5

Assessing Future Climate Risks

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CONTENTS

5.1. Introduction

This technical paper (TP) describes techniques for assessing future climate risk and therefore, adaptation needs, under a changing climate. In doing so, this TP outlines a process that is consistent with Adaptation Policy Framework (APF) Component 3, *Assessing Future Climate Risks*. The techniques described here utilise information about future climate in assessments that build on an understanding of current climate risks. Two pathways to assessing risk are described, the hazards-based approach and the vulnerability-based approach. The former begins with plausible changes in future climate, then projects biophysical and socio-economic conditions from those changes. The vulnerability-based approach sets criteria based on socio-economic or biophysical outcomes, then determines how likely these criteria are to be met or exceeded (this approach was introduced in TP3). The climate risks that are described using either pathway can be managed through policy changes that reduce a population's exposure to current and future climate hazards.

The material presented here builds on the concepts addressed in TP4 for assessing current risks by adding information on climate change to assess future risks. Unless historically unprecedented hazards are indicated by climate studies, criteria for risk management of future climate can be based on an understanding of current climate risks (TPs 3 and 4). If knowledge of those current risks is established, then assessments may commence by characterising how climate risks may change due to future climate and socio-economic changes (TP6).

The paper briefly describes the latest climate information and summarises methods on scenario development, directing the researcher towards source material on how to develop climate scenarios. It then outlines how climate scenario information can be used to extend our understanding of current climate–society relationships into the future, how to analyse risk relevant to different planning horizons, and how to assess planned adaptations as a form of risk management.

5.2. Relationship with the Adaptation Policy Framework as a whole

With its focus on future climate risks, this paper contributes primarily to Component 3 of the APF. Yet it is closely linked to the other TPs, as outlined here.

TP2 – *Engaging stakeholders in the adaptation process:* Engaged stakeholders can be a key element of modern risk assessments, and can contribute by extrapolating their current experience to possible future climate and identifying adaptations to address changing risks.

TP3 – *Assessing vulnerability for climate adaptation:* Assessment of the consequences of climate change form a key part of climate risk assessment. TP3 describes the tools required to characterise vulnerability in preparation for assessing both current and future climate risks.

TP4 – *Assessing current climate risks:* Knowledge of current climate risks, and adaptation to those risks provide a sound basis for assessing future adaptation needs. TP4 describes how climate risk is a combination of the likelihood of a climate event (or a combination of events) and its consequences. This paper builds on the techniques described in TP4, describing methods for incorporating information about future climate into the risk assessment. TP4 is paired with the current paper within the APF.

TP6 – *Assessing current and changing socio-economic conditions:* A dynamic understanding of future risk requires knowledge of both biophysical and socio-economic change. Socio-economic analysis can be used to describe change in human systems that will affect a group's ability to cope with future climates, as outlined in TP6.

TP7 – *Assessing and enhancing adaptive capacity:* Adaptive capacity is the ability of a group to expand their coping range in response to an anticipated or experienced climate stress. Analysis of historical changes in the coping range can indicate the adaptive capacity of a particular group or activity.

TP8 – *Formulating an adaptation strategy:* The process of preparing an adaptation strategy involves making decisions on specific adaptation options – choices that respond to the risks recognised in this paper.

5.3. Key concepts

Climate risk arises from interactions between climate and society, and can be approached from its social aspect through vulnerability-based assessment, from its climatic aspect through natural hazards-based assessment, or through complementary approaches that combine elements of both. The coping range, described and illustrated in TP4, provides a framework that can accommodate these approaches under climate change. As such, it can be used as an analytic tool or communication device in assessments.

When carrying out a risk assessment, the team needs to be aware of what type of information is needed to apply the results to planning or policy. In some cases, qualitative information may be all that is needed. For instance, in a region under water stress, an indication that drought risks are likely to increase in the future may be sufficient to warrant adaptation (Box 5-3, Section 5.5.5). In other cases, decisions about natural resource allocations based on climate change may be open to legal challenge, requiring outcomes based on scientific assessments that can stand up in court (where scientific evidence will be assessed on the balance of probabilities). However, uncertainty also limits choice. Sometimes, although stakeholders want hard numbers, uncertainty may only allow qualitative responses. In this case, a compromise is to rely less on analytic techniques and modelling, and rely more on techniques from the social sciences, such as eliciting information from different stakeholders (TP2) on how they perceive climate risks, to provide semi-quantitative assessments.

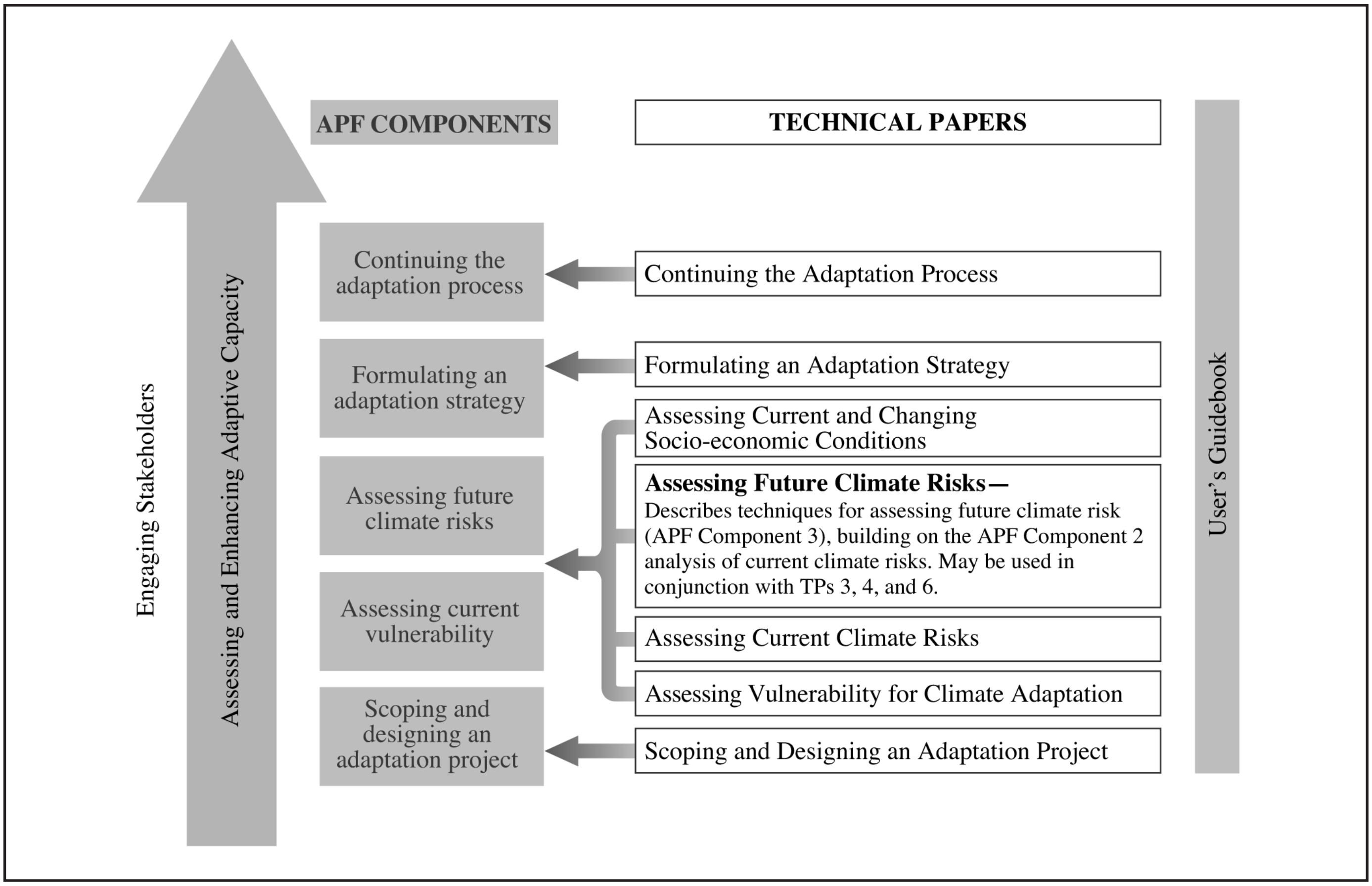

Figure 5-1: Technical Paper 5 supports Components 2 and 3 of the Adaptation Policy Framework

5.3.1. Uncertainty

Climate change assessments are permeated by uncertainty, requiring the use of specialised methods such as climate scenarios. This is a principle reason to recommend that adaptation assessments be anchored with an understanding of current climate risk; it helps to provide a road map from known territory into uncertain futures. Risk assessment also utilises a formalised set of techniques for managing uncertainty that can be used to expand the methods developed and utilised in Intergovernmental Panel on Climate Change (IPCC) assessments. For example, Moss and Schneider (2000) prepared a cross-cutting paper on uncertainty for the IPCC Third Assessment Report (TAR) that provides valuable guidance on framing and communicating uncertainty. Particularly valuable is the advice on providing guidance on the confidence used in terms such as *likely*, *unlikely*, *possible* and *probable*. Further guidance on managing uncertainty within assessments (both qualitative and statistical) is provided by Morgan and Henrion (1990) and, on communicating risk, in Morgan et al. (2001).

The major tool used to assess the impacts of future climate is the climate scenario. *A scenario is a coherent, internally consistent and plausible description of a possible future state of the world*. It is one of the main tools for assessing future developments in complex systems that may be unpredictable, are insufficiently understood and have high scientific uncertainties (Carter and La Rovere, 2001). Scenarios can range from the simple to the complex, and from the qualitative to quantitative, encompassing narrative descriptions of possible futures to complex mathematical descriptions combining mean climate changes with climate extremes. Climate scenarios are not restricted to Global Climate Models (GCM) output – any information about future climate utilised in an assessment will suffice. Even when scenarios are constructed in narrative form, or are based on broad projections of climate change (e.g., Section 5.5.1.2), plausibility and consistency should be maintained as much as possible. Usually, a scenario has no likelihood attached to it beyond being plausible. However, it is the basic building block of risk assessment approaches under climate change that use scenarios, ranges of uncertainty, probability distribution functions and Bayesian analysis. Section 5.5.4 contains examples of how to apply some of these techniques.

5.3.2. Coping ranges

The coping range was introduced in TP4 (Section 4.3.4) to show how current climate can be related to socially-related outcomes in order to carry out risk assessment. It can be used to assess how the ability to cope is affected by a perturbed climate (Figure 5-2) and to assess the changing ability to cope over time (TP4, Annex A.4.3).

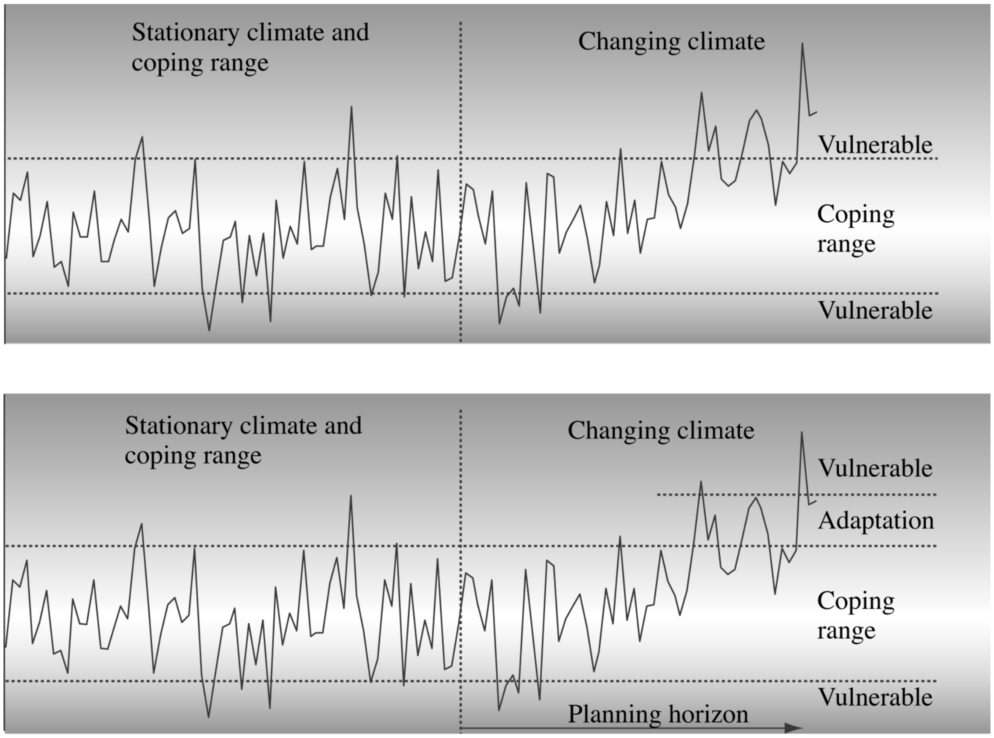

Figure 5-2: Relationships between climate change, coping range, vulnerability thresholds and adaptation

The upper panel shows how a coping range may be breached under climate change if the ability to cope is held constant. If that range is represented in terms of temperature (or rainfall), the upper hot (or wet) baseline or reference threshold is exceeded more frequently, while the exceedance of the lower cold (or dry) baseline threshold reduces over time. Vulnerability will increase to extreme levels for the hot (wet) threshold over time. The lower panel represents the expansion of the coping range through adaptation and the consequent reduction of vulnerability. The amount of adaptation required depends on the planning horizon under assessment and the likelihood of exceeding given criteria over that planning horizon.

The coping range can also be used to explore how both climate and the ability to cope may interact over time. For example, an agricultural assessment could account for projected growth in technology, yield and income that broadens the coping range. An assessment could then determine whether these changes are adequate to cope with projected changes in climate. These assessments should be carried out on an appropriate planning horizon.

5.3.3. *Risk quantification*

Approaches for quantifying risk and the use of coping ranges under climate change are emerging areas and, as yet, there are limited assessments to draw from for guidance. Introductory material is described in the IPCC Third Assessment Report: Mearns and Hulme (2001) for risk, and Smit and Pilifosova (2001) for coping ranges. This is developed further in Jones et al. (2003). An illustrative approach to using coping ranges is described by Yohe and Tol (2002). Methods for undertaking risk assessments utilising critical thresholds built around the conventional seven-step method of Carter et al. (1994) are described in Jones (2001). A guide for assessing risk (Willows and Connell, 2003), principally designed for decision-makers, contains participatory, qualitative and quantitative approaches.[1] Further information on setting risk criteria and thresholds can be found in TP4 (Section 4.4.4).

While the qualitative aspects of risk and coping ranges can be readily utilised in conceptual models (i.e., by stakeholders identifying the point where the level of harm exceeds tolerance levels), the more applied methods require a well-developed research capacity. The probability of exceeding a given level of vulnerability is an exceedingly useful concept to develop in methodological terms, and is discussed by Jones et al. (2003). While it would be useful, it is not always possible to have models linking the entire process from climate change to socio-economic outcomes.

For example, if only biophysical models are available, or if vulnerability cannot be adequately quantified, stakeholders may decide to identify levels of vulnerability in biophysical

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[1] This guide, *Climate adaptation: risk, uncertainty and decision-making*, can be found at http://www.ukcip.org.uk/risk_uncert/risk_uncert.html

terms where there is an agreed consensus about the degree of vulnerability:

- in terms of flooding, there may be a particular water level associated with widespread damage.
- if only rainfall data is available, researchers may quantify the rainfall amounts preceding similar levels of inundations. These amounts can then be used to construct a threshold providing the bounds of the coping range for a community within a catchment.
- for agriculture, rainfall may be used as a proxy for loss of production or given levels of food security. In terms of sustainability, stakeholders may identify a level of crop production that they think is sustainable and assess how they may reach that target under climate change.

Socio-economic scenarios may need to be developed to explore how coping ranges may evolve (TP6). More applied methods of exploring vulnerability are detailed in TP3.

The "learning by doing" aspect of the APF will help in this regard. Assessments that build capacities and tools that then become available for successive assessments will consequently build the capacity to develop new techniques. Meanwhile, policy makers and stakeholders, once they have learned that firm forecasts of climate change are not forthcoming, are generally receptive to working with risk, especially if it is framed in terms of what they already know (i.e., couched in terms of their current exposure to climate risk). An example of a quantitative risk assessment for the water sector detailing the methods used and policy response is described in Annex A.5.1 (Jones and Page, 2001).

5.4. Guidance on assessing future climate risks

A broad structure for assessing future climate risks is provided in Figure 5-3. Included are some initial activities to carry out with stakeholders, such as exchanging information on what is already known. At this point in the process, some level of prior knowledge of climate change is assumed to exist in most countries, including that generated by National Communications to the United Nations Convention on Climate Change (UNFCCC). This flowchart is meant to provide guidance for constructing a risk assessment – it is not meant to be followed step-by-step if the assessment, material and circumstances do not readily permit it.

There are several ways an assessment can be approached. It may build on an assessment of current climate risks as described in TP4, or may be based on pre-existing knowledge. It is also possible to integrate an assessment of current and future climate risks. One way to do this would be to take important elements from Figure 5-3 and Figure 4-2 in TP4, and order them to create a logical sequence relevant to a particular assessment. Elements from TPs 3 and 6 could be introduced in the same way. The decision of what elements need to be included can be carried out jointly by researchers and stakeholders as part of conceptual model development.

5.4.1. *Selecting an approach*

The two major pathways through risk assessment are the natural hazards and the vulnerability-based approaches. (TP4, Section 4.4.) The natural hazards approach is a climate scenario-driven approach. It starts off with climate scenarios, applies them to impact models and determines possible changes in vulnerability. The vulnerability-based approach starts with possible future outcomes in the form of biophysical or socio-economic criteria that represent a given state of vulnerability. It then determines how likely those criteria are to be met/exceeded under different future climates, again by applying a range of climate scenarios. Outcomes used as criteria for risk assessment can be desirable (e.g., a future sustainable state) or undesirable (e.g., an important activity losing viability).

1. The natural hazards-based approach fixes a level of hazard (such as a peak wind speed of 10ms^{-1}, hurricane severity, or extreme temperature threshold of 35°C), and then assesses how changing that particular hazard, according to one or more climate scenarios, changes vulnerability. Limitations in climate modelling often mean that changing hazards cannot be represented specifically but scenario-building methods are continually evolving. A broad formulation is *Risk = Probability of climate hazard x Vulnerability*.
2. The vulnerability-based approach sets criteria based on the level of harm in the system being assessed, then links that to a specific frequency, magnitude and/or combination of climate events. For example, loss of livelihood linked to severe drought, loss of property due to flooding, critical thresholds for management, or system viability. The level of vulnerability that provides this "trigger" can be decided jointly by researchers and stakeholders, chosen based on past experience, or defined according to policy guidelines. With this approach, *Risk = Probability of exceeding one or more criteria of vulnerability*.

These methods are complementary and can be used separately or together. Table 5-1 provides a quick checklist that may help to decide which technique may be most appropriate. If the ranges of uncertainty described by climate scenarios and/or characterisation of hazard under climate change are well-calibrated and if the drivers of change and the processes by which change can be represented are understood, then the natural hazard approach may be best suited. If the climate hazards cannot easily be characterised under climate change, there are many drivers of change and many pathways along which change can take place, then a vulnerability-based approach may be best suited. Another important distinction is that the natural hazard method is largely exploratory, i.e., given the underlying assumptions and conditions, a specific outcome is predicted; and the vulnerability-based method is more normative, i.e., a future outcome is proposed (either positive or negative) and the risk of attaining or exceeding that outcome is assessed. Adaptation will aim to reduce the likelihood if that outcome is negative, or increase the likelihood if it is positive.

5.4.2. Gathering information on future climate

Information on what future climate may be like has increased substantially in the past decade. The most recent and complete information on the climate change science community's assessment of this subject is found in the IPCC TARs (Houghton et

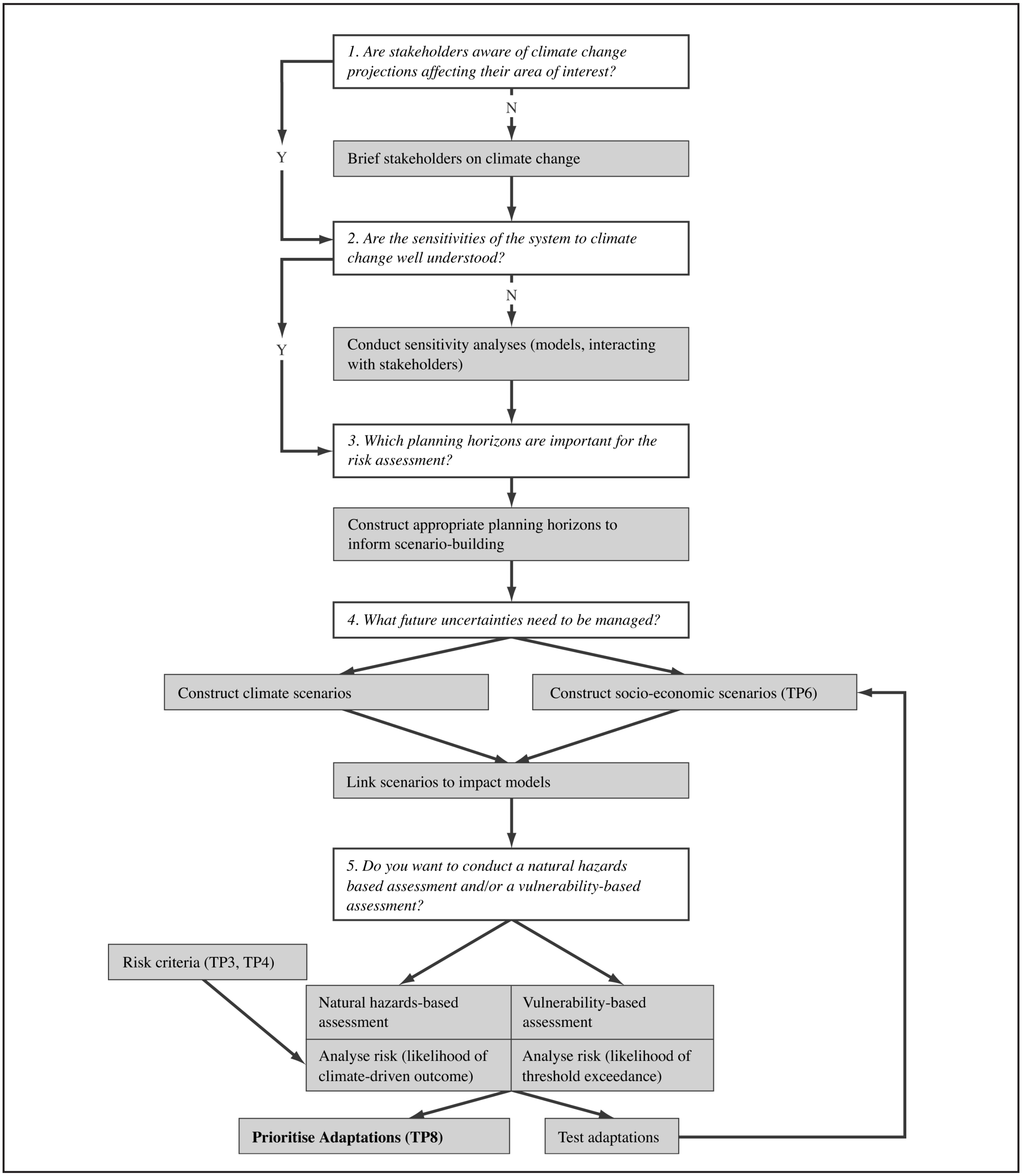


Figure 5-3: Flow chart for assessing future climate risks *(as described in this chapter)*

Table 5-1: *Checklist to determine the efficacy of using the natural hazard- and vulnerability-based approaches in an assessment*

Method	Natural hazard-based approach	Vulnerability-based approach
Hazard characterisation	Ranges of uncertainty described by climate scenarios and/or characterisation of hazard under climate change well-calibrated	Ranges of uncertainty described by climate scenarios and/or characterisation of hazard under climate change not well-calibrated
Drivers of change	Main drivers known and understood	Many drivers with multiple uncertainties
Structure	Chain of consequences understood	Multiple pathways and feedbacks
Formulation of risk	Risk = P (Hazard) x Vulnerability	Risk = P (Vulnerability) e.g., critical threshold exceedance
Approach	Exploratory	Normative

al., 2001; McCarthy et al., 2001; Metz et al., 2001; available at: http://www.ipcc.ch/), the main points of which are summarised hereafter.

Based on the most recent information, mainly from simulations of GCMs, it is believed that the average global temperature of the earth will be between 1.4°C to 5.8°C warmer than present by the end of the 21st century. Moreover, there is increasing evidence that the warming of the earth over the past 50 years is attributable to increased greenhouse gases resulting from human activities.

5.4.2.1. IPCC Special Report on Emission Scenarios

The estimate of the range of temperature change at the end of the 21st century is based on results from climate models forced with scenarios of increasing greenhouse gases and aerosols, developed for the TAR (Nakicenovic and Swart, 2000). These scenarios, in turn, were based on four "storylines" of what the future of the world might be from the point of view of demographic, technological, political, social and economic developments (Box 5-1). Forty different scenarios were developed from those storylines. In addition to producing very different outcomes in terms of climate, the range of possible developments paths will also produce different adaptive capacities (TPs 6 and 7).

Across all Special Report on Emission Scenarios (SRES), the range of atmospheric CO_2 would reach levels between 540 ppm to 970 ppm by the end of the present century. There are also significant ranges of change across the scenarios for the other greenhouse gases such as methane and nitrous oxide. The trajectory of sulphate aerosols also varies considerably across the scenarios with some steadily decreasing and others with an initial increase, but then decreasing by the second half of the century.

Box 5-1. SRES scenario storylines

A1	Characterised by very rapid economic growth, global population peaking in mid-century, and then declining, and rapid introduction of new, efficient technologies. Three different subgroups in the A1 storyline are defined that present alternative changes in technology: fossil intensive (A1FI), non-fossil (A1T) and balanced across sources (A1B).
A2	Characterised by heterogeneity. Self-reliance and local identities are emphasised. Population increases continuously. Economic development is regionally oriented, and economic and technological growth is relatively slow compared to other storylines.
B1	A convergent world, having the population growth of the A1 storyline. Economic structures change rapidly toward a service and information economy, clean and resource-efficient technologies are introduced, with emphases on social and environmental sustainability.
B2	Local solutions to economic, social and environmental sustainability are emphasised. Global population grows continuously, but at rate lower than that of A2.

5.4.2.2. Projected climate changes

Based on atmosphere-ocean GCM (AOGCM) results, the IPCC determined that global annual average precipitation would increase from about 1.2% to 6.8% in the last 30 years of the 21st century, across the A2 and B2 scenarios. Global sea level is expected to increase by between 0.09 and 0.88 m by the end of the 21st century, based on the full range of the SRES scenarios. Regional increases in sea level rise show large variations between models.

Uncertainties in the responses of mean climate change, including variability, increase as one goes to finer levels of assessment (perception) than the global scale, especially for changes in regional precipitation. However, some specific regional changes are considered likely. It is believed that land temperatures will warm faster than the global average and oceans will warm more slowly. Polar regions are expected to experience greater increases in temperature than will tropical regions, and will also experience increases in precipitation in most seasons.

Based on a regional analysis of results of nine AOGCMs that used both the A2 and B2 emissions scenarios, more detailed common regional changes in temperature and precipitation were determined in the IPCC report (Giorgi and Hewitson, 2001). However, these results are more uncertain than those described in the previous paragraph. Large warming will occur during the winter in all high northern latitude regions, as well as in Tibet, whereas it is indicated to take place during the summer in the Mediterranean basin, as well as in northern and central Asia. Increases in precipitation are anticipated over northern mid-latitudes and tropical African regions in the boreal winter. Increases in precipitation are also seen in the boreal summer in South Asia (e.g., India), East Asia (i.e., central China), and Tibet. Consistent decreases in winter precipitation are seen over Central America in the boreal winter (December–February) and over Australia and southern Africa in the austral winter (June–August). Changes in precipitation tend to be larger in the A2 scenario, compared to the B2. In other regions of the world and/or seasons, there was a lack of consistency in the changes in precipitation across the models and scenarios and no clear signal could be determined. More details on these results can be found in Giorgi and Hewitson (2001) and Giorgi et al. (2001).

The IPCC also assessed possible future changes in extreme events. These estimates are particularly important since vulnerability to extreme events is usually high in human society, and our need to adapt to them is high. It is now believed that extreme high temperatures will increase, as will high-intensity precipitation events. Low temperature extremes would decrease. Mid-continental areas will likely experience greater drought in the summer. Unfortunately, little is known regarding how intense hurricanes or mid-latitude storms will change. There is some evidence that, on average, more El Niño-like conditions would be seen (TP4, Annex A.4.2 provides a summary).

5.4.3. ***Conducting sensitivity experiments***

To obtain a first-order sense of how possible climate changes may affect different impacts and because of the degree of uncertainty in climate change, particularly at the regional scale, sensitivity experiments are a good means of exploring how impacts may respond to climate change. These make use of incremental changes in climate, e.g., applying a 1°, 2°, and then 3°C increase in temperature; and/or 5%, 10%, 15% increase/decrease in precipitation, and so on. These can be constructed as quantitative data sets for use as input to quantitative impact models (e.g., crop and hydrologic models; Risbey, 1998; Mehrotra, 1999) or applied to mental models (i.e., thought experiments) constructed with stakeholders.

Sensitivity experiments can produce important information on the basic sensitivity and vulnerability of the particular system and aid in the establishment of critical climate thresholds in the system (levels at which serious damage occurs). It is often recommended that such incremental changes be used early in a project so as to better understand the response of the system to climate shifts in a systematic way and to establish thresholds (e.g., Mearns and Hulme, 2001). The use of incremental changes should be limited to such explorations because they do not necessarily produce internally consistent and plausible scenarios of change. It is also possible to assess sensitivity to changes in climate variability, especially if it is difficult to develop scenarios for those changes from climate model data (e.g., assessing plausible but artificial changes in daily rainfall as part of flood modelling).

5.4.4. ***Selecting planning and policy horizons***

Planning horizons will affect how far into the future a risk assessment may be projected. Planning horizons relate to the lifetime of decision-making associated with a particular activity – how far into the future is it planned? Is climate change likely to occur with this planning horizon? Do current planning decisions assume the continuation of historical conditions? How do we incorporate climate change into long-term planning?

The same activity can be affected by several planning horizons used by different stakeholders (e.g., financial, urban planning and engineering horizons for infrastructure). For example, in a water resource or catchment-based assessment, the planning life of water storages may be 50+ years, but planning for supply may only be 5–15 years (Figure 5-4). A risk assessment may then want to create scenarios based on two time horizons such as 2020 and 2050 to accommodate both water policy and infrastructure horizons respectively.

The policy horizon is related to the period of time over which a particular policy is planned to be implemented. This may not be on the same time scale as a planning horizon. For instance, the infrastructure affecting an activity will have an engineering life of many decades, but the policy horizon governing the operation of that infrastructure may be much shorter. Most natural resource policy is implemented over periods of 5 to 15 years. Such policies may be reviewed or updated over time but

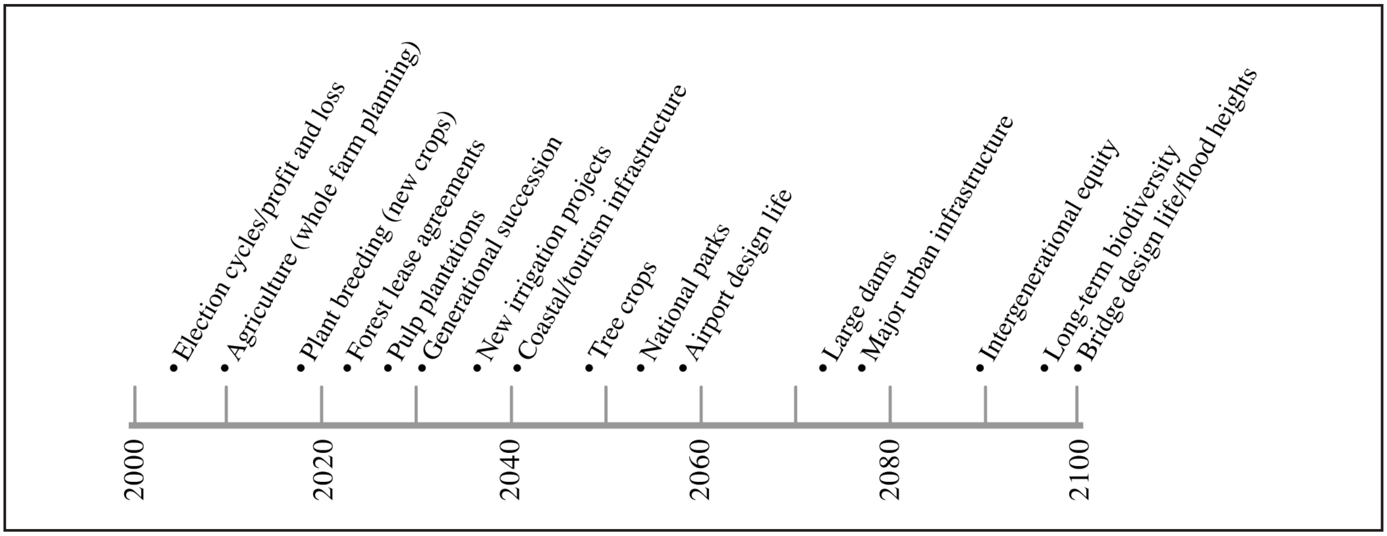


Figure 5-4: A representative section of planning horizons relevant to climate risk assessments. Few of these planning horizons are fixed. They cover a range of time and some (e.g., long-term biodiversity) will extend long beyond 2100.

are often expected to manage resources over a much longer planning horizon. Risk assessment may be extended over the longer planning horizon, but adaptations developed to manage those risks are likely to be applied over shorter-term policy horizons (e.g., a long-term strategic outlook is often used to inform shorter-term adaptations). These longer-term outlooks are important, because to ignore strategic objectives in favour of exclusively short-term management may lead to incremental changes accumulating in unintended or irreversible outcomes. If the existing planning horizon does not extend beyond the policy horizon, assessment of the potential risks under climate change may be used to alert policy-makers to the value of taking a longer-term view.

Planning and policy horizons influence the choice of climate scenario. Scenarios may represent a time slice in the future (e.g., 2020 or 2050), or project a pathway from the present into the future. The planning horizon may extend further than the policy horizon but knowledge of possible risks will influence the path taken, in policy terms, of reaching that planning horizon in good shape. If climate scenarios far into the future are chosen, but policy needs are much more immediate, several time-slices over the short to long-term may be used to bridge the distance between policy and planning horizons. A tension exists between the long-term needs of sustainable development and the short-term needs of economic and policy development. However, if adaptations can serve both shorter-term policy needs and long-term strategic objectives, the likelihood of achieving sustained benefits is maximised (as it is if both short- and long-term climate risks are managed). If adaptation is incremental, then policy horizons can be updated using adaptive management, by reviewing shorter-term actions in the light of new information about longer-term outcomes. If irreversible changes with significant consequences are possible, or if retrofitting infrastructure at some future time is likely to be too expensive, then adaptation may need to anticipate long-term changes almost immediately.

5.4.5. Constructing climate scenarios

The major methods for constructing climate scenarios utilise results from climate model simulations. While there are other means (Table 5-1; Carter et al., 1994; Mearns and Hulme, 2001), climate model results provide the user with internally consistent and plausible scenarios of the future that are sufficiently detailed for use with quantitative impacts models.

5.4.5.1. Introduction to climate modelling

Climate projections are produced by mathematical representations of the earth's climatic system using GCMs. These models are as physically representative as possible within the limitations of scientific knowledge, the ability to represent physical phenomena on an appropriate scale, and computer capacity. They link the atmosphere, ocean, land, and biosphere both vertically and horizontally in a series of three-dimensional grid boxes that partition the earth into layers and grids. The scale and thus the number of those boxes are limited by the computer power available to carry out the necessary computations. GCMs have grid box resolutions in the order of 100 km to 500 km on a side, while Regional Climate Models (RCMs) have a resolution between 5 km and 100 km. Regional climate models have a limited domain of higher resolution allowing large-scale simulations to be run, and may be nested in a GCM or as a zone of high resolution of grid squares within a lower resolution GCM.

The current generation of GCM is the *coupled GCM*, or AOGCM, that links a three-dimensional representation of the ocean to the atmosphere. In these experiments, the enhanced greenhouse effect is simulated by gradually increasing the radiative forcing equivalent to historical increases in greenhouse gases and sulphate aerosols to 1990 or 2000, then simulating the response to greenhouse gas and aerosol scenarios to 2100 or beyond. Although climate models are run on many time-steps per day usually, only daily and monthly data is saved. Monthly data is saved for many variables in the atmosphere and ocean, whereas daily data is generally saved for surface variables important for the diagnosis of results and for impact studies. Due to the large amounts of data saved and stored, monthly data is usually preferred to the use of daily data.

5.4.5.2. Uncertainties of future climate

The uncertainties affecting climate change are biophysical and socio-economic. Biophysical uncertainties are those dealt with in climate models and include interactions between the oceans, atmosphere and biosphere. Socio-economic uncertainties include the economy, technology, population and society. These uncertainties interact, e.g., where greenhouse gas emissions alter the climate and biosphere, which then affect human systems. Accurately forecasting the rest of this century's climate is not possible because we cannot accurately predict the necessary socio-economic drivers in terms of greenhouse gas futures – we can only produce a large range of possible outcomes. The uncertainties in the climate models themselves also contribute to this inability.

While there are many uncertainties in climate change, this section reviews only some of the major ones that impacts researchers can most likely take account of in their work.

The uncertainties in technological, political and economic futures are integrated in the production of emissions scenarios. Hence, the different emissions scenarios can be said to summarize a range of those uncertainties. The major uncertainties in climate system responses are represented by the different climate models that respond differently to the different emissions scenarios. These are the two summary types of uncertainty that are most available for consideration in impacts (and hence) adaptation research. Uncertainties also tend to propagate as one progresses through an assessment and as one moves from the global to local scale (Figure 5-5). Risk assessments need to account for these uncertainties as much as is practical. (A brief summary is in Box 5-2; IPCC-TGCIA, 1999; Carter and La Rovere, 2001; Mearns and Hulme, 2001).

Progress is rapidly being made in quantifying the uncertainties of climate change. These efforts have lead to recent papers quantifying the near future (i.e., next 20 years) using a combination of climate observations and climate model results (Allen et al., 2000; Forest et al., 2002). Moreover, attempts to assign probabilities to longer-term future climate have also been made (e.g., Schneider, 2001; Wigley and Raper, 2001). More recently progress has been made in determining the reliability of climate model results (Giorgi and Mearns, 2001, and assigning probabilities to climate change on a regional scale Giorgi and Mearns, 2003; Tebaldi et al., 2003). However, these works should be viewed as providing subjective examples as opposed to objective probabilities of long-term future climate. Box 5-2 summarises how climate scenarios can be used to manage uncertainty.

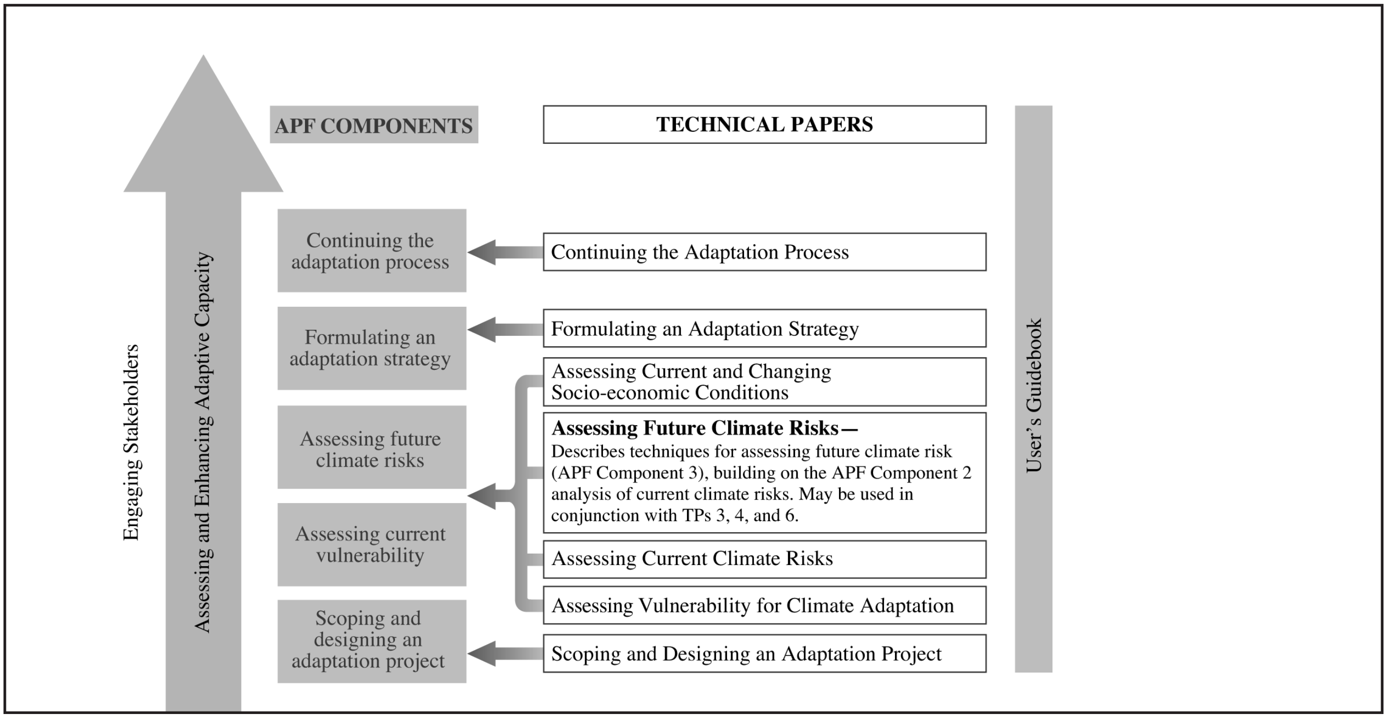


Figure 5-5: The relationship between (upper diagram) ranges of uncertainty cascading through an assessment, and (lower diagram) individual scenarios, S1 to S4, and resultant ranges of uncertainty. These diagrams are sourced from Jones (2000) and Schneider and Kuntz-Duriseti (2002).

Box 5-2: Assessing likelihoods of climate change

Within the resources available to an assessment, the choice of how many and what kind of scenarios are needed has to balance the concerns between precision and the ability to explore key uncertainties. For instance, daily rainfall data from climate models is very imprecise and may need to be downscaled to obtain plausible values and distributions, but this task is resource intensive and may limit the number of scenarios that can be produced. The trade-off is between producing plausible scenarios that properly represent the data needed to simulate impacts, and exploring the major uncertainties that will affect an assessment's outcomes. This box outlines some strategies for assessing uncertainty and likelihoods. The IPCC Data Distribution Centre has both data and supporting material, as do a number of climate modelling centres. Even if only a limited number of climate scenarios are used, it would be valuable to scope the range of projected climate changes for the area in question before constructing those scenarios.

Single scenario

A single scenario can be used as a plausible outcome or to illustrate a storyline that tests various options in an environment of high uncertainty. It can be located within a range of uncertainty (e.g., low, median or high warming) or may be used to give a specific realisation to a generally accepted direction of change (e.g., increase in extreme rainfall). The downside is that a single scenario is often taken (erroneously) as a prediction.

Two scenarios

Two different scenarios will overcome the possibility of a single scenario being seen as a prediction. Strategies are to sample a range of uncertainty by choosing extreme outliers, or just to illustrate two distinctly different possibilities (as in the U.S. National Assessment).

Several scenarios

Undertaken to explore one or more ranges of uncertainty (e.g., greenhouse gas emissions, climate sensitivity, regional climate change). Three scenarios are sometimes discouraged to prevent users from gravitating towards the central estimate.

Range of outcomes

Constructing a range of uncertainty bounded by high and low estimates of the outcomes (e.g., global warming as expressed by the IPCC). This limits the uncertainty by identifying outcomes that are not likely, but on the other hand, can identify large ranges in impacts that make it difficult to design adaptation policy. Figure 5-5 shows how scenarios are related to a well-calibrated range of uncertainty (e.g., global warming, regional temperature, rainfall or sea level rise).

Relating likelihood to global warming and sea-level rise

It is possible to quantify likely impacts and the consequences of those impacts for systems affected by variables that can be linked closely to global warming, such as mean temperature and sea-level rise. For example, low-lying land in any given region will be the first to be affected by sea level rise and elevated land will be the last. This allows relative likelihoods to be attributed across a range of coastal areas, where the lowest levels of coast are the most likely to be inundated, and the highest are the least likely. This distribution is conditional and depends on factors such as trend in land movement, regional variability in mean sea-level rise, and changes in patterns of surge events. However, where mean sea-level rise is a significant driver of change, then the IPCC (2001) range of change will give a guide as to likelihood, and damage sea-level rise relationships will provide a guide as to consequences. Any section of coast proven vulnerable below the IPCC minimum projected sea-level rise will almost certainly be affected, the median part of the range is moderately likely to occur and the upper part of the range is unlikely to be reached. The same principle holds for systems strongly affected by temperature including coral reefs, tropical montane systems, permafrost regions and where biological thresholds are close to their upper temperature limits. Those impacts vulnerable to small levels of warming will be the first and most likely to be affected. If the direction of rainfall change is either overwhelmingly wetter or drier, then this principle can also apply to hydrological systems.

This principle is much more difficult to apply for variables that may either increase or decrease (e.g., rainfall in many regions), where systems are subject to complex interactions between variables, or where systems are driven largely by changes to variability rather than by accompanying changes to means. This covers many biological, health and hydrological systems.

Combining ranges and probability distribution functions

Recent efforts are beginning to quantify risk in terms of applying prior distributions to input ranges of uncertainty. These methods are in their early stages of development but where they have been applied (in Australia), policy makers have responded positively.

5.4.5.3. Current climate data

Current climate data is generally necessary in developing climate scenarios because errors in the reproduction of current climate by AOGCMs are still quite large. In general detailed climate data on a daily time scale are most easily acquired from the meteorological service of the relevant country. Monthly long-term datasets are available for the entire world on some web sites and institutes, such as the IPCC Data Distribution Centre, described in the next section. The way in which climate data is used to construct climate scenarios is described in later sections.

5.4.5.4. Climate model output

There are many sources of climate model output from future climate experiments. Different climate modelling centres provide their data upon request, and many have web sites from which one can download climate data.

The most complete repository of climate model data is the IPCC Data Distribution Centre web site, which was created to provide up-to-date climate and related scenarios for impacts researchers. The DDC is the main product of the Task Group on Climate Impact Assessment of the IPCC. At this site, GCM results for nine different AOGCMS are available using two of the SRES emissions scenarios (A2 and B2). Additional climate model results will be made available in the near future. Data for the major climate variables of interest for impacts work (e.g., temperature, precipitation, solar radiation) on a monthly timescale are made available. There are also data on the socio-economic scenarios that were used in the formation of the emissions scenarios, as well as guidance material on how to develop scenarios and how to use them.

Observed climate data on a monthly timescale for the world is also available. Over time, results from many climate models for three additional SRES emissions scenarios will also become available. The web site is: http://ipcc-ddc.cru.uea.ac.uk/

5.4.5.5. Methods of constructing scenarios

There are various ways of constructing climate scenarios (reviews of methods in Carter et al., 1994, and Mearns and Hulme, 2001). These include climate model-based approaches, temporal and spatial analogues, expert judgement and incremental scenarios for sensitivity studies as discussed above. Table 5-2 presents an overview of the methods with their main advantages and disadvantages. The most common means is by using results from AOGCM simulations in combination with climatological observations. The classic method entails determining the change in climate, and using this change to perturb observed climate data. In the case of results from transient runs of AOGCMs, this is accomplished by taking the average of a series of simulated years of the current climate (1961–1990) and the same for a series of simulated future years (2071–2100), taking the difference of the future minus the current simulations, and then appending these differences (generically referred to as “deltas”) to the observed data set. Quantitative impact models can be run using the actual observed data for present conditions and the “changed” observed data set to represent the future. In this manner, the errors in the climate model simulations do not directly affect the impact model results. In the case of presenting information on changes in climate to stakeholders, results from the simulations can also be discussed with them.

To account for uncertainties in future climate, it is recommended that results from multiple AOGCMs forced with multiple emissions scenarios be used.

5.4.5.6. Using and communicating single-event and frequency-based probabilities

A project may want to quantify likelihoods, or levels of confidence in outcomes developed using climate scenarios and communicate these to stakeholders. If no guidance as to likelihood of the outcomes of an assessment is provided to stakeholders, they may attach their own assumptions in an ad hoc manner, perhaps jumping to the wrong conclusions (Schneider, 2001). Therefore, we may want to qualify or even quantify the outcomes or to attach confidence levels to the conclusions as recommended by Moss and Schneider (2000). There are two aspects of probabilities that need to be considered before doing this:

1) What type of probabilities are you representing in your scenarios? They may be represented implicitly – so be mindful of such implicit assumptions.

Table 5-2: The role of various types of climate scenarios and an evaluation of their advantages and disadvantages according to the five criteria described in the table endnotes. Note that, in some applications, a combination of methods may be used (e.g., regional modelling and a weather generator). From Mearns and Hulme (2001).

Scenario type or tool	Description/use	Advantages[a]	Disadvantages[a]
Incremental	• Testing system sensitivity • Identifying key climate threshold	• Easy to design and apply (5) • Allows impact response surfaces to be created (3)	• Potential for creating unrealistic scenarios (1, 2) • Not directly related to greenhouse gas forcing (1)
Analogue			
Palaeoclimatic	• Characterising warmer periods in past	• A physically plausible changed climate that really did occur in the past of a magnitude similar to that predicted for ~2100 (2)	• Variables may be poorly resolved in space and time (3, 5) • Not related to greenhouse gas forcing (1)
Instrumental	• Exploring vulnerabilities and some adaptive capacities	• Physically realistic changes (2) • Can contain a rich mixture of well-resolved, internally consistent, variables (3) • Data readily available (5)	• Not necessarily related to greenhouse gas forcing (1) • Magnitude of the climate change usually quite small (1) • No appropriate analogues may be available (5)
Spatial	• Extrapolating climate/ecosystem relationships • Pedagogic	• May contain a rich mixture of well-resolved variables (3)	• Not related to greenhouse gas forcing (1, 4) • Often physically implausible (2) • No appropriate analogues may be available (5)
Climate model-based			
Direct AOGCM outputs	• Starting point for most climate scenarios • Large-scale response to anthropogenic forcing	• Information derived from the most comprehensive, physically-based models (1, 2) • Long integrations (1) • Data readily available (5) Many variables (potentially) available (3)	• Spatial information is poorly resolved (3) • Daily characteristics may be unrealistic except for very large regions (3) • Computationally expensive to derive multiple scenarios (4, 5) • Large control run biases may be a concern for use in certain regions (2)
High resolution/ stretched grid (AGCM)	• Providing high-resolution information at global/ continental scales	• Provides highly resolved information (3) • Information is derived from physically-based models (2) • Many variables available (3) • Globally consistent and allows for feedbacks (1,2)	• Computationally expensive to derive multiple scenarios (4, 5) • Problems in maintaining viable parameterisations across scales (1,2) • High resolution is dependent on SSTs and sea ice margins from driving model (AOGCM) (2) • Dependent on (usually biased) inputs from driving AOGCM (2)

Scenario type or tool	Description/Use	Advantages[a]	Disadvantages[a]
Regional models	• Providing high spatial/ temporal resolution information	• Provides very highly resolved information (spatial and temporal) (3) • Information is derived from physically-based models (2) • Many variables available (3) • Better representation of some weather extremes than in GCMs (2, 4)	• Computationally expensive, and thus few multiple scenarios (4, 5) • Lack of two-way nesting may raise concern regarding completeness (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Statistical downscaling	• Providing point/high spatial resolution information	• Can generate information on high resolution grids, or non-uniform regions (3) • Potential for some techniques to address a diverse range of variables (3) • Variables are (probably) internally consistent (2) • Computationally (relatively) inexpensive (5) • Suitable for locations with limited computational resources (5) • Rapid application to multiple GCMs (4)	• Assumes constancy of empirical relationships in the future (1, 2) • Demands access to daily observational surface and/or upper air data that spans range of variability (5) • Not many variables produced for some techniques (3, 5) • Dependent on (usually biased) inputs from driving AOGCM (2)
Climate scenario generators	• Integrated assessments • Exploring uncertainties • Pedagogic	• May allow for sequential quantification of uncertainty (4) • Provides "integrated" scenarios (1) • Multiple scenarios easy to derive (4)	• Usually rely on linear pattern scaling methods (1) • Poor representation of temporal variability (3) • Low spatial resolution (3)
Weather generators	• Generating baseline climate time-series • Altering higher order moments of climate • Statistical downscaling	• Generates long sequences of daily or sub-daily climate (2, 3) • Variables are usually internally consistent (2) • Can incorporate altered frequency/intensity of ENSO events (3)	• Poor representation of low frequency climate variability (2, 4) • Limited representation of extremes (2, 3, 4) • Requires access to long observational weather series (5) • In the absence of conditioning, assumes constant statistical characteristics (1, 2)
Expert judgment	• Exploring probability and risk • Integrating current thinking on changes in climate	• May allow for a "consensus" (4) • Has the potential to integrate a very broad range of relevant information (1, 3, 4) • Uncertainties can be readily represented (4)	• Subjectivity may introduce bias (2) • A representative survey of experts may be difficult to implement (5)

Numbers in parentheses under advantages and disadvantages indicate that they are relevant to the criteria described. The five criteria are: (1) *Consistency* at regional level with global projections; (2) *Physical plausibility and realism*, such that changes in different climatic variables are mutually consistent and credible, and spatial and temporal patterns of change are realistic; (3) *Appropriateness* of information for impact assessments (i.e., resolution, time horizon, variables); (4) *Representativeness* of the potential range of future regional climate change; and (5) *Accessibility* for use in impact assessments.

2) How do your stakeholders understand likelihood and probability? This understanding may or may not be compatible with the management of climate uncertainties, so a common understanding may need to be developed as part of an assessment.

Regarding the first aspect; there are two major types of probability that may be represented when dealing with climate risks. These can be divided into frequency-based and single-event uncertainties. Frequency-based uncertainties concern recurrent phenomena such as those that comprise climate variability and extremes (e.g., a flood, drought, or tropical cyclone). This type has a known or unknown statistical distribution that describes a series of events in terms of frequency and magnitude. The quantification of single-event uncertainties aims to determine the likelihood of a single event occurring within a given period (i.e., what is the likelihood of an El Niño event occurring next year or of global warming exceeding 3°C by 2100?).

Most climate hazards are described by frequency-based probabilities such as return periods or as a given frequency per unit time, including those contributing to the assessment of current climate risks, as described in TP4. These uncertainties are usually assessed using historical data and statistical and dynamical relationships based on that data. People familiar with weather and climate are most used to this type of uncertainty. Even if they are not well-versed in statistics, people understand that the more extreme events generally occur less frequently and that the more extreme events have the larger consequence. Risk assessment requires weighing up these two factors of frequency and magnitude. Return events such as the 1-in-100 year flood, likelihood of a specific extreme temperature, probability of a given severity of drought, cyclone frequency and magnitude are all examples (Table 4-1, TP4). Many criteria for assessing exceedance are also built on frequentist uncertainties (e.g., a given sequence of hot days >35ºC and both thresholds described in Annex A.5.1).

Part of the scenario-building task involves deciding how explicitly these uncertainties need to be represented. If historical climate variability is used as a basis and the mean changed, then the implicit assumption is that the variability around the mean remains unchanged. Changing mean climate as a response to global warming requires the management of single event uncertainties.

Single-event uncertainties represent an event that may or may not occur (e.g., collapse of the West Antarctic Ice-Sheet), or an event with a range of potential outcomes where only one outcome is possible, (e.g., global warming in °C by 2100). Questions such as "How much will the earth warm by 2050?" or "What is the direction and magnitude of rainfall change in my region under global warming?" are examples. Many single-event uncertainties associated with climate change are without precedent, and have no prior statistical history from which a probability distribution can be constructed.

The uncertainties surrounding variables such as mean global warming and regional changes in average temperature, rainfall and other such factors are single-event uncertainties. That is, only one outcome is possible. This is why such uncertainties are generally expressed as scenarios and ranges of change instead of forecasts with central estimates. Care must be taken when communicating such ranges because a range of rainfall change constructed from several GCM of -15% to +15% does not mean that zero rainfall change is the most likely outcome. If most of the GCM analysed simulate some change in mean this may suggest that zero rainfall change is very unlikely.

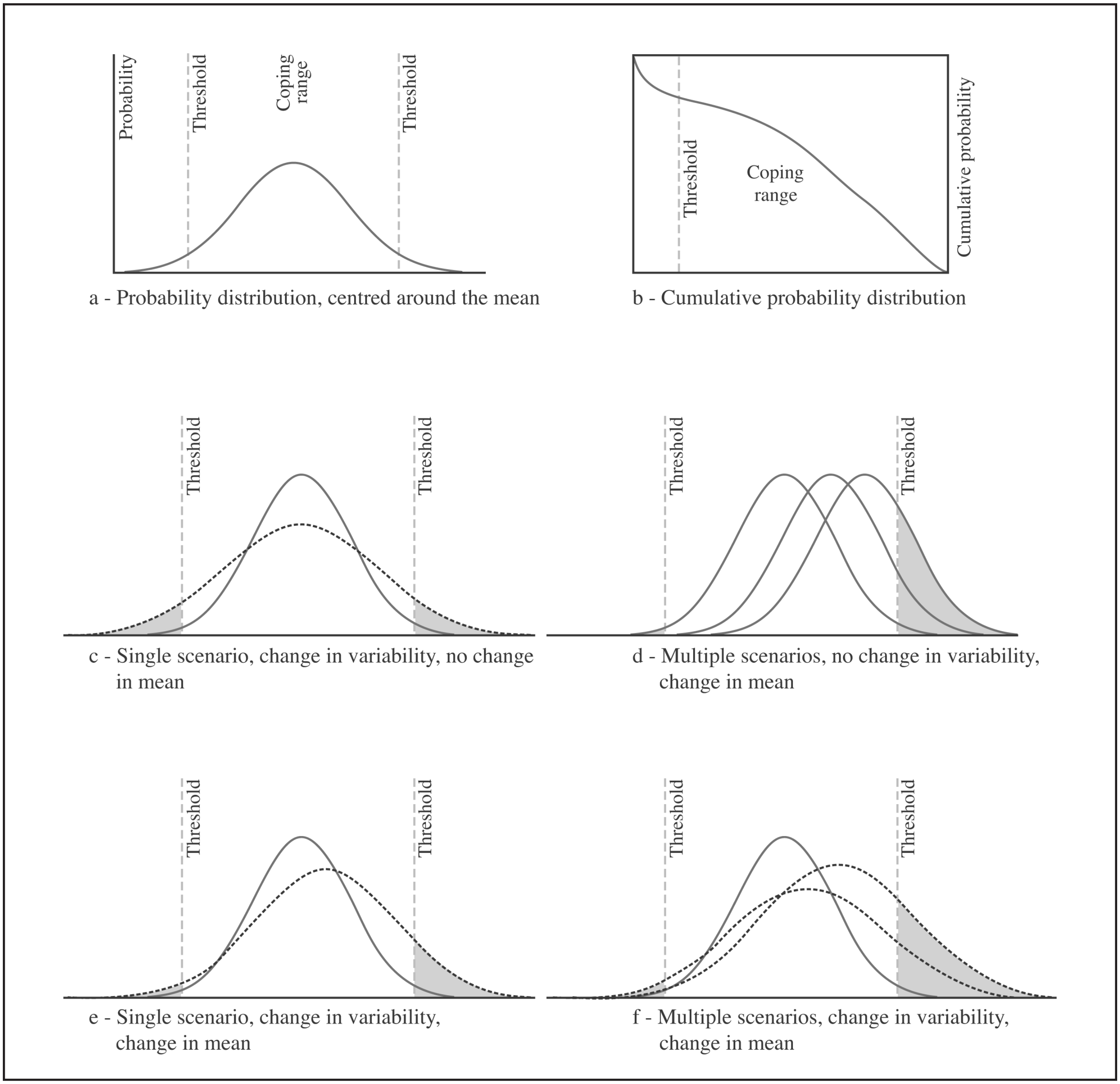
Many scenarios will combine both frequency-based and single-event uncertainties. Care will need to be taken to track both implicit and explicit assumptions in scenarios and to ensure that stakeholders understand how different uncertainties are being applied. If stakeholders can see how their existing understanding about climate and risk is incorporated into scenarios, then they will have a better chance of understanding how climate change uncertainties have been managed.

Figure 5-6 features different combinations of these two types of uncertainty in probabilistic terms:

- Graph "a" shows a normal distribution for a single variable shown as a distribution around the mean with nominal thresholds or risk criteria shown. This is a two-sided distribution.
- Graph "b" is a cumulative probability distribution that may be one sided, as for daily rainfall, or a cumulative representation of a probability distribution similar to the one on the left. These are typical of the types of frequency-based probabilities discussed in TP4.
- Graph "c" represents a change in variance with no change in mean.
- Graph "d" indicates multiple scenarios with changing means but fixed variance. This is the type of climate scenario where historical climate variability is scaled by a change in mean to estimate the impacts of different degrees of warming.
- Graph "e" exhibits a change in both mean and variance for a single scenario.
- Graph "f" displays changes in both variance and mean and is the most complex to produce and interpret.

Assessments that are considering the types of analyses illustrated in Figure 5-6 are encouraged to undertake a sensitivity analysis first, to quantify the impact for a given level of change. If changes in variance are likely to be dominated by changes to the mean (e.g., as in Figure 5-6, Graph d) then do not attempt producing scenarios for altered climate variability – use the historical variance. If changes in variance are important (e.g., where heavy rainfall is critical), then variability may be the most important factor.

By comparing scenarios to each other and situating them within broader ranges of uncertainty, it is possible to build up a picture of relative likelihoods. For example, if different climate models produce a consistent change in regional climate of warmer, wetter or drier conditions, then this change may seem



a - Probability distribution, centred around the mean

b - Cumulative probability distribution

c - Single scenario, change in variability, no change in mean

d - Multiple scenarios, no change in variability, change in mean

e - Single scenario, change in variability, change in mean

f - Multiple scenarios, change in variability, change in mean

Figure 5-6: Constructions of different types of probabilities changing mean and variance, shown with thresholds/risk criteria to demonstrate how different representations of probability in scenario construction can be used to estimate change in risk.

more likely. Critical thresholds linked to small magnitudes of global warming will be more likely to be exceeded than those that manifest under larger magnitudes of global warming. The same situation exists for sea level rise, low lying areas will be those most at risk from inundation and surge.

5.4.6. Conducting climate change risk assessments

The conventional seven-step method has been to apply climate change scenarios, either to perturb a baseline climate, or directly to impact models, to see how much impacts may change (Carter et al., 1994; Carter and Parry, 1998). Adaptation options are then assessed to reduce those impacts. Types of assessments and their needs have multiplied since that method was first formulated (Carter et al., 1994) creating a demand for a variety of assessment techniques. For that reason, Figure 5-3 is a generic procedure that can be populated by many different analytic techniques, including those used in the seven-step method. These techniques can range from qualitative analysis (e.g., partitioning the outcomes into low, medium and high risk) to highly advanced numerical techniques (probabilities calculated using statistical and/or modelling techniques).

Qualitative methods can use conceptual models incorporating elements of climate change (see TP4 for the development of conceptual models under current climate), informed by broad projections of global or regional climate change as being representative of "typical" climate scenarios. Narrative approaches may develop several plausible storylines of how climate may change, encouraging stakeholders to investigate how they would personally cope with such changes, suggesting adaptation options to manage potential risks. At the very least, this process will sensitise stakeholder groups to the issues surrounding adaptation to climate change. Hybrid approaches using existing quantitative models with qualitative assessments of future climate and socio-economic outlooks can also be instructive. The development of integrated scenarios, where consistent climate and socio-economic scenarios may also be addressed in a qualitative or semi-quantitative way, can also be used to promote a dialogue with stakeholders. See TP6 for issues relating to the alignment of SRES climate and greenhouse gas emission scenarios at a local or regional scale. Morgan et al. (2002) contains a rich assortment of techniques that can be used in risk communication. Willows and Connell (2003) also contains a range of useful methods.

Most risk assessments undertaken in developing countries are generally qualitative or semi-quantitative, but requests for quantitative information by policy makers require an improved capacity to quantify outcomes. Many of the established methods will still be used but will increasingly be modified for particular styles of assessment. For methods on how to create and apply climate scenarios, the IPCC-TGCIA guidelines (1999) and seven-step method of impact assessment (Carter et al., 1994; Carter and Parry 1998; UNEP, 1998) users are referred to existing guides.

Four assessments of current climate risk are featured in TP4. Of those, Box 4-2 has a future Component but is largely an assessment of current risk together with a brief assessment of possible future changes to determine whether managing current risk would also reduce future risks. This next example is similar but opens up the question of how to follow up once short-term adaptations are put in place.

Box 5-3 details an example of a risk assessment investigating a natural hazard (drought). The analysis shows that current climate risks are severe; climate variability, and therefore drought risk, is increasing. Projections from three GCM show that rainfall is likely to decrease and temperature (and by extension evaporation) will increase. A vulnerability study shows that drought currently causes armed conflict. This risk has been communicated to the government and stakeholders who have negotiated a series of adaptations.

In this case, adaptation was badly needed to prevent recurring shocks that were causing famines, requiring years of recovery. Once basic protection against climate hazards is achieved, the emphasis can shift to adapting to increase productivity and protection of the natural resource. This requires longer-term planning horizons, gradually moving the emphasis of assessments from current risks towards future climate risks. Permanent water points create their own environmental stresses, population growth will continue and further drying is projected to increase climate risks. Risk assessments that explicitly formulate the likelihood of continuing climate hazards, and those that investigate the vulnerability of local populations to climate will clearly be of value in ensuring a growing population can continue to reduce their exposure to environmental risks in a changing climate.

Box 5-3: Drought risk assessment in Uganda

Location: The Ugandan cattle corridor, running from the northeast to the southwest of the country, is a semi-arid area populated by over 41% and 60% of Uganda's human and cattle population respectively. The Karamoja region in the northeast of the cattle corridor is a nomadic pastoralist region covering approximately 24,000 km^2 (10% of the country). It has an average annual rainfall of 745 mm, ranging between 450 mm during severe drought years to 1000 mm during wet years.

Impacts: Droughts are increasing in frequency resulting in loss of water supply and pastures. Cattle keepers are forced to move livestock to other areas, resulting in cattle rustling, intertribal fighting and overall environmental insecurity. A recent study identified this area as one where environmental degradation, particularly drought, has caused armed conflict.

Traditional adaptation: Nomadism and migration are the major adaptive measures. Population growth is placing pressure on nomadic lifestyles while migration has been the catalyst for armed conflict and warfare. Warfare has moved from using bows and spears to automatic machineguns and rifles, threatening regional and national security.

Risk analysis: An initial vulnerability assessment under climate change using three GCM was carried out. It concluded that a doubling of CO_2 would increase the temperature by 2–4°C and decrease rainfall by 10–20% (>1 mm day^{-1}). The annual rainfall variability of the area has been increasing over the last 3 decades and is expected to increase further due to climate change.

Adaptation measures: Through a wide stakeholder consultation, the government has agreed to construct valley dams and tanks (surface water reservoirs) to supply stock during drought years. Eight reservoirs have been constructed of the 58 planned. The risk to drought impacts has decreased and the coping range increased, with available water for most drought years. However, land degradation is occurring near the reservoirs and water supply has periodically been contaminated. (Source: S. Magezi)

Although the APF stresses the need to assess current vulnerability and adaptation as part of planning for the future, current levels of adaptation need to be assessed for their adequacy in managing a changing climate. Box 5-4 shows an assessment that looks at possible changes to agricultural production in India. It uses an approach that accounts for current adaptations in agriculture, as expressed as farm-level net revenue aggregated to state and national scale (Kumar and Parikh, 2001). This assessment suggests two things: 1) that developing countries face possible decreases in agricultural production compared to gains in developed countries using similar assessment techniques and 2) that current adaptations may be insufficient to manage losses under climate change.

The advantage of this approach is that it factors current adaptation into the assessment, and includes climate variability, albeit as it affects mean net revenue. The disadvantage is that the effects of CO_2 are not included as they would be in a more conventional crop modelling exercise. However, crop models generally do not simulate adaptations all that well, although a new generation of models such as the Agricultural Production Systems sIMulator (APSIM) (Keating et al., 2003) are beginning to do so. Both the method in Box 5-4, and crop modelling approaches, have distinct advantages that can be used to illustrate different aspects of risk. When different methods agree, some added confidence can be attached to the results.

Annex A.5.1 summarises a risk assessment of water supply that uses both a natural hazards and vulnerability-based approach to assessing risk in a catchment in eastern Australia. This assessment applied multiple climate scenarios to an existing rainfall-runoff and river management model to determine changes in mean annual water supply, irrigation allocations and environmental flows. A relationship between changes in rainfall, potential evaporation and water supply allowed conditional probability distributions of possible outcomes to be created. A natural hazards-based approach concluded that storage, irrigation and environmental flows would most likely change by 0% to -15% by 2030 from a total range of possibilities of +10% to -35%.

A complementary vulnerability-based assessment utilised two thresholds that represented a serious risk within the catchment. The first was a failure of irrigation supply to exceed 50% of the allocation levels five years running and the second that breeding of colonial water birds in a RAMSAR-gazetted wetland failed ten years running. It was found that the risk of exceeding this threshold depended on long-term rainfall variability in addition to climate change. If rainfall variability was “normal”, the probability of exceeding critical thresholds was negligible by 2030. However, if rainfall variability was in a drought-dominated phase, then the chance of exceeding the critical thresholds was about one in three. This catchment has been designated as fully to over-allocated in a recent audit (NLWRA, 2002), so adaptation to climate change is now seen as a necessary part of ongoing water reform, and investigations are ongoing.

Few risk assessments under climate change have so far utilised vulnerability-based approaches in a quantitative manner. However, a rich literature assessing qualitative approaches and vulnerability, to current climate suggests that significant development in this area is possible (TP3). Probabilistic approaches that apply a natural hazards approach in a “top down” manner, applying climate change scenarios to impact models to determine vulnerability are also being developed. Bottom-up approaches, where local criteria for risk denoting critical thresholds are constructed, then assessed for likelihood of exceedance are few, but this method has the potential to manage some (but not all) of the limitations of the natural hazards-based approach.

5.4.7. Managing climate risks

The main purpose of risk assessment is to determine the need for risk management (the reduction of risk). Adaptation to climate change reduces risk by altering human and environmental responses to climate hazards. (The hazards themselves are altered by the mitigation of greenhouse gases). Adaptation will increase the breadth of the coping range allowing successively

Box 5-4: Sensitivity of agricultural production in India to climate change

This study estimated the relationship between farm-level net revenue and climate variables in India using cross-sectional evidence (Kumar and Parikh, 2001). It used an economic approach expressed as farm-level net revenue. A number of variables including temperature, rainfall, soil, technology, fertiliser and altitude were used to estimate a regression relationship with economic data from the yields of twenty crops across India. Temperature and rainfall of January, April, July and October are converted into anomalies, along with crop prices. Data for the 271 districts was from the decade 1970–1980; climate data was from the 1960–1980 time period. The response functions that explain the variation in price across districts therefore incorporate climate variability and adaptation to the mean climate and variability for the 10-year period that baseline climate data were available.

A “best-guess” climate change scenario was used to estimate possible changes due to climate. A rise of 2°C and an increase in rainfall of 7% was used as an illustrative scenario to determine how a mid-range or “best guess” climate change might affect Indian agriculture. The decrease in total economic yield was approximately 8%, being largest in the northern states. The eastern states registered increases. The impacts were larger than for those estimated in the United States using similar models, presumably due to India’s warmer temperatures and lower levels of technology.

larger and/or frequent climate hazards to be managed. For example, the provision of a reliable water supply or food aid to dryland farming communities will mean they can manage more severe and frequent droughts – to a point (Box 5-3 and TP4, Box 4-2). If an assessment system can quantify a change in critical thresholds, then it will be possible to quantify the benefits of adaptation under climate change, and to create the conditions by which a cost-benefit analysis may be carried out (TP8).

5.5. Conclusions

The major purpose of assessing climate change risk within the APF is to help prioritise possible adaptations that may be feasible. Some measures, such as no-regrets options, or generic measures that will provide adaptation benefits in a broad range of plausible circumstances, will prove to be better than others. This applies to the development of adaptive capacity in particular (TP7). A detailed knowledge of both current and future hazards, and how they may affect societies, can help provide guidance for adaptation, even if a modelling system that quantifies these links cannot be constructed.

Again, given the levels of uncertainty that accompany assessments of future climate risks, teams will need determine how much information is needed in order to make decisions on adaptation policy. Projects should not over-deliver, but if policy makers have significant demands, projects can inform them of the resources needed to meet those demands, including the resources needed to develop assessment methods. There are some recipes available, but continuing exploration of a relatively new area of assessment will be needed.

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ANNEX

Annex A.5.1. Climate change risk assessment utilising probabilities and critical thresholds

This annex describes a recent assessment that quantifies likely changes and assesses critical thresholds for an Australian catchment (Jones and Page, 2001). The modelling system coupled a climate scenario generator to a rainfall-runoff and river management model. Regional changes to potential evaporation (Ep) and precipitation (P) were used to perturb daily records of P and Ep from 1890–1996. The historical time series includes a drought-dominated (dry) period (1890–1947) and a flood-dominated (wet) period (1948–1996) allowing different modes of decadal rainfall variability to also be assessed. Three outputs were considered for risk assessment: storage in the Burrendong Dam (the major water storage), environmental flows to the Macquarie Marshes (nesting events for the breeding of colonial water birds), and proportion of irrigation allocations met over time.

Quantifying outcomes

Fifty-six simulations were run using a range of scenarios exploring the IPCC (2001) range of global warming, and regional changes in P and Ep from nine climate models. These models were then used to create the following transfer function:

$$\delta\text{flow} = a \text{ ¥ } (\text{atan}\,(\delta Ep / \delta P) - b)$$

where δEp and δP were measured in mm yr^{-1}, δflow is mean annual flow in GL yr^{-1} and percent, atan is the inverse tan function, and a and b are constants. The results have an r^2 value of 0.98 (suggesting that 98% of the results fall within one standard deviation of the uncertainty contained within the relationship) and a standard error ranging from 1% to 2%.

According to the central limit theorem of statistics, if multiple ranges of uncertainty are combined, then the central tendencies are favoured at the expense of the extremes (e.g., Wigley and Raper, 2001). Three ranges of uncertainty contributed to the analysis: global warming and regional δP and δEp. Monte Carlo methods (repeated random sampling) were used to sample the IPCC (2001) range of global warming for 2030 and 2070. These were then used to scale a range of change per °C of global warming on a quarterly basis for P, sampling Ep using the above transfer function to estimate possible changes in mean annual water supply. The quarterly changes for P and Ep were then totalled to determine annual δP and δEp.

The following assumptions were applied:

- The range of global warming in 2030 was 0.55°–1.27°C with a uniform distribution. The range of change in 2070 was 1.16°–3.02°C.
- Changes in P were taken from the full range of change for each quarter from the sample of nine climate models.
- Changes in P for each quarter were assumed to be independent of each other (seasonally dependent changes between seasons could not be found).
- The difference between samples in any consecutive quarter could not exceed the largest difference observed in the sample of nine climate models.
- Ep was partially dependent on P ($\delta Ep = 5.75 - 0.53\delta P$, standard error = 2.00, randomly sampled using a Gaussian distribution, units in percent change).

Figure A-5-1-1 shows the results for 2030 where the probability distribution is tallied from wettest (best) to driest (worst) outcomes. Although there is an increased flood risk with increases, the drier outcomes are considered worse in terms of lost productivity and environmental function. The driest and wettest outcomes are less likely than the central outcomes where the line is steepest. The extremes of the range are about +10% to –30% in 2030 and about +25% to –60% in 2070, but the most likely outcomes range from about 0% to –15% in 2030 and 0% to –35% in 2070.

Critical thresholds

Two critical thresholds for the system were established:

1. Bird breeding events in the Macquarie Marshes, taken as 10 consecutive years of inflows below 350 GL.
2. Irrigation allocations falling below a level of 50% for five consecutive years.

Both thresholds are a measure of accumulated stress rather than a single extreme event. From the sample of runs described above, both thresholds were exceeded if mean annual flows fell below 10% in a drought-dominated climate, 20% in a normal climate and 30% in a flood-dominated climate.

Uncertainty analysis

Uncertainty analysis was carried out to understand how each of the Component uncertainties contributed to the range of outcomes. Three ranges of input uncertainty, global warming and local changes in P and Ep, were assessed by keeping each input constant within a Monte Carlo assessment, while allowing the others free play, consistent with Visser et al. (2000). Global warming was held at 0.91°C in 2030 and 2.09°C in 2070. δP was taken as the average of the nine models in percent change per °C global warming for each quarter. δEp was linearly regressed from δP, omitting the sampling of a standard deviation. In both 2030 and 2070, δP provides almost two-thirds of the total uncertainty, global warming about 25% and δEp just over 10% (Table A-5-1-1).

Table A-5-1-1: *Results of uncertainty analysis for water storage in 2030 and 2070. The ranges shown are in percent change from mean annual storage.*

2030	**Limits of range**	**Range**	**Contribution to uncertainty**
All	+10.3 to – 28.4	38.7	
Constant global warming	+7.7 to –21.4	29.1	25%
Constant P	–1.9 to –15.9	14.0	64%
Constant Ep	7.2 to –26.7	33.9	12%
			101%
2070			
All	+23.8 to –60.1	83.9	
Constant global warming	+17.3 to –45.8	63.1	25%
Constant P	–4.6 to –34.0	29.4	65%
Constant Ep	16.3 to –57.7	74.0	12%
			102%

Bayesian analysis

Bayesian analysis involves testing of input assumptions on the resulting probabilities. The tests are as follows:

1. Sampling intervals for δP and δEp were altered from quarterly to six-monthly and annually to determine whether the sampling interval affected the results. Figure A-5-1-2 shows the results as they affect the probability distribution of changes to mean annual Burrendong storage in 2030. Also shown are the original individual scenario runs, which are treated as having equal probability. The resultant probability distributions for six-monthly and annual sampling produce higher flows, but the results do not change by more than 10% from the original distribution in most cases.

2. The next test was to determine this impact of a non-uniform distribution of global warming, compared to the uniform distribution originally used. Wigley and Raper's (2001) non-linear distributions for global warming in 2030 and 2070 – based on input uncertainties for emissions scenarios, radiative forcing, atmospheric greenhouse gas modelling and climate sensitivity – were substituted for a uniform distribution. This has little effect on the results (Figures A-5-1-3 and A-5-1-4), which is consistent with global warming forming only 25% of the input uncertainties. Only very large changes in the range or distribution of global warming would be expected to significantly affect the outcome.

3. The distributions of rainfall change were altered by applying cubic polynomial regressions to the range provided by the nine models, counting the lowest and highest sample as the 10th and 90th percentile, respectively, thereby extending the range of rainfall change. These were added to the non-linear distributions for global warming (Figures A-5-1-3 and A-5-1-4). Although the total ranges have increased by 2% and 31% in 2030 and 20% and 55% in 2070 for the "W&R warming" and "All" cases, the distributions remain similar for the major part of the range.

These results show that the "most likely" parts of the ranges are not greatly expanded by increasing the ranges of uncertainty by the amounts here. The input ranges of uncertainty for rainfall for the Macquarie catchment are about ±4% per degree of global warming. These would have to be expanded considerably to alter the risk to water supply.

Impact on policy

Previously, water managers in Australia were influenced by the uncertainty in rainfall change that indicated increases and decreases (in the Macquarie catchment, the range is about ±4% per degree of global warming), transferring this outcome to similar uncertainties in flow. The identification of seasonal decreases of rainfall

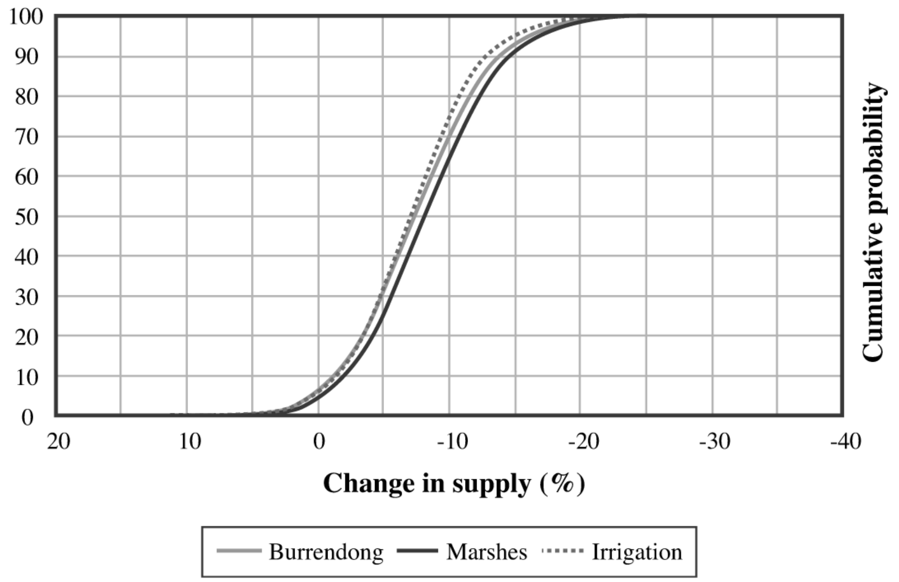

Figure A-5-1-1: Probability distribution for changes to mean annual Burrendong Dam storage, Macquarie Marsh inflows and irrigation allocations, based on Monte Carlo sampling of input ranges of global warming, δP and δEp in 2030.

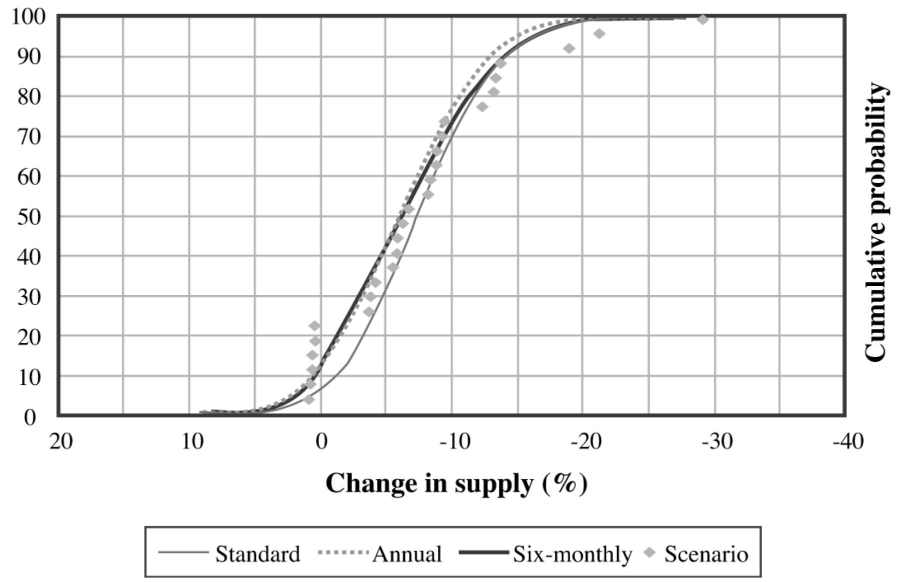

Figure A-5-1-2: Impact of individual scenarios, quarterly (standard), six-monthly and annual sampling of δP and δEp on the probability distribution for changes to mean annual Burrendong storage in 2030.

in the winter-spring period in all the climate models investigated, construction of potential evaporation scenarios and this work, has contributed to a change in attitude.

This risk assessment has already contributed to policy that is overseeing the development of environmental flow regimes for the Murray River. The finding that water availability is likely to decrease, and that critical thresholds may be crossed under a drought-dominated climate, has been sensitised by a series of dry years and findings that allocations in the catchment being investigated were above sustainable levels. It is now being speculated that the decrease in rainfall may be similar to decadal shifts experienced in southwest Western Australia and in the Sahel. Further work is investigating whether current water policy measures and changes being planned are sufficient to manage the risks that have been identified.

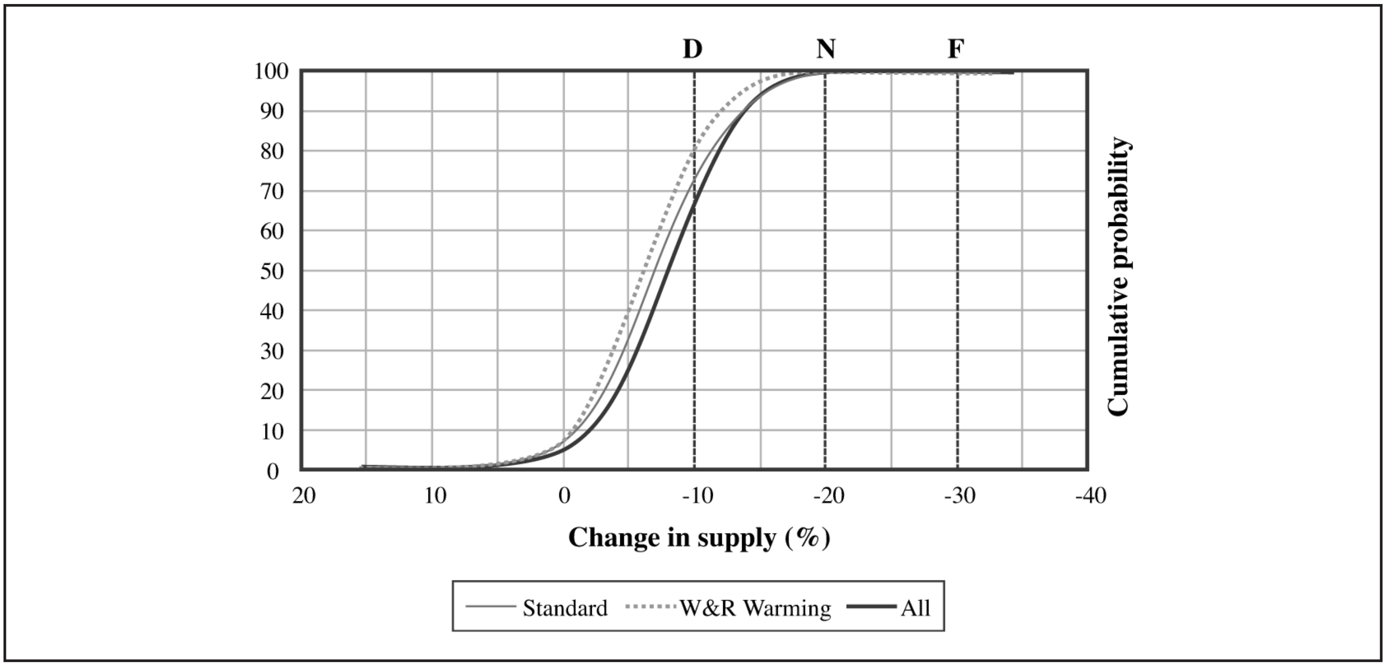

Figure A-5-1-3: Impact of uniform sampling, non-linear sampling of global warming (Wigley and Raper, 2001) and non-linear sampling of rainfall change (All) on the probability distribution for changes to mean annual Burrendong storage in 2030. Critical thresholds under a drought-dominated climate (D), flood-dominated climate (F) and normal climate (N) are also shown.

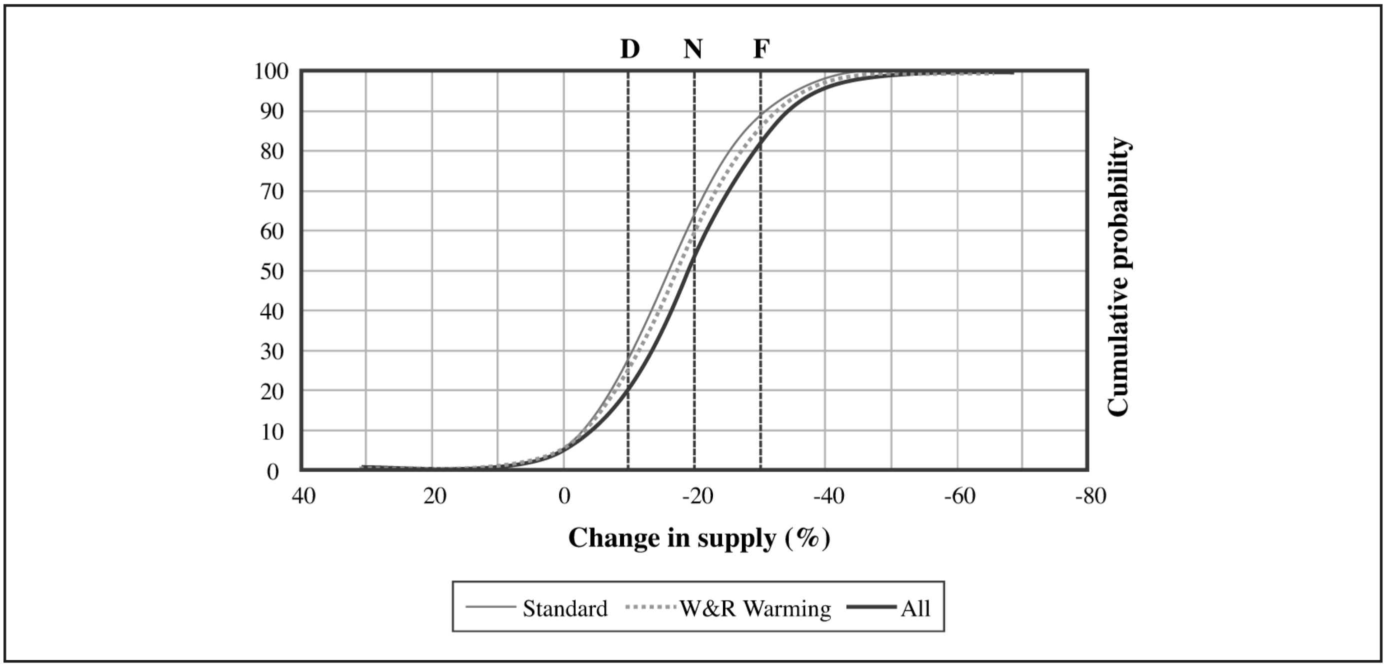

Figure A-5-1-4: Impact of the uniform sampling, non-linear sampling of global warming (Wigley and Raper, 2001) and non-linear sampling of rainfall change (All) on the probability distribution for changes to mean annual Burrendong storage in 2070. Critical thresholds under a drought-dominated climate (D), flood-dominated climate (F) and normal climate (N) are also shown.