Section A

Institution: Durham University

Unit of Assessment: UoA 10 Mathematical Sciences

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

Period when the underpinning research was undertaken: 2001 - 2014

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Michael Goldstein	Professor, Statistics	1990 – Present
Prof. Peter Craig	Professor, Statistics	1989 – Present
Dr Allan Seheult	Senior Lecturer	1970 – 2010
Dr Jonathan Rougier	Research Associate	1997 – 2006

Period when the claimed impact occurred: August 2013 to present

Is this case study continued from a case study submitted in 2014? Y

Section B

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

The Climate Change Act, 2008, constructed a legally-binding long-term framework for building the UK's ability to adapt to a changing climate. The Act requires a UK-wide climate change risk assessment (CCRA), setting out the Government's policies for responding to the risks identified in the CCRA by means of a National Adaptation Programme. This programme draws heavily on the uncertainty analysis for future climate outcomes carried out by the Met Office in their UK Climate Projections 2009 and 2018, which both exploited fundamental research into the Bayesian analysis of uncertainty for physical systems modelled by computer simulators, as carried out at Durham University. These climate projections further impact on all those industries and public sector organisations which must address the uncertainties in future climate in order to make decisions on policy and investment.

2. Underpinning research (indicative maximum 500 words).

The Durham statistics group has developed a very general probabilistic framework for linking mathematical models to the physical systems that they purport to represent [**R1, R2**]. This framework takes account of all sources of uncertainty, including model and simulator imperfections, and 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 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. Fast surrogate forms, which approximate the computer model with an associated uncertainty assessment of the quality of the approximation, are integrated into this approach, both to address issues of evaluation speed for slow and expensive models and also to bridge

important gaps arising from model imperfections. This research is part of an ongoing exploration at Durham University of the question 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. The work is quite general, but the group did have in mind the application to collections of evaluations of climate models in this development [**R2**] and one aspect of the research is work which develops the underlying structure in such a way that it may be directly applied to such problems in climate science [**R3-R5**]. This application of the research forms the core of the current impact case.

[**R1**] is a key paper in the technical development of our approach, which constructs a general core methodology for forecasting real world system behaviour based on computer simulators, while addressing all of the uncertainties associated with such problems. [**R2**] summarises, formalises and generalises all of the preceding work in Durham University, such as [**R1**], on uncertainty in physical systems represented by computer models, adding sufficient structure that the approach can be directly applied in large scale problems such as climate science, as will be discussed in the impact section. [**R2**] provided core ideas for much further development at Durham University. In particular, Dr Rougier, while at Durham University, wrote a follow-up paper [**R3**] which applied its formulation directly to the problem of climate science and Goldstein and Rougier wrote the first draft of a general conceptual paper in this area which extended the formulation and eventually appeared as [**R4**]**.** Finally, a summary of ongoing research in this area is provided in [**R5**].

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

R1. P. Craig, M. Goldstein, J. Rougier, and A. Seheult, (2001) Bayesian forecasting for complex systems using computer simulators, J. Amer. Statist. Assoc., 96 (2001), pp. 717–729. DOI: 10.2307/2670309

R2. Goldstein, M and Rougier, J (2004) Probabilistic formulations for transferring inferences from mathematical models to physical systems, Siam J. Sci Comput., 26, 467-487 http://dx.doi.org/10.1137/S106482750342670X

R3. 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

R4. Goldstein M and Rougier JC (2009) Reified Bayesian modelling and inference for physical systems, Journal of Statistical Planning and Inference, 139, 1221-1239 https://doi.org/10.1016/j.jspi.2008.07.019

R5. Rougier JC and Goldstein M (2014) Climate Simulators and Climate Projections, Annual Review of Statistics and Its Application Vol. 1:103-123. https://doi.org/10.1146/annurev-statistics-022513-115652

R1-R4 are highly cited and influential original research articles. R1, R2 and R4 introduce the key concepts and develop the core methodology, including uncertainty analysis, for simulators of complex physical systems. R4 was chosen as the first ever discussion paper in that journal.

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

The research at Durham University had a key role in the Met Office UK Climate Projections 2009 (UKCP09) and UK Climate Projections 2018 (UKCP18). These projections had a fundamental impact upon Government, public and private planning for adaptation to climate change. These impacts are as follows.

UKCP09 and UKCP18

The UKCP18, an updated version of the UKCP09, is the Met Office's climate analysis tool. It provides projections for UK and global climate change throughout the 21st century using the latest climate science and analysis. It is designed to assist decision-makers by enabling them to assess climate change risks and is used by both public and private users to plan for a wide spectrum of environmental impacts. UKCP09 provided authoritative climate forecasts which were widely used in climate adaptation planning, within a statutory legal framework that we will describe below, until they were replaced by the enhanced forecasts arising from UKCP18. Thus, they continued to have impact throughout the current REF impact period until the updated forecasts took over.

THE IMPORTANCE OF UNCERTAINTY IN UKCP09, UKCP18

The science and methodology used to construct UKCP09 are described in the Met Office report [**E1**] and in [**E2**] for UKCP18. Each report emphasises the importance of the careful treatment of uncertainty in the climate projections. Here is an indicative quotation from [**E1**]. "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..... 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." [**E1**, p19]

DURHAM UNIVERSITY RESEARCH IMPACT ON UKCP09, UKCP18

The methods developed at Durham University play an important role in the uncertainty analysis throughout each report and Durham University research is referred to explicitly in the UKCP09 and UKCP18 documents. For example, for UKCP18 "These results support the chosen approach, allowing Strand 1 to provide an updated product that combines evidence from HadCM3-based PPEs and CMIP5 models in a consistent manner, retaining the Bayesian statistical framework used for UKCP09 (Goldstein and Rougier, 2004) [**R2**]." [**E2**, p11] and "Prior pdfs ... are then produced using the Bayesian method of Sexton et al (2012)**,** based on the general framework of Goldstein and Rougier (2004) [**R2**]." [**E2**, p17]. Our contribution is amplified in Sexton et al (2012) [**E3**], which explains in detail the uncertainty methodology used by UKCP09 and later by UKCP18. For example, in [**E3**] section 3 "Here we describe the general steps in Goldstein and Rougier (2004) [**R2**] necessary to determine a probability distribution of some aspects of climate change that we want to predict." while section 6.2 begins "...Goldstein and Rougier (2004) [**R2**] 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....."

STATUTORY CLIMATE RESPONSIBILITIES: CCA, CCRA AND NAP

With the Climate Change Act (CCA) 2008, the UK constructed a legally-binding long-term framework to cut greenhouse gas emissions and a framework for building the UK's ability to adapt to a changing climate [**E4**]. The Act requires a UK-wide climate change risk assessment (CCRA) to take place every five years. The CCRA constructs sector reports describing a wide range of potential risks in each of the following sectors: Agriculture; Biodiversity & Ecosystem Services; Built Environment; Business, Industry & Services; Energy; Floods & Coastal Erosion; Forestry; Health; Marine & Fisheries; Transport; Water. The CCRA facilitates the Climate

Change Act mandated National Adaptation Programme, (NAP) produced in 2013 [**E6**] (covering the period of 2013 to 2018) and updated in 2018 [**E7**]. The NAPs set out the Government's objectives, proposals and policies for responding to the risks identified in the CCRA as detailed in [**E6**, p8] "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."

UKCP09, UKCP18 IMPORTANCE FOR CCRA AND NAP

The original 2012 CCRA [**E4**], and thus the 2013 NAP, draws heavily on the uncertainty analysis in UKCP09 [**E4**, p9]. The impact of that report is still being felt heavily through this REF impact period. The second report was published in 2017 **[E5]**. The CCRA used the UK Climate Projections (UKCP09) for three – 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). UKCP09 therefore played a key role within the Government's statutory responsibilities for assessing and responding to climate change throughout the current REF period and the updated UKCP18 is continuing this role. The ministerial foreword to the updated version, NAP 17 [**E7**], links the various strands of activity as follows.

"Later this year we will be launching a revised set of UK climate projections ('UKCP18'), replacing the current 2009 set and providing the most up to date and scientifically robust estimations of climate scenarios out to the end of this century. These projections are a key tool to enable everyone to future proof policies and activities to ensure our resilience to possible future climate change. ... so that we take back control of our fisheries and agriculture, restore nature and care for our land, rivers and seas. Using a natural capital approach ensures that we take account of all the many benefits our environment provides, and we will develop policies that ensure our seas and lands are healthy and productive and resilient to climate change."

When the UKCP18 was launched, Environment Secretary Michael Gove said: "This cutting-edge science opens our eyes to the extent of the challenge we face and shows us a future we want to avoid. By having this detailed picture of our changing climate, we can ensure we have the right infrastructure to cope with weather extremes, homes and businesses can adapt, and we can make decisions for the future accordingly." [**E9**]

PUBLIC AND PRIVATE SECTOR IMPACT OF UKCP09, UKCP18

In addition to the statutory role, the Met Office has worked with a wide range of public and private sector organisations to use UK climate impacts to inform decisions on investment amounting to billions of pounds to future-proof projects against climate change.

The UKCP09 website [**E8**] contains case studies showing how the UKCP09 products have been used, with topics including: national assessment of river flows, climate change and pollution, strategic planning for flood management, changes in flood damages at a catchment scale, 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.

As early evidence of the ways in which the Met Office are rolling out the effects of UKCP18 to user groups, the document [**E10**] details a set of six project leaflets. Each leaflet describes how UKCP09 has been used in the area and how UKCP18 will improve adaptation planning for climate change. The titles show some of the range of areas of application that UKCP18 affects. (i) Assessing climate change risk in Yorkshire; (ii) Future surface water flood hazard risk; (iii) Coastal cliff recession under climate change; (iv) Thermal performance of buildings; (v) Forests for the future; (vi) Water resources and drought planning.

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

E1. Murphy JM, et al., (2009) UK climate projections science report: climate projections Met Office Hadley Centre, Exeter.
http://cedadocs.ceda.ac.uk/1320/1/climate_projections_full_report.pdf

E2. J.M. Murphy, et al., (2018) UKCP18 Land Projections: Science Report. Available from https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Land-report.pdf

E3. Sexton DMH, et al., (2012) Multivariate probabilistic projections using imperfect climate models part 1:outline of methodology, Climate Dynamics, 38, 2513-2542
https://doi.org/10.1007/s00382-011-1208-9

E4. The UK Climate Change Risk Assessment 2012, Evidence Report. Defra 2012.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69487/pb13698-climate-risk-assessment.pdf

E5. The UK Climate Change Risk Assessment 2017 (Presented to Parliament pursuant to Section 56 of the Climate Change Act 2008)
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/584281/uk-climate-change-risk-assess-2017.pdf

E6. The National Adaptation Programme, Making the country resilient to a changing climate, July 2013 (www.gov.uk/defra).
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727259/pb13942-nap-20130701.pdf

E7. Climate change: second national adaptation programme (2018 to 2023)
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727252/national-adaptation-programme-2018.pdf

E8. Case studies UKCP09
https://webarchive.nationalarchives.gov.uk/20181204111030/http://ukclimateprojections-ukcp09.metoffice.gov.uk/23081

E9. UK Climate Projections Project Newsletter April 2019
https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/newsletters/ukcp18-newsletter.april-2019.pdf

E10. UKCP18 Demonstration Projects
https://www.metoffice.gov.uk/research/collaboration/ukcp/ukcp18-demonstration-projects