MANAGING UNCERTAINTY IN CLIMATE CHANGE PROJECTIONS – ISSUES FOR IMPACT ASSESSMENT

An Editorial Comment

Abstract. Climate change projection is the term the IPCC Second Assessment Report (SAR) uses for model estimates of future climate. In that report, projections are presented in two forms: as single model scenarios and as projected ranges of uncertainty. In climate studies, scenarios are commonly regarded as being plausible, but have no further probability attached. Projected ranges of uncertainty can have probabilities attached to the range and within the range, so are more likely to occur than individual scenarios. However, as there is significant remaining uncertainty beyond the projected range, such projections cannot be regarded as forecasts. An appropriate terminology is required to communicate this distinction. The sources of uncertainty in projected ranges of global temperature to 2100 are analysed by Visser et al. (2000), who recommend that all major sources of uncertainty be incorporated into global warming projections. This will expand its projected range beyond that of the IPCC SAR. Further sources of uncertainties are contained within projections of regional climate. Several strategies that aim to manage that uncertainty are described. Uncertainty can also be managed where it is unquantifiable. An example is rapid climate change, where discarding the term climate 'surprises' in favour of more precise terminology to aid in identifying possible adaptation strategies, is recommended.

1. Introduction

Research can support the UN Framework Convention for Climate Change (FCCC) by assessing the risk faced by ecosystems, food production and economic development under climate change (Article 2), then by assessing the adaptation and mitigation options capable of managing that risk (Article 4). To establish levels of risk, climate change impact assessments need to move beyond investigations of sensitivity and vulnerability where outcomes are presented as being plausible. The largest barrier to establishing levels of risk is uncertainty, which is propagated through every step of an assessment. Scientists must communicate this uncertainty but when they do, non-scientists often conclude that no action is necessary because the uncertainties are so large. This may not be the message that is intended. It is also contrary to both the uncertainty principle as outlined in the FCCC (Article 3.3) and to the advice given to policymakers in the IPCC Second Assessment Report (SAR) (IPCC, 1996a,b,c).

Tools are needed to analyse and manage the uncertainty accompanying climate change assessments. Where the propagation of uncertainty is a concern, Katz (1999) recommends that 'disintegrated' uncertainty analysis be undertaken where each of the elements within an integrated framework is assessed separately. The

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DIALOGUE model, introduced by Visser et al. (2000) does this. DIALOGUE is an integrated assessment model that estimates global temperature from linked greenhouse gas emission scenarios, and gas cycle, radiative forcing and simple climate models. Each of the components has been assessed separately to determine its individual contribution to the total range of uncertainty contained within projected global temperature.

Uncertainty contained in projections of global change combines with uncertainties in projections of regional change, with both propagating through to impact assessments (e.g., Figure 10-1, Arnell et al., 1996). Tools such as DIALOGUE may be suitably adapted to manage uncertainty in regional climate change projections by calculating conditional probabilities. The broad context of such a role is discussed in this paper, and examples for managing uncertainty in regional climate change projections are presented with recommendations for future research.

2. The Portrayal of Uncertainty within the IPCC Second Assessment Report

Although the IPCC SAR on impacts, adaptation and mitigation (Watson et al., 1996) explicitly linked dangerous climate change with mitigation and adaptation assessment in its Technical Summary (IPCC, 1996b), the body of the report was mostly restricted to describing sensitivity and vulnerability assessments. Most of these assessments were based on the output of one to four climate models or to arbitrary changes of climate. If arbitrary changes are used, then the results are strictly sensitivity assessments. If model output is used, the outcomes are plausible but contain no information as to their likelihood, how the results fit into broader ranges of uncertainty, and what those ranges of uncertainty may be. Adaptation outcomes utilising both types of assessment tend to be broad and generic. These limitations are also a feature of the subsequent IPCC assessment of regional vulnerability (Watson et al., 1998).

Adaptation to climate change is largely time and scale dependent, this dependence being a function of both climate impacts on a particular activity and its adaptive potential. The assessment of climate change in the assessment process begins at the global scale with global climate models (GCMs). A predictive capability for climate at the regional and local scale is vital but to do this, uncertainty at the global scale must first be better managed. Mitigation assessments aiming to avoid dangerous climate change at the global scale also require this capability.

Two levels of uncertainty portrayal can be identified in the IPCC Working Group I (WGI) SAR (Houghton et al., 1996) with regard to estimates of climate change: scenarios and projections. A scenario is a description of a plausible future used without reference to its likelihood. Examples of scenarios are the individual IS92a–f emission scenarios, and the climate scenarios (projections) generated by general circulation models (GCMs) where a single emission scenario is used. Scen-

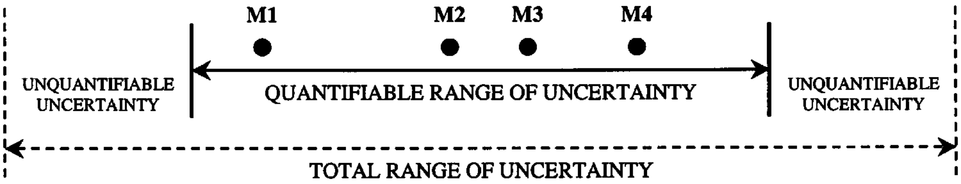

Figure 1. Schematic depiction of the relationship between scenarios, a projected range and total uncertainty. M1 to M4 represent scenarios produced by four models. The projected range consists of a quantifiable range of uncertainty that encompasses the scenarios. This lies within a total range of uncertainty that cannot be fully quantified.

arios may contain several sources of uncertainty but generally do not acknowledge them explicitly.

Careful reading of the WGI Technical Summary (IPCC, 1996a) reveals that the term projection is used in two senses:

(a) single trajectory over time produced from one or more scenarios e.g., projected global temperature using the IS92a emissions scenario with a climate sensitivity of 2.5 °C.

(b) a range of projections expressed at a particular time in the future incorporating one or more sources of uncertainty e.g., projected global warming of 0.8–3.5 °C at 2100 based on the IS92a–f emission scenarios and a climate sensitivity of 1.5–4.5 °C at 2 × CO_2.

Projections are used instead of *predictions* to emphasise that they do not represent attempts to forecast the most likely evolution of climate in the future (IPCC, 1996a; Section F.1). In the SAR, both projection and scenario are used to describe possible future states, with projections used mainly in terms of climate change and sea-level rise. This usage defines climate projections expressed as a single trajectory, as a subset of scenarios. When used as input into impact assessments, the same climate projections are commonly referred to as climate scenarios.

Projected ranges are constructed from two or more scenarios where one or more sources of uncertainty may be acknowledged. Examples include projections of atmospheric CO_2 derived from the IS92a–f emission scenarios (IPCC, 1996a), global temperature ranges (IPCC, 1996a) and regional temperature ranges (CSIRO, 1996). These differ from the projection as a single trajectory through time, as a range of projections will always be more likely. The issue of likelihood in the construction of climate scenarios needs to be addressed if impact assessments are to investigate dangerous climate change. Projected ranges are more likely to occur than single scenarios but are not fully-fledged forecasts, as they incorporate only part of the total uncertainty. The relationship between scenarios, projected ranges and forecasts is shown in Figure 1.

In Figure 1, M1 to M4 represent four different scenarios. If the example of global warming is used, these four scenarios may represent projected temperature increases from four different GCMs at a particular time (e.g., 2100). A projected range quantifying the full range of uncertainties contributing to the spread of results produced by models M1 to M4 will encompass those scenarios. A projected range is a quantifiable range of uncertainty situated within a population of possible futures that cannot be fully quantified (nominated as ‘knowable’ and ‘unknowable’ uncertainties by Morgan and Henrion (1990)). The limits of this total range of uncertainty are unknown.

If the full range of uncertainty in Figure 1 was known, then the probability of a particular outcome could be expressed as a forecast. However, at present impact and adaptation research is restricted to working with projected ranges, as there are significant sources of uncertainty that cannot yet be quantified. Conditional probabilities may be calculated within a projected range even though the probability of the range itself remains unknown. The construction of conditional probabilities is discussed in Section 3.2.

3. Projected Ranges

3.1. THE UNCERTAINTY EXPLOSION

The use of projected ranges in impact assessment results in the propagation of uncertainty if it is not adequately managed. The process whereby uncertainty accumulates throughout the process of climate change prediction and impact assessment has been variously described as a cascade of uncertainty (Schneider, 1983) or the uncertainty explosion (Henderson-Sellers, 1993). When the upper and lower limits of projected ranges of uncertainty are applied to impact models the range of possible impacts commonly becomes too large for the practical application of adaptation options (Pittock and Jones, 1999). This technique is less explicitly applied in assessments where two or more scenarios (e.g., M1 to M4 in Figure 1) are used and the results expressed as a range of outcomes. If an assessment is continued through to economic and social outcomes, even larger ranges of uncertainty can be accumulated (Figure 2).

Based on advice given by Pittock (1993), a number of Australian impact assessments have used CSIRO regional climate change scenarios (CSIRO, 1992, 1996) bound by high and low extremes of projected climate change (e.g., Schreider et al., 1996; Whetton et al., 1996; Basher and Pittock, 1998). Such assessments tend to produce a wide range of possible outcomes. Upon being presented with such large ranges, stakeholders often fail to see the utility of this information, given the large uncertainties they already deal with.

The IPCC Technical Guidelines for Impact Assessment (Carter et al., 1994) present a fairly linear framework, progressing from climate modelling (Working Group I), to biophysical impacts (Working Group II) with the optional further addition of socio-economic analyses (Working Group III). Feedback loops are

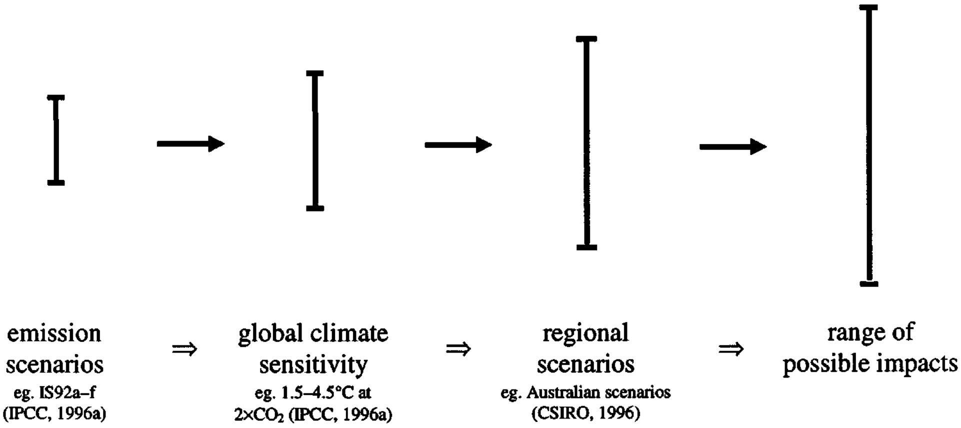

Figure 2. Range of major uncertainties typically involved in Australian impact assessments, showing the 'uncertainty explosion' as these ranges are multiplied to encompass a comprehensive range of future possibilities.

incorporated in the methodology but they are accompanied by few descriptions of how they can be used. While appropriate for testing sensitivity and vulnerability of systems, this methodology is poorly suited for planning or policy purposes as it is limited to yielding plausible outcomes without attaching any measure of likelihood to them.

Pittock and Jones (1999) recommend the construction of thresholds that can be linked to projected ranges of climate change in order to calculate their probability of exceedance. Such thresholds can account for either biophysical and socio-economic criteria in the initial stages of an assessment but must be expressed in climatic terms (e.g., above a certain temperature, rainfall frequency, water balance or a combination of several factors). Further analysis compares these with projected regional climate change. Similar approaches are contained in concepts of tolerable climate change as applied to climate change projections applied by Hulme and Brown (1998).

3.2. QUANTIFYING UNCERTAINTY

Visser et al. (2000) analyse four sources of uncertainty contributing to projections of global warming:

- greenhouse gas emissions
- greenhouse gas cycle
- radiative forcing
- climate sensitivity.

The projected range of global warming in the IPCC SAR (IPCC, 1996a) incorporates uncertainties only for emission scenarios and climate sensitivity (Kattenberg et al., 1996). Uncertainties for radiative forcing and the greenhouse gas cycle are represented by median values in the simple climate model, MAGICC (Hulme et al., 1995), used by the IPCC to produce projected ranges of global warming and sea level (IPCC, 1996a). Matrices showing the IPCC (1996a) global warming projections with the associated ranges of uncertainty for greenhouse gas emissions and climate sensitivity in 2030, 2070 and 2100 are shown in Table I.

The relative contribution of climate sensitivity to the total range of uncertainty decreases towards 2100 as the importance of greenhouse gas emissions increases. This is shown in Figure 18 of the SAR WGI Technical Report (IPCC, 1996a), where the projected range due to the IS92a–f scenarios is negligible for the first half of the 21st century, while rapidly expanding in the second half. After analysing the relative influences of all four sources of uncertainty, Visser et al. (2000) nominate radiative forcing as the largest contributor. Sulphate aerosol forcing comprises about half of that range. They found that the uncertainties surrounding the radiative forcing of greenhouse gases and sulphate aerosol are larger than the uncertainties due to either greenhouse gas emissions or climate sensitivity at 2100.

Using a dynamic modelling approach, Hansen et al. (1998) reach a similar conclusion and propose that the uncertainty analysis of radiative forcing should take precedence in scientific assessments of uncertainty. Hansen et al. (1998), also considered several other forcings including land-use and solar irradiance not included in Visser et al's. analysis.

If all four ranges of uncertainty assessed by Visser et al. (2000) were used to construct projections of global temperature consistent with the uncertainty ranges used in the SAR, the resultant range of global temperature would be even larger than it is now. This was confirmed by running MAGICC with the low and high limits of uncertainty for the direct and indirect effects of sulphate aerosols and biomass derived aerosols from Schimel et al. (1996) and for the CO_2 fertilisation effect (influencing the greenhouse gas cycle). The resulting range of uncertainty for IS92a–f emission scenarios with increasing sulphate aerosols increased from 2.7 °C (0.8–3.5 °C) to 3.8 °C (0.7–4.5 °C). Having followed the recommendation of Visser et al. (2000) and Hansen et al. (1998) a more comprehensive result is obtained which is hard to communicate effectively to policymakers, and difficult to apply in impact studies. Uncertainty management is required if this difficulty is to be overcome.

3.3. MANAGING UNCERTAINTY

Few assessments have managed large ranges of uncertainty as part of the analysis. Two notable examples are:

(a) the integrated assessment model, ICAM-2 (Morgan and Dowlatabadi, 1996) where ranges of uncertainty from climate change to the economics of mitigation and adaptation are linked via statistical and dynamic relationships, and

TABLE I

Uncertainty matrices for global warming (°C) in 2030, 2070 and 2100 based on the greenhouse emission scarious IS92a–f with a climate sensitivity of 1.5–4.5 °C at $2 \times CO_2$, using MAGICC

Sensitivity ⇒ emissions ⇓	Low	Med.	High
2030 [a]			
Low	0.4	0.5	0.8
Med.	0.4	0.6	0.8
High	0.4	0.6	0.8
2070 [b]			
Low	0.7	1.1	1.6
Med	0.9	1.4	1.9
High	1.0	1.5	2.1
2100 [c]			
Low	0.9	1.4	2.0
Med	1.4	2.0	3.0
High	1.7	2.5	3.5

[a] Sensitivity uncertainty range = 0.4 °C; Emissions uncertainty range = <0.1 °C.

[b] Sensitivity uncertainty range = 0.9 °C to 1.1 °C; Emissions uncertainty range = 0.3 °C to 0.5 °C.

[c] Sensitivity uncertainty range = 1.1 °C to 1.8 °C; Emissions uncertainty range = 0.8 °C to 1.5 °C.

(b) an assessment that combines expert opinion, Monte Carlo analysis and dynamic links to assess the risk of global sea-level rise (Titus and Narayanan, 1996).

Similar approaches are needed for applying projected ranges of regional climate to impact models. As mentioned above, several Australian impact assessments have used projected ranges of regional climate, encompassing low and high extremes of possible regional change. These regional projections incorporate projections of global warming from IPCC (1996) and regional ranges of change per degree of global warming for temperature and rainfall derived from a sample of GCMs (CSIRO, 1992, 1996). Their use satisfies the requirement that the fullest possible ranges of uncertainty should be used, but the results are vulnerable to the uncertainty explosion, especially where the default assumption for a range of outcomes is one of uniform probability (see Figure 2).

Tools similar to those used by Visser et al. (2000), Morgan and Dowlatabadi (1996) and Titus and Narayanan (1996) can be used to manage the uncertainty within such projections (Jones, 1998; Jones et al., 1999; Walsh et al., 1999). For instance, when two or more ranges of uniform probability are multiplied together, as in Figure 2, the result is not uniform but is peaked (Jones, 1998; Parkinson and Young, 1998). Utilising this property in a study of irrigation demand, Jones (1998) constructed probabilistic scenarios for changes to temperature and rainfall in inland Australia based on CSIRO (1996).

Figure 3a shows the projected climate for inland southern Australia in 2100 from CSIRO (1996) assuming uniform probability across the ranges of projected rainfall and temperature. Figure 3b show conditional probabilities based on the random sampling of the component uncertainties of those ranges. For the temperature scenarios, two ranges were randomly sampled and multiplied 50,000 times:

(i) the global warming projections of 0.8–3.5 °C (IPCC, 1996a), encompassing the IPCC-estimated range of climate sensitivity and the IS92a–f emission scenarios, and
(ii) regional climate change expressed as local warming per degree of global warming.

Rainfall was calculated in a similar manner. A matrix across the ranges was constructed and the percentage frequency of outcomes in each square calculated and summed from the most frequent to the least frequent. Each contour contains a cumulative probability of particular climates being reached, tallied from the most to the least likely. In Figure 3b, based on the input assumptions, 50% of projected climate shown in Figure 3a lies outside the 95% probability contour, therefore has $<5\%$ chance of occurring. These simple methods show a great potential to manage uncertainty in climate projections despite Figure 3b containing only two ranges of uncertainty.

In this example, projected global warming was sampled as a uniform range. To test the assumption of uniformity, the following test was performed on its two component ranges of uncertainty as shown in Table I: greenhouse gas emissions and climate sensitivity. The simple model MAGICC (Hulme et al., 1995) was used to assess whether a non-uniform distribution of global warming may be more appropriate by uniformly sampling its component range of climate sensitivity of 1.5–4.5 °C and multiplying these samples with each of the IS92a–f scenarios (Figure 4a). Climate sensitivity was sampled in seven 0.5 °C increments from 1.5–4.5 °C and multiplied with each of the six IS92a–f emission scenarios to create 42 estimates of global warming. In Figure 5a, the resultant range is almost uniform, showing that the assumption of uniformity for the range of global warming used in Figure 3b is appropriate.

A second test was then conducted to determine whether altering the probability distribution of the range of climate sensitivity to accommodate new information would reduce uncertainty in the regional climate projection shown in Figure 3b.

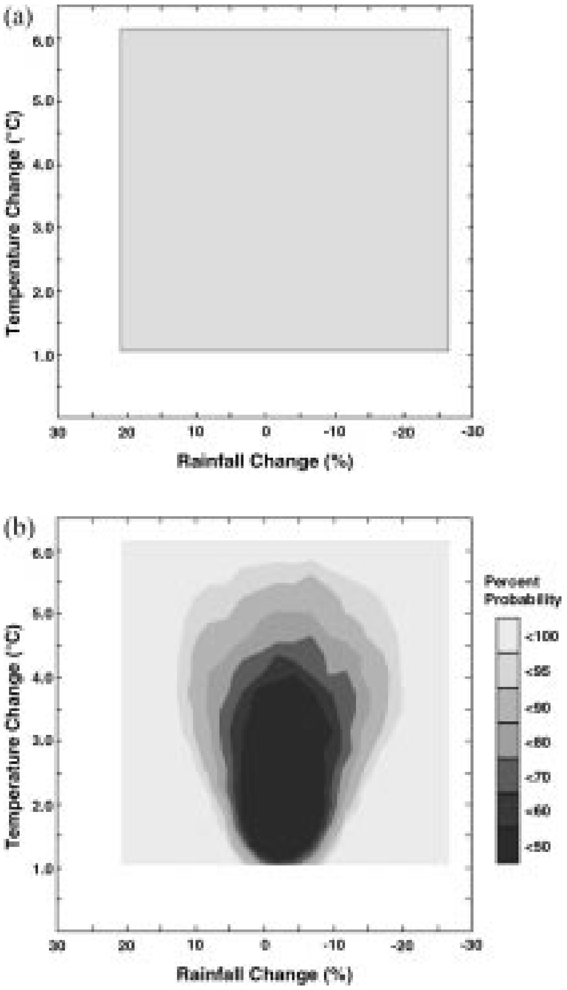

Figure 3. (a) Projected ranges of regional temperature and rainfall for inland southern Australia in 2100 extrapolated from CSIRO (1996) assuming a uniform distribution across the range. (b) The same ranges in Figure 3a with temperature sampled randomly across projected ranges of both global and regional warming then multiplied. Projected regional summer and winter ranges for rainfall were randomly sampled, then multiplied by randomly sampled global warming as above then averaged. The probability plots were calculated by cumulatively adding percentage frequency in order from the most to the least likely for all gridpoints (see text).

A non-uniform distribution was constructed, where the range 2–4 °C was considered as being equally likely, consistent with the recommendation of Hansen et al. (1998), reducing linearly to 1.5 and 4.5 °C at the extremes (Figure 4b). Seven samples spaced according to equal probability as per the distribution in Figure 4b (0.9, 1.3, 1.65, 3.0, 3.35, 3.7, 4.1 °C) were then multiplied with the six IS92a–f emission scenarios. The resultant range is shown in Figure 5b and more non-linear

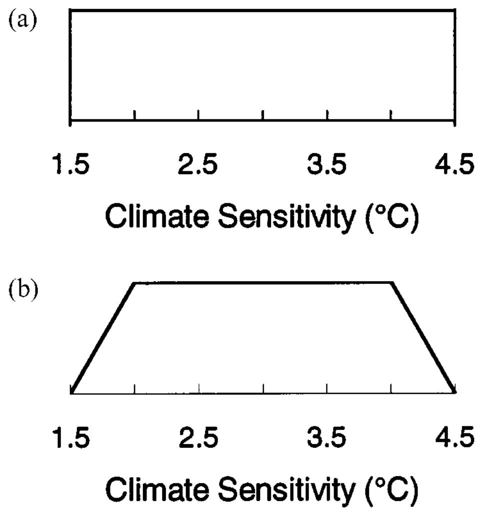

Figure 4. (a) Probability distribution for a climate sensitivity of 1.5–4.5 °C. 3a. Uniform distribution. (b) The range of 2–4 °C has equal likelihood, reducing linearly to 1.5 and 4.5 °C at the extremes.

than Figure 5a, although this difference is not statistically significant. However, is it sufficient to alter the probability distribution for regional climate?

When the probability distribution function for Figure 4b is used to re-calculate projected regional climate as shown in Figure 3, the most likely climates occupy yet a smaller space (Figure 6). The area outside the 95% probability contour has increased from 50% in Figure 3b to about 60% of the total range and all the other contours occupy a smaller space. If a more non-linear distribution that that shown in Figure 5b could be justified, these reductions would be even more pronounced.

Techniques such as this will be valuable where more ranges of uncertainty, such as those for the greenhouse gas cycle and radiative forcing, are to be added to a projected range of climate change. Other forms of disintegrated uncertainty analysis can also be tested using these techniques. For example, all four sources of uncertainty included in the DIALOGUE model could be used to create conditional probabilities in regional climate change projections, similar to Figures 2 and 5, to test their relative contribution to uncertainties in regional climate. This type of analysis can also be used to test the relative contributions of the various sources of uncertainty to impact outcomes. For example, such an exercise may involve the coupling of the DIALOGUE model to an impact assessment model. Hulme and Carter (1999) have also carried out a similar analysis to Figure 3b where the application of statistical relationship between temperature and rainfall produces a tighter distribution than if they are treated independently, as they are here.

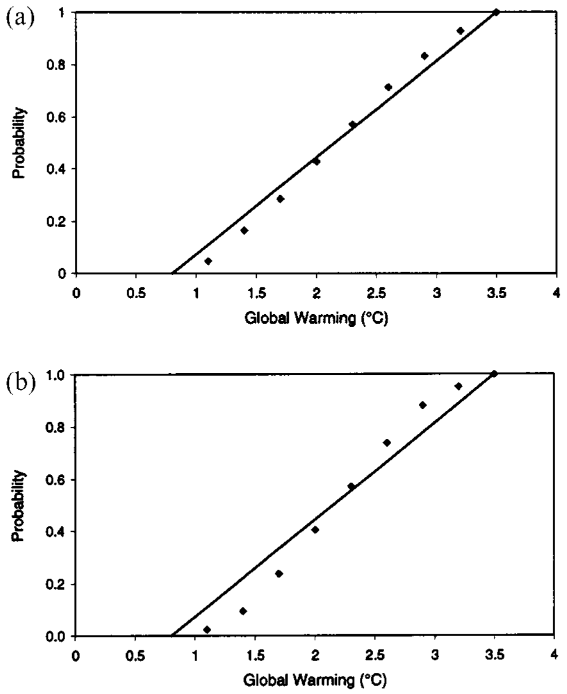

Figure 5. (a) Cumulative distribution of projected ranges of global warming, calculated by the simple climate model MAGICC with sampled inputs of a. climate sensitivity sampled for seven 0.5 °C increments over the range of 1.5–4.5 °C run with each of the six IS92a–f greenhouse gas emission scenarios, and (b) by seven samples of global warming with equal probability as per Figure 4b run with each of the six IS92a–f greenhouse gas emission scenarios.

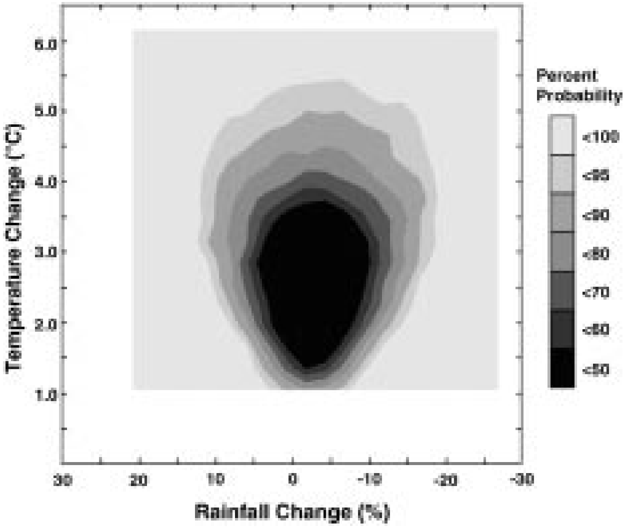

Figure 6. Projected probabilities of climate change for 2100 in northern Victoria as for Figure 2 but with global warming sampled according to the distribution shown in Figure 2b.

4. Unquantifiable Uncertainties – Rapid Climate Change

When a range of quantifiable uncertainty is applied to one or more sources of uncertainty and used to calculate the probability of an outcome, then the result can be expressed in probabilistic terminology. These probabilities are highly conditional due to the significant unquantifiable uncertainties that remain. Unquantifiable sources of uncertainty with the potential to influence global climate include feedback effects due to changing atmospheric chemistry, the effects of altered land surface cover, rapid climate change, volcanoes and social disasters occurring on a global scale.

Where a high degree of uncertainty precludes quantification, the careful application of language can be used to provide a degree of precision. One example where this can be achieved is in the area of climate surprises. In the WGI SAR Summary for Policymakers, ‘surprises’ is a blanket term that covers rapid climate change, non-linear forcings, and non-linear responses to stochastic processes that result in changed climates. A true surprise is an unexpected occurrence, which would appear to preclude planned adaptation to climate surprises.

Rapid climate change is becoming increasingly recognisable in palaeoclimatic reconstructions, including during ‘stable’ periods such as the Holocene. The increasing knowledge concerning rapid climate change during both glacial and interglacial stages suggests that comparable changes in the future can be anticipated (Overpeck, 1996). With such expectations, it may be possible to plan ahead for rapid climate changes, although it may not be possible to quantify such changes according to the paradigm of transient climate change addressed in the previous section. In fact, rapid climate change shows all the signs of being a normal part of the earth’s climate, where self-organised criticality results in pseudo-periodic, catastrophic events. The timing and degree of each event may be unexpected but they do occur within a broad statistical framework (Bak, 1996).

A major aspect of rapid climate change is its combination of a low probability of occurrence over short time scales with a potential for severe impacts. These impacts may be felt on a global to a regional scale. Two global examples are the deep-ocean convection system and the stability of the West Antarctic Ice Sheet. They can have potentially large impacts on the climate and other systems, although these are unlikely to be experienced over the next century. Supra-regional or hemispheric systems where rapid changes occur include the North Atlantic Oscillation and El Niño Southern Oscillation. More local systems will be associated with ocean currents, zones of upwelling, ice-shelves and monsoonal systems. As the considered spatial scale decreases, the likelihood of rapid changes occurring in such localised systems increases. Some regions will be more vulnerable than others.

An important task is to identify the most likely causes of rapid climate change and the regions in which they are most likely to impact. Where there is a potential for severe impacts, a lack of predictability should not delay adaptation assessments. For instance, rapid regional climate change can alter rainfall patterns, making historical climate records obsolete for design purposes. Climate assessments will have to be carried out using dynamic models initialised with the newly observed conditions in order to facilitate adaptation. Unless some initial planning is done beforehand, the institutional capability to adapt to such changes is likely to be low. Low probability/high impact outcomes may not be well accounted for within the methods of constructing climate projections used by the IPCC and described in this paper, so assessments more suited to this phenomenon may have to be carried out (Patt, 1999).

This shows a need to be much more discerning about rapid climate change. The term surprises should be dropped and precise terms regarding sources of uncertainty, mechanisms and likely impacts used in its place. If a rapid climate change is assessed as posing a risk to a particular region, it should not be labelled as a surprise, discounting the possibility of planned adaptation. Similar steps may be taken to better identify other, so-called climate surprises.

5. Discussion and Conclusions

Visser et al. (2000) significantly advance the understanding of several sources of uncertainty contributing to global warming. They also provide the basis to assess how improvements in our knowledge may change the relative balance of those sources. This paper utilises similar tools to those used by Visser et al. to demonstrate how such analyses can apply to the construction of regional climate projections for impact analysis.

New information that may change our knowledge of sources of uncertainty under climate change includes improved knowledge of direct and indirect forcing or sulphate aerosol, and new emissions scenarios commissioned by the IPCC. These are the SRES scenarios (Nakicenovic, 1998), which provide a greater range of future emissions pathways than the IS92a–f scenarios, so are likely to produce a different range of global warming. Many of these scenarios project decreasing emissions of sulphate aerosol by 2050, reducing its relative importance after that time. The approach used in DIALOGUE will be of great value by analysing the relative uncertainties of this new information.

Shifting the emphasis on the construction of climate projections from plausible outcomes to ranges incorporating probability will result in projected ranges of climate that do not qualify as scenarios. In Section 2, two types of climate projection were identified. The single projection is a scenario, whereas a projected range is not. This creates problems with terminology. From Figure 1, a projected range is not a scenario but nor is it a forecast, as a significant range of unquantifiable uncertainty still exists. Rather, it is somewhere in between. Any conclusions based on the use of projected ranges of climate must remain highly conditional.

Using the term climate projection for information that exists in two different states is a recipe for confusion. For climate research to be successful it has to move beyond scenarios, but it is not realistic to expect that this movement will lead straight to forecasts. This paper is describing a state somewhere in between, and the appropriate terminology for that state needs to be defined. Projection perhaps, if its usage as a type of scenario is removed. Conditional forecasts may be another term, but there is a danger that the ‘conditional’ will be lost outside the scientific literature.

The assignation of probabilities to a projected range of emission scenarios, or whether they should be assigned at all, is controversial and requires discussion and some agreement between the various disciplines involved. The approach of sampling individual scenarios as in Visser et al. and in Figures 2b and 6, implicitly treats them as having an equal probability, a position which has been criticised on the basis that no relative probabilities can be established for these scenarios. However, a way forward has to be found so that the uncertainty created by the range of emission scenarios can be analysed and managed in an acceptable manner. The creation of a separate identity for describing the future that is more than a scenario but less than a forecast may help this process.

Techniques to manage uncertainty within climate scenarios and impact assessments are greatly needed by impact scientists (Carter et al., 1999). For instance, tools designed to manage uncertainty, such as DIALOGUE and probabilistic climate projections, need to be tested with impact models to:

- Assess the relative contributions of an expanded set of the sources of uncertainty contributing to global warming on projected ranges of regional climate.
- Assess the relative contributions of this set of uncertainties associated with various impact assessments, e.g., conduct Bayesian analysis of various assumptions regarding the types and sources of uncertainty on impact outcomes to determine whether specific sources need to be included, or whether they can be safely omitted from an assessment.

The following recommendation is also made to provide greater precision to scenario development and the portrayal of uncertainties associated with such scenarios:

- The definition of a scenario should be restricted to a single, plausible future to which no probability can be attached.
- That projected ranges of climate or a similar term be used to refer to ranges constructed of two or more climate scenarios encompassing a range of uncertainty, where sufficient unquantifiable uncertainties remain for it not to be justified as a forecast.

While it is still too early to make definitive statements about how uncertainty should be managed in climate assessments, the following points are re-emphasised:

- Disintegrated uncertainty analysis is a valuable tool for assessing climate change uncertainty and for carrying out impact assessments.
- There is little evidence to show which methods are best for managing uncertainty, so a number need to be tested under a range of conditions and for different purposes.
- Assumptions of probability in scenario construction and impact assessments should be explicit rather than assumed.
- The concept of climate surprises should be jettisoned in favour of more precise terminology.
- The full ranges of quantifiable uncertainty from all sources should be incorporated into climate change assessments wherever possible. Tools such as DIALOGUE and those described in this paper will aid that process.

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