Handling uncertainties in the UKCIP02 scenarios of climate change

Hadley Centre technical note 44

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1 Introduction

The publication of detailed climate change scenarios for the UK (Ref 1, referred to as UKCIP02) represented a major step forward in the development of climate change scenarios for adaptation studies. In response to user demands they were based on predictions from a regional climate model (that of the Hadley Centre), with all the advantages which this brings in terms of improved spatial detail and representation of extremes. Four scenarios were presented, corresponding to four different possible pathways of future emissions, so as to take into account of this cause of uncertainty. We also showed the uncertainty which arises due to the natural variability of climate.

However, as was carefully pointed out in the report, it was not possible to include the other main cause of uncertainty in predictions, that due to our limited understanding of the climate system and ability to model it (known as "science uncertainty" or "model uncertainty"), because no other regional climate predictions were available, although an attempt was made to quantify it using coarse-scale regional predictions from global models. Appendix 1 of UKCIP02 gave some guidance on using the scenarios, pointing out the need to consider more than one UKCIP02 scenario for most studies, and include consideration of predictions from other climate models to scope uncertainty, in cases where adaptation to major infrastructure is being planned.

This note reviews in more general terms the uncertainties in predictions of climate change and suggests ways in which they can be handled. It is necessarily quite open and detailed about the several types of uncertainty, as their understanding is a prerequisite to handling them; this carries the danger that the users can become daunted. Paradoxically, as our knowledge and modelling of climate change increases (by, for example, inclusion of a newly recognised climate process previously omitted), adding the uncertainty due to that process will appear to widen overall uncertainty in predictions; this reflects the fact that we are more certain about the nature of the uncertainties. However, decisions on all manner of actions need to be informed by scenarios of the future (eg in demography, economy, technology) many of which are much less well constrained than those of climate change. In addition, in some cases decisions on "no-regrets" adaptive measures, or decisions which prevent future options being closed, can be taken even under quite a high degree of uncertainty, for example where only the broad direction of change is known

Of course, uncertainties will also arise from the impacts models which use the climate scenarios, and uncertainty in future patterns of socio-economic development; these should be taken into account but are not discussed here. More general guidance on treating climate change in adaptation planning, indicating tools and techniques, is given in a recent report. (Ref 2)

2 Predictions, projections and scenarios

There has been considerable debate about the use of the terms "prediction", "projection" and "scenario", and the Intergovernmental Panel on Climate Change (IPCC) in their Third Assessment Report (TAR), (Ref 3), chose to abandon the word "prediction" in favour of "projection". Because, in practice, modellers and users have continued to use "prediction", we have reverted to this term here for simplicity. For the purposes of this note a climate prediction is defined as a description of a future climate from a climate model based on an assumed profile of future emissions. A climate-change prediction is the change between a model simulation of recent climate (generally 1961-90) and the model climate prediction for a period (in this note generally taken as the period 2071-2100) in the future, under a specific emissions scenario. Thus we say, for example, "The change in summer-average temperature for Berkshire under Medium-High Emissions by the 2080s is predicted to be..."

A climate scenario is a plausible, self-consistent, state of climate in the future. As long as a climate scenario meets these criteria by, for example, being generated from a climate model, then it has, by definition, no uncertainty attached to it. It follows that, if planners require to know how high they should build flood defences, existing scenarios do not provide a complete picture; predictions, with quantified uncertainty would provide a much better basis for risk assessment. However, again for simplicity and to reflect common practice, we use the terms prediction and scenario interchangeably here.

3 Uncertainties in predictions

The climate of the future will be determined by two factors: the amount of man-made emissions of greenhouse gases and other pollutants, and the response of the climate system to these emissions. The only independent way we have of predicting climate change in the future is to use global climate models (GCMs). In order to carry out useful impacts assessments, we then have to downscale the global predictions from GCMs to a smaller scale. This is illustrated in Fig 1, which also shows the influence of natural variability, which can either add to, or subtract from, any man-made changes. Natural variability can be due to either internal "chaos" in the climate system, or factors external to the climate system such as energy from the sun or emissions from energetic volcanoes. Each of these stages and factors is a source of uncertainty in predictions, and although the level of uncertainty in some of these factors is being reduced through research, the complexity of the system makes this a slow process, and this will never reduce to zero. We have to find ways of coping with these uncertainties for the foreseeable future.

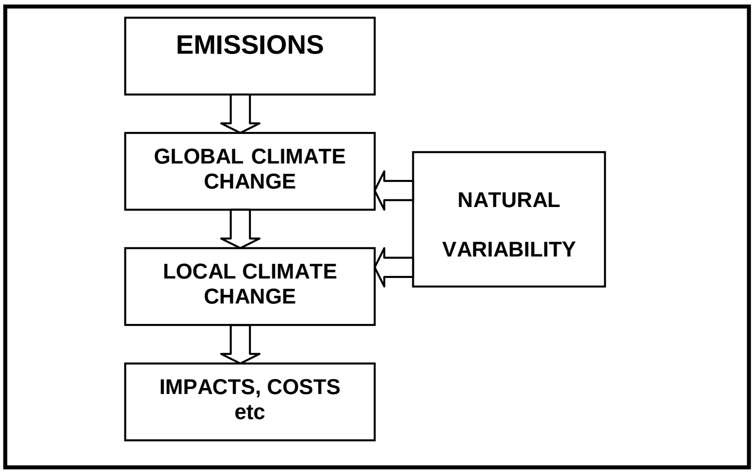

Fig 1 The stages of generating climate change scenarios, each of which carries uncertainties. (Note: Impacts, costs, etc are not considered here)

3.1 Uncertainty due to emissions

Future emissions from human activities depend upon socio-economic factors such as population, economic growth, technology etc. We do not, and never will, know how these will change in the future. The best we can do is to envision several plausible ways in which the world will develop over the next century, and use models to estimate what emissions will be generated from these. IPCC Special Report on Emission Scenarios (Ref 4) carried out this exercise in 1999, resulting in a wide range of possible future emissions in four groups (further details are given in UKCIP02). Each of these has a marker scenario, labelled A1FI, A2, B2 and B1. These emissions scenarios diverge immediately and rapidly; Fig 2 shows the CO2 emissions for each, which range in 2100 from less than today's to a fourfold increase on today's levels. SRES clearly state that it is not possible to put relative probabilities on any of the emissions scenarios, ie, they may not be equally probable, nor should any of the SRES groups be discounted.

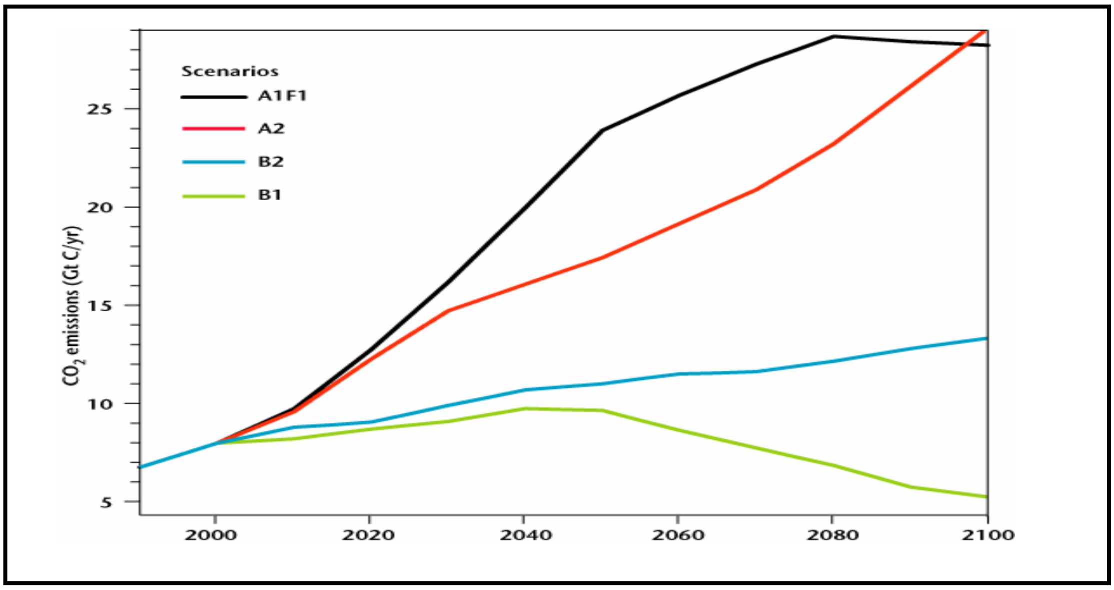

Fig 2: Emissions of carbon dioxide (as Gt of carbon) in four of the SRES emissions scenarios.

The global warming produced by these emissions scenarios, estimated by the Hadley Centre global climate model, is shown in Fig 3. It is noticeable that, despite the immediate divergence of future emissions in the four scenarios, the warming over the next 40 years or so from each emissions scenario is very similar. This is mainly due to the very long effective lifetimes of CO_2 and the large inertia of the climate system; much of the warming over the next few decades is already built into the climate system due to current emissions and those over the past several decades.

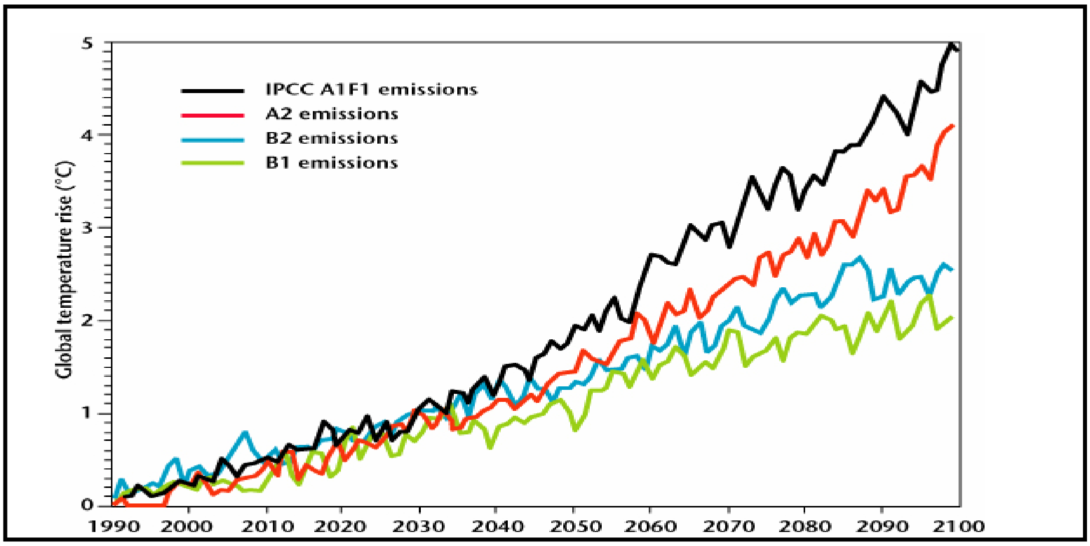

Fig 3: Global-mean surface-air temperature rise, estimated by the Hadley Centre HadCM3 model, resulting from the four emissions profiles shown in Figure 2.

On the other hand, warming by the end of the century does strongly depend on future emissions; the Hadley Centre model predicts 2^{o}C for the lowest scenario and 5^{o}C for the highest. In summary: uncertainty in emissions makes little contribution to uncertainty in climate change over the next 40 years; in the latter half of the century it makes a major contribution. We can scope the range of possibilities, but do not know which of these is more or less likely, although research on this is underway, for example in the USEPA.

3.2 Science uncertainty at a global scale

Figure 4, due to the IPCC TAR, shows the change in global-average temperature from nine climate models, all under the same scenario of future emissions (SRES A2). The range shown represents current modelling uncertainty in temperature rise. The actual rise may even be outside this range, if for example all models are missing some important feedback. Although the IPCC TAR did examine the uncertainty in the relationship between emissions and concentrations for many gases, it did not include this uncertainty in the range of temperature, and hence the range of results shown in Fig 4 (and Fig 5 below) is an underestimate of the total modelling uncertainty.

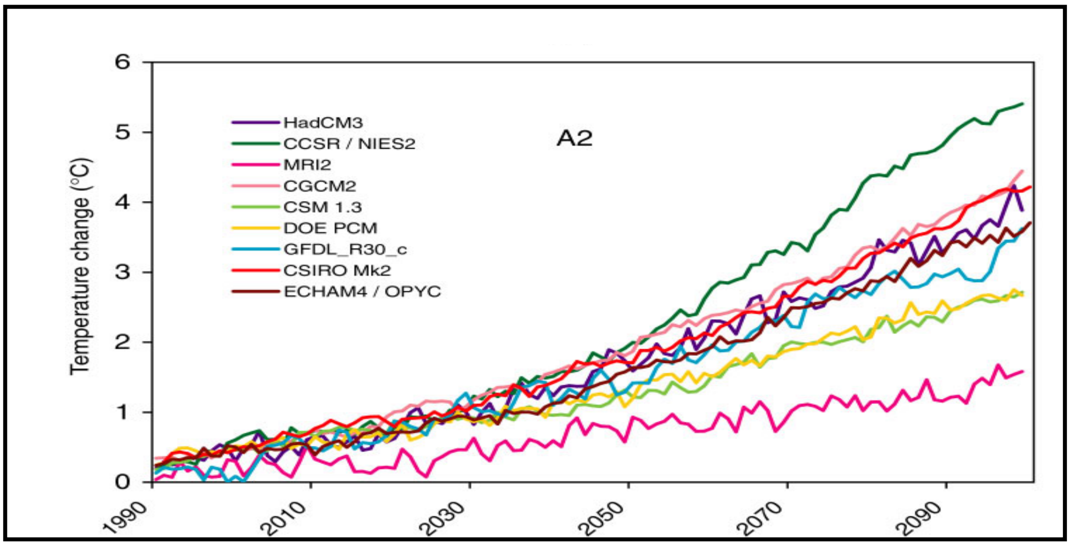

Figure 4: The change in global-mean temperature estimated by nine climate models forced by the SRES A2 emission scenario. (Source: IPCC TAR, Chapter 9)

Figure 5, from the same source, shows the change in global-average precipitation; the model-to-model differences are large, with a range of about ±70% about the mean by 2100. Contrast that range with the uncertainty due to emissions (Fig 6) predicted by one model (HadCM3) which amounts to about ± 25% by the end of the century. The uncertainty in future global precipitation change due to uncertainty in future emissions is seen to be smaller than the modelling uncertainty.

Predictions from the various models do not have an equal probability of representing the true outcome, but evaluating the relative credibility of each model (and hence their predictions) in an objective way is not straightforward to do, and requires a detailed knowledge of climate modelling and the climate system, together with a comprehensive database of observations. Even then an element of informed subjectivity will almost certainly be needed at present (but see Section 3.4)

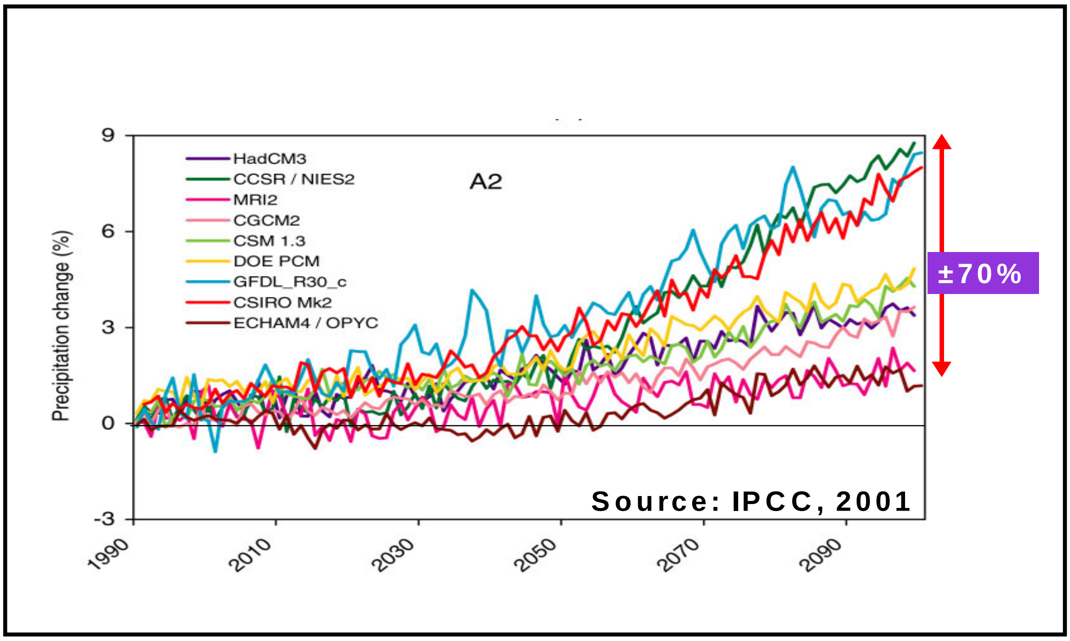

Figure 5: The change in global-mean precipitation estimated by nine climate models forced by the SRES A2 emission scenario. (Source: IPCC TAR, Chapter 9)

3.3 Science uncertainty at a regional scale

Next, we can zoom into a specific area of interest, but still using global models, and see what the uncertainties are at this scale. Figure 7 shows predictions of change by the 2080s in winter seasonal precipitation over the British Isles, from nine different climate models shown in IPCC TAR.

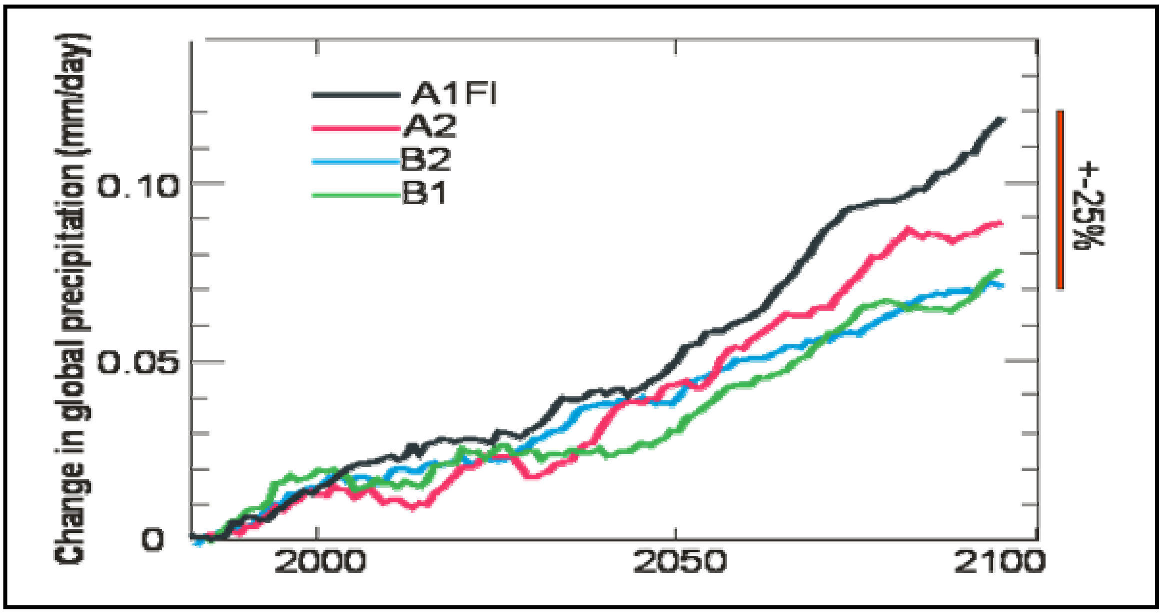

Figure 6: The change in global-mean precipitation estimated by one climate model (HadCM3) when forced by the four SRES marker emissions scenarios

Although all models show an increase in rainfall averaged over the UK, the size of this increase is very different from model to model. In one model it increases by 1%; if this prediction was accurate there would be less need to adapt to changing rainfall. (Of course, it may be worthwhile to improve infrastructure in order to give a greater level of protection against current climate extremes). In another model winter precipitation increases by 60%; if this turned out to be the case, failure to invest substantial sums of money to adapt could lead to substantial damage and loss of life. Figure 8 shows the corresponding picture for summer precipitation, where the change averaged over the UK land area ranges from -30% to +4%.

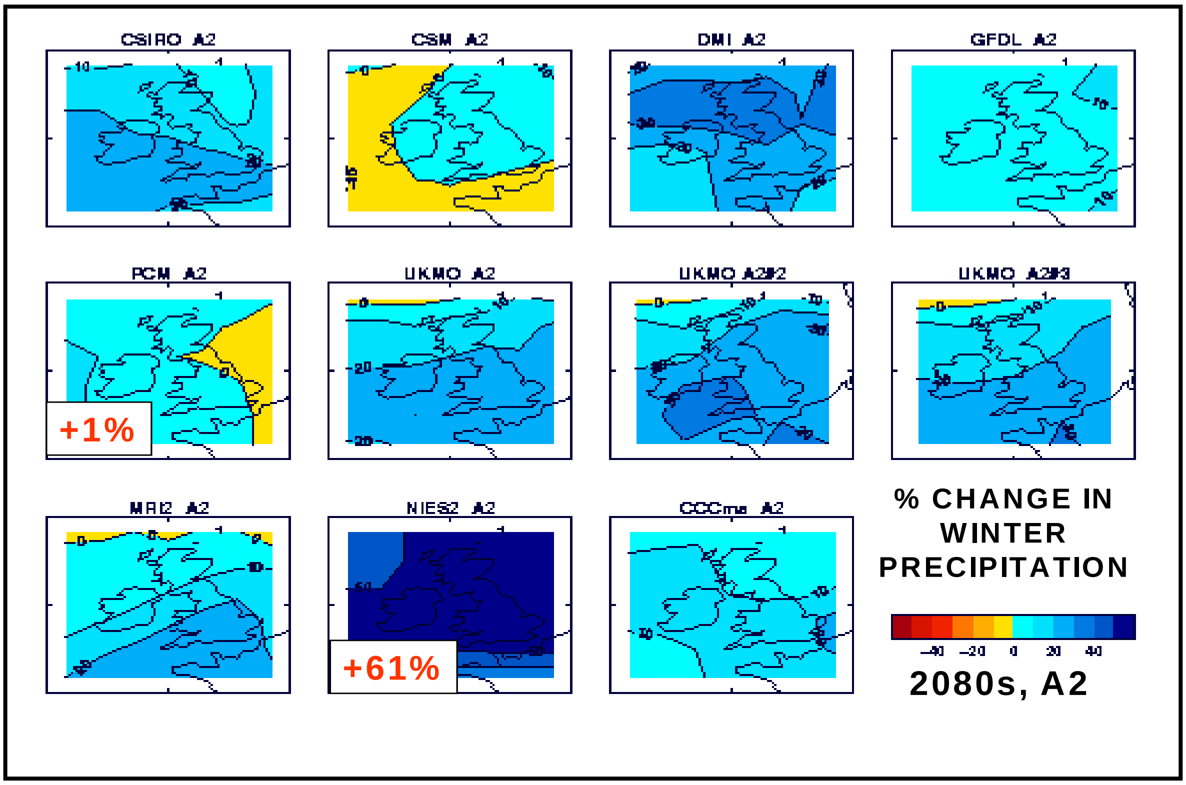

Figure 7: Change in winter mean rainfall over the British Isles by the period 2071-2100, relative to 1961-90, as predicted by nine climate models, all forced with the SRES A2 emissions scenarios. (Note there are three predictions from HadCM3 to illustrate natural variability; this is covered in section 3.5)

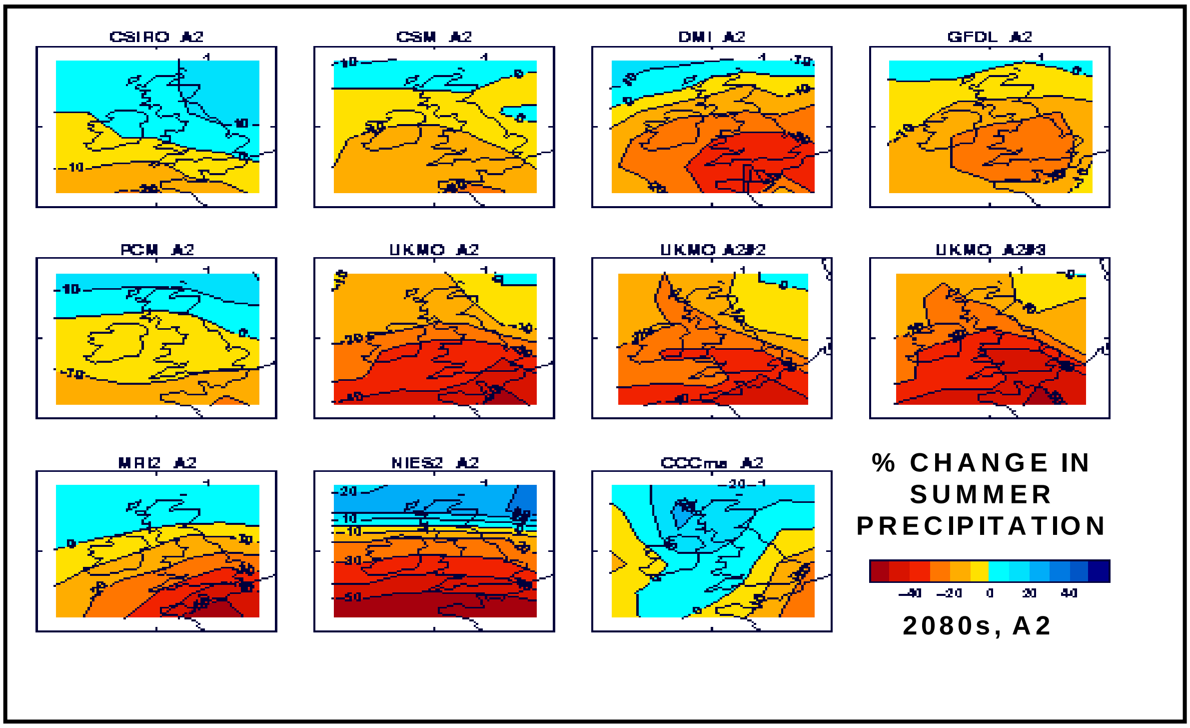

Figure 8: As Figure 7 but for summer mean rainfall.

To give another example: climate models predict different global-average rises in sea level over the next 100 years; IPCC TAR quotes a range of between about 10 and 90cm. All models show substantial regional variations in sea level rise; typically ±50% around the mean, but they do not agree on the patterns of higher and lower rise. In the North Sea, and considering thermal expansion alone, we find that in one model there is almost no mean rise, in another the rise is over half a metre. When the effect of changes in storminess on extreme surges is also included this range is even greater. Once again, decisions on upgrading coastal flood defences are likely to be better informed and less likely to either waste money or lead to significant damage, if they consider a variety of models.

The reason for these model-to-model differences in predictions lies in the construction of the models. Climate models have to represent all the elements of the climate system; atmosphere, ocean, land surface, cryosphere, biogeochemical cycles etc. The largest part of climate change arises not from the direct effect of increasing greenhouse gases (which is relatively easy to calculate) but from the interaction between different components of the climate system, which give rise to a large number of positive and negative feedbacks. For example, in the present climate high (ice crystal) clouds act to warm climate whereas low (water droplet) clouds act to cool climate. If warming changes the characteristics (amount, height, droplet or crystal size) of these clouds then this would have a considerable feedback on the eventual climate change. Because we have a limited understanding of many climate processes, different scientists will represent them in different (but plausible) ways in their models, and hence the predictions will also be different.

Figure 9 shows the effect of including new processes in the same climate model. Inclusion of the positive feedback from the carbon cycle in the Hadley Centre global model increases the prediction of temperature change over the UK substantially.

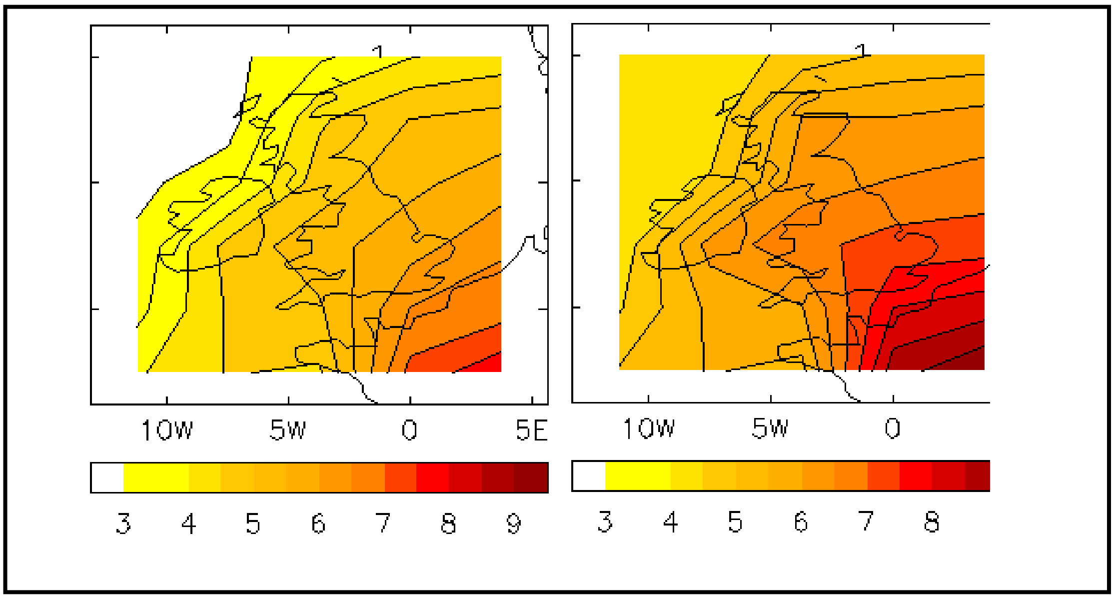

Figure 9: Summer-mean temperature rise by the 2080s under the SRES A2 emissions scenario, in the Hadley Centre coupled GCM without carbon-cycle feedback (left) and with the feedback added (right).

Another type of scientific uncertainty is that in the methods applied to climate model output, for example the choice of statistical methods used to extrapolate precipitation and storm surge extremes to longer return periods.

3.4 Handling the science uncertainty

3.4.1 We could estimate a range of modelling uncertainty in GCM predictions by looking at results from all available global models, as in Figs 7 and 8 above, but we do not know *prima face* which of these predictions is more or less likely. Furthermore, changes which will take place in the real climate system could be outside the range of all the model predictions, for example, if all the models missed some important process which amplified or attenuated the change in climate. There are criteria which we could apply to each climate model to assess its credibility, and these are suggested in Appendix 1 of UKCIP02; for example, the accuracy of its representation of current climate or its ability to simulate recent climate change or of climates of the past. However, all of these are to a certain extent subjective, and we describe below ways of deriving the uncertainty in future predictions in an objective way.

3.4.2 A novel way of deriving uncertainties in future predictions from a given climate model has recently been reported. In this technique, observed patterns of change in surface temperature over the last 50 years are compared with those simulated by the model. From this, the likely error and its distribution in the model simulation of global-mean temperature over the past 50 years is deduced, and extrapolated forward into the future, to provide a "corrected" prediction and uncertainty. Figure 10 shows the global temperature rise predicted by the Hadley Centre global model under the SRES A2 emissions scenario, together with the "corrected" prediction and its associated uncertainty limits.

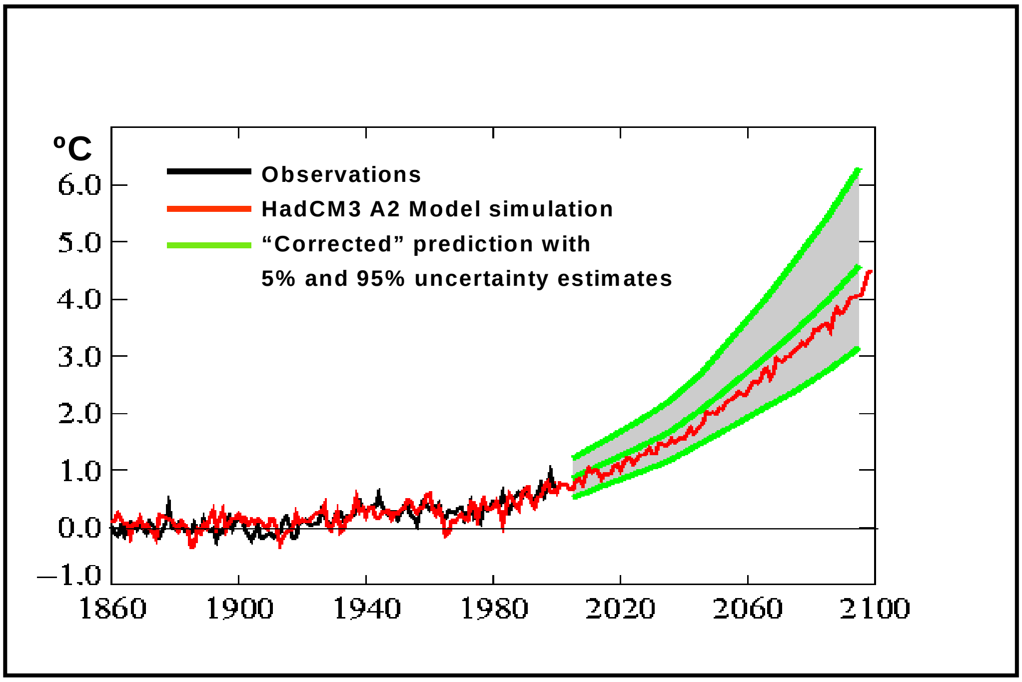

Figure 10: The red line is the HadCM3 model simulation of global-mean temperature rise, 1860-2100, compared to observations (to 2000)in black. Corrected estimates of future warming, with 5% & 95% uncertainty limits, are shown in green

An extension of this technique involves scaling regional patterns of change in temperature and rainfall from a number of global models, by the global-mean errors derived from each model. The "corrected" error distribution at a particular location from a number of models can then be added (again, on the assumption that all models are equally valid) to give a combined probability distribution of the change at a specific location. However, it is not clear to what extent errors in various regional climate quantities scale with global mean temperature error, and the technique will only be valid when scaling quantities which have a clear relationship with temperature.

3.4.3 The most rigorous way of handling modelling uncertainty in predictions, which is also the most complex and computer-intensive, is to use so-called "physics ensembles" of climate models. In this technique, large numbers of global climate models are built, each having different, but plausible, representations (parametrisations) of the climate system. These global models will be used to make a simulation of climate over an historical period, forced by observed changes in greenhouse gases and estimated changes in aerosols, and run on to predict changes to 2100 based on emissions from one of the SRES scenarios (for example, A2 (the Medium-High Emissions of UKCIP02)). The predictions of a specific quantity from all the models can then be shown as a *frequency* distribution. To derive a *probability* distribution of change in a particular quantity, the result from each model is weighted according to a broadly-based measure of model reliability. This would then allow the user to see the probability of changes in a quantity they require, for example summer rainfall over Oxford.

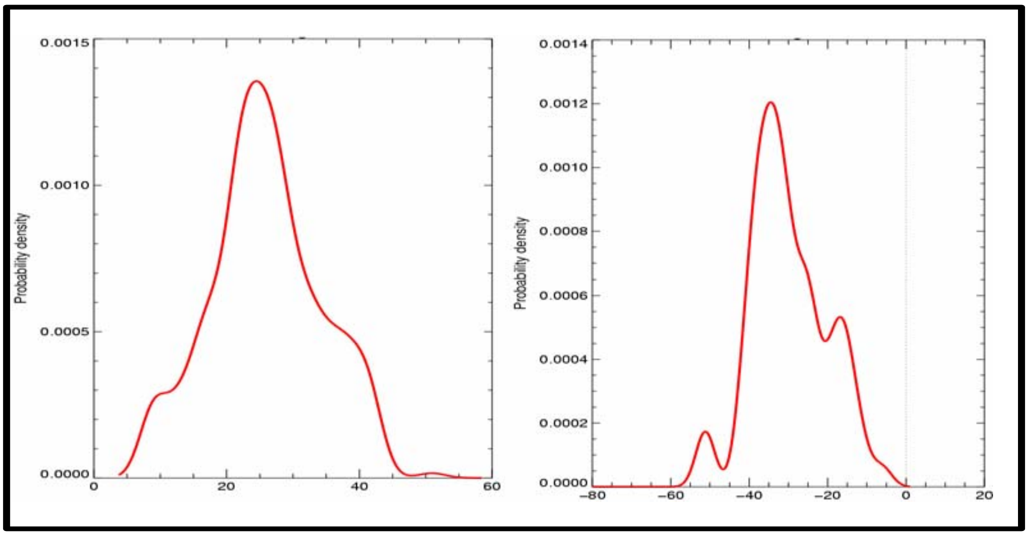

Fig 11: Probability distributions of % change in summer (right) and winter (left) mean precipitation over South-East England in a doubled-CO2 world, relative to recent climate. The distribution comes from a 53-member ensemble of the Hadley Centre HadAM3 model, in which representations of atmospheric processes are different in each model. Note that this distribution will also include within it a contribution due to natural variability. The preliminary nature of these pdfs cannot be overstressed; including representations of more climate processes will lead to a widening of the distributions. The changes shown here cannot be directly compared with changes shown in the UKCIP02 scenarios.

The first results using this technique have recently been completed at the Hadley Centre. They are based on a 53-member physics-ensemble of global models having a simplified treatment of the ocean ("slab models") run first for present day CO_2 and then for doubled CO_2 concentrations. Figure 11 shows a probability distribution of the increase in the summer- and winter-mean precipitation over South-East England derived from this ensemble. Similar probability distributions could also be derived for extremes, of daily rainfall for example

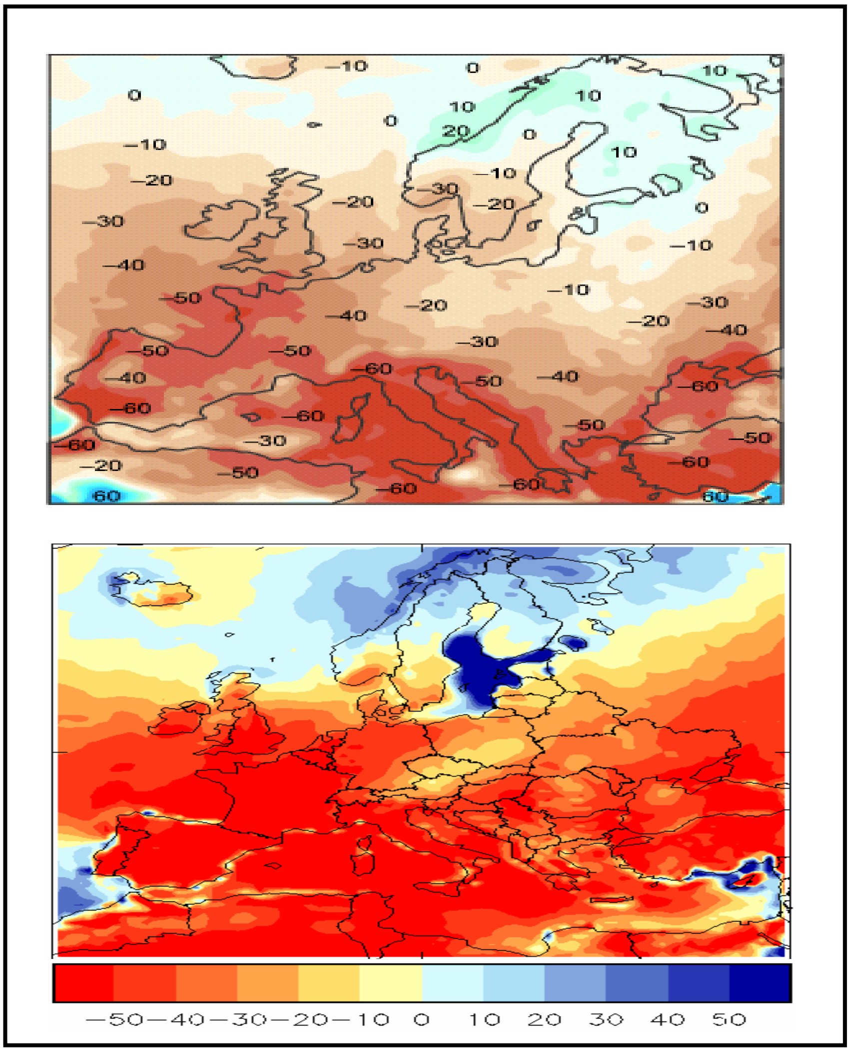

Figure 12: Changes in summer precipitation over Europe, predicted by the end of the century under the A2 emissions scenario, from the SWECLIM RCM (top) and the Hadley Centre RCM (bottom), both driven by the same Hadley Centre global model predictions.

Although initial results are encouraging, they have not yet reached the point where they can provide reliable information to planners, and research is ongoing aimed at more comprehensive (and therefore more reliable) probability predictions. These will sample uncertainties in a much wider range of climate processes. Other global models, which have a different construction to the Hadley Centre model, will also be involved. This research will produce probability distributions which will evolve in their comprehensiveness and credibility, and which can increasingly be used inform adaptation decisions.

3.5 Uncertainty due to downscaling

Although global climate models are the only tool we have for making predictions of climate change, their resolution is too coarse to be used directly in most impacts studies. GCM results are generally downscaled to show greater detail, using either statistical downscaling, or dynamical downscaling with a regional climate model.

Regional climate models (RCMs) are higher resolution versions of atmospheric GCMs, with a comprehensive representation of physical processes. They have a domain covering a small fraction of the globe, typically 5000 x 5000km, at a resolution of typically 50km (as used to generate the UKCIP02 climate scenarios mentioned earlier). Subsequent scenarios for islands of the British-Irish Council (BIC), (Ref 5) used the 25km resolution RCM. Regional Climate Model predictions show a great improvement over those from GCMs in not only the spatial detail of climate change but the representation of extremes. They take fuller account of the effects of terrain (for example, hills, coasts) and smaller scale weather features - hurricanes and cyclones can not be resolved in GCMs but they can in RCMs. They are "driven" by time-slices (10-30 years) of the output from a global model; in the case of UKCIP02 and BIC this was for the "recent" period 1961-90 and the future period 2071-2100. The downscaling technique has been validated by driving the RCMs global weather re-analysis fields (such as that from the European Centre for Medium-Range Weather Forecasting) and comparing RCM simulations with station observations of weather.

Of course, uncertainties will also be added by the dynamical downscaling process, as different RCMs will have different representations of climate processes. Fig 12 shows some initial results from the EC PRUDENCE project, of predicted changes in summer precipitation from two RCMs, one from the Hadley Centre and one from the Swedish SWECLIM programme (Ref 6) both driven by the Hadley Centre global model. At least for seasonal mean changes in temperature and precipitation, the two RCMs are in broad agreement. Further analysis will investigate differences in extremes, etc.

Figure 7 shows that differences in predictions from different GCMs are generally much larger than the downscaling uncertainty, and so we would expect differences in results from the same RCM driven by different GCMs to be bigger than those from different RCMs driven by the same GCM. In other words, the largest uncertainty probably lies with the global prediction rather than the RCM downscaling. Fig 13 shows changes in winter-mean precipitation over Scandinavia predicted by the SWECLIM RCM, driven by global predictions from the Hadley Centre GCM and the Hamburg GCM (Ref 6). The differences are very obvious. The EC PRUDENCE project is expected to generate predictions from a number of RCMs driven by a number of GCMs; a clearer picture of relative uncertainties will then emerge. However, even then the range of predictions will be limited by the small number of available models of unknown relative credibility and, eventually the "physics ensemble" technique being currently employed with global models will need to be also extended to regional climate models. This will require a vast amount of computing resources.

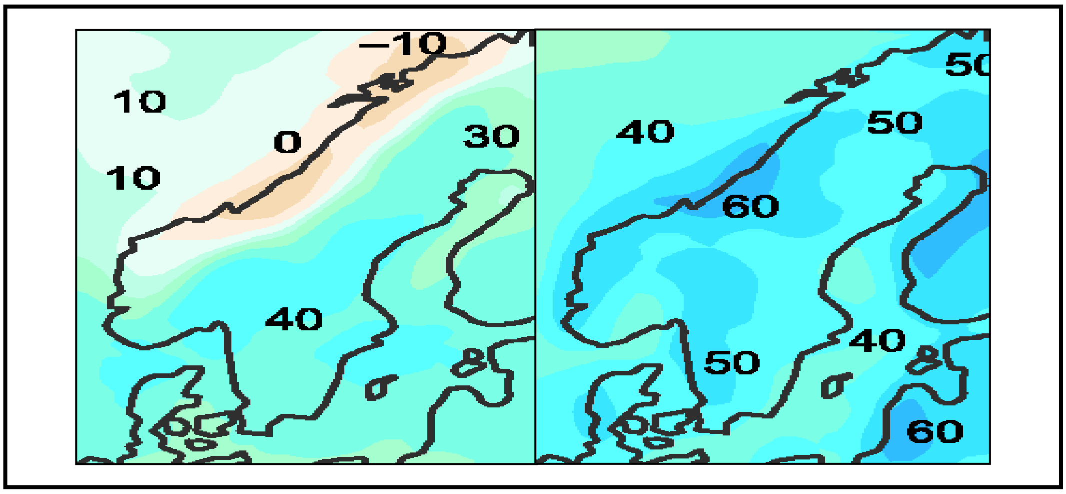

*Figure 13: Changes in winter precipitation over Scandinavia, due to A2 emissions by the end of the century, predicted by the SWECLIM RCM, driven by the Hadley Centre GCM (left) and the Hamburg GCM (right) (*Figure from the SWECLIM report, Ref 6)

Climate quality	Medium high emissions
Average winter temperature	±1.5°C
Average summer temperature	±1.5°C
Average winter precipitation	±15%
Average summer precipitation	+30%

Table 1 (taken from Table 5 of UKCIP02): Suggested uncertainty margins to be applied to the UKCIP02 Medium High Emissions scenario of changes in average winter and summer temperature and precipitation, based on predictions from a number of global climate models

In the meantime, estimates have been made of the uncertainty in predictions from Regional Climate Models by taking information from a number of GCM predictions in the same area and using expert judgement. Table 1 (Taken from Table 5 of UKCIP02) shows estimates of the uncertainty margin in seasonal changes in temperature and precipitation by the 2080s under the "Medium High Emissions" scenario. This was further refined in the British-Irish Council report on climate change over islands, (Ref 5) where global model predictions for the grid box over each island were used semi-objectively to form a margin of uncertainty relative to the prediction from the Hadley Centre global model. This margin was then applied to the corresponding prediction from the Hadley Centre regional model. As an example, Table 2 shows the margins of uncertainty in seasonal changes for the Isle of Man. This estimate is not ideal, but represents the best that can be done in the absence of a range of other regional model predictions. Again, in both these examples, we have no option but to implicitly assume that all the global models have equal credibility, which will not be the case.

Climate quantity	Hadley Centre RCM estimate	Uncertainty margin, to be added to RCM prediction
Mean summer temperature	+2.7	+2.5, -0.6
Mean winter temperature	+1.7	+1.3, -0.5
Mean summer precipitation	-36	+36, -0
Mean winter precipitation	+20	+13, -19

Table 2: Changes in mean summer and winter daily temperature (°C) and precipitation (%) for the Isle of Man, by the 2080s (compared to 1961-90) under the SRES A2 (Medium-High) emissions scenario, together with an estimated uncertainty margin based on global model predictions. (Ref 5)

An alternative technique to downscale GCM output is to use statistical downscaling. In this technique relationships are established between large scale quantities (generally in the free atmosphere, for example, geopotential height) and local observed quantities (for example, temperature or precipitation at an observing station). On the basis that global climate models capture changes in large scale flow better than local detail, these empirical relationships are then applied to the large scale quantities predicted by a climate model for a future period, to generate local changes. This method is based on the assumption that relationships developed from past data will be applicable in the future, and the validity of this assumption is not always easy to demonstrate. For example, variations in precipitation at a point in the current climate may be mainly determined by the direction of atmospheric circulation and less by changes in atmospheric water content. In future, changes in water content may dominate change in precipitation. The statistical relationships formed are in the recent climate based on associating patterns of higher frequency variability which clearly will not be sampling the very low frequencies implied by long term trends such as climate change.

When considering which technique to use, the RCM should clearly provide a better physical basis for change, although differences between RCMs still need to be investigated. Statistical techniques have limitations inherent in their empirical nature, in that predictors developed in recent climates may exclude predictions important for determining change under future climate models. Until this issue is resolved, doubts will remain about the applicability of statistical techniques. However, statistical techniques can be appropriate for some variables (for example, temperature) and for downscaling from RCM output to point locations.

3.6 Uncertainty due to natural variability

The third factor in our list of sources of uncertainty in the prediction of climate of a future period is the natural internal variability of climate. Climate in the future will vary from year to year and decade to decade, just as it does at present, due to the chaotic nature of the climate system, particularly the interaction between the ocean and the atmosphere. If the direction of the change (for example, in summer-average precipitation over central England) in a future period (for example, the last 30 years of this century) due to natural variability is the same as the direction due to human-made climate change, then the two will reinforce and the net change will be enhanced, assuming there is no threshold change in the climate system. If the direction of the two is opposite then they will offset and the resulting overall change will be reduced. We cannot (yet) predict the effect of this natural variability in a given future decade, but we can quantify its range of uncertainty by making a large number of climate simulations each starting from a different initial condition in the control run of the model

Note that climate in the future will also be affected by changes in the output of the sun or the amount of stratospheric aerosol from volcanoes; because theses factors are not predictable on the timescales of interest here, we do not consider them further. We could estimate their potential magnitude based on previous history, although there is no reason to believe that this will stay within historical limits.

To investigate the uncertainty due to natural internal variability, the regional climate model is initialised with three different (random) starting conditions of the climate system and then used to make three predictions with the same assumed emissions scenario (Medium-High, A2). Fig 14 shows the average change in summer precipitation over a 30 year period (2071-2100) from each of the runs. In the centre panel, natural variability has acted to reinforce the change due to human activity; in parts of Central England rainfall changes by about -55%. In the right-hand panel, natural variability has partially countered man-made trends and the change is only about -35%. Figure 15 shows the effect of natural variability on winter precipitation, from the same ensemble. The uncertainty in extremes will be greater than that in seasonal means.

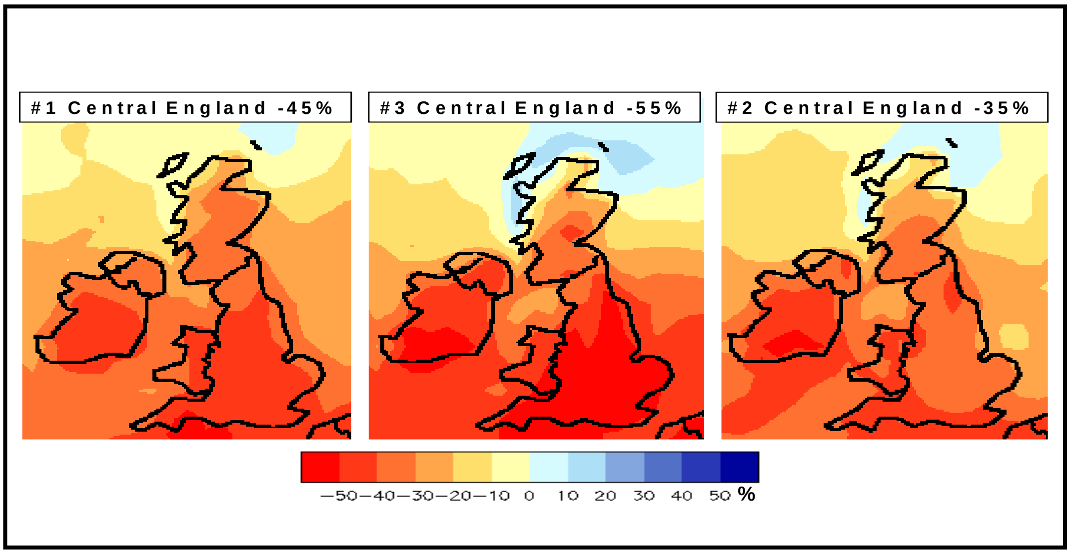

Fig 14: Changes in summer precipitation by the period 2071-2100, relative to 1961-1990, assuming the SRES A2 emissions scenario, from three predictions with the same model (HadCM3) each with different initial conditions

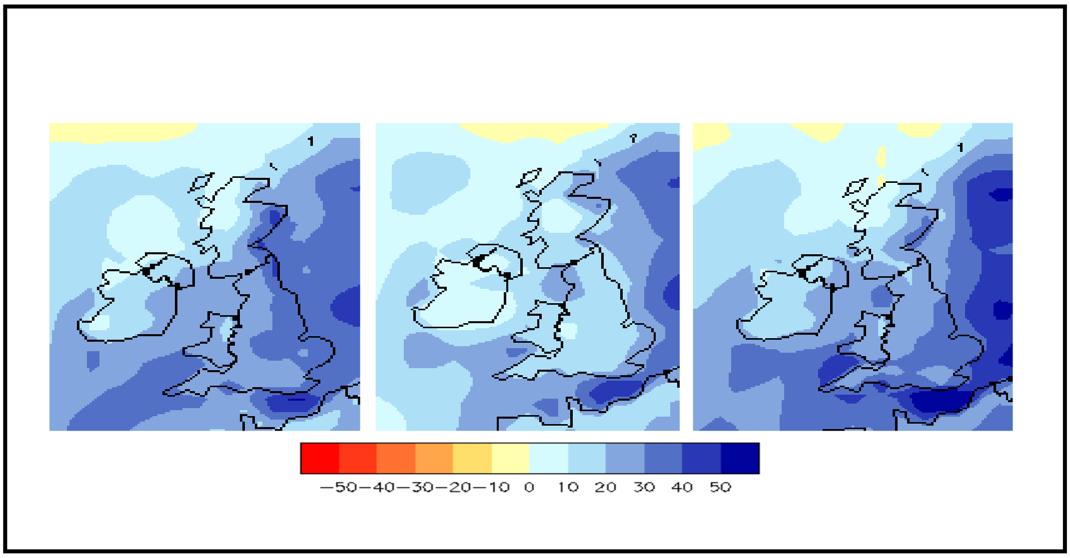

Figure 15. As Fig 14 but for changes (%) in winter precipitation.

4. Combining uncertainties

In principle, we can combine the uncertainty from the three causes discussed here (emissions, modelling, downscaling, natural variability) to give an estimate of overall uncertainty in predictions. However, this has the practical difficulty that raw results from the "physics ensemble" (Fig 11) include both the science uncertainty and natural variability. The relative importance of these two uncertainties has been investigated; for seasonal-mean quantities it depends upon the quantity of interest and the location. For temperature, the science uncertainty dominates at most locations, but for precipitation natural variability becomes more important and dominates over much of Europe. For extremes of precipitation, natural variability is again the most important source of uncertainty in many regions, although the science uncertainty becomes more important in the storm-track area, suggesting that future improvements in the way this is modelled could lead to sizeable reductions in the total uncertainty in predictions over Europe.

Science uncertainty becomes wider as we include predictions from several GCMs, as in Fig 7. A crude estimate of the relative importance of emissions, modelling and natural variability can be made from existing "ensembles of opportunity". Fig 16 shows the standard deviation of predictions of change by the 2080s in seasonal UK precipitation, showing the general tendency of science uncertainty to be largest, followed by emissions uncertainty and natural variability. The estimates of science and emissions uncertainty also include natural variability.

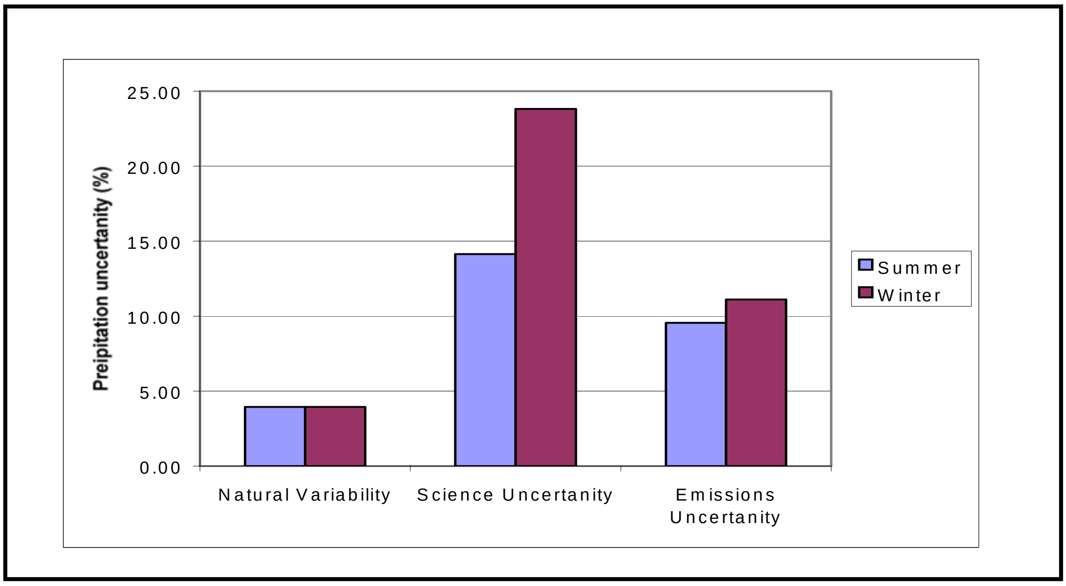

Figure 16. Relative uncertainty (taken as one standard deviation) in predictions of changes in seasonal rainfall due to (a) natural variability, taken from a 3-member HadCM3 ensemble of 30 year mean changes, as shown in figures 14 and 15, (b) modelling uncertainty, taken from the nine model ensemble shown in Figures 7 and 8, (c) emissions uncertainty, taken from a 4-member ensemble of models driven with each of the emissions scenarios shown in Figure 2. This focuses on the 30 year period at the end of the century; for earlier periods the science uncertainty will dominate much more strongly

4.1 Risk assessments

Climate predictions are used as input to impacts models. For planners and engineers who intend to make decisions based on the impacts of climate change, two further sources of uncertainty are also important:

- Uncertainty in non-climate inputs to the impacts models. This includes, for instance, uncertainty in the future value of assets at risk, or the assumptions made about adaptation to natural variability which will also reduce vulnerability to climate change.

- Uncertainty resulting from the impacts models themselves

Including these uncertainties should be part of the risk assessment process, but the details will depend on the specifics of the problem being considered. This will not be discussed further here but more details of how climate change uncertainty can be incorporated into the risk assessment procedure can be found in publications from UKCIP and the Environment Agency (Ref 2) and Defra (Ref 7).

4.2. Probability predictions

The early uptake of probability predictions by impacts modellers and the user community in general will depend crucially on the presentation of these new results. Some dialog with climate change scenario users will be necessary to ensure the full power of the probability predictions will be utilised, rather than just the most-likely change. For example, a probability prediction of change in winter flood heights might be convolved with a relationship between level of flood protection and cost, to derive some risk-cost-benefit parameter which would help in decision making.

5. Conclusion

Predictions of climate change, such as those used for the UKCIP02 scenarios, are accompanied by uncertainties from three separate sources: future emissions, imperfect understanding of climate science and modelling (including downscaling models), and natural variability. Each of these should be taken into account by users, especially when planning major infrastructure or regulatory changes. Some ways of handling these uncertainties are already available, and results from improved techniques currently under development will be progressively available over the next few years. It is also worth re-iterating that there are some adaptive measures that can be taken even with the current level of uncertainties.

References

1. UKCIP02:
Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. M.Hulme, G.J.Jenkins et al. Published by the Tyndall Centre, UEA Norwich, April 2002. ISBN 0 902170 60 0

2. Climate adaptation: Risk, uncertainty and decision-making. UKCIP/Environment Agency Technical Report. R Willows and R Connell (Eds.). UKCIP.Oxford, May 2003

3. IPCC Third Assessment Report (TAR):
Climate Change 2001: The Scientific Basis. J.T.Houghton et al (Eds). Cambridge University Press, Cambridge, 2001. ISBN 0521 807 67 0

4. IPCC SRES:
Special Report on Emission Scenarios. N Nakicenovic et al. Cambridge University Press, Cambridge, 2000.

5. British-Irish Council (BIC) report:
Scenarios of climate change for islands within the BIC region.
G Jenkins, C Cooper, D Hassell and R Jones. Published by the Met Office, Bracknell, July 2003.

6. SWECLIM Report:
A Warmer World: The greenhouse effect and climate change. (Monitor 18). Claes Bernes. Swedish Environmental Protection Agency, Norrkoping, Sweden, 2003. ISBN 91-620-1229-0.

7. Guidelines for Environmental Risk Assessment and Management. Defra, joint with the Environment Agency and the Institute for Environment and Health. August 2000. http://www.defra.gov.uk/environment/eramguide/

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