Institution: UDur: University of Durham

Unit of Assessment: Unit 10: Mathematical Sciences

Title of case study: Policy implications of uncertainties related to climate change

1. Summary of the impact

The Climate Change Act, 2008, constructed a legally-binding long-term framework for the UK to cut greenhouse gas emissions and a framework for building the UK's ability to adapt to a changing climate. The Act requires a UK-wide climate change risk assessment (CCRA) that must take place every five years and a national adaptation programme (NAP), setting out the Government's objectives, proposals and policies for responding to the risks identified in the CCRA. The CCRA, and thus the NAP, drew heavily on the uncertainty analysis for future climate outcomes, published in 2009 by the Met Office as the UK Climate Projections UKCP09, which in turn drew heavily on research into the Bayesian analysis of uncertainty for physical systems modelled by computer simulators carried out at Durham University. A wide range of industries and public sector organisations likely to be affected by climate change have consulted with the Met Office on UKCP09 to inform decisions on policy and investment, involving billions of pounds, in sectors as diverse as flood defence, transport, energy supply and tourism.

2. Underpinning research

The Durham statistics group has developed a very general probabilistic framework for linking one or several mathematical models to the physical systems that the models purport to represent, taking account of all sources of uncertainty, including model and simulator imperfections. This framework is a necessary precondition for making probabilistic statements about the system on the basis of historical observations and evaluations of the computer simulators. The formulation distinguishes simulators according to their quality and the nature of their inputs. Further modelling constructs are introduced to account for imperfections in the available simulators and, within the framework of Bayesian graphical modelling, to unify the composite inference, from the collection of available simulators, observed historical data and the judgements of experts, for the behaviour of the actual physical system. The work **[1]** in section 3 is quite general, but the group did have in mind the application to collections of evaluations of climate models in this development and part of the research is the paper **[2]** making this connection explicit. The research led to a very general formalism **[3]** for relating models to physical systems.

The particular work leading to the climate-related impacts in this case study was carried out over the period 2001-2006 by Michael Goldstein, permanent member of staff, and Jonathan Rougier, PDRA. Dr Rougier left Durham at the end of 2006 and took up a lectureship at the University of Bristol.

3. References to the research

The basic work that summarises, formalises and generalises all of the preceding work in Durham on uncertainty in physical systems represented by computer models, and with which this impact case is directly concerned, is contained in the paper

[1] Goldstein, M & Rougier, J (2004) *Probabilistic formulations for transferring inferences from mathematical models to physical systems*, Siam J. Sci Comput., 26, 467-487, doi:10.1137/S106482750342670X.

The paper **[1]** has been well referenced and its practical value can be judged by the role that it has played in areas such as climate science, as will be discussed in the next section. This paper

forms a part of the ongoing exploration at Durham of the question, of fundamental interest in all areas of science and technology, as to what is the actual information about a physical system that is conveyed by one or more models for that system, and how can that information be uncovered and exploited for better understanding of the behaviour of the system. It provided the core ideas for much further development of that theme at Durham; in particular, Dr Rougier, while at Durham, wrote a paper which applied its formulation directly to the problem of climate inference, namely

[2] Rougier, J.C. (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

and Goldstein and Rougier wrote the first draft of the general conceptual paper which extended the formulation and eventually appeared as

[3] Goldstein M and Rougier J.C. (2009), *Reified Bayesian modelling and inference for physical systems*, Journal of Statistical Planning and Inference, 139, 1221-1239, doi:10.1016/j.jspi.2008.07.019

which was chosen as the first ever discussion paper in that journal.

During the period of this research, Dr Rougier was funded by the following grants:

The probability of rapid climate change (01/01/2004 – 31/12/2006)
Funder: NERC; grant value: £173 074.68

Uncertainties integrated assessment process (01/09/2002 – 31/08/2005)
Funder: Tyndall Centre; grant value: £13 606.40

4. Details of the impact

There were regular discussions on probabilistic climate projection, from 2002, between members of the Durham Statistics group and individuals with responsibility for uncertainty analysis in climate projections in the Met Office Hadley Centre. Therefore, there was general familiarity with our approach, in which Dr. Rougier consulted closely with the Hadley Centre. By this route, the Durham research into Bayesian modelling became a central methodological component of the UK Climate Projections 2009 (UKCP09), the Met Office's climate analysis tool for the UK for the 21st century, funded by DEFRA. The science and methodology used to construct UKCP09 is described in detail in the 200 page report[1], from the Met office. The report [1] emphasises the importance of the careful treatment of uncertainty in the climate projections. Here is an indicative quotation from the introduction:

“Uncertainty in climate change projections is a major problem for those planning to adapt to a changing climate. Adapting to a smaller change than that which actually occurs (or one of the wrong sign) could result in costly impacts and endanger lives, yet adapting to too large a change (or, again, one of the wrong sign), could waste money. In addition there is the risk of maladaptation – adapting to climate change in a way that prevents or inhibits future adaptation. The 2008 projections are the first from UKCIP to be designed to treat uncertainties explicitly ... This means that probabilities are attached to different climate change outcomes, giving more information to planners and decision makers." [page 19]

The methods developed at Durham play an important role in the uncertainty analysis throughout the report. Here are some indicative quotes from the report (all references to Goldstein and Rougier (2004) and Rougier (2007) refer to papers **[1]** and **[2]** cited in the preceding section).

“These results are then incorporated into our uncertainty analysis, based on a statistical framework devised by Goldstein and Rougier (2004), discussed in Chapter 3. This allows us to create a probability distribution function accounting for uncertainties arising from both model parameters and structural errors, and constrained by observations," [page 39]

"The method is based on a general statistical framework for the derivation of probabilistic projections of real systems from simulations carried out using complex but imperfect models of those systems (Goldstein and Rougier, 2004; Rougier, 2007)." [page 49]

"Our ensemble projections are converted into probabilistic projections using a Bayesian statistical framework developed to support inference of future information about real systems from complex but imperfect models (Goldstein and Rougier, 2004; Rougier, 2007). This process allows our projections to be constrained by a set of observations of past climate (Section 3.2.9), and also involves the use of expert judgements ... The probabilities which emerge from this approach represent the relative credibility of a family of different possible outcomes, taking into account our understanding of physics, chemistry, biology, observational evidence, and expert judgement." [page 82]

The contribution of the Durham approach to UKCP09 is amplified in a paper[2] by several of the authors involved with that uncertainty analysis, which explains in detail the uncertainty methodology used by UKCP09. For example, section 3 of the paper, "Outline of the calculations", begins "Here we describe the general steps in Goldstein and Rougier (2004) necessary to determine a probability distribution of some aspects of climate change that we want to predict." Similarly, the final subsection, section 6.2 begins "... Goldstein and Rougier (2004) gives us several key advantages. ...First, the multivariate nature of this probabilistic framework allows us to have more than one prediction variable. Predicting joint probabilities provides us with important information on how uncertainty is related across different climate variables..."

UKCP09 plays a key role within the Government's statutory responsibilities for assessing and responding to climate change. The Climate Change Act 2008 constructed a legally-binding long-term framework for the UK to cut greenhouse gas emissions and a framework for building the UK's ability to adapt to a changing climate. The Act requires a UK-wide climate change risk assessment (CCRA) that must take place every five years and a national adaptation programme (NAP), setting out the Government's objectives, proposals and policies for responding to the risks identified in the CCRA. The CCRA, and thus the NAP, drew heavily on the uncertainty analysis in UKCP09. The purpose of CCRA and the role of UKCP09 are indicated by the following two quotes from the Evidence Report[3]:

"The UK Climate Change Act (CCA) 2008 makes the UK the first country in the world to have a legally binding, long-term framework to cut carbon emissions. It also requires a series of assessments of the risks of climate for the UK, under both current conditions and over the long term, to 2100. The CCRA provides the first of these assessments and was laid before parliament in January 2012." [page V]

"The CCRA makes use of the UKCP09 climate projections that represent a range of possible future changes in UK climate. The range of possibilities is necessarily wide to take account of uncertainties in natural climate variability, how the UK's climate may respond to global warming, the future trajectory of emissions, and how these might magnify any regional climate change effects." [page 9]

The CCRA constructed sector reports describing a wide range of potential risks in each of the following sectors (followed by a more detailed analysis of selected risks that were judged to be the most important): Agriculture; Biodiversity & Ecosystem Services; Built Environment; Business, Industry & Services; Energy; Floods & Coastal Erosion; Forestry; Health; Marine & Fisheries; Transport; Water. The CCRA used the UK Climate Projections (UKCP09) for three time periods – 30-year periods centred on the 2020s, 2050s and 2080s. The CCRA attempted to monetise the most important risks to the UK, and concluded that the results indicated that the net economic costs to the UK are of the order of tens of billions/year by the 2050s (in current prices) even for the middle of the uncertainty range for these costs at the middle of the projected emission scenarios (see the Scoping Study[4], page 6, which suggests that this figure is an underestimate).

The CCRA is constructed to facilitate the Climate Change Act mandated National Adaptation Programme (NAP, 2013). The NAP report[5] (laid before Parliament in 2013) explains:

"The Climate Change Risk Assessment 2012 (CCRA) for the UK brought together the best available evidence, using a consistent framework to identify the risks and opportunities related to climate change. The assessment distilled approximately 700 potential risks down to more than 100 for detailed review. The government's response to the CCRA, which meets the requirements laid down in the Climate Change Act 2008, is the first NAP. In developing the NAP for England, we have taken the highest order risks from the CCRA and working in partnership with businesses, local government and other organisations, have developed objectives, policies and proposals to address them." [page 8]

In addition to its statutory role, the Met Office has worked with a wide range of public and private sector organisations to use UKCP09 to inform decisions on investment amounting to billions of pounds to 'future proof' projects against climate change. On the UKCP09 website (http://ukclimateprojections.defra.gov.uk) there is a link to a Case Studies web-page[6], which states "Working with our stakeholders, we have put together a number of case studies to show how UKCP09 data can be used." As of 17/10/13, these included case studies with Councils for Devon, Hampshire, Kent, Milton Keynes and Oxford City, and organisations including Atkins/UKWIR, CEH, Environment Agency/Acclimatise /JBA consulting, Macaulay Institute, United Sustainable Energy Agency, Proclimation, Prometheus, Royal Haskoning, Severn Trent Water, South West Tourism. Each case study describes how the UKCP09 products were used, and how the results would be communicated to the target audience. The range of topics covered includes: national assessment of river flows, climate change and pollution at water courses in Birmingham, strategic planning for flood management, changes in flood damages at a catchment scale, assessments of storm surge and sea level rise, emergency planning, defining land capability for agriculture specifications, assessing potential vulnerabilities to climate change, future proofing design decisions in the buildings sector, investigating coastal recession & shore profile development, storm surge and sea level rise and assessing impacts of climate change on tourism in South West England.

5. Sources to corroborate the impact

1. Murphy JM, Sexton DMH, Jenkins GJ, Booth BBB, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA (2009) *UK climate projections science report: climate projections*, Met Office Hadley Centre, Exeter, available from http://ukclimateprojections.defra.gov.uk/22544

2. Sexton DMH, Murphy JM, Collins M, Webb MJ (2012) *Multivariate probabilistic projections using imperfect climate models part 1: outline of methodology*, Climate Dynamics, 38, 2513-2542, doi:10.1007/s00382-011-1208-9.

3. *The UK Climate Change Risk Assessment 2012, Evidence Report,* DEFRA 2012.

4. *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.

5. *The National Adaptation Programme, Making the country resilient to a changing climate*, July 2013, available at https://www.gov.uk/government/publications/adapting-to-climate-change-national-adaptation-programme.

6. UKCP09 Case Studies webpage http://ukclimateprojections.defra.gov.uk/23081 (accessed 17/10/2013).