Report

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Climate adaptation: Risk, uncertainty and decision-making

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Editors
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Forewords

Climate change is one of the most significant challenges we face over the coming century. We must try to avoid the worst effects, by reducing emissions of greenhouse gases. The Environment Agency as the leading body responsible for protecting the environment in England and Wales, has a key role to play as a regulator and in partnership with others.

Yet however successful we are at reducing emissions, some climate change is already inevitable, so we will need to adapt. Climate change poses a risk to many of our policies, strategies and plans. We must learn to manage this risk, and provide appropriate climate change 'headroom' when we make decisions. The Environment Agency already takes account of climate change when planning improvements to flood protection, and as part of our water resources strategy. Our fisheries and biodiversity policies are kept under review and we are ready to respond to any future changes in industrial regulation in relation to emissions and energy efficiency.

The management of climate risk is a developing area, and one that will not go away. I encourage other decision-makers to read this report, and apply the framework for risk-based decision-making that it provides. By doing this, we can all ensure that our policies and projects will be robust enough to cope with the uncertain future climate.

Barbara Young
Chief Executive, Environment Agency

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2001), indicates that some signs of climate change are now detectable and that adaptation has become a necessity. Recent decisions of the Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) have raised the profile of adaptation and drawn attention to the need to incorporate adaptation into economic development and policy decisions in all countries.

The issue of how best to adapt to climate change including climate variability and extreme events is no longer a theoretical question that can be left to the research community alone. Decision-makers at all levels, and a wide array of stakeholders, now find that they are obliged to deal with the issue of climate change and how to facilitate the adaptation process. Decisions have to be made.

This new set of circumstances has generated a worldwide debate about adaptation decisions and a search is underway for the best practices for managing the risks that face individual countries and the world community as a whole. Attempts are being made within the UNFCCC process and elsewhere to develop appropriate frameworks and methods. We are both involved in this process and have an appreciation of the difficulties of handling the uncertainties with which decision-makers are faced.

This report is a substantial pioneering effort to synthesize existing knowledge and to provide guidance to help those engaged in the decision-making and policy process. It also makes creative contributions to current understanding.

Especially helpful is the clarification it brings to the distinction between climate adaptation decisions, climate influenced decisions, and climate adaptation constraining decisions, and to "no regret" climate adaptation options. The report goes on to propose a clear step-wise approach in a risk-uncertainty-decision-making framework.

While the report has been written primarily in the UK context, and includes an excellent case study on land use and forestry development in Wales, it can be expected to find a wide international readership. In many governments and research institutions, and in international agencies, people are asking for the sort of help and guidance that this report provides so well and so abundantly. We encourage all those concerned to use this publication and to draw upon it in the context of their own priorities and circumstances.

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Part 2

1. Risk and uncertainty

1.1 Introduction

All decisions are intended to bring about some future benefit to someone or something, and involve choices (e.g. whether to act, whether to implement policy A or B, etc.). Without uncertainty, these decisions would be straightforward. Reality, however, is far more complex and hence all decisions involve judgements regarding uncertainty. Identifying the sources of uncertainty, understanding how they contribute to decision uncertainty, and the management of uncertainties within the assessment and decision-making process, are therefore essential to making well-informed decisions. While not all decisions produce the benefits that were intended, any decision should, even with the advantage of hindsight, be justifiable on the basis of the available knowledge at the time of the decision.

In this chapter the concepts of risk and uncertainty are briefly discussed. The principles of risk assessment and risk analysis are introduced, and their usefulness to the management of risk discussed. Different types of uncertainty are described, including their importance to decisions that might be influenced by, or concern the management of, future climate. The importance of identifying climate-dependent risks, and their relevance for decision-making, is discussed in Chapter 2. The key features of climate change risk assessments are described in Chapter 3.

1.2 Risk, uncertainty and confidence

Before introducing the principles of risk assessment and risk analysis, it is important that the meanings of the terms 'risk' and 'uncertainty' are made clear, especially as they can mean different things to different people. The use of the terms risk and uncertainty in this report is set out in Box 1.1.

Risk is commonly defined as the product of the **probability** or **likelihood** of occurrence of a **consequence** (see Figure 1.1). The consequence (or set of consequences or impacts) is usually associated with exposure to a defined hazard, which is often detrimental or harmful. However, risk assessment is equally applicable to the analysis of uncertain beneficial outcomes.

Uncertainty describes the **quality of our knowledge** concerning risk. Uncertainty may affect both the probability and consequence components of the risk. Hence our knowledge of future hazards posed by a changing climate involves uncertainty, which is compounded by the prospect of man-made changes in climate. The impacts associated with any particular future climate are also uncertain. The outcome of decisions taken to reduce climate impacts, or exploit climate-dependent opportunities, is a further source of uncertainty. While research aims to reduce uncertainties, the primary purpose of adopting a risk-based approach to decision-making is to

Box 1.1: Definitions of risk and uncertainty

Risk: Risk is the combination of the probability of a consequence and its magnitude. Therefore risk considers the frequency or likelihood of occurrence of certain states or events (often termed 'hazards') and the magnitude of the likely consequences associated with those exposed to these hazardous states or events.

Uncertainty: Uncertainty exists where there is a lack of knowledge concerning outcomes. Uncertainty may result from an imprecise knowledge of the risk, i.e. where the probabilities and magnitude of either the hazards and/or their associated consequences are uncertain. Even when there is a precise knowledge of these components there is still uncertainty because outcomes are determined probabilistically.*

* The term 'aleatory uncertainty' is sometimes used where probabilities and dependent consequences are **precisely** known. 'Epistemic uncertainty' is used to describe situations in which probabilities and consequences are **imprecisely** known.

ensure that uncertainty is acknowledged and treated rigorously in the decision-making process.

It is also important to recognise the definitions used in decision theory (e.g. Tversky and Kahneman, 1992; Camerer and Weber, 1992), based on the original work of Knight (1921). Some decisions are taken under circumstances where the probabilities that particular outcomes or consequences will occur in the future can be known (as in a fair game of chance). These are **decisions taken under precise uncertainty**, and they are sometimes referred to as 'decisions taken under risk'. For many decisions, however, probabilities cannot be known or estimated. These are a special class of **decisions taken under uncertainty**. '**Risk**' is commonly used to describe situations in which both types of uncertainty apply (Knight, 1921; Morgan and Henrion, 1990).

Risk assessment is the process of establishing information concerning hazards, and the exposure and vulnerabilities of defined receptors. **Risk analysis** is the process by which knowledge concerning the probabilities, uncertainties and magnitude of future events is brought together, analysed and organised by the decision-maker. Risk analysis includes risk assessment, risk evaluation, and the identification and assessment of risk management alternatives.

Risk assessment may involve either *quantitative* or *qualitative* techniques and information to describe the nature of the probability component of the risk. Both techniques can be used to describe our knowledge of risk where probabilities can be estimated with some level of confidence. Qualitative techniques are particularly useful in circumstances where we lack knowledge of the probabilities. Risk assessment may therefore involve the combination of qualitative and quantitative information.

Both the hazard and the consequence have *magnitude*. For example, the risk of *significant* damage to trees in an area of forest due to winds *greater than Force 10* may be one event in a hundred years[7]. Many statements of risk, such as this, result

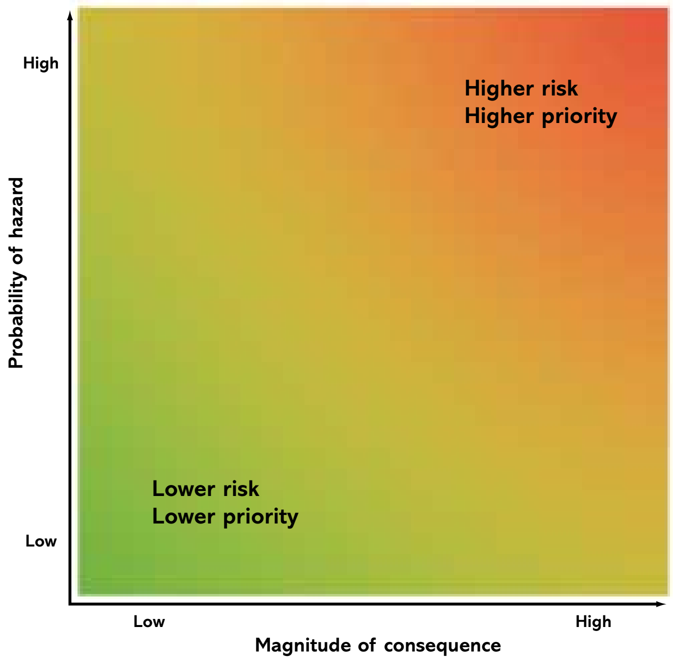

Figure 1.1: Risk depends on both probability and consequence. Climate represents a present-day hazard that we manage based largely upon past experience. Global warming may change the future probability associated with a hazard of a particular magnitude, thereby affecting the probability associated with a particular consequence. For example, intense rainfall may become more frequent, leading to an increase in flooding risk. The aim of climate change risk assessment and adaptation decision-making is to assess and manage the risk to defined receptors or exposure units.

[7] In this risk statement, the probability is expressed in terms of the expected frequency or return period of the event. This may be communicated as a percentage, e.g. a 1% annual risk of an event.

from an analysis of data in some form of risk assessment. As such they describe the observed or historical risk. However, the usefulness of a risk analysis is to provide a forecast or predictor of a future risk of concern to a decision-maker.

In other words, the risk associated with a particular circumstance is a characteristic of that situation, and can be estimated or forecast (in terms of probability and consequence). Both the probability and the magnitude components of a consequence may be uncertain. Since future climate change is uncertain, and variations in local weather and climate are governed (within uncertain limits) by chance (see Chapter 3), the assessment of climate change impacts, and the appraisal of decisions regarding adaptation, falls within the area of applied forecasting, risk assessment and risk analysis.

The degree of uncertainty associated with an 'estimate' of risk is reflected in the degree of associated confidence (i.e. the lower the uncertainty, the greater the degree of confidence in the estimate of risk). Where data exist on the occurrence of past events (e.g. measurements of daily rainfall) it may be possible to calculate the probability (or 'risk') of a future event (e.g. daily rainfall exceeding a certain threshold that may be associated with a particular level of harm or benefit). With suitable data, and using statistical techniques (e.g. **maximum likelihood methods**), it is possible therefore to obtain a quantitative estimate of the uncertainty associated with the calculated probability or risk.

In many situations, however, relevant data, information or understanding about the risk will be very limited. Nevertheless, it may be possible to identify upper and lower bounds to the risk (e.g. worst- and best-case scenarios), based on the available information. These bounds should reflect the extent of our uncertainty of the risk. In other cases it may be useful to obtain subjective judgements (e.g. from people with acknowledged expertise) regarding the level of confidence associated with the probability, consequence and nature of the risk. Clearly, these subjective judgements are uncertain, and the extent of the uncertainty should be acknowledged by the expert, or estimated by canvassing the expert judgement of a larger sample of people with similar expertise.

1.3 Risk analysis and risk management

The focus of many risk analyses is about making decisions concerning the management of rare (i.e. low probability) and/or uncertain detrimental events, for example avoiding the risk of extreme flooding. Risky decisions are usually associated with a number or range of potential outcomes: for many real-world decisions these outcomes may be either detrimental or beneficial, depending on the decision-maker's perspective. For example, flooding events may help to maintain or improve the conservation status of wetlands, but at a cost to property or farming incomes. These different outcomes may be associated with different probabilities, such as the probability of a river level exceeding the height of a flood defence. Associated with each possible outcome of a decision is a level of performance or 'pay-off' (the balance between all the benefits and disbenefits). For a detrimental event, the pay-off is negative, but in the absence of the event, the pay-off may be zero (see Section 2.6 for further details). However, most decisions entail some level of investment and the associated cost will usually enter into the calculation of the pay-off. The decision-maker will be interested to identify options or strategies that, in some sense, minimise the disbenefits or maximise the benefits associated with the risk.

For most decisions it may be neither possible nor desirable to determine the risk as a single figure or statement. Often it is more useful to retain and communicate the **likelihood** and impact components of risk. This allows the decision-maker rather than the risk assessor to decide policy and ethical issues. For example, the decision-maker may wish to implement a policy of risk-aversion. This requires information on the relative likelihoods of severe as opposed to low-consequence outcomes. The impact of different decision options on all the components that contribute to the overall risk can then be assessed (even though the overall value of risk may be similar).

Similarly, it may be possible to assess all impact types in common currency, but the decision-maker may well wish to impose his own value-judgements on different types of impact (environmental, social, economic, for example). It is generally, therefore, best for the risk assessor to present outcomes in terms appropriate to the receptor, using multiple attributes where necessary (see Section 2.6.3).

1.4 Risk-based decision-making

Decision-making on the basis of risk is relatively straightforward if several conditions are met:

- The analysis includes all significant hazards and impacts that could affect and be affected by a decision;
- Likelihoods and consequences are known or can be calculated for all significant outcomes for all decision options (now and in the future);
- Costs of implementing all decision options are known;
- Consequences can all be expressed in a common unit of 'currency' that is comprehensible to all stakeholders;
- The decision-maker is '**risk neutral**', or if not risk neutral is able to specify a preference for particular types of risk. (This may include a preference for high probability/low consequence events over low probability/high consequence events. It might include a preference to address risks where the uncertainty is low, compared to those where the uncertainty is high.)

These conditions are rarely met in full. Risk assessment is rarely a purely quantitative or objective process that leads to an unambiguous 'preferred option'. A range of options appraisal techniques is linked to assessment of risk to account for complex objectives, constraints and values which cannot be simply quantified (see Table 13 in Part 1 for further details). In addition, the decision-maker will need to be aware of important differences between the public perception of risk and the results of any 'objective' risk appraisal.

see part 1 stage 5 table 13

1.5 Frameworks for environmental risk assessment

Defra, the Environment Agency and the Institute for Environment and Health published revised overarching guidance (including a framework) on the use of risk assessment for environmental decision-making (DETR, 2000b). Defra and the Environment Agency recommend the use of this framework in their assessment and management of environmental risks.

The principal elements of the framework are:

- the importance of correctly defining the actual problem at hand;
- the need to screen and prioritise risks before detailed quantification;
- the need to consider all risks at the options appraisal stage; and
- the iterative nature of the process.

Central to the framework is advice on the use and structuring of environmental risk assessment for improved risk management (see Part 1, Figure 2). The framework introduces many issues pertinent to decision-making, such as: the role of uncertainty; social aspects of risks, risk perception and the role of the media; quantification of risk; and the relationship between risk estimation, risk management and decision-making. The present report conforms to the DETR (2000b) framework as appropriate, while reflecting the particular characteristics of decisions that will need to take account of climate variability and future climate change.

1.6 Risk and the assessment of climate change impacts

Climate change will result in changes to the frequency of occurrence of climate hazards, such as a heavy rainfall day or a drought (Chapter 3 and Hulme *et al*, 2002). Expressed another way, it will result in a change in magnitude of an event that occurs at a given frequency (e.g. once per decade). The rate of future climate change is uncertain, and therefore decisions regarding the future need to be informed by an analysis of the climate risk, or change in risk. Risk assessment can be used to assess the likelihood of uncertain future events or 'hazards' on specified receptors and exposure units. Combined with impact assessment and valuation techniques, risk assessment can also assess the significance of these events. More information on climate change risk assessment is provided in Chapter 3.

Two components of the approach to risk assessment as recommended in DETR (2000b) are particularly useful for the assessment and analysis of complex environmental problems:

(i) **Tiered approaches** are used to enable the problem to be studied in a broad, holistic way to begin with, before more in-depth studies are undertaken. This enables a wide range of hazards, processes and impacts to be identified and assessed in a qualitative fashion. The most significant risks, from the decision-maker's point of view, can then be assessed in more detail. The use of tiered approaches facilitates risk characterisation, risk screening and prioritisation. Not only can high priority risks be identified, but also areas of uncertainty that may be reduced by additional work can be highlighted.

(ii) **Conceptual models** are used to help to identify possible connections and dependencies between the hazard(s) and receptor(s) that may be impacted. These models can help identify the ways in which risks and harm may arise, identify important processes, (including environmental pathways) and possible risk control points. They may also be used as a basis for more detailed quantitative assessment and modelling where appropriate.

Climate change risk assessments attempt to define the consequences (or impact) of future climate on vulnerable or climate-sensitive exposure units and receptors (see Figure 1.2). The **exposure unit** is defined as the system considered at risk from hazardous events. Exposure units are often described in terms of the geographical extent, location and distribution of the population or populations of **receptors** at risk. Further information is provided in Sections 3.2 and 3.3.

An important aspect of climate risk assessments is to define the **pathway** or hierarchy of cause and effect that leads from climate variability and change to the consequence for the exposure unit and receptors. These pathways may be represented by **influence diagrams**, process diagrams, **event trees,** or more complex system models. The reason risk assessment has such an important role in making decisions about the need to adapt to climate change is that the subsequent analysis should identify the key processes and critical factors by which the risk can be reduced or otherwise managed. Knowledge about the risk, and areas of uncertainty, are identified. The process helps identify the range of options available to the decision-maker, and contributes to the appraisal of their likely performance.

Hence there are many benefits of a formal, risk-based approach to climate impact assessment:

- Risk assessment, alongside **environmental impact assessment** and valuation techniques,[8] provides an assessment of the severity of consequences arising from different decisions, and this analysis often includes assessment of outcomes ('what might happen') arising from specified causes.

- This approach provides a framework for combining probabilities and consequences to provide additional information of value to the decision-maker. This might include, for example, profiles of risk allowing assessment of the importance of low probability/high consequence events compared with more frequent events with less severe consequences.

- Risk assessment deals explicitly with uncertainty concerning our knowledge of events and outcomes – in fact if there were no uncertainty then a decision would be a matter of weighing-up options on the basis of 'perfect' knowledge of future events. This would include perfect knowledge of the probabilities and consequences of random events (i.e. risk as defined in Section 1.2). As it is, the future is uncertain, and risk assessment naturally deals with uncertainty.

- The risk assessment process also requires the decision-maker to address some difficult questions. In particular, risk assessment as such does not answer the question of how to value dissimilar types of impact. For example, various decision-makers (e.g. industry and regulators) may have different decision-mak-

[8] See, for instance, the UKCIP report "Costing the impacts of climate change in the UK" (Metroeconomica, 2003).

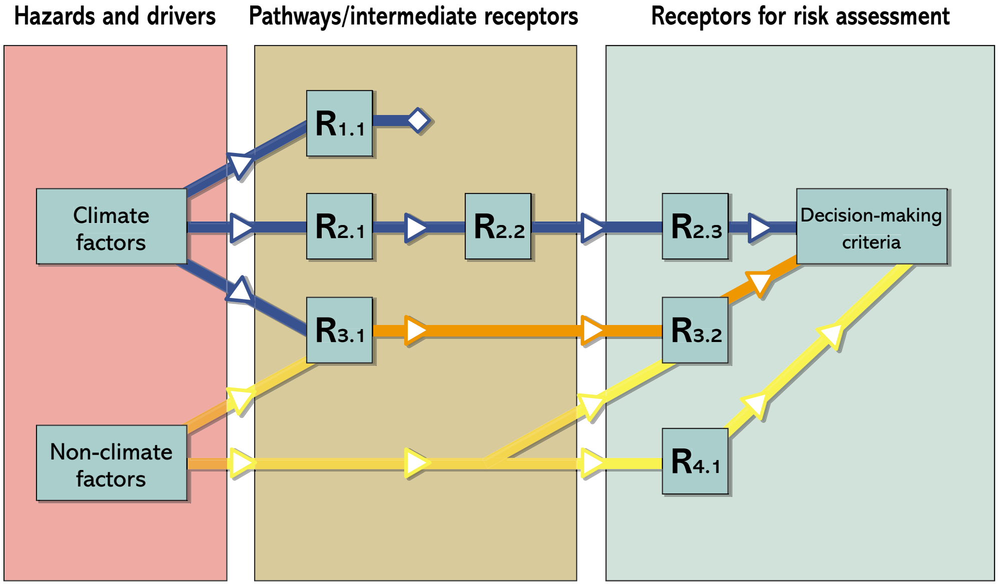

Figure 1.2: The pathway linking hazards (climate and non-climate factors), receptors and decision criteria. Probabilities may be associated with events or circumstances that link components in each pathway, connecting possible climate or non-climate hazards to particular consequences for particular receptors $R_{1\cdot1}$, $R_{2\cdot1}$, etc. Events may be defined in terms of the probability of a climate variable exceeding a certain magnitude, and the consequences for the receptor. The receptors represent important features within the exposure unit, or system at risk. Decision criteria will be defined in terms of risk assessment endpoints that apply to one or more important receptors ($R_{2\cdot3,}$ $R_{3\cdot2}$ and $R_{4\cdot1}$ in the case shown here). Risk assessment endpoints may be defined for intermediate receptors (eg $R_{2\cdot2}$) in some circumstances, for example where existing data would support the analysis. The risk assessment endpoints should help the decision-maker define levels of risk (probabilities and consequences or impacts) that are acceptable, tolerable or unacceptable. Note that the receptors are not equally affected by climate hazards. Hence, if the decision criteria were properly defined only in terms of $R_{1\cdot1}$ and/or $R_{2\cdot3}$, this would be a climate adaptation decision (see Section 2.3.1). Criteria properly defined in terms of $R_{3\cdot2}$, or in terms of $R_{2\cdot1}$ and $R_{4\cdot1}$, would be a climate-influenced decision (see Section 2.3.1). Criteria properly defined in terms of $R_{4\cdot1}$ would exclude consideration of climate change. Note that not all receptors and consequences are necessarily equally relevant to the decision criteria. Some that are relevant may be excluded from the risk assessment for a variety of reasons (e.g. less relevant than others, lack of data, correlation of response with other receptors and endpoints, etc).

ing criteria. Nor does it provide an answer to ethical issues such as how a small risk to many people should be compared with a large risk to few. It does, however, provide a framework that enables these issues to be raised.

- Importantly, risk assessment deals explicitly with uncertainty in decision-making rather than giving an over-confident view of what is known. It provides a tangible means of incorporating risk into decision-making. Tools and techniques of risk assessment, in conjunction with environmental assessment and economic appraisal techniques, have been widely used for:

➤Identifying hazards, consequences and 'pathways' of events or processes that lead to a risk occurring.

➤Identification of important components, weak links, and redundant elements of complex systems.

➤The optimisation of designs, particularly in the engineering field, that account for risks and costs while meeting other performance criteria.

➤Analysis and presentation of the implications of a range of decisions on risk. For example, a decision option that reduces commonly occurring low-consequence outcomes may need to be compared with one that is more effective at reducing rarer, higher-impact outcomes.

1.7 Types of uncertainty

As described in Section 1.2, the concept of risk combines knowledge of both the probability of a consequence and its magnitude. Uncertainty describes a condition where we lack certain knowledge that we think may be important to making a decision. Where we know the probability associated with a particular rainfall event and the consequences of the event, but not when or where such an event will occur, that is risk. Where we do not know the probability and/or the consequence, that is uncertainty. Hence we are confident in our knowledge that the climate is changing (IPCC, 2001a, p.4) but our knowledge of the precise nature, extent and rate of these changes is imperfect or limited.

Nevertheless, we may be able to estimate or understand the consequences of particular events, even though we are uncertain as to their likelihood – we are confident of the outcomes, but uncertain or ignorant of the probability of their occurrence. Vulnerability studies aim to determine how sensitive or how vulnerable[9] a receptor is to a particular hazard. In such studies we effectively analyse a scenario (see Section 3.6) that assumes that a particular hazardous event may occur, and determine the likely consequences. For example, the consequences of flooding are well known. Hence the consequences of an increase in flood frequency and magnitude can be determined with considerable confidence, even if the probability of such an event is itself very uncertain. However, for many climate change risk assessments, there may also be considerable uncertainty about the impacts. This uncertainty is imposed on top of the uncertainty concerning the events that lead to the impacts. Figure 1.3 presents these concepts of risk and uncertainty concerning both hazards and impacts. In the figure, the top-right quadrant shows risk. The other three quadrants show different kinds of uncertainty.

There are many ways of classifying sources of uncertainty. Some climate-related examples are given below.[10] However, in terms of climate change risk assessment, it needs to be emphasised that these types of uncertainty apply to both the assessment of the change in climate dependent hazard and to the assessment of the impact or consequence associated with the hazard.

Future emissions of greenhouse gases, and the global and local climate consequences of these emissions, are all subject to uncertainty, due to imperfect knowledge of future changes in energy use and other emission sources. A fuller discussion of the sources of the uncertainties incorporated in scenarios of future climate is provided in Section 3.6.3 and 3.6.4 of this report, and in Chapter 7 of the Scientific report on the UKCIP02 climate scenarios (Hulme *et al*, 2002). Climate downscaling models (see Section 3.6.7) and climate impact models (see Section 3.8) are also subject to model uncertainty.

1.7.1 'REAL WORLD' ENVIRONMENTAL UNCERTAINTY; INHERENT AND NATURAL INTERNAL VARIABILITY

The world we live in is characterised by events that, despite perfect knowledge, can only be described probabilistically (pure 'risk'). For example, life expectancy can only be described statistically as the probability (or risk) of surviving to a particular age, or dying of a particular cause. Many environmental processes possess these statistical characteristics, reflecting essentially random processes that govern particular events. For practical purposes this includes the weather and climate, which are variable over all spatial and temporal scales. Weather, for example, cannot be predicted reliably more than a few days in advance (see Section 3.5.3 for further details). There is uncertainty in the timing, duration, spatial location, extent and other characteristics of weather 'events' such as droughts, cold spells and storms. So, while it may be possible to estimate the probability and magnitude of a particular event (such as a flood) that is likely to occur within the next 20 years, it is not possible to say whether this will occur in 2003 or 2023. **Natural variability** may, within a defined period, act to reinforce human-induced climate change, or reduce it. Examples of uncertainty due to natural variability include:

- Environmental events such as the timing and magnitude of volcanic eruptions, earthquakes, or the collapse of sections of the Antarctic ice sheet.

[9] See Section 3.1 for an explanation of these terms.
[10] Draws on Moss and Schneider (2000).

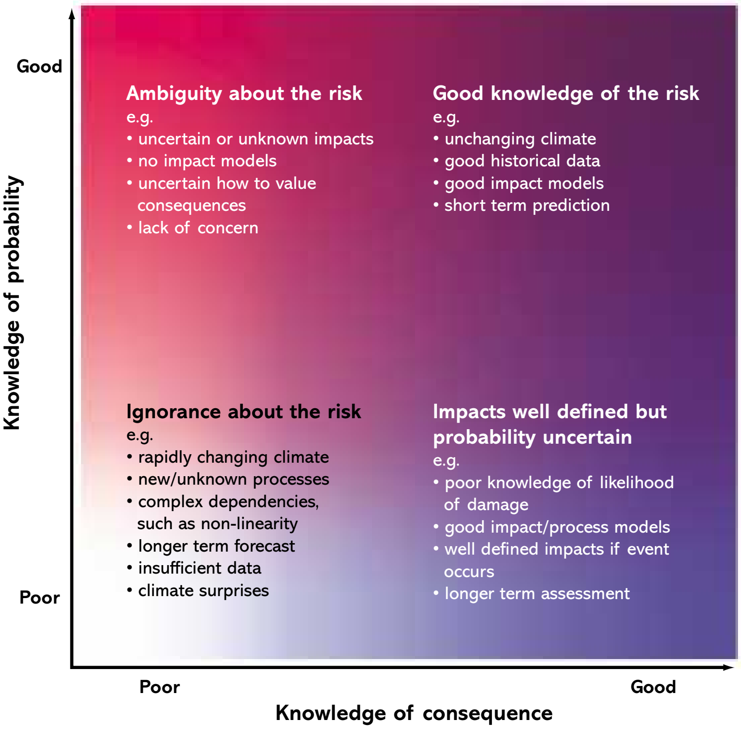

Figure 1.3: Uncertainty is a result of a lack of knowledge of either the probability of an event, or its consequences. Where we have good knowledge of both, then we are able to characterise the risk, both quantitatively and accurately (top right). Examples of some of the factors that contribute to uncertainty about the probabilities associated with future climate statistics, and the consequences of a changed climate, are indicated.

- Average climate (mean April daily rainfall), extremes of climate (maximum April daily rainfall), frequency of climate events (number of April 'showers').
- Stock markets, social and some ecological systems. These are characterised by many interrelated players or processes interacting in complex, often non-linear ways. There is no prospect of predicting the future or understanding a large part of the variability shown by these systems, which are therefore described probabilistically.
- Future choices made by societies, businesses or individuals that affect the social and economic environment in which climate adaptation decisions are taken and implemented (see Section 3.7). There is little prospect of predicting just what those choices will be. For example, changes in longer-term demographics, planning, and taxation are all inherently uncertain, but could all influence the outcome of adaptation decisions.

1.7.2 DATA UNCERTAINTY

There are limitations on the accuracy and precision with which we can measure the physical state of the world, and the amount of data that we have available or can collect. Data uncertainty arises because of:

- Measurement error (random and systematic, such as bias);
- Incomplete or insufficient data (limited temporal and spatial resolution); and
- Extrapolation (based on uncertain data).

Care needs to be taken to determine that where measurements or data exist they correspond to the process or object that we wish to know about. For example, monitoring data on off-shore wave heights may not be precise or accurate. However, even if it was not subject to measurement error, off-shore wave height may be a poor predictor of the height of waves arriving on adjacent beaches due to other, perhaps unknown, factors contributing to uncertainty governing on-shore wave height.

Data uncertainty can be particularly acute when attempting to determine the risk associated with extreme events, including those dependent on weather and climatic conditions. Although there is often extensive information on climate conditions, for example, long-term average rainfall, establishing past (or forecasting future) probabilities of extreme events, such as the 1 in 100 year rainfall event, is often uncertain. Because such events are rare, the consequences may also be more uncertain, because they will seldom have been observed. Even if they have been observed, the observations may be difficult to extrapolate to other situations or locations.

1.7.3 KNOWLEDGE UNCERTAINTY

For most real-world decisions the available theoretical and empirical knowledge is unlikely to provide complete, sufficient, or even partial understanding of the problem facing the decision-maker. The risk analyst may lack knowledge or useful data about the nature of the processes, the interactions and dependencies between different parts of the system, or the probabilities of possible outcomes. In such cases one approach is to seek expert or public opinions as to the degree of belief concerning knowledge of possible futures or process outcomes. The subjective assessment of probability and the associated confidence may, in many circumstances, be the only way to obtain estimates for quantitative risk assessments. In circumstances where we are aware or have some insight that there is a chronic lack of knowledge we should acknowledge 'ignorance' (Hoffmann-Riem & Wynne, 2002).

Knowledge uncertainty includes **uncertainty about the future**. The future evolution and/or aspects of the dynamics of certain physical systems can be forecast or hindcast with considerable skill and confidence. Examples include tidal movements and short-term weather. However, social, economic and ecological systems provide a forecasting challenge. An obvious example is the future emissions of greenhouse gases, or the effectiveness of policies to mitigate these emissions. Scenarios (e.g. of future emissions) are used to capture aspects of this uncertainty.

1.7.4 MODEL UNCERTAINTY

Most decisions are based on some form of underlying model of the important influences and pay-offs associated with different options. Model uncertainty is a particular example of knowledge uncertainty (see above). It reflects the situation in which we have insufficient understanding to form the basis of a rational, self-consistent model that describes a system that can be used to analyse decisions. These models may be conceptual or heuristic (learning by trial and error). Other, technical models are used to:

- describe data (statistical models);
- describe known processes (e.g. environmental systems models);
- assess risks (risk assessment and **stochastic process models**) and impacts (impact and valuation models);
- examine the influence of decisions on the future (decision models);
- study the influence of the future social/ environmental systems on the outcomes of decisions.

Sources of model uncertainty include:

Model choice and structure. There may be uncertainty concerning which processes to represent, and how they are represented, within a particular model.[11] It is, of course, desirable that the model used to assess climate risk explicitly includes all those variables that can be influenced or controlled by the decision-maker to help appraise options for the effective management of the risk. However, this is rarely possible unless incorporated into the design of the model. Any difference between the model output and the options available to the decision maker contributes to uncertainty concerning the effectiveness of particular options, and hence the choice of the best option (decision uncertainty, see Section 2.2).

The model designer and user must satisfy themselves that the model structure incorporates known or suspected sensitivities to climate variables expected to change over the period of any climate

[11] For example, different Global Climate Models differ in their forecasts of future climate, due to differences in their detailed structures, even though they are based on the same fundamental physics (see Section 3.6.4).

change risk assessment. Using different models may also help to improve confidence in predictions.

Model input values. The values of the variables needed as inputs to models may be uncertain (e.g. as represented by values for climate variables taken from each scenario or **ensemble** member,[12] such as the UKCIP02 scenarios (Hulme *et al*, 2002)). These uncertain inputs may be described by a range, as a fuzzy set, or taken from a probability distribution of potential values for use in a quantitative Monte Carlo-based risk model (see Appendix 3 and the web-based tools resource).

Model parameters. In certain models based on fundamental understanding of the underlying physical processes, **parameter** values may be known with high confidence. However, for many climate forecasting, downscaling, and impact assessment models used in climate impact risk assessments (see Chapter 3), parameter values are estimated from limited data of uncertain quality. This is achieved by a process known as model or parameter-fitting. The goodness-of-fit can be estimated by a variety of statistical techniques of varying sophistication, including the use of maximum likelihood estimators. The goodness-of-fit is dependent on a number of factors, including: (i) the quality and quantity of the data; (ii) the structure of the model (see above); (iii) the number of free parameters; (iv) the values of the parameters. As a consequence, the values of the model parameters are estimated with uncertainty. This can be of particular concern where the statistical parameter estimates are shown not to be independent. As with input values, the consequences of this uncertainty can be explored through techniques of sensitivity or uncertainty analysis (Saltelli *et al*, 2001).

As with the structure of the model, there is a possibility that certain model parameters may be dependent on climate in a way not recognised by the model designer. For example, many environmental models, including water quality assessment models (UKWIR, 2002) and, in particular, ecological models, have been designed for specific purposes and have not included climate sensitivities within the structure of the model. In effect they have assumed that the past patterns of climate variability will be maintained in the future. Such models have not been framed in a way that allows them to account for climate change. Hence there is uncertainty as to their validity under changed climate conditions.

Models that provide a good match to observed data sets, and are validated under a range of different conditions, with the fewest number of 'free' (or fitted) parameters, are deemed to have a high degree of predictive of forecasting skill. Risk assessors place higher confidence in well skilled models.

Model output variables and values. The consequences of model uncertainties for model output variables can be determined to a certain extent using methods of **uncertainty** and **sensitivity analysis** (Saltelli *et al*, 2001). Output variables frequently become the inputs to the next stage of the impact assessment, so the uncertainty propagates through the assessment process. However, some of the climate variables predicted by the climate models often need some additional translation, such as downscaling (see Section 3.6.7) to make them appropriate and relevant to the needs of the impact assessment. These processes/models will also carry with them some model uncertainty.

Incorporating available knowledge within a formal model structure facilitates the examination of the consequences of different types of uncertainty, especially in model sub-components and processes, parameters, and resulting from data uncertainty. Different models or model structures can be used to assess the consequences of more fundamental uncertainties (e.g. comparing **global climate model**-based climate change scenarios). Model developers often control sources of uncertainty by making simplifying assumptions. It is therefore essential in developing or using a particular model that important assumptions are identified and assessed for their possible consequence for any analysis, and that subsequent users are aware of their limitations when arriving at their decision.

1.8 Recognising uncertainty – implications for decision-making

Clearly, for a particular outcome or decision, uncertainties may arise from a variety of sources. Categorising these, and ranking or estimating the

[12] The term 'ensemble' refers to a set of simulations (each one an ensemble member) made by the same model, using the same emissions scenario but initialised at different 'starting conditions' of climate. Hence, the difference in climate between ensemble members is a measure of the natural internal climate variability. The UKCIP02 scenarios are ensemble means, produced by averaging individual ensemble members.

magnitude of different sources of uncertainty is frequently a process that relies on expert, subjective judgement. There is not always a 'right' categorisation, and assigning a category is not as important as recognising that uncertainty is present. Failing to provide an estimate of the full range of outcomes does exclude a full representation of sources of uncertainty.

Uncertainty also affects how we as individuals or society value different issues on which decisions are made. This can be particularly significant when weighing-up different types of impact (e.g. economic, environmental, social), or impacts over different time periods. This can be considered to be a form of data uncertainty or variability.

Decisions must be made despite uncertainty – the degree and type of uncertainty can have a fundamental influence on decisions. The emphasis of this framework on an adaptive management strategy supported by post-decision monitoring and appraisal is essentially a defence against uncertainty, recognising that for many aspects of climate change adaptation, uncertainty will be significant.

Uncertainty increases the further you look into the future. It is possible to determine the climate parameters (if not the specific weather) for the next few years with reasonable confidence. This may justify a fairly detailed (quantitative) probabilistic representation of climate risk. Further into the future, uncertainties accumulate. These uncertainties are not peculiar to climate. Uncertainties associated with other future social, economic and environmental changes may be particularly important for the appraisal of decision options. Climate change is an important source of risk to the achievement of objectives established by the decision-maker. However, other non-climate factors may also be important, especially in the increasing uncertainty of the longer term. A key objective for the climate change risk assessment is to determine the balance of importance of climate vis-à-vis other risk factors that contribute to the overall risk posed to the objectives of the decision-maker.

2. Decision-making with climate change uncertainty

2.1 Introduction

Decisions must be made despite uncertainty. The knowledge that the climate has changed in the past, and is now changing as a result of elevated atmospheric concentrations of greenhouse gases (IPCC, 2001a, p.4), requires that decisions be taken to exploit potential benefits and reduce deleterious impacts (DETR, 2000a). These decisions involve choices between adaptation options. What is important is deciding what to do, given our uncertain knowledge of the future in general, and uncertain knowledge of future climate and its consequences in particular. In this context a decision to 'do nothing' should be recognised as an appropriate and positive risk management option, one that can be justified against other 'do something' options.

2.2 Outcome uncertainty and decision uncertainty

Outcome uncertainty concerns uncertainties in the environmental, economic and social impacts or outcomes associated with each **climate change scenario**, socio-economic scenario or with each decision option. In contrast, **decision uncertainty** is the rational doubt as to which decision to adopt (Green *et al*, 2000). It is partly a product of uncertainty concerning the future outcomes, including uncertainty about how quickly and by how much the climate may change, as well as uncertain changes in the future social and economic environment. Decision uncertainty may also arise due to uncertainties in present-day social and economic values (e.g. conflicting value systems) that may govern the choice between particular options. The decision-maker needs to know which option offers the best outcomes, or prospect of meeting his goals. It is not always necessary to know the precise outcome, or level of impact associated with each option. The decision-maker simply needs to know whether one option is better than another (the rank order of options). Therefore, while there will always be some degree of outcome uncertainty, this will not always result in decision uncertainty.

Nevertheless, in many cases decision uncertainty will be associated with outcome uncertainty. In these cases it may be possible to estimate the probability associated with particular outcomes, and therefore make a decision based on risk. However, in many cases estimates of probability will not be available or possible to obtain, and then the choice between options will have to be made under uncertainty.

2.3 Climate sensitive decisions and maladaptation

see part 1 stages 1 & 6

This section provides guidance on identifying how decisions may, in broad terms, depend upon climate. It emphasises the potential risks associated with misjudgements concerning the significance of climate change and adaptive decision-making.

2.3.1 TYPES OF ADAPTATION DECISION

see part 1 stage 4

Experts such as the scientists on the Intergovernmental Panel on Climate Change recognise that climate change represents a significant risk to many activities, and emphasise the need to make decisions that will reduce any associated negative impacts.

So the task of policy-makers, planners and other decision-makers is to recognise those activities and decisions at risk from a changing climate, and to modify their decision making accordingly. In order to do so, they must (i) form a judgement as to those activities and decisions that are sensitive to climate variability and climate change, and (ii) determine the circumstances where climate will be the dominant or one of the more significant sources of risk determining a successful outcome. This judgement will be reached with reference to objectives and criteria established by or known to the decision-maker.

In this report we distinguish three types of climate-sensitive decision:

- Climate adaptation decisions;
- Climate-influenced adaptation decisions; and
- Climate adaptation constraining decisions.

Climate-sensitive decisions are distinguished from decisions for which climate is not a material factor (climate independent decisions, see Figure 2.1).

Many climate sensitive decisions are directly driven by the need to reduce or otherwise manage known or anticipated climate risks. Climate and climate change are often an acknowledged part of the decision-maker's initial problem. We call these **climate adaptation decisions** (see Figure 2.1). Such decisions are particularly needed in areas where climate variability and climate extremes have historically been the subject of management. In essence, we know (from past experience) that activities in these areas, and associated decisions, are sensitive to climate variability. Therefore there is greater certainty that, dependent on the extent of future climate change, additional benefits or disbenefits will be a consequence. Examples include fluvial and coastal flood defence, extreme weather-related insurance, and the management of seasonal variability in water supply. Climate adaptation decisions will also be needed to reduce impacts consequent upon changes in average climate (e.g. average seasonal temperature, or yearly total rainfall). For example, the future choice of which crop to grow will largely be determined by the expectation that the climate will, on average, produce a satisfactory crop. However, the probability of success of any particular harvest will largely be determined by climate variability.

There are, however, many decisions which are not primarily about managing present climate variability or directly driven by a recognised need to adapt to future climate change, but whose outcomes may nevertheless be affected by climate change. In such cases decision-makers may not recognise that climate change forms a part of the decision problem. For example, climate may represent only one of many factors of varying importance in determining the outcome of the decision. Alternatively, an outcome may only be indirectly affected by variations in climate. In some cases the outcome of the deci-

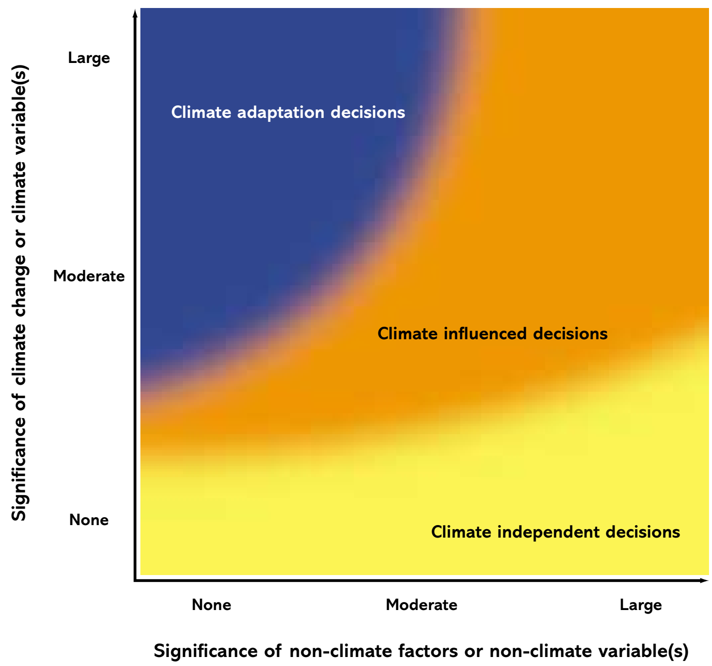

Figure 2.1: The relationship between the significant climate and non-climate risk factors, and the definition of climate adaptation and climate-influenced decision types. The boundaries are not precisely defined. Many decisions are not and will not be influenced by climate (climate independent decisions).

sion may be affected by adaptation choices made by other decision-makers. We call these **climate-influenced decisions**. Climate-influenced decisions may or may not require adaptation, depending on the significance of the climate influence.

An example of an area of climate-influenced decision-making is the management of future water demand (Environment Agency, 2001a). Changing patterns of climate are likely to influence the demand for water by agriculture, heavy industry and private citizens. However, the demand for water by these groups will also be determined by changes in technology, changes in demand for particular products and services, and changing attitudes to water use. None of these aspects of water demand can be described with certainty, but they all pose risks to the effective management of the balance between water supply and demand. It is likely that many business and investment decisions will also be climate-influenced decisions, especially those related to infrastructure development and other long-term investments.

There is not a clear distinction between climate adaptation and climate-influenced decisions. For climate adaptation decisions, climate change is likely to be one of a small number of important factors in determining the appropriate decisions. For climate-influenced decisions, climate change will represent one of a larger number of factors of varying importance, and varying degrees of uncertainty.

A third type of decision we term **climate adaptation constraining**. Climate adaptation constraining decisions lead to actions that limit or constrain the ability of other decision-makers to manage, reduce or otherwise adapt to the consequences of climate change. Such outcomes are called climate maladaptations (IPCC, 2001b). Climate adaptation constraining decisions may be implemented in order to achieve perfectly proper and well-intentioned objectives. However, they have negative consequences for others in terms of the future level of climate risk and its effective management.

In order to avoid climate adaptation constraining decisions, decision-makers need to consider the impact that their decisions may have on the ability of their successors, or the ability of other decision-makers with other areas of responsibility, to adapt to future climate change. Hence, climate adaptation constraining decisions include the consequences of decisions taken today that restrict the freedom of future decision-makers to manage future climate risks. Climate adaptation constraining decisions can be characterised as examples of unsustainable development or a lack of 'joined-up governance'.

The risk associated with adaptation constraining decisions emphasises the need for decision-makers to review the basis by which others make decisions, and understand the consequences of those decisions for their own ability, within their area of responsibility, to adapt to climate change. The avoidance of maladaptation resulting from adaptation-constraining decisions can be made an objective of a precautionary decision-making policy or process (see Section 2.5.2).

Examples of adaptation constraining decisions include the construction of long-lived assets, such as housing developments, in areas vulnerable to increased risk of fluvial and coastal flooding (IPCC, 2001b). Such developments can reduce the options available to flood risk managers to implement flood protection measures within a flood risk area both now and in the future, perhaps when the climatic hazard has become greater and more certain. They may also require specific present and future flood protection measures as a consequence of their location, thereby reducing resources available for existing developments in need of flood mitigation measures. The UK's planning policy guidance for construction and development in areas at risk of flooding is a practical example of a **precautionary approach** aimed at avoiding maladaptation (DTLR, 2001b).

2.3.2 DECISION ERRORS: OTHER MALADAPTIVE DECISIONS

see part 1 stage 1

Decision-makers want to identify the best options, and choose the option that best meets their objectives and criteria. However, decision-making in the face of uncertainty inevitably leads to decisions being taken that, with hindsight, are less than ideal. Decision-makers need to consider the risks associated with the future being different to that expected, when choosing to implement a particular option.[13]

This principal can be extended to decisions concerning adaptation to climate change, and the three types of decision described above. Risk analysis does not provide a guarantee that climate change risks will be correctly identified and characterised, and the best decisions taken. Decision-makers need to be aware of the consequences of mistaken decisions. This will be conditioned by their attitude to the risk associated with climate-sensitive decisions. Therefore it is useful to consider the risks associated with incorrectly identifying climate adaptation, climate-influenced and climate adaptation constraining decisions. Climate-influenced decisions may need to consider the need for climate adaptation, even though climate is not driving the decision-making process. On the other hand, decisions being driven by a perceived need for climate adaptation may still be vulnerable to other (non-climate) sources of risk.

In addition to climate adaptation constraining decisions, we distinguish two further types of climate adaptation decision error faced by decision-makers (see Figure 2.2):

- **Over-adaptation**. Over-adaptation results when too much **weight** or significance is placed on the need to adapt to climate change. Climate adaptation decisions are most at risk of over-adaptation. It can occur for one or both of the following reasons:

  ➤ Where actions are taken as a consequence of climate change (or a particular climate variable) being wrongly identified as a significant risk or factor influencing a decision. For example, if the anticipated amount of climate change is not observed over the lifetime of the decision, or if the changes that do take place have no significant impact on the problem under consideration, but resources are committed to unnecessary adaptation.

  ➤ Where actions are taken to adapt to future climate change but where the decision-maker has failed to identify other significant, non-climate risks or factors that should have a greater influence on the choice of option. For example, while climate change may directly affect the demand for water to irrigate domestic lawns, other social and economic factors are believed to be of greater significance for the overall management of water supplies.

- **Under-adaptation**. Under-adaptation results when too little weight or significance is placed on the need to adapt to climate change. Under these circumstances opportunities for climate adaptation may not be given a sufficiently high priority. Both climate adaptation and climate-influenced decisions are particularly at risk of under-adaptation. Under-adaptation can occur for one or both of the following reasons. They are the converse of those given above:

  ➤ Where the decision-maker has failed to consider or identify climate change (or a particular climate variable) as a factor when it may be relevant or central to making the most appropriate decision. Examples include scepticism towards the science underpinning forecasts of global warming, or basing decisions concerning coastal flood defence management upon underestimates of the rate of future sea level rise.

  ➤ Where the decision-maker has placed too great an importance on non-climate factors, compared to climate factors.

The prudent decision-maker will wish to consider the risks associated with these errors. He may wish to minimise the risk of making one or other type of error. Depending on the decision-maker's attitude to risk, he may prefer to err towards over-adaptation or under-adaptation to the climate risk.[14]

Implementing decisions that result in over-adaptation can be regarded as a wasteful use of resources. These resources may have been used in areas where adaptation to climate change is required. However, where a **precautionary approach** (see Section 2.5.2) is adopted by the decision-maker the additional cost of over-adaptation can be legitimately

[13] No blame should necessarily be attached to such a 'mistake' if an appropriate risk-based methodology was used to evaluate the available options.

[14] Note that while the decision-maker may wish to avoid these errors he may still make a decision that, due to the inherent uncertainties, subsequent events prove to have been a mistake. Hindsight is likely to show that all decisions are flawed to some degree. However, a robust process, that considers the range of risk and associated uncertainty, should increase the chance of producing better decisions.

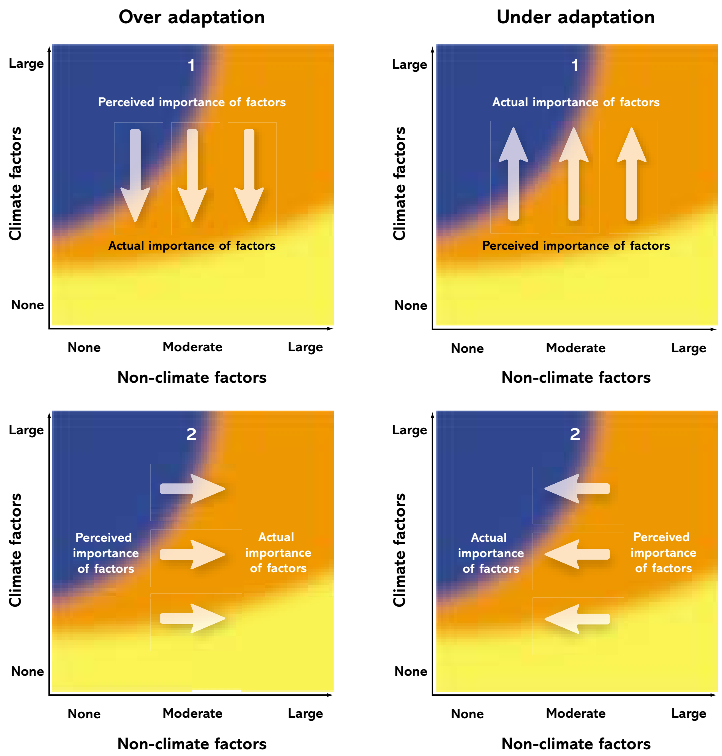

Figure 2.2: Types of decision errors associated with climate adaptation and climate-influenced decisions. A further type of maladaptive decision, climate adaptation constraining decisions (not shown) are decisions that are perceived (correctly or incorrectly) to constrain the ability of other decision-makers to cope with climate change (see Section 2.3.1).

incurred in order to provide a higher level of confidence that the adaptation will be successful in dealing with the risk. For under-adaptation errors, the risks associated with climate change will have been underestimated and negative consequences suffered (or opportunities lost) as a result of insufficient adaptation.

2.4 Hierarchical decision-making

see part 1 stage 1

Public sector decisions can be viewed as typically concerning (i) developments and investments, (ii) regulation or (iii) acting as a (statutory) consultee, expressing views on a proposal by another decision-maker. Each of these areas can involve decisions at policy, strategic, programme and project levels. Each decision type can require particular choices regarding the appraisal approach and criteria to be adopted. A key difference between decision types is typically the amount and reliability of available data. The decision may involve different temporal and spatial complexity, uncertainty and level of analysis detail. Some may be more contentious than others. This section provides guidance on the types of appraisals and criteria that can be adopted when taking account of climate change uncertainty for different types of decision. In principle they can be applied to a wide range of public, private and business decision-making.

2.4.1 POLICY DECISIONS

Policy decisions set out overall objectives and a framework for deciding on strategies and programmes on a particular subject. They tend to be national in scope, may involve significant costs and can have major consequences, some of which may not be foreseen. Hence policy decisions are likely to involve judgements concerning uncertain outcomes. Such policy decisions require a broad-brush analysis of the issues associated with sources of decision uncertainty, so as to highlight the best policy options to be implemented. The appraisals (see DETR, 1998) involve approximate 'orders of magnitude' estimates (or assessments) of the benefits and costs of the options. They also need to take account of the wider implications of the options, including their effects on incentives and any unintended side effects.

2.4.2 STRATEGIC DECISIONS AND PROGRAMMES

Strategic decisions and appraisals tend to be taken in an overall manner at the national level, but there may be some regional variations in the specific allowances to take account of regional variations. Strategic decisions concerning climate adaptation may take account of regional variations in future climate change, based on climate scenarios.

Decisions concerning programmes can include choosing between broad types of project that may be implemented within an area or budget head (e.g. expenditures on flood defence projects).

The appraisal of decisions for both strategies and programmes will generally entail an initial broad-brush analysis of costs and benefits, and will be more focused on particular issues or sectors (e.g. water resources or quality or flood defence), than higher-level policy decisions at the national level. However, the potential impacts of strategic and programme decisions on other sectors must not be overlooked. Greater, in-depth appraisal will be needed, involving a more detailed assessment of outcomes (and outcome uncertainties) than in the case of policy decisions, since the appraisal needs to be able to yield specific guidance on the actual level of, for example, the allowance for sea level rise or headroom factor.

Decisions concerning strategies and programmes will be guided, where appropriate, by decisions concerning broader policy in the area. In circumstances where policies are not taking account of risks associated with climate change, such policies may constrain adaptation measures being incorporated in strategies, programmes and lower levels of decision-making.

2.4.3 PROJECT DECISIONS

It is at this level of individual projects that the risks associated with future climate change may be realised. Project decisions usually entail fairly low individual costs, and consequences whose effects are limited to a specific area or group of people. However, project decisions may entail additional uncertainty because of the difficulty in downscaling long-term climate scenario information for site-specific locations and projects (see Section 3.6.7).

Decisions concerning smaller projects usually have to be taken fairly rapidly, by a decision-maker who may have little expertise regarding the implications of climate change. Moreover, many projects are not big enough to merit buying in such expertise. Consequently, it may be appropriate to rely on guidance and simple decision rules that have been formulated by more in-depth, generic analyses or higher-level policy guidance. However, project decision-makers will in general have considerably greater knowledge of the specific project area, and this knowledge may reduce uncertainty concerning the consequences of climate change. Hence, the project-level decision-maker may wish to form a judgement as to whether the general consideration of climate change at the strategic level was adequate to his specific circumstances.

Decisions concerning strategically important projects will usually require detailed, project-specific analysis of climate change risks. For major individual projects with long design lives, climate change could have significant consequences and costs. An example is the Thames Barrier and associated flood defences. These decisions will require in-depth and highly focused appraisal of the consequences of possible climate changes for the available options for the project.

The decision-maker must also be aware of the relationships between projects developed at a strategic/programme level when implementing an individual project. This should help him to avoid undesirable knock-on impacts of his decision on other projects. For instance, although building a sea defence in one location may provide protection for property behind it, it may also enhance the risk of erosion or flooding elsewhere along the shore.

see part 1 section 2.2.1

see part 1 stage 2

2.5 Decision-making criteria

2.5.1 ALTERNATIVE APPROACHES TO RISK MANAGEMENT

The different criteria by which risk management decisions can be taken have been divided into three main groups (Morgan and Henrion, 1990). These are:

- Utility-based;
- Rights-based; and
- Technology-based.

Utility-based criteria focus on the outcomes associated with different decision options, and accomplish this using a variety of different forms and methods of evaluation. In contrast, rights-based criteria are not concerned with the evaluation of different outcomes. Rather they relate to the process that determines what actions or activities are permitted. Technology-based criteria are frequently used in the context of environmental regulation. Examples of the different forms these different decision-making approaches may take are provided in Box 2.1. The choice of criteria that can be applied in any particular circumstance may be guided or constrained by policy or other high-level guidance, for example on appraisal methods (e.g. HM Treasury 2001, 2003). The **precautionary principle** is an example of a rights-based approach, and this is discussed in Section 2.5.2.

2.5.2 THE PRECAUTIONARY PRINCIPLE AND CLIMATE CHANGE ADAPTATION DECISIONS

There is no one, single agreed definition of the precautionary principle. Sandin (1999) identified as many as 19 different usages, while Sand (2000) describes its use in a European context. Wiener (2002) and ILGRA (2002) provide recent reviews. One widely agreed definition of the precautionary principle is set out in Article 15 of the Rio Declaration (1992) '*…where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*' (see Green Alliance, 2002). While the precautionary principle is usually invoked in the context of risks to the environment and human health, it can be applied in the context of any uncertain, negative outcomes. In a climate change context the precautionary principle may often be invoked to justify a need to implement adaptation options given uncertainty concerning impacts. However, it could equally be applied to the avoidance of over-adaptation, depending on the attitude of the decision-maker to these risks.

Climate change certainly represents a potential threat, but in order to use the definition above, '*serious damage*', '*scientific certainty*' and '*cost-effective*' need to be defined for a particular decision. Recourse to the precautionary principle *requires* that any actions taken in the face of uncertainty be both robust and reversible. Moreover the principle requires the decision-maker to put in place a programme of research to reduce uncertainty, potentially therefore requiring the modification of key assumptions or changing the data used in the assessment.

As a consequence, decision-makers have tended to favour the adoption of a **precautionary approach** over the precautionary principle. Green Alliance (2002) describes the precautionary principle and precautionary approaches to decision-making, as seen from the perspective of business, NGOs and Government decision-makers. It lays out a framework for precautionary action (a **precautionary process**) that includes criteria that can be applied as part of the decision-making process. Elements of a precautionary process include:

- Precaution is part of, not instead of, good science.
- Continuing scientific monitoring and research is essential.
- Tools such as risk assessment and cost benefit analysis should be used in context.
- There is a need for genuine stakeholder and public involvement (see IEMA, 2002).
- Openness and transparency are essential.
- A precautionary decision-making process will not necessarily result in a decision to implement an extremely risk-averse option. The level of precautionary actions should be proportional to the risk.

The guidelines described in Part 1 of this report are consistent with the precautionary process recommended in Green Alliance (2002).

2.6 Decision analysis under uncertainty and risk

It is useful to consider the concept of uncertainty in relation to climate adaptation decisions. Under normative decision theory, decision-makers try to identify the options that offer the highest **expected value**. In other words, decision-makers should make choices that provide the best chance of an outcome meeting their goals. In the case of adaptation decisions, decision-makers must judge whether the adaptation they are considering using offers a better set of potential outcomes under an uncertain future climate than that offered by inaction, or some alternative action.

see part 1 section 2.2.1
see part 1 stages 2, 5 & 6

Box 2.1: Summary of the alternative decision criteria that can be applied for risk management (based on Morgan and Henrion, 1990).

1. Utility-based criteria

Deterministic benefit-cost. Estimates the benefits and costs of adaptation options in economic or monetary terms, and selects the one with the highest overall net benefit.

Probabilistic benefit-cost. As for deterministic benefit-cost, but uncertainties are incorporated probabilistically, and the greatest expected value of resulting uncertain net benefit is selected.

Cost effectiveness. A desired level of adaptation performance is selected, perhaps on non-economic grounds, and then the adaptation option selected that achieves the desired level of performance at the lowest cost.

Bounded cost or regulatory-budget approach. Aims to achieve the greatest level of climate adaptation possible within the imposed budgetary constraints.

Maximise multi-attribute utility. This is the most general form of utility-based criterion. Rather than using monetary value as the evaluation measure, multi-attribute utility involves specifying a utility function that evaluates outcomes in terms of all the attributes identified as being important to the decision. These attributes may include risks and uncertainties. The option with the greatest utility is then selected.

2. Rights-based criteria

Zero-risk. Independent of the benefits and costs, and of how big the risks are, eliminate the risks and do not allow their reintroduction. Applying the precautionary principle in its strongest sense (see Sandin, 1999) is an example of a zero-risk criteria. Zero-risk approaches cannot be applied to the management of climate risks, since these risks cannot be eliminated. However, choices over climate adaptation options may include other consequent risks that may be considered unacceptable.

Bounded or constrained risk. Independent of the costs and benefits, constrain the level of risk so that it does not exceed a specific level or, more generally, so that it meets a set of specified criteria. Applying the precautionary principle in a less strong sense (see Sandin, 1999) is an example of a criteria based on constrained risk.

Approval/compensation. Only allow people who have voluntarily given their consent to be exposed to an agreed level of risk. Such consent may be given in exchange for some form of compensation.

Approved process. The most widely used rights-based approach, although it is not strictly a decision criterion. In essence an approval process approach specifies that, if the decision-maker and other parties to a decision follow a specified or agreed process or set of procedures, then the resulting decision will be acceptable. Hence policy, regulatory and planning guidance, often stipulated by or based upon legislation, are examples of approved processes. An approved process may specify particular decision-criteria, such as cost-benefit or technology-based criteria, that should be considered as part of the process.

3. Technology-based criteria

Best available technology. Reduce the risk as far as possible with the current or best available technology. To a large extent the meanings of the words 'current' or 'best available' are determined by economics, hence technology-based criteria are often modified forms of utility-based criteria, such as BATNEEC (Best Available Technology Not Entailing Excessive Cost).

In order to identify the choice offering highest expected value, it is necessary to know all possible outcomes associated with every potential option, and the probabilities associated with each outcome (see Section 2.6.2). Once a decision problem or opportunity has been recognised and relevant objectives defined (Part 1, Stage 1), there are five further steps:

see part 1 stages 1 - 5

(i) determine the decision-maker's attitude to risk and decision uncertainty, and agree decision criteria (Part 1, Stage 2);
(ii) identify the variables that influence potential outcomes, determine the states of these variables and the cause and effect relationships between them (Schrader *et al*, 1993) (Part 1, Stage 3);
(iii) identify the alternative future states or circumstances that may occur (Part 1, Stage 3);
(iv) identify the alternatives or options available to the decision-maker (Part 1, Stage 4); and
(v) identify and calculate potential pay-offs associated with each combination of option and future state (Part 1, Stage 5).

In addition, the decision-maker will want to know whether his decision can be reversed. If a decision-maker can reverse a choice that led to an undesirable outcome with little effort or tangible cost, the set of potential outcomes associated with that choice will be viewed more positively than if the consequences of the decision were costly or impossible to reverse.

Only in exceptional cases will it be possible to quantify risk. In most climate adaptation cases, decision-makers will be missing one or more of the elements listed above, and therefore cannot identify the possible outcomes associated with the choice of options and the probabilities associated with each outcome. A particular challenge for climate adaptation decision-making is uncertainty concerning the extent of future changes in climate, together with changes in social, economic and other environmental states. Scenarios can be used to represent this uncertainty, where each scenario uniquely represents one possible, alternative state (see Section 3.6).

2.6.1 DECISION-MAKING UNDER UNCERTAINTY

see part 1 stage 5 table 13

Where the probability or risk associated with a decision is unknown or cannot be reliably estimated, the decision is being made under uncertainty. Psychologists have found empirical evidence for heuristics (learning by trial and error) and other cognitive mechanisms that humans routinely use to inform decisions under uncertainty, where decision-makers act in the absence of all the desired information (Tversky & Kahneman, 1974). A number of different approaches to decision-making under uncertainty are described below. The choice of approach is dependent on the decision-maker's attitude to the risk associated with the decision. Each approach can yield a different decision – the decision-maker must select the approach that best suits his needs.

The following approaches are described briefly in Box 2.2:

- High-risk strategy – approach based on determining and implementing the option that might provide the best outcome;
- Strategy to avoid under-adaptation – a precautionary (risk averse) approach with respect to climate impacts;
- Strategy to avoid over-adaptation – a precautionary (risk averse) approach with respect to the need to adapt to climate change and the costs of adaptation;
- Regret-based strategy – a precautionary (risk averse) approach with respect to the possible benefits associated with opportunities for adaptation that might be missed by implementing a particular option.

2.6.2 DECISION-MAKING UNDER RISK

see part 1 stage 5 table 13

Where the probability or risk (see Section 1.2) is known or can be estimated, the **maximum expected value** can be used to identify the best decision option. The expected value is calculated by multiplying each decision outcome (payoff value) for each future state by the probability of its occurrence. The best option would be that associated with the largest (or smallest) expected value. The largest expected value would be used when the problem is framed in terms of maximising a benefit, and the

Box 2.2: Illustration of approaches to decision-making under uncertainty, using a simple, hypothetical, climate adaptation example

Table 2.1 gives a **pay-off matrix** giving the anticipated pay-offs associated with each of four levels of investment in climate adaptation measures. Pay-off matrices are derived from the application of cost-benefit or other appraisal methods that provide an overall estimate or series of estimates of the relative performance of the various options being considered. The approaches require that a common currency can be defined in order to express the overall benefits and disbenefits in terms of a value for each pay-off. The currency may be monetary, or result from an agreed, non-monetary scoring system. Illustrative pay-offs are provided for each of three scenarios of future climate change (scenario 1: rapid change, scenario 2: some change, scenario 3: no change). The choice of scenarios could be based on the UKCIP climate scenarios (Hulme *et al*, 2002). The example assumes that the impact of climate change will be negative, and will increase with the level or rate of future climate change (see bottom row of Table 2.1). Increased levels of adaptation, off-setting the potential adverse effects of climate change, are assumed to require greater levels of action and/or investment (see last column of Table). The net pay-offs are the difference between the expected adaptation benefits and the expected cost of the adaptation measures. These are the values in each cell of the matrix in Table 2.1.

High-risk strategy: the Maximax approach. This approach is based on selecting the option associated with the best of all possible outcomes, that associated with the highest possible overall pay-off. Of the pay-offs given in Table 2.1, +20 is the highest value. This is therefore the Maximax strategy – in this case, a low level of investment in climate adaptation measures (Scenario 2, low investment, pay-off = +20). Maximax is, therefore, a high-risk strategy, since the probability associated with each scenario and the pay-off are unknown. It would be the approach adopted by an optimistic decision-maker, or one who would benefit from a successful outcome, but not suffer the consequences of unsuccessful outcomes.

Strategy to avoid under-adaptation: the Minimax approach. Where we wish to be precautionary with respect to the uncertain risk posed by future climate change (i.e. we believe climate change will be important, and believe that our decisions should be weighted towards adapting to climate change), our decision could be based on applying the Minimax approach. Minimax identifies the option that results in the **lowest** value of the **maximum** pay-off associated with each option. Referring to Table 2.1, the maximum pay-offs for each option are as follows:

- High investment = -10
- Medium investment = 0
- Low investment = +20
- No investment = 0

Table 2.1: Example of a performance matrix, giving the expected pay-offs associated with four levels of investment in climate adaptation measures, for three future scenarios of climate change. The pay-off values chosen for illustration assume that the impact of climate change will be negative and increase with the level or rate of future climate change (see bottom row). Increased levels of adaptation, providing potential protection against the adverse effects of climate change, are assumed to require greater levels of investment (see last column). Pay-off values associated with each decision under each scenario may derive from cost benefit analysis.

Investment in climate adaptation options (Measured as overall cost)	**Scenario 1** Large or rapid climate change forecast	**Scenario 2** Medium climate change forecast	**Scenario 3** No climate change
High	-10 **Minimax decision**	-50	-100
Medium	-20	0	-50 **Maximin decision**
Low	-50 **Maximin decision**	+20 **Maximax decision**	-10
No investment	-150	-75	0

Box 2.2: *continued*

The lowest value from these is (Scenario 1, high investment, -10). Therefore the Minimax strategy would comprise a high level of investment in climate adaptation measures.

Strategy to avoid over-adaptation: the Maximin approach. Where we wish to be precautionary with respect to the **investment** being made in climate adaptation measures, our decision could be based on the Maximin approach. Maximin identifies the option that results in the **highest** value of the **minimum** pay-offs under each potential option (i.e. the least bad 'worst possible' outcome). Referring to Table 2.1, the minimum or lowest pay-offs for each option are as follows:

- High investment = -100
- Medium investment = -50
- Low investment = -50
- No investment = -150

The highest value from these is -50. Hence the Maximin strategy is either a medium or low level of investment in adaptation measures, since the anticipated pay-offs are equal for the medium investment option under scenario 3 (no climate change) and the low investment strategy under scenario 1 (rapid climate change). Examining the pay-offs associated with each option under the other scenarios, the decision-maker may choose the low-investment option as providing better overall prospects than the medium investment option.

Note that, in this example, the application of each of the chosen approaches to decision-making leads to the selection of an option that delivers **some** level of adaptation to climate change, but a level that reflects the decision-maker's attitude to the uncertainty.

Regret or opportunity loss: no regret options and Minimax Regret approach. We feel **regret** if we discover that a decision made in the past produced less benefit than we expected, or if we have missed an opportunity. We may wish to identify options that could be associated with the minimum level of regret. This again is a risk averse or cautious decision strategy.

The level of regret associated with each option k can be defined for each possible future scenario j as:

Regret {k, j} = [Pay-off for the option with the highest pay-off under scenario j] minus [the pay-off for each other option k under scenario j].

This formula together with the pay-off values in Table 2.1 is used to calculate the regret values illustrated in Table 2.2.

No regret options. From Table 2.2 it can be seen that the value of regret associated with the best option under each scenario is always zero. When the highest pay-off (i.e. regret equals zero) is associated with the same option, irrespective of the future scenario, this is termed a **no regret decision** or option (see also Section 2.7.2 below). The choice of a no regret option is a formality, since it provides by definition the best outcome under any scenario. However, in Table 2.2, we do not have a no regret option.

Minimax regret approach. However, we can still select the option associated with the lowest level of regret across all possible future scenarios. This can be determined by applying the Minimax approach to the regret matrix in Table 2.2.

The Minimax regret option is identified by first determining the maximum value of regret associated with each option (see Table 2.2). These are:

- High investment = 100
- Medium investment = 50
- Low investment = 40
- No investment = 140

The minimum value of maximum regret is 40. Therefore the Minimax regret option is to have a low level of investment in adaptation measures.

Box 2.2: ***continued***

Table 2.2: Regret or opportunity loss matrix. Values for the regret matrix are derived from the pay-off matrix (Table 2.1). Given the values in Table 2.1, the Minimax regret decision is to adopt a low level of investment in adaptation measures.

Investment in climate adaptation options (Measured as overall cost)	**Scenario 1** Large or rapid climate change forecast	**Scenario 2** Medium climate change forecast	**Scenario 3** No climate change
High	-10-(-10) = 0	20-(-50) = 70	0-(-100) = 100
Medium	-10-(-20) = 10	20-0 = 20	0-(-50) = 50
Low	-10-(-50) = 40 **Minimax regret decision**	20-20 = 0	0-(-10) = 10
No investment	-10-(-150) = 140	20-(-75) = 95	0-0 = 0

smallest expected value used when framed in terms of minimising a disbenefit.

Since it may be impossible to determine with objectivity the probabilities associated with future scenarios, such as the emissions scenarios that underpin the UKCIP climate scenarios, so it can be difficult to apply the maximum expected value approach, except by using subjective estimates of scenario probability. Such approaches are not recommended, but continue to be the subject of research. However, such approaches can be useful in helping to understand the value of additional information in improving confidence in a decision.

see part 1 stage 5 table 13

2.6.3 DECISION-MAKING WITH MULTIPLE OBJECTIVES

Many decisions that involve consideration of the influence of climate or adaptation to climate are likely to be highly complex. They require an appraisal of the impacts of multiple factors, options and uncertainties on multiple objectives or a range of different criteria. In these circumstances techniques of **multi-criteria analysis (MCA)** can greatly aid decision-makers. The main role of MCA techniques is to deal with the difficulties that human decision-makers have in handling large amounts of diverse and complex information in a consistent way.

MCA complements techniques that rely primarily on criteria expressed in terms of monetary valuation. Monetary techniques such as **financial analysis**, cost effectiveness analysis, and cost-benefit analysis are widely recommended and used for the appraisal of options, and are the subject of a number of guides and manuals (see HM Treasury, 2003; Metroeconomica, 2003; also Boardman *et al*, 1996).

Multi-criteria analysis includes a range of related techniques such as multi-criteria decision analysis, multi-attribute utility theory, the analytic hierarchy process, and applications of **fuzzy set theory**. MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities.

All MCA approaches make the options and their contribution to the different criteria explicit, and all require the exercise of judgement. They differ, however, in how they combine the data. Formal MCA techniques usually rely on the provision of an explicit relative weighting system for the different criteria. For example multi-criteria decision analysis (MCDA) involves the assignment of scores to each option on each criterion, and then combining these scores by means of a system of weights to yield an overall ranking for each option. DTLR (2001a) provides non-technical descriptions of these techniques, potential areas of application, criteria for choosing between different techniques, and sets out the stages involved in carrying out multi-criteria analyses.

see part 1 stage 4

2.7 Climate change adaptation strategies and options

2.7.1 GENERIC ADAPTATION STRATEGIES

A climate adaptation strategy represents a combination of measures and options chosen to meet particular risk management criteria. Hence an integral part of an adaptation strategy is the decision-maker's attitude to climate and non-climate risks, their risk management priorities, and level of tolerable risk.

A variety of generic climate adaptation measures have been described as responses to the impacts of climate change (see Table 2.3, developed from Burton, 1996). These may be used individually, but more often a portfolio of measures may be the most appropriate option. Many of these essentially represent improved resource management (e.g. in agriculture, water resources and the coastal zone) and many have benefits in dealing with current climate variability as well as future risks. The generic benefits of adaptation include (Klein and Tol, 1997):

- increasing the robustness of infrastructure designs and long-term investments;
- increasing the flexibility of vulnerable managed systems – e.g. by allowing mid-term adjustments (including changes of activities and location) and reducing economic lifetimes (including increasing depreciation);
- enhancing the adaptability of vulnerable natural systems;
- reversing trends that increase vulnerability to climate;
- improving societal awareness and preparedness.

The success of adaptation options will depend on:

- the flexibility or effectiveness of the measures, including their ability to meet the decision-maker's criteria under a range of climate and non-climate scenarios;
- their potential to produce benefits that outweigh their costs;
- whether they are consistent with or complementary to, measures being undertaken by others in related sectors; and
- the ease with which they can be implemented.

The choice of measures will be determined by the particular objectives set by the decision-maker. The objective may be to reduce risk by attempting to manage either the hazard (e.g. increasing flood defences) or the exposure (e.g. reducing the population at risk) or both. The objective may be to minimise either the overall risk (e.g. to life or property) subject to a cost constraint, or the cost of implementing an agreed level of protection. The objective may be to maximise benefit per unit cost, in which case cost-benefit analysis might be an appropriate decision aid. In all cases, analyses need to consider uncertainties in the values of key variables for the performance of different measures, and acknowledge an acceptable level of residual risk.

One important class of risk management strategy is to reduce vulnerability by identifying other parties willing to accept the risk. Offsetting risk in this way frequently involves the payment of a risk premium, perhaps through the use of some form of insurance contract, to the party accepting the risk.

Diversification strategies aim to reduce an overall vulnerability to climate risk by developing business areas that are not sensitive to climate. In particular, diversified portfolios aim to avoid negative correlations between the performance of different business areas to climate. Diversification can also be used to reduce the risk associated with the choice of a particular adaptation measure: a variety or mixture of suitable measures may provide a more appropriate risk management strategy.

2.7.2 NO REGRET AND LOW REGRET OPTIONS

see part 1 section 2.2.1

see part 1 stage 4

A decision option that is assessed to be worthwhile now (in that it would yield immediate economic and environmental benefits which exceed its cost), and continues to be worthwhile irrespective of the nature of future climate, is an example of a **no regret option**. The process by which no regret options are identified is outlined in Box 2.2, Table 2.2. No regret options should be clearly identified and pursued, particularly if the net benefits increase under a plausible set of climate futures. However, barriers may exist to the implementation of no regret options, and careful analysis is needed to include the possible costs of overcoming such barriers.

Limited or **low regret** are terms sometimes used to describe decisions where the cost implications of the decision are very low while, bearing in mind the uncertainties in future climate change projections, the benefits under future climate change may potentially be large (DETR, 2000a).

Implementing **no regret** and **low regret** options may only go part of the way towards resolving the decision uncertainty concerning effective climate change adaptation. Adaptation options known to be costly, or with uncertain future benefits or relative performance advantages, will remain (e.g. the construction of reservoirs). Knowledge of potential benefits will be limited by our uncertain knowledge of future climate. Consequently, some important choices will remain regarding the uncertain impacts of possible climate change. These will require careful appraisal, and the decision strategies outlined in Section 2.6.1 can help in structuring the decision-maker's approach.

There may also be '**win-win**' situations – options which reduce the impacts of climate change and have other environmental, social or economic benefits. Win-win decisions may primarily be taken for reasons not directly motivated by the need to adapt to climate change, but may simultaneously deliver some longer-term adaptation benefits. It will be useful for decision-makers to identify the circumstances where such additional benefits may arise.

see part 1 stage 4

2.7.3. WHEN TO IMPLEMENT ADAPTATION MEASURES

Burton (1996) describes six reasons to adapt to climate change now:

(i) Climate change cannot be totally avoided.
(ii) Anticipatory and precautionary adaptation is more effective and less costly than forced, last minute, emergency adaptation or retrofitting.
(iii) Climate change may be more rapid and more pronounced than current estimates suggest, that is, there is a risk of under-adaptation. Unexpected events are also possible (i.e. there is potential for high levels of regret associated with climate change).
(iv) Immediate benefits can be gained from better adaptation to climate variability and extreme climatic events – i.e. no regret options may be available.
(v) Immediate benefits can be gained by removing policies and practices that result in maladaptation. An important aspect of adaptive management is to avoid the implementation of decisions that constrain or reduce the effectiveness of future options for adaptation ('climate adaptation constraining decisions' – see Section 2.3.1).
(vi) Climate change brings opportunities as well as threats. Future benefits can result from climate change, and these opportunities can be realised or increased by appropriate adaptation.

Where it is determined that climate adaptive management options may be needed, certain measures may 'buy time', delaying the point at which other options, particularly significant investment decisions, have to be made or implemented. For example, measures to manage water demand may help reduce the climatic risk to supply security, and allow decisions concerning supply-side adaptation measures to be postponed. The merits of such measures will depend on their relative costs and benefits. These include confidence that any immediate measures will achieve their objectives, and the extent to which any extra time bought will allow improved forecasts for the key climate change variables and better assessments of the direct and indirect impacts of climate change for the asset in question. In many cases, measures that buy time will also be no regret or low regret.

A decision to delay the implementation of adaptation measures can be an appropriate risk management strategy. Delay can help reduce the risk of over- and under-adaptation where uncertainties can be reduced and better information on future climate risk become available.

see part 1 stage 4

Table 2.3: Typology of possible adaptation strategies (modified from Burton, 1996)

Adaptation type	Description/examples of application identified from UKCIP studies
Share loss	Insurance type strategies Use other new financial products that off-lay the risk Diversify
Bear loss	Where losses cannot be avoided: Certain species of montane fauna and flora (e.g. some arctic alpine flora may disappear from the UK) Loss of coastal areas to sea level rise and/or increased rates of coastal erosion
Prevent the effects: structural and technological (usually dependent on further investment)	Hard engineering solutions and implementation of improved design standards: Increase reservoir capacity Increase transfers of water Implement water efficiency schemes Scale up programmes of coastal protection Upgrade waste water and storm-water systems Build resilient housing Modify transport infrastructure Install or adopt crop irrigation measures Create wildlife corridors
Prevent the effects: legislative, regulatory and institutional	Find new ways of planning that cut across individual sectors and areas of responsibility (integration) Change traditional land use planning practices, to give greater weight to new factors such as flood risk and maintaining water supply-demand balance and security of supply Adopt new methods of dealing with uncertainty Provide more resources for estuarine and coastal flood defence Revise guidance notes for planners Factor climate change into criteria for site designation for biodiversity protection Amend design standards (e.g. building regulations) and enforce compliance
Avoid or exploit changes in risk: change location or other avoidance strategy	Migration of people away from high-risk areas Grow new agricultural crops Change location of new housing, water intensive industry, tourism Improved forecasting systems to give advance warning of climate hazards and impacts Contingency and disaster plans
Research	Use research to: Look at long-term issues Provide better knowledge of relationship between past and present variations in climate and the performance of environmental, social and economic systems (e.g. fluvial and coastal hydrology, drought tolerance and distribution of flora and fauna, economic impacts on key industrial sectors and regional economies), i.e. reduce uncertainty about the consequences of climate for receptors and decision-makers Improve short-term climate forecasting and hazard characterisation Produce higher resolution spatial and temporal data on future climate variability from model-based climate scenarios Provide more information on the frequency and magnitude of extreme events under climate change Find better regional indicators of climate change Develop more risk-based integrated climate change impact assessments
Education, behavioural	Lengthen planning timeframes (need to consider not just the next two to five years, but 2020s, 2050s and beyond) Reduce uneven stakeholder awareness on climate change Increase public awareness to take individual action to deal with climate change (e.g. on health, home protection, flood awareness) and accept change to public policies (e.g. on coastal protection, landscape protection, biodiversity conservation)

However, it is recommended that any delay strategy should be supported by an assessment that the existing and future level of risk is tolerable. Such a decision should depend on clear climate thresholds (benchmarks), or other criteria, being established that specify the level of climate risk at which a decision to implement adaptation measures should be reconsidered. This should be subject to regular review. Delay strategies can include the use of a factor of safety, to account for the uncertainty in the assessment of future climate risk.

Where considerable lags are involved in the implementation of adaptation measures, for example the construction of major infrastructure, attention should be given to measures to reduce the implementation phase. This may allow decisions concerning adaptation measures with potentially large but currently uncertain benefits and/or significant costs or disbenefits to be delayed, but implemented more quickly should increasing knowledge dictate.

see part 1 stage 4

2.7.4 CLIMATE CHANGE ADAPTATION OPTIONS AND ADAPTIVE MANAGEMENT

Adaptive management is an important strategy for handling the uncertainties associated with climate change (Green *et al*, 2000). It is the sequential process of making the best possible decision at each decision point, based upon a risk assessment and analysis of the information available at the time. Adaptive management leaves scope for decisions to be reviewed, and further decisions implemented at a series of later dates, as improved information becomes available on the nature of the present day and future climate risk.

However, this sequential process does not mean that an incremental response to climate change (i.e. adapting by a small amount in response to gradual increases in climate change) is the best response. This may well be more costly overall than implementing a long-term strategy. Nevertheless, where incremental adaptation options can be implemented, these can provide the basis of a flexible approach to the uncertainty associated with climate change.

Reducing the time required to reach and implement a decision can itself be an important adaptive response, reducing the risk of hasty or over adaptation. It may be achieved through institutional, legislative, regulatory or planning reform, or by canvassing in advance support for actions that may be required when certain future, pre-defined and agreed conditions may be met. Delays to decision-making should be supported where the acquisition of improved knowledge, data and methods can help to reduce decision uncertainty. Where uncertainty cannot be reduced, delay should not be regarded as a substitute for making an appropriate decision concerning the management of the risks identified.

see part 1 stage 3

3. Key aspects of climate change risk assessment

3.1 Introduction

Climate change risk assessments form an important stage in the decision-making framework described in Part 1. This chapter describes the key issues to be considered when undertaking a risk assessment that may involve climate change as a significant factor. **In this report, the term 'climate change risk assessment' is used to refer to any impact assessment that includes consideration of the probability or uncertainty associated with the consequences of climate variability or climate change**. In most cases, probabilistic assessments of risk will not be possible. We emphasise that uncertainty is an integral component of a climate impact assessment, and therefore an approach based on risk assessment represents good practice.

Climate change risk assessments are used to determine how climate change could affect outcomes in a sector, and to evaluate the effectiveness of decisions regarding existing or new policies, programmes and projects. The risks associated with climate should be evaluated in comparison to other, non-climate-dependent risk factors. The objective of these assessments is to help decision-makers identify where adaptation to climate may be required, the adaptation options that could best accommodate the expected impacts of climate change, and the uncertainty associated with those impacts. Decisions made on this basis should lead to a better outcome in social, economic and environmental terms and can be considered as contributing to sustainable development.

3.2 Purpose and key components of a climate change risk assessment

The purpose of a climate change risk assessment is to assist the decision-maker in examining the possible consequences associated with an uncertain future climate.

It should help the decision-maker form an opinion of the:

(i) likely sensitivity (see Box 3.1) of a particular sector or area of responsibility or concern (the 'exposure unit') to potential changes in climate;

Box 3.1: Climate sensitivity, adaptive capacity and vulnerability

Sensitivity. The degree to which a system, receptor or exposure unit would be affected, either adversely or beneficially, by a particular change in climate or climate-related variable. (E.g. a change in agricultural crop yield in response to a change in the mean, range or variability of temperature.) Different systems may differ in their sensitivity to climate change, resulting in different levels of impact.

Adaptive capacity. The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, take advantage of opportunities, or cope with the consequences. Adaptive capacity can be an inherent property of the system, i.e. it can be a spontaneous or autonomous response. Alternatively, adaptive capacity may depend upon policy, planning and design decisions carried out in response to, or in anticipation of, changes in climatic conditions.

Vulnerability. Vulnerability defines the extent to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It depends not only on a system's sensitivity but also on its adaptive capacity.

(Based on IPCC, 2001a, p. 238).

(ii) relative sensitivity of the exposure unit to climate factors compared with other, non-climate factors;
(iii) the vulnerability of the exposure unit to climate change, including the identification of critical thresholds and coping ranges;
(iv) the capacity of the exposure unit to adapt autonomously to climate change (adaptive capacity, see Box 3.1);
(v) ease or difficulty of implementing adaptation measures; and
(vi) degree of success anticipated in mitigating any impact though an adaptive management strategy.

Consideration of adaptive capacity has largely been confined to national and regional assessments of climate change impacts, and the capacity of ecological systems to respond to climate change. Hertin *et al* (2003) consider some of the properties of businesses and management systems, that may increase the ability of organisations to adapt to climate change. These include flexible management processes that are able to integrate climate considerations into existing processes, technical capacity in climate change, risk assessment and risk management, and good relationships with key other decision-makers driving the adaptation issues.

A climate change risk assessment involves the following tasks, which are briefly discussed in this chapter:

see part 1 stages 2 & 3

(i) Identify and define the nature and extent of the exposure unit and receptors, agree assessment endpoints and assessment period (Part 1, Stage 2);
(ii) Identify and define a set of climate and non-climate variables to which the exposure unit may be sensitive (Part 1, Stage 3);
(iii) Use climate scenarios to help determine the climate change-dependent risk (Part 1, Stage 3), by:
  - forming a knowledge-based opinion on the extent and nature of the exposure unit's sensitivity and potential vulnerability to changes in climate variables over the assessment period;
  - determining the uncertainty of the exposure unit's sensitivity and vulnerability to climate change over the assessment period; and
  - modelling of climate influence.
(iv) Use non-climate scenarios to help determine the non-climate-dependent risk (Part 1, Stage 3), by:
  - identifying the vulnerability of the exposure unit to non-climatic changes over the period being considered; and
  - determining the uncertainty of the exposure unit's sensitivity and vulnerability to non-climate change factors over the assessment period.

The sensitivity of the exposure unit is assessed by reference to the component receptors.

3.3 Identification of exposure units, receptors and assessment endpoints

see part 1 stage 2

The exposure unit will in general be defined by the nature of the decision-maker's problem. The decision-maker will need to specify the location and geographical extent of the exposure unit and, in particular, the types of receptors at risk. These may be identified by preliminary risk assessment. Some of the receptors identified to be at risk may lie outside the decision-maker's initial boundaries for the exposure unit. The choice of receptors for more detailed risk assessment will need to be relevant to the decision-making criteria established by the decision-maker. The choice of receptor(s) and their relationship to decision criteria will need to be negotiated and agreed between the risk analyst and decision-maker.

Risk assessment endpoints represent an agreed frame of reference for the assessment of the significance of risk for the receptor(s). The choice of assessment endpoint is dependent on the exposure unit and receptor. Examples might include existing flood defence standards (e.g. a 1:200 year return period for coastal floods) or measures of water supply security.

Assessment endpoints are often referred to as 'thresholds' in the climate impact assessment literature (e.g. Jones, 2001; Smit & Pilifosova, 2001). Thresholds are often determined by reference to past records or experience of events or circumstances that define a tolerable limit to climate (see Yohe & Toth,

2000) (for example a particular dry summer or series of summers). A related concept is that of the **coping range** (Hewitt & Burton, 1971; Jones, 2001). This concept acknowledges that the majority of natural, social, and economic systems are adapted to and tolerate some (usually large) part of the range of climate variability normally experienced. Within this range of variability, conditions vary from beneficial to tolerable. However, limits beyond which intolerable levels of harm may be suffered often exist (see Figure 3.1) or can be defined as the basis of environmental management, climate adaptation or other policy.

Jones (2001) distinguishes two types of assessment endpoint or threshold. These can be either a fundamental property of the system or *biophysical threshold*, or a *behavioural* threshold. Biophysical thresholds '*mark a (bio)physical discontinuity on a spatial or temporal scale*'. Behavioural thresholds '*trigger a change in behaviour in the form of a social or economic outcome*'. Biophysical thresholds recognise environmental system thresholds that form a natural basis for defining risk. Examples include the water level or effective rainfall at which a river overtops its bank, or the wind speed that leads to the felling of large areas of forest.

In contrast behavioural thresholds represent points at which individuals, or society as a whole, would respond by a change in action, or points at which agreement can be reached that action would be required. Hence behavioural thresholds might be defined on the basis of a policy judgement, by decision-makers or other stakeholders, regarding the point at which climate change impacts can be regarded as intolerable. The choice of assessment endpoints in these cases will necessarily require value judgements as to the significance of the threshold (Swart & Vellinga, 1994; Parry *et al,* 1996), i.e such thresholds often require policy decisions regarding the level of risk that can be tolerated. This might also include consideration of practical and reasonable costs, through the use of criteria similar to those used to determine best practical environmental option (BPEO) and best available technology not entailing excessive cost (BATNEEC).

For these reasons, agreement upon practical assessment endpoints will usually need to be negotiated between the decision-maker, other stakeholders, and technical risk analysts. In certain circumstances, appropriate assessment endpoints might already be agreed, or can be easily adapted, based on existing practice. Where existing standards are being adapted, it will be important to determine whether the chosen standard is independent of climate change.

3.4 Identification of a set of climate variables for the climate change risk assessment

see part 1 stage 3

Some areas of climate risk assessment and risk management are well established, underpinned by empirical evidence and theoretical understanding of the current ('historical') influence of climate on the performance of systems. Many of these are areas that may require climate adaptation decisions as the climate changes.

However, as climate moves away from that which we have previous experienced (Hulme *et al*, 2002) there will be a need to take account of climate sensitivity in a wider range of decisions. In many of these areas there will be substantial uncertainty concerning the influence of climate. For climate-influenced decisions the choice of climate variables of potential relevance to the decision may be particularly unclear.

An important task of the risk assessment exercise, therefore, is to identify the particular climate variables that may be important in determining the nature of climatic risk. Hence the choice of climate variables should not be confined to those known in advance to be relevant to the exposure unit, or for which data are available, or for which climate forecasts or projections exist. Nor should it be confined to those variables where significant change is anticipated, given the current state of uncertain knowledge.

In all cases it will be necessary to select a suite of 'key' variables, based on:

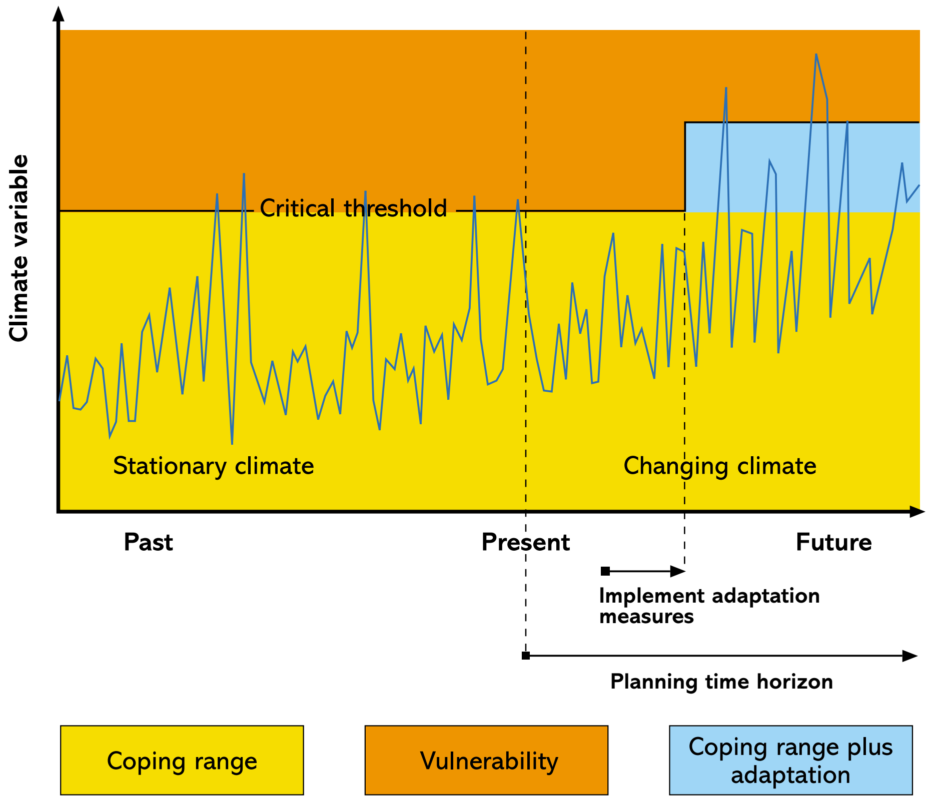

Figure 3.1: Schematic diagram showing the relationship between coping range, critical threshold, vulnerability, and a climate-dependent variable. The climate-dependent variable shows a significant degree of temporal variability. This variability is superimposed upon an upward trend, representing a change in climate that starts at the mid-point of the time series. The coping range represents the tolerable climate and the coping range boundaries may lie above and/or below the average value of the climate variable. Vulnerability to climate in this example is represented by an upper boundary, or critical threshold above which unacceptable impacts may be suffered. Adaptation aims to reduce vulnerability by increasing the critical threshold, countering the increased risk that the un-adapted threshold will be exceeded due to climate change. The figure indicates the relationship between the management of the critical threshold, and the time taken to plan and implement adaptation measures. The figure also indicates the time available to plan and implement adaptation measures from a given starting point.

(i) knowledge, information and data concerning the exposure unit's sensitivity or vulnerability to past climate variability;
(ii) knowledge of analogous situations;
(iii) conceptual models (including the use of process influence and dependency diagrams, event trees, etc); and
(iv) empirical, statistical and/or process-based models (including simulation models).

A classification of climate variables is provided in Table 3.1 to help undertake preliminary climate change risk assessments. The table classifies climate variables as primary, **synoptic**, compound and proxy. In order to properly define the climate variables it is important to consider their statistical characteristics. These are described in Table 3.2. These tables have been combined into one **checklist** for use in preliminary climate change risk assessments (see Part 1, Table 7). Further information on the type and statistical characteristics of climate variables is provided in Section 3.5.

see part 1 stage 3 table 7

Knowledge of the sensitivity of the exposure unit, receptors and associated assessment endpoints to past variability in particular climate variable(s) can be of enormous value in determining the likely future response under a changed climate. The influence that these variables may have either individually or in combination should be considered, taking account of any statistical or other evidence of past or future dependence between the variables.

see part 1 stage 3

3.5 Further information on climate variables and the description of variability

3.5.1 TYPES OF CLIMATE VARIABLE

Climate variables can be divided into those derived from:

- the past measurement of weather (which may include the use of **weather generator** output or other model-derived output based on observed data); and
- the forecasts derived from global and regional climate models.

These variables, together with other climate response variables described below, may be used as inputs to impact assessment models. For climate change risk assessment, it can be useful to group them as follows (as shown in Table 3.1):

- **Primary variables**. These include atmospheric carbon dioxide (CO_2) concentrations, temperature, wind speed and precipitation. Long time series of historical data may be available for these variables for particular locations. These are also the principal variables modelled and predicted by global and regional climate models. As such they inherit uncertainties in the greenhouse gas emissions used to drive the climate models (see Section 3.6.3 and 3.6.4), but are also subject to climate model-based uncertainties. Primary variables are available at resolutions that are governed by the particular climate model used to generate them. That is they are averaged over particular spatial dimensions and time intervals.[15]

- **Variables describing synoptic scale climate features**. These variables represent features measured over a larger spatial domain. Examples of **synoptic variables** include the frequency, intensity or description of the movement of thunder-storms, cyclonic conditions, frontal systems, cloud cover, storm tracks, atmospheric or oceanic circulation indices including marine currents, swell, etc. The ability of climate models to directly represent synoptic features is dependent on the spatial resolution of the model. In general the higher the spatial resolution of the climate model, the smaller is the spatial scale at which synoptic variables can be distinguished by the model.

- **Compound variables**. In many cases the key variable of interest may be a function of (or dependent upon) one or more primary or synoptic variables. Examples include humidity, evaporation, mist, fog and growing season.

- **Proxy or derived variables**. There are many potential derived or proxy climate variables. Their strong relevance or utility in helping undertake a particular assessment will govern their use. Derived or proxy variables will be recognised as having a close and possibly complex dependence on one or (more frequently) a number of other climate variables. Examples include wave climate, soil moisture, catchment run-off, and river discharge or flow velocity.

3.5.2 CHARACTERISTICS OF CLIMATE VARIABLES

see part 1 stage 3

Climate variables, in common with other variables that distinguish dynamic systems, may be described on the basis of particular characteristics or attributes. For decisions affected by climate change, the decision-maker will require information on a variety of characteristics of each climate variable for the risk assessment.

Climate variables are usually defined relative to their spatial and temporal domains. For example an average value may be defined:

- spatially – at a point in time (an instantaneous spatial average);
- temporally – over a defined time interval (a temporal average at a geographical point); or
- both spatially and temporally (e.g. a 30-year average value for a particular global climate model (**GCM**) or regional climate model (RCM) grid-box).

The following attributes are particularly relevant to the **characterisation** of climate (and other variables) used within climate risk assessments (see also Table 3.2):

[15] For the Hadley Centre global climate models (e.g. HadCM3), the resolution is of the order of 300km x 350km, while for the regional model, HadRM3, it is 50km x 50km (see Section 3.6.3).

see part 1 stage 3 table 7

Table 3.1: A classification of the more common climate variables for use in preliminary climate change risk assessments. This table is to be used in conjunction with the variable properties list in Table 3.2. Note that compound and proxy variables may be influenced by non-climate factors, but these are not highlighted in this table.

Variable	Assessments should consider these aspects of the climate variable
PRIMARY	
Carbon dioxide	Particularly atmospheric concentration. Concentrations in other media (water, land) generally equilibrate rapidly with respect to atmospheric concentration, but may be significantly influenced by local biogeochemical processes.
Sea level	Long-term mean sea level is determined (with a considerable lag) by long-term climate changes. Tidal range, and distribution of tidal maxima and minima will be influenced by a number of other climate variables (see sea level entry under 'compound variables', and wave climate entry under 'proxy variables').
Temperature	Assessments of temperature will often be media-specific. Includes occurrence of frosts and freezing conditions. Assessments may need to have regard to synoptic conditions (see below).
Precipitation	All forms of precipitation are included e.g. rain, snow, sleet, hail.
Wind	Includes both wind speed and compass direction (including change in direction: backing/ veering; see Table 3.2).
Cloud cover	Conversely, ground incident light intensity. May be represented by 'cloud' or 'sunshine-days'.
SYNOPTIC	*These are variables measured over a large spatial domain*
Weather types	Classification (such as that due to Lamb) of synoptic weather types, such as cyclonic, anticyclonic, or air flow directions like westerly or southerly may be useful.
Pressure	E.g. mean sea level pressure.
Pressure gradient	Includes established indices based on pressure, such as the North Atlantic Oscillation.
Storm tracks	Determined in part by the pressure patterns and the position of the high-level jet stream.
Ocean climatology	Sea surface temperatures, ocean circulation, currents and other large scale water movements, including the El Nino/La Nina.
Lightning	As determined by the synoptic situation likely to bring about lightning incidence.
COMPOUND	*Compound variables are dependent on combinations of several of the above primary (and other) variables*
Humidity	Dependent on temperature, pressure, moisture content of the air.
Evapo-transpiration	Dependent on temperature, radiation (cloud cover), wind speed, humidity.
Mist, Fog	Dependent on synoptic conditions, temperature, moisture content of the air, wind.
Sea level	Dependent on wind speed and direction and synoptic variables including pressure and antecedent weather types. (See also sea level entry under 'primary variables' and wave climate entry under 'proxy variables'.)
Growing season	Dependent on temperature (perhaps expressed as degree-days), precipitation, cloud cover/ sunshine.
PROXY CLIMATE VARIABLES	*There are many potential proxy climate variables. Proxy variables will be recognised as having a close and possibly complex dependence on one or (more frequently) a number of other climate variables.*
Soil moisture	Dependent on temperature, precipitation, evapotranspiration.
Water run-off	Seasonal distribution of flows dependent on antecedent rainfall, evapotranspiration, as well as catchment characteristics (geology, soils, land-use).
Wave climate	Dependent on storm surge, water level, local and synoptic scale wind speed, direction and duration. (See also sea level entries under 'primary variables' and 'compound variables'.)

Table 3.2: A description of the statistical characteristics associated with the definition of climate variables for use in climate change risk assessments.
Relevant climate variables for risk screening can be identified from Table 3.1. The potential contribution to the overall risk posed to receptors associated with each characteristic of each variable should be examined. This will help determine the nature of risk posed by climate, and the relative importance of different climate variables. Possible changes in these characteristics in the future can facilitate understanding of the sensitivity of the system or particular receptors to possible changes in climate. Under each characteristic there are a number of options (combinations of characteristics) that need to be considered.

Climate variable	Characteristics of variable				Sensitivity of decision criteria/system to changes in variable	Confidence in the assessment of link between variable and decision criteria/system
	Magnitude and direction	Statistical basis of change	Averaging or sampling period	Joint probability events and variables		
Notes on the characteristics of the variables being considered. See also additional guidance in Section 3.5.2.	Changes in magnitude (M) (increases/ decreases) and direction (D) (orientation) are important in determining the changes in the associated risk. Under climate change, either the magnitude or the direction of a variable may change.	The assessment will have regard to the statistical basis by which the variables are described. These will be determined in part by the sampling period (see next column). Often the mean or other measure of the average value over a particular period, or a cumulative (time-integrated and/or spatially-integrated) value, will be of interest.	The risk assessor will need to consider the temporal period and spatial scale over which the values of particular variables are determined or described. The following periods are often a relevant basis of assessment.	In certain cases it is the sequence of particular values of variables that is important. In some cases, changes in the joint probabilities of combinations of variables (wind speed, direction and rainfall, etc) will be important.	This column asks the respondent to qualitatively assess the sensitivty of their decision criteria and exposure unit to changes in the climate variable. Would a small change (increase or decrease) in (e.g.) mean summer temperature have no effect, a small, medium or large effect on the receptors of interest? The assessment of sensitivity may be relative, i.e. in comparison to other climate or non-climate variables that may affect the system or decision criteria.	This column asks the respondent to note their confidence (or lack of certainty) in their assess-ment of the linkage between each climate variable and their decision criteria or system of concern. IT IS NOT A JUDGEMENT ABOUT THE CONFIDENCE ASSOCIATED WITH FORECASTS OF FUTURE CHANGES IN THE CLIMATE VARIABLE BEING CONSIDERED.
Primary, synoptic, compound or proxy climate variables to be selected from Table 3.1. Other variables dependent on climate may also be identified as required by the nature of any specific assessment.	• No change (M&D) • Change (M&D) • Decrease (M only) • Increase (M only) • Rate of change (M&D)	• Average value • Cumulative (or time integrated) value • Variability in values • Frequency of values, including percentiles, extreme values, maxima and minima	• 'Instantaneous' values • Hourly or sub-hourly • 'Day' or 'Night' • Daily • Monthly • Seasonal • Annual • Decdal or longer	• Not consecutive • Consecutive occurrences • Coincident or joint occurrence with second (or more) climate variables	• Not sensitive • Low sensitivity • Medium sensitivity • High sensitivity	• Known, established • Reliable • Extremely doubtful

see part 1 stage 3 table 7

- **Magnitude and direction**. Most climate variables have magnitude, but some have both direction and magnitude. For example, the variable 'wind' has both magnitude and direction, but wind speed only has magnitude, whereas wind direction has no magnitude. It is changes in magnitude (increases or decreases) and direction (in the sense of orientation) that are important in determining the changes in the nature of the climate hazard and associated risk. Under climate change, either the magnitude and/or direction of a variable may change.

- **Statistical characteristics**. Risk assessors need to have particular regard to the statistical basis by which variables are described. These will be determined in part by the sampling and averaging periods (see below). Often the mean or average, mode or median of values of a variable, determined over a particular period, will be of interest. In certain circumstances the cumulative (time-integrated and/or spatially-integrated) value will be of interest.[16] In other cases the frequency or probability of particular values or events, or the probability that values of variables will fall between particular bounds, or exceed a particular (often extreme) value, will be of concern. Variables may also be defined in terms of the absolute maximum or minimum values that may be recorded, usually over a particular interval of time, or over a particular geographical area. Such variables are described as censored. Examples include daily minimum or maximum temperature. It may be that average or other **percentile** values (e.g. the monthly average value of minimum daily temperature) are required. Measures of variability are also important (e.g. changes in the year-to-year annual rainfall totals). Relevant statistics may include measures of variance, standard deviation or standard error, or more complete descriptions in terms of probability distributions or functions.

- **Averaging and sampling periods and scales**. The risk assessor will need to consider the temporal period and spatial scale over which the values of particular variables are determined or described. For example, a rainfall variable defined as annual-average six-hour-duration rainfall would represent data (actual or forecast) on total cumulative rainfall recorded over a six-hour sampling period, averaged over one year. The variable should also be defined in terms of spatial area or location(s) to which it applies.

  The averaging and sampling periods need to be chosen so that they are relevant to the dynamics of the system being assessed. In many cases the periods will be determined by the availability of data on the system and its driving climate, non-climate and response variables. In part the choice of averaging period may be constrained by past observations or available climate data. The following periods are often a relevant basis of assessment: 'instantaneous', hourly, night or daytime, daily, monthly, seasonal, annual, decadal or longer.

- **Joint probability events, association and co-variation between climate and non-climate variables**. An association between particular values of variables can be important in determining impacts. For example, two or more consecutive high or low rainfall periods (e.g. years, or summers, or days) may represent an increased level of risk. Therefore changes in the probability of occurrence of such events needs to be considered. The association between variables may include the **joint probability** of occurrence of sequences (e.g. dry winters) or combinations of particular variables (wind speed, direction and rainfall, etc). The climate variables or events may be either independent, correlated or have a degree of dependence, and these properties need to be considered if the risk is to be well characterised.

  In many cases the climate variable may depend upon other, non-climate variables. For example, annual average daily temperature may be defined in terms of altitude (e.g. sea level temperature). These dependencies are an important part of the definition of the variable, and will condition the use of such variables in impact assessment.

[16] For example, degree-days or total winter rainfall may provide useful measures of climate for certain types of impact assessment.

Whatever the basis on which the variable is defined, the risk assessment will need to distinguish data uncertainty from natural variability (see Section 1.7.1 and 1.7.2). All variables are measured, estimated or predicted with limited accuracy and precision, and possibly with bias, i.e. there will be uncertainty as to the value of the variable. The risk assessor will need to determine or form a judgement on whether this uncertainty prejudices the use of information on the variable. The risk assessor will, in general, be interested in characterising the variability in values of climate variables. Techniques exist that allow uncertainty to be described or estimated. These apply to both data uncertainty and variability. The most familiar techniques, such as estimating the **confidence intervals** associated with variable or model parameter value estimates, make use of a wide variety of statistical techniques, based on probability theory. In situations where data are sparse, techniques derived from **fuzzy arithmetic** and **interval analysis** may be of value (see Appendix 3). Whatever techniques are used, the assessor will be required to make certain assumptions. The validity of these assumptions, and their importance for the assessment, should be considered explicitly.

3.5.3 IMPLICATIONS OF CLIMATE VARIABILITY FOR SHORT-TERM DECISION-MAKING

Climate is inherently variable and this variability is a form of uncertainty (see Section 1.7.1). Climate variability has a number of important implications for risk assessment used to support climate-sensitive decisions with relatively short payback periods.

Natural climate variability acts to 'swamp' the signal due to climate change, particularly at sub-regional geographical scales and over relatively short time periods (at least up to two decades – see Section 3.6). Many of the more important impacts of climate are associated with climate variability, and in many cases the decision-maker will be concerned with managing the consequences of low frequency, high consequence events. Examples include sub-daily extreme rainfall leading to increased flood risk, or storm-force winds, or longer-term extremes such as low seasonal or annual rainfall. Such events are usefully described by the return period or probability of exceedance of an event of a particular magnitude (e.g. 1 in 100 year rainfall event).

The extent of variability, and hence the probability or return period of an event of a particular magnitude, can be estimated from monitoring records, especially lengthy time series for particular variables (see Hulme *et al* 2002, Section 2.6). Variability can also be determined from statistical models, or can be derived from individual **ensemble members** from GCMs or RCMs. However, any assumption that future probabilities of climate extremes will be similar to that in the past should be regarded with caution. As climate changes, historical observations will either underestimate (if the values of climate variables are generally increasing in magnitude) or overestimate (if they are decreasing) the present-day probability of observing a particular value of a variable. This source of uncertainty (a bias) increases with the rate of change in underlying climate, and the length of time over which the observed weather or climate series is extrapolated.

For longer and higher-quality[17] time-series (e.g. temperature, sea level), statistical techniques of **trend analysis** may help distinguish underlying changes in climate variables (see Hulme *et al*, 2002, Chapter 2). Trend analysis may be particularly useful for climate variables that can be averaged over longer temporal and spatial scales. It can be used to extrapolate or adjust estimates of the present-day or near-term future climate, including the probability of events of a particular magnitude. Assumptions regarding the basis of the extrapolation should be clearly identified, together with statistical estimates of confidence in the extrapolated values.

For many climate-sensitive decisions, however, trends in climate will not be distinguishable within an available data series, even when there is an expectation that climate may change. The use of such data to estimate present-day or future climate will therefore involve a trade-off between the value gained in providing improved estimates of climate (averages, variance, ranges, correlations), and errors due to the uncertainty concerning the underlying change in climate. For advanced applications,

[17] Where quality refers to the precision, accuracy, frequency and geographical density of observations.

Bayesian methods can be used to update prior estimates of climate trends, based on new knowledge and data, and to estimate the associated uncertainty (see Morgan & Henrion, 1990).

For decisions with time horizons up to 20 years, **incremental scenarios** (see Section 3.6.5) can be used to represent 'near-future' and/or 'present-day' climate, and as a basis for examining uncertainty in climate. Incremental scenarios can be based on information and data of recent past climate variability (baseline meteorology). Incremental scenarios acknowledge that historical data may represent a biased estimate of present-day or near-future climate under conditions of a changing climate and will need to make explicit assumptions regarding likely changes in climate. Assumptions might include changes in the average, variance and covariance of important climate variables over the period of the assessment.

Longer-term scenarios, constructed from the output of global climate models, such as the UKCIP02 climate scenarios (Hulme *et al*, 2002), expert judgement exercises, or climate analogues should inform assumptions regarding incremental scenarios where possible. These are considered further in Sections 3.6.3 and 3.6.4.

see part 1 stage 3

3.6 Climate and non-climate scenarios: tools for climate change risk assessment and decision-making

see part 1 stage 5 table 13

3.6.1 INTRODUCTION

Scenarios are a key tool for climate change risk assessment. They are used to identify various sources and types of uncertainty associated with our knowledge of the future, and as a tool to help analyse the consequences of this uncertainty. For decisions involving climate change, the following types of scenario are useful:

- Scenarios that represent uncertainty in **future climate**. For the UK climate, this includes the UKCIP02 scenarios (Hulme *et al*, 2002), which have superseded the UKCIP98 scenarios (Hulme & Jenkins, 1998). Other climate scenario techniques are discussed in Sections 3.6.5 and 3.6.6.
- Scenarios that describe uncertainty in the **future socio-economic environment** (see Section 3.7). Such scenarios provide a context allowing climate change risk to be judged against other sources of risk. Scenarios relevant to a particular sector or problem are available from a variety of sources, or can be developed. For the nearer-term future, scenarios may be developed based on the uncertainty revealed within quantitative and qualitative analyses of past trends. For the longer term, contextual descriptions of the future, such as those produced for use in the UKCIP (UKCIP, 2000), can be useful.

It may also be appropriate to develop other types of scenario for some studies, for example, land-use change scenarios, environmental scenarios or even impacts scenarios, so that climate risks can be analysed in the context of non-climate risks, and suitable adaptation strategies devised.

3.6.2 CHOOSING AND USING SUITABLE CLIMATE SCENARIOS IN RISK ASSESSMENTS AND DECISION-MAKING

There are a number of sources of information for climate scenarios:

- the output of climate models;
- simple incremental scenarios; and
- climate analogues.

The type and time-scale for the climate change risk assessment will determine the most appropriate scenarios to use.

see part 1 stage 3 tier 1

For initial assessments of vulnerability or sensitivity assessments (as in Part 1, Stage 3, Tier 1), **incremental scenarios** (see Section 3.6.5) can provide information across a wide range of climate variations.

For decision time horizons of less than 20 years, scenarios will be required representing 'near-future' and possibly 'present-day' climates. These are discussed in Section 3.5.3. However, for longer-term decisions (time-scales exceeding 20 years), such as decisions with long-lasting consequences and concerning long-lived assets, a range of climate scenarios developed from global climate model output should be used (see Section 3.6.3 and 3.6.4). These should include, but should not be limited to, the UKCIP02 climate change scenarios (Hulme *et al*, 2002).

Where the UKCIP02 scenarios are used, it is recommended that all four component scenarios are used. This will:

- assist in the identification of critical thresholds in the response of the exposure unit to climate change;
- make the analysis more robust to the publication of new scenarios, which may be subject to significant revision; and
- allow decisions to be taken which are robust to the uncertainties in future climate.

If decision-makers do not have the time or resources to explore all four UKCIP02 or other scenarios, an alternative would be to use the scenarios associated with the highest and lowest emission scenarios.

However, for applications with major policy recommendations or major investment decisions, it is recommended that decision-makers should make use of the full range of UKCIP02 scenarios, as well as scenarios from other global climate models (see Hulme *et al*, 2002, Section 3.5, Table 5 and Appendix 1).

Uncertainty relating to the natural variability of the climate system can be captured through the use of several individual ensemble members. (Ensemble runs are available for the UKCIP02 scenarios.)

If data are not available for the climate variable of interest, scenario approaches based on present-day **analogues** of future climate (see Section 3.6.6) may be of value (Mearns *et al*, 2001). Care must be taken to identify the assumptions associated with the analogue chosen, and to identify ways in which it may differ from expected future scenarios for the site of interest. This approach is limited in that future changes in variability may not be captured.

More information on choosing appropriate scenarios is available in the IPCC Third Assessment Report, Working Group II (IPCC, 2001b) and the UKCIP02 scenarios Scientific Report (Hulme *et al*, 2002).

The types of scenarios outlined above are discussed further in the following sections.

3.6.3 SCENARIOS FROM CLIMATE MODEL OUTPUT

see part 1 section 2.2.2

A key framework for the assessment of risks associated with future UK climate is the set of four UKCIP02 climate change scenarios (Hulme *et al*, 2002). These scenarios provide information on possible future changes in UK climate, and climate variability, for 30-year periods centred on the 2020s, 2050s, and 2080s, and comparative data for the baseline period 1961-90. The data provided are monthly average values for climate variables, at a spatial resolution of 50 x 50km. The UKCIP02 scenarios also provide information on possible changes to extreme events, including changes in the daily statistics for some key climate variables.

The UKCIP02 scenarios have the following important properties, which are discussed further in Section 3.6.4:

(i) Some of the many uncertainties regarding our knowledge of future climate are summarised within the four scenarios. Each scenario is based on one of four different, explicit assumptions about future emissions (emissions scenario) (see Hulme *et al*, 2002, Section 3.1 and Figure 20). Hence they reflect (at least in part) the uncertainty about future emissions.

(ii) No one scenario represents a more likely future than another, and there are no 'best guess' scenarios. Each scenario is contingent on the unknown probability associated with the assumptions that underpin it. Therefore one cannot say that any one scenario is more likely or less likely because we cannot attach probabilities to the underlying emissions scenario. Further research may provide subjective estimates of the probability associated with a scenario, or delineated by two or more scenarios. Such information could be used to assess the risk associated with the scenarios.

(iii) Since only the Hadley Centre climate models are used to generate the UKCIP02 scenarios, the uncertainty associated with our incomplete understanding of the climate system, and how it should be represented in models, is not reflected in the UKCIP02 scenarios. This includes differences between climate models in their sensitivity to accumulated emissions (see Section 3.6.4 below, also Hulme *et al*, 2002, Box D).

(iv) The four scenarios do not represent bounds on the future expected climate. As knowledge of the climate increases, new climate scenarios will become available, which may show different climate changes (for instance, the UKCIP98 scenarios have been updated by the UKCIP02 scenarios and these show a slightly higher rate of warming for the UK). This demonstrates the importance of understanding the sensitivity of the decisions to present-day climate variability and to changes in climate. It also stresses the need for flexible adaptation strategies for those particularly sensitive exposure units, as recommended here.

(v) The uncertainty (or lack of confidence) associated with certain climate variables (e.g. precipitation) is greater than others (e.g. temperature).

(vi) The uncertainty associated with modelling variability in climate is greater than that associated with average values for the same variables. Hence information on future extremes (e.g. local daily precipitation) is more uncertain than information on future averages (e.g. global annual mean temperature).

(vii) The confidence in modelling average values increases with the length of time over which they are averaged. Hence there is more confidence in 30-year average values than decadal averages, and more confidence in yearly average values than seasonal values. However, averages that are superimposed on trends in values need to be interpreted with care.

3.6.4 UNCERTAINTY IN CLIMATE SCENARIOS FROM GCMS

Uncertainty in climate change scenarios based on the output of GCMs derives from a number of sources. They include:

(i) **Future emissions scenarios**: The starting point for predicting future climate change are scenarios of future emissions of the greenhouse gases and other pollutants that affect climate (e.g. sulphur dioxide). Such estimation relies on combining data on past emissions (with associated data uncertainty) with predictions of how emissions may change with future changes in technology, politics, global economic development, etc (which will be characterised by real world uncertainty (see Section 1.7.1)). All these factors, and hence future emissions of greenhouse gases, are uncertain. Hence, future greenhouse gas emissions are essentially unknowable, except within extreme bounds, and therefore present an area of uncertainty that cannot be removed. The most comprehensive attempt so far to characterise emissions scenarios is the IPCC Special Report on Emissions Scenarios (Nakicenovic *et al*, 2000). It should be noted that the consequence for climate prediction of uncertainty in emissions is much less for the near future climate (2020s) than for the distant future (2080s) (see Table 7 in Hulme *et al*, 2002). Climate pathways for the four emissions scenarios do not start to diverge until just before mid-century (see Chapter 4 in Hulme *et al*, 2002 and Figure 3.2 in this report). Near-future climate is dominated by historic emissions of greenhouse gases, and natural variability in climate (see Section 7.7 in Hulme *et al*, 2002). The predicted rate of change in climate is particularly important since it affects the time available for adapting to the changes.

(ii) **Global climate models (GCMs) and regional climate models (RCMs)**: Scenarios of climate change are simply the predictions from global or regional climate models. GCMs represent the processes that govern global climate. The prediction from these climate models is uncertain, due to imperfect representation of the processes in the climate system, e.g. clouds, ocean circulation, soils, vegetation and the interactions between them. Because different climate models represent these processes in different ways, their predictions (for the same emissions scenarios) will be different. The consequences of this uncertainty is clearly illustrated in Hulme *et al* (2002), by showing changes in summer and winter temperature and precipitation from eight different GCMs. The Hadley Centre is currently developing ways of quantifying uncertainties in their climate models. These involve running many versions of the model, with slightly different model parameters and starting conditions (a form of sensitivity or uncertainty analysis). It is hoped that this method will provide information on climate changes for a given location and time as probabilities or probability density functions, rather than as discrete values. This information would represent a significant advance for quantitative climate change risk assessments, although it does not overcome the difficulty of not having probabilities for the emissions scenarios that underpin longer-term model forecasts of climate. The output of these models will always be contingent on the unknowable probability associated with future emissions.[18] The IPCC (Albritton *et al*, 2001) and Hulme *et al* (2002) describe many of the uncertainties in climate modelling. Improving GCMs will remain a significant long-term scientific challenge.

In order to provide climate change information at a scale (50km) smaller than GCMs give (typically 300km), UKCIP02 used the Hadley Centre RCM. RCMs take account of geography and topography (e.g. mountains and oceans), and small-scale weather phenomena, and are therefore better at representing local variations in climate. As with GCMs, RCMs are also subject to ‘science uncertainty’ and also (as with any regionalisation technique) they inherit errors from the GCMs that drive them.

(iii) **Appropriate information on climate**: Global and regional climate models provide information on future climate for a restricted range of climate variables and at a spatial resolution determined by the climate model. The coarse scale of the modelling, particularly in global climate models, does not adequately represent local variations in climate. Even RCMs often do not generate the detail required for climate impact assessments and models, and further downscaling may be required, e.g. using statistical techniques (see Section 3.6.7).

Figure 3.2 shows the uncertainty in predictions of global temperature rise from various global climate models for the present day until 2100. The range of temperature rises demonstrates the uncertainties in future emissions (B1 (lowest emissions) to A1FI (highest emissions)) as well as the differences in the GCMs.

There is a broad consensus amongst climate modellers that, for a given emissions scenario, changes in atmospheric carbon dioxide concentrations, global mean sea level, and to a lesser degree annual average temperature can be modelled with some confidence. At the other end of the spectrum, information about climate extremes – such as changes in maximum daily wind speed – has a very low confidence attached to it. There is more confidence concerning the direction of change (i.e. whether a variable will increase or decrease in value) than in the magnitude of change, and more confidence concerning longer-term and larger spatial-average changes in climate. These different levels of confidence reflect the experts’ view of the associated uncertainties – the higher the confidence, the lower the uncertainty. Examples of the confidence in some of the main climate changes are provided in Table 3.3 and are also discussed in the UKCIP02 Scientific Report (Hulme *et al*, 2002).

3.6.5 INCREMENTAL CLIMATE SCENARIOS AND UNCERTAINTY ANALYSIS

The consequences of uncertainty concerning present or future values of climate variables or climate-dependent parameters can be investigated by the use of sensitivity-type analyses (Saltelli *et al*, 2001, provide a formal description of sensitivity analysis techniques). Climate variables or parameters may be changed by small but realistic increments to inform the decision-maker about how other variables, relevant to the assessment endpoint or exposure unit, might respond to certain climate stimuli. Often these

[18] Although experts may form opinions as to the range and temporal pattern of likely future emissions, and attach subjective probabilities to particular ranges of emissions scenarios.

approaches take as a baseline a 'no change' scenario, i.e. an assumption that future climate will be similar to that experienced in the past, for which relevant and detailed data might be available. These approaches are useful for gauging likely impacts and determining the level of detail required for the risk assessment to adequately inform the decision. They can also provide a relatively simple framework for exploring the importance of joint changes in more than one climate variable, and for investigating the potential vulnerability to changes in extreme events.

These methods can also allow an examination of the sensitivity of the exposure unit to changes in climate statistics that are not readily available from other sources. Incremental scenarios can be developed for changes in extremes, inter-annual, daily and diurnal variability. These may be informed, or even bounded, by information on changes derived from the output of GCMs.

3.6.6 CLIMATE ANALOGUE-BASED SCENARIOS

If future values for climate variables for the system of interest are not available, scenario approaches based on present-day **analogues** of future climate may be of value (Mearns *et al*, 2001). Analogue scenarios can be based on historical, instrumental climate series. Reconstructed palaeoclimatic series can provide useful analogues, particularly for ecological climate impact studies. Climate analogues may be spatial (e.g. anticipating a northward shift in climatic zones) or temporal (e.g. anticipating a series of benchmark hot summers, such as 1976). However, as in all scenario approaches, care must be taken to identify the many important assumptions associated with the choice of particular analogues, and to identify any ways in which the chosen analogue may differ from expected future scenarios. In addition, the amount of information that this

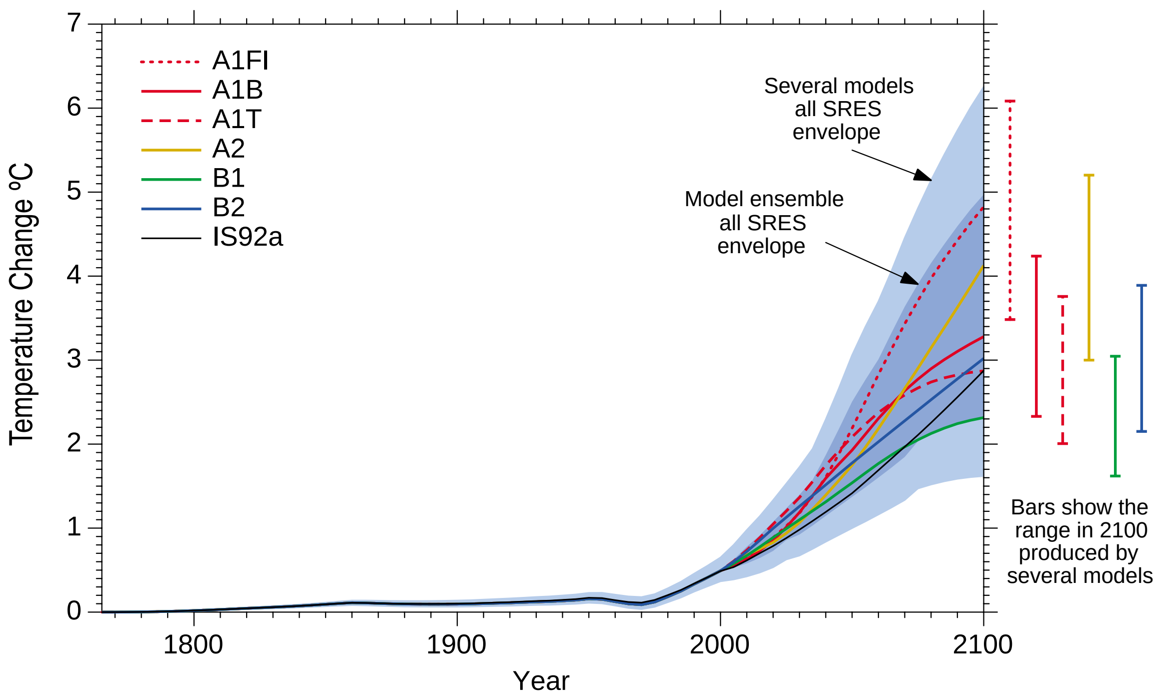

Figure 3.2: Estimated historical and range of predicted future global average temperature rises for various emission scenarios (A1FI – B1) and various global climate models (Cubasch *et al*, 2001, p.554). Note that up to the mid-21st century, 'science' uncertainty (i.e. the range of temperature change produced by the different climate models) heavily dominates over emissions uncertainty, and they are roughly equal by the end of the century. (However, at a regional level, science uncertainty dominates even by the end of the century.)

approach can yield may be limited – for example, future changes in variability may not be captured. Ideally, a suitable set of analogues (rather than a single analogue) should be considered, to represent some of the inherent uncertainty.

3.6.7 DOWNSCALING TECHNIQUES

see part 1 stage 3 tiers 2 & 3

Quantitative risk assessments may make use of downscaling techniques, **weather generators** and **climate typing**. These techniques allow climate scenarios to be developed (downscaled) at more detailed time and space resolutions than those available from GCMs. Wilby *et al* (2002) discuss the various types of downscaling that can be performed:

(i) **Dynamical downscaling**: This involves nesting higher resolution, regional models within GCMs, such as was done to produce the UKCIP02 scenarios. The technique is computationally demanding, restricting the geographic domain that can reasonably be modelled and the time period over which the simulation can be run.

(ii) **Weather generators**: These tools simultaneously model the occurrence of rainfall, temperature, radiation, etc, and can be used to generate climate change scenarios by running the weather generator models with altered parameter sets, scaled according to the corresponding variable in the GCM, where this is available. These models perform well in representing observed weather, but often the information they need to generate future climate data is not produced by GCMs, so they tend to produce output that is useful within a incremental scenario or sensitivity-type study.

(iii) **Weather typing**: This technique involves developing relationships between groups of local weather variables and large-scale atmospheric circulation patterns (Bardossy and Plate, 1992). Future climate scenarios are then produced by using future atmospheric circulation indices, derived from GCMs. These schemes assume that the relationship between the local variables and the circulation patterns are stationary.

Table 3.3: Estimates of confidence in projected changes in extreme weather and climate events (IPCC, 2001a, p.15)

Phenomenon	Confidence in projected changes (during the 21st century)[1]
Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Reduced diurnal[2] temperature range over most land areas	Very likely
Increase of heat index[3] over land areas	Very likely, over most areas
More intense precipitation events	Very likely, over many areas
Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors. (Lack of consistent projections in other areas).
Increase in tropical cyclone peak wind intensities[4]	Likely, over some areas
Increase in tropical cyclone mean and peak precipitation intensities[4]	Likely, over some areas

[1]This assessment is based on expert judgement, and the following definitions apply:
"Very likely" – 90-99% confidence. "Likely" – 66-90% chance
[2]Diurnal temperature range is the range experienced within a 24-hour period
[3]Heat index: a combination of temperature and humidity that measures effects on human comfort
[4]Changes in tropical cyclone location and frequency are uncertain

(iv) **Statistical/regression-based downscaling**: This is based on empirical relationships between local-scale variables and their large-scale predictors. These relationships can be based on a range of mathematical transfer functions, predictor variables and statistical fitting routines (Wilby *et al*, 2002). Applying these modelled relationships using information on future changes in the large-scale predictors from GCMs produces the required climate scenarios. Again, this technique assumes that these statistical relationships will not change under a future climate. This important assumption should be carefully examined for each case. For example, it has been shown to be misleading in the case of precipitation (Murphy, 2000), where present-day relationships are dominated by changes in wind direction, but future precipitation will be more dependent on changes in moisture content. However, statistical approaches do have advantages: they take advantage of observed relationships; are relatively easy and quick to apply; they can produce site-specific, daily time series for future time periods; and uncertainty estimates can be obtained for the outputs.

3.7 Non-climate scenarios and scenario planning

see part 1 stage 3

see part 1 stage 5 table 13

Climate and climate change is only one source of risk and uncertainty influencing the decision-maker, even where climate adaptation is the focus of the decision. Climate change may represent an important additional stress but many exposure units are already influenced by other natural (e.g. relative sea level rise) or anthropogenic environmental (e.g. over-abstraction of groundwater) change, or economic conditions, and decision-making and risk management must consider all these important risk factors.

These societal and economic pressures may have a greater or lesser influence on a decision than future climate change. Assessing the relative importance of the risks posed by climate and non-climate factors will be key to achieving sound decisions. Uncertainties about future trends (rate and magnitude) in the development of society, technological innovation, etc, may be less, equal to or greater than the uncertainties associated with a changing climate. This non-climate context to the assessment of vulnerability becomes increasingly uncertain when the timeframe of assessment extends beyond decades. Scenario planning techniques provide a means by which these uncertainties and their consequences can be explored by decision-makers (see Schoemaker, 1991).

The four UKCIP socio-economic scenarios (UKCIP, 2000) provide contextual socio-economic descriptions and other information for use in the assessment of climate change futures. In a balanced assessment, these scenarios can help to structure analyses of non-climate sources of future uncertainty. They can also inform the choice of values for non-climate variables that are important components of risk assessments. (An example of their use is provided in Environment Agency, 2001b).

3.8 Modelling climate influence

When addressing climate risk and impact problems, knowledge of the system and its relationship to climate is clearly important. This knowledge is especially valuable when the processes linking climate variables to the response of the exposure system are understood, even where significant uncertainties have to be acknowledged. While relevant monitoring data may be available for some systems, experimental evidence will rarely be available, so the risk assessment stage may need to be informed by an impact model or modelling studies.

These models summarise the relevant information and knowledge about how climate change and other important non-climate factors could affect the system under a variety of decision options. Models may be needed for the following reasons:

- The variables of interest are not provided directly by the climate scenarios.
- The impact of concern may relate to the components and properties of a specific system – and this will be a function of system variables and parameters as well as other

secondary or compound climate variables (e.g. water reservoir storage capacity, wind resistance of a building).

These modelling studies generally take climate scenario data as input, and model additional processes, often at finer spatial and temporal resolution, to generate information more closely related to the specific impact and decision being considered. The influence of the various statistical properties of each climate variable (see Section 3.5) should be considered where appropriate.

In this context, a 'model' may range from conceptual insights into the influence of climate and other variables on a system, to more sophisticated and technical approaches using computer-based mathematical or other forms of model (e.g. wind tunnel or wave tank physical model).

see part 1 stage 3 tier 1

A hierarchical approach should be adopted to modelling climate influence on a system. Gaining a thorough and broad-brush understanding of the system is recommended before more resource-intensive modelling of specific parts is undertaken. Techniques that help identify possible interactions, process links and sensitivities should be used in these initial stages (see Part 1, Stage 3, Tier 1). **Process influence diagrams, conceptual models, dependency mapping** are frequently used, preceding and possibly providing a basis for development of quantitative models and methods. Such techniques will often be more appropriate than detailed process modelling, which may not be supported by the available data.

see part 1 stage 3 tiers 2 & 3

Where relationships can or have been established between the various components, statistical and risk-based techniques (Stage 3, Tier 2) and more sophisticated **process-response models** (Tier 3) can be used. In some cases, existing models of complex systems will be available. Studies using these models are normally carried out by specialists in specific disciplines and techniques. Examples include rainfall-runoff modelling for fluvial flood assessment, sea level rise and storm surge modelling for coastal flood risk assessment, or the modelling of ecological systems to assess changes to plant and animal populations.

More advanced quantitative risk assessments (as described in Part 1, Stage 3, Tier 3) should consider making use of probability density functions and other statistical methods and models (e.g. to characterise the variance, covariance and causality between climate and other system variables), where suitable data are available.

3.8.1 IMPACT MODEL UNCERTAINTY

These additional modelling studies cannot reduce the uncertainty stemming from the original climate model. In fact, as all models are subject to model uncertainty (see Section 1.7.4), the need to use an impact model adds to the uncertainty inherited from the climate model. In the majority of cases an impact model will require other types of input, in addition to those dependent on climate. Some of these inputs may reasonably be assumed not to change over the period of the assessment (i.e. show no time-dependent trend). However, they may still be subject to variability and other forms of uncertainty. Other inputs may be expected to change over the period of the assessment, and forecasts for these variables will be needed. These forecasts may come from a model-based trend analysis, some other forecasting model, or using a scenario-based approach (see Section 3.6). All these approaches will carry with them particular assumptions and other sources of uncertainty. Some of these uncertainties may be amenable for quantification, using the model, as part of a probabilistic risk assessment. However, others will remain unquantified and the results of any probabilistic risk assessment will be contingent on these assumptions. It is therefore an important requirement of any risk assessment that such assumptions are clearly identified and where possible supported, and justified in terms of their importance for any conclusions.

Hence it should not be assumed that the uncertainty associated with future climate change (e.g. summarised within the climate scenarios) is necessarily more important or significant, in terms of its relevance to a particular decision, than that contained within the impact model. Both contribute towards the overall uncertainty associated with an impact assessment. Indeed, in order to reduce uncertainty in climate change risk assessments, a decision-maker may find that increasing knowledge of how a particular system responds to present-day climate variability, or to uncertain future values of non-climate variables, may be more important than reducing the uncertainty over the extent of future climate change.