UK Climate Impacts Programme

SKCC Sustaining Knowledge for a Changing Climate

EPSRC Engineering and Physical Sciences Research Council

SKCC Briefing Paper 1: Probabilistic climate information for the built environment and infrastructure

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SUMMARY

- The first SKCC workshop held in Norwich in November 2006 focused on the use of probabilistic climate information for built environment and infrastructure impacts and adaptation assessments.
- SKCC Briefing Paper 1 was produced before the workshop and provides a general background to probabilistic climate projections for non-specialists.
- The move towards probabilistic information is motivated by the cascade of uncertainties inherent in the construction of climate and impacts scenarios as well as by decision-making considerations.
- Methods for constructing probabilistic climate projections are reviewed, focusing on the technical and communication challenges in providing information at the regional and local scales relevant for the built environment.
- The propagation of uncertainty through to impacts and decision-making is also an issue of concern.
- Finally, the extent to which relevant lessons can be learnt from weather and seasonal climate forecasting is considered.

INTRODUCTION

A series of researcher and stakeholder workshops are planned as part of the SKCC programme. The first of these - on 'The Use of Probabilistic Climate Scenarios in Impacts Assessment and Adaptation Studies' was held at the University of East Anglia, Norwich on 10 November 2006. SKCC Briefing Paper 1 was prepared in advance of the workshop to provide a general background to the issues both for workshop participants and a wider readership. It builds on work undertaken as part of the Building Knowledge for a Changing Climate (BKCC) CRANIUM (Climate change Risk Assessment: New Impact and Uncertainty Methods) project and complements information provided on the CRANIUM climate scenarios website - http://www.cru.uea.ac.uk/cru/projects/cranium/.

WHAT ARE PROBABILISTIC CLIMATE PROJECTIONS?

The UKCIP02 scenarios, on which much climate change impacts and adaptation work in the UK is focused, are examples of 'story-line' scenarios. In this deterministic approach, each scenario can be considered as 'a coherent, internally consistent and plausible description of a possible future state of the world' (IPCC, 2001). Each story-line scenario is considered equally plausible. This contrasts with probabilistic climate projections. Instead of a single estimate of change, a distribution range (typically presented as a probability density function, see Figure 1) is provided – constructed using output from multiple climate model simulations (i.e., from an ensemble). See the UKCIP08 website for further background information.

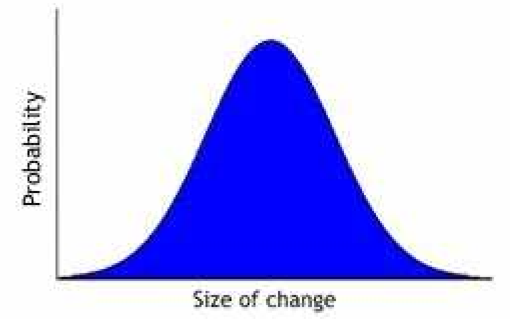

Figure 1: Schematic illustration of a probabilistic climate change projection.

WHY WE NEED PROBABILISTIC CLIMATE PROJECTIONS

The move towards probabilistic climate information is now firmly underway in the UK (e.g., the UKCIP08 projections will be probabilistic and the Environment Agency is actively involved in research on this issue) and in the European (e.g., http://www.ensembles-eu.org/) and US (e.g., http://www.assessment.ucar.edu/uncertainty_models/) research communities.

This move is motivated by the cascade of uncertainties inherent in the construction of climate and impacts scenarios as well as by decision-making considerations. These uncertainties concern the underlying greenhouse gas emissions scenarios as well as a range of scientific uncertainties (due to inter- and intra-model variability, natural variability and sub-grid scale processes). The growing availability of large ensembles from climate models permits a more comprehensive approach to the assessment of uncertainty.

The move towards probabilistic projections is fully consistent with the growing emphasis on risk and uncertainty in decision-making in the built environment and other sectors (Goodess *et al*., 2007). The UK has played a leading role in promoting a risk-based approach to climate change impacts and adaptation decision-making (e.g., Willows and Connell, 2003) – an approach now being followed by countries such as Australia (http://www.greenhouse.gov.au/impacts/publications/risk-management.html).

Whilst uncertainty in emissions scenarios is rightly considered at the top of the cascade of uncertainty, most current work is focused on the construction of conditional probabilistic climate projections, i.e., conditional on a single emissions scenario. This is consistent with the IPCC Special Report on Emissions Scenario (SRES) policy of not attempting to assign probabilities to the different emissions scenarios (Figure 2). Thus the UKCIP08 projections, for example, will be conditional on a framework of three SRES emissions scenarios: B1 (equivalent to UKCIP02 Low Emissions), A1B and A1FI (equivalent to UKCIP02 High Emissions) – with no probabilities assigned to the emissions scenarios.

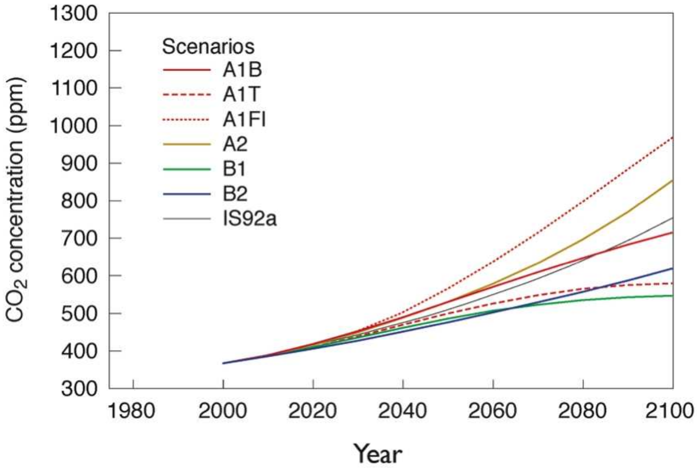

Figure 2: The IPCC SRES emissions scenarios: atmospheric CO_2 concentration.

METHODS FOR CONSTRUCTING PROBABILISTIC CLIMATE PROJECTIONS

Global and sub-continental scales

Earlier work on probabilistic climate projections, which began to appear following publication of the IPCC Third Assessment Report in 2001, focused on the estimation of global temperature change and climate sensitivity (the global temperature change due to a doubling of the pre-industrial atmospheric concentration of carbon dioxide) and was largely based on work with relatively simple climate models (such as MAGICC; Wigley, 2003).

Over the last five years or so, larger ensembles from global climate models (GCMs) have become available. In the UK, two such 'super-ensembles' exist and continue to be developed. The Hadley Centre's QUMP (Quantifying Uncertainty in Model Predictions) perturbed-physics ensemble currently consists of 129 runs performed with the HadAM3 atmospheric model coupled to a relatively simple slab ocean model with different values assigned to a number of key model parameters for each run (Murphy *et al.*, 2004; Harris *et al.*, 2006). Figure 3 shows the first estimates of climate sensitivity from the perturbed physics ensemble (based on 53 members). A larger ensemble is provided by the climate*prediction*.net experiment (Stainforth *et al.*, 2005) - currently 2700 15-year long simulations are available to researchers.

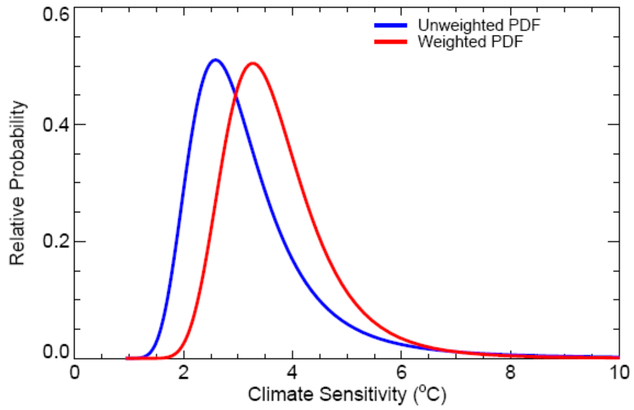

Figure 3: Probability distributions of climate sensitivity for the Hadley Centre perturbed physics ensemble (Murphy et al., 2004)

New statistical techniques are being developed to process these large model ensembles - incorporating estimates of model reliability (assessed by comparing output for the present-day with observed data) and, in some cases, estimates of natural variability - in order to construct probabilistic projections (see this ENSEMBLES summary report - http://ensembles-eu.metoffice.com/Archive/Archived_deliverable_submissions/D1.2_systematic_documentation.doc and the Further Reading list on the CRANIUM web site).

The relatively coarse spatial scale of the GCMs used to create these super-ensembles means that results are generally presented for sub-continental regions – typically the 24 'Giorgi and Francisco' regions (Giorgi and Francisco, 2000) which include Northern Europe. Harris *et al*. (2006), for example, present frequency distributions and show the evolution of median and confidence limits for temperature and rainfall changes for these regions over the next 150 years based on QUMP output – clearly demonstrating how the uncertainty range increases with time.

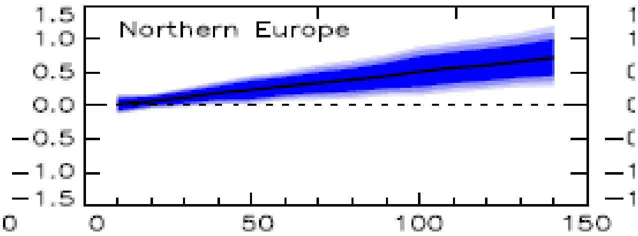

Figure 4: Evolution in the median and 80, 90 and 95% confidence ranges for winter rainfall changes (vertical axis - mm per day), for a 1% per annum increase in carbon dioxide concentration for 150 years (horizontal axis), for Northern Europe (Harris et al., 2006).

The regional scale

Information at the sub-continental scale (e.g., Northern Europe) is, however, of limited direct value for UK impacts assessment and adaptation studies focusing on the built environment. For these studies, whether new probabilistic projections or existing 'story-line' climate scenarios are used, there is a need for downscaling to higher spatial and, in some cases, temporal resolutions. Two general approaches to downscaling are available: statistical methods which can be used to provide information at the station or point scale, and dynamical methods in which higher-resolution regional climate models (RCMs) are nested within the coarser GCMs. Statistical downscaling can also be used to provide further downscaling from the RCM scale (the current generation of RCMs have a grid-box resolution of 50 or 25 km). A statistical downscaling approach (a stochastic weather generator) was used by the Climatic Research Unit (CRU) to construct daily and hourly scenarios for 10 UK locations as part of the BKCC BETWIXT project (http://www.cru.uea.ac.uk/cru/projects/betwixt/). The weather generator produces daily/hourly time series with the characteristics of the station location, which can be input directly to impacts models. Figure 5 shows daily output for Manchester Ringway – here seasonal indices of extremes have been calculated from the daily series to allow comparison with observed data and to show future changes.

In the CRANIUM project, this weather generator has been combined with output from the largest-existing ensemble of RCM output for Europe (from the EU PRUDENCE project – (http://prudence.dmi.dk/) to construct daily probabilistic projections for the 2080s conditional on the IPCC SRES A2 emissions scenario (equivalent to the UKCIP02 Medium-high scenario). These probabilistic projections are available from the CRANIUM climate scenario web site, which describes how they were constructed using RCM grid-box output to perturb the weather generator parameters (see also Goodess *et al*., 2007). The projections are presented in a number of different formats [histograms, probability and cumulative density functions (PDFs and CDFs), percentiles, class probabilities and event thresholds] to suit the needs of a range of different users and to illustrate the range of output formats under consideration for the UKCIP08 projections. The web site also describes a number of illustrative outputs in order to help users interpret the figures and tables of results. Examples of PDFs and CDFs for Coltishall are shown in Figure 6 and are discussed by Goodess *et al.* (2007).

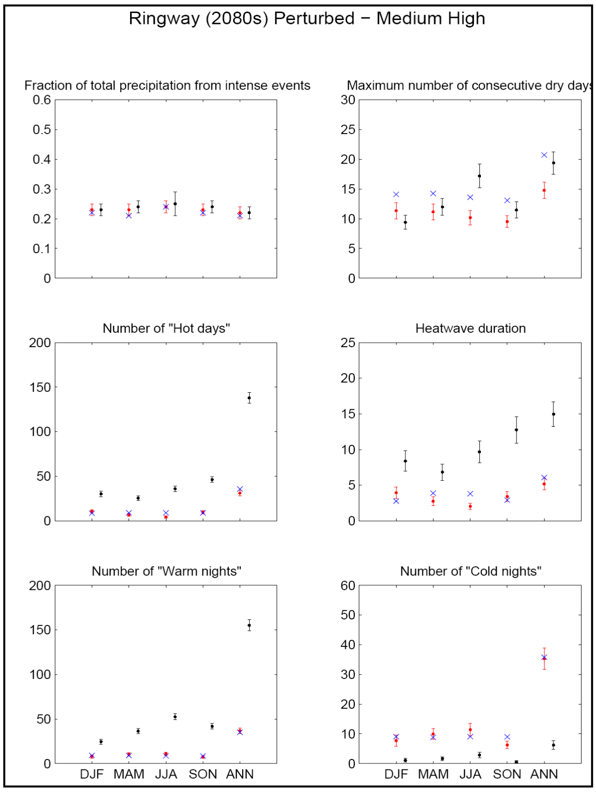

Figure 5: Seasonal rainfall and temperature extremes simulated by the CRU weather generator for Ringway. The close agreement between blue (observed) and red (modelled) values reflects the generally good performance (although longest dry spell length is underestimated). Differences between red (modelled present day) and black (modelled 2080s, Medium-high scenario) indicate future changes. The bars indicate the range across 100 stochastic weather generator runs.

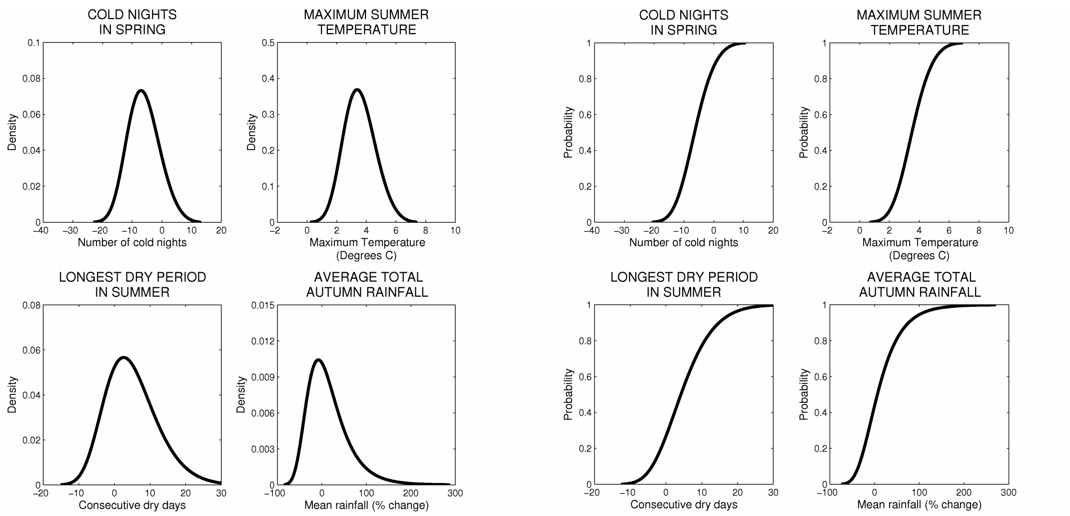

Figure 6: Probability (left) and cumulative (right) density functions of the seasonal change in selected variables for Coltishall in the 2080s, conditional on the A2 emissions scenario.

THE COMMUNICATION CHALLENGES

Looking at the PDFs and CDFs above, each user is likely to draw their own conclusions as to whether the uncertainty ranges shown are 'large' or not. However, what is not apparent, because these examples have been presented here without any supporting information, are the underlying assumptions (other than the emissions scenario – A2) or the range of uncertainties considered.

In fact, the examples shown above consider inter-model uncertainty at the global and regional model scales - four GCMs are used to provide boundary conditions for the 13 PRUDENCE RCM runs. Most of the RCM runs are, however, based on a single GCM run (HadAM3), thus only a small part of the GCM uncertainty range – which tends to dominate other sources of uncertainties in the PRUDENCE outputs (Déqué *et al*., 2007) – is addressed. And the issue as to how well each RCM/GCM performs in comparison with reality is not addressed. Inter-model uncertainties at the local scale are also not considered – only one statistical downscaling model (the CRU weather generator) is used. Intra-model uncertainties are, however, addressed because each stochastic weather generator-RCM pairing is run 100 times. This takes some account of natural variability as well as sub-grid scale uncertainties and extends the range of projected changes considerably beyond that of the original RCM grid-box changes. The skewed nature of some of the distributions is primarily a reflection of driving GCM uncertainty.

While the researchers who constructed the CRANIUM probabilistic projections consider it important to be explicit about the extent to which the various sources of uncertainty are represented, the question arises as to whether scenario users find such information relevant and/or understandable. This question is also relevant to other methodological issues relating to the construction of probabilistic climate projections which are discussed next.

THE TECHNICAL CHALLENGES

The ensemble means presented for the CRANIUM probabilistic climate projections, including those shown in Figure 6, are un-weighted, i.e., they do not take any account of differences in GCM or RCM model performance for the present day. Weighting is one of a number of technical approaches and issues which developers of probabilistic regional projections are currently exploring and which are identified briefly below.

- Weighting ensemble members: Weights are calculated by comparing model output for the present-day with observed data. Better performing models are assigned higher weights and hence given more emphasis in ensemble averages. How to calculate weights is a major research issue, e.g., should they be tailored to specific applications and/or reflect underlying synoptic and other physical processes? Weights differ depending on the variable and season considered, so a consistent way of producing them is needed.

- Ensemble averaging and resampling: Re-sampling is a technique used to calculate ensemble averages. If a Bayesian framework is used, prior distributions are identified (e.g., for global temperature change, regional grid-box changes). Monte Carlo sampling is then typically used to construct posterior distributions of regional change. Results can be very sensitive to prior distributions (e.g., whether a uniform, gaussian, skewed or some other distribution is used) as well as sampling method (e.g., Latin hypercube is common).

- Pattern scaling: This technique is used to estimate regional changes from larger-scale model output. It was used in UKCIP02, for example, to construct scenarios for time periods and emissions scenarios for which RCM output was not available. Its potential advantage for probabilistic climate projection construction is that it allows larger ensembles to be built at the regional scale. It is, however, based on an assumption of linearity which may not always be applicable, particularly with respect to rainfall and extreme events.

- Model emulation: Statistical approaches are being developed to draw probabilistic inferences about the values of outputs from computationally expensive models for parameter values at which the models have not yet been evaluated (thus giving the potential to extend, for example, the uncertainty range encompassed by the QUMP perturbed-physics ensemble).

It is evident that the move towards probabilistic climate projections raises many technical challenges for scenario developers. These are currently being explored by a number of research groups in the UK, including those at the Universities of East Anglia, Edinburgh, Oxford and Newcastle and at the Hadley Centre, and are a major focus of the EU ENSEMBLES project (http://www.cru.uea.ac.uk/projects/ensembles/ScenariosPortal) in which several of these groups are involved. Since this is very much work in progress, the published literature is still rather limited (see Dessai *et al*., 2005 and Tebaldi *et al.*, 2005 for examples of how some of the above techniques can be applied), although a number of very relevant papers have recently been submitted for publication. The presentations from a workshop held in Edinburgh in September 2006 provide a flavour of the work (see Further Reading and Resources) and links to a number of relevant ENSEMBLES working papers and reports are provided from the CRANIUM climate scenarios web site.

Many users may understandably argue that they do not need to know about the details of scenario construction. However, the resulting projections may be rather sensitive to such methodological details. This is demonstrated in Figure 7 using a readily-available illustrative example, which happens to be for runoff in an Iranian catchment, developed during a student visit to the CRU. Nine different prior distributions and weighting approaches were used to construct probabilistic projections of winter runoff changes using a neural network downscaling model based on output from seven GCMs. The details of the different methods are not important – what is important is that each is equally plausible and yet can produce very different CDFs of change from the same input data.

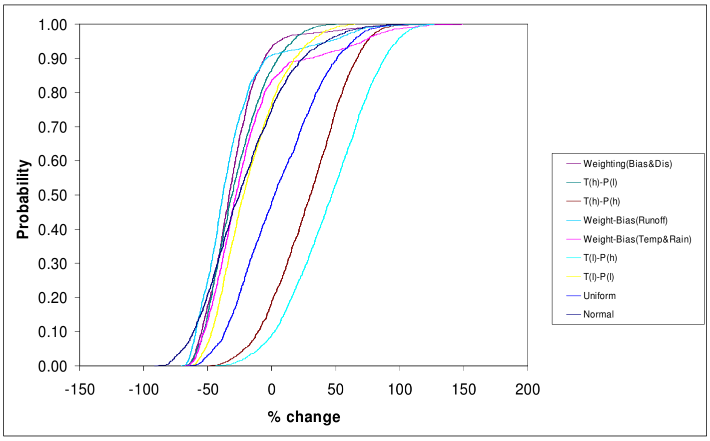

Figure 7: Effect of prior distribution and weighting method on winter runoff cumulative density distributions for Zayandeh Rud river, Iran. Conditional on the A2 emissions scenario. Figure provided by Ali Reza Massah Bavani, University of Tarbiat Modarres, Iran.

The right-hand CDF in Figure 7 indicates that runoff changes are most likely to be positive, whereas most of the CDFs suggest that negative changes (i.e., less runoff) are more likely. There are also differences in the spread of changes indicated by individual CDFs, i.e., in the uncertainty range. It is, however, possible that construction methods may artificially constrain the uncertainty. The spread across the PDFs and CDFs in Figure 6 could, for example, be reduced by leaving out the most divergent results based on one of the driving GCMs – though this would clearly give a misleading impression of the 'true' uncertainty range.

More work is needed to test the sensitivity of high-resolution UK probabilistic projections to construction methods. Preliminary work undertaken by CRU in the ENSEMBLES project, for example, shows that the CRANIUM scenarios are not sensitive to weighting the individual RCMs - http://www.cru.uea.ac.uk/projects/ensembles/crupdfs/. This is due to the dominance of GCM uncertainty and the limited number of GCMs available for this study, as well as the stochastic weather generator variability. But different approaches to weighting may give different sensitivities.

PROPAGATION OF UNCERTAINTY THROUGH TO IMPACTS AND DECISION-MAKING

Figure 7 is of interest because it extends the cascade of uncertainty down through climate projection uncertainties to impacts model uncertainties.

Extending the probabilistic approach to the impacts assessment process is considered important in the context of risk-based decision making. Wilby and Harris (2006) explored uncertainty in hydrological impacts modelling [both with respect to model structure, i.e., inter-model variability) and parameter values (i.e., intra-model variability)] alongside other sources of uncertainty (i.e., emissions scenario, driving GCM and downscaling method) in a study of low-flow scenarios for the River Thames. Although the resulting CDFs were found to be most sensitive to the climate projection uncertainties, uncertainties due to hydrological model parameters and emissions scenario were found to increase with time. This paper is important because it provides one of the first demonstrations of how the cascade of uncertainties can be represented in an end-to-end application (i.e., going from emissions to impacts) using a consistent probabilistic framework. This preliminary study has since been extended in joint work led by the University of Oxford and funded by the Environment Agency of England and Wales and Tyndall Centre (see presentation by Mark New at the September 2006 Edinburgh workshop and at the Norwich workshop – SKCC Briefing Paper 2).

How users and stakeholders might react to such probabilistic impacts information is beyond the scope of this briefing paper – but was discussed during the SKCC workshop – see SKCC Briefing Paper 2. Aspects of decision-making under uncertainty are also discussed by Goodess *et al*. (2007). The latter paper uses the phasing of the upgrading of the Thames tidal defences as an example of a built environment adaptation decision with imprecise information, i.e., the implications of uncertainties that are not completely captured in probabilistic representations of uncertainty. Consideration is also given to the extent to which managers integrate climate change information into long-term projects in the built environment (based on interviews undertaken as part of the CRANIUM project). Decision making when confronted with deep uncertainty about the future is the topic of a RAND project which will draw on interactions with decision makers, including those involved in the long-term management of Californian water resources (see Further Reading and Resources and SKCC Briefing Paper 2).

LEARNING LESSONS FROM WEATHER AND SEASONAL CLIMATE FORECASTING

The experience of the seasonal-to-decadal forecasting community in handling large model ensembles is potentially very useful for the climate change modelling community – both communities are involved in the ENSEMBLES project, for example. It has also been suggested that relevant lessons can be learnt from how users work with probabilistic seasonal-to-decadal and weather forecasts. Probabilistic impacts forecasts are considered useful for malaria early warnings based on seasonal climate forecasts (Thompson *et al*., 2006) and forecasts of the magnitude and timing of peak electricity demand up to two weeks ahead (McSharry *et al*., 2005), for example. One of the advantages of working on these shorter timescales, is that hindcasts can be validated after the forecast period and the value/utility of the forecasts to the user can potentially be evaluated.

In the context of UK built environment and infrastructure applications, meteorological forecasts and data are currently used in civil engineering practice. Numerical weather prediction is also routinely used in flood forecasting and seasonal forecasts are used for water resources planning. It is also worth noting the widespread use of hydrological frequency information (and also wind, wave and tidal information). Engineers are also used to using (stationary) probabilities – though this is also a potential source of misunderstanding in the non-stationary context of climate change. These examples indicate that there is scope for discussion and research on these issues.

Shorter-timescale probabilistic forecasts are only recently becoming available in the UK. A useful indication of the type of information that is available, together with background information on the issues and methods, is provided by the Met. Office web pages:

Weather prediction:
http://www.metoffice.com/research/nwp/ensemble/index.html - Ensemble Prediction
http://www.metoffice.com/research/nwp/ensemble/probability.html - Probability Forecasts
http://www.metoffice.com/weather/europe/uk/public/forecastuncertainty_results.html - user feedback on how uncertainty in forecasts could be presented

Seasonal forecasting:
http://www.metoffice.com/weather/seasonal/winter2006_7/index.html - winter 2006/7 forecast
http://www.metoffice.com/research/seasonal/user_guide.html - guide to methods/outputs

CLOSING REMARKS

This briefing paper provides a summary of the current state-of-art in the construction of probabilistic climate projections focusing on UK work. Although the UK is leading international research in this area, it is still very much work in progress, particularly with respect to development of the high-resolution information which is essential for built environment impacts assessments and adaptation studies. The issues which need to be addressed and the numerical modelling techniques being developed to meet the challenges are highly complex and cannot be covered in detail in such a briefing paper – references and links are, however, provided for those wanting more information.

Successful communication and use of the new generation of probabilistic climate projections will be enhanced if different areas of research expertise (i.e., the climate change scenarios and impacts research communities, together with the weather/seasonal forecasting, risk and decision-making communities) can be brought together in forums also involving scenario users and stakeholders. The SKCC Norwich workshop and other planned SKCC activities are seen as very important in this respect. SKCC Briefing Paper 2 was produced after the Norwich workshop, and provides a summary of presentations and discussions, as well as identifying key messages from the workshop.

FURTHER READING AND RESOURCES

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Willows, R. and Connell, R. (eds), 2003: Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report. http://www.ukcip.org.uk/risk_uncert/risk_uncert.html.

CRANIUM climate scenarios website: http://www.cru.uea.ac.uk/cru/projects/cranium/ - includes a more detailed list of further reading as well as detailed scenario results.

UKCIP08: http://www.ukcip.org.uk/scenarios/ukcip08/

University of Edinburgh workshop on probabilistic future climate and climate impacts prediction, September 2006, workshop summary and presentations: http://www.bioss.ac.uk/staff/adam/climworkshop/

Summary and results from the US NCAR programme on uncertainty in model simulations: http://www.assessment.ucar.edu/uncertainty_models/

Climate*prediction*.net: http://www.climateprediction.net/

RAND project on Making Better Decisions When Confronted with Deep Uncertainty About the Future: http://www.rand.org/ise/projects/improvingdecisions/

ENSEMBLES project regional scenarios web portal: http://www.cru.uea.ac.uk/projects/ensembles/ScenariosPortal