DECADAL CLIMATE FORECASTING TECHNIQUES FOR ADAPTATION AND DEVELOPMENT PLANNING

A BRIEFING DOCUMENT
ON
AVAILABLE METHODS, CONSTRAINTS, RISKS AND OPPORTUNITIES

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Introduction

1. Integration of climate risk information in adaptation planning is now a priority for donor and environmental agencies alike. Although the use of climate scenarios for impact assessment has grown steadily since the 1990s, uptake of such information for adaptation is only just beginning. In terms of volume of scientific output, adaptation is trailing impact assessment by nearly a decade.

2. This project was commissioned by the UK Government's Department for International Development (DFID) to consider what steps could be taken to adapt infrastructure investments and economic planning to climate variability and change in the 2020s (defined hereon as 2011-2040). Attention in this report is focused, in particular, on the information needs for regional climate prediction and impact assessment in Africa, but Asia and Latin America are also considered.

3. The purpose of this document is to:

- describe the climate outlook for the next couple of decades and derive the implications of this outlook on adaptation assessments;
- review ways in which climate risk information is already being incorporated in adaptation assessments;
- evaluate the strengths and weaknesses of available approaches;
- identify knowledge gaps and opportunities for improving the production and uptake of climate change risk information for the 2020s.

The climate outlook for the next 20 years

4. Despite variations in process representation, there is now remarkable agreement amongst different Global Climate Models (GCMs) on projected global mean temperatures for the next two or three decades. The consensus is that much of the warming in coming years will reflect the climate's response to past emissions and the thermal inertia of the oceans. According to the UK Met Office, the year 2014 is predicted to be 0.30º ± 0.21ºC warmer than 2004, and at least half the years after 2009 are expected to be warmer than 1998, currently the warmest year on record

5. However, global averages conceal significant regional variations in temperature anomalies and, despite significant technical advances in decadal forecasting capability, the products will remain of limited value to policy-makers and planners until skilful forecasts of regional climate anomalies become available. Nonetheless, existing technology *could* help quantify changes in the *risk* of occurrence of certain types of extreme (such as severe heatwaves, droughts or widespread flooding).

Implications with regards to adaptation assessment approaches

6. The human signal, though detectable and growing, will be a relatively small component of climate change over the 2020s. Although the sustainability of MDGs could be undermined by climate change in the long-term, the risk exposure of donor

portfolios will be greatest where human and environmental systems are already marginal (such as semi-arid regions, or coastal zones subject to frequent flooding). In these cases, even modest changes in the mean climate or to extremes could be sufficient to cross a threshold or tipping point. Furthermore, meteorological changes could be amplified by non-linear responses in secondary impacts in ways that are currently not reflected in climate models.

7. This implies the need for a twin-track approach. On the one hand, development of the scientific and economic capacity to identify critical thresholds and to better understand and cope with climate variability. On the other hand, development of climate forecast tools and data sets that capture incremental changes in risk over the scales needed for adaptation planning.

Uses of climate risk information for adaptation planning

8. A wide range of end users are already seeking climate risk information to inform their actions. Table 2 in the report, reproduced here, summarises this range.

Table 2 Examples of adaptation activities that require climate risk information.

Adaptation	**Examples of activity using climate information**
New infrastructure	Cost-benefit analysis, infrastructure performance and design
Resource management	Assessment of natural resource availability, status, allocation
Retrofit	Scoping assessments to identify risks and reduce exposure to extreme events
Behavioural	Measures that optimise scheduling or performance of existing infrastructure
Institutional	Regulation, monitoring and reporting
Sectoral	Economic planning, sector restructuring, guidance, standards
Communication	Communicating risks to stakeholders, high-level advocacy and planning
Financial	Services to transfer risk, incentives, insurance

9. No single climate scenario can meet the needs of all these adaptation activities. There is an over-riding imperative that the most appropriate scenario method is matched to the intended application, taking into account local constraints of time, resources, human capacity and supporting infrastructure. As a result, a wide range of approaches to climate forecasting have been developed to suit the particular needs of the end-users, which are described and evaluated below.

Overview of scenario methods

10. The approaches used by practitioners can be classified into three groups, reflecting increasing demands on technical, infrastructure and resource capacity:

- ***Entry level methods*** include sensitivity analysis, change factors, climate analogues, and trend extrapolation. These offer site- or area-specific climate risk information, are modestly data dependent, and place minimal demands on technical resources. As such they are valuable for scoping assessments and awareness raising.
- ***Intermediate level methods*** include pattern-scaling, weather generation and empirical downscaling. These employ statistical methods to describe present and future climate behaviour at regional or site specific scales. Some bespoke software allows free access to sophisticated models through user-friendly interfaces.
- ***Advanced level methods*** include regional climate models (RCMs) and coupled Ocean-Atmosphere/Global Climate Models (OA/GCMs). Both require a high degree of specialist knowledge and computing resource but are the only methods that physically represent radiative forcing of the climate. Since GCMs provide output used by many other methods, unhindered access is paramount.

11. Table 4 in the main report, reproduced below, considers the technical advantages and disadvantages of these different methods.

Evaluation of forecasting approaches

12. Tables 5 in the main report, reproduced below, summarises the criteria used to evaluate the usefulness of the approaches to decadal forecasting for the purpose of adaptation planning.

13. The way in which the different approaches fare against these criteria is summarised in table 6 of the main report, reproduced below:

Secondary impacts modelling

14. Environmental models, such as crop growth and watershed models are often used to translate climate change projections into secondary impact forecasts. These models compound the uncertainties of climate forecast models, which is, unfortunately, seldom quantified , let alone reported. This oversight is of particular concern whenever impacts for the 2020s are evaluated because the emission uncertainty is negligible and the climate change signal can be weak relative to climate variability. Under these circumstances impact model uncertainties can dominate, particularly when analysing extreme events. Therefore, much greater onus should be placed on improving and critiquing secondary impact models, as standard practice.

Table 4 Options for constructing regional climate change scenarios, listed in order of increasing complexity and resource demand. Example adaptation activities (from Table 2) are shown in *italics*.

Method (application)	**Advantages**	**Disadvantages**
Sensitivity analysis *Resource management, Sectoral*	1. Easy to apply; 2. Requires no future climate change information; 3. Shows most important variables/ system thresholds; 4. Allows comparison between studies.	1. Provides no insight into the likelihood of associated impacts unless benchmarked to other scenarios; 2. Impact model uncertainty seldom reported or unknown.
Change factors *Most adaptation activities*	1. Easy to apply; 2. Can handle probabilistic climate model output	1. Perturbs only baseline mean and variance; 2. Limited availability of scenarios for 2020s.
Climate analogues *Communication, Institutional, Sectoral*	1. Easy to apply; 2. Requires no future climate change information; 3. Reveals multi-sector impacts/ vulnerability to past climate conditions or extreme events, such as a flood or drought episode.	1. Assumes that the same socio-economic or environmental responses recur under similar climate conditions; 2. Requires data on confounding factors such as population growth, technological advance, conflict.
Trend extrapolation *New infrastructure (coastal)*	1. Easy to apply; 2. Reflects local conditions; 3. Uses recent patterns of climate variability and change; 4. Instrumented series can be extended through environmental reconstruction; 5. Tools freely available.	1. Typically assumes linear change; 2. Trends (sign and magnitude) are sensitive to the choice/length of record; 3. Assumes underlying climatology of a region is unchanged; 4. Needs high quality observational data for calibration; 5. Confounding factors can cause false trends.
Pattern-scaling *Institutional, Sectoral*	1. Modest computational demand; 2. Allows analysis of GCM and emissions uncertainty; 3. Shows regional and transient patterns of climate change; 4. Tools freely available.	1. Assumes climate change pattern for 2080s maps to earlier periods; 2. Assumes linear relationship with global mean temperatures; 3. Coarse spatial resolution.
Weather generators *Resource management, Retrofitting, Behavioural*	1. Modest computational demand; 2. Provides daily or sub-daily meteorological variables; 3. Preserves relationships between weather variables; 4. Already in widespread use for simulating present climate; 5. Tools freely available.	1. Needs high quality observational data for calibration and verification; 2. Assumes a constant relationship between large-scale circulation patterns and local weather; 3. Scenarios are sensitive to choice of predictors and quality of GCM output; 4. Scenarios are typically time-slice rather than transient.
Empirical downscaling *New infrastructure, Resource management, Behavioural*	1. Modest computational demand; 2. Provides transient daily variables; 3. Reflects local conditions; 4. Can provide scenarios for exotic variables (e.g., urban heat island, air quality); 5. Tools freely available.	1. Requires high quality observational data for calibration and verification; 2. Assumes a constant relationship between large-scale circulation patterns and local weather; 3. Scenarios are sensitive to choice of forcing factors and host GCM; 4. Choice of host GCM constrained by archived outputs.
Dynamical downscaling *New infrastructure, Resource management, Behavioural, Communication*	1. Maps regional climate scenarios at 20-50km resolution; 2. Reflects underlying land-surface controls and feedbacks; 3. Preserves relationships between weather variables; 4. Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high; 2. Scenarios are sensitive to choice of host GCM; 3. Requires high quality observational data for model verification; 4. Scenarios are typically time-slice rather than transient; 5. Limited availability of scenarios for 2020s.
Coupled AO/GCMs *Communication, Financial*	1. Forecasts of global mean and regional temperature changes for the 2020s; 2. Reflects dominant earth system processes and feedbacks affecting global climate; 3 Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high (supercomputing); 2. Scenarios are sensitive to initial conditions (sea surface temperatures) and external factors (such as volcanic eruptions); 3. Scenarios are sensitive to choice of host GCM; 4. Coarse spatial resolution.

Table 5 Summary of attributes to assess the relative merits of different scenario options.

Indicator	**Preferred attributes for development and adaptation planning**
Capacity	Low personnel, technical and infrastructure requirements
Resources	Low data, time and financial costs
Spatial	High spatial resolution (site or region, not continental or global)
Temporal	High temporal resolution (hourly or daily, not monthly or annual)
Outputs	High realism and joint behaviour of weather variables
Forcing	High ability to represent different external forcing (land cover, aerosols)
Uncertainty	High capability for providing probabilistic information
Pattern	High ability to produce surfaces or maps of climate change
Transient	High ability to produce transient (rather than time-slice) scenarios
Tools	High availability of tools, supporting data and guidance

Table 6 Assessment of the extent to which different scenario methods can support climate impact and adaptation assessments for the 2020s[1].

Scenario methods	**Capacity**	**Resources**	**Spatial**	**Temporal**	**Outputs**	**Forcing**	**Uncertainty**	**Pattern**	**Transient**	**Availability**
Sensitivity analysis	🟩	🟩	🟩	🟧	🟩	🟧	🟩	🟧	🟥	🟩
Change factors	🟩	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟥	🟩
Climate analogues	🟧	🟧	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟩
Trend extrapolation	🟩	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩	🟩
Pattern-scaling	🟧	🟧	🟥	🟧	🟩	🟧	🟩	🟩	🟩	🟩
Weather generation	🟧	🟧	🟩	🟩	🟩	🟥	🟩	🟧	🟧	🟩
Empirical downscaling	🟧	🟧	🟩	🟩	🟩	🟥	🟩	🟧	🟩	🟧
Dynamical downscaling	🟥	🟥	🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟧
Coupled OA/GCMs	🟥	🟥	🟥	🟧	🟩	🟩	🟩	🟩	🟩	🟩

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[1] The headings refer to the desirable attributes listed in Table 5. Key to cells: **red** (disagree), **amber** (neutral or depends), **green** (agree).

Future opportunities to improve the science and information

15. There is an over-arching need to *translate available scientific evidence into guidance* for practitioners. Technical guidance is urgently needed on:

- appropriate infrastructure design and climate sensitive planning,
- avoidance of high-risk areas through land use regulations,
- incorporation of climate change allowances in the engineering standards applied to flood defences and water supply systems,
- the management of natural resources
- climate change impacts on and adaptation options for economic growth strategies.

16. The report lists several opportunities for improving the usefulness of decadal climate forecasting in development planning. These include:

- Improving the primary data base:
  - Reviewing progress since publication of the Gleneagles Plan of Action in 2005 on securing observing networks and access to climate data;
- Improving the science base:
  - Designing field and model experiments to address fundamental knowledge gaps on teleconnections and climate mechanisms affecting vulnerable regions;
  - Improving forecasting of climatic hazards, such as intense heatwaves, air pollution episodes or flooding in urban environments;
- Improving communication of climate data and forecasts:
  - Supporting online portals that target the specific needs of developing regions by increasing access to climate scenario tools, user guidance and products.
- Improve guidance for interpretation:
  - Improving guidance on the treatment of impacts model uncertainty;
  - Developing frameworks for upscaling knowledge on impacts to assist country-level adaptation;
  - Developing and applying composite climate change indices alongside measures of human development and vulnerability, to help target resources for adaptation.

1. Introduction

Integration of climate risk information in adaptation planning is now a priority for donor and environmental agencies alike (DFID, 2005; World Bank, 2006; EEA, 2007). Success will depend on improving access to high-quality meteorological data to characterise present climate variability; credible climate change scenarios at the spatial and temporal scales needed to support decision-making; technical capacity to undertake impacts assessment, options appraisal, and adaptation planning; institutional and sectoral structures in place to deliver climate-proofed development programmes and projects; and the type of adaptation. The use of climate scenarios for impact assessment has grown steadily since the 1990s; in contrast uptake of such information for adaptation is only just beginning. In terms of scientific output, work on adaptation is trailing impact assessment by nearly a decade (Figure 1).

This project was commissioned by the UK Government's Department for International Development (DFID) to consider what steps could be taken to adapt infrastructure investments and economic planning to climate variability and change over the next couple of decades. Attention will focus, in particular, on the information needs for regional climate prediction and impact assessment in Africa, but Asia and Latin America are also considered.

The purpose of this document is to: (1) describe climate forecasts for the next couple of decades; (2) review ways in which climate risk information is already being incorporated in adaptation assessments; (3) explain the factors affecting choice of climate scenario method; (4) describe the strengths and weaknesses of the available approaches (from the perspective of secondary impacts modelling); and (5) identify opportunities for improving production and uptake of climate change risk information for the 2020s (defined hereon as 2011-2040). To increase accessibility of the material, scenario methods are grouped by three levels of sophistication (entry, intermediate and advanced). Although arbitrary, the categories broadly reflect increasing demands on technical, infrastructure and resource capacity.

The reader is directed to accompanying sections in the Bibliography and Annex for supporting information and supplementary case studies. Where possible, examples have been drawn from Africa, Asia and Latin America. Recommended guidance material, scenario tools, impact models and data portals are listed in the Resources section, and a Glossary provides definitions of widely used technical terms.

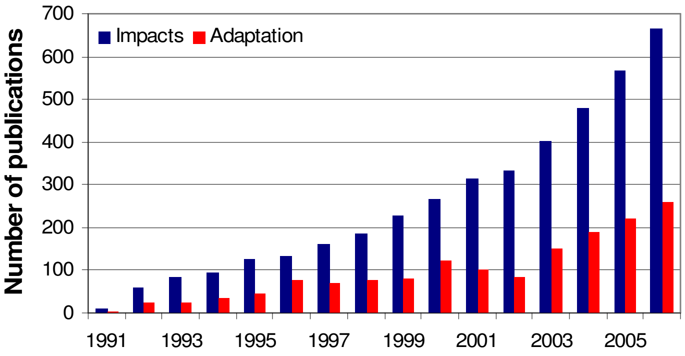


Figure 1 Annual number of climate change science publications with the words "impact" or "adaptation" in either the title or abstract. Data: Web of Science [accessed 31 July 2007].

2. The climate outlook for the next 20 years

Despite variations in process representation, there is now remarkable agreement amongst different Global Climate Models (GCMs) on projected global mean temperatures for the next two or three decades (Zwiers, 2002). The agreement stems from the fact that much of the warming in coming years will reflect the climate's response to past emissions and the thermal inertia of the oceans. The consensus is also largely independent of the assumed emission scenario. Regardless of the GCM or SRES emissions, the change in global mean temperature is projected to be ~0.2ºC/decade, compared with ~0.1ºC/decade if emissions are held at year 2000 levels (Table 1). Furthermore, the projected mean warming to 2030 is twice as large as model-estimated natural variability during the 20th century (Meehl et al., 2007).

Table 1 Global mean warming from the IPCC multi-model ensemble mean for three periods relative to 1980-1999 under A2, A1B and B1 SRES emissions scenarios. The 'Commit' row refers to the committed warming with emissions stabilised at year 2000. Source: IPCC (2007).

Emissions	**2011-2030**	**2046-2065**	**2080-2099**
A2	0.64	1.65	3.13
A1B	0.69	1.75	2.65
B1	0.66	1.29	1.79
Commit	0.37	0.47	0.56

Natural climate variability over decades is closely connected to the behaviour of major ocean circulations in the Atlantic and Pacific. For example, the Atlantic Multidecadal Oscillation (AMO) charts variations in the conveyance of warm surface water from the Caribbean to the North Atlantic that have been linked to a host of global climate shifts including drought in the Sahel, levels of hurricane activity, and rainfall anomalies over Brazil (Baines and Folland, 2007). This implies that a swing from a warm to a cool state could trigger an abrupt shift in the climate (as in the 1960s) that could, in the short-term, counteract long-term anthropogenic warming over large parts of the globe. Such a cool downturn could pose a significant reputational risk to organisations that communicate or plan only for a warming scenario over the next few decades.

Despite improving understanding of decadal climate controls, there is even less certainty about temperature forecasts for individual years over the next 10-years. On this timescale, temperature forecasts are dominated by higher frequency climate variations and external forcing by natural and anthropogenic factors. Whilst changes in forcing by external factors such as solar irradiance and volcanic eruptions can have a substantial and lasting impact on the climate system (e.g., Gleckler et al., 2006), their magnitude in the near-term is much harder to predict. However, the impact of the assumed initial condition of the atmosphere and ocean on model generated variability is much more tractable and has long been recognised (Pielke, 1998).

Hence, the long-term "memory" of ocean heat content is now being exploited in state-of-the-art decadal climate forecasts (Figure 2). According to the UK Met Office, the year 2014 is predicted to be 0.30º ± 0.21ºC warmer than 2004, and at least half the years after 2009 are expected to be warmer than 1998, currently the warmest year on record (Smith et al., 2007). However, global averages conceal significant regional variations in temperature anomalies and, despite significant technical advances in decadal forecasting capability, the products will remain of limited value to policy-makers and planners until skilful forecasts of regional climate anomalies become available. Nonetheless, existing technology *could* help quantify changes in the *risk* of occurrence of certain types of extreme (such as severe heatwaves, droughts or widespread flooding). For example, it has been estimated that emissions of atmospheric greenhouse gases to date have more than doubled the risk of a European heatwave exceeding that of summer 2003 (Stott et al., 2004). Detecting and attributing a human influence on regional water balance terms will not be possible for many more decades because of the relatively small climate change signal in relation to large year-to-year variations (e.g., Ziegler et al., 2005). Furthermore, the strength of the human signal to natural "noise" tends to become even weaker at finer spatial scales.

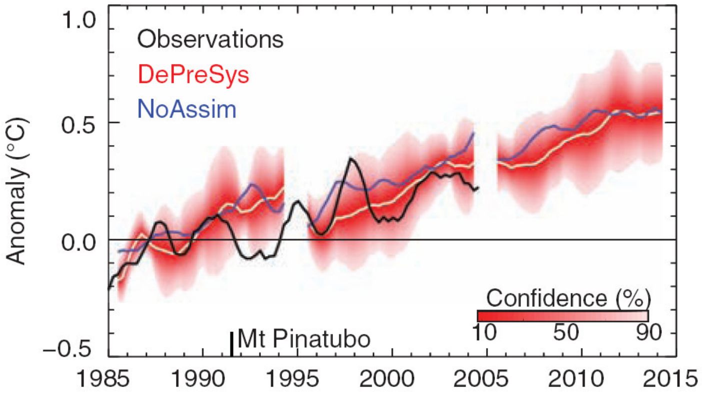


Figure 2 Global annual mean surface temperature anomaly forecast to 2015. The model provided with information about current ocean temperatures (white line) more closely matched observations (black line) than a model without (blue line). The temporary cooling effect of the Mount Pinatubo eruption is clearly evident. Source: Smith et al. (2007).

Given such uncertainty in regional-scale climate projections as well as small increments expected over the next 15-20 years, the question arises as to whether climate change will have a significant impact, especially when compared with rapid human development changes (as witnessed, for example, in China)? Or framed another way, how much climate change has to happen to be of *practical* significance? The answer(s) have a significant bearing on how climate risk assessment should addressed within adaptation and development planning – a point that is explored further in the next section.

3. Approaches to adaptation assessment

Climatologists and policy makers are calling for a more practical approach to the use of climate change scenarios – shifting the debate from high-level advocacy on "the need to act", to regional- and country-level responses on "how to" adapt (Schiermeier, 2007). However, the scope for mainstreaming scenario information in adaptation planning depends on the adaptation assessment approach, availability of technical and financial capacity, scale of the risk(s), and the type(s) of adaptation being considered (Adger et al., 2005; Dessai et al., 2005). Top-down (so-called "IPCC") approaches rely heavily on climate change scenarios, culminating in an evaluation of the adjustments needed to adapt to the projected scenarios. Conversely, human development approaches focus on reducing vulnerability to present-day climate variability and hence do not necessarily require climate change scenarios (but may deploy seasonal forecasting to provide early warning as in Dilley [2000]). Risk management frameworks lie somewhere in between because climate change scenarios are analysed, but with respect to critical impact thresholds defined by stakeholders.

The time-scale for adaptation activity is also an important consideration. Fears that climate change could undermine many of the United Nations Millennium Development Goals (MDGs), or that new investments could under perform (or even lead to maladaptation), mean that users of climate risk information are most interested in the next few decades. As has been shown, this poses huge technical problems because the global climate of coming decades will be dominated by natural variations from year-to-year and decade-to-decade arising from the chaotic nature of ocean-atmosphere interactions, changes in the output of the sun, and the amount of aerosol injected into the stratosphere by explosive volcanic eruptions.

As discussed previously, uncertainty of the climate is magnified still further at continental and country scales, and the human signal, though detectable and growing, is a relatively small component of the change. Although the sustainability of MDGs could be undermined by climate change in the long-term, the risk exposure of donor portfolios will be most immediate where human and environmental systems are already marginal (such as semi-arid regions, or coastal zones subject to frequent flooding). In these cases, even modest changes in the mean climate or to extremes could be sufficient to cross a threshold or tipping point. Furthermore, meteorological changes could be amplified by non-linear responses in secondary impacts.

This implies the need for a twin-track approach. On the one hand, development of the scientific and economic capacity to identify critical thresholds and to better understand and cope with climate variability (Washington et al., 2006). On the other hand, development of climate forecast tools and data sets that capture incremental changes in risk over the scales needed for adaptation planning. Although decadal forecasting will be the focus of the remainder of this report, it should be recognized that the two are related. Improved understanding of the causes of decadal climate variability should translate into improved predictability of regional climates and explanations for abrupt changes. For example, many studies highlight the role played by sea surface temperatures in forcing rainfall variability across Africa (Giannini et al., 2003), India (Wang et al., 2006) and Latin America (Nobre et al., 2004). Hence, improved monitoring of the changing conditions of oceans should, in turn, lead to more accurate seasonal to decadal forecasts (see below).

4. Uses of climate risk information for adaptation planning

Uses of climate information for adaptation can be sorted into categories interpreted from Smit et al.'s (2000) system (Table 2). These activities are not mutually exclusive and often overlap. As will be shown, some methods are better placed than others to meet the specific needs of different adaptation assessments. There are also large disparities between techniques in terms of their respective technical capacity and resource requirements – factors that can narrow the choice still further.

Table 2 Examples of adaptation activities that require climate risk information.

Adaptation	Examples of activity using climate information
New infrastructure	Cost-benefit analysis, infrastructure performance and design
Resource management	Assessment of natural resource availability, status, allocation
Retrofit	Scoping assessments to identify risks and reduce exposure to extreme events
Behavioural	Measures that optimise scheduling or performance of existing infrastructure
Institutional	Regulation, monitoring and reporting
Sectoral	Economic planning, sector restructuring, guidance, standards
Communication	Communicating risks to stakeholders, high-level advocacy and planning
Financial	Services to transfer risk, incentives, insurance

Adaptations involving ***new infrastructure*** typically require data for a cost- function (such as annual flood damages) in relation to climate event magnitude. The function is adjusted upwards or downwards in line with anticipated changes in risk, or assumed adaptation measures, to assess long-term benefits of a scheme (e.g., Conway et al., 2006). At the screening stage, coarse resolution climate data can help compare adaptation options, or determine whether a given scheme should proceed. At the design step, more detailed information on conditions (such as water-levels at a flood defence site, or reservoir inflows) are needed to assess structure performance throughout the intended life (e.g., Caspary and Katzenberger, 2006).

Natural ***resource management*** has been the subject of many climate change impact studies to date (see IPCC [2007] or Warren et al [2007]). Spatial scales of interest span from the crop yields of individual plots (Abraha and Savage, 2006), through the disproportionate contribution of mountain regions (Viviroli et al., 2007) to the global water balance (Alcamo et al., 2007). Time scales vary from soil loss over a few hours (Michael et al., 2005) through to the changing mass balance of glaciers over decades (Schneeberger et al., 2003). The adaptation responses vary accordingly and may include integrated natural resource management plans, re-allocation of resources between users, reduction of co-stressors on ecosystems, and so on.

Adjustment to natural hazards and measures to reduce exposure to extreme events follow a similar line though often emphasizing finer spatial and temporal scales of climate change. For example, climate information might be used to ***retrofit*** existing buildings to improve human comfort or reduce risks from excessive heat (Hacker et al., 2007). The scenario tool might also be required to incorporate local feedbacks, for example, between heat dissipation, city design and intensity of the urban heat island (Betts and Best, 2004). A key challenge for modelling extreme events is representing both the frequency and magnitude of phenomena that are, by definition, at the very margins of statistical distributions (Tebaldi et al., 2006).

Other categories of adaptation involve non-structural ***behavioural*** measures. Here, climate risk information can be used operationally to optimize the performance of existing assets (such as reservoirs and irrigation systems) or to adjust scheduling of activities (such cropping patterns or water releases for hydropower). In these cases, information on the changing temporal sequencing of weather events is of interest. For example, onset of the spring snowpack melt, limiting soil moistures, or first/last frost dates (Payne et al., 2004). This requires that the scenario method produces realistic daily sequences of weather.

Institutional and multi-***sector***-wide adjustments to climate change must account for changes in physical drivers as well as shifts in policy, regulatory and planning controls. Whereas country-level assessments based on macro-economic modelling may have relatively modest climate information needs, micro-economic studies require data at finer resolutions (c.f., Mendelsohn et al., 2000). Furthermore, there may be need for scenario evaluation across multiple regions to capture local constraints to development or changes in competitive advantage under different climate regimes. In which case, accurately resolving spatial patterns of climate change (due to variations in altitude, land cover or proximity to water, etc.) may be of particular importance (see Vuille and Bradley, 2000).

Climate information for ***communicating*** risks and raising awareness depends on the target stakeholder group(s) and their level of scientific understanding. Core scenarios help build capacity, benchmark impact studies and mainstream adaptation (McKenzie-Hedger et al., 2006), but there is a danger that wider uncertainties are not recognised (for instance, over-reliance on a single climate model). Scenarios used for high-level advocacy or policy change may focus on a very specific aspects of climate change to achieve a shift in (funding) priorities. Recognition of the need for greater investment in flood defences in the UK following intense downpours and flash-flooding during the summer of 2007 is a case in point (see McKenzie-Hedger [2005]).

The ***financial*** sector already relies on risk information (e.g., Rodwell and Doblas-Reyes, 2006). Insurance mechanisms that spread costs of adverse climatic conditions between regions require an accurate picture of expected patterns of risk. For example, maps of coincident drought and flooding (as shown by McCabe and Palecki, 2006) could be used to hedge losses of hydropower in one region with gains in another. Future scenario needs may be met by maps of global “hot spots” (Giorgi, 2006). The World Bank and UN World Food Program favour the development of weather indices that trigger payouts in developing countries following weather disasters or collapses in commodity prices. If these indices are to promote activities that are compatible with projected climate changes then scenarios must provide meaningful information on metrics such as cumulative rainfall totals or degree days.

The above examples show that no single climate scenario meets all needs of different adaptation activities. The following section sets out some criteria for comparing scenario methods, and is followed by an overview of the properties, strengths and weaknesses in each case. Again, it is assumed that the intended purpose is adaptation planning, and that the time horizon is the 2020s.

5. Overview of scenario methods

Regional climate change projections have been reviewed at length elsewhere (see Christensen et al., 2007). Although comparison of different scenario methods has become a trade-mark activity for parts of the climate science community (Fowler and Wilby, 2007), there is no agreed set of diagnostics for appraising tools from the point view of development planning. However, there have been recent moves to bring together and better coordinate groups interested in climate adaptation tools, recognising that there may be advantages from shared approaches to G8, OECD and UNFCC processes (Tanner, 2007).

In some contexts it may be advantageous if the scenario method has low demands for technical capacity, supporting infrastructure, or data for calibration and simulation. Additionally, if the scenarios can be prepared in minutes rather than months, and the necessary tools are freely available. More rapid production of scenarios, for example, can release time for repeat investigations of key uncertainties, such as sensitivity of impacts to choice of climate model.

In addition to logistical considerations there are several properties that constrain the ultimate use of the scenario. The low spatial resolution of GCMs has often been cited as the rationale for downscaling. So for site to river basin scale applications, direct use of GCM outputs may not be appropriate. Applications demanding finer spatial scales often require finer temporal resolution, as in the example of urban drainage design. Conversely, if global assessments of water resources are needed then monthly or annual GCM scenarios may suffice.

Many assessments require realistic behaviour for several outputs, such as daily temperature, wind speeds, solar radiation and cloud cover, to compute evaporation in ecosystem or crop models. Others may depend on local estimates of climate change but simultaneously across multiple sites, for example within a single river basin to simulate flood peaks. Still others need information on the time-evolving climate, rather than shifts in climatological mean, say between 1961-1990 and the 2020s. In all cases, the relationship amongst climate and non-climate influences should be internally consistent such as between socio-economic, population, atmospheric CO_2 concentration scenarios, when assessing direct and indirect climate change effects on crop or water yields (e.g., Arnell, 2004).

Over the second half of the 21st century, climate change projections are couched in uncertainty due to unknown future forcing by solar output, volcanic eruptions, rates of ocean heat uptake, and human activity affecting the composition of the atmosphere and feedbacks from the land surface. Over the next four decades, global mean temperature rise is largely insensitive to differences among emission scenarios (Stott and Kettleborough, 2002). Some techniques can accommodate these components alongside model uncertainty but are very demanding computationally. Even so, increased supercomputer power and distributed climate modelling experiments are enabling multi-model ensemble and multi-physics ensemble experiments and hence the development of probabilistic scenarios (e.g., Stainforth et al., 2005).

Whether or not the term “probabilistic” is fully justified, or indeed if such information is actually helpful except for high-risk adaptation decisions is debatable (Hall, 2007).

This is because results from even the most complex experiments are still conditional on a host of factors (such as the suite of climate models or statistical assumptions applied). The value-added to decision-making by probabilistic scenarios is, as yet, largely unproven except for a few pilot studies (as in New et al., 2007).

Finally, it is evident that the predictability of climate is not the same everywhere, and that gaps in knowledge of regional climatology are revealed wherever there is a lack of agreement between climate model projections (the white areas in Figure 3). Although there is now high confidence in future patterns of warming and sea level rise there is much less confidence in projections of the numbers of tropical storms and of rainfall changes over large parts of Africa, south Asia and Latin America (Table 3). Indeed, the list of regions with inconsistent projections provides a manifesto for research into the most poorly understood regional climates. The table also shows where reliance on a single climate model projection is especially inadvisable.

Table 3 A summary of climate model consistency in regional precipitation projections for 2090-2099 under SRES A1B emissions. Regions in which the middle half of all model projections show disagreement on the sign of change are classified as inconsistent. Regions showing model consensus are indicated as small (5-20%) or large (>20%) increases or decreases. Source: IPCC (2007)

Region	**December-January**	**June-August**
Sahara	Small decrease	Inconsistent
West Africa	Inconsistent	Inconsistent
East Africa	Small increase	Inconsistent
Southern Africa	Inconsistent	Large decrease
Northern Asia	Large increase	Small increase
Central Asia	Inconsistent	Small decrease
Tibetan Plateau	Small increase	Inconsistent
East Asia	Small increase	Small increase
South Asia	Inconsistent	Small increase
Southeast Asia	Small increase	Small increase
Central America	Small decrease	Small decrease
Amazonia	Inconsistent	Inconsistent
Southern South America	Inconsistent	Inconsistent

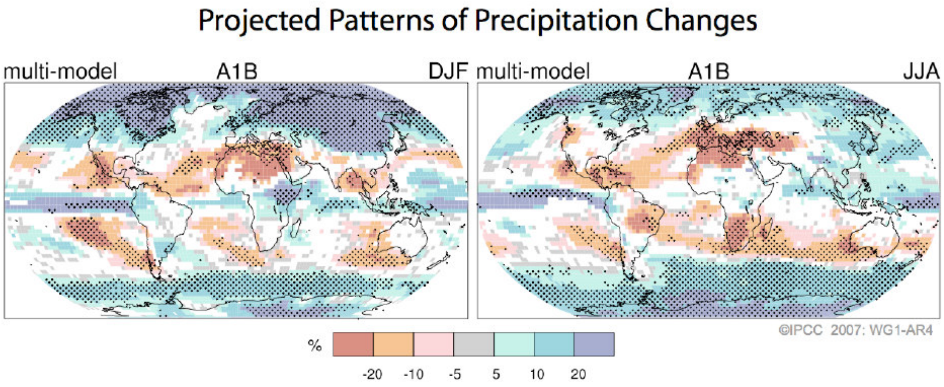


Figure 3 Changes (%) in precipitation for 2090-2099 compared with 1980-1990 based on multi-model average projections under the SRES A1B scenario. White areas show where the model consensus about the sign of the change is less than 66%; stippled areas where 90% of models agree about the sign. Source: IPCC (2007).

6. Entry level methods

Four entry level methods are described: sensitivity analysis, change factors, climate analogues, and trend extrapolation. This group tends to offer site- or area-specific climate risk information, is modestly data dependent, but places minimal demands on technical resources. As such the approaches can be valuable for scoping assessments.

6.1 Sensitivity analysis

A climate sensitivity analysis does not depend on any climate change scenarios, but the assessment may be directed by accepted regional temperature and precipitation changes, such as those published in IPCC AR4. The main requirement is a fully calibrated and validated model of the chosen system, whether it is for snow cover in the Himalayas (Singh and Bengtsson, 2003) or for coastal zone inundation in the Philippines (Perez et al., 1999). First, observed climate data are fed into the model to establish the baseline condition of the response variable (e.g., snow cover area, seasonal runoff volume). Next, the same input data are perturbed by a fixed amount to reflect an arbitrary rise in temperature for instance (such as +0.5, 1, 1.5, and 2ºC). A model simulation is performed for each change and any response is measured against the baseline. In this way, it is possible to build up a picture of the system sensitivity to changes in climate element. It is also possible to vary other system properties such as crop type or atmospheric concentration of CO_2 in concert with the climate change (as in Abraha and Savage, 2006).

The sensitivity method has some distinct advantages. The resulting climate-response relationships can reveal critical thresholds, amplification by combinations of stressors and non-linear behaviour, or help isolate outcomes from individual stressors. For example, a 10% reduction in rainfall over the Ketar river basin, Ethiopia produces a 30% reduction in simulated annual runoff, whereas conversion of grazing/cultivated land to woodland reduces runoff by ~8% (Legesse et al., 2003. Once calibrated, the model parameters and inputs can also be modified to represent adaptation measures, such as changes in land use to reduce diffuse pollution (Whitehead et al., 2006). The method is also portable in the sense that responses of different sectors or locations can be compared using the same synthetic scenarios.

However, without reference to historic trends or climate change scenarios cited elsewhere, it is not possible to comment on the likelihood or timing of simulated responses to given adjustments. As an observed climate series underpins both the baseline and perturbed experiment, the effects of unseen sequences of weather events (such as more protracted wet or dry spells) can not be investigated. Furthermore, the uncertainty due to the impact model *per se* is seldom reported (see section 9) but can be substantial relative to climate change impacts expected by the 2020s.

6.2 Change factors

This method is one of the most straightforward and popular procedures for rapid impact assessment. The change factors are typically calculated for calendar months by comparing the present and projected climatology in a Regional Climate Model (RCM) (as in Sato et al., 2007) or GCM (as in Tate et al., 2004) for grid-box(es) overlying the target region. Alternatively, the change factors can be obtained from ensemble experiments by sampling distributions of present and future climate scenarios produced by a single GCM (as in New et al., 2007) or by several different GCMs (Favis-Mortlock and Guerra, 1999).

Change factors for temperature (ΔT) are calculated by subtracting the model averages representing baseline (1961-1990) from the future (e.g., 2020s, 2050s or 2080s) temperatures (Figure 4). Change factors for precipitation (ΔP) are normally derived from the ratio of the projected to baseline averages but absolute differences can also be applied. The ΔT quantities are then added to observations (or in the case of ΔP multiplied by observations) to yield perturbed climate series at the study location.

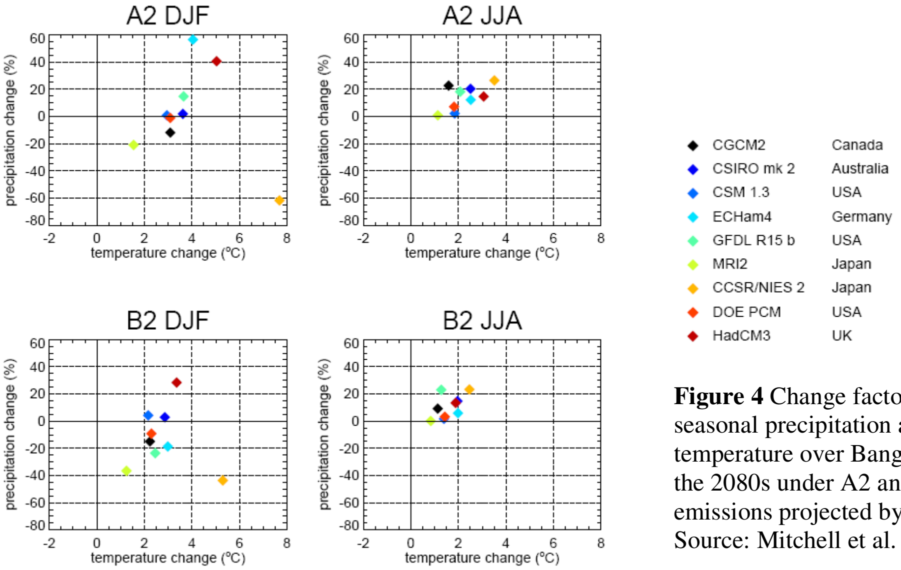


Figure 4 Change factors for seasonal precipitation and temperature over Bangladesh for the 2080s under A2 and B2 emissions projected by nine GCMs. Source: Mitchell et al. (2002).

A major disadvantage of change factors is that perturbed and baseline series differ only in terms of their respective means, maxima and minima; all other properties of the data are unchanged. The procedure can also yield quite erratic changes in monthly factors when applied to the 2020s due to relatively large statistical uncertainty in the baseline and future climatology compared with the actual change expressed by different GCMs. Furthermore, without refinement, the method does not change the frequency of rainfalls or temporal sequencing of events. Hence, the method may not be helpful in circumstances where changes in drought duration or onset are critical to the assessment. Change factors will also reflect any gross biases in GCM climatology at the scale of individual model grid cells, such as timing of the monsoon onset. Most critically, the method is only feasible if the underlying RCM and GCM scenarios are freely available and accessible for the 2020s. Unfortunately, most archives hold only products for the 2080s (as in Figure 4) so additional steps are needed to scale back to the 2020s (see section 7.1).

6.3 Climate analogues

Analogue scenarios are constructed from palaeo- or more recent instrumental records that give plausible representations of the future climate of a region. Temporal analogues are taken from the previous climate of the region; spatial analogues are taken from another region that presently has conditions that could become the future climate at the study site. For example, the present rainfall and temperature regime of Mauritania could be a spatial analogue for expected climate changes across Morocco. In doing so, the assumptions are made that the geographic context (e.g., land-sea juxtaposition or continentality) are comparable, and that latitudinal controls (e.g., day length or storm track position) are not important to the impact assessment.

A major advantage of the analogue approach is that the climate scenario and associated impacts may be described in far greater temporal and spatial detail than might otherwise be possible. For example, the summer 2003 heatwave in Europe provided early sight of possible environmental (Fink et al., 2003), societal (Palutikof et al., 2004) and health (Haines et al., 2006) impacts of extreme temperatures that could become the norm by the 2040s (Stott et al., 2004). Similarly, the severe drought of 1991/92 in southern Africa gave proxy evidence of actual impacts on vegetation condition and ground cover under higher temperatures and evaporation rates as projected by several GCMs (Mkanda, 1999). Like sensitivity analysis, the given impacts can be explicitly linked to a tangible climate anomaly or extreme event which is helpful for visualizing consequences and identifying critical thresholds.

The most significant disadvantage of temporal analogues is that the climate forcing that led to the extremes are unlikely to be repeated over coming decades. Past vegetation-climate feedbacks, for example, may not be applicable in the future due to recent human modifications of land cover (Claussen et al., 2003). There is little scope for exploring uncertainties in future climate forcing because of the small sample of events. Furthermore, even if the same extreme event recurred, the human impacts would almost certainly differ because of confounding factors such as changes in economy, infrastructure developments, or adaptation measures invoked during the interim. The analogue method is also relatively data demanding: in the absence of surveillance systems, necessary human and environmental statistics may be hard to assemble. Even so, catastrophic weather events can trigger major shifts in policy and attitudes to risk despite being problematic to attribute to climate change (Figure 5).

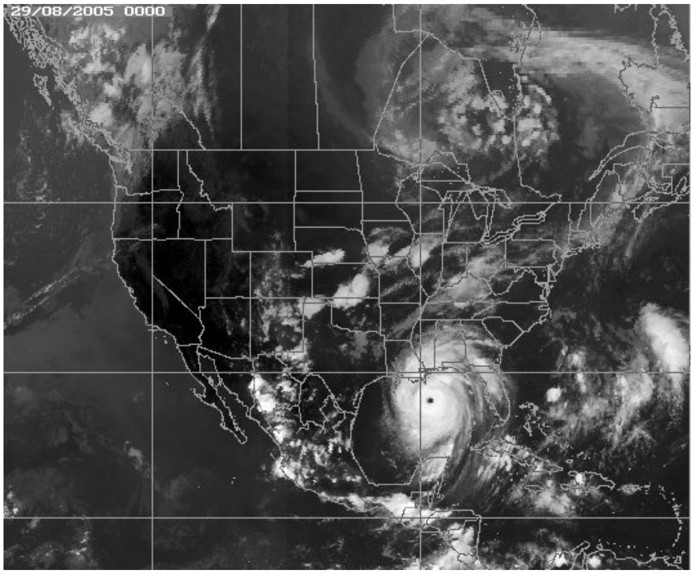


Figure 5 Infrared image of hurricane Katrina prior to landfall on 29 August 2005. Source: UK Met Office (http://www.metoffice.com/satpics/namerica_IR.html)

6.4 Trend extrapolation

Climate trend analysis can be a very appealing option, at least when extrapolating over the next few years. The attendant data and technical requirements are low compared with other scenario methods. But an underlying assumption is made that past climate behaviour is a sound basis for predicting the future. This may be reasonable for slowly varying components of the earth system such as sea level, or ocean temperatures which are highly correlated between successive years, even decades (see section 8.2). Regional climate trends that are largely driven by these elements may be robust in the near term (e.g., Marengo and Camargo, 2007). The trend need not be linear as testified by the extensive literature on climate cycles. For example, the frequency of occurrence of precipitation in the Yangtze River basin is predicted to peak around 2012, 2015 and 2018 on the basis of spectral analyses of a 40 year daily data set (Becker et al., 2007).

However, trends are higly susceptible to false tendency (see Legates et al., 2005; Chappell and Agnew, 2004). This can arise because data are not homogeneous, having been affected by a host of non-climatic influences such as changes in observer, instrumentation, monitoring network density, station location or exposure (see Davey and Pielke, 2005). For example, encroachment of urban areas and land use changes can affect long-term temperature records (Kalnay and Cai, 2003). Even if a physically plausible climate trend is found, the amount of explained variance may be low as in the case of regional rates of sea level rise (Plag, 2006). There is also no guarantee that a trend will persist, as evidenced by the abrupt changes in rainfall and atmospheric circulation of the last century (Baines and Folland, 2007; Narisma et al., 2007).

Apparent trends can also emerge because of the undue influence of a single outlier, particularly if it occurs towards the end of the record. Multi-decadal variability in annual rainfall totals can cause the strength and/or even the sign of an extrapolated trend to change depending on the period and/or length of record chosen (Figure 6). Others have demonstrated that misleading trends can be an artefact of the statistical method used to divide data, such as percentile-based indices for temperature and precipitation extremes (Michaels et al., 2004; Zhang et al., 2005).

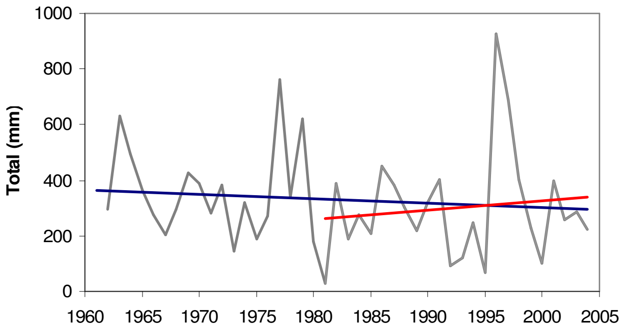


Figure 6 Trends in annual winter rainfall at Tanger, Morocco since 1961 (blue line) and 1981 (red line). Extrapolating each trend forward to the year 2015 gives changes of -16% and +14% respectively compared with the 1961-1990 mean. If the 1996 outlier is removed, the post 1981 gradient weakens by 55%.

In short, trend analysis plays an important role in climate change detection and attribution (e.g., Zhang et al., 2007) but is problematic when extrapolating variables such as regional rainfall. Even where the causes of a trend are well understood, the inherent variability of the climate system can cause the trend to break down from one decade to the next.

7. Intermediate level methods

Three intermediate level methods are described: pattern-scaling, weather generation and empirical downscaling. This group is founded on statistical methods for characterising present and future climate behaviour at regional scales. In some cases, bespoke software allows broader access to sophisticated models through user-friendly interfaces. All methods depend on climate model output to run future scenarios.

7.1 Pattern-scaling

The pattern-scaling method has similarities with the change factor approach (see section 6.2). In both cases, a “change field” or pattern is derived by taking differences between a baseline (1961-1990) and future (typically 2071-2100) climate scenario. Whereas change factor methods tend to rely on differences for a single climate model grid box, change fields are derived for multiple grid boxes using either RCM or GCM outputs. These local patterns are then scaled using projections of the global mean temperature. For example, one GCM might suggest a 40% reduction in spring rainfall over a region by the 2080s due to a 4ºC global mean temperature rise. Hence, precipitation decreases at a rate of 10% per 1ºC in global mean temperature change. With scenarios of annual global mean temperature changes for the period 2000-2100 expressed as a ratio of the mean in the 2080s (centred on 2085) it is possible to scale quantities such as regional rainfall for intervening periods.

Future emissions are the main driver of transient temperature changes projected by climate models, so each emission pathway has a different scaler trajectory (Figure 7). For example, under high (A1FI) and low (B1) emissions, PCM yields scalers of 0.248 and 0.477 respectively for 2025. In the example above, these scalers translate into 10% and 19% reductions in spring rainfall. The apparent paradox of smaller changes under higher emissions is due to higher concentrations of sulphate aerosols (and hence cooling) under the A1FI scenario. Differences between climate models are also negligible if each is scaled by their respective global mean temperature change for the 2080s. However, if different climate models are scaled by a common reference temperature change (such as their ensemble mean) the resulting scalars would differ. This is the method applied by the MAGICC/SCENGEN system to scale baseline data from a range of climate models and emission scenarios (Hulme et al., 2000).

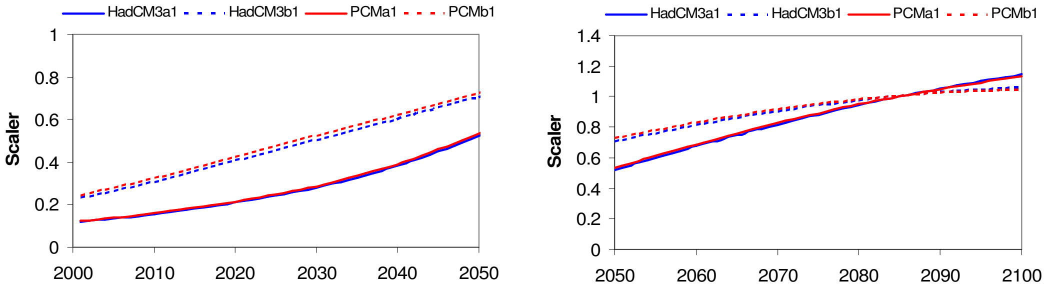


Figure 7 Annual scalers for 2000-2050 (left panel) and 2050-2100 (right panel) derived from the climate models HadCM3 (blue) and PCM (red) under A1FI (solid) and B1 (dashed) SRES emissions. Data Source: http://www.cru.uea.ac.uk/~timm/climate/ateam/TYN_CY_3_0.html
[accessed 2 August 2007].

Pattern-scaling is convenient for exploring uncertainty because the technique addresses the scarcity of model experiments covering different emissions, initial conditions, and intervening periods (see Annex A). As high resolution RCM simulations are costly and time-consuming to perform, very few transient experiments for 1961-2100 have been undertaken to date so, without pattern-scaling, information from RCMs would rarely be available for the 2020s. Furthermore, it is assumed that by the 2080s, the regional climate change pattern emerges more strongly from the "noise" of natural variability. Hence, there is greater confidence that a climate change signal, rather than variability, is being scaled backward to earlier decades.

Pattern-scaling rests on several major assumptions. First, that the regional climate change *pattern* is constant between decades, and that only the *magnitude* of change varies. This may be invalidated where the pattern is affected by land surface feedbacks on albedo or by changing spatial patterns of aerosols composed of sulphate, soot and dust (Shine and Forster, 1999). Second, that the regional response depends on a linear relationship with global mean temperature. This may be reasonable for temperature, but less so for seasonal precipitation, or climate extremes (Good et al., 2006). Third, that patterns of change can be scaled between different emission scenarios (such as A1FI to estimate B1). In this case, errors may be minimised by scaling from a stronger to a weaker forcing scenario (Mitchell, 2003). Finally, the temporal and spatial scales of the resultant scenarios will depend on the resolution of the RCM or GCM supplying the patterns of change. Subtle variations in responses at sub-grid scales due to orography or land surface may not be captured.

7.2 Weather generation

Weather generators are models that replicate statistical attributes of meteorological station records (such as the mean and variance) but do not reproduce actual sequences of observed events (Wilks and Wilby, 1999). At the heart of most weather generators is a Markov model that emulates transitions between wet- and dry-spells or -days. The optimum statistical distribution for representing daily rainfall totals varies from place to place, but the gamma, exponential, and fourth root are most popular (Figure 8). Secondary variables such as maximum and minimum temperatures, solar radiation and wind speed are grouped into sets of wet and dry days. Inter-variable relationships are preserved using multiple regression equations and it makes sense, for example, that dry-days have on average more sunshine than wet-days. The whole process is driven by random number generation to determine whether a day is wet or dry, if wet how wet, how warm, how windy, and so on. This enables weather generators to efficiently simulate long synthetic series, useful for estimating extreme events for design purposes (e.g., Smithers et al., 2002).

Adapting weather generators for climate change assessment involves adjusting model parameters in one of two ways. First by relating key parameters such as wet-day probabilities to other, slowly-varying indices of atmospheric circulation (e.g., ENSO, or NAO) (Katz, 1996). Inter-annual or decadal changes in the frequency of these patterns (as projected by GCMs) are then translated into revised weather generator parameters, and hence daily weather sequences under future forcing. The second approach involves recalibrating the weather generator using daily weather series that have been derived from the change factor method (section 6.2) (Kilsby et al., 2007). Hence change factors for the 2020s would be applied to each weather variable, the model recalibrated, then run to synthesize infinitely long daily sequences with the same statistical properties as the 2020s series.

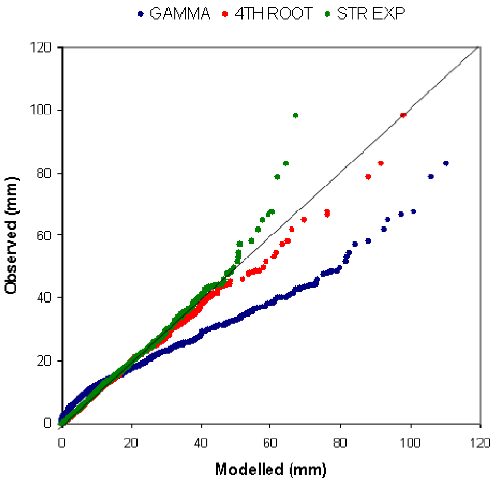


Figure 8 Comparison of observed and modelled distributions of daily rainfall at Addis Ababa, Ethiopia. In this case the fourth root transformation (4TH ROOT) would be used in preference to the gamma or stretched exponential distributions.

Unfortunately, weather generator parameter modification for future climate scenarios can cause unanticipated outcomes (Katz, 1996). For example, changes to parameters governing rainfall occurrence can have unintended affects on secondary variables such as temperature and solar radiation. Moreover, weather generators based on first-order Markov chains (i.e., one-day-to-the-next transitions) typically underestimate the persistence of wet- and dry-spells. More sophisticated procedures are also needed for multi-site applications, or to disaggregate daily series into sub-daily quantities, or to simulate lower frequency variability, such as inter-annual rainfall totals (see Wilks and Wilby, 1999).

Weather generators are relatively data intensive, requiring at least a decade of daily data, or more for arid sites (Soltani and Hoogenboom, 2005). The parameters are sensitive to missing or erroneous data, as well as to the number of rain days in the calibration set (Taulis and Milke, 2005). However, weather generators are already in widespread use and there is scope for their extension to climate change assessments.

7.3 Empirical downscaling

Empirical downscaling methods overcome one of the most serious limitations of applying raw GCM output to regional impact assessment – the mismatch in scale between climate model projections (~300 km) and the response units under investigation (~individual sites to river basin areas). One of the simplest forms of downscaling involves spatial interpolation of gridded GCM or RCM output to required locations (so-called "unintelligent" downscaling). More sophisticated techniques rely on building quantitative relationships between large-scale atmospheric variables (predictors) and local surface variables (predictands). So for example, the strength of airflow and humidity have been used to downscale daily precipitation totals at sites across South Africa (Hewitson and Crane, 2006). Different downscaling approaches are often distinguished by their predictor variable(s) suite, or by the form of the statistical term relating predictors to predictands. The merits of different empirical methods have been exhaustively reviewed elsewhere (see: Fowler et al., 2007; Christensen et al., 2007; Goodess et al., 2007; Wilby and Wigley, 1997). These reviews indicate that there are no universally optimal sets of predictors, or forms of relationship, each must be assessed on a case by case basis.

Provided that predictor variables are available, empirical downscaling can be an efficient tool for exploring uncertainties in climate change scenarios (Prudhomme et al., 2003; Wilby and Harris, 2006), or for producing fully transient daily scenarios up to 2100 (Immerzeel, 2007). This enables appraisal of near-term changes in both the mean and variability of climate. Methods are also being developed to apply probabilistic climate change information within downscaling schemes (Benestad, 2004). Other advantages include the ability to downscale 'exotic' predictands (e.g., tidal surges, air quality, extreme event indices) assuming that physically plausible relationships to large-scale weather can be found. Where predictor variables are difficult to obtain, direct scaling relationships can be applied, for example between daily GCM- and station-scale precipitation (Schmidli et al., 2006).

Uptake of empirical downscaling techniques has been encouraged by provision of free software and documentation (see the Resources). Nonetheless, access to the predictor variables necessary for calibration and scenario development continues to be a major constraint to their widespread use. Even if (daily) GCM outputs are available, further processing may be needed to derive predictors (such as vorticity from pressure data) or to ensure compatibility between different climate model grids. Likewise the reliability of downscaled scenarios depends on the quality of observations used for model calibration, the predictability of the local variable from the large-scale forcing, and the constancy of these relationships under changing climate conditions. Above all, results are highly sensitive to the choice of GCM providing the predictor variables and (to a lesser extent) the choice of downscaling technique (Figure 9).

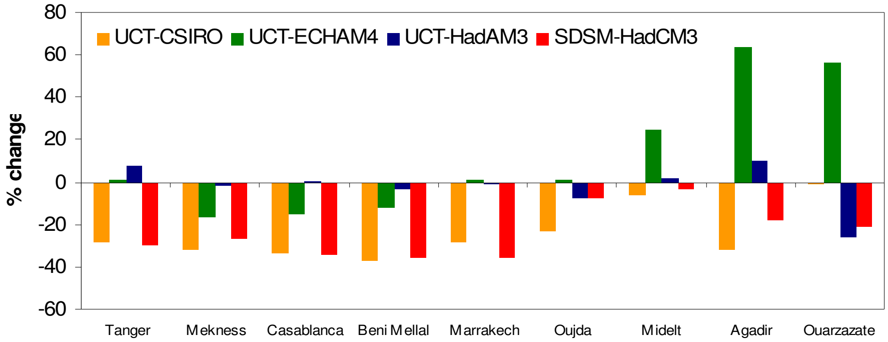


Figure 9 Changes (%) in winter precipitation totals for sites across Morocco, projected by different downscaling methods (UCT, SDSM) and GCM forcing (ECHAM4, CSIRO, HadAM3, HadCM3) under A2 emissions by the 2080s. Source: World Bank (unpublished).

There have been relatively few empirical downscaling studies for Africa, Asia or Latin America, and even fewer that explicitly deal with climate changes for the 2020s (as in Immerzeel, 2007). In the tropics and for small islands, strong ocean-atmosphere coupling makes consideration of the role of the ocean unavoidable, thus enlarging the set of potential predictors. Also the relationships between these predictors and local variables may vary strongly within the annual cycle. In the case of precipitation, statistical models especially designed for a particular month (such as the start or end of rainy season) may be needed (Jimoh and Webster, 1999).

8. Advanced level methods

Two advanced level methods are described: dynamical downscaling and coupled Ocean-Atmosphere/Global Climate Models (OA/GCMs). Both require a high degree of specialist knowledge and computing resource but these are the only methods that can produce internally consistent climate behaviour in response to the full range of climate forcings (i.e., radiative and land surface feedbacks). GCMs are, therefore, the primary tool for representing the global climate system and nearly all other scenario methods rely on their output.

8.1 Dynamical downscaling

Regional climate models (RCMs) simulate climate features dynamically at resolutions of 10–50 km given time-varying atmospheric conditions at the boundary of a specified domain (Figure 10). Atmospheric fields simulated by a GCM (such as surface pressure, wind, temperature and vapour) are fed into the boundary of the RCM at different vertical and horizontal levels. This information is then processed by the RCM such that the internal model physics and dynamics can generate patterns of climate change that differ from those of the "host" GCM. The nesting of the RCM within the GCM is typically one way, so the behaviour of the RCM can not influence the GCM scenario. To date, RCMs have been used for a wide variety of applications, including numerical weather prediction, studies of palaeoclimates, the effects of land surface modification(s), and future climate change in selected regions of the world.

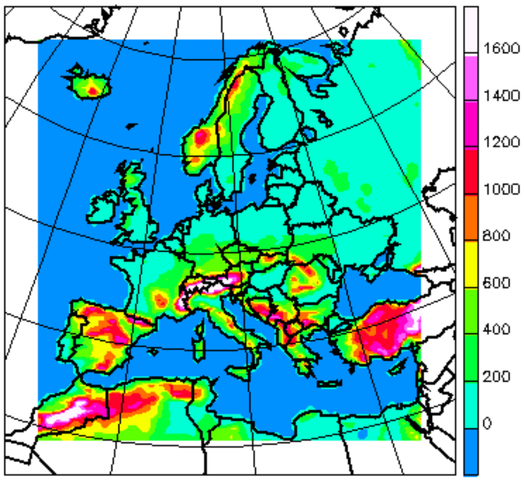


Figure 10 Domain and elevations (m) of the Met Office Hadley Centre's regional climate model HadRM3.
Source: http://prudence.dmi.dk/
[accessed 8 August 2007]

A key advantage of RCMs is their ability to model regional climate responses to changes in land-cover or atmospheric chemistry in physically consistent ways. The higher spatial resolution and hence improved representation of surface elevations, enable RCMs to resolve important atmospheric processes (such as orographic rainfall or interactions with water bodies) better than the host GCM (e.g., Song et al., 2004). This is particularly important for the representation of extreme events such as intense precipitation (Ekström et al., 2005). However, RCMs are computationally demanding, requiring as much processor time as the GCM to compute equivalent scenarios. The results from RCMs are also sensitive to the choice of the initial conditions (especially soil moisture and soil set at the start of experiments), and to the schemes that represent sub-grid processes (see section 8.2).

Like empirical downscaling, the quality of regional climate simulations depends not only on the validity of the RCM physics but, more critically, on the realism of GCM boundary information. For example, gross errors in an RCM's precipitation climatology may arise if the GCM misplaces storm tracks. The results are also sensitive to the size of model domain and grid-spacing. Ideally, the domain should be large enough to allow the free development of mesoscale atmospheric circulations, and the grid-pacing fine enough to capture detailed topographic, coastal or dynamical features such as tropical cyclones (Walsh, 2004). In practice, domain size and grid-spacing are constrained by computational resources, as simulation times increase exponentially with increasing vertical and horizontal resolution. The actual location of the domain should capture the most significant circulations that affect climate over the region of interest (e.g., low-level jets, storm tracks, cyclones).

Tools such as RegCM3 and PRECIS (Figure 11), are opening the way for more widespread use of RCMs in climate vulnerability and adaptation studies (Islam et al., 2007; Pal et al., 2007). However, in common with empirical downscaling, there is currently a real paucity of published dynamical downscaling studies for developing regions, and especially for the 2020s.

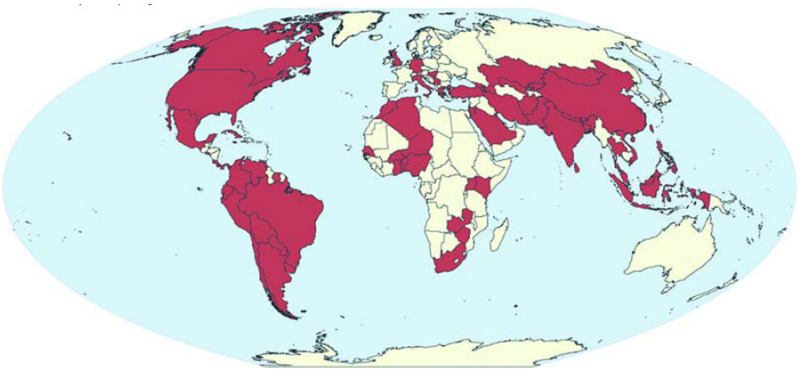


Figure 11 Countries presently using PRECIS. Source: Met Office Hadley Centre (2006)

8.2 Coupled climate models

Like RCMs, Global Climate Models (GCMs) represent the three-dimensional climate system using four primary equations describing the movement of energy (first law of thermodynamics) and momentum (Newton's second law of motion), along with the conservation of mass (continuity equation) and water vapour (ideal gas law). Unlike RCMs, each equation is solved at discrete points on the entire surface of the Earth, at a fixed time interval (typically 10-30 minutes), and for separate layers in the atmosphere defined by a regular grid. For example, the UK Met Office Hadley Centre third generation ocean-atmosphere GCM (HadCM3) has an atmospheric model with a horizontal resolution of 2.5 x 3.75 degrees and 19 vertical levels, and an ocean model with a horizontal resolution of 1.25 x 1.25 degrees and 20 vertical levels (Figure 12).

The computational burden of solving equations at thousands of grid-points means the horizontal resolution of GCMs is coarse, typically 100-400km. Unfortunately, many important components of the climate system have scales much finer than this (e.g., convective clouds, coastal breezes, etc.) and must be parameterized. This involves simplified representations of the effect of small-scale processes on large scale responses and are necessary features of all GCMs (and RCMs). The parameterisation of clouds is particularly challenging, not least because of their role in the energy balance and feedbacks arising from increased atmospheric moisture with global warming. As well as simplifying key processes through parameterization, GCMs also average conditions over the entire grid-box. For example, precipitation is assumed to occur at a uniform rate everywhere within the cell, leading to an overestimation of rainfall frequencies and underestimation of intensities compared with reality.

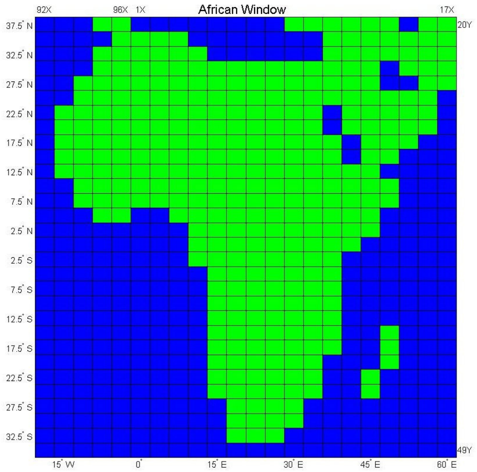


Figure 12 The African land-sea mask and grid of the coupled OA/GCM HadCM3. Source: http://www.cics.uvic.ca/scenarios/sdsm/select.cgi [accessed 9 August 2007]

GCMs compute radiative transfers through the atmosphere (involving water vapour and cloud interactions), the direct and indirect effects of aerosols (on radiation and precipitation), changes in snow cover and sea ice, the storage of heat in soils and oceans, surface fluxes of heat and moisture, and finally, the large-scale transport of heat and water by the atmosphere and ocean. Some GCMs incorporate land-surface schemes including the freezing and melting of soil moisture, and the regulation of evaporation by plant stomata due to variations in temperature, vapour pressure and CO_2 concentration (e.g., Betts et al., 2007). More sophisticated models include carbon cycling and atmospheric chemistry for trace gases (e.g., CH_4, N_2O, CFC_{11}, CFC_{12}, and $HCFC_{22}$). However, representation of urban surfaces is seldom incorporated in either RCM or GCM land-surface schemes.

Recent GCM experiments show that global (and some regional) mean temperatures are hindcast with substantially improved skill when provided with information about the upper ocean heat content (Smith et al., 2007). Much of the increased skill arises from the persistence and predictability of ocean temperatures over decadal timescales (Sutton and Allen, 1997). This underlines the importance of maintaining ocean monitoring systems (Dickey and Bidigare, 2005), such as the ARGO floats, to provide initial conditions for decadal forecasting systems, as well as early detection of changes in water properties (King and McDonagh, 2005). Forecast skill is expected to improve with time as more data on ocean conditions become available. Even so, decadal forecasts will continue to be accompanied by strong caveats for unforeseen volcanic activity and/or rapid nonlinear climate change and feedbacks, both of which could cause a sudden cool downturn (Lee et al., 2006).

Despite significant technical advances in decadal forecasting capability, the products will remain of limited value to policy-makers and planners until skilful forecasts of regional climate anomalies become available. Work in this area has only just begun. For example, Figure 13 shows a prototype forecast of regional precipitation anomalies out to 2017 based on the UK Met Office's Decadal Climate Prediction System (DePreSys) (Smith et al., 2007). Although the model predicts strong positive anomalies over the Indian subcontinent and negative anomalies over east Africa, much more research is needed to try to understand whether the signals are robust, and if so, the underlying physical mechanisms. This would require multi-model and multi-physics ensemble experiments to quantify the large uncertainty that exists in (precipitation) forecasts at such fine resolutions.

Further work is also needed to determine whether the rainfall anomalies have any practical significance when propagated through secondary impact models. Taken at face value, this particular forecast implies greater flood risk over India, and higher soil moisture deficits and/or less river flow in the Nile basin. However, the extent to which decadal climate risk information provides a useful basis for adaptation planning is a legitimate research question in its own right.

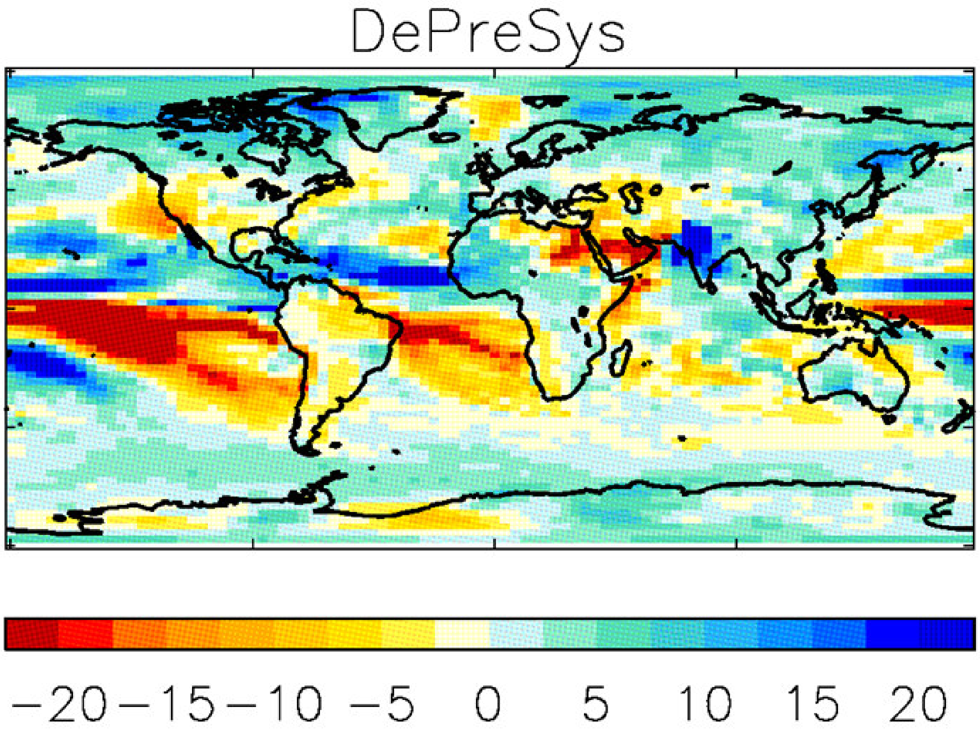


Figure 13 Regional precipitation anomalies for 2007-2017 as a percentage of the 1979-2001 mean. The forecast was produced by the UK Met Office's Decadal Climate Prediction System (DePreSys) given information on surface ocean heat content up to June 2005. Source: Doug Smith (*pers.comm.*)

9. Secondary impacts modelling

Environmental models play an integral part in many climate change impact studies (whether for water resource, crop yield, ecosystem response, coastal inundation, human health, or multi-sectoral assessment). The impact model can even be the most complex element in the case of sensitivity analyses (section 6.1). However, uncertainty in the responses due to the impact model structure and/or parameters is very seldom specified let alone reported; much more attention is typically paid to the influence of different climate models or downscaling methods on the outcome.

This oversight is of particular concern whenever scenarios for the 2020s are applied because the emission uncertainty is negligible and the climate change signal can be weak relative to climate variability or non-homogeneity of the model calibration data (Niel et al., 2003). Under these circumstances impact model uncertainties can be prominent, particularly for extreme events (see Cameron et al., 2000). From the handful of published studies it is evident that uncertainty in both model *structure* (processes included) and *parameterisation* (process representation) should be considered (just as is in the case of climate model ensemble experiments) (Füssel [2007], Jiang et al. [2007] and Wilby [2005]). In extreme cases, inadequate process representation totally undermines confidence in projections (e.g., Arnell et al., 2003).

To illustrate the extent of parameter uncertainty, a Ricardian model of net farm revenues (Kurukulasuriya and Ajwad, 2006) was run using annual mean temperature projections originating from different climate models and emissions scenarios for the period 2010 to 2100 (Annex B). This model was chosen because the authors provided a clear description of several model structures and associated parameter uncertainty.

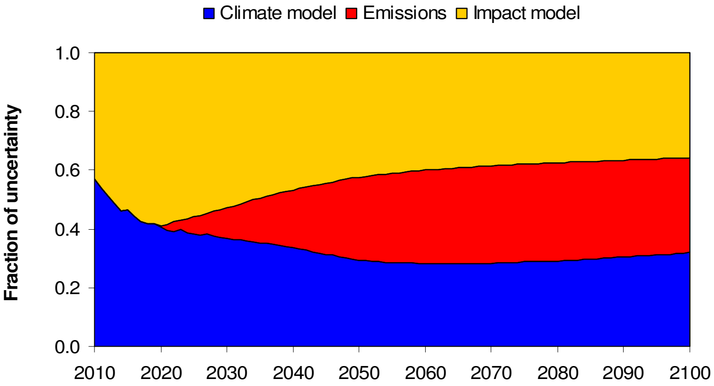


Figure 14 The contribution of climate model, emissions and impact model uncertainty as a time-varying fraction of the total uncertainty in net farm revenues for Sri Lanka under projected increases in annual mean temperature.

As expected, the analysis reveals declining farm revenues with rising annual temperatures (see Figure B.1). By 2030 total uncertainty in the net revenue is ~$20/Ha, compared with ~$150/Ha by 2100. Initially, climate model uncertainty is the dominant component, but this is soon replaced by impact model uncertainty which contributes the largest fraction of total uncertainty around the 2020s (Figure 14). Thereafter, both climate and impact model uncertainty contribute proportionately less uncertainty as emission scenario uncertainty gains prominence. This simple example highlights the potential reductions in uncertainty that could be achieved by improving a linear impact model, at least for the 2020s. The benefits could be even greater for non-linear response models.

10. Summary

This report has critiqued climate scenario methods from the perspective of impacts modelling and adaptation planning over the next 20-30 years (Table 4). Decadal forecasting presents special technical challenges but there is growing evidence that models are skilful over this time horizon, at least for global mean temperatures (Smith et al., 2007). The traditional distinction between weather forecasting and climate change prediction is thus becoming increasingly blurred at these time-scales.

Table 4 Options for constructing regional climate change scenarios, listed in order of increasing complexity and resource demand. Example adaptation activities (from Table 2) are shown in *italics*.

Method (application)	**Advantages**	**Disadvantages**
Sensitivity analysis *Resource management, Sectoral*	1. Easy to apply; 2. Requires no future climate change information; 3. Shows most important variables/ system thresholds; 4. Allows comparison between studies.	1. Provides no insight into the likelihood of associated impacts unless benchmarked to other scenarios; 2. Impact model uncertainty seldom reported or unknown.
Change factors *Most adaptation activities*	1. Easy to apply; 2. Can handle probabilistic climate model output	1. Perturbs only baseline mean and variance; 2. Limited availability of scenarios for 2020s.
Climate analogues *Communication, Institutional, Sectoral*	1. Easy to apply; 2. Requires no future climate change information; 3. Reveals multi-sector impacts/ vulnerability to past climate conditions or extreme events, such as a flood or drought episode.	1. Assumes that the same socio-economic or environmental responses recur under similar climate conditions; 2. Requires data on confounding factors such as population growth, technological advance, conflict.
Trend extrapolation *New infrastructure (coastal)*	1. Easy to apply; 2. Reflects local conditions; 3. Uses recent patterns of climate variability and change; 4. Instrumented series can be extended through environmental reconstruction; 5. Tools freely available.	1. Typically assumes linear change; 2. Trends (sign and magnitude) are sensitive to the choice/length of record; 3. Assumes underlying climatology of a region is unchanged; 4. Needs high quality observational data for calibration; 5. Confounding factors can cause false trends.
Pattern-scaling *Institutional, Sectoral*	1. Modest computational demand; 2. Allows analysis of GCM and emissions uncertainty; 3. Shows regional and transient patterns of climate change; 4. Tools freely available.	1. Assumes climate change pattern for 2080s maps to earlier periods; 2. Assumes linear relationship with global mean temperatures; 3. Coarse spatial resolution.
Weather generators *Resource management, Retrofitting, Behavioural*	1. Modest computational demand; 2. Provides daily or sub-daily meteorological variables; 3. Preserves relationships between weather variables; 4. Already in widespread use for simulating present climate; 5. Tools freely available.	1. Needs high quality observational data for calibration and verification; 2. Assumes a constant relationship between large-scale circulation patterns and local weather; 3. Scenarios are sensitive to choice of predictors and quality of GCM output; 4. Scenarios are typically time-slice rather than transient.
Empirical downscaling *New infrastructure, Resource management, Behavioural*	1. Modest computational demand; 2. Provides transient daily variables; 3. Reflects local conditions; 4. Can provide scenarios for exotic variables (e.g., urban heat island, air quality); 5. Tools freely available.	1. Requires high quality observational data for calibration and verification; 2. Assumes a constant relationship between large-scale circulation patterns and local weather; 3. Scenarios are sensitive to choice of forcing factors and host GCM; 4. Choice of host GCM constrained by archived outputs.
Dynamical downscaling *New infrastructure, Resource management, Behavioural, Communication*	1. Maps regional climate scenarios at 20-50km resolution; 2. Reflects underlying land-surface controls and feedbacks; 3. Preserves relationships between weather variables; 4. Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high; 2. Scenarios are sensitive to choice of host GCM; 3. Requires high quality observational data for model verification; 4. Scenarios are typically time-slice rather than transient; 5. Limited availability of scenarios for 2020s.
Coupled AO/GCMs *Communication, Financial*	1. Forecasts of global mean and regional temperature changes for the 2020s; 2. Reflects dominant earth system processes and feedbacks affecting global climate; 3 Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high (supercomputing); 2. Scenarios are sensitive to initial conditions (sea surface temperatures) and external factors (such as volcanic eruptions); 3. Scenarios are sensitive to choice of host GCM; 4. Coarse spatial resolution.

There are a growing number of techniques that allow inference to be made about medium-term trends in local climate variables of use to decision makers. However, this review has identified very few examples of studies for the 2020s, or even 2050s, so many of the scenario methods remain largely untested for these time periods. Table 5 provides a summary of desirable attributes which are mapped in Table 6 to produce a ready-reckoner of scenario methods, based largely on applications to the 2080s.

Table 5 Summary of attributes to assess the relative merits of different scenario options. These indicators cross-reference to the columns in Table 6.

Indicator	**Preferred attributes for development and adaptation planning**
Capacity	Low personnel, technical and infrastructure requirements
Resources	Low data, time and financial costs
Spatial	High spatial resolution (site or region, not continental or global)
Temporal	High temporal resolution (hourly or daily, not monthly or annual)
Outputs	High realism and joint behaviour of weather variables
Forcing	High ability to represent different external forcing (land cover, aerosols)
Uncertainty	High capability for providing probabilistic information
Pattern	High ability to produce surfaces or maps of climate change
Transient	High ability to produce transient (rather than time-slice) scenarios
Tools	High availability of tools, supporting data and guidance

Table 6 The author's subjective assessment of the extent to which different scenario methods can support climate impact and adaptation assessments for the 2020s. The headings refer to the desirable attributes listed in Table 5. Key to cells: **red** (disagree), **amber** (neutral or depends), **green** (agree).

Scenario methods	**Capacity**	**Resources**	**Spatial**	**Temporal**	**Outputs**	**Forcing**	**Uncertainty**	**Pattern**	**Transient**	**Availability**
Sensitivity analysis	🟩	🟩	🟩	🟧	🟩	🟧	🟩	🟧	🟥	🟩
Change factors	🟩	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟥	🟩
Climate analogues	🟧	🟧	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟩
Trend extrapolation	🟩	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩	🟩
Pattern-scaling	🟧	🟧	🟥	🟧	🟩	🟧	🟩	🟩	🟩	🟩
Weather generation	🟧	🟧	🟩	🟩	🟩	🟥	🟩	🟧	🟧	🟩
Empirical downscaling	🟧	🟧	🟩	🟩	🟩	🟥	🟩	🟧	🟩	🟧
Dynamical downscaling	🟥	🟥	🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟧
Coupled OA/GCMs	🟥	🟥	🟥	🟧	🟩	🟩	🟩	🟩	🟩	🟩

At the very least, Table 6 helps to exclude methods that would be wholly inappropriate for a given activity or level of resources. For example, temperature forecasting with weather generator or empirical downscaling methods would not be recommended for regions that are likely to experience dramatic changes in land-surface properties (such as snow cover, water body or irrigated areas); this would be better addressed by dynamical downscaling (e.g., Snyder et al., 2004). Conversely, a capability in dynamical downscaling will be hard to sustain without continued investment in infrastructure and training.

In practice, local expertise in one or more of the above methods develops through related activities such as weather hazard prediction or seasonal forecasting. Likewise, weather generators are already in relatively widespread use for crop-yield and water resource modelling. Under these circumstances it is advisable to build on existing knowledge and capabilities. However, the over-riding imperative is that the most appropriate scenario method is matched to the intended application (section 4). For example, sensitivity analysis or change factors for macro-economic analysis; climate analogues or empirical downscaling for the design of community based livelihoods programmes; dynamical downscaling for communicating with stakeholders and national policy-making across multiple sectors; pattern-scaling or weather generators for natural resource assessment; and coupled OA/GCMs for international advocacy.

Regardless of the intended application and choice of method, consideration should be given to how the scenarios will enable stakeholders and managers to make more informed, robust decisions on adaptation in the face of deep uncertainty. This means that the suppliers and users of climate risk information need to be closely aligned from outset. It also makes sense to demonstrate the value-added (if any) when more sophisticated scenario methods are applied – underlining the merit of benchmarking against simpler procedures whenever time and resources permit.

11. Future opportunities to improve the science and information

This final section offers suggestions for improving the technical base for the production and uptake of climate risk information for the 2020s. The options are grouped into three themes: (i) basic science, (ii) uncertainty and (iii) decision support.

I Basic science

11.1 Monitoring and surveillance

From outset it was recognised that benefits arise from a combined approach to adaptation involving vulnerability assessment and scenario development. Both strategies require high quality information to characterise the full range of climate variability together with associated societal and environmental consequences; both are hampered by deteriorating meteorological networks (Figure 15). Indeed, without basic meteorological data to verify model representations of the present climate, there can be little confidence in future projections or interpolated information, no matter how sophisticated the tool. Similarly, secondary impacts modelling presupposes the existence of reliable records of river flow, crop yields, groundwater levels, and so on. The need for collective action to improve the status of all such observing systems, especially in Africa, has been stated many times before. It may be timely and sobering to measure progress against the specific recommendations made before the Gleneagles G8 summit in 2005 (Washington et al., 2004).

Figure 15 The global network of the World Weather Watch (WWW) stations colour coded to indicate silence (red dot) or reporting rates in 2004. Source: WMO (2005)

11.2 Understanding and predictability of Africa's regional climate

There are gaps in understanding of fundamental climate controls for large parts of Africa (including central-east Africa, the Ethiopian Highlands, and Sahel), as well as tropical cyclone behaviour (over Madagascar), stability of Arctic Oscillation/ El Niño teleconnections, and land-surface feedbacks on regional climate (Hewitson *pers. comm.*). This is evidenced by divergent outlooks for vulnerable regions such as the Sahel (where Held et al. [2005] assert that the future will be "drier" and Hoerling et al. [2006] "wetter"). Part of the solution involves supporting intense field campaigns (like EU AMMA) to collect data on poorly understood climate processes, or primary information for data sparse regions, especially in the tropics. More could be done to assess the realism of teleconnection patterns within GCMs using existing model runs (Sutton, *pers. comm.*). This might involve evaluations of the stability of known teleconnections over multi-decadal timescales, or the consequences of poorly understood teleconnections (such as the warming of the southwest Atlantic).

11.3 Urban climates

There is growing appreciation that the populations, infrastructure and ecology of cities are at risk from the impacts of climate change. At present, roughly 50% of the world's population live in cities, but this is expected to rise to more than 60% over the next 30 years. Most of the future growth of the urban population is anticipated in the developing world (Figure 16). Vulnerable populations of many low-income countries are already exposed to shortages of clean drinking water and poor sanitation, and often occupy high-risk areas such as floodplains and coastal zones (Haines et al., 2006). Target 11 of MDG7 ('ensure environmental sustainability') aims to achieve a significant improvement in the lives of at least 100 million slum dwellers by 2020. Although the situation is improving, surprisingly little is known about how built environments will respond to climate change (Walsh et al., 2007; Wilby, 2007) especially in developing regions (du Plessis et al., 2003; Magadza, 2000). Adaptation options include improving preparedness and forecasting of climatic hazards, such as intense heat island or air pollution episodes, to safeguard human comfort and health. Technical guidance is also needed for appropriate building design and climate sensitive planning, avoidance of high-risk areas through more stringent development control, incorporation of climate change allowances in engineering standards applied to flood defences and water supply systems, and for optimum management of green spaces for urban cooling and flood attenuation.

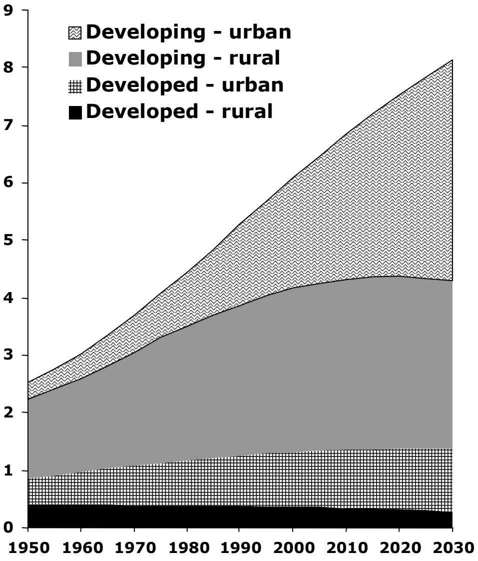


Figure 16 An increasingly urbanised global population. Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2004).

11.4 Forecasting environmental resources

Improved skill at forecasting decadal temperatures is expected to translate into improved skill at forecasting regional water cycle components (e.g., rainfall, evaporation, soil moisture, groundwater, and river flow) (Smith, *pers. comm.*). These products are potentially of greater interest to planners than global mean temperatures alone. However, natural internal climate variability will be magnified at finer spatial scales, increasing uncertainty in forecasts. An interim step might be to test probabilistic decadal forecasts for strategically significant sub-continental regions such as the River Yangtze (Blender and Fraedrich, 2006; Weng et al., 1999), or the Nile basin, where environmental and human responses to decadal climate variability are already well understood (Eltahir, 1996; Conway, 2005). River flow forecasts may be more skilful if decadal forecasts are downscaled to river basins before water balance modelling (Lettenmaier, *pers. comm.*) rather than relying on flows computed within the coarse resolution GCM itself (as in Manabe et al., 2004) – but this needs to be tested.

II Uncertainty

11.5 Hindcasting climate change scenarios for the 2020s

Decadal forecasting and empirical downscaling are forward running scenario methods that emphasize the importance of initial conditions and GCM predictors respectively. A counterview is to hindcast scenarios for the 2020s from emergent regional climate change patterns in multi-GCM ensembles or RCM runs for the 2080s (as in Hulme et al., 2002; Xiong et al., 2007). The latter is preferable to bespoke RCM simulations for the 2020s because RCMs are sensitive to initial conditions, and the regional climate change signal is expected to be small relative to inter-annual variability. Furthermore, pattern-scaling offers the prospect of extrapolation beyond the limited set of RCM experiments to evaluate uncertainties due to the host GCM forcing or emission scenario. In contrast, decadal forecasting and empirical downscaling can be more resource intensive but provide information on inter-annual behaviour. Thus, it would be informative to compare the value-added of forward running experiments for the 2020s with pattern-scaling back from the 2080s (see Figure 17 and the Annex for more detail). Conversely, the same experiments could test the validity of assumptions about invariant patterns, and linear scaling of regional climate (including extremes) by global mean temperatures (see section 7.1).

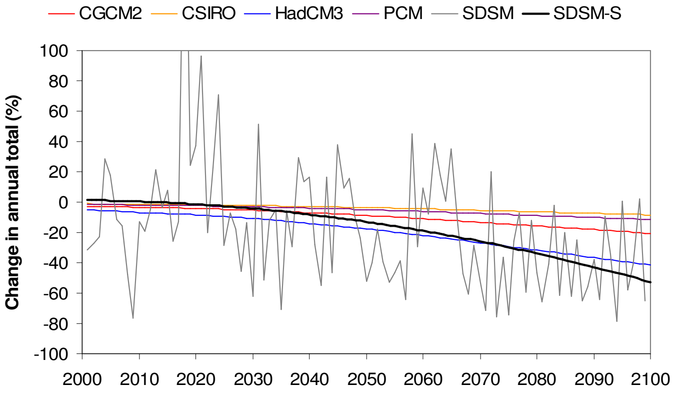


Figure 17 Changes (%) in annual precipitation totals at Casablanca under SRES A2 emissions comparing pattern-scaled (CGCM2, CSIRO, HadCM3, PCM) and empirically downscaled (SDSM) scenarios. SDSM results were downscaled from HadCM3. SDSM-S were smoothed to removed inter-annual variability.

11.6 Improving awareness and embedding impact model uncertainty

Uncertainties in climate change impacts attributed to the secondary impact model *per se* are seldom recognised let alone quantified alongside those due to the climate model scenario(s). To date, climate risk assessments have focused almost exclusively on climate model uncertainty and have, therefore, overlooked a major component of uncertainty. Part of the responsibility lies with the research community taking a much broader perspective on uncertainty and combining traditionally separate elements within unifying assessment frameworks (as in Wilby and Harris, 2006). The problem can also be addressed closer to source whenever climate information is being generated centrally on behalf of a broader constituency. For example, the latest set of river flow change factors provided to UK water utilities to inform their 25-year plans incorporate both climate and hydrological model uncertainty (Figure 18). At the very least guidance for climate risk assessment should reflect latest understanding of impact model uncertainty, and stress its importance particularly when non-linear and/or discontinuous responses are likely.

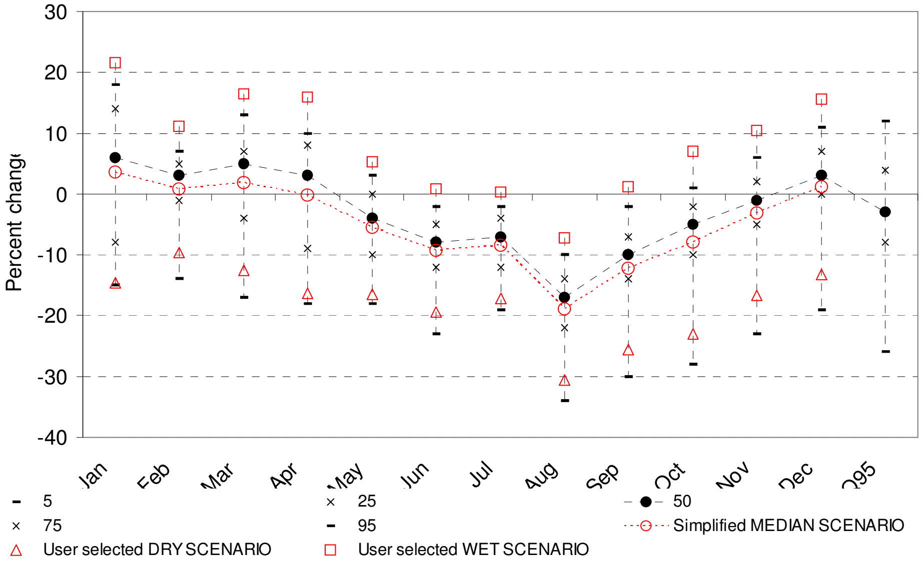


Figure 18 Climate change factors for monthly mean flows in the River Kennet. Vertical bars denote uncertainty due to climate and hydrological model uncertainty in the 2020s. Source: UKWIR (2007).

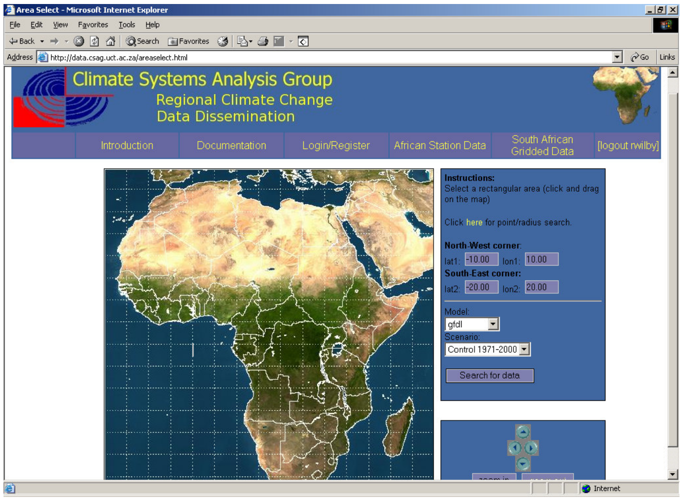
III Decision support systems

11.7 Aggregating local impacts for adaptation planning

Downscaling methods provide finer resolution scenarios for impacts modelling, but adaptation policy and planning needs economic information at sectoral, national and global levels (Burton, 2007). New conceptual and modelling frameworks will be required to 'upscale' from the plethora of local studies. Macro-models and integrated assessment tools already exist for testing multi-sector impacts of climate and socio-economic change (e.g., Hayhoe et al., 2004; Holman et al., 2005) but what is still lacking are the means to incorporate plausible adaptation mechanism at such coarse scales. Above all, there is an urgent need to convert awareness of local climate change impacts into tangible adaptation measures at all levels of governance. This will involve translating available scientific evidence into guidance for practitioners. In addition, composite indices of the strength of future climate change relative to natural variability, alongside measures of human development and vulnerability, could help target resources for adaptation. Existing indices could be enhanced by inclusion of sea level rise alongside metrics of temperature and precipitation change (Baettig et al., 2007) and applied to the 2020s and 2050s.

11.8 Accessing online resources and tools

Improved access to climate model products and scenario tools would significantly increase opportunities for generation and uptake of climate risk information at the country-level. There are a few good examples of online scenario tools that exploit climate products, combined with local meteorological data, to deliver climate simulations at time and space scales relevant to stakeholders (see Figure 19 and the Resources). However, a more strategic approach is needed to better coordinate and maintain existing portals, as well as to provide guidance in the appropriate use of scenario products at the country-level. Online training materials tailored to local adaptation priorities and capacity needs could be delivered through the same portal. A specific recommendation would be to improve the accessibility and format of AR4 climate change scenarios held by the IPCC Data Distribution Centre (DDC) portal.



Instructions:
Select a rectangular area (click and drag on the map)

Click here for point/radius search.

North-West corner:
lat1: -10.00 lon1: 10.00
South-East corner:
lat2: -20.00 lon2: 20.00

Model: gfdl
Scenario: Control 1971-2000

Figure 19 The web portal of the University of Cape Town Climate Systems Analysis Group provides empirically downscaled climate change scenarios for sites across Africa. Source: http://data.csag.uct.ac.za/areaselect.html [accessed 9 August 2000]

IV Next steps

The purpose of this document has been to provide a compendium of information sources for climate change risk assessment within the 2020s timeframe. Attention has focused on the available technical methods, their comparative strengths and weakness, infrastructure and capacity requirements.

Scope for mainstreaming scenario information in adaptation planning depends on the adaptation assessment approach, country-level technical and financial capacity, scale of the risk(s), as well as the timing and type(s) of adaptation being considered. Benefits arise from a combined approach to adaptation involving vulnerability assessment to cope with climate variability in the short-term, and use of climate scenarios to capture incremental changes in risk over coming decades.

Recommendations for improving the production and uptake of decadal climate forecasts will be carried forward into the final project deliverable: a schedule of work addressing technical and non-technical constraints at both international and country-levels. This final step will consider relative priorities, timing and resource implications, as well as the potential for shared approaches with partner organisations.

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Annex A – Pattern-scaled and downscaled scenarios for Casablanca

Pattern-scaled (PAT) and empirically downscaled (SDSM, UCT) scenarios are compared using annual rainfall changes at Casablanca, Morocco. PAT-HadCM3 and SDSM-HadCM3 scenarios are directly comparable because they employ the same host GCM and emissions (Figure A.1). PAT eliminates variability because all changes are scaled back from the 2080s using the ratio between local (Morocco) to global mean temperature change. PAT also applies the same scaling regardless of location so, for example, the same trend would be produced for Marrakech and Tangier. In contrast, SDSM and UCT produce site specific, transient precipitation scenarios on a daily basis. These were aggregated to annual totals for comparison with PAT. All methods point to long-term reductions in annual rainfall (except for the 7% increase returned by SDSM for the 2020s which is within the bounds of natural variability). In comparison, the multi-method ensemble uncertainty for the 2080s was -7 to -49%.

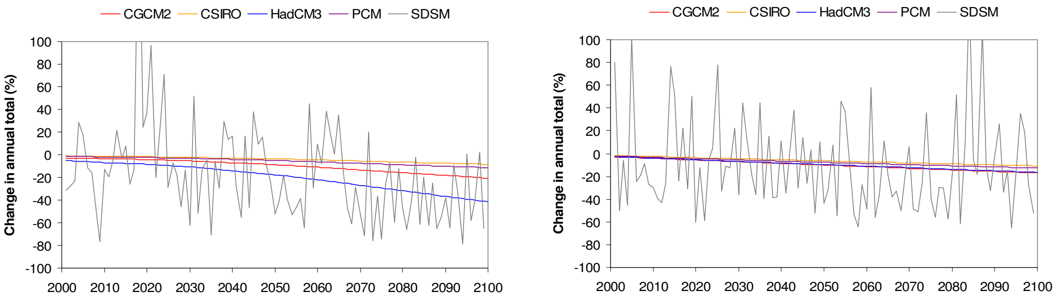

Figure A.1 Annual series of precipitation changes under SRES A2 (left) and B2 (right) emissions.

Table A.1 Changes (%) in annual precipitation totals at Casablanca, Morocco arising from different scenario methods (UCT, SDSM, PAT) and GCM forcing (CSIRO, ECHAM4, HadAM3, HadCM3, PSM) under SRES A2 and B2 emissions for the 2020s, 2050s and 2080s.

	2020s		**2050s**		**2080s**	
Scenarios	**A2**	**B2**	**A2**	**B2**	**A2**	**B2**
UCT-CSIRO	-	-	-	-	-44	-
UCT-ECHAM4	-	-	-	-	-49	-
UCT-HadAM3	-	-	-	-	-20	-
SDSM*-HadCM3	7	-4	-18	-17	-40	-9
PAT-CGCM2	-5	-6	-10	-11	-17	-15
PAT-CSIRO	-2	-4	-4	-7	-7	-10
PAT-HadCM3	-10	-6	-20	-10	-34	-14
PAT-PSM	-3	-5	-6	-8	-10	-11
Ensemble mean	-3	-5	-12	-11	-28	-12

Key to scenarios methods: UCT (University of Cape Town tool: Hewitson and Crane [2006]); SDSM (Statistical DownScaling Model: Wilby et al. [2002]); PAT (Pattern-scaling from Tyndal CY 3.0 scalers: Mitchell et al. [2002]). * Ensemble member M1.

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Annex B – Impact model uncertainty

Time-varying uncertainty in climate change impacts are demonstrated using a Ricardian model of smallholder farm incomes in Sri Lanka. The relative contributions of three components are investigated, sourced from climate model, emissions and impacts model (parameter) uncertainty. Ricardian model coefficients and their associated standard errors were taken from Kurukulasuriya and Ajwad (2006).

The model estimates variations in net revenue ($/Ha) as a function of seasonal climate, household and farm-level data, types of markets, and income streams. Farm profitability is most heavily loaded against mean annual temperature (TEMP) so this variable alone was chosen to explore uncertainty in future revenue due to the impact model. This was performed using the best estimate and 95% upper/lower confidence limits of the temperature parameter. However, a more comprehensive analysis of different model parameters and structures would be expected to increase uncertainty bounds still further.

Pattern-scaled TEMP scenarios for Sri Lanka were constructed from four SRES emission scenarios (A1FI, A2, B1, B2) and four GCMs (CGCM2, CSIRO2, HadCM3, PCM). These scenarios were input to the Ricardian model to project net revenues over the period 2001 to 2100. Changes in net revenue were calculated with respect to the year 2000 baseline used by Kurukulasuriya and Ajwad (2006) and expressed as absolute changes (Figure B.1). Total uncertainty can be estimated by summing the contributions of the three sub-components (climate model, emissions, impact model). Because pattern-scaled temperature scenarios were applied, uncertainty due to natural climate variability could not be considered. However, it is recognised that natural variability will be a major source of uncertainty affecting climate risk assessments for the 2020s.

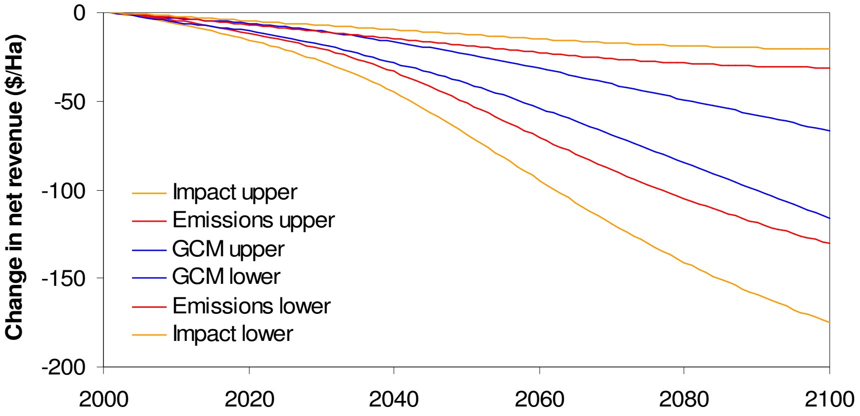

Figure B.1 Changing net revenue ($/Ha) reflecting uncertainty in GCM projections of TEMP (blue envelope) combined with emissions (red envelope) and impact model parameter uncertainty (gold envelope).

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Tool	**Source**
clim.pact	R functions for downscaling monthly and daily mean climate scenarios http://cran.r-project.org/src/contrib/Descriptions/clim.pact.html
CSAG	Data portal for downscaled African precipitation scenarios for the 2080s http://data.csag.uct.ac.za/
ENSEMBLES	Experimental portal for downscaling tools applied to Europe http://grupos.unican.es/ai/meteo/ensembles/index.html
FINESSI	Multi-sector/ multi-variable climate change scenarios for Finland http://www.finessi.info/finessi/?page=explore
LARS-WG	Tool for producing time series of a suite of climate variables at single sites http://www.rothamsted.bbsrc.ac.uk/mas-models/larswg.php
MAGICC/ SCENGEN	Interactive software for investigations of global/regional climate change http://www.cgd.ucar.edu/cas/wigley/magicc/
PRECIS	UK Met Office portable regional climate model http://precis.metoffice.com/
RClimex	Graphical interface to compute 27 core indices of climate extremes http://cccma.seos.uvic.ca/ETCCDMI/software.shtml
SDSM	Downscaling tool for scenario production at single sites http://www-staff.lboro.ac.uk/~cocwd/SDSM/

Public domain data portals and archives [accessed 13 August 2007]

Host	**Source**
BADC	British Atmospheric Data Centre http://badc.nerc.ac.uk/home/
CICS	Global predictor variable sets for statistical downscaling http://www.cics.uvic.ca/scenarios/index.cgi?Scenarios
CLIVAR VACS	Baseline climate data for Africa http://www.geog.ox.ac.uk/~clivar/ClimateAtlas/
CPC	Climate Prediction Center historic teleconnection indices and outlooks http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/climwx.shtml
CRU Global Climate Data set	High-resolution global and country-level climate data (present & future) http://www.cru.uea.ac.uk/cru/data/hrg/
CSAG	Gridded precipitation data for South Africa http://www.csag.uct.ac.za
ECMWF	European Centre for Medium Range Weather Forecasts http://www.ecmwf.int/
GHCN	Global Historical Climatology Network monthly station data http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php
GPCC	Global gridded monthly precipitation data set http://daac.gsfc.nasa.gov/interdisc/readmes/gpcp_global_precip.shtml
ICOADS	International Comprehensive Ocean-Atmosphere Data Set http://icoads.noaa.gov/
IPCC DDC	GCM scenario archive and supporting guidance http://www.ipcc-data.org/
KNMI Climate Explorer	Monthly and daily meteorological data http://climexp.knmi.nl/start.cgi?someone@somewhere
NCDC	National Climate Data Center – Palaeoclimatoloy data archive http://www.ncdc.noaa.gov/paleo/data.html
NSIDC	National Snow and Ice Data Center http://nsidc.org/sotc/
PSMSL	Global data bank for long term sea level change from tide gauges http://www.pol.ac.uk/psmsl/
World Data Center	Repository for data sets prepared under international research programmes http://www.ncdc.noaa.gov/oa/wdc/index.php

Glossary

Where appropriate, the following definitions were drawn from the Glossary of terms in the Summary for Policymakers (2001), A Report of Working Group I of the Intergovernmental Panel on Climate Change, and the Technical Summary of the Working Group I Report. Terms in *italics* are found elsewhere in this Glossary.

Aerosols Airborne solid or liquid particles, with a typical size between 0.01 and 10µm that reside in the atmosphere for at least several hours. Aerosols influence the *climate* directly through scattering and absorbing radiation, and indirectly through the formation and optical properties of clouds.

Anthropogenic Resulting from, or produced by, human beings.

Atmosphere The gaseous envelope surrounding the Earth, comprising almost entirely of nitrogen (78.1%) and oxygen (20.9%), together with several trace gases, such as argon (0.93%) and *greenhouse gases* such as carbon dioxide (0.03%).

Baseline The reference *climate* against which any change is measured. The datum may be observable, present-day conditions as recorded in meteorological data, typically for the standard period 1961-1990. Alternatively, the datum may be the present-day conditions as represented by a climate model. The latter is typically used to calculate changes with respect to future conditions represented by the same model. This enables removal of climate model biases assuming that they are unchanged between the present and future climate states.

Black box Describes a system or model for which the inputs and outputs are known, but intermediate processes are either unknown or not prescribed. See *regression*.

Climate The "average weather" described in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organisation (WMO).

Climate change Statistically significant variation in either the mean state of the *climate*, or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or to *external forcings*, or to persistent *anthropogenic* changes in the composition of the atmosphere or in land use.

Climate model A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some its known properties.

Climate prediction An attempt to produce a most likely description or estimate of the actual evolution of the climate in the future, e.g. at seasonal, inter–annual or long–term time scales.

Climate projection A projection of the response of the climate system to emission or concentration scenarios of *greenhouse gases* and *aerosols*, or *radiative forcing* scenarios, often based on simulations by *climate models*. As such climate projections are based on assumptions concerning future socio–economic and technological developments.

Climate scenario A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic *climate change*.

Climate variability Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events.

Deterministic A process, physical law or model that returns the same predictable outcome from repeat experiments when presented with the same initial and boundary conditions, in contrast to *stochastic* processes.

Domain A fixed region of the Earth's surface and over-lying atmosphere represented by a *Regional Climate Model*. Also, denotes the grid box(es) used for statistical *downscaling*. In both cases, the downscaling is accomplished using pressure, wind, temperature or vapour information supplied by a host GCM.

Downscaling The development of climate data for a point or small area from regional climate information. The regional climate data may originate either from a *climate model* or from observations. Downscaling models may relate processes operating across different time and/or space scales.

Dynamical See *Regional Climate Model.*

Emission scenario A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g. *greenhouse gases*, *aerosols*), based on a coherent and internally consistent set of assumptions about driving forces and their key relationships.

Ensemble (member) A set of simulations (members) in which a deterministic *climate model* is run for multiple *climate projections*, each with minor differences in the initial or boundary conditions. Conversely, *weather generator* ensemble members differ by virtue of random outcomes of successive model simulations. In either case, ensemble solutions can be grouped and then compared with the ensemble mean to provide a guide to the *uncertainty* associated with specific aspects of the simulation.

External forcing A set of factors that influence the evolution of the climate system in time (and excluding natural internal dynamics of the system). Examples of external forcing include volcanic eruptions, solar variations and human–induced forcings such as changing the composition of the atmosphere and land use change.

Extreme weather event An event that is rare within its statistical reference distribution at a particular place. Definitions of "rare" vary from place to place (and from time to time), but an extreme event would normally be as rare or rarer than the 10th or 90th percentile.

Global Climate Model (GCM) A three–dimensional representation of the Earth's atmosphere using four primary equations describing the flow of energy (first law of thermodynamics) and momentum (Newton's second law of motion), along with the conservation of mass (continuity equation) and water vapour (ideal gas law). Each equation is solved at discrete points on the Earth's surface at fixed time intervals (typically 10–30 minutes), for several layers in the atmosphere defined by a regular *grid* (of about 200km resolution). Coupled ocean–atmosphere/ global climate models (O/AGCMs) also include ocean, land–surface and sea–ice components. See *climate model.*

Greenhouse gas Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. The primary greenhouse gases are water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3).

Grid The co–ordinate system employed by *GCM* or *RCM* to compute three–dimensional fields of atmospheric mass, energy flux, momentum and water vapour. The grid spacing determines the smallest features that can be realistically resolved by the model. Typical resolutions for GCMs are 200km, and for RCMs 20–50km.

Parameter A numerical value representing a process or attribute in a model. Some parameters are readily measurable climate properties; others are known to vary but are not specifically related to measurable features. Parameters are also used in climate models to represent processes that are poorly understood or resolved.

Predictand A variable that may be inferred through knowledge of the behaviour of one or more *predictor* variables.

Predictor A variable that is assumed to have predictive skill for another variable of interest, the *predictand.* For example, day–to–day variations in atmospheric pressure may be a useful predictor of daily rainfall occurrence.

Probability Density Function (PDF) A distribution describing the probability of an outcome for a given value for a variable. For example, the PDF of daily temperatures often approximates a normal distribution about the mean, with small probabilities for very high or low temperatures.

Radiative forcing The change in net vertical irradiance (expressed as Watts per square metre) at the *tropopause* due to an internal change or a change in the *external forcing* of the climate system, such as, for example, a change in the concentration of carbon dioxide, or the output of the Sun.

Random See *stochastic.*

Regional Climate Model (RCM) A three–dimensional, mathematical model that simulates regional scale climate features (of 20–50 km resolution) given time–varying, atmospheric properties modelled by a *Global Climate Model*. The RCM *domain* is typically “nested” within the three–dimensional *grid* used by a GCM to simulate large–scale fields (e.g., surface pressure, wind, temperature and vapour).

Regression A statistical technique for constructing empirical relationships between a dependent (*predictand*) and set of independent (*predictor*) variables. See also *black box, transfer function*.

Resolution The *grid* separation of a climate model determining the smallest physical feature that can be realistically simulated.

Scenario A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a “narrative story–line”.

Station The individual site at which meteorological measurements are systematically observed and recorded.

Stochastic A process or model that returns different outcomes from repeat experiments even when presented with the same initial and boundary conditions, in contrast to *deterministic* processes. See *weather generator*.

Teleconnection The apparent ability of one part of the earth system to affect the behaviour of weather in another region, separated by space and/or time. For example, ocean temperatures in the Indian Ocean are known to affect seasonal rainfall in East Africa.

Transfer function A mathematical equation that relates a *predictor*, or set of predictor variables, to a target variable, the *predictand*. The predictor(s) and predictand represent processes operating at different temporal and/or spatial scales. In this case, the transfer function provides a means of *downscaling* information from coarse to finer resolutions.

Tropopause The boundary between the lowest part of the atmosphere, known as the troposphere, and the highly stratified region of the atmosphere, known as the stratosphere. The tropopause is typically located 10km above the Earth’s surface.

Uncertainty An expression of the degree to which a value (e.g. the future state of the climate system) is unknown. Uncertainty can result from a lack of information or from disagreement about what is known or knowable. It can also arise from poorly resolved climate model parameters or boundary conditions.

Weather generator A model whose stochastic (random) behaviour statistically resembles daily weather data at single or multiple sites. Unlike *deterministic* weather forecasting models, weather generators are not expected to duplicate a particular weather sequence at a given time in either the past or the future. Most weather generators assume a link between the precipitation process and secondary weather variables such as temperature, solar radiation and humidity.

Weather pattern An objectively or subjectively classified distribution of surface (and/or upper atmosphere) meteorological variables, typically daily mean sea level pressure. Each atmospheric circulation pattern should have distinctive meteorological properties (e.g. chance of rainfall, sunshine hours, wind direction, air quality, etc). Examples of subjective circulation typing schemes include the European Grosswetterlagen, and the British Isles Lamb Weather Types.