, different climate models have different formulations and approximations according to the research institutions where they have been developed. Processes operating on a scale which is less than the grid resolution of the climate model, such as the formation and evolution of clouds, have to be parameterised, and these parameterisations will vary from model to model. Additionally, although models are constantly developed and updated to reflect new scientific discoveries and understanding, there will always be some potentially influential processes which are missing. A good example is the representation of the carbon cycle. This is clearly an important component of the climate, but it has taken some time for it to be represented in many climate models. C4MIP (Coupled Climate Carbon Cycle Model Intercomparison Project), an intercomparison of 11 models with a 'first-

generation' interactive and parameterised carbon cycle, was recently undertaken (Friedlingstein *et al.*, 2006), but the models involved have typically been especially constructed for carbon cycle studies, rather than being the 'mainstream' model developed by a particular climate research institution. It is only recently that the 'mainstream' models have begun to include a coupled carbon cycle, for example the Met Office Hadley Centre's earth system model, HadGEM2-ES (Jones *et al.*, 2011). Finally, the absence of particular processes may lead to further uncertainties in the regional responses of climate models, as the importance of a particular process (such as the monsoon, for example) may be greater or smaller in a particular region.

There are various methods for addressing modelling uncertainty, and typically a particular method will only address a subset of the factors contributing to this uncertainty. Here we discuss two of the major approaches. The first is use of a multi-model ensemble (MME) - that is a set of climate projections comprising results from different climate models and/or different research institutes. The IPCC AR4 MME comprised 21 different ensemble members; the differing degrees of consensus between these models for different variables (e.g. temperature and precipitation) will be briefly discussed below. Use of an MME is usually an improvement on using just one model to make a projection. However, one potential drawback of an MME is that it is typically an 'ensemble of opportunity' - that is a collection of model runs which happen to be available, rather than having been subject to any particular scientific design criteria. As such, the sampling is neither systematic nor random (Tebaldi and Knutti, 2007). A related fact is that models from which an MME is formed are not designed to sample the known full range of uncertainty, because they are (not surprisingly) tuned to match observational data as closely as possible. As such, there is always the possibility that a model gives "*the right result for the wrong reason*" (Tebaldi and Knutti, 2007). It has also recently been suggested (e.g. Pennell and Reichler, 2011) that, despite there being 21 ensemble members in the AR4 MME, the effective number of independent models is actually considerably fewer than this, because of the similarities in formulation between different models (e.g. the sharing of a particular module of code between models, the development of more than one model at the same institution, etc.).

The second approach is to use a perturbed physics ensemble (PPE), which is a set of climate projections comprising results from one climate model, but run many times with slightly different input parameters. Expert judgement is used to determine (a) which parameters may vary, (b) between which values each parameter may vary and (c) which parameters may co-vary in physically sensible ways. The PPE does not sample the structural uncertainty (the fact that different models are set up differently), but it does sample the parameter uncertainty (the fact that our scientific understanding may not be sufficient to know a particular parameter's 'true' value in the real world, or how this may evolve in future).

Technically, it is also possible to combine the MME and PPE approaches, and a state-of-the-art suite of climate projections in which there has been some incorporation of information from the IPCC MME into a PPE will be discussed later in this paper. However, combining MME and PPE approaches from first principles is a demanding task, both from an organisational and computational perspective, and hence has not yet been undertaken comprehensively.

CLIMATE CHANGE PROJECTIONS FOR THE UK

We have already noted that there have been periods in the geological past where the climate is thought to have been warmer or cooler than the present (Jansen *et al.*, 2007), but the speed of the recent observed changes, and the projected future changes, is surprisingly rapid. The projected change in global average surface temperature by 2090-2099 (relative to 1980-1999) is between 1.1 and 6.4°C (IPCC, 2007c), depending on the climate model used, emissions scenario considered, and

strength of carbon cycle assumed, which is a projected change of considerable magnitude over the course of just one century. When driven by non-mitigation scenarios (i.e. those emissions scenarios where no attempt is made to mitigate the effects of climate change by for example reducing atmospheric GHG concentrations), all models in the IPCC AR4 MME project increases in global average surface temperature over the 21st Century.

Projected changes in precipitation are for an increase in globally-averaged precipitation in future, consistent with the fact that a warmer atmosphere can hold (and thus release) more water vapour. However, the projected regional variation in the response for precipitation is less certain, with some regions projected to experience an increase in precipitation, and some a decrease. Agreement across climate model projections from different centres is also lower for precipitation than for temperature.

These very broad conclusions pertain to global climate change and are generally arrived at using global climate models (GCMs), whose resolution is relatively coarse. To assess climate change on a regional basis, it is instructive to use climate information at a higher resolution. In 2009 the most recent set of climate projections covering the UK - UK Climate Projections 2009 (Defra, 2011), hereafter 'UKCP09' - was released. UKCP09 describes projected changes to the UK's climate during the 21st Century, using leading science developed at the Met Office Hadley Centre. UKCP09 is a probabilistic set of projections, into which some of the uncertainties associated with the climate system have been systematically incorporated. The probabilities have been estimated by using a sophisticated approach combining a large ensemble of climate model projections, expert judgement, and statistical methods. The result is that UKCP09 explores a large range of possible climate futures and much larger than that of its predecessor, UKCIP02, which did not follow this probabilistic approach. Projections are available under three different emissions scenarios - low, medium and high, corresponding to SRES B1, A1B and A1FI respectively (Nakićenović *et al.*, 2000) - and for seven 30-year timeslices, from the 2020s to the 2080s (each named after their middle decade, i.e. '2020s' indicating 2010-2039, etc.), relative to a baseline climate of 1961-1990.

UKCP09 was developed using the Met Office Hadley Centre's regional climate model (RCM), HadRM3 (Jones *et al.*, 1997), which has a resolution of 25 km. GCMs have global coverage, but RCMs are typically run over a limited domain of the Earth's surface. They therefore require 'boundary conditions', which are data from the GCM at the boundaries of the simulation domain, to drive them. For UKCP09, HadRM3 was driven by data from a version of the HadCM3 GCM (Gordon *et al.*, 2000). Information from other GCMs has also been incorporated into the methodology, thereby sampling some of the structural uncertainty, but only HadCM3 was used to provide the RCM driving data. It is therefore reasonable to assume that any systematic biases in HadCM3 could be represented to some extent in UKCP09. Similarly, the extent to which particular climate processes/constituents are modelled in the driving GCM and the other models contributing to the UKCP09 methodology will directly affect the way in which those processes/constituents are represented in UKCP09 (Murphy *et al.*, 2009). An example is the representation of Atlantic blocking events in models. Atlantic blocking events are high-pressure systems which impede the progress of depressions along the Atlantic 'storm track'. In the UK, blocking can cause summer heatwaves and winter cold spells, yet its representation in IPCC AR4-generation models (of which HadCM3 is one) is known to be subject to systematic errors. The simulation of blocking in climate models has only recently begun to be improved (Scaife *et al.*, 2011). Despite these caveats, the UKCP09 methodology represents a state-of-the-art approach to providing climate change projections in a format which may be used to inform probabilistic risk-based planning.

The following are some of the conclusions quoted in the UKCP09 briefing report (Jenkins *et al.*, 2009). These are for

changes by the 2080s under the medium emissions scenario:

- 1) All areas of the UK are projected to become warmer, with greater projected warming in summer than winter.
- 2) There is little evidence for a change in annual precipitation amounts around the UK. However:
 - a) The largest projected increases in winter precipitation are seen along the western side of the UK. Decreases are projected over parts of the Scottish Highlands.
 - b) The largest projected decreases in summer precipitation are seen in parts of the far south of England. Changes close to zero (ranging from a slight decrease to a slight increase) are projected over parts of Northern Scotland.
- 3) Sea levels are projected to rise around the UK, with larger rises in the south of the UK than in the north. This geographical variation is due to differences in vertical land movement as a result of glacial isostatic adjustment since the last Ice Age.

For the UK, this summary shows that there is greater uncertainty in the projected precipitation response (which may be an increase or decrease) than that for temperature. This is analogous with the global responses from the MME and also with those from the global HadCM3 PPE, which was used to drive the RCM simulations underlying UKCP09 (the latter is not surprising as there will be a relationship between the global PPE and regional PPE simulations because one is used to drive the other). Note also that the briefing report summary above is for one time period and one emissions scenario; other time period/scenario combinations will give different projected changes.

Probabilistic projections for temperature, precipitation, humidity, cloud, pressure and atmospheric radiation fluxes are available from the initial release of UKCP09. Subsequently, various technical notes updating the initial release, and probabilistic projections for wind speed, have been added (UKCP09, 2012). Here, only projections for changes in temperature, precipitation and sea level are discussed to illustrate the utility of UKCP09. Probabilistic results from UKCP09 are typically quoted at the 10, 50 and 90% 'probability levels' (though results for other levels are available). Probability levels should be interpreted as indicating the relative likelihood of the projected change being at or less than the given change. To illustrate this concept, a representative cumulative distribution function (CDF) for a projected temperature change is shown in Figure 1. The 10, 50 and 90% levels can be considered using the phrases 'very unlikely to be less than', 'central estimate' and 'very unlikely to be greater than', respectively. Hence, a projected change of +1.2°C at the 10% level, +2.3°C at the 50% level and +3.2°C at the 90% level (Figure 1) can be described as "*very unlikely to be less than +1.2°C, very unlikely to be greater than +3.2°C, with a central estimate of +2.3°C*". This kind of information is useful in terms of risk-based planning. For example, a decision-maker may choose to formulate their plans based on the central estimate or the unlikely outcomes depending on their appetite for risk.

Other visualisation products besides the CDF are available from UKCP09. These aim to represent the uncertainty in the projections in a variety of different ways, so that the information contained in the projections can be maximally useful to a range of users with widely-varying requirements. More details can be found in the UK Climate Projections Science Report (Murphy *et al.*, 2009).

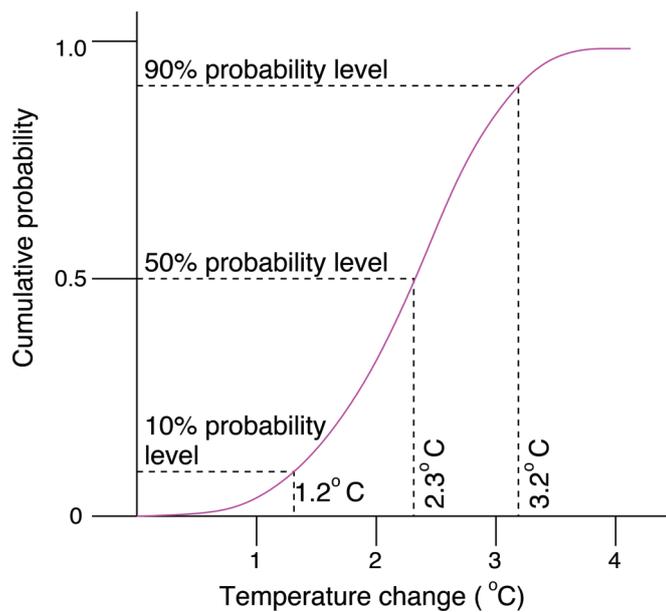


Figure 1. Schematic cumulative probability distribution function (CDF) for a projected temperature change, showing the concept of ‘probability levels’.

CLIMATE CHANGE PROJECTIONS FOR SOUTH-WEST ENGLAND

A previous geological perspective on climate change presented to the Ussher Society included a variety of climate projections for South-West England (Hart and Hart, 2000). Since UKCP09 provides projections aggregated to the level of administrative regions, of which South-West England is one, an updated set of region-specific results for South-West England is presented here. It should once more be borne in mind that, since the same methodology underlies the region-specific and UK-wide projections, the caveats and uncertainties relevant for the UK-wide projections will also be relevant for the South-West England projections.

Projected changes to temperature and precipitation in South-West England

Key findings for temperature and precipitation in South-West England for the 2050s (under all three UKCP09 emissions scenarios), with respect to a 1961-1990 baseline, are given in Table 1. For the 2050s, under all three scenarios, there is a projected increase in mean temperatures in both winter and summer, and mean daily minimum and maximum summer temperatures are also projected to increase. In winter, precipitation is projected to increase, whilst summer precipitation projections are more uncertain; the mean change is for a decrease, but the fact that the 90% probability level shows a positive change means that an increase in summer precipitation in this region cannot be ruled out. Once again it should be stressed that these projected changes are for a particular time period and projected changes for other time periods will be different.

Projected changes to sea level around South-West England

The three major processes affecting sea level are (a) thermal expansion of sea water (with warmer water occupying a larger volume than cooler water), (b) the exchange of water between the oceans and other stores (e.g. glaciers and ice caps, ice sheets, etc.), and (c) vertical land movement (e.g. glacial isostatic adjustment, tectonic processes, etc.) (Bindoff *et al.*,

Parameter	Projected change under given emissions scenario in 2050s			
	Probability level	10%	50%	90%
Twm (°C)	Low	+0.8	+1.8	+2.9
	Medium	+1.1	+2.1	+3.2
	High	+1.3	+2.3	+3.5
Tsm (°C)	Low	+1.1	+2.5	+4.1
	Medium	+1.3	+2.7	+4.6
	High	+1.4	+3.1	+5.1
Tsx (°C)	Low	+1.2	+3.4	+6.2
	Medium	+1.4	+3.8	+6.8
	High	+1.7	+4.3	+7.6
Tsn (°C)	Low	+1.0	+2.5	+4.5
	Medium	+1.2	+2.9	+5.0
	High	+1.5	+3.3	+5.5
Pwm (%)	Low	0	+12	+30
	Medium	+4	+17	+38
	High	+3	+18	+41
Psm (%)	Low	-39	-14	+16
	Medium	-42	-20	+7
	High	-45	-20	+8

Table 1. Projected changes to climate parameters for South-West England, under low, medium and high emissions scenarios, at a range of probability levels by the 2050s, with respect to 1961-1990 values. Twm = mean winter temperature; Tsm = mean summer temperature; Tsx = mean daily maximum summer temperature; Tsn = mean daily minimum summer temperature, Pwm = winter mean precipitation, Psm = summer mean precipitation. Source: UKCP09.

2007). The first two of these affect the global ocean volume, whilst the third changes the size and shape (and thus volume) of the basins themselves. There are various uncertainties and assumptions about the nature of these different contributions to sea level which affect our confidence in projected sea-level changes.

Projected changes in relative sea level from UKCP09 around South-West England, under the UKCP09 medium emissions scenario, are of the order of 0.45-0.5 m by 2090-2099, with respect to a 1980-1999 baseline⁸. This range is that shown around the coast of South-West England in figure 3.7 of Lowe *et al.* (2009). The estimate quoted here combines the absolute sea-level change estimates averaged around the UK (for the central estimate, under the UKCP09 medium emissions scenario only) and the vertical land movement resulting from glacial isostatic adjustment since the last Ice Age. Regarding projected future contributions to sea-level change from ice sheets, it is assumed that recently-observed acceleration of glacial outflow at ice-sheet edges will remain as recently observed, rather than

ceasing or increasing. Changes in ice-sheet dynamics are currently not well understood and there is considerable uncertainty in this component of projected sea-level change. A coastal flooding scenario for 2100, called 'H++', was also included in UKCP09 (Lowe *et al.*, 2009; Nicholls *et al.*, 2011). This scenario is based on faster rates of ice sheet melt. It was designed to enable users to consider a more extreme outcome than those in the main suite of projections, but one which is still physically plausible (though with low probability). Only the 2100 time horizon was considered and so no time series is given. This scenario will be discussed below together with the other UKCP09 projections.

A plot of the projected change in relative sea level throughout the 21st Century under all three UKCP09 emissions scenarios is given for the example location of Penzance (Figure 2). There is relatively little variation in the projections for locations around the coast of South-West England. Projected changes for three other locations were assessed, but are not shown for this reason. The 50th percentile (central estimate) of the projected changes under the three emissions scenarios for Penzance is around 0.4-0.6 m by the end of the century; however, factoring in the uncertainties on these estimates increases the projected range (5th-95th percentile range) to around 0.2-0.9 m. Note that changes greater than this cannot be ruled out as the H++ scenario range for time-mean sea-level rise around the UK is 0.93-1.9 m. The top of this range is very unlikely⁹ to occur in the 21st Century, but no further quantification of the probability of occurrence of the H++ scenario is made (Lowe *et al.*, 2009).

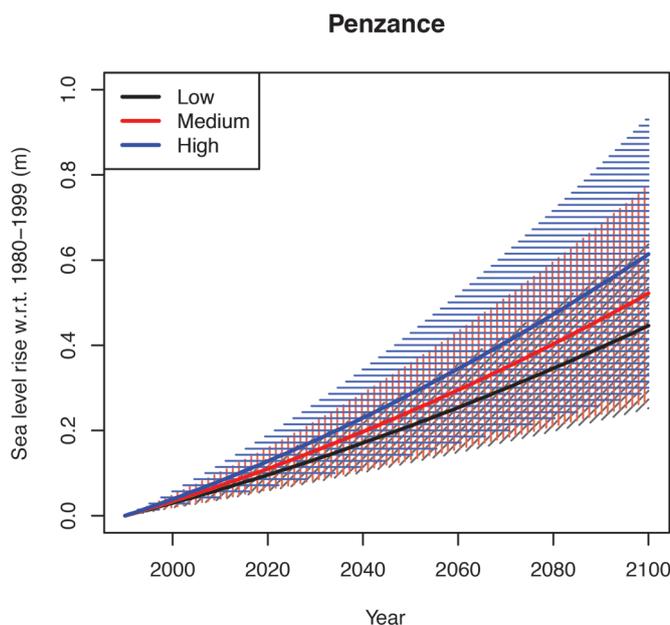


Figure 2. Projected changes in relative sea level for Penzance, under low, medium and high emissions scenarios. Solid lines represent the 50th percentile values and the shaded areas around each solid line represent the 5th-95th percentile range. Note that the data are plotted w.r.t. 1990, as this is representative of the centre of the 1980-1999 baseline period. Source: UKCP09.

Projected changes to other marine phenomena around South-West England

As well as sea-level changes, projected changes to storm surges and waves have also been assessed (Lowe *et al.*, 2009). Storm surges¹⁰ are short-lived, local increases in water level above that of the tide, and are driven by weather (atmospheric pressure gradients and winds). One of the most infamous surge events in the UK was that which affected the coastline of the southern North Sea in 1953, in which over 2,000 lives were lost

in the UK, the Netherlands and Belgium (Gerritsen, 2005), and 24,000 houses were damaged in the UK alone (Baxter, 2005). In UKCP09, changes in storm surge have been considered in terms of the '50-year return level'. This is the size of surge that could be statistically expected to occur once per 50 years¹¹. The largest projected changes in storm surge around the UK are found in the Bristol Channel and Severn Estuary, where the trend is for an increase in the 50-year skew surge return level of around 0.8 mm a⁻¹ not including relative mean sea-level change. However, overall it is suggested that the storm surge component of extreme sea level will be much less than that projected previously in UKCIP02. In terms of offshore wave climate, seasonal mean and extreme waves are generally projected to increase slightly to the south-west of the UK (Lowe *et al.*, 2009). There is large uncertainty in projected changes to both storm surges and wave climate, however, and only a small ensemble of climate model projections were used. The ranges of the projected changes in these quantities should therefore be considered as minimum ranges.

STRATEGIES FOR MANAGING PROJECTED CHANGES TO THE CLIMATE

In view of the types of projected changes to the climate which have been outlined above, what courses of action are possible in order to manage the potential impacts of these projected changes? There are two main approaches, namely adaptation and mitigation. Climate change adaptation is defined as adjustment in natural and human systems in response to actual or projected climate changes, which lessens the effect of these changes or exploits any benefits (IPCC, 2007a). Examples of actions constituting adaptation include:

- 1) building a new coastal power station on an elevated platform in order to improve its resilience to sea-level rise;
- 2) migration of a species within a particular ecosystem to a new habitat, in response to the climate of the old habitat becoming unsuitable for the species;
- 3) choosing to grow crop varieties which are more drought-tolerant in areas affected (or projected to be affected) by water availability issues.

These examples show that adaptation can be 'planned' (i.e. the result of a deliberate policy decision) or 'autonomous' (i.e. not constituting a conscious response).

Climate change mitigation is defined as human intervention which reduces the anthropogenic forcing of the climate system, usually through reductions in GHG emissions and/or enhancing GHG sinks (IPCC, 2007a). Examples of actions constituting mitigation include:

- 1) improving domestic and industrial energy efficiency, so that for a given amount of usable energy, a smaller amount of fossil fuel is burned, and fewer GHGs are emitted;
- 2) making use of alternative energy sources where CO₂ emissions are lower than those associated with burning fossil fuels;
- 3) making use of carbon capture and sequestration (CCS) technologies at power generation facilities, so that GHGs which would otherwise be emitted to the atmosphere are captured *in situ* and subsequently pumped into underground geological formations for long-term storage;
- 4) enhancing natural processes which remove GHGs from the atmosphere, for example afforestation/reforestation to enhance the CO₂ sink associated with photosynthesis.

The following important points (Parry *et al.*, 2007) about adaptation and mitigation strategies should also be noted:

- 1) Because a certain amount of warming of the climate is already unavoidable, due to past GHG emissions, adaptation is seen as a necessary action.
- 2) Different temporal and spatial scales are relevant to adaptation and mitigation respectively - mitigation has global benefits but these may not be perceivable until the middle of this century (as a result of the unavoidable warming outlined in the preceding point). On the other hand, adaptation is typically undertaken at local or regional scales, but its benefits may be immediate.
- 3) The best strategy for managing projected changes to the climate is to undertake a mixture of both adaptation and mitigation measures.
- 4) There can be complex interactions between adaptation and mitigation strategies. (For example, an adaptation action to increased temperatures inside buildings is to use air-conditioning. However, if the energy source for this is derived from fossil-fuel sources, there is a negative impact in terms of mitigation).
- 5) The costs (both financial and otherwise) of some adaptation and mitigation strategies mean that not all actions are accessible to all societies.

CLIMATE CHANGE RISK AND SELECTED GEOHAZARDS IN SOUTH-WEST ENGLAND

The complex links between the various elements of the Earth system include the potential for changes in the climate to influence a selection of geological and geomorphological hazards (Forster *et al.*, 2009; Liggins *et al.*, 2010). Many of the links between climate and geohazards, such as those in volcanic and mountainous regions, are not relevant for South-West England. However, others do have relevance, including the links between:

- 1) rainfall and flash flooding as evidenced by the Boscastle and Lynton/Lynmouth flooding events;
- 2) rainfall, local geology/geomorphology, and river flooding in, for example, the risk of flooding in Exeter, which is a key focus of the Environment Agency (EA) (Environment Agency, 2012a);
- 3) rainfall, local geology/geomorphology, and rockfalls/landslides in, for example, the rockfall and landslide events at Burton Bradstock and Beaminster in July 2012, which resulted in three fatalities (BBC, 2012; British Geological Survey, 2012);
- 4) sea-level change and impacts on the coastal zone.

The first and last of these examples are examined in the following sections, through the use of case studies, which will also be used to explain a selection of other challenges associated with climate modelling and climate impacts research, in particular the assessment of the climate change risk.

There are many definitions of the term 'risk'; one common definition is " $risk = hazard \times vulnerability$ " (e.g. Taubenböck *et al.*, 2008 and references therein). Here, 'hazard' describes the projected change in a climatic parameter, typically defined as a function of the probability of the change and the magnitude of the change, and 'vulnerability' is a function of the exposure to the change, resilience to the change and adaptive capacity (ability to adapt to the change). In a risk assessment, metrics of all the components of the hazard and vulnerability functions

may be assigned scores relative to each other, and a particular risk may be quantified by multiplying the relevant hazard and vulnerability scores together.

Often, the aim of undertaking a climate change risk assessment is to inform future resilience planning in terms of managing the risk. Risk may be addressed through adaptation and/or mitigation; since the risk is location- and context-specific, any strategy for reacting to a particular risk (or risks) will be similarly specific. However, using the above framework, a climate change risk assessment can be used in order to quantify and compare different risks in different contexts and/or locations. Describing the uncertainties associated with making projections and assessing risk serves to highlight the challenge of making decisions about the future, such as those relevant to adaptation and/or mitigation, in the face of uncertain information. Given the potential for non-linear changes to the climate system and/or the possible future occurrence of climatic variations outside the present realm of human experience, it may become increasingly inappropriate to assume that past conditions are fully representative of those which might be seen in the future, and this is an additional uncertainty to be considered.

Risk associated with sea-level rise

Projected rises in sea level pose a threat to the coastal environment. An increase in average sea level can not only result in direct inundation itself, but also increase the potential impact of waves, storm surges, etc., since these would then be superimposed on a higher background water level.

Projections for South-West England are for a relative sea-level rise of up to ~0.9 m (relative to 1980–1999) by the end of this century, and a greater rise of up to 1.9 m under the H++ scenario (excluding storm surge and wave contributions in both cases). What might this mean for the coast of the South-West? An assessment of relative rock resistance across Great Britain (Clayton and Shamooin, 1998; May and Hansom, 2003) found that the coast of South-West England is generally less resistant to erosion than that of either Scotland or Wales, but generally more resistant than most of the rest of England. Considering the South-West specifically, the assessment found that most of Devon and Cornwall's coast falls into the 'low average' or 'high average' categories². The main 'resistant' stretches are along the North Devon coast and around the Penwith peninsula in Cornwall. Most of the coast of Dorset, Somerset, Avon and Gloucestershire is classed as 'weak' or 'very weak'. A previous study (Jones *et al.*, 1988) identified five sections of the South-West England coast which were particularly prone to landsliding (including parts of Weymouth Bay and Lyme Bay, and the coast from Boscastle to the Taw Estuary). Four of these five coastal sections are in areas identified as having 'low average' or 'weak' resistance (the fifth is in an unclassified area). However, it should be noted that the causes of these coastal landslides are not necessarily related to erosion by the sea. Furthermore, Jones *et al.* (1988) also stressed that reporting of coastal landslides tended to be limited to those which were conspicuous or which had implications for coastal defence works.

Whatever an area's degree of resistance to erosion, if it is relatively low-lying and/or has critical infrastructure in the coastal zone, it is potentially sensitive to sea-level rise. An illustrative example is the coast near Dawlish in Devon. The route of the main railway line linking London with Cornwall and much of south Devon passes along this coast. The railway is protected by sea defences, with the line frontage in this vicinity being actively managed and maintained by Network Rail and the EA (Dawson, 2012). However, severe weather can still result in disruption to services, either directly or as a result of remedial works following weather-related damage to the defences. As well as this obvious logistical importance, Dawlish Warren, a sandspit extending across the mouth of the Exe estuary, is largely covered by a National Nature Reserve, indicating a further ecological importance. The area is also a

popular destination for tourism and recreation.

Figure 3 illustrates some key points of Dawlish Warren that are relevant to the way in which the climate risk associated with sea-level rise in this area might be assessed. Elevation data, from the NEXTMap® Britain digital terrain model (DTM), are shown on the figure¹³. The elevation intervals used have been chosen to be an illustrative indicator of certain scenarios of projected sea-level rise as follows: 0.5 m to represent a moderate sea-level rise projection for the end of the century (approximately the 50th percentile/central estimate value under the UKCP09 medium emissions scenario, see Figure 2); 1 m to represent a high sea-level rise projection for the end of the century (greater than the 95th percentile value, ~0.9 m, under the UKCP09 high emissions scenario, see Figure 2); and 1.9 m, the upper end of the H++ scenario¹⁴. Hence, areas with elevation below 0.5 m could be viewed as potentially sensitive to sea-level rise of that amount. This is known as the 'bathtub' approximation, for obvious reasons. It is a rather crude approach, in that it does not account for winds and tides, erosional/accretional processes, or landform migration, and it assumes no hydrological connectivity and no human intervention (e.g. flood defences). However, in view of the other uncertainties, including the fact that only the projected mean sea-level rise component and not the projected changes in storm surge is considered, it is an appropriate approximation to give an indication of potentially sensitive areas.

Also included in Figure 3 are flood map data provided by the EA (Environment Agency, 2006) showing present-day 'extreme flood'. This denotes a flood which has a 1-in-1000-year return level (i.e. a 1-in-1000 probability of occurring during a particular year) but does not differentiate between flooding from rivers or the sea. Other relevant elements shown in Figure 3 are the railway line, areas of settlement, and the extent of the National Nature Reserve.

In terms of a climate risk assessment, it would be useful to use the types of information presented in Figure 3 to make estimates of key elements of the risk posed to this area by projected sea-level rise. For example, almost all of Dawlish Warren, and areas adjacent to the railway line (though not much of the line itself, as it generally has a higher elevation) are in present-day 'extreme flood' zones, as are a few settlement areas at the southern end of Dawlish Warren. Only one small flood defence system, adjacent to the railway, is present in the flood map database. However, the EA is still in the process of adding existing defences to its database, so the sea defences protecting the railway, between Dawlish and the southern end of Dawlish Warren, are not yet included in its flood map, nor are the defences along Dawlish Warren itself which include gabion baskets, rock armour and timber groynes (Environment Agency, 2012b).

A moderate sea-level rise, of the order of 0.5 m, has the potential to threaten part of the Nature Reserve and the margins of the sand spit itself. As the amount of sea-level rise increases, so does the threatened area of the Nature Reserve. For the most part, the elevation of the railway is greater than the upper H++ value of 1.9 m, although there are areas further up the Exe estuary (near Powderham Castle) where the railway has an elevation of less than 1 m. A few settlement areas near the Warren could be threatened by sea-level rise of the order of 1 m, and the number of potentially threatened settlement areas rises if we consider sea-level rise of up to 1.9 m.

One of the challenges of understanding the risk posed to a particular asset¹⁵ by climate change is to understand adequately the hazard and vulnerability, even for the baseline period against which future projected changes are measured. Understanding these components of the baseline risk is an essential step in being able to assess the projected future changes in risk. For Dawlish Warren, the hazard is the projected change in sea level. Although we have present-day flood map information for this area, we do not know whether the relevant driver is river or sea flooding, so we cannot assess the contribution of sea flooding in the present day. In terms of the future, a change in the hazard is a function of the

probability and the magnitude of the change. Hazard can be a fairly complex function, with inherent uncertainty, and the vulnerability can be even more difficult to define as it depends on exposure, resilience and adaptive capacity. The exposure could be considered in terms of a metric such as the percentage of land in an area whose elevation is less than a certain value, or the 'value' of infrastructure/assets - such as the settlement areas, the railway, or the Nature Reserve - which lies inside the 'extreme flood' risk zone, or below a certain elevation. (Consideration would be required as to how a 'value' could be assigned to both the Nature Reserve and the railway so that these 'values' are directly comparable. Typically the 'value' of a natural system is quantified in terms of its ecological importance, but the railway's 'value' is of a more financial/infrastructural nature). The resilience might be defined in terms of the quality and quantity of existing flood defences - for example, the return level of flooding which the flood defences in this area are built to resist. The adaptive capacity could be the relative ease with which existing flood defences can be modified to cope with the projected change in hazard, or the extent to which a species living in the Nature Reserve could tolerate (e.g. by migration) any loss of its habitat as a result of the projected change in hazard.

All of these quantities require some effort in order to understand and define them appropriately, which would be a crucial early stage of any risk assessment. Nonetheless, progress is being made in this type of research. Integrated coastal models are being developed which incorporate many processes in the ocean and atmosphere, and on land. Other elements such as socio-economic factors may also be incorporated. These models are used in various approaches to coastal risk assessment, often using case studies in the UK (e.g. Dawson *et al.*, 2009; Robins *et al.*, 2011). An example with relevance to South-West England is the study by Purvis *et al.* (2008) which proposed a framework for coastal flood risk assessment that incorporates the uncertainty in future sea-level rise projections, and applied it to a case study area encompassing Weston-super-Mare, on the Somerset coast. The study used an inundation model to examine the effects of potential future extreme water levels and concluded that a risk assessment based on a single (the 'most plausible') sea-level rise scenario could underestimate financial losses, as this neglected low-probability/high-impact scenarios. Further work (Lewis *et al.*, 2011) has built on this study, using the same inundation model and incorporating UKCP09 data and thereby allowing further quantification of uncertainties. Some attempt was made to express the flood risk using an approach based on financial losses, but the assessment was approximate. In addition, although the H++ scenario was mentioned, it was not used quantitatively in a risk assessment.

A further, more direct way in which this type of issue can be addressed is to facilitate the sharing of information and expertise between different organisations such as the Met Office, EA, Ordnance Survey, British Geological Survey, etc., so that an 'all hazards' approach (i.e. considering weather/climate-related hazards along with other natural hazards) may be followed. This is now beginning to be considered as part of the 'Natural Hazards Partnership' (NHP), a recently-formed collaboration between the Met Office and twelve other partners whose scope includes a variety of natural hazards. Although the focus is on responding to hazards on the timescale of weather rather than climate, the NHP will doubtless encourage collaboration between experts from these organisations on issues relevant to longer timescales. As such, there is hope that the assessment of the hazard and vulnerability components of climate risk will gradually become less complex. Additionally, there are clear advantages of collaborative efforts between natural/social scientists and stakeholders. For example, in a recent initiative the EA worked with local residents to design new flood mitigation measures in the Yorkshire town of Pickering (Whatmore and Landström, 2011).

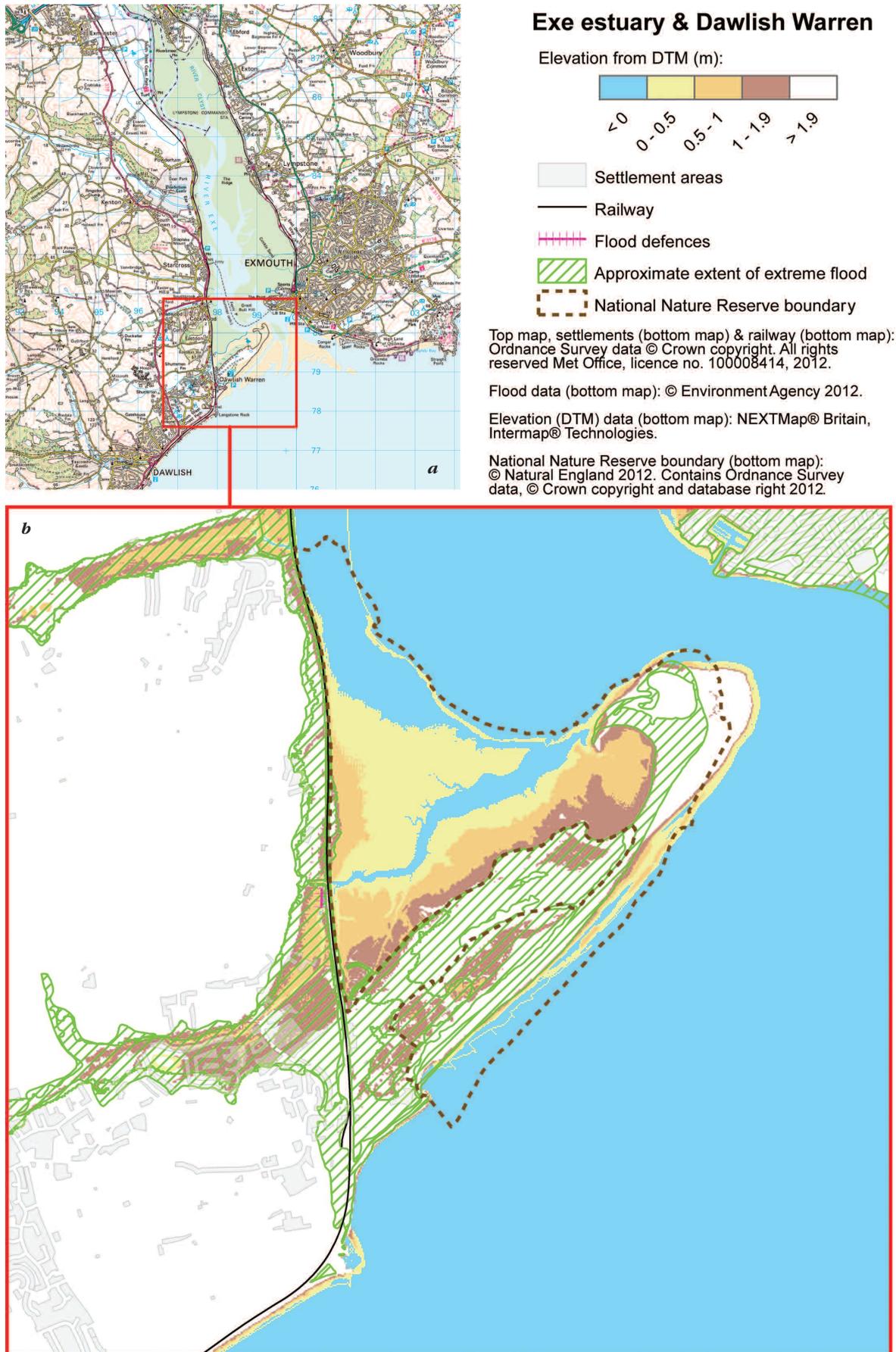


Figure 3. (a) The Exe estuary and (b) Dawlish Warren, showing a variety of local information relevant to a potential assessment of the risk posed to the area by projected sea-level rise. NEXTMap® Britain elevation data (Intermap Technologies, 2012) are used for Dawlish Warren to give a broad, illustrative indicator of areas which are potentially sensitive to projected sea-level rise of varying amounts. EA flood map data - which are for present-day, not projected future, flood risk - are also included. The 'extreme flood' (green hatching) data are based on a flood with a 1-in-1000-year return period.

Risk associated with flash flooding

Examples of major flash flood events in South-West England, which occur as a direct result of localised, very heavy rainfall, include the Lynton and Lynmouth floods of 15th/16th August, 1952 (Delderfield, 1953) and the Boscastle floods of 16th August, 2004 (HR Wallingford Ltd., 2005). Both of these events were generated by periods of exceptionally heavy rainfall in a relatively small area, with the Lynton and Lynmouth floods claiming 34 lives (Delderfield, 1953). Rainfall totals for the 16th August, 2004 across South-West England from the UK 5 km gridded daily precipitation data set, which covers the period 1958-2009 (Perry *et al.*, 2009), are shown in Figure 4a, while the same data expressed as a percentage of the 1961-1990 climatological monthly (average total) rainfall for August are presented in Figure 4b. The largest gridbox total in the Boscastle area is 186.5 mm (*cf.* nearby observations of 200.4 mm at Otterham and 184.9 mm at Trevalec), which is the second-highest daily total in any gridbox in the region for the period 1958-2009. Around Boscastle, the daily rainfall totals on 16th August, 2004 are of the order of 1-2 times that of the average total August rainfall for 1961-1990.

Figure 5a shows observed and forecast rainfall rates for the day of the Boscastle event. The event was associated with a localised band of very heavy convective rainfall which persisted for some hours over the same area. Figures 5b-d show the effect of different resolutions of the forecast model on the nature of the rainfall that was forecast. The 12 km model does not identify any areas of heavy rainfall; the 4 km model predicts some heavy rain, but does not correctly identify the shape of the features. Only the 1 km model comes close to matching the shape of the observed rainfall features (Roberts, 2006).

Unfortunately, at the time of the event, the operational model was that with 12 km resolution, and the 4 km and 1 km cases were run retrospectively to investigate their ability to reproduce the meteorological features of this event.

The research challenge embodied by this case study is of a more directly technical nature than that for Dawlish Warren discussed above. Extreme events like the Boscastle and Lynton and Lynmouth rainfall events are often the ones which are of the greatest interest, because of their impacts. Yet climate models, which typically have a far coarser resolution (25-300 km) than the forecast models just discussed, are unable to represent convective rainfall extremes. In consequence, projection of future changes in flash flooding events of this magnitude, using the present generation of climate models, is currently not possible. Therefore, in order to draw any conclusions about the potential effects of climate change on flash flooding, it is necessary to find alternative approaches which provide a useful, and scientifically robust, insight into the subject. One such approach is to examine moderately high percentiles of the rainfall distribution as represented by a climate model. In so doing, it is assumed that changes in moderately high percentiles, which climate models are better at representing than more extreme events, give useful information about changes in more extreme events. Figure 6 shows an example using output from a perturbed physics ensemble of the Met Office's regional climate model, HadRM3.

This PPE contains 11 ensemble members, and is part of the larger ensemble underlying UKCP09. Rainfall distribution for the winters (December, January, February) and summers (June, July, August) of the years 1961-1990 was assessed, and the amount of rainfall corresponding to the 95th percentile at each 25 km gridbox was noted. The exceedance of this amount for

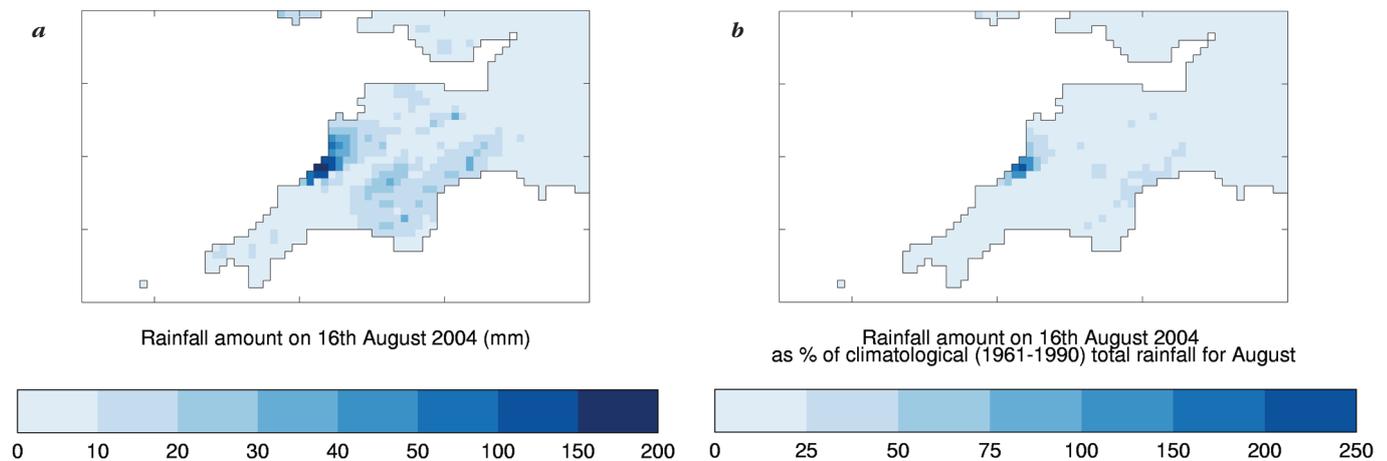


Figure 4. Rainfall amounts from the Met Office 5 km gridded observational data set on 16th August 2004 (Boscastle flooding event), expressed (a) in mm and (b) as a percentage of the mean monthly rainfall (1961-1990) for August. Note non-linear scales in both figures.

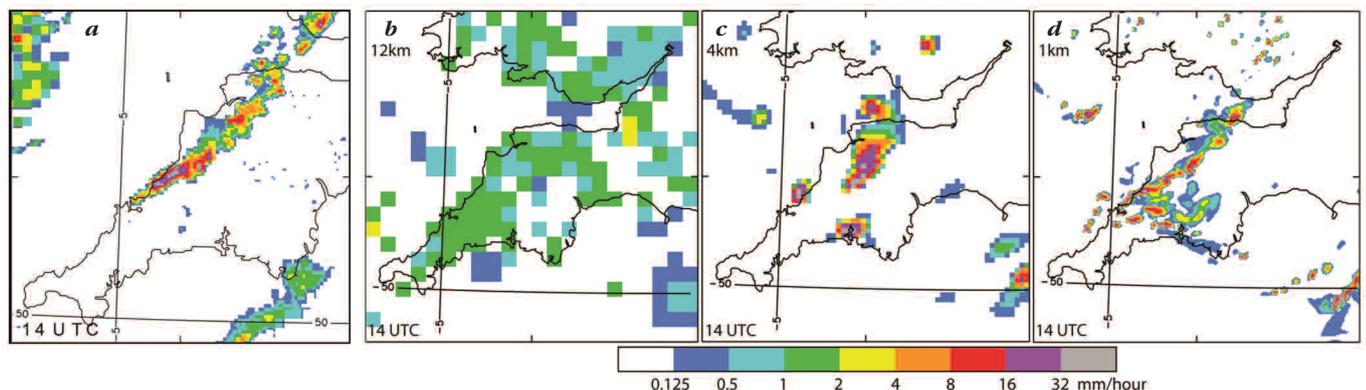


Figure 5. Rainfall data from observations and forecasts for 16th August 2004, the day of the Boscastle floods. (a) Observed hourly rainfall rates, from radar data, for 1500BST (BST = UTC+1). Forecast model output - forecast rainfall rates at 14 UTC from (b) 12 km forecast starting at 00 UTC, (c) 4 km forecast starting at 01 UTC and (d) 1 km forecast starting at 01 UTC. Reproduced from Roberts (2006).

three future time horizons - the 2020s, 2050s and 2080s - was then computed and is presented in Figure 6. The maps in the rows of this figure represent the percentage change in exceedance of the rainfall amount representing the wettest 5% of days in the model's baseline climate, at the three future time horizons. The future time horizons have been defined in the same way as those in UKCP09 (see above). Use of an ensemble also allows the calculation of a minimum, mean and maximum projected change across the ensemble; and these are shown in the maps of the columns of Figure 6.

It is evident that the mean projected change is an increase in exceedance for winter (Figure 6b), and a decrease in exceedance for summer (Figure 6a). Thus, on average, the occurrence of rainfall corresponding to the modelled 5% of wettest winter days in 1961-1990 is projected to increase in future, and rainfall corresponding to the modelled 5% of wettest summer days in 1961-1990 is projected to decrease in future. However, for both summer and winter rainfall, the modelled range spans zero for all time periods (summer, Figure 6a) and for the 2020s (winter, Figure 6b), so that there is uncertainty even in the sign of the projected changes for these cases. Conversely, an increase for winter rainfall in the 2050s and 2080s is robust across the ensemble.

However, the caveats and limitations of this analysis should be noted. Firstly, regarding the extent to which various uncertainties are sampled, an 11-member PPE run under the medium emissions scenario does not sample structural uncertainty (all 11 ensemble members are versions of the same climate model), but it does sample parameter uncertainty to some extent (different values of key parameters are used, though this type of uncertainty is sampled more extensively in UKCP09). Nor is emissions uncertainty sampled here, as only one scenario has been used. Natural internal variability is sampled to some extent. Changes have been quoted for three different future periods, but with respect to only one baseline period (and with no assessment of external variability). Secondly, regarding the abilities of the model itself, projected changes in 95th-percentile rainfall at the 25 km RCM grid scale have been examined. This corresponds to heavy, but not extreme, rainfall at a relatively large spatial scale. Our confidence in the ability of models to capture such events, and hence projected changes in these, is relatively high. However, it is less clear whether the projected changes to this type of rainfall are indicative of what might be expected for more extreme events. There are issues with the ability of current climate models to capture the convective rainfall extremes associated with summer storms, and research is ongoing (e.g. Kendon *et al.*, 2012) using higher-resolution models to look at extreme rainfall processes and projected changes in more detail. Thirdly, the rainfall amounts associated with the 95th percentile have not been validated against observed rainfall data. However, here we are using the top 5% of events in the model as being representative of the top 5% of events in reality, even if there is disagreement in their absolute amount. Finally, the Boscastle event was a >99th percentile event, whereas the 95th percentile has been used here, because the statistics of exceedance of the 99th percentile are less robust, since it is only exceeded 1% of the time. The 95th percentile is an appropriate compromise involving better statistics of exceedance, but still a relatively heavy event.

UKCP09 includes a "change in precipitation on the wettest day of the season" variable, which (given the length of a season is ~100 days) corresponds approximately to the 99th percentile of the season. We can compare the PPE results with projections for this variable, although it must be borne in mind that (a) the results are for different percentiles of the rainfall distribution and (b) the range in the PPE projections does not directly translate into a range across UKCP09 probability levels. The best approach is to compare the mean PPE response for the 95th percentile with the 50% probability level (central estimate) of the UKCP09 wettest day change, under the medium scenario for consistency. This shows that the sign of the change (positive) is consistent between the two for winter, for all three

future time periods. The situation is less clear for summer. The UKCP09 wettest day change at the 50% level across South-West England can be positive or negative in different 25 km grid squares, but the mean PPE response is negative for all three time periods. The differences between UKCP09 and the 11-member PPE for summer rainfall can be explained by the fact that the full UKCP09 ensemble samples more uncertainty.

As is the case for the sea-level rise example, the projected future risk posed by flash flooding events is a complex function of both the hazard of, and vulnerability to, these events. For Boscastle, and Lynton and Lynmouth, geological and geomorphological aspects are evident in the vulnerability. Boscastle and the River Valency catchment within which it lies are underlain by sedimentary rocks of late Devonian to early Carboniferous age (British Geological Survey, 2011a, b). Lynton and Lynmouth are underlain by early-to-mid Devonian mudstone, siltstone and sandstones of the Lynton Formation while the wider River Lyn catchment is mostly underlain by mid-Devonian interbedded sandstone and conglomerates of the Hangman Sandstone Formation (British Geological Survey, 2011a, b). The geomorphology of both areas is similar, with deep, steep-sided river valleys. For both events, the antecedent weather conditions had been relatively wet (Delderfield, 1953; Doe, 2004), leading to increased saturation of the land and thus an increased likelihood that further rainfall would lead to runoff rather than drainage through the soil, especially since the soils in these two areas are comparatively shallow. Other contributing factors included the damming of the rivers by debris being carried downstream, and the subsequent failure of these temporary dams resulting in sudden surges of water along the path of the rivers (particularly in the case of the Lynton and Lynmouth event).

As well as emphasising again that assessing climate risk can be a complex process, this case study has highlighted the further challenge that there are important aspects of the climate which are difficult or impossible to assess using the current generation of climate models. This can be addressed by continuing to push forward the development of models, but the timescales involved mean that alternative ways to assess some of these issues using current models must be found. As a result, there will always be caveats and limitations associated with a given approach, which must be clearly stated along with the results of any analysis.

SUMMARY AND CONCLUSIONS

This paper has provided a brief overview of the main causes, both natural and anthropogenic, of (geologically) recent global climate change. Climate change projections at the global, UK and regional scale have been discussed, and UKCP09, the UK's most recent government-funded suite of climate change projections, has been used to give a summary of the projected changes in temperature, precipitation and sea level rise for South-West England in the coming decades, together with commentary on the differing levels of confidence in the projected changes of different variables.

The types of uncertainty in climate projections have been considered, together with ways in which these can be managed, and in some cases quantified and/or reduced. A brief overview of the types of strategies for managing projected changes to the climate, namely, climate change adaptation and mitigation, has been presented. However, for a given asset (whether it be a location, organisation, ecosystem, etc.), climate change projections are only part of the story in assessing the potential risk posed by climate change to that asset. Information is required not only about the projected evolution of a climate-related quantity (and thus the changing 'hazard'), but also about what impacts the change in hazard might have (and thus the changing 'vulnerability'). It is also clear from this that the hazard and vulnerability for the baseline period must also be well understood, in order to make a meaningful assessment of the potential changes in these. Finally, in order

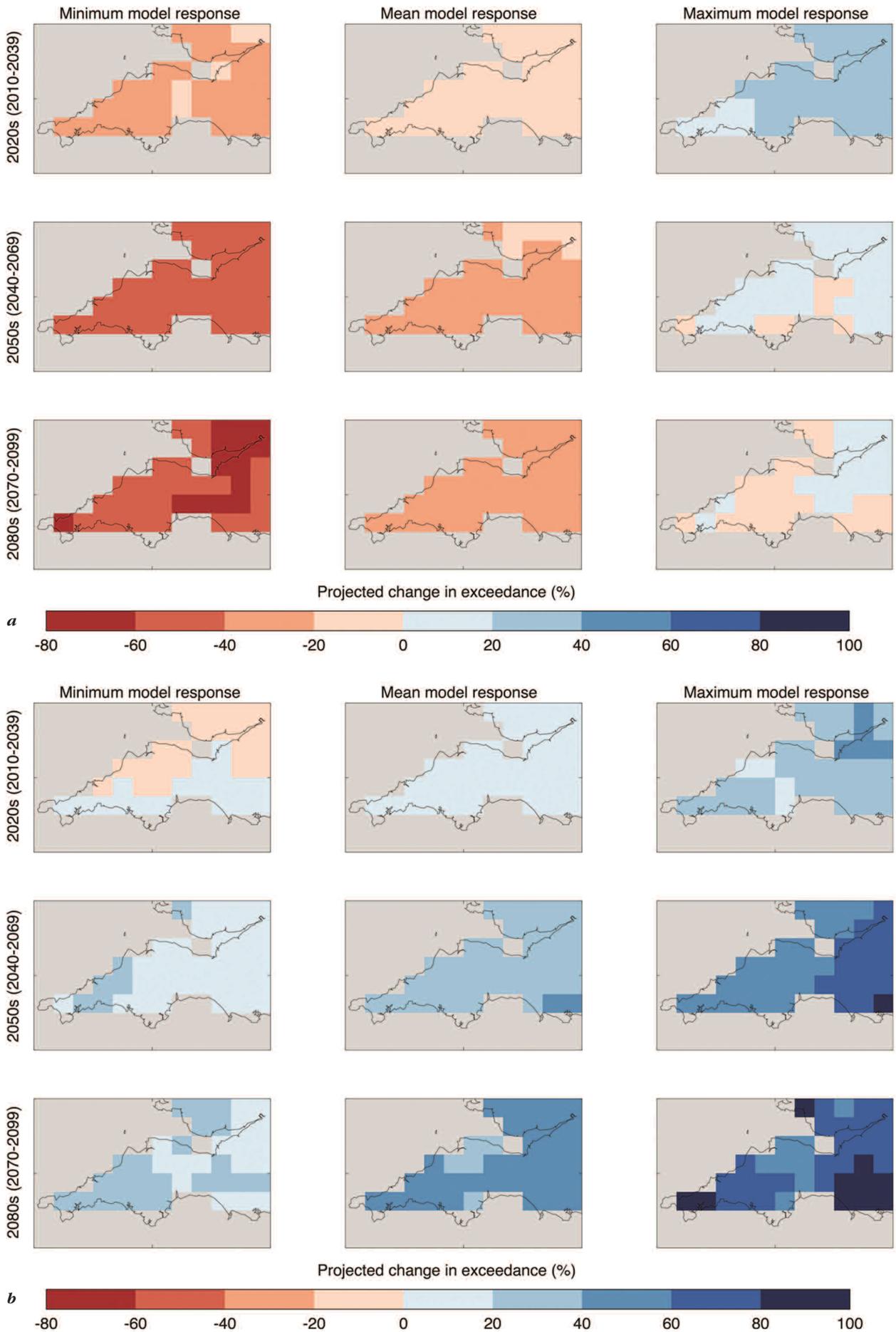


Figure 6. Projected changes in exceedance of 95th percentile (a) summer and (b) winter rainfall amounts in South-West England, calculated from an 11-member PPE of HadRM3, relative to a baseline of 1961-1990.

to bring together some of the concepts covered in this paper, some of the challenges associated with assessing climate risk (in terms of both the hazard and vulnerability components) have been explored, using two examples with both geological and local relevance.

In summary, it remains a crucially important task for those working in the fields of climate science and climate impacts research to ensure that the science of climate change, the potential impacts of climate change, and the consequences of these impacts for society are assessed as effectively as possible, and equally that the findings of these research areas are communicated appropriately to stakeholders and the general public.

NOTES

¹ Here, 'very likely' and 'likely' are IPCC terminology, with particular definitions in terms of probability (given in the brackets).

² Lorenz's analogy in this reference is to a seagull's wings - it was not until the early 1970s that the butterfly metaphor arose (Hilborn, 2004).

³ The link between orbital cycles and climate was proposed previously by James Croll (Croll, 1864), a largely self-taught scientist whose work as a museum caretaker allowed him access to the books which helped him to develop his ideas - so we might more properly refer to the cycles as 'Croll-Milankovitch cycles'.

⁴ The various known aerosol effects are summarised in figure 2.10 of Forster *et al.* (2007).

⁵ A further complication is that humans have an influence on the extent of deserts, because of anthropogenic land-use change, so not all desert-derived dust aerosol can be considered as being natural in origin.

⁶ The IPCC defines 'radiative forcing' as "*the change in the net (downward minus upward) irradiance (expressed in $W.m^{-2}$) at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. [...]*". The full definition may be found in IPCC (2007b), Annex I.

⁷ The 'baseline' climate is that against which projected future changes are measured. It is often, though not always, taken to be a period broadly representative of 'present' conditions. When a climate parameter is arithmetically averaged over a 30-year period, the resulting value is sometimes termed a 'climate normal' (WMO, 2012).

⁸ Definitions of the baseline and future periods differ for sea level rise projections from those for the other variables. This is because the UKCP09 sea level rise projections are based on IPCC projections and these time periods were used in the IPCC assessment (Meehl *et al.*, 2007).

⁹ The use of 'very unlikely' in connection with H++ is not in line with the IPCC definitions of similar phrases discussed elsewhere in this paper.

¹⁰ More formally we should use the term 'positive storm surges', as negative storm surges do occur under some conditions.

¹¹ The return level is a purely statistical quantity. If a surge greater than the 50-year return level occurs once, that does not mean it will not then occur for another 50 years, nor must a surge with 50-year return level occur exactly every 50 years.

¹² There were some areas which are unclassified in the original

assessment, so some stretches of coast are not represented in the discussion presented here.

¹³ Since these DTM data are being discussed here in conjunction with UKCP09 sea level rise projections, it should be noted that the vertical datum for the DTM is ODN (Ordnance Datum Newlyn), the Ordnance Survey's national coordinate system for heights above mean sea level, for which the time period is May 1915–April 1921. Some sea level rise will therefore have occurred between this time and the baseline period for UKCP09 sea level rise projections, which is 1980–1999. A value of 13 cm has been estimated for this discrepancy, using Newlyn tidal gauge data (Permanent Service for Mean Sea Level (PSMSL), 2012; Woodworth and Player, 2003). It has been assumed that this correction, valid for Newlyn, also applies to Dawlish (P. Woodworth pers. comm.). For simplicity, the correction has not been applied to the data shown on Figure 3, as its magnitude is likely smaller than other uncertainties on the various data shown in this figure.

¹⁴ It has been assumed that the vertical error in DTM elevations allows one to distinguish adequately between these categories.

¹⁵ The word 'asset' is used in a very general sense to represent any phenomenon or entity which may be affected by climate change. Examples of 'assets' could include a business, an item of infrastructure, a biological species, etc.

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