Institution: University of Bristol

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Uncertainty quantification for UK climate change legislation, and for climate change impact assessment

1. Summary of the impact (indicative maximum 100 words)

Climate change is one of the defining challenges of our time. The net costs of climate change in the UK could be tens of billions of pounds per year in the 2050s, and tidal flooding alone could affect over half a million UK properties by 2100. Dr Jonathan Rougier worked with the UK Met Office (UKMO) to produce the climate scenarios for the UK Climate Impacts Programme (UKCIP) 2009 report (UKCP09). His research and advice (funded as a UKMO External Expert) was critical in a key innovation in the UKCP09: a comprehensive uncertainty assessment. A Director of the UKCIP writes "The UKMO team with Dr Rougier [have] put the UK at the leading edge of the science and service aspects of providing climate information for users" [b].

The UKCP09 formed the basis of the UK Climate Change Risk Assessment and the recommendations of the UK National Adaptation Programme, which was submitted to Parliament as part of the Government's obligations under the Climate Change Act. The UKCP09 has been used for the assessment of the impact of climate change by hundreds of organisations, including agencies and non-governmental organisations (NGOs), utilities companies, consultancies, and County Councils and Local Authorities.

2. Underpinning research (indicative maximum 500 words)

Dr Jonathan Rougier, Reader in Statistics at the University of Bristol (appointed Jan 2007), worked with the UKMO over the period 2007-2009 to produce the climate scenarios for the UKCP09. Much of his published research from that period reflects this collaboration.

Rougier's research concerns uncertainty assessment for complex systems — notably environmental systems, including climate and natural hazards. He has developed much of the core statistical theory in this area, and, in his on-going collaboration with the UKMO, has been influential in changing the way in which climate uncertainty is treated. Two aspects of his research were particularly important for the UKCP09 [a]:

1. A statistical framework for a comprehensive assessment of uncertainty for complex systems, such as climate.

The climate system manifests complicated dependencies in space and time, as a consequence of the underlying physical constraints of continuity and conservation. These are best represented in a climate simulator, a computer code which attempts to solve the underlying physical equations. But such codes are limited, partly due to our lack of knowledge, and partly due to computing constraints. Rougier's framework provides a simple representation of a simulator's limitations, in the form of parametric and structural uncertainty. In [1] he provided a statistical reinterpretation of current practice in climate science, while [6] provided a generalisation suitable for collections and sequences of simulators, such as the evolving simulators of the world's major climate research groups.

2. Emulation approaches to make the most efficient use of a limited number of simulator runs.

A large climate simulator runs at about one hundred model years per calendar month. Even with some of the largest computers in the world, climate research groups cannot afford to do more than a handful of runs. This makes it challenging to tune the simulator parameters to historical observations, and to assess uncertainty in climate projections. Rougier has been influential in developing efficient emulators for large simulators, notably those with complex outputs [4], with immediate applications in climate [5]. In his collaboration with scientists at the UKMO, he has advocated general approaches for computer experiments and scalar emulation [2], and provided new levels of detail concerning the behaviour of the UKMO climate simulator HadCM3 [3].

3. References to the research (indicative maximum of six references)

*[1] J.C. Rougier (2007), Probabilistic Inference for Future Climate Using an Ensemble of Climate Model Evaluations, *Climatic Change*, **81**, 247-264. DOI:10.1007/s10584-006-9156-9.

[2] J.C. Rougier and D.M.H. Sexton (2007), Inference in Ensemble Experiments, *Philosophical Transactions of the Royal Society, Series A*, **365**, 2133-2143. DOI:10.1098/rsta.2007.2071.

*[3] J.C. Rougier, D.M.H. Sexton, J.M. Murphy, and D. Stainforth (2009), Analysing the climate sensitivity of the HadSM3 climate model using ensembles from different but related experiments. *Journal of Climate*, **22**(13), 3540-3557. DOI:10.1175/2008JCLI2533.1.

[4] J.C. Rougier (2008), Efficient Emulators for Multivariate Deterministic Functions, *Journal of Computational and Graphical Statistics*, **17**, 827-843. DOI:10.1198/106186008X384032.

[5] J.C. Rougier, S. Guillas, A. Maute, A.D. Richmond (2009), Expert Knowledge and Multivariate Emulation: The Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM), *Technometrics*, 51, 414-424. DOI:10.1198/TECH.2009.07123.

*[6] M. Goldstein and J.C. Rougier (2009), Reified Bayesian Modelling and Inference for Physical Systems, *Journal of Statistical Planning and Inference*, **139**(3), 1221-1239. DOI:10.1016/j.jspi.2008.07.019. With discussion and rejoinder.

* references that best indicate the quality of the underpinning research.

Rougier was the sole author or lead author on [1-5], and equal co-author on [6].

4. Details of the impact (indicative maximum 750 words)

The UK Climate Impacts Programme (UKCIP) is a government-funded organisation which provides climate projections for the UK, for the purposes of adaptation to climate change. The current report is the fifth in the sequence, denoted UKCP09 (2009) and summarised in [c]. Users of the previous report (UKCIP02, 2002) requested more information about uncertainties: "The uncertainty aspects of [the UKCP09] were seen as instrumental in better preparing the UK to address the challenges of climate change" [b]. The UK Met Office (UKMO) was asked by the UKCIP to implement new methods to meet this demand, which included: modelling uncertainty, uncertainty associated with statistical processing, and use of observations to weight projections [d, p1]. Rougier's statistical framework [1] was "chosen [by the UKMO] to provide the statistical core of the UKCP09 projections" [a], and thus represents a key innovation in climate change impact assessment.

Additionally, Rougier's research on climate model emulators [2,3] was crucial in the practical implementation of the methods:

> "Dr Rougier's guidance was instrumental in helping [UKMO] understand how to find appropriate transformations of variables, build emulator regression relationships, and evaluate emulator performance in validation tests. His use of emulators to identify the individual and combined effects of key parameters on the climate sensitivity to doubled carbon dioxide [3] provided a clear demonstration of the importance of ruling out unrealistic parts of parameter space through the calculation of relative likelihood. [UKMO] was later able to cite this as a key justification in its estimation of relative weights for different model variants." [a]

Rougier was retained as an External Expert by the UKMO for the UKCP09 (2007-2009, £10K honorarium):

> "More generally, Dr Rougier provided expert steer and advice on the implementation of his Bayesian methodology as a whole. His advice also provided key insights into the strengths, limitations and principles behind alternative methods for the quantification of uncertainties in climate projections, helping [UKMO] to justify and communicate its approach in an area inevitably subject to a variety of potential techniques and choices." [a]

In delivering the UKCP09,

> "the UKMO team with Dr Rougier [have] put the UK at the leading edge of the science and

service aspects of providing climate information for users" [b].

The UKCP09 has been critical in helping the UK Government to meet its obligations under the Climate Change Act (2008). This act made the UK the first country in the world to have a national, legally binding, long-term framework to cut carbon emissions. The UKCP09 formed the basis for the first UK Climate Change Risk Assessment (CCRA, 2012), and Rougier's contribution to the uncertainty assessment in the UKCP09 played a crucial role:

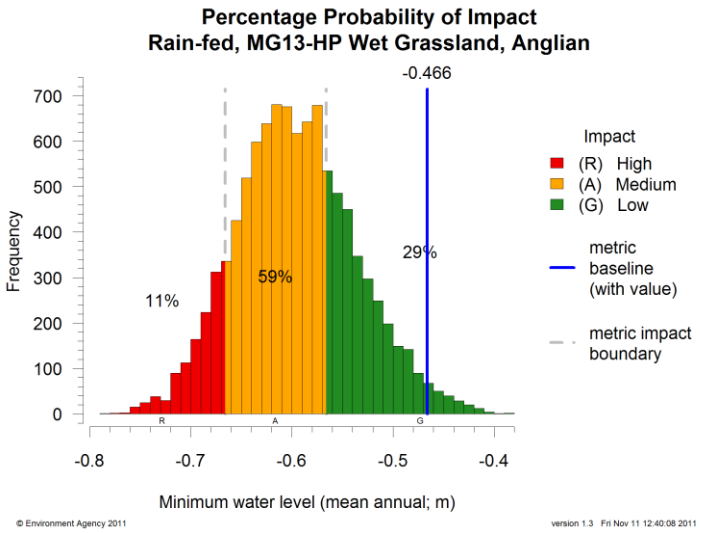
> "The assessment of future climate risks needs to take account of a wide range of outcomes … The CCRA considered a range of potential changes in climate, informed by the [UKCP09], to provide an indication of these uncertainties" [e, p11].

> "The risk assessment used UKCP09 climate projections, where possible, to assess future changes to sector risks. Some risks were analysed using single climate variables, for example temperature. Others, including flood risks, considered the combined effects of many climate variables and sea level rise." [f, piii]

Statement [a] notes that a powerful feature of Rougier's statistical framework is its ability to handle multiple climate variables in a consistent manner. This is crucial for planning, where impact typically arises from a combination of climate variables (such as temperature and precipitation) or a sequence of weather states (such as a drought). The CCRA has in turn formed the basis for the recommendations in the UK's first National Adaptation Programme (NAP, 2013). The CCRA and the NAP were laid before Parliament (in 2012 and 2013, respectively) as part of the Government's obligations under the Climate Change Act.

The CCRA monetised 100 of the direct risks of climate change, suggesting that the net costs of climate change are of the order of tens of billions of pounds per year in the 2050s for the 50th percentile outcome under the Medium emissions scenario. But, as noted by source [g], this does not fully capture the risk for several different reasons, including that some outcomes with non-negligible probabilities are substantially worse. To give one example, for tidal flooding the UKCP09 50th percentile outcome is 550 thousand properties affected; but the 90th percentile is 620 thousand properties, and the more extreme H++ scenario is 1.25 million properties [g, p27]. The wide range of possible losses in this example illustrates the importance of uncertainty quantification in a full assessment of risk, and the impact of the UKCP09 on the UK's risk assessment for climate change.

The UKCP09 is being used by a wide range of organisations to assess and manage the impact of climate change (about 7,000 downloads [a]). Case studies on the UKCIP website include Agencies and NGOs (Environment Agency, Macaulay Institute, South West Tourism), utilities companies (Severn Trent Water), consultancies (JBA consulting, Royal Haskoning, United Sustainable Energy Agency), and County Councils and Local Authorities. Many of these users have incorporated the UKCP09 uncertainty assessment into their decision support tools.



As an illustration, the figure to the right shows an output from the Wetland Toolkit for Climate Change created for the Environment Agency. This illustrates the type of decision support tool that can be developed once a probabilistic uncertainty assessment for future weather is provided. In this case, impact thresholds for different regions are determined from ecological considerations, and represented by the grey dashed lines (the current level is indicated by the solid blue line). A probabilistic ensemble for future weather, based on the UKCP09, is used to assign probabilities for the three different levels of impact, which can then be used to screen regions in order to identify those most at risk.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[a] *Hadley Centre, UK Met Office (UKMO).* Statement corroborating the UKMO's role in the UKCP09, Rougier's role as the developer of the statistical methods, the importance of Rougier's research, and Rougier's collaboration with the UKMO.

[b] *UK Climate Impacts Programme (UKCIP)*. Statement corroborating the user demand for statistical climate impact assessment in the UKCP09, the role of the UKMO and Rougier, and the breadth and depth of impact of the UKCP09.

The following documents are publicly available, and can be supplied on demand.

[c] G.J. Jenkins *et al.* (2009), *UK Climate Projections: Briefing Report*. Met Office Hadley Centre, Exeter, UK. ISBN 978-1-906360-04-7.

[d] *Assessing the differences - UKCIP02 & UKCP09*. UKCIP 2009.

[e] *UK Climate Change Risk Assessment: Government Report*. Defra 2012. ISBN 9780108511257.

[f] *The UK Climate Change Risk Assessment 2012, Evidence Report*. Defra 2012.

[g] *Scoping Study: Reviewing the Coverage of Economic Impacts in the CCRA*. Report to the Committee on Climate Change, Adaptation Sub-Committee, Paul Watkiss Associates, 2009.