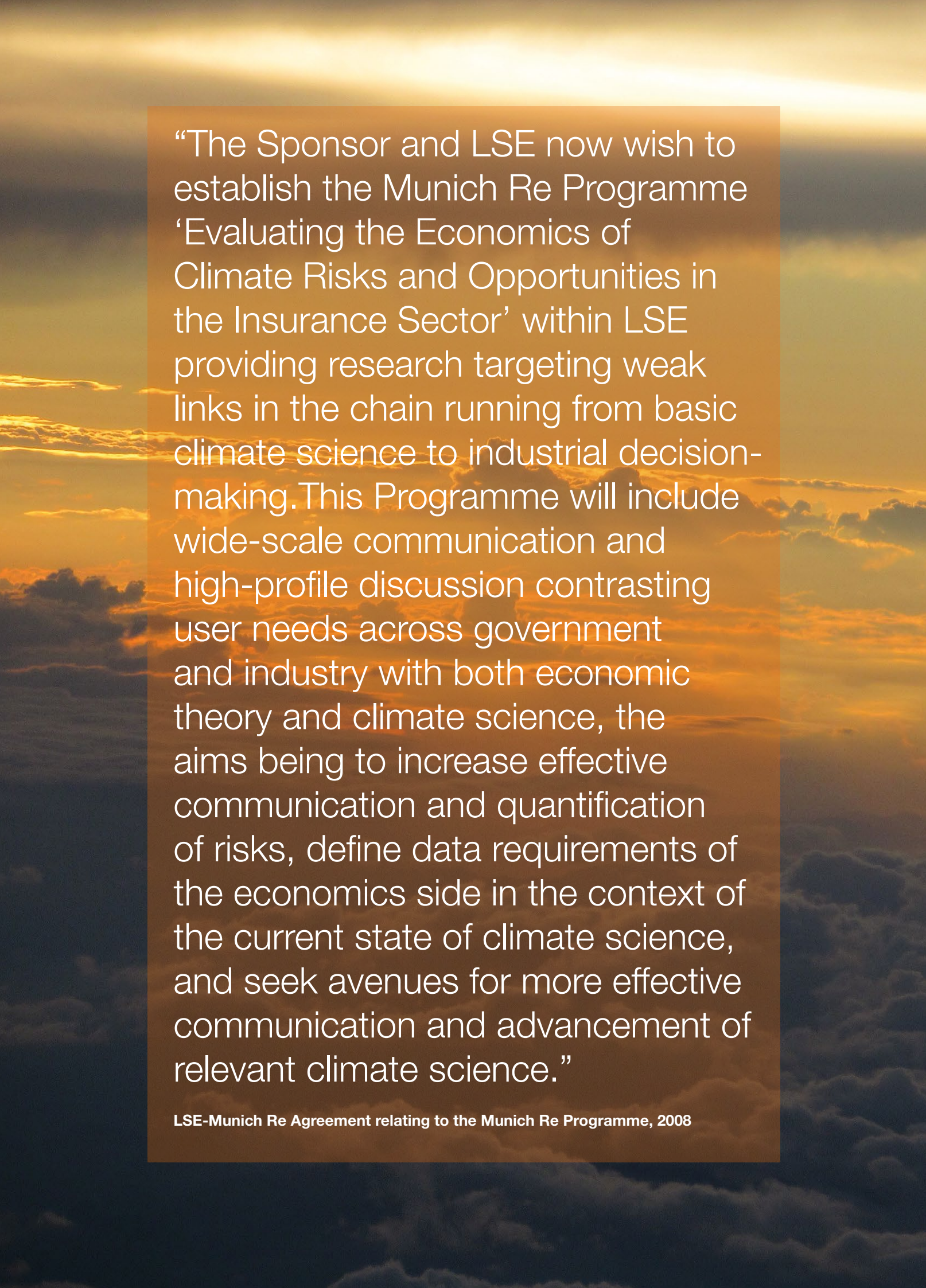
Munich RE

Centre for
Climate Change
Economics and Policy

LSE THE LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

Evaluating the Economics of Climate Risks and Opportunities in the Insurance Sector

Progress and Insights from the LSE "Munich Re Programme"



“The Sponsor and LSE now wish to establish the Munich Re Programme ‘Evaluating the Economics of Climate Risks and Opportunities in the Insurance Sector’ within LSE providing research targeting weak links in the chain running from basic climate science to industrial decision-making.This Programme will include wide-scale communication and high-profile discussion contrasting user needs across government and industry with both economic theory and climate science, the aims being to increase effective communication and quantification of risks, define data requirements of the economics side in the context of the current state of climate science, and seek avenues for more effective communication and advancement of relevant climate science.”

LSE-Munich Re Agreement relating to the Munich Re Programme, 2008

Preface

In 2008, Munich Re approached the London School of Economics and Political Science with the innovative and far-sighted idea of funding a major research programme on how climate change would affect the insurance sector. It was an idea that was entirely in keeping with the reinsurance company's leadership role, having been one of the first to recognise that the impact of climate change on the frequency and severity of extreme weather events could have profound implications for the insurance industry.

The result was the establishment of the five-year Munich Re research programme on "Evaluating the economics of climate risks and opportunities in the insurance sector", which was undertaken by the Centre for Climate Change Economics and Policy, a joint venture by LSE and the University of Leeds that was established through a major grant from the UK Economic and Social Research Council.

The Programme created an enormous intellectual challenge for the researchers to understand the issue of climate change from the perspective of reinsurance companies. Munich Re assisted their efforts not just through its financial support, but also through its staff, led by Peter Höppe, who gave freely of their time and expertise, and by supplying invaluable data and information.

As a result, the researchers on the programme were able to apply the latest knowledge and techniques from the natural and social sciences to a broad range of business-relevant issues and problems. Through the publication of more than 20 technical papers and industry briefs, the research programme yielded valuable insights for the insurance sector as a whole.

The partnership between LSE and Munich Re has been unique and innovative, and provides an example of how universities and businesses can work together to further knowledge and understanding of the risks and opportunities posed by climate change.

Nicholas Stern, May 2015.

Professor Lord Stern of Brentford is Chair of the ESRC Centre for Climate Change Economics and Policy and President of the British Academy.

Nicholas Stern speaking at the inaugural lecture: A Global Deal for Climate Change. LSE, 6 October 2008

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"The increased importance and recognition of the changes in weather-related risks that arise from climate change could bring opportunities for new markets and products for the industry"

Ranger and Ward (2010) Aiming for a 2°C goal: What does it mean for the insurance Industry?

Foreword

Early in 2007 Judith Rees, Nick Stern and I met in Nick's office to discuss potential futures of what was then called the "LSE Climate Programme". We had three opportunities to fund academic research: a call from the Economic and Social Research Council (ESRC), an interest expressed by the Grantham Foundation, and an interest expressed by Munich Re. Success rates in academia being what they are, we pursued all three. This led to the establishment of the LSE Grantham Research Institute and the ESRC Centre for Climate Change Economics and Policy, the latter jointly with the University of Leeds. The Centre combined five Programmes, four funded by the ESRC and the fifth, the Munich Re Programme, funded by Munich Re. I had the privilege of leading that Programme, and this report provides an overview of the work done, insights accomplished and a hint of the ongoing impacts of that programme.

The only deliverables under contract consisted of Technical Papers and industry briefs. It is unusual to find a commercial entity thinking deeply enough to fund a multimillion pound project with limited immediate operational relevance, rather targeting strategic long-term importance. A total of 20 Munich Re Technical Papers were envisaged, as listed in the table below. The Programme produces much more, of course. At present 26 academic (peer reviewed) papers directly supported by the Munich Re Programme have appeared in print, the latest in early 2015. The differences in academic timescales and industrial timescales are what they are: the Munich Re Programme will continue to have impact on timescales long even compared to those of academic institutions.

Within LSE, the research view of dozens of people, physical scientists and social scientists, graduate students, postdocs and tenured faculty, have been widened by the Munich Re Programme. Most senior academics in the Programme remain at LSE, although Nicola Ranger is now seconded to DIFD. Postdocs and students supported by the Programme have dispersed around the world, and are now employed at institutions including ETH, University of Chicago, University of Oxford, and companies including Risk Management Solutions.

It is through this broadening of the background and experiences of these individuals that the Munich Re Programme will continue to significantly impact our understanding of the risks and opportunities posed by climate change. As academics we learned a great deal from professionals, including scientists and philosophers, within Munich Re. Perhaps my favourite recollection was a knock-down drag-out dispute over a pub table in the Leadenhall Market after one of our joint meetings. The dispute was over the meaning and interpretation of what constituted a "trend"; no clear sides could be drawn between those in academia and those in industry; it was as insightful, inspired and honest a discussion as any I have witnessed in academia. There was no clear "winner", but importantly the discussion helped me to better understand an important difference in current terminology. Teasing apart the strong feelings that led to that discussion took time, and a clarification which broadens our understanding beyond any of the views stated at the table that evening will soon become a chapter in an LSE statistics PhD thesis later this year.

The Munich Re Programme made possible these intense interactions, and personal relationships of trust and understanding developed through true interactions between academics and their counterparts in industry. These enduring relationships are the true legacy of the Munich Re Programme. I am proud to have been a part of it.

Leonard Smith, May 2015
Director, Centre for the Analysis of Time Series at LSE.
PI, LSE-Munich Re Programme

Munich Re Programme Technical Papers

Abstracts of the Technical Papers can be found in Appendix 1

TP	Date	Title	Authors
1	Jul 2009	Economic policy when models disagree	Barrieu (with Sinclair-Desgagné)
2	Sep 2009	High impact, low probability? An empirical analysis of risk in the economics of climate change	Dietz
3	Nov 2009	Properly designed emissions trading schemes do work!	Fehr (with Carmona & Hinz)
4	Aug 2010	Ambiguity and climate policy	Millner and Dietz (with Heal)
5	Nov 2010	A trend analysis of normalized insured economic damage from natural disasters	Neumayer and Barthel
6	Nov 2010	Normalizing economic loss from natural disasters: A global analysis	Neumayer and Barthel
7	Mar 2011	Integrated EUA and CER price modelling and application for spread option pricing	Barrieu and Fehr
8	Jul 2011	Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments	Ranger and Niehoerster
9	Aug 2011	Scientific Uncertainty: A User's Guide	Bradley
10	Sep 2011	A representation result for choice under conscious unawareness	Walker and Dietz
11	Sep 2011	Forecasting non-life insurance demand in the BRICS economies: a preliminary evaluation of the impacts of income and climate change	Ranger and Williamson
12	Sep 2011	A preliminary assessment of the impact of climate change on non-life insurance demand in the BRICS economies	Ranger and Surminski
13	Dec 2011	Pattern scaled climate change scenarios: are these useful for adaptation?	Smith, Lopez and Suckling
14	Sep 2012	Policy indexes – what do they tell us and what are their applications? The case of climate policy and business planning in emerging markets	Surminski and Williamson
15	Sep 2012	The roles of public and private actors in the governance of adaptation: the case of agricultural insurance in India	Fisher and Surminski
16	Nov 2012	Ambiguity and insurance: Robust capital requirements and premiums	Walker and Dietz
17	Jan 2013	Laplace's Demon and climate change	Frigg, Bradley, Du and Smith
18	Jul 2013	Do flood insurance schemes in developing countries provide incentives to reduce physical risks?	Surminski and Oramas-Dorta
19	Oct 2013	An evaluation of decadal probability forecasts from state-of-the-art climate models	Suckling and Smith
20	Feb 2014	Probabilistic skill in ensemble seasonal forecasts	Du, Smith, Suckling, Niehoerster

About the Programme

Evaluating the Economics of Climate Risks and Opportunities in the Insurance Sector (the LSE "Munich Re Programme") was a five-year research programme funded by Munich Re as part of the Centre for Climate Change Economics and Policy (CCCEP)[1], a joint LSE-University of Leeds centre funded by the ESRC. The programme focused on informing the insurance sector on the impacts of alternative approaches to carbon finance and emission trading; aiding the design of trading schemes and suggesting new financial service products to be developed; and informing decision-makers, at the company level and the country level, on how better to balance investment between mitigation and adaptation, survivability and sustainability. The programme consisted of five research and research communication areas, ranging from the impacts of climate change on extreme weather events to the economic impacts of climate change in emerging economies:

A) Evidence of current economic reaction and future financial products

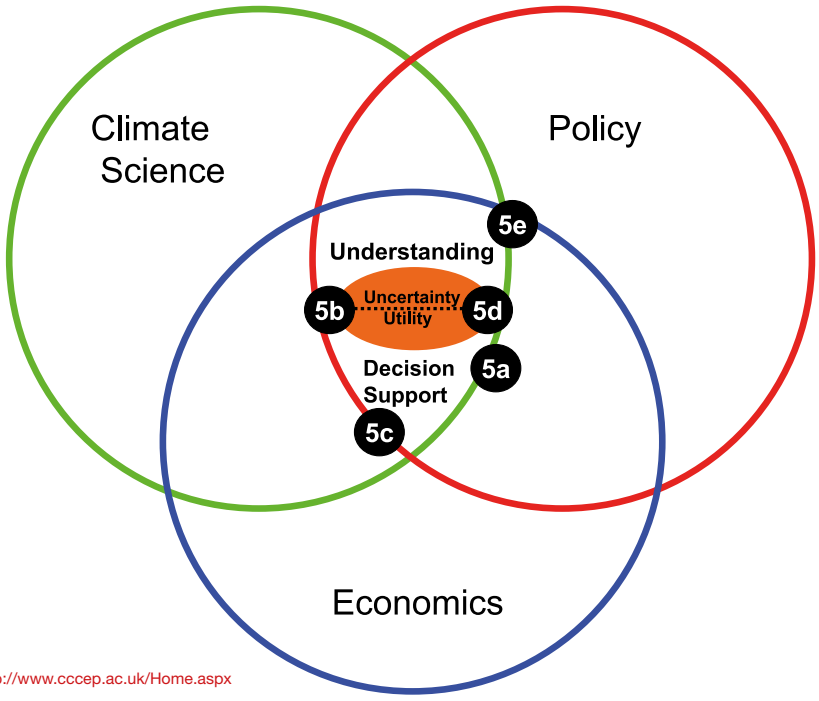
B) Quantifying the uncertainty in economic impacts and increasing the economic relevance of climate modelling

C) Normalising and interpreting trends in disaster losses using the Munich Re NatCatService database

D) Quantitative applied climate economics

E) Economic impacts of climate change in emerging economies

Established in October 2008 with a budget of £2.9 million over a five-year period, the Programme funded both academic and research staff, visiting professors and a PhD student, as well as a number of events and activities. The Programme's research was directed at LSE by Professor Leonard Smith, with management oversight by CCCEP Director Professor Judith Rees.



[1] http://www.cccep.ac.uk/Home.aspx

© Idiz | Dreamstime.com - Road of Thailand Photo

Synopsis of the research streams

The Programme consisted of five research streams. A synopsis of the research conducted under each of these streams is described below.

A) Evidence of current economic reaction and future financial products

Mitigation and adaptation activities will bring about a plethora of new financial products, introducing new risks and opportunities into the financial sectors. This research package aimed to inform the insurance sector on the impacts of alternative approaches to carbon finance and emission trading, which might then aid the design of trading schemes and suggest new financial service products to be developed. The outputs of this package were targeted to inform decision-makers, at the company level and the country level, as to how to better balance investment between mitigation and adaptation, survivability and sustainability.

This research stream ran for the first three years of the programme, 2008-11. The primary focus was initially on carbon finance and emission trading, and subsequently on Insurance-linked Securities. The research examined potential future accounting and trading schemes and their consequences for different industries, and undertook analyses of potential future financial service products to promote new and already decided trading schemes. The principal researchers were Pauline Barrieu and Max Fehr, working closely with the Carbon Markets Group within the Centre for Climate Change Economics and Policy (CCCEP).

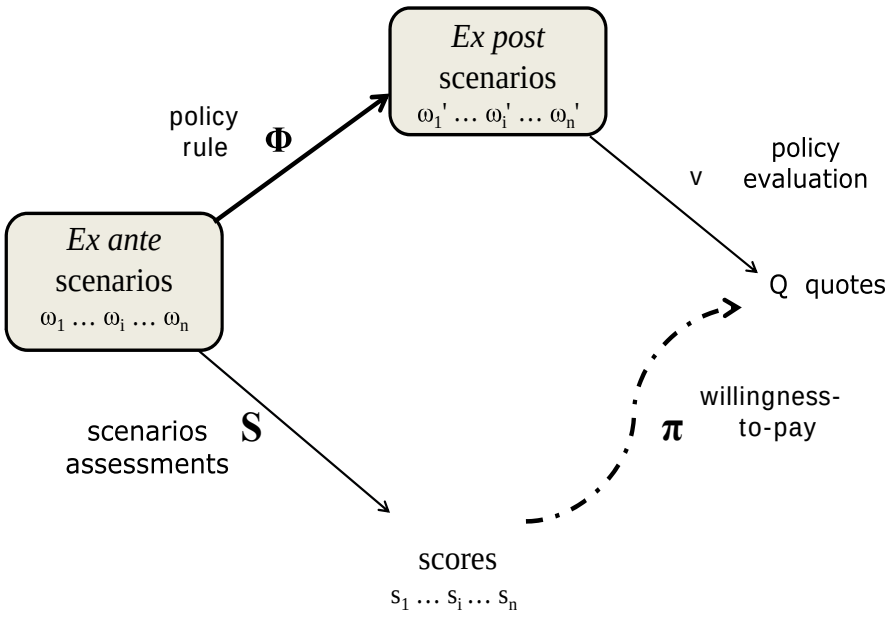
Together with co-author Bernard Sinclair-Desgagné, Pauline Barrieu produced a technical paper entitled 'Economic policy when models disagree' (Barrieu and Sinclair-Desgagné 2009, MRe TP1), in which they build a general approach to conceive public policy or to take a decision when there is no consensual account of the situation of interest. This approach builds on a basic attribute of rational decision-makers – namely their ability to appraise their experts' scenarios and forecasts – and uses only one normative criterion: that the value to decision-makers of a remedy's projected outcomes meets their willingness to get out of the current situation. Unlike the methods

currently put forward in the literature, it does not need (but is compatible with) a representative decision-maker's objective function (as in the ambiguity aversion literature), a reference model (as in robust control theory) or some prior probability distribution over the set of supplied scenarios (as in Bayesian model-averaging). Policies and decisions constructed in this manner are shown to be effective, robust, simple and precautionary in a precise and intuitive sense. This result could have some implication in the insurance industry for the assessment of risk when several experts or models offer diverging views on a situation.

In the context of moves in Europe and elsewhere to complement emissions trading schemes with other policies, either to underpin or cap the carbon price, Max Fehr co-authored a paper with René Carmona and Juri Hinz proposing that 'Properly Designed Emissions Trading Schemes Do Work' (Fehr, Carmona et al. 2009, MRe TP3). They show that cap-and-trade systems often fail to reach their emission targets as too generous an allocation of pollution permits serves as a disincentive for emissions reductions and deflates pollution prices. Moreover, the implementation of the first phase of the European Union's Emissions Trading Scheme (EU ETS) was widely criticized for providing significant windfall profits for power producers. By means of a rigorous quantitative modelling undertaking the authors provide an insight into what went wrong in the first phase of the EU ETS, and propose alternative reduction schemes with provable advantages. Using market equilibrium models and numerical tools, they demonstrate that properly designed market based pollution reduction mechanisms can reach pre-assigned emissions targets at low reduction cost and windfall profits, while being flexible enough to promote clean technologies. They illustrate their claims with the results of a hypothetical cap-and-trade scheme for the Japanese electricity market.

Max Fehr, Pauline Barrieu and Umut Cetin expanded research in this area, developing a model for risk neutral futures price dynamics in the EU ETS. Historical price dynamics suggest that both allowance prices for different compliance periods and Certified Emission Reductions (CER) prices for different compliance periods are significantly related. To obtain a realistic price dynamics they take into account the specific details of the EU ETS compliance regulations, such as banking and the link to the Clean Development Mechanism (CDM), and exploit arbitrage relationships between futures on EU allowances and CER. Barrieu and Fehr produced a technical paper on this work entitled 'Integrated EUA and CER price modelling and application for spread option pricing'

A unifying approach to decision-making under uncertainty



From: Barrieu, P. and B. Sinclair-Desgagné (2009). Economic policy when models disagree. *Munich Re Technical Paper 1*, LSE

(Barrieu and Fehr 2011, MRe TP7). The paper was subsequently extended and published in *Operations Research*, one of the top operational research journals, under the title 'Market-consistent modelling for cap-and-trade schemes and application to option pricing' (Barrieu and Fehr 2014).

The focus of research under this stream moved to Insurance-Linked Securities (ILS) markets. Pauline Barrieu and Nicola Ranger (in collaboration with members of the Munich Re Risk Trading Unit) considered the implications of uncertainty in risk for cat bond pricing. They explored the potential impact of natural climate fluctuations on risk assessment on an annual and multi-annual basis (up to five years), and considered approaches to incorporate uncertainty in forecasts of these fluctuations into cat bond pricing. First, they demonstrated the potential scale of uncertainty in risk assessment due to natural climate variability and illustrate the potential implications for cat bond pricing. They developed an initial case study on the influence of the ENSO (El Niño Southern Oscillation) on Florida hurricane risk. This case was chosen due to the availability of data. Implications of ENSO for risk in terms of metrics such as average annual loss (AAL) and exceedence probability (EP) curves were explored and this work was extended to consider work with a "toy" cat bond structure to explore the implications for pricing, including the Expected Shortfall. An exploration of pricing rules that would reflect the level of belief that the following year would be an El Niño, La Niña or neutral year was undertaken (our ability to make probability forecasts to support various levels of belief was investigated in Alex Jarman's PhD thesis, see research stream D). Interesting questions regarding the sensitivity of pricing to the level of belief remain open. This line of research was continued by Ranger and Niehörster under research stream B.

Leonard Smith and Pauline Barrieu gave presentations on the role of medium-term forecasting in ILS markets (ILS Summits in New York and London, 2010), in which they examined uncertainties in climate models, focusing especially on forecasting the impact of best- and worst-case climate scenarios on the future of the ILS market.

B) Quantifying the uncertainty in economic impacts and increasing the economic relevance of climate modelling

Over the last five years we have developed a more realistic quantitative evaluation of the strengths and weaknesses of current climate information, with a view to improve both the use of the information today and also the long-term improvement of the information itself, making scientific insight of more immediate relevance to decision-makers with regard to policy, insurance and adaptation activities.

Climate science provides critical information for decision-makers, both for policy-making and with regard to insurance and adaptation decisions. By providing realistic, quantitative information on the strengths and limitations of our current insights into future climate, both next season and over the next decades, the LSE Munich Re Programme has advanced this understanding and thereby effectiveness of its use in decision-making. Analysis of model performance and a better understanding of the variety of meanings of "uncertainty" and "reliability" are aiding the communication of climate information both for decision-making and within the sciences.

This research stream ran the full five years of the Programme, and contributed to a number of Technical Papers and publications in high impact journals including *Nature Climate Change, Nature Geoscience,* and *Philosophical Transactions of the Royal Society.* Several publications noted under this stream have already established a high profile; these include Rowlands, Frame et al. 2012 'Broad range of 2050 warming from an observationally constrained large climate model ensemble' in *Nature Geoscience,* which appeared in 2012 and already has over 40 citations in Thomson-Reuters' Web of Science. Simon Dietz's 2011 paper in *Climatic Change,* 'High impact, low probability? An empirical analysis of risk in the economics of climate change' (Dietz 2011), has been widely cited, serving to focus more research on exploring the implications of "deep uncertainty" in economic models of climate change.

Smith and Stern's 'Uncertainty in science and its role in climate policy' (Smith and Stern 2011), which appeared in the Royal Society's *Philosophical Transactions A*, has also nuanced the discussion of different varieties of "uncertainty" and the importance of clear communication.

One significant outcome of this project was an invitation to join Dutch government scientists and policy-makers at the 'Dutch Government Expert Panel on Uncertainty Communication in the IPCC AR5 WG I SPM' in the run-up to negotiations finalising the IPCC's AR5 Report (June 2013)[2]. At the invitation of Professor Arthur Petersen, the Dutch Chief Scientist at the PBL Netherlands Environmental Assessment Agency, a group of four LSE academics spent several days in the Netherlands, discussing the draft report, and discussing and refining the official questions and requests for clarification to be submitted by the government. This invitation resulted in part from relationships developed by Professor Petersen in his role as the LSE Munich Re Programme Visiting Professor.

The impact of this stream is ongoing. Not only has work under this stream inspired follow-on research around the world, but several of the individuals funded directly by the Munich Re Programme have moved on to new positions at major research universities and organisations. For example, Hailiang Du is now at the University of Chicago; Ana Lopez is now at Oxford University; Emma Sucking is now at the University of Reading; Nicola Ranger is now seconded to DIFD; Falk Niehörster is now at RMS.

The breadth of work accomplished under this research stream, the follow-on research inspired, and the range of new international academic, governmental and industrial connections established, reflect the impact of this very successful element of the Munich Re Programme.

Details of the advances made under this research stream

Broadly speaking, the research fell under four overlapping headings. The first focus was on understanding the nature of the quantitative insights available by climate modelling regarding impacts, and how the economic relevance of modelling studies to the insurance sector and to policy-making might be increased by altering the style of experiments designed. A second focus was on the use of forecasting in the short-term climate scales (seasonal forecasting). Long-term hurricane risk was the third focus in this research stream. The fourth focus was on decision-making under uncertainty, both for adaptation planning and in greenhouse gas mitigation policy.

i) Understanding the limitations of climate models to quantify the impacts of climate change

Research, led by Leonard Smith, explored the spatial and temporal scales at which climate and weather information is robust and decision-relevant, and quantifying uncertainties in key decision-relevant climate parameters at a regional level based on large-ensemble climate experiments and exploring implications for decision-making. Key to progress in this area was the appointment of Munich Re Programme Visiting Professor Arthur Petersen. Research and management contributions by David Stainforth played a critical role in this research stream. Progress under this stream was to be judged by our increased understanding of (i) the information available from models, (ii) decision-making under uncertainty, and (iii) how models might be more effectively deployed and improve support for decision-makers in policy and the insurance sector.

Climate Policy as a Risk Management Task

Investigating both the deep uncertainties and the quantified risks of climate change more clearly exposes both the opportunities and the hazards of a changing climate, and thus allows more effective risk management. This stream was energised by an academic-industry symposium entitled 'Interpreting Models in a Climate Change Context' held in July 2009, which brought together experts in a range of different modelling techniques relevant to issues of climate and climate change risk management, and was attended by over 80 participants. By discussing the various approaches to interpreting model results, it explored how models are best used to improve decision-making and risk assessment, and what is meant by "uncertainty", "reliability" or "robustness of modelling results".

This research stream continued to explore how different types of models – climate, economic and risk models – are interpreted in the context of today's climatic conditions, and to examine the role of today's models in decision-making in politics and the insurance industry under current climatic conditions. Other questions were raised regarding how models impact on planning and insurance-related risk assessment in the context of future climate change and the utility of "better" probabilistic forecasts to the insurance industry even in the short term. By identifying novel approaches to future

[2] See www.pbl.nl/en/news/newsitems/2013/bridging-the-gap-between-stakeholders-and-climate-modellers

model development research focused on improving their utility in the context of planning for future climate change. Key academic outputs here included the paper by Smith and Stern on the role of uncertainty (Smith and Stern 2011) and a paper written jointly with co-authors from the Dutch meteorological office discussing a new approach creating useful 'Tales of Future Weather' (Hazeleger, Hurk et al. 2015).

The 50 shades of "reliability"

The paper entitled 'Reframing the Reliability of Models: Moving from Error to Quality for Use' was presented by Petersen and Smith and extensively discussed at the ESF workshop "Exploring Epistemic Shifts in Computer Based Environmental Sciences", June 2010 at Aarhus University, Denmark, where it stimulated extensive discussion (for a link to the paper see Appendix 5ii). The main thrust of the paper is that even when we have no absolute quantitative yardstick for the reliability of a model, we may be able to identify shortcomings of models and thereby increase our understanding. A major limitation of a purely statistical definition of "reliability" is that it is often not possible to establish the accuracy of the results of a simulation or to quantitatively assess the impacts of different sources of uncertainty. Furthermore, disagreement (in distribution) between different modelling strategies would argue against the reliability of some, if not all, of them. "Reliability" then will have to be defined in more pragmatic terms. In those cases, one may instead have recourse to qualitative judgments of the relevant procedures, the methodological quality given the purpose of use. Given the presence of many different ways the reliability of models is established in scientific practices and the importance attached to the assessed reliability in particular decision-making contexts, such as in climate-policy-making, it is important for science studies to further investigate the notion of reliability. The paper presents some first analytical steps. Research done in a multi-disciplinary fashion, combining philosophical, sociological, anthropological and historical expertise, carries significant advantages when deployed. The paper was subsequently further developed by Smith and Petersen and resulted in a chapter in the book *Error and Uncertainty in Scientific Practice* (Smith and Petersen 2014).

Assumptions of Linearity in Climate Modelling

The impact and realism of simplifying assumptions sometimes required in order to make progress in understanding huge simulation exercises is a recurring theme in this research stream. Good science can advance our understanding without taking it to the point where the numbers emerging from simulations can be taken at face value when making decisions; thus it is critical to clarify the implications these assumptions hold (specifically, the extent to which they enhance or restrict the application of the simulations). The question here is the extent to which assumptions required in today's best available models impact the adequacy of their simulation for a given purpose. Leonard Smith, David Stainforth and Falk Niehörster investigated a number of questions in climate modelling here. The question of linearity in general circulation model (GCM) simulations of global warming as a function of an increasing atmospheric CO_2 concentration is one focus. The assumption that climate response is "linear" is widely used and multiply defined. Indeed, the assumption of linearity is crucial for several applications of climate science including pattern scaling and the interpretation and use of "anomalies" in place of the actual simulated model values. The extent to which linearity approximations hold is evaluated in large (512) initial condition ensembles (ICE). These simulations consider the equilibrium response of HadSM3 to three different levels of CO_2 concentration increase. By comparing the singular value decomposition (SVD) and the leading singular vectors of the three initial condition ensembles we evaluate not only the relevance of the linearity assumption, but also the robustness of the principal pattern of temperature change. This work was presented in 2010 at the 11th International Meeting on Statistical Climatology (IMSC) in Edinburgh where it generated significant discussion (see details in Appendix 5ii).

Pattern scaling, noted above, is another common application tool which exploits linearity assumption. Ana Lopez, Emma Suckling and Leonard Smith found these assumptions to severely limit the fidelity of the procedure, even in a mathematically ideal setting. Lopez was invited to present these results at NCAR in Boulder at a meeting on the design of CMIP6. This work was published as a technical paper entitled 'Pattern scaled climate change scenarios: are these useful for adaptation?' (Smith, Lopez et al. 2011, MRe TP13). The work was further developed and subsequently published in the journal *Climatic Change* (Lopez, Smith et al. 2014).

Improving the information available to decision-makers

Ranger and Lopez conducted decision-making case studies on the UK water and coastal flood sectors, some of which were reported in two chapters in the book *'Modelling the Impact of Climate Change on Water Resources'* (Fai-Fung, Lopez et al. 2010).

Erica Thompson, who joined the Programme in year four, accelerated the work on designing climate model simulation experiments explicitly for information to support decision-makers in the insurance sector and in policy-making and in constructing "translators" to allow interactive exploration of various climate choices. Her follow-on work with DECC on the UK Global Calculator is a good example of how complex information from climate models may be "interpreted" in a dynamic and useful manner.

Given that climate projection is an extrapolation problem, we can never really know how good our climate models are in the same way that we can know the limitations of information from today's weather models. We can, however, probe the limits of their fidelity in the past using tools based upon the dynamical systems notion of "shadowing". In order to increase the economic relevance of climate modelling, the feasibility of using shadowing techniques simulations of high dimensional systems was analysed. Progress here has been slow, as the work is as challenging as it is potentially useful. Hailiang Du has now left LSE for a research position at the University of Chicago where an NSF-funded centre for decision-making has created a research stream to extend the ambitious goals of the Munich Re Programme and determine the ability of GCMs to shadow reality.

ii) Quantification of climate model skill in seasonal forecasting of economic relevant indices

The Munich Re Programme helped generate significant advances in understanding the skill and relevance of large simulation forecasting with General Circulation Models (GCM) to decision-making. On decadal time scales we have learned that current GCM forecast systems sometimes add very little to empirical models even in terms of global mean temperature. This severely limits their value in determining the implications of climate change for the insurance sector (Suckling and Smith 2013, MRe TP19; Suckling and Smith 2013). That said, we have for the first time shown that changing the design of the forecast system (lengthening the forecast-outcome archive, improving the ensemble design and interpretation, and so on) allows even older climate simulations to add significant value to empirical benchmark forecasts (Smith, Suckling et al., in press, 2015). The key insights achieved here relate to the importance of understanding the strengths and weaknesses of projections currently available.

Seasonal forecasts produced in the projects DEMETER[3] and ENSEMBLES[4] with state-of-the-art climate models were analysed in order to quantify their skill of forecasting the El Niño phenomenon as well as the sea surface temperature in the hurricane genesis region of the Atlantic. This was contrasted by analysing the skill of statistical models to forecast these indices. It was determined that the ENSEMBLES models provide significant information for several months both in the Pacific Niño 3 region and in the Atlantic Main Development Region. This work appeared under the title 'Probabilistic skill in ensemble seasonal forecasts' firstly as a technical paper and subsequently in the Quarterly Journal of the Royal Meteorological Society (Du, Smith et al. 2014, MRe TP20; Smith, Du et al. 2014). A poster on this work, entitled 'Skill of Ensemble Seasonal Probabilistic Forecast' (Du, Niehörster et al. 2009), was presented at the ENSEMBLES final symposium in Exeter, November 2009.

Exploration of the efficacy of combining information from purely empirical (simple) models with GCM simulations is ongoing under Smith, working alongside Du (now at University of Chicago), and Thompson in LSE CATS. This work is being extended by Smith and Suckling with a view to improving the utility of probability forecasts issued by the Bank of England. Related work was also conducted on quantifying uncertainties in key decision-relevant climate parameters at a regional level based on large-ensemble climate experiments and exploring implications for decision-making. A working paper entitled 'Probabilistic regional and seasonal predictions of twenty-first century temperature and precipitation' was produced in August 2010 (Stainforth 2010), and work in this area continues.

[3] http://oceanrep.geomar.de/4693/1/559_Palmer_2004_DevelopmentOfAEuropeanMultimodel_Artzeit_pubid11720.pdf

[4] http://ensembles-eu.metoffice.com/index.html

What do we really know about US Hurricane Risk in 2020?

Nicola Ranger and Falk Niehoerster

The Grantham Research Institute on Climate Change and the Environment & the Centre for the Analysis of Time Series
London School of Economics and Political Science, UK

How will the frequency and intensity of Atlantic tropical cyclones change, on average, over the next 10 years and what does this mean for insured losses? These are important questions for long-term business strategy. But, even for the most fundamental metrics, such as the frequency of landfalling hurricanes, still even the most recent state-of-the-art studies give contradictory results. How can the insurance industry prepare for climate change given this level of uncertainty?

This study, is one part of a larger body of research at the *Grantham Research Institute, LSE*, that aims to help to address this question.

Objectives

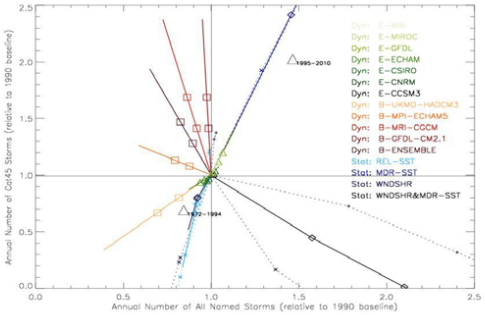
The goal of this study is to **produce a set of robust risk scenarios that can be used by the insurance industry to inform long-term risk management and business strategies.** On-going work explores implications for decisions today.

We reprocess and analyse **three groups of state-of-the art projections**: two sets based on leading dynamical modelling approaches (Emanuel et al. 2008 and Bender et al. 2010) and one set based on simple statistical models. From these projections, we develop a set of hazard scenarios for the 2020s, 2040s and 2090s.

Hazard scenarios are used to tune a **simple coupled climate-catastrophe model** to generate a set of **risk scenarios for wind-related hurricane losses across one case study US state - Florida**.

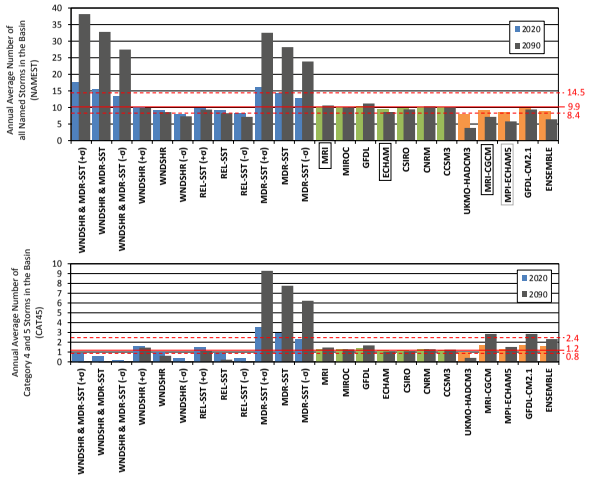
We **assess the robustness of these scenarios and explore how they should be interpreted within a decision making process**. Finally, we consider the implied priorities for future climate research to better inform decisions.

Fig 1. Projected changes in All Named Storms versus CAT45 Storms from Several Recent Modelling Studies *(relative to 1990)*



Notes on Fig. 1: All projections start at the baseline (at 1,1) and evolve to the 2090 estimate, with the squares or triangles marking the 2020 and 2040 projections. Scenarios representing the mean ± 1 standard deviation predictions are indicated by the dotted line.

Fig 2: Projections of the Average Annual Number of All Named Storms (top) and Category 4 and 5 Storms (bottom) in the Basin



Notes on Fig. 2: The blue bars are the Statistical Model scenarios and the green and orange bars the scenarios from Emanuel et al. 2008 and Bender et al. 2010, respectively, in 2020. Three scenarios are shown for each Statistical Model; these are projections based on the ensemble mean of the 21 individual GCMs and the ±1 standard deviation. The dark shaded bars are the equivalent projections for 2090. The red lines show benchmark points: the solid line is the 1990 baseline level and the two dashed lines are the average rates over the recent active (defined as 1995-2010) and inactive (defined as 1972-1994) periods.

Hazard Scenarios

- The majority of scenarios show **either little change or a reduction in the total number of Named Storms** in the Atlantic Basin (Figs 1 and 2). The findings are more mixed for the number of intense storms; **nine out of the twelve Dynamical Model scenarios show an increase in the number of Category 4 and 5 Storms and only one of the Statistical Models**.
- The diversity of projections is partly driven by differences in predictions of future Atlantic windshear

How should these scenarios be interpreted?

- **Scenarios will be most useful in stress testing strategies**. We can not exclude the possibility that the actual changes in risk experienced will be outside of the range given in this study.
- **Each scenario should be treated with equal confidence**. Future hazard and risk is 'deeply' uncertain - scenarios can not be excluded, or meaningfully weighted based on current evidence.
- **Uncertainty must be fully accounted for in decisions**: the use of hazard projections from climate models, without an appropriate treatment of uncertainty, could lead to poor risk management decisions and unnecessary risks.

What are the implications for US Hurricane Risk and Insured Losses? A Case Study on Florida

A simplified catastrophe risk model, based on data provided by Risk Management Solutions Inc., is tuned to estimate the wind-related residential property losses in Florida for each hazard scenario. We conclude that:

- Natural variability is likely to remain the main driver of the level and volatility of US hurricane risk over the coming decade (Fig. 2).
- The combined effects of climate change and natural variability could create **notably higher levels of risk and insured losses within the decade** (Figs. 2 and 3).
- The volatility of loss is highly sensitive to climate changes (Fig 4). **Even in the 2020s, we may see significant changes in the probability of multi-billion USD losses** (even while changes in average annual losses are more moderate). For example, in the highest scenario, the 1-in-250 year loss increases by 50%.
- Current science gives little clarity over long-term risks. **All else being equal, wind-related losses could halve by the 2090s, or increase four-fold due to climate change** (Fig. 3).
- **The scale of the risks and uncertainties calls for a more forward-looking and robust approach to risk management.** It is foolish to believe that science can provide a 'perfect' prediction of risk on decadal timescales. Risk management must work with the uncertainty.

Fig 3. Average Annual Loss: Wind-Related Hurricane Losses in Florida *(expressed as a ratio relative to the 1990 baseline)*

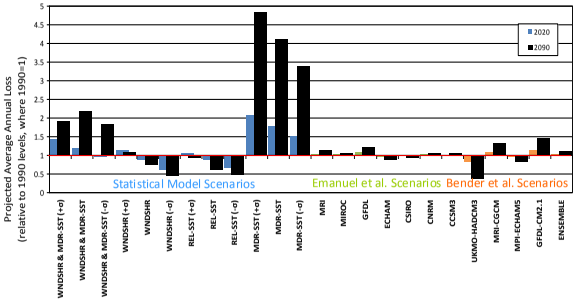
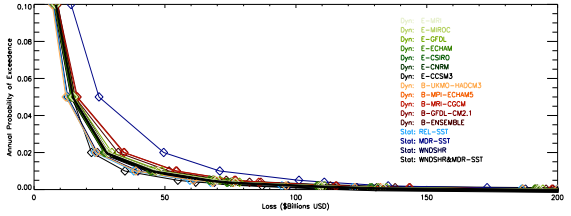


Fig 4. Exceedance Probability Curves for 2020: Wind-Related Hurricane Losses in Florida *(black line represents the 1990 level)*



What are the priorities for climate science to better inform the insurance industry?

- **Understanding of the role of natural variability** (versus manmade climate change) in driving current and past variability in tropical cyclone activity and the climate of the Atlantic.
- **Assessing the adequacy and robustness of current climate models and forecasting techniques**.
- **Better quantifying the range of plausible future risk,** rather than focussing on producing a set of 'best-guesses' based on the latest 'state-of-the-art' modelling technique.
- **Narrowing the range of uncertainty** by tackling the key sources of those uncertainties, for example, Atlantic windshear.
- **Improved monitoring networks** to identify early signals of changes in tropical cyclones, and the climate conditions that drive them.

Acknowledgements
We are grateful to colleagues who provided helpful discussions toward the development of this paper, including: Simon Dietz, Jan Eichner, Eberhard Faust, Kerry Emanuel, Patricia Grossi, Iris Grossmann, Greg Holland, Thomas Knutson, Howard Kunreuther, Erwann Michel-Kerjan, Robert Muir-Wood, Leonard Smith, David Stainforth, Pantea Vaziri, Gabriel Vecchi and Michael Young. We are particularly grateful to Risk Management Solutions (RMS) Inc. for sharing loss information for Florida and to Professor Emanuel for supplying projections from Emanuel et al. (2008). Drs Niehörster and Ranger's research was supported by the Centre for Climate Change Economics and Policy, funded by the Economic and Social Research Council and Munich Re.

The paper is entitled "**Deep Uncertainty in Long-term Hurricane Risk: scenario generation and implications for future climate experiments**" and can be downloaded from the CCCEP website (working paper version) or Global Environment Change (full version) Vol. 22 (2012) pp. 703–712, http://dx.doi.org/10.1016/j.gloenvcha.2012.03.009

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The work with these forecasts has led to new insights, both on the use of ensemble forecasts and on their evaluation. Further research laid the foundation for a paper on forecast skill scores, clarifying strengths and weaknesses to show which are of most use in applications including the insurance sector (Smith, Suckling et al., in press). A spin-off from this research was a further paper outlining a new measure for the internal consistency of probability forecasts focused on parameter selection: 'Parameter estimation using ignorance' (Du and Smith 2012). This new measure aids discussions of the value of forecasting to the insurance sector more generally, in addition to particular applications determining the economic relevance of climate modelling.

iii) Developing long-term hurricane risk scenarios and exploring the implications of adaptation, disaster risk management and insurance

Developing a better understanding of long-term hurricane risk was a central aspect of the programme. Nicola Ranger developed a number of case studies to explore the impacts of climate change and other drivers on disaster risk and the economic benefits of risk reduction and insurance. As part of the Programme, Dr Ranger contributed to three academic papers based on earlier analyses funded by the OECD. These all concern climate change and flood risks in port cities and were published in the journal *Climatic Change* in 2011 (Hallegatte, Ranger et al. 2011; Hanson, Nicholls et al. 2011; Ranger, Hallegatte et al. 2011)

Ranger and Niehörster also began new analyses towards developing long-term hurricane risk scenarios and exploring the implications for insurance, disaster risk management and adaptation. The aim of this project has been to develop robust long-term scenarios of Atlantic basin hurricane hazard and use this to explore the implications for insurance and adaptation in Florida, including new types of financial products and public-private systems. Professor Howard Kunreuther (Visiting Professor on the Munich Re Programme) facilitated collaboration with his team at the Wharton School to explore the implications for insurance systems in Florida and linkages with adaptation. This included a joint project exploring the feasibility of multi-year insurance contracts.

Nicola Ranger and Antony Millner, together with Ana Lopez, developed a number of smaller case studies to explore the implications of uncertainty in projections for the economics of adaptation and decision-making. These include case studies related to UK Storm surge, the UK water sector and St Lucia wind risks.

In May 2010, LSE held an academic workshop with the Wharton Risk Centre to discuss a framework for moving from the risk scenarios (above) to modelling the implications for insurance and the role of financial products in managing risks, as well as modelling the economics of disaster risk management in a changing climate, building on Wharton expertise in this area. The relationship of the relative influence of long-term anthropogenic climate change and short-term natural climate variability in the near-term (up to 2020) was considered. The outcomes of this workshop were shared with Munich Re and then presented in a technical paper, entitled 'Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments' (Ranger and Niehörster 2011, MRe TP8) which was further developed and published in the journal *Global Environmental Change* (Ranger and Niehörster 2012). A poster based on this paper, entitled 'What do we really know about US Hurricane Risk in 2020?' (Ranger and Niehörster 2012) was presented at the Lloyd's Science of Risk Prize event, 29 November 2012. The outcomes of the research were also used in the collaborative project with the Wharton School, an output of Howard Kunreuther's Munich Re Visiting Professor appointment during 2009-10. A follow-on paper was published in *Climatic Change* in 2013 entitled: 'Insuring future climate catastrophes' analysing insurance pricing and capacity in Florida under various scenarios of climate change and adaptation measures (Kunreuther, Michel-Kerjan et al. 2013).

Distinguishing between Skill and Value in Hurricane Forecasting

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[2] Oxford Centre for Industrial and Applied Mathematics, Oxford University, U.K.

Identifying skill with small datasets

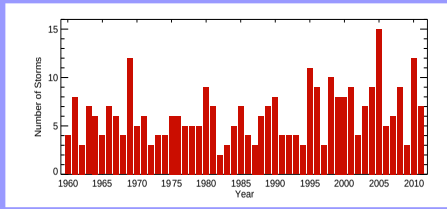

Fig 1: HURDAT data: Number of Atlantic Basin hurricanes from 1960 to 2011 [1]

Establishing out-of-sample skill in an annual hurricane forecasting system is unrealistic on less than decadal timescales because of the slow rate new verification information is gathered. The range of uncertainty in a sample of forecast model evaluations increases with decreasing time duration, and thus genuine skill cannot be reliably ascribed to a forecast model which is verified with few data.

If demonstrating genuine skill with limited datasets is not possible, then should a decision maker wait for proof of skill in a model before using it? Might they be forgoing the opportunity to benefit from forecast information whilst seeking statistical reassurance? The expectation may be that forecast value is similarly indemonstrable in the short term so here we address the following questions: 1) what would be the cost of waiting to prove skill for a decision-maker? And 2) how long does it actually take to prove skill?

Profit and Proof: What is the cost of waiting?

If a decision-maker believes in the skill of their model, they might rationally choose to begin implementing it and will begin to receive value before those who choose to delay. The chance to profit before proving can be conceptualised in the context of what is called the "Swindled Statistician Scam" (see Box 1).

Consider a toy hurricane system in which the mean number of storms follows a 24 year cycle, while the number of storms in any given year is determined at random.

To illustrate that structural model error does not preclude value to a decision-maker, consider an imperfect model of that system with the same cycle period, but where the probability distribution function used is incorrect in shape, not merely in parameter.

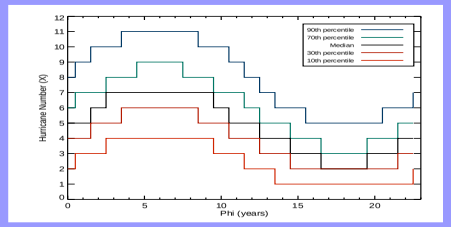

Fig 2: Contours of the cumulative distribution function showing how the system probability distribution changes as a function of the phase of the 24 year cycle. Note that occurrences of higher hurricane numbers are more likely in years with phase 5, 6 or 7 than those with phase 17, 18 or 19.

This model will then be used in games of Hurricane Roulette, where the imperfect (but time dependent) model probabilities are used to place bets against odds set by a house using the correct (but not time dependent) climatological probability distribution. The results can be reported in either bits of information or as an expected annual return (see [2]).

The system is defined as a Poisson process, $X \sim Pois(\lambda(t))$, where X is the number of hurricanes in a given year and has a sinusoidal time-dependent mean determined by the equation $\lambda(t) = 2.5sin(2\pi t/T + \phi) + 5.0$. The probability distribution of the system over each of the 24 phases is illustrated in Figs. 2 and 3 which describe the cumulative distribution function for all phases, and the probability density function corresponding to phase year 12.

Box 1. The Swindled Statistician Scam: A wily underwriter approaches a non-Floridian statistician with a business deal: the statistician will produce a probability forecast of the number of destructive events in the coming year, the underwriter will use her market contacts to bet on the forecast. As soon as the statistician can prove the forecast really does have skill, the underwriter will pay royalties. Will this leave the statistician swindled out of a small fortune?

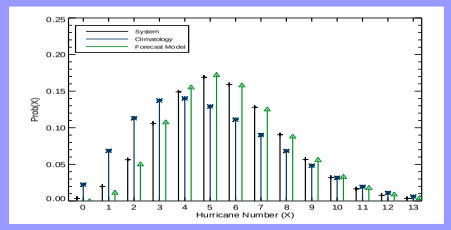

Fig 3: This figure shows the probability distributions for the system (black), and an imperfect model (green) for phase year 12 of the 24 year cycle. The climatological distribution (computed over all values of phase) is also shown in blue.

Hurricane Roulette proceeds as follows: at the start of each annual hurricane season a decision-maker is offered odds defined by the climatology PDF (equally-weighted sum of the 24 system phase PDFs). She then places her bet by distributing all of her current wealth (based on the Kelly betting strategy [3]) according to the forecast probabilities assigned to each possible hurricane number outcome (X). The actual outcome determines the pay-off on each annual bet.

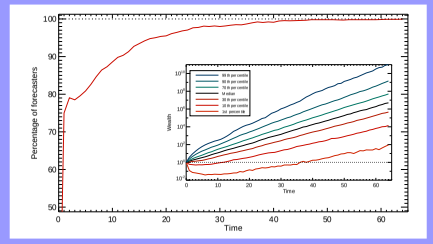

Fig 4: Percentage of 2048 decision-makers expected to make a profit with time when betting against climatology using the imperfect model in a game of hurricane roulette (main plot), and frequency distribution of decision-makers' wealth with time (inset plot).

The results of a sample of 2048 realisations (or worlds) of roulette demonstrate that the decision-maker would be very likely to have made a non-trivial profit even before two system cycles have completed (NB: the phase, ϕ, is selected at random for each realisation to avoid bias). This is evident in Fig. 4 which shows the percentage of decision-makers who are likely to profit and frequency distribution of their wealth over time.

How long does it take to prove skill?

To complete the assessment of the cost of waiting for the statistician the forecasts of the 2048 decision-makers are evaluated with the ignorance skill score [4]. Figure 5 shows the distribution of the decision-makers' forecast skill - measured by the ignorance of their forecasts relative to climatology. In this case, the minimum time required for over 99% of the decision-makers to prove skill is at least 2^7 (128) years; much longer than the time required to profit by betting on the forecasts.

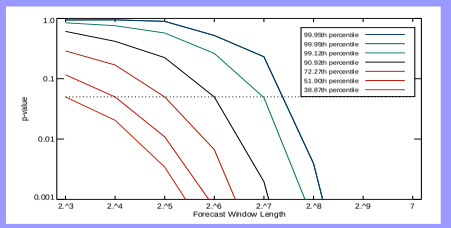

Fig 5: Distribution of forecast skill p-values (H1: $IGN < 0$) of 2048 decision-makers; 99.12% have established statistically significant skill ($p \leq 0.05$) by 128 years. NB: this percentage of d-ms had already made a nontrivial profit by 40 years (see Fig. 4).

Box 2. Discussion Points

- Establishing forecast skill on systems with long time scales poses a challenge
- A decision-maker may accept risk in order to gain profit, rather than first wait to establish statistical confidence in the forecast
- Ways of benefiting from an imperfect model can be demonstrated through the use of games like Hurricane Roulette

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[1] National Oceanic and Atmospheric Administration. Atlantic hurricane database re-analysis project. http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html.

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[3] J. L. Kelly. A new interpretation of information rate. Bell Systems Tech., 35:917-926, 1956.

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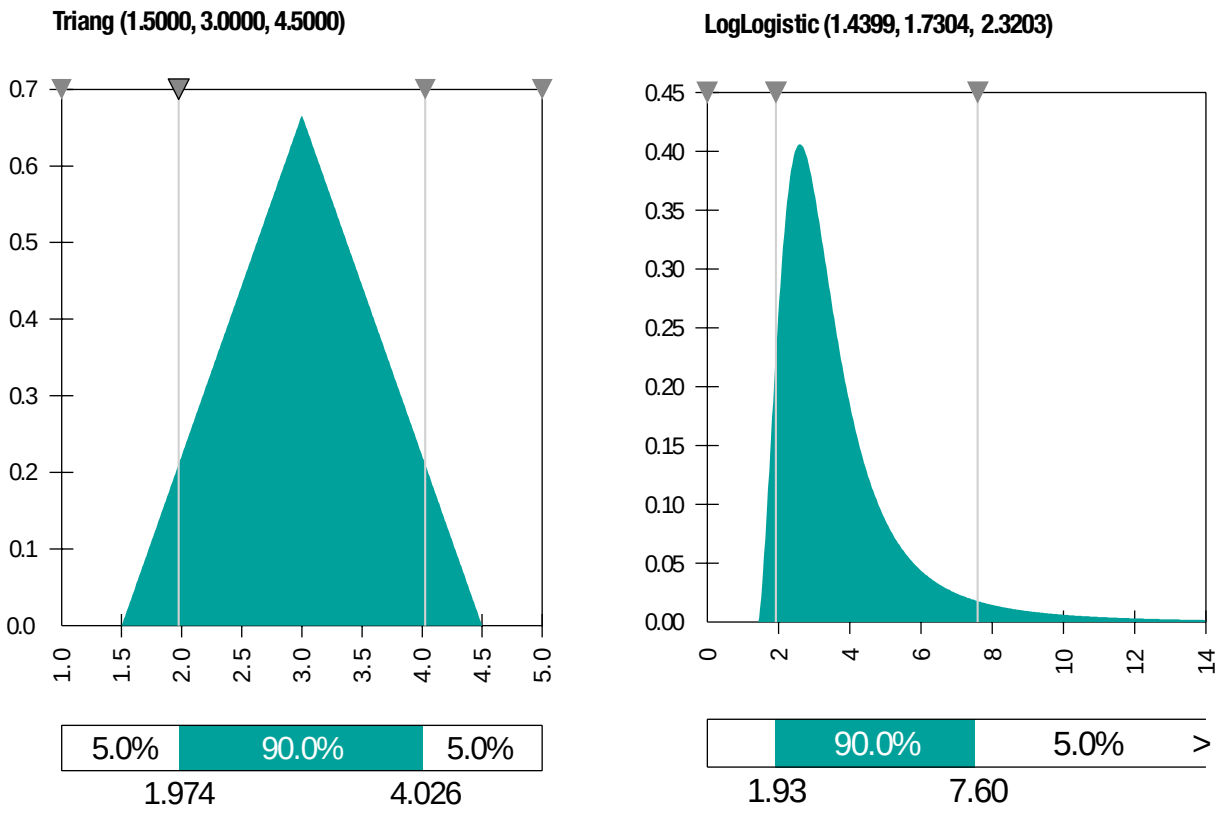
iv) Decision-making under uncertainty, adaptation planning, and greenhouse gas mitigation policy

Here the focus was on the interplay between uncertainties in climate change information and policy decisions and aims to develop formal frameworks for decision-making under uncertainty. Simon Dietz produced a technical paper on the economics of high-impact, low-likelihood events, 'High impact, low probability? An empirical analysis of risk in the economics of climate change' (Dietz 2009, MRe TP2). This paper conducted the first empirical investigation of Martin Weitzman's now famous "Dismal Theorem" about the results of cost-benefit analysis of highly uncertain climate policies, finding that estimates of the overall economic cost of climate change do strongly depend on "fat tails", but that discounting still matters. The paper was subsequently published in *Climatic Change* in 2011 (Dietz 2011).

Millner and Dietz, together with Geoffrey Heal (Columbia Business School) produced an approach for incorporating inter-model differences in projections into decisions about greenhouse gas (GHG) mitigation actions.

Climate sensitivities compared: Stern Review on the left, Stainforth et al. on the right.



From Dietz, S. (2011). "High impact, low probability? An empirical analysis of risk in the economics of climate change." *Climatic Change* 108(3): 519-541

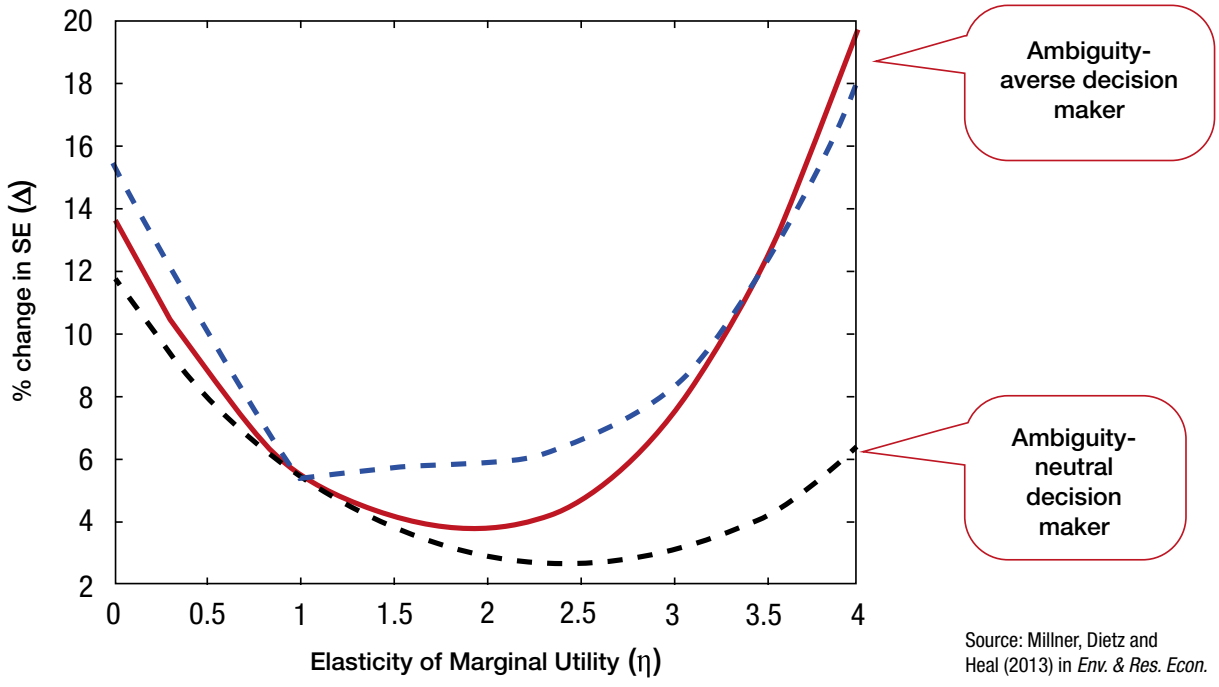
This work on the implications of ambiguity and precaution for international climate-change policy was published as a technical paper entitled 'Ambiguity and Climate Policy' (Millner, A., Dietz, S. et al. 2010, MRe TP4) and was included in the prestigious working paper series of the US National Bureau of Economic Research (NBER). Their paper shows that moving from a standard risk-based economic evaluation to one that recognises ambiguity, in the sense of uncertain estimates of probability, is likely to increase the net benefits of cutting carbon emissions, and they provide some evidence using William Nordhaus' famous DICE model to show that this "ambiguity premium" could be very large indeed, if the damages from runaway global warming are expected to be severe. The paper attracted considerable academic attention, and was subsequently published in 2013 as "Scientific Ambiguity and Climate Policy" in the journal *Environmental and Resource Economics* (Millner, Dietz et al. 2013). Millner, Dietz and Heal presented the paper at several important international conferences, including the inaugural conference of the American Association of Environmental and Resource Economists in Seattle in June 2011, and the 18th annual conference of the European Association of Environmental and Resource Economists in Rome, also in June 2011.

Relating to this work, Millner, Calel, Stainforth and McKerron produced a new research paper entitled 'Do probabilistic expert elicitations capture scientists' uncertainty about climate change?' (Millner, Calel et al. 2013). The paper extends the analysis of ambiguity developed in Millner's previous work with Dietz and Heal, looking to investigate the confidence that climate scientists place in their own model-based forecasts of future climate. They are able to identify the existence, in the minds of experts in climate science, of ambiguity about the probabilities of future temperature change, which underlines the importance of work in this area.

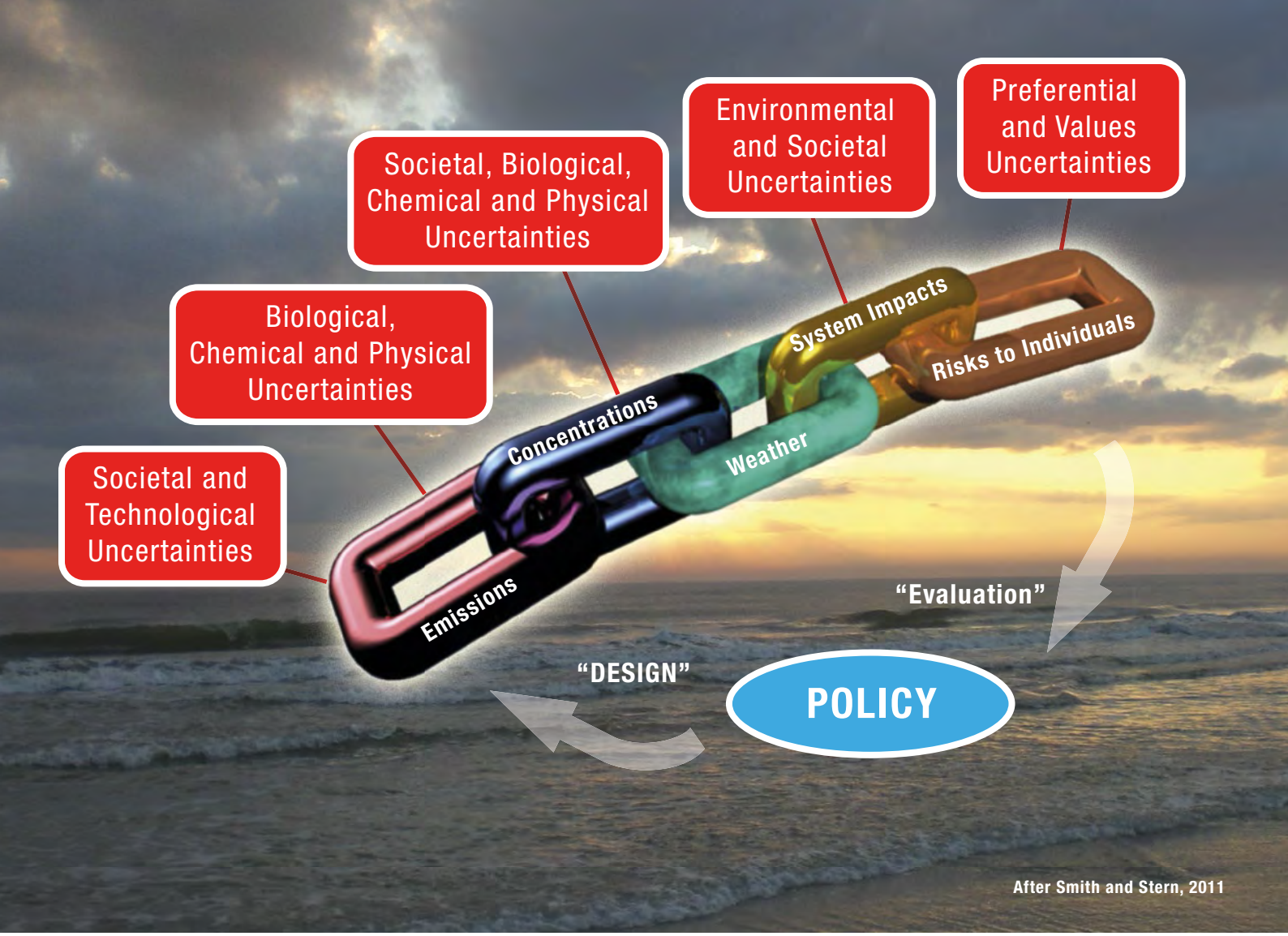
Seamus Bradley (working with Roman Frigg and Leonard Smith) produced a technical paper entitled 'Scientific Uncertainty: A User's Guide' (Bradley 2011, MRe TP9). The paper is a conceptual and philosophical analysis of the myriad ways uncertainty can enter into a scientific study. Methods for dealing with the uncertainties are also looked at. The aim is to distinguish different sorts of error in terms of severity, and in terms of how they might be reduced and mitigated against. This work was central to Bradley's PhD thesis, 'Scientific uncertainty and decision-making' (Bradley 2012).

Simon Dietz and Oliver Walker produced a major new research paper, 'A representation result for choice under conscious unawareness' (Walker and Dietz 2011, MRe

Ambiguity aversion can significantly increase the value of emissions cuts



Source: Millner, Dietz and Heal (2013) in *Env. & Res. Econ.*



TP10), which focused on the problem of decision-making when the decision-maker is worried that her knowledge about future scenarios is incomplete: ie, that there may exist scenarios about which she is currently unaware (called "conscious unawareness"). Using tractable concepts in the economics of risk and uncertainty, Dietz and Walker are able to derive a workable formula, for example for investment decisions, which takes into account the possibility that the future is incompletely described. They show how these ideas could be applied to climate change, but in fact the work is of more general relevance, and could in the future be applied to problems in, for example, the financial services sector, where incomplete knowledge about the performance of future investments is a major concern.

Dietz and Walker also developed a paper on the application of ambiguity theory to insurance and reinsurance pricing. They aim to develop a pricing formula for (re)insurance when there are competing estimates of the probability of losses, as is the case in eg, hurricane insurance. There is evidence to suggest that, when faced with writing policies for ambiguous losses, insurers increase their premium prices or decline to offer cover, but there is also evidence to suggest that the upward adjustments lack a theoretical basis. This work was published first as a technical paper entitled 'Ambiguity and insurance: Robust capital requirements and premiums' (Walker and Dietz 2012, MRe TP16) and is now in revise and re-submit mode for the *Journal of Risk and Insurance.* The paper has attracted interest from the insurance industry, including within the catastrophe modelling community. Follow-on work is looking to apply the fundamental theories put forward in the paper to data from industry models on predicted insured losses from hurricanes in the Southeastern USA.

Ranger, Millner, Dietz and others provided a wide-ranging report to the Committee on Climate Change's Adaptation Sub-Committee entitled *Adaptation in the UK: a Decision-Making Process* (Ranger, Millner et al. 2010). This paper explored the role of decision-theoretic techniques in making adaptation decisions under uncertainty. The findings provide guidance on how to

interpret uncertain climate model information in making decisions on short and long timescales, relevant to industry and policy. This work has also been considered in a developing country context. Discussions were held with Phillip Hasenmueller (Munich Re) on the potential for translating this research to an insurance perspective.

Nicola Ranger, in collaboration with Bob Ward, Alex Bowen and Nick Stern, completed an analysis of the rationale for a 2°C long-term goal for climate policy, and its scientific and economic feasibility. This was published as an insurance industry brief entitled 'Aiming for a 2°C goal: What does it mean for the insurance industry?' (Ranger and Ward 2010, MRe IB2). This was launched at the Munich Re Programme roundtable event held in May 2010 with representatives of the insurance industry, and it received much media attention.

Exploring the Fundamental Foundations of Forecasting with Laplace's Demon(s)

Frigg, Bradley, Du and Smith produced a technical paper entitled 'Laplace's Demon and climate change' (Frigg, Bradley et al. 2013, MRe TP17) which extended the consideration of the requirements for making probability forecasts adequate for quantitative interpretation as probabilities in the insurance sector. This work was the foundational piece of work on which five subsequent journal and book publications are based: two appeared in the journal *Philosophy of Science* – 'The Myopia of Imperfect Climate Models: The Case of UKCP09' (Frigg, Smith et al. 2013) and 'Laplace's Demon and the Adventures of His Apprentices' (Frigg, Bradley et al. 2014); a chapter entitled 'Model Error and Ensemble Forecasting: A Cautionary Tale' (Bradley, Frigg et al. 2014); another chapter entitled 'Probabilistic Forecasting: Why Model Imperfection Is a Poison Pill' (Frigg, Bradley et al. 2013); and a new paper 'An Assessment of the Foundational Assumptions in High-Resolution Climate Projections: The Case of UKCP09' in the journal Synthese (Frigg, Smith et al, 2015). These papers have started to make an impact in the field. They were discussed extensively at two recent high-profile conferences, where entire talks were dedicated to them: "Knowledge and Models in Climate Science: Philosophical, Historical, and Scientific Perspectives" at the Rotman Institute of the University of Western Ontario (October 2014) and "Biennial Meeting of the Philosophy of Science Association" in Chicago (November 2014). Written versions of these discussions are due to appear this year, which will generate further interest in them. One of the papers has also been submitted to the consultation for "Climate Change Risk Assessment 2017" and we hope that it will have an impact on how the next round of assessment is carried out.

Follow-on research

The UK Department for Energy and Climate Change (DECC) has funded follow-on work by Thompson and Smith on interpreting and visualising the output of climate models for a web tool allowing users to explore possible future pathways. The aim is to present comprehensive and coherent real-world results to decision-makers via the DECC Global Calculator.[5] Discussions with decision-makers from DECC, including DECC's Chief Scientific Advisor David Mackay, and other members of the Climate KIC team were deeply informed by work done under the Munich Re Programme. The importance of clarity in the translation of scientific information, and in the outputs being actionable and the caveats being transparent, were each driven home during this work, which was launched in January 2015.[6]

Smith and Thompson are also working on a paper on assessment of the CMIP5 decadal forecast ensembles, demonstrating our statistical methodology, and a paper about the wider importance of clarifying the properties of the 34 per cent of unspecified probability mass in the IPCC judgments about future temperature change. This paper should appear in late 2015.

[5] www.gov.uk/government/publications/the-global-calculator/the-global-calculator

[6] The DECC press release can be viewed at www.gov.uk/government/news/world-can-cut-carbon-emissions-and-live-well

C) Normalising and interpreting trends in disaster losses using the Munich Re NatCatService

This research stream ran for the first three years of the Programme, until the summer of 2011. It was led by Professor Eric Neumayer with research assistant Fabian Barthel. The work comprised the development of a new normalisation methodology, advancing existing methodologies in the literature. Neumayer and Barthel worked closely with Munich Re colleagues, in particular Eberhard Faust and Jan Eichner, to refine the new methodology as well as support the development of Munich Re's own disaster loss analyses.

In October 2009, Nicola Ranger and Fabian Barthel, in collaboration with Munich Re colleagues, organised and held a workshop in Munich to discuss normalisation approaches, which was attended by 23 academic and insurance industry researchers. Neumayer and Barthel's methodology and preliminary findings were also presented to Munich Re colleagues at a workshop in November 2009.

In 2010 Neumayer and Barthel produced two technical papers: 'A Trend Analysis of Normalized Insured Economic Damage from Natural Disasters' (Neumayer and Barthel 2010, MRe TP5), and 'Normalizing Economic Loss from Natural Disasters: A Global Analysis' (Neumayer and Barthel 2010, MRe TP6). Bob Ward and Nicola Ranger produced an Industry Brief on this work, entitled 'Trends in Economic and Insured Losses from Weather-Related Events: A new analysis' (Ward and Ranger 2010, MRe IB1). The papers and industry brief were presented at an industry symposium entitled 'Quantification and interpretation of trends in economic and insured natcat losses: How does climate change affect the frequency and severity of natural disasters?', held in Munich in November that year (the event was attached to the annual re-insurance Chief Risk Officers event). This was followed a week later by a science symposium, 'The Study of Economic Loss from Natural Disasters', held in London. (For details of these events see Appendix 5.) The economic loss paper was subsequently published in the journal *Global Environmental Change* in 2011 (Neumayer and Barthel 2011). The insured loss paper was published in the journal *Climate Change* in 2012 (Barthel and Neumayer 2012), and was also featured in *Nature*.

Follow-on work continues today by Leonard Smith and LSE graduate student Trevor Maynard contrasting variations in the definition of what constitutes a "trend" and how this definition in turn impacts detection methodologies – work inspired directly by Neumayer and Barthel's 2010 paper; it should appear late in 2015.

In the last year of this research stream, Neumayer and Barthel, in collaboration with Thomas Plümper at the University of Essex, developed the research further by exploring the relationship between disaster propensity and the vulnerability to disasters. They analyse political economy reasons why economic damage from natural hazards varies strongly across countries. Damage can sometimes be prevented and always mitigated. Private individuals, however, tend to under-invest in disaster preparedness and mitigation measures due to collective action, information asymmetry and myopic behaviour problems. Governments, which can in principle correct these market failures, also face incentives to under-invest in costly disaster preparedness policies and damage mitigation regulations. Yet, disaster damage varies greatly across countries. They argue that the larger a country's

propensity to experience frequent and strong natural hazards, the more rational actors will invest in preparing for disasters and mitigating damage. Accordingly, economic loss from an actually occurring disaster will be smaller the larger a country's disaster propensity – holding everything else equal, such as hazard magnitude, the country's total wealth and per capita income. Even if governments implement effective mitigation measures, damage is not entirely preventable and smaller losses tend to be random. A higher disaster propensity will therefore have a more pronounced negative effect on predicted damage at the top end of the disaster damage distribution than at the bottom end. Empirical support for these predictions is found in a quantile regression analysis of economic loss from the three disaster types causing the vast majority of damage worldwide: earthquakes, floods and tropical cyclones. This research by Neumayer, Plümper and Barthel was subsequently published in the paper 'The Political Economy of Natural Disaster Damage', in the journal *Global Environmental Change* (Neumayer, Plümper et al. 2014).

Annual frequency count of geophysical and weather-related disasters

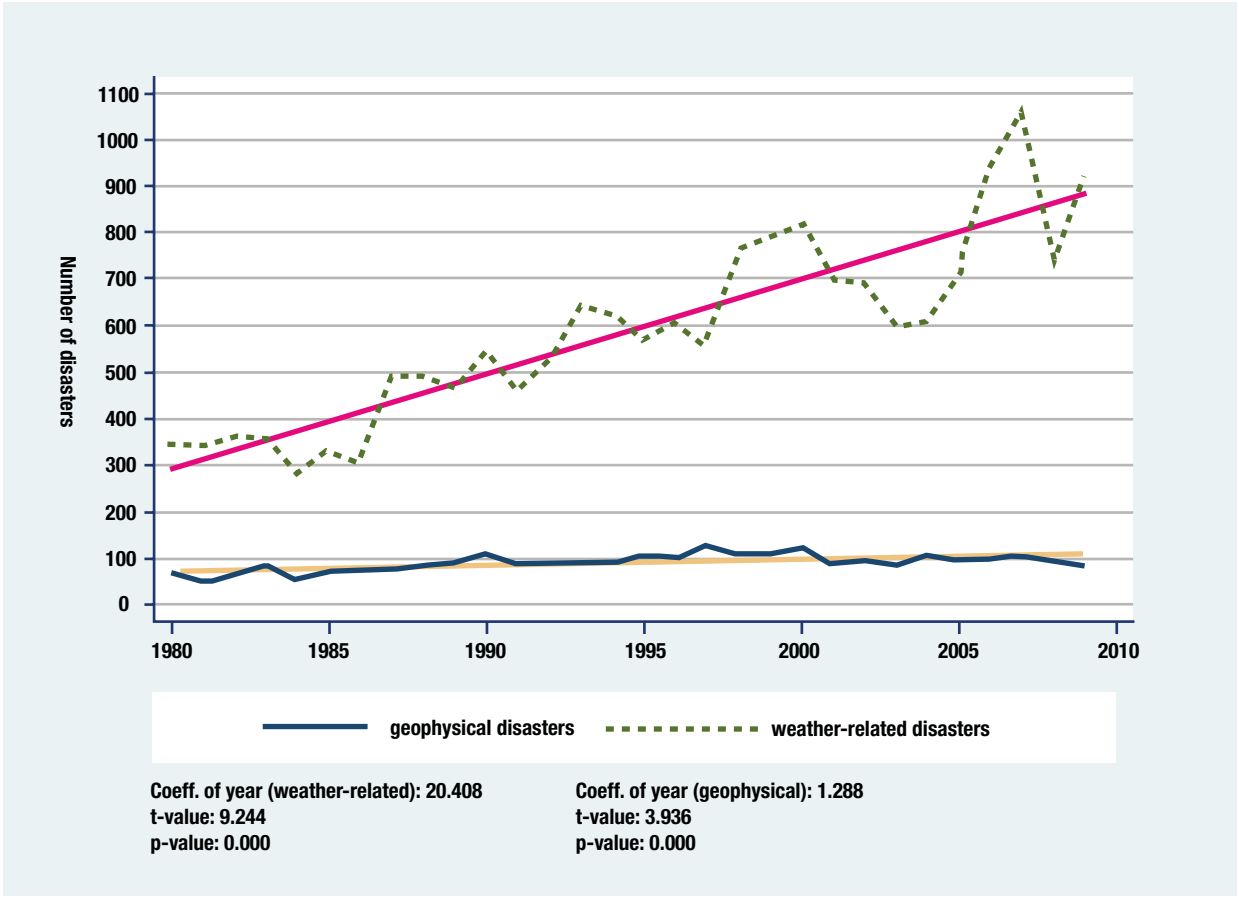


Figure 8 from Neumayer, E. and F. Barthel (2011) "Normalizing Economic Loss from Natural Disasters: A Global Analysis" *Global Environmental Change* 21(1): 13-24

D) Quantitative applied climate economics

Work under this stream was led by Leonard Smith, together with Nicola Ranger, Falk Niehörster and PhD student Alex Jarman. The research fell broadly into two sub-projects: one focusing on metrics reflecting the effectiveness of forecasts for the insurance sector, the second on the fidelity of the seasonal forecasts themselves.

i) Developing economic metrics for evaluating the effectiveness of near-term forecasts into the insurance sector

Interviews were conducted with members of the insurance industry (RMS, Willis and Lloyd's) to better understand how weather forecasts are perceived by the industry and how they would measure the usefulness of a forecast from an underwriting perspective. Jarman initially undertook a literature review on traditional and economic skill metrics, and then began work on the development of economic skill metrics, using both insurance loss data and simulated hurricane data (eg, the 'Hurricane Roulette'), for evaluating the effectiveness of near-term forecasts for the insurance sector. He also compared a range of statistical skill metrics using dummy forecasts. He then embarked upon the process of building a model to evaluate traditional versus economic skill metrics for a simple insurance case study: Atlantic hurricane risk.

ii) Mapping the skill in forecasting hurricane-relevant climate parameters on near-term (eg, seasonal to decadal) timescales.

Falk Niehörster and Leonard Smith worked on the analysis and mapping of the skill in forecasting hurricane-relevant climate parameters on near-term (eg, seasonal to decadal) timescales, such as Nino3.4, MDR SSTs, and Global Mean Temperature, and also the interpretation of climate modelling experiments. The approach has been used to assess the predictability of Nino3.4 from the ENSEMBLES dataset and its linkages to predicting Atlantic basin hurricane characteristics (frequency and intensity).

Jarman, together with Smith, developed a methodology to disentangle the difference in proving a model has skill and rational use of the model in expectation of profit. This clarification indicates that some of the claims of Roger Pielke Jr do not, in fact, reduce the value of hurricane forecasts as drastically as suggested.
Two posters on this work were produced: 'Small-number statistics, Common Sense, and Profit: Challenges and Non-challenges for Hurricane Forecasting' (Jarman and Smith 2011) presented at the EQUIP conference in January 2011, which uses a methodology based on the concept of "Weather Roulette" to demonstrate there are imperfect forecast systems which almost certainly have nontrivial value long before one might establish that their skill was statistically significant; and 'All models are wrong: Which are worth paying to look at? A case study for Global Mean Temperature' (Suckling and Smith 2011) presented at the "All Models are Wrong" conference in Groningen in March 2011, in which they show that large simulation models (GCMs) are expensive to construct and interpret, while the statistical assumptions underlying them assume "small" data-based models are more transparent. Models which "capture the physics" are expected to outperform data-based models in extrapolation; does today's "best available" simulation model do so? A framework is presented to justify the time and cost of using complicated models by demonstrating in-sample skill (ideally value) as a function of lead time. (Details of both the events and the posters can be found in Appendix 1 and 5.)

Small-number statistics, Common Sense, and Profit: Challenges and Non-challenges for Hurricane Forecasting

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Abstract

When making only one forecast per year, or per decade, it can take some time to establish statistical confidence in the skill of a given forecast scheme. Must a risk tolerant decision maker wait decades until skill is "proven" if that decision maker believes the system to have value? What of a risk neutral decision maker? A methodology is illustrated to demonstrate there are imperfect forecast systems which almost certainly have nontrivial value long before one might establish that their skill was statistically significant.

1 Identifying skill with small datasets

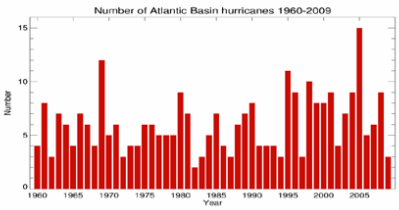

Figure 1: HURDAT data: Number of Atlantic Basin hurricanes from 1960 to 2008 [3])

The forecasting of US hurricanes has become a high profile endeavour over recent years largely due to its potential applications for the insurance industry, and the search for climate change signals in hurricane activity data. Establishing out-of-sample skill in an annual hurricane forecasting system poses a challenge on decadal timescales due to the slow rate new information is gathered with which to verify forecasts. The range of uncertainty in a sample of forecast model evaluations increases with decreasing time duration, and thus genuine skill cannot be reliably ascribed to a forecast model which is verified with a small dataset.

It has been argued that to robustly assess the predictive skill of a hurricane forecasting system, it would need to sustain an accurate enough performance over at least a period of several decades [4]. Otherwise, there is no way of knowing whether any skilful predictions made by the model are attributable to the quality of the model or to just chance alone. This raises two interesting questions: 1) would it truly take several decades to establish skill in practice? And 2) even if so, should the lack of established skill deter a decision-maker from using a forecast they believe to be valuable? The second question is investigated in this poster, and we argue that the answer to this question is "no".

2 Does a decision-maker need to wait?

If demonstrating genuine skill with limited datasets is not possible, then should a decision-maker wait for proof of skill in a model before using it? Might they be forgoing the opportunity to benefit from forecast information whilst seeking statistical reassurance? We examine the cost of waiting. If the decision-maker believes in the skill of their model, they might rationally choose to begin implementing it and will begin to receive value before those who choose to delay. The chance to profit before proving can be conceptualised in the context of what is called the "Swindled Statistician Scam" (see Box 1).

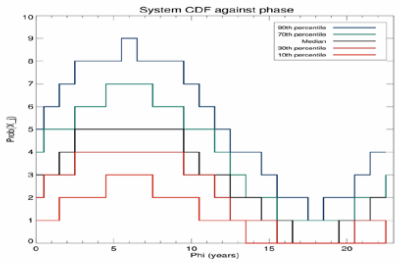

Figure 2: Contours of the cumulative distribution function showing how the system probability distribution changes as a function of the phase of the 24 year cycle. Note that occurrences of higher hurricane numbers are more likely in years with phase 5, 6 or 7 than those with phase 17, 18 or 19.

3 Profit or Proof: how should a decision-maker decide?

Consider a toy hurricane system in which the mean number of storms follows a 24 year cycle, while the number of storms in any given year is determined at random. To illustrate that structural model error does not preclude value to a decision-maker, consider an imperfect model of that system with the same cycle period, but where the probability distribution function used is incorrect in shape, not merely in parameter. This model will then be used in games of Hurricane Roulette, where the imperfect (but time dependent) model probabilities are used to place bets against odds set by a house using the correct (but not time dependent) climatological probability distribution. The results can be reported in either bits of information or as an expected annual return (see [1]).

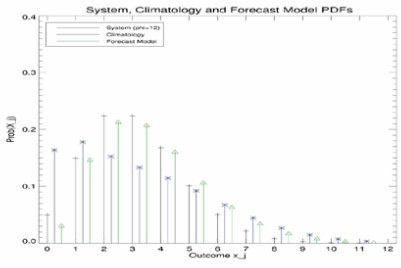

Figure 3: This figure shows the probability distributions for the system (black), and an imperfect model (green) for phase year 12 of the 24 year cycle. The climatological distribution (computed over all values of phase) is also shown in blue. Note that one need not know the true system PDF in order to outperform climatology. In this case the imperfect model PDF is expected to have a better ignorance score than the climatology; 0.18 bits on average (corresponding to a 1.13% per year interest rate).

Box 1. The Swindled Statistician Scam: A wily underwriter approaches a non-Floridian statistician with a business deal: the statistician will produce a probability forecast of the number of destructive events in the coming year, the underwriter will use her market contacts to bet on the forecast. As soon as the statistician can prove the forecast really does have skill, the underwriter will pay royalties. Will this leave the statistician swindled out of a small fortune?

The system is defined as a Poisson process, $X \sim Pois(\lambda(t))$, where X is the number of hurricanes in a given year and has a sinusoidal time-dependent mean determined by the equation $\lambda(t) = 2.5sin(2\pi t/T + \phi) + 3.0$. The probability distribution of the system over each of the 24 phases is illustrated in Figs 2 and 3 which describe the cumulative distribution function for all phases, and the probability density function corresponding to phase year 12 respectively.

The forecast model is defined by a squared Gaussian distribution with a mean equal to the climatological hurricane number average i.e. if $V \sim \mathcal{N}(\mu_{clim}, \sigma^2)$ then the random variable $Y = \lfloor V^2 + 0.5 \rfloor$ represents the distribution of annual forecast hurricane numbers. In addition, the model parameter σ has been fitted to each phase of the 24-year system cycle by minimising the expected ignorance of the forecast.

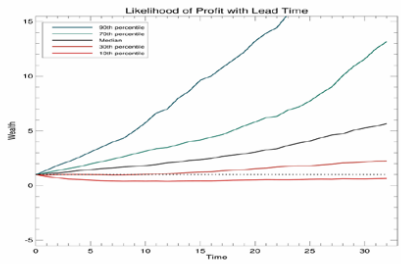

Figure 4: Frequency distribution of wealth of 2048 decision-makers who bet using the imperfect hurricane forecast model, as a function of the duration of time over which they bet. The dotted line shows their initial wealth (set equal to one unit), so the fraction of those above this line reflects the likelihood of being in profit by using the model. Note that the 30th percentile (brown) crosses and stays clearly in profit after about year 12: this is long before one could establish that the model had statistically significant skill.

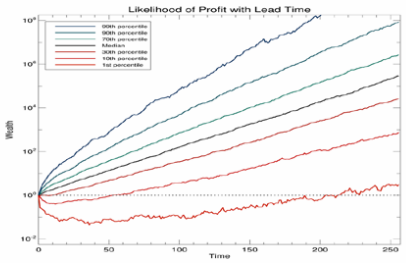

Figure 5: Frequency distribution of wealth as in Fig 4, but shown over a longer time period and on logarithmic scales. Note that on the time scales on which one could establish statistically significant skill by time series analysis given a model with a period of 24 years, most of the decision-makers have made a nontrivial profit.

Hurricane Roulette proceeds as follows: at the start of each annual hurricane season a punter, or in this case the decision-maker, is offered odds defined by the climatology PDF (equally-weighted sum of the 24 system phase PDFs). She then places her bet by distributing all of her current wealth (based on the Kelly betting strategy [2]) according to the forecast probabilities assigned to each possible hurricane number outcome (X_j). The actual outcome determines the pay-off on each annual bet.

The results of a sample of 2048 realisations (or worlds) of this game of Hurricane Roulette demonstrate that the decision-maker would be very likely to have made a non-trivial profit even before two system cycles have completed - which is much shorter than the time it would take to reach a sufficient level of statistical significance (NB: the phase, ϕ, is selected at random for each realisation to avoid bias). This is evident in Fig 4 which shows the frequency distribution of wealth of 2048 betting decision-makers.

If the game of Hurricane Roulette is extended out to 256 years, the likelihood of profit significantly increases and we find that 99% of decision-makers will have made a non-trivial profit before 250 years have passed. This is shown in Figs 5 and 6. Even though this is an idealised situation, it does demonstrate why a decision-maker might consider and potentially benefit from the use of a forecasting system they believe to be skilful. The results above illustrate a case in which the fleeced statistician would be kicking himself for a long time before the first royalty payment came in.

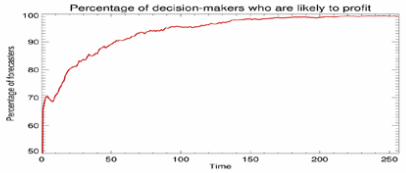

Figure 6: Percentage of decision-makers expected to make a profit with time when betting against climatology using the imperfect model in a game of hurricane roulette: the sample size is 2048 worlds.

Box 2. Discussion Points

- Establishing Forecast Skill on Systems with long time scales poses a challenge
- A decision-maker may accept risk in order to gain profit, rather than first wait to establish statistical confidence in the forecast. In such cases, any difficulty in establishing forecast skill is a non-challenge.
- Ways of benefiting from an imperfect model can be demonstrated through the use of games like Hurricane Roulette

References

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[3] National Oceanic and Atmospheric Administration. Atlantic hurricane database re-analysis project. source: http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html.

[4] R. A. Pielke. United states hurricane landfalls and damages: Can one- to five-year predictions beat climatology? *Environmental Hazards*, 8:187–200(14), September 2009.

Acknowledgements: The support of EQUIP, of the Economic and Social Research Council (ESRC), and of Munich Re is gratefully acknowledged.

Jarman also investigated the effects of serial dependence in a verification time series on skill score statistics – specifically the score sample variance is inflated, thereby increasing the sample size required to reach statistical significance in forecast skill, and identifying an additional two different cases of effects or non-effects on the statistical inference of forecast skill. This work is expected to result in a paper in the summer of 2015.

In April 2012 Jarman gave a talk entitled 'Misleading estimates of forecast quality: quantifying skill with sequential forecasts' which presented research on the effects of serial dependence on estimating the skill of a forecast system at the annual EGU (European Geophysical Union) meeting. Jarman and Smith also presented a further poster entitled 'Distinguishing between skill and value in hurricane forecasting' (Jarman and Smith 2012) at the same conference. The poster presents the 'swindled statistician scam', a gambling scenario, to demonstrate how imperfect models can possess non-trivial value before being proven to be skillful.

As part of the Programme a symposium was held at LSE in May 2012: the Symposium on Hurricane Forecasting: Skill and Value. The aim of the symposium was to present the findings from the LSE's work in this area to participants from the climate research and forecast user communities. The event provided a wealth of information, particularly on the importance of distinguishing meteorological skill from actual utility (value) in the insurance context. (Details and a link to the full report from the meeting can be found in Appendix 5.)

In year four of the programme Jarman's work focused on the interpretation and use of probabilistic hurricane forecasting. A technical note was written on the reliability of the US National Hurricane Center's forecasts and is expected to become a paper by the summer of 2015. A second technical investigation into the statistical recalibration of forecasts formed a chapter in Jarman's thesis.

A poster by Jarman and Smith entitled 'Forecasting the Probability of Tropical Cyclone Formation: the reliability of NOAA forecasts from the 2012 hurricane season' (Jarman and Smith 2013) was presented at EGU 2013. The poster discussed the performance of the National Hurricane Center's short-term binary forecasts of hurricane occurrence using reliability diagrams, and the implications of varying time elapsed between forecast and event for forecast reliability. (For details and link see Appendix 3.) See poster overleaf.

In May 2014 Jarman submitted and successfully defended his PhD thesis entitled 'On the Provision, Reliability, and Use of Hurricane Forecasts on all Timescales' (Jarman 2014). (See Appendix 3 for details.)

Follow-on research

Following on from submission of his thesis in 2014, Jarman began work on several papers based on his thesis research. Three academic papers are expected: "The Effects of Serial Dependence on Estimates of Probabilistic Forecast skill", "On the Accuracy and Improvement of the National Hurricane Center's Tropical Cyclone Genesis Forecasts", and "What is the Appropriate Role of Recalibration in Probabilistic Forecasting?"

Forecasting the Probability of Tropical Cyclone Formation: the reliability of NHC forecasts from the 2012 hurricane season

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NHC Short-term Tropical Cyclone Forecasts

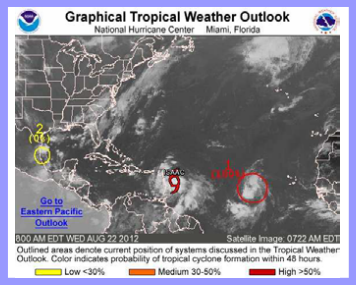

Fig 1: NHC Graphical Tropical Weather Outlook 2nd October 2012

The US National Hurricane Center (NHC) issues 6-hourly binary probability forecasts of tropical cyclone (TC) formation in a specific area of weather disturbance in the north Atlantic Basin within the next 48 hours during the hurricane season (June 1st to November 30th). These subjective probability forecasts called Tropical Weather Outlooks (TWO) can be found at *http://www.nhc.noaa.gov/pastall.shtml*. Probabilities of a TC occurrence are typically assigned in 10% increments by the NHC forecaster but those stated as 0% (and 100%) are called near zero (near 100) in the supporting text (see Fig 1).

Reliability diagrams for each season plot the observed relative frequencies of a TC event, given by

$$f_k = \frac{\sum_{i \in I_k} Y_i}{\#I_k}, \qquad (1)$$

($Y_i = 1$ for an occurrence and $Y_i = 0$ for a non-occurrence over $i = 1, ..., N$ forecast/verification pairs) against the averaged forecast probabilities,

$$r_k = \frac{\sum_{i \in I_k} X_i}{\#I_k}, \qquad (2)$$

assigned to the outcome (where $\#I_k$ is the number of elements in a collection of indices I_k for which forecast X_i falls into bin B_k, $k = 1, ..., K$).

A perfectly reliable forecast system is indicated if all the points line up near to the diagonal, $f_k = r_k$. The diagrams in their traditional format do not convey a truly representative measure of reliability, however, because they do not account for sampling error. Even perfectly reliable forecasts would be expected to deviate from the diagonal line.

Detecting (In)Consistent Points on a Reliability Diagram

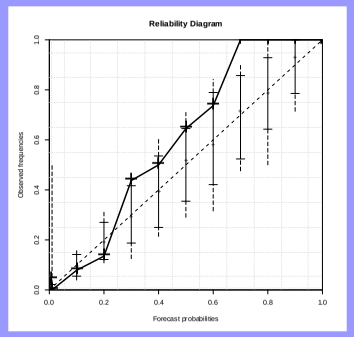

Fig 2: Reliability diagram for NHC 2012 hurricane forecasts with 5% - 95% (1% - 99% dashed line) consistency bars. The bin boundaries (light grey vertical lines) are positioned at $[0.0075, 0.055, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95]$.

To indicate the expected sampling error 5% to 95% consistency bars [1] are included in the reliability diagram at each forecast probability bin (Fig 2).

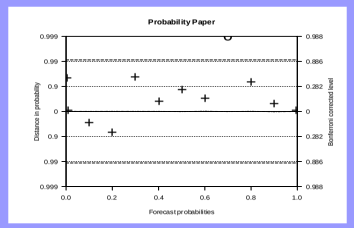

Fig 3: Reliability diagram on probability paper for NHC 2012 hurricane forecasts. The dash–dotted line denotes the exact position of the diagonal, and a semi-circle indicates an observed frequency outside the range of the y axis. The right-hand axis indicates the equivalent Bonferroni corrected levels i.e. for a reliable forecast, all of the points (12 bins) would be expected to fall within the 0.99 probability distance band with an 88.6% chance. In addition, the dashed lines indicate where the entire diagram would be expected to fall within with a 90% chance.

Forecast reliability is indicated if the observed frequencies lie within the consistency bars.

Plotting the reliability diagram on probability paper (see Fig 3) provides a useful companion to the main diagram by displaying the observed frequencies by their distance in probability from the 50% quantile of the consistency bars. This should lie close to or on the diagonal. Comparisons of forecast reliability between probability bins and an assessment of the calibration of a forecast system can be made using this diagram.

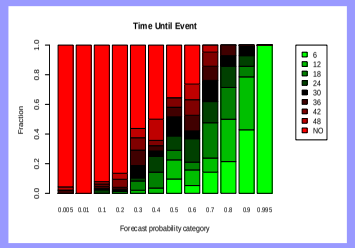

Fig 4: Relative frequencies of time until formation (in hours) for each NHC 2012 hurricane forecast probability bin. The categories indicate the occurrence of TC formation between the time given and 6 hours previous to it. A "NO" indicates a non-occurrence of TC formation within 48 hours.

We note that the time until formation is not uniformly distributed across the 48 hour window. Indeed all of the highest probability forecasts correspond to near immediate formation, as shown in Fig 4.

Strengths and weaknesses of 2012 NHC short-term TC forecasts

Figure 2 indicates overforecasting for the lowest forecast probabilities (except for 0.5% probability forecasts), and more significant underforecasting for higher forecast probabilities. This demonstrates a degree of underconfidence but good resolution in the 2012 forecasts [2]. Most of the observed frequencies lie within the 5% to 95% consistency bars (Fig 3) and the 90% reliability band (Fig 4), demonstrating a skilful forecast system on the whole. Underforecasting at the highest probabilities may suggest less predictability of tropical cyclone formation at shorter times until formation.

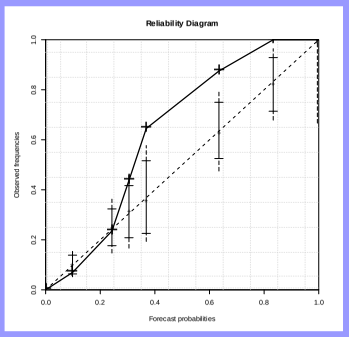

Fig 5: Recalibration reliability diagram (using 2011 forecasts as training set) for the NHC 2012 hurricane forecasts with 5% - 95% (1% - 99% - dashed line) consistency bars. The bin boundaries (light grey vertical lines) are positioned at $[0.0075, 0.055, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95]$.

Attempts to recalibrate forecast systems by reassigning the probabilities, r_k, with observed relative frequencies, f_k are often suggested. Figure 5 shows how the forecast system would have performed for the 2012 hurricane season using the 2011 forecasts as a training set (see Fig 3) - it is significantly less skilful.

Discussion Points

- Reliability diagrams provide a quick and simple view of forecast performance
- The NHC 2012 forecasts are skilful
- Times until formation vary between the 2012 NHC forecasts suggesting additional analysis to identify information beyond reliability of the 48 hour forecast
- Recalibration of the 2012 forecasts using the 2011 forecasts leads to a poorer forecast performance

References [1] J. Broecker and L. A. Smith. Increasing the reliability of reliability diagrams. Weather and Forecasting, 22(3):651-661, 2007.

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[3] A. S. Jarman and L. A. Smith. On the reliability of 2012 Hurricane forecasts, 2013 (in preparation).

Acknowledgements: This research was funded as part of and the ESRC Centre for Climate Change Economics and Policy, funded by the Economic and Social Research Council and Munich Re.

E) Economic impacts of climate change in emerging economies

During its first year, this research stream focused on disaster risk management and climate change adaptation in developing countries, highlighting the role of insurance and its relationship to risk reduction. This research has led to a number of outputs, largely focused on informing national and international policy, led by Nicola Ranger, with input from Bob Ward. Ranger, in collaboration with Munich Re colleagues and LSE, organised a half-day academic workshop on “Understanding the Role of Insurance and Disaster Risk Reduction in Adaptation” in October 2009. The workshop was attended by 23 international researchers from across the academic and insurance communities. The output was also used for informing the Munich Climate Insurance Initiative on disaster and insurance in developing countries.

In the second year of the Programme the work on developing countries and insurance continued, with Nicola Ranger conducting work on vulnerability and providing input to UNFCCC and MCII discussions. Judith Rees (China), Lord Stern (India) and Sam Fankhauser (Russia) established contacts and in-country relationships for the analysis of climate impacts in the BRIC states. Swenja Surminski joined the Programme in September 2010 and worked with colleagues on reviewing the impacts of climate change on economic growth and development in BRIC countries. An analysis of the linkages between insurance demand and economic growth and development was conducted. Surminski and Ranger attended a workshop with Munich Re in November 2010 to kick-off this research stream, discussing priorities and sharing information on current demand projections and the methodologies that underlay them. This led to close collaboration with several Munich Re colleagues.

In January 2011, a new research stream on insurance demand and climate change in the BRICS economies was initiated. In the first phase the overall drivers of insurance demand in emerging markets were explored and the role of climate change assessed. In addition to discussions with colleagues at Munich Re, this research stream hosted a workshop in Munich and another in London to investigate and evaluate with other academics. This work led to the publication of two Munich Re technical papers: 'Forecasting non-life insurance demand in the BRICS economies: a preliminary evaluation of the impacts of income and climate change' (Ranger and Williamson 2011, MRe TP11) in which Ranger and Williamson conducted an investigation of trends in normalized economic losses from meteorological related disasters in China and India; and 'A preliminary evaluation of the impact of climate change on non-life insurance demand in the BRICS economies' (Ranger and Surminski 2011, MRe TP12) in September 2011. This phase concluded with LSE hosting an expert workshop on 'Insurance demand and climate change in the BRICS economies' in London in November 2012 (Symposium 5; for details see Appendix 5).

The second phase of research stream E commenced at the end of 2011, with Surminski and Williamson exploring the interplay of climate change, public policy and insurance opportunities in emerging markets, following on from the first phase, where it was concluded that "the most significant influence on growth is likely to come through firstly, public policy and regulatory responses to climate change, and secondly, new opportunities related to GHG mitigation and adaptation policies" (Ranger and Surminski 2011, MRe TP12), (Ranger and Williamson 2011, MRe TP11). Munich Re country experts in China and Russia provided input to this work. Two case studies on China and India were led by Surminski – with support of CCCEP-funded staff: Delioma Oramas-Dorta (China) and Susannah Fisher (India). Fisher and Surminski produced a technical paper looking at the roles of public and private actors in the governance of adaptation, with a focus on agricultural insurance in India (Fisher and Surminski 2012, MRe TP 15). Surminski and Oramas-Dorta produced a technical paper examining whether flood insurance schemes in developing countries provide incentives to reduce physical risks (Surminski and Oramas-Dorta 2013, MRe TP18). Surminski and Williamson, with direct input from colleagues at Munich Re, undertook an investigation of political, regulatory and legal drivers of insurance together with a literature review of methods to quantify the impacts of changes in the insurance regulatory environment. This led to an investigation of the current state of climate policy across the BRICS countries and metrics to compare national policies, resulting in a technical paper 'Policy indexes – what do they tell us and what are their applications? The case of climate policy and business planning in emerging markets' (Surminski and Williamson 2012, MRe TP14), which was subsequently developed into a journal paper and published in *Global Policy* (Surminski and Williamson 2014).

The final year of the Programme saw the conclusion of the above work streams by Surminski and Ranger, supported by research assistants funded under other programmes within CCCEP. Several of the technical papers were successfully published (see Appendix 1 for full list), while there were a wide range of dissemination activities across stakeholders within the industry and outside. Surminski was invited to contribute to the IPCC AR5 WGII (as a contributing author on the role of insurance). Collaboration between three LSE colleagues (Niehörster, Ranger and Surminski) led to the Geneva Association's publication on Warming of the Oceans. The Ranger and Surminski paper on non-life insurance demand (Technical Paper 12) was subsequently published in the journal *International Journal of Disaster Risk Reduction* (Ranger and Surminski 2013), and it was shortlisted for the Lloyd's Science of Risk Prize in 2014. (See text after the poster opposite for summary and key findings.)

A preliminary assessment of the impact of climate change on non-life insurance demand in the BRICS economies

Nicola Ranger and Swenja Surminski

s.surminski@lse.ac.uk This research is published in the International Journal of Disaster Risk Reduction, (2013) Volume 3, pages.14-30

Objective: This study investigates the impacts of climate change on BRICS economies and the potential influence of climate change on future growth with a view to informing long-term strategic planning in the insurance industry. We conduct a preliminary evaluation of their relative scale and directions based on evidence available today.

1. Observations: Understanding non-life insurance demand

What drives non-life insurance demand in the BRICS beyond income?

- **Macroeconomic**
  - Economic stability
  - Inflation rates
  - Stable financial markets
  - Openness to trade
- **Risk factors**
  - Stable legal and institutional frameworks
  - Adequate insurance law
  - Opening distribution channels
  - Conducive regulatory environment
  - Property rights
  - Judicial efficiency and transparency
  - Mandatory insurance lines
- **Socio-cultural factors**
  - Education
  - Financial literacy
  - Religious and cultural attitudes to risk and insurance
  - Perception of other available financing in the event of a loss,
- **Political, regulatory and legal factors**
  - The nature of exposure, such as the number of cars
  - Natural catastrophe exposure
  - Risk awareness linked with recent catastrophe experience

Economic growth is an important driver of insurance demand in emerging economies

Baseline projections suggest significant increases in non-life premium volumes in the BRICS are primarily due to rising wealth. This effect promotes affordability and a more conducive environment for insurance penetration.

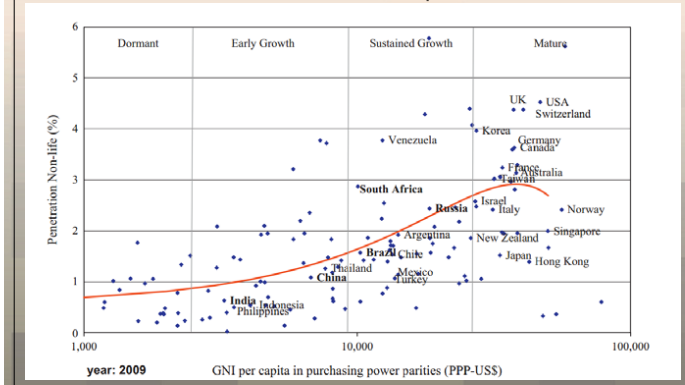


Fig. 1.Gross national income (GNI) per capita and the penetration of non-life insurance (% of GDP) in 2009 with red 'Global Trend Line' Source: data provided by Munich Re.

2. Analysis: What are the pathways that will influence future insurance demand?

We identified five pathways influenced by climate change that will impact future insurance demand, the most significant influence being **policy and regulatory responses** to climate change.

Pathway	Impact on premium volumes in BRICS economies in 2015 ($ bn estimated)
Impact on income levels	-4 to +1
Public policy and regulation	Up to +6 (India) up to +12 (China)
Supply factors	*No data*
Willingness to pay for insurance	*No data*
New products and services	>+1 across all BRICS
Baseline economic growth (i.e. no climate change)	Up to +20 to +30 in most countries, up to +125 in China

3. Implications for insurers

Scenarios for insurance demand in the BRICS that impact the trend of pathways

A number of uncertain factors e.g. scale of physical risks, government, insurer and insured response may impact insurance demand, we therefore suggest two distinct scenarios:

- **Optimistic scenario** with an increase in demand
  - Strong curb on emissions
  - Proactive governmental policy
  - Awareness of risks results in favourable environment for insurers
  - Confidence in the industry rises and insurance seen as implicit solution to climate change impacts
- **Pessimistic scenario** with little increase in demand
  - Government measures passive and too little
  - Losses increase
  - Industry fails to anticipate full implications of risk
  - Insurers withdraw from market segments
  - Confidence in insurance fails, shift to state sector products

Climate change- implications for insurers

The impacts of climate change including both the scale and direction of action are influenced by insurer response and five key actions have been identified that may bring opportunities for insurers, including:

- **Raising awareness of risk and climate change** through education and information dissemination
- **Adopting a longer term perspective** in strategic business planning and anticipating changing risk levels in underwriting and risk management practices
- **Supporting adaptation** through innovative product design and public-private partnerships
- **Building technical capacity** to capture new market opportunities
- **Informing the debate and lobbying government** on climate change and taking action to reduce risks

A Preliminary Assessment of the Impact of Climate Change on Non-Life Insurance Demand in the BRICS economies

N. Ranger & S. Surminski, *International Journal of Disaster Risk Reduction*, v.3, pp.14-30, 2013.

[Based on Technical Paper 12]

Summary

Theory and evidence from existing insurance markets suggests that a riskier and more uncertain world would be associated with an increase in insurance demand, at least until some local threshold were reached where the affordability of insurance or the insurability of risk were threatened. We investigate this for the case of climate change, an area that has previously been identified as a risk and opportunity for the insurance industry.

While the complex interactions and uncertainties mean that it is impossible to quantitatively forecast the future impacts of climate change on insurance demand, we conduct a preliminary evaluation of their relative scale and directions based on evidence available today. Mapping the influence and trends through the use of scenarios is important for long-term planning as well as for informing (re)insurers and other stakeholders on what actions can be taken today to minimise future threats and capture opportunities.

Our analysis focuses on emerging markets, where over the past decade rising insurance demand has been a key driver of global non-life premium growth. Particularly the BRICS countries have been seen as areas of significant growth due to their rising per capita income; the recent economic slow-down as well as increased geopolitical concerns, however, pose challenges for the emerging insurance industry in those countries.

For our analysis we consider the time horizons to 2015 and 2030. The 2015 time interval will likely be considered most relevant to the (re)insurance industry. Both time horizons are short compared with the timescales of climate change, where the impacts are predicted to be most significant beyond around 2030.

Key findings

Our study identifies five main determinants of insurance demand within the context of climate change: economic growth, the willingness to pay for insurance, political conditions, the insurability of natural catastrophe risks, and possibilities of adjusting to the impacts of climate change.

We conclude that the influence of climate change on insurance demand to 2030 is likely to be small but not insignificant when compared with the expected growth due to rising incomes. This effect could intensify, however, if politicians introduce regulatory mechanisms to counter climate change, such as obligatory insurance, state-subsidised insurance products or the imposition of stricter solvency capital requirements. The same also applies if new business opportunities arise following measures designed to reduce greenhouse gas emissions or adapt to climate change. Based on these assumptions, we outline two scenarios:

- Optimistic scenario with a substantial increase in demand; and
- Pessimistic scenario with little increase in demand.

To some extent, the scale of the impacts and their direction depend on (re)insurer responses to the challenges of climate change. We outline five actions that could pave the way for future opportunities:

- Raising awareness of risk and climate change through risk education and disseminating high-quality risk information.
- Taking a longer-term perspective in strategic business planning (for example, to 2030) and anticipating changing risk levels in underwriting and risk management practices to reduce the chance of insolvencies, rapid increases in premiums (or hardening in conditions) and withdrawals from markets in response to rising hazard levels.
- Supporting and encouraging adaptation, as well as enhancing reputation, through innovative product design and public-private partnerships.
- Innovating and building technical capacity to capture

new market opportunities associated with the transition to a low-carbon economy.

- Informing the debate on climate change and actively lobbying government to take action to reduce risks and curb emissions of greenhouse gases.

Across the BRICS the largest impacts are expected in China and India, where there are the greatest opportunities for a catch-up in insurance penetration due to improved market conditions, increased risk awareness and new opportunities associated with climate policy.

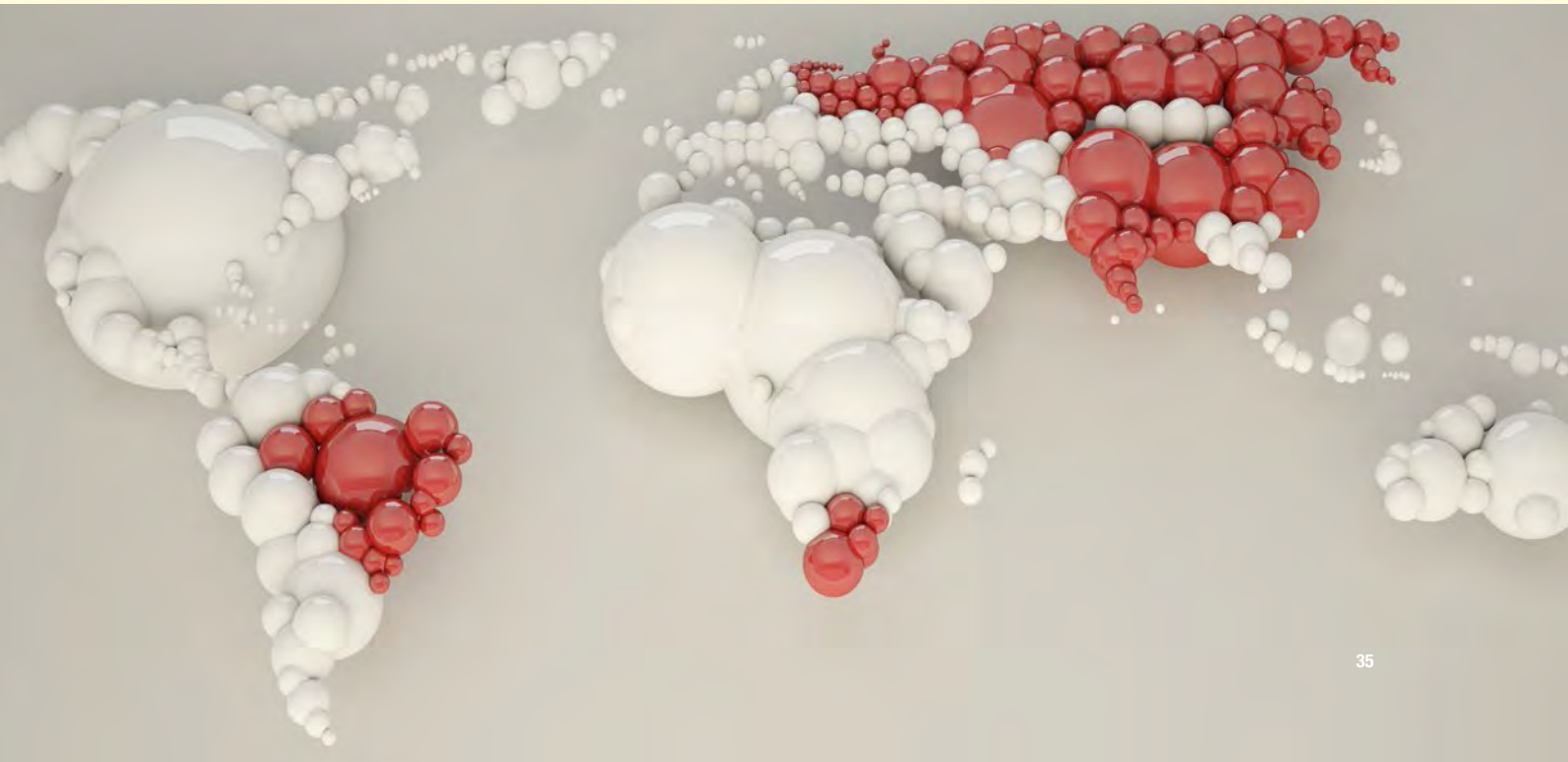
We consider the arguments made in this paper to be applicable to insurance demand beyond the BRICS. The impacts of climate change on insurance demand, however, are expected to be larger in the BRICS economies than the industrialised countries: firstly, as both the positive and negative impacts of climate change on economic growth are generally expected to be larger in these countries and the income elasticities of demand are greater; secondly, opportunities for new markets associated with GHG mitigation and adaptation are predicted to be deeper in the BRICS; and finally, the significant “catch-up” potential in terms of the market conditions for insurance suggest a larger and more positive potential influence related to public policy and regulation and risk awareness.

Academic relevance

Our paper has been published in a leading academic journal and continues to have impact on our own and others’ research. The analytical focus on insurance demand in the BRICS provides a novel perspective and enhances our understanding of growth in insurance markets. Previous studies have explored the long-term implications of climate change for the global insurance industry, but none has focused on the implications of insurance demand, or the BRICS. We respond to this gap, but also highlight the challenges of forecasting demand trends.

Relevance to the industry

Climate change is expected to alter the global landscape of natural catastrophe risk and the nature of energy markets, and increase awareness of risk and investment in climate risk management. This may impact many insurance products. Our study evaluates the potential influence of climate change on future insurance growth with a view to inform long-term strategic planning in the insurance industry. We conclude that while many of the factors that define our two scenarios cannot be controlled by the insurance industry, others are at least partly dependent on how the industry itself responds to the challenges of climate change. We provide examples of the different types of strategic responses available to the industry, which complements our quantitative analysis. Our study is the result of research collaboration between the London School of Economics and Political Science and Munich Re. Building on these findings we are engaged in further work with researchers and industry to explore insurance and private sector adaptation in the BRICS countries.



Linkages between the core research streams and related work led to additional academic output, such as on the topic of Loss and Damage, and on flood insurance in low-income countries. The research also created a range of spin-offs, such as analysis of the role of the private sector in adaptation. This directly follows on from the study of the possible impact of climate change on insurance demand in emerging markets (Ranger and Surminski 2013, above). The paper concluded that "many of the factors that define the scenarios (increase in demand, stagnation) cannot be controlled by the insurance industry, others are at least partly dependent on how the industry itself responds to the challenges of climate change". Building on from this work on insurance in emerging markets a new research project was started within GRI/CCCEP, initiated and led by Surminski: 'Multinational Corporations and adaptation to climate change'. To investigate this further in 2013 and 2014 Surminski conducted research on insurance and private sector adaptation in Brazil, Russia and India, in collaboration with colleagues at GRI and externally. The aim of the work is to investigate private sector engagement with government in climate change adaptation.

Further outputs and dissemination activities resulting from this stream can be found in the Appendices.

Follow-on research

The broader reach of the Munich Re-LSE collaboration is visible through the spin-offs that were triggered by the research. In many cases this has contributed to further work in the programme research areas; in addition to the work already noted above, two are stressed here. First, work on insurance in developing countries and in the loss and damage context. For example the policy paper 'Developing countries can adapt to future climate change impacts despite uncertainties in predictions' by Nicola Ranger and Su-Lin Garbett-Shiels, 2011, in which they show that developing countries can adapt to future risks from climate change, such as changes in the frequency and intensity of extreme weather events, despite uncertainties in predictions about the long-term impacts. See: http://www.cccep.ac.uk/newsAndMedia/Releases/2011/MR240311_climate-change-impacts-uncertainties.aspx

Second, work on risk management partnerships and flood insurance in Europe (ENHANCE project). For example 'New flood insurance scheme could be unsustainable because it overlooks climate change' (Swenja Surminski, Florence Crick, Jillian Eldridge and Bob Ward, August 2013), in which the authors argue that a proposed new scheme for flood insurance in the UK may not be sustainable because the impacts of climate change have not been taken into account. See: www.cccep.ac.uk/newsAndMedia/Releases/2013/MR190813-home-insurance-in-areas-of-flood-risk.aspx

In relation to this work, Munich Re hosted a workshop on flood insurance for researchers, academia and policy-makers in December 2012 in Munich.

Work conducted by the Programme Visiting Professors

The visiting professor programme allowed the LSE research community to develop and cement strong, long-term relationships with two researchers from outside the United Kingdom. Research conducted under the Munich Re Programme is noted in the two sections below. Relationships with each of our Munich Re Visiting Professors remain vibrant today. Our joint research with Professor Kunreuther directly influenced Working Group III of the IPCC AR5: he was an author of Chapter 2. The Munich Re Programme led to significant collaborations between CATS and Munich Re Programme Professor Arthur Petersen which continue today. An example of fortuitous follow-on outcomes with Professor Petersen would include vibrant working relationships between CATS and KNMI (the Dutch MetOffice) both on forecast uncertainty over all timescales (daily to centennial) of interest to KNMI and on the communication of uncertainty and ambiguity within the last IPCC report and in preparation for the next working group with the Dutch government's IPCC team.

Munich Re Programme
Professor Howard Kunreuther

Professor Kunreuther's work focused on the linking together of catastrophe modeling on climate change and its impact on insurance and reinsurance prices and long-term insurance contracts that take climate change into account. This research was facilitated by a workshop in New York City organized by Professor Kunreuther and Dr Nicola Ranger on *Mapping Future Hurricane Activity to Inform Long-Term Risk Management Strategies* on 11 March 2010. The aim of the workshop was to gather information on the applicability of future hurricane-related projections for making local adaptation and insurance decisions to reduce losses from future hurricanes. Dr Eberhard Faust (Munich Re) participated in the workshop, which included experts from the climate science community such as Kerry Emanuel, Greg Holland, Tom Knutson, and Gabe Vecchi.

Two papers have resulted from this research that link climate change to insurance pricing and more broadly to risk management:

'Insuring Future Climate Catastrophes' by Kunreuther, Michel-Kerjan and Ranger appeared in *Climatic Change* (Kunreuther, Michel-Kerjan et al. 2013). The paper evaluates the premiums that private insurers are likely to charge and their ability to cover residential losses against hurricane risk in Florida as a function of (a) recent projections on future hurricane activity in 2020 and 2040; (b) insurance market conditions (ie, soft or hard market); (c) the availability of reinsurance; and (d) the adoption of adaptation measures (ie, implementation of physical risk reduction measures to reduce wind damage to structures and buildings). The paper finds that uncertainties in climate projections translate into a divergent picture for insurance in Florida.

'Risk Management and Climate Change' by Kunreuther, Heal, Allen, Edenhofer, Field and Yohe appeared in *Nature Climate Change* (Kunreuther, Heal et al. 2013). The paper highlights the value of robust decision-making tools for examining alternative strategies for doing this, and emphasizes that one can make good choices without well-specified probabilities for characterizing future climate risks. This is a crucial point, since these probabilities are rarely available in this field; a recurrent theme across the Munich Re Programme. The paper shows that robust decision-making approaches are very versatile, and can be applied under a variety of climate change scenarios.

Other impacts of this research are evidenced in the chapter on *Integrated Risk and Uncertainty Assessment of Climate Change Response* for the Intergovernmental Panel on Climate Change (IPCC), 5th Assessment Report on which Howard Kunreuther served as a Coordinating Lead Author: 'Integrated Risk and Uncertainty Assessment of Climate Change Response Policies' (Kunreuther, Gupta et al. 2014).

Munich Re Programme
Professor Arthur Petersen

Professor Petersen, as part of his Munich Re Visiting Professor appointment at LSE and with continued support from his employer the PBL Netherlands Environmental Assessment Agency, has produced seven key peer-reviewed publications on climate science and policy (a renewed edition of his book with CRC Press, four peer-reviewed journal articles in *Climate of the Past*, *Climatic Change* and *Nature Climate Change*, and two peer-reviewed book chapters with Springer and Pickering and Chatto). These publications have informed Professor Petersen's work as Chief Scientist at the PBL and as Dutch government delegate within the Intergovernmental Panel on Climate Change (IPCC). In particular, by bringing LSE CATS researchers together with colleagues from the Royal Netherlands Institute (KNMI), at workshops in Amsterdam (January 2011) and Bilthoven (June 2013), he has been able to channel the critical assessment of the role of models in climate scenarios into the Dutch government and the IPCC. As part of his Munich Re Visiting Professor appointment, Professor Petersen has given several lectures at LSE and attended a number of academic workshops. The most important conclusion of all his work on this topic is that uncertainty assessment has to include (model structure) scenario uncertainty and to recognize ignorance in addition to statistical uncertainty. It is "methodological reliability" that counts!

Petersen's papers reflecting his research as a Munich Re Visiting Professor include:

'Climate simulation, uncertainty, and policy advice: The case of the IPCC' (Petersen 2011)

'Simulating Nature: A Philosophical Study of Computer-Model Uncertainties and Their Role in Climate Science and Policy Advice' (Petersen 2012)

'Variations on reliability: Connecting climate predictions to climate policy' (Smith and Petersen 2014)

'Detecting instabilities in tree-ring proxy calibration' (Visser, Büntgen et al. 2010)

'Inferences on weather extremes and weather-related disasters: a review of statistical methods' (Visser and Petersen 2012)

'On the relation between weather-related disaster impacts, vulnerability and climate change' (Visser, Petersen et al. 2014)

'Tales of future weather' (Hazeleger, Hurk et al. 2015)

Abstracts and links to the above papers can be found in Appendix 1.

Afterword

As documented in the pages above, the Munich Re Programme has had a significant impact on the production and dissemination of research related to the challenges and opportunities of a changing climate. It has contributed directly to the training of young academics and broadening the range of understanding of somewhat older academics. In addition, it has played a fundamental role by enriching the infrastructure of research into climate and climate policy at the LSE. Ultimately the Munich Re-LSE Programme has also been important in supporting the Centre for Climate Change Economics and Policy in winning second phase funding from UK Economic and Social Research Council.[7]

Research programmes of many LSE researchers and departments have benefited from the Programme. It has played a major role by increasing the profile of the Centre for the Analysis of Time Series (CATS) as both a neutral broker for the interpretation and evaluation of forecast information and the quantitative communication of climate information. By successfully targeting weak links across the chain running from basic climate science to industrial decision-making, research has strengthened many arguments and drawn attention to the weakness of others. Both within academia and industry, the positive impact of the Munich Re Programme on climate research worldwide will cast a long shadow.

[7] See: www.cccep.ac.uk/newsAndMedia/Releases/2013/MR170913-centre-for-climate-change-economics-and-policy-second-phase.aspx

Appendix 1: Papers and posters

Academic dissemination of the new ideas and insights generated under the Munich Re Programme progressed both by novel channels during the Programme and through traditional academic channels of papers and posters which cast a long shadow into the future. This appendix first notes (i) academic papers generated directly by the Munich Re Programme. (Where these were developed from an earlier Munich Re Programme Technical Paper this is noted.) Then (ii) academic papers closely related to the Programme (papers which would not exist in their current form were it not for the Programme). Full citations and abstracts are given. Next (iii) the Munich Re Technical Papers are noted in the same format (the abstracts being omitted if they are identical to those of a corresponding academic paper). And finally (iv) a summary of the posters produced by the Programme. Each of those posters can be found, reproduced in full, within this booklet.

i) Academic papers from the Munich Re Programme

Market-consistent modelling for cap-and-trade schemes and application to option pricing

Barrieu, P. and Fehr, M. (2014), *Operations Research,* vol. 62, 234-249

[Based on Technical Paper 7, 'Integrated EUA and CER price modelling and application for spread option pricing' (March 2011)]

In this paper, we propose a market consistent futures price dynamics model for cap-and-trade schemes, designed in the spirit of the European Union's Emissions Trading Scheme (EU ETS). Historical price dynamics for the EU ETS suggest that both European emission Allowances (EUAs) and Certified Emission Reductions (CERs) certificates, which are generated through the Clean Development Mechanism (CDM) – a non-domestic offset mechanism – are significantly related. We use an equilibrium framework to demonstrate that compliance regulation singles out special joint futures price dynamics. Based on this result, we propose an arbitrage-free futures price model, and apply it to the pricing of spread options between EUAs and CERs.

DOI: 10.1287opre.2013.1242

A trend analysis of normalized insured damage from natural disasters

Barthel, F. and Neumayer, E., (2012) *Climatic Change,* 113 (2), pp. 215-237

[Based on Technical Paper 5, November 2010]

As the world becomes wealthier over time, inflation-adjusted insured damages from natural disasters go up as well. This article analyzes whether there is still a significant upward trend once insured natural disaster loss has been normalized. By scaling up loss from past disasters, normalization adjusts for the fact that a hazard event of equal strength will typically cause more damage nowadays than in past years because of wealth accumulation over time. A trend analysis of normalized insured damage from natural disasters is not only of interest to the insurance industry, but can potentially be useful for attempts at detecting whether there has been an increase in the frequency and/or intensity of natural hazards, whether caused by natural climate variability or anthropogenic climate change. We analyze trends at the global level over the period 1990 to 2008, over the period 1980 to 2008 for West Germany and 1973 to 2008 for the United States. We find no significant trends at the global level, but we detect statistically significant upward trends in normalized insured losses from all non-geophysical disasters as well as from certain specific disaster types in the United States and West Germany.

DOI: 10.1007/s10584-011-0331-2

Tall tales and Fat tails: The science and economics of extreme warming

Calel, R., Stainforth, D.A. and Dietz, S. (2013) *Climatic Change,* DOI 10.1007/s10584-013-0911-4

This paper considers the physical uncertainties in economic models of climate mitigation, in particular the significant impacts implied by the "fat tailed" distributions commonly identified in climate science. It has recently been highlighted that the economic value of climate change mitigation depends sensitively on the slim possibility of extreme warming. This insight has been obtained through a focus on the fat upper tail of the climate sensitivity probability distribution. However, while climate sensitivity is undoubtedly important, what ultimately matters is transient temperature change. A focus on transient temperature change stresses the interplay of climate sensitivity with other physical uncertainties, notably effective heat capacity. In this paper the authors present a conceptual analysis of the physical uncertainties in economic models of climate mitigation, leading to an empirical application of the DICE model, which investigates the interaction of uncertainty in climate sensitivity and the effective heat capacity. The paper expands on previous results exploring the sensitivity of economic evaluations to the tail of the climate sensitivity distribution alone, and demonstrates that uncertainty about the system's effective heat capacity also plays a very important role. The authors go on to discuss complementary avenues of economic and scientific research that may help provide a better combined understanding of the physical and economic processes associated with a rapidly warming world.

DOI: 0.1007/s10584-013-0911-4

On predicting climate under climate change

Daron, J.D. and Stainforth, D.A. (2013) ***Environmental Research Letters,*** **8 (034021)**

This paper considers whether today's global climate model ensembles characterize the 21st century climate in their own 'model-worlds'. This question is at the heart of how we design and interpret climate model experiments for both science and policy support. Using a low-dimensional nonlinear system that exhibits behaviour similar to that of the atmosphere and ocean, the authors explore the implications of ensemble size and two methods of constructing climatic distributions, for the quantification of a model's climate. Small ensembles are shown to be misleading in non-stationary conditions analogous to externally forced climate change, and sometimes also in stationary conditions which reflect the case of an unforced climate. These results show that ensembles of several hundred members may be required to characterize a model's climate and inform robust statements about the relative roles of different sources of climate prediction uncertainty.
DOI: 10.1088/1748-9326/8/3/034021

Assessing pricing assumptions for weather index insurance in a changing climate

Daron, J.D. and Stainforth, D.A., (2014) ***Climate Risk Management,*** **1, 76-91**

Weather index insurance is being offered to low-income farmers in developing countries as an alternative to traditional multi-peril crop insurance. There is widespread support for index insurance as a means of climate change adaptation but whether or not these products are themselves resilient to climate change has not been well studied. Given climate variability and climate change, an over-reliance on historical climate observations to guide the design of such products can result in premiums which mislead policyholders and insurers alike, about the magnitude of underlying risks. Here, a method to incorporate different sources of climate data into the product design phase is presented. Bayesian Networks are constructed to demonstrate how insurers can assess the product viability from a climate perspective, using past observations and simulations of future climate. Sensitivity analyses illustrate the dependence of pricing decisions on both the choice of information, and the method for incorporating such data. The methods and their sensitivities are illustrated using a case study analysing the provision of index-based crop insurance in Kolhapur, India. The authors expose the benefits and limitations of the Bayesian Network approach, weather index insurance as an adaptation measure and climate simulations as a source of quantitative predictive information. Current climate model output is shown to be of limited value and difficult to use by index insurance practitioners. The method presented, however, is shown to be an effective tool for testing pricing assumptions and could feasibly be employed in the future to incorporate multiple sources of climate data.
DOI: 10.1016/j.crm.2014.01.001

High impact, low probability? An empirical analysis of risk in the economics of climate change

Dietz, S. (2011) ***Climatic Change*****, 108, Issue 3 (October 2011), 519-541**

[Based on Technical Paper 2, September 2009]

To what extent does economic analysis of climate change depend on low-probability, high-impact events? This question has received a great deal of attention lately, with the contention increasingly made that climate damage could be so large that societal willingness to pay to avoid extreme outcomes should overwhelm other seemingly important assumptions, notably on time preference. This paper provides an empirical examination of some key theoretical points, using a probabilistic integrated assessment model. New, fat-tailed distributions are inputted for key parameters representing climate sensitivity and economic costs. It is found that welfare estimates do strongly depend on tail risks, but for a set of plausible assumptions time preference can still matter.
DOI: 10.1007/s10584-010-9993-4

Probabilistic Forecasting: Why Model Imperfection Is a Poison Pill

Frigg, R., Bradley, S., Machete, R.L. and Smith, L.A. (2013) in Andersen, H., Dieks, D., Wheeler, G., Gonzalez, W. and Uebel, T. (eds.) *New Challenges to Philosophy of Science.* Springer, 479-491

Foretelling the future is an age-old human desire. Among the methods to pursue this goal mathematical modelling has gained prominence. Many mathematical models promise to make probabilistic forecasts. This raises the question of exactly what these models deliver: can they provide the results as advertised? The aim of this paper is to urge some caution. Using the example of the logistic map, we argue that if a model is non-linear and if there is only the slightest model imperfection, then treating model outputs as decision-relevant probabilistic forecasts can be seriously misleading. This casts doubt on the trustworthiness of model results. This is nothing short of a methodological disaster: probabilistic forecasts are used in many places all the time and the realization that probabilistic forecasts cannot be trusted pulls the rug from underneath many modelling endeavours.
DOI: 10.1007/978-94-007-5845-2_39

Laplace's Demon and the Adventures of his Apprentice

Frigg, R., Bradley, S., Du, H.L and Smith, L.A. (2014) *Philosophy of Science,* 81(1), 31-59

[Based on Technical Paper 17, January 2013]

The sensitive dependence on initial conditions (SDIC) associated with nonlinear models imposes limitations on the models' predictive power. We draw attention to an additional limitation than has been underappreciated, namely, structural model error (SME). A model has SME if the model dynamics differ from the dynamics in the target system. If a nonlinear model has only the slightest SME, then its ability to generate decision-relevant predictions is compromised. Given a perfect model, we can take the effects of SDIC into account by substituting probabilistic predictions for point predictions. This route is foreclosed in the case of SME, which puts us in a worse epistemic situation than SDIC.
DOI: 10.1086/674416

The Myopia of Imperfect Climate Models: The Case of UKCP09

Frigg, R., Smith, L.A. and Stainforth, D.A. (2013) *Philosophy of Science*, 80 (5), 886-897

This paper aims to introduce and analyze the methodology used in the United Kingdom Climate Impacts Programme's UKCP09 project, which makes high-resolution forecasts of climate during the twenty-first century using state-of-the-art global climate models. Given the acknowledged systematic errors in all current climate models, the paper considers how treating model outputs as decision-relevant probabilistic forecasts can be seriously misleading. This casts doubt on our ability, today, to make trustworthy, high-resolution predictions out to the end of this century.
DOI: 10.1086/673892

An Assessment of the Foundational Assumptions in High-Resolution Climate Projections: The Case of UKCP09

Frigg, R., Smith, L.A. and Stainforth, D.A. (2015), *Synthese*

The United Kingdom Climate Impacts Programme's UKCP09 project makes high resolution projections of the climate out to 2100 by post-processing the outputs of a large-scale global climate model. The aim of this paper is to describe and analyse the methodology used and then urge some caution. Given the acknowledged systematic, shared errors of all current climate models, treating model outputs as decision-relevant projections can be significantly misleading. In extrapolatory situations, such as projections of future climate change, there is little reason to expect that post-processing of model outputs can correct for the consequences of such errors. This casts doubt on our ability, today, to make trustworthy, high-resolution probabilistic projections out to the end of this century.
DOI: 10.1007/s11229-015-0739-8

Tales of future weather

Hazeleger, W., van den Hurk, B.J.J.M., Min, E., van Oldenborgh, G.J., Petersen, A.C., Stainforth, D.A., Vasileiadou, E. and Smith, L.A. (2015), *Nature Climate Change*, 5, 107-113

Society is vulnerable to extreme weather events and, by extension, to human impacts on future events. As climate changes weather patterns will change. The search is on for more effective methodologies to aid decision-makers both in mitigation to avoid climate change and in adaptation to changes. The traditional approach uses ensembles of climate model simulations, statistical bias correction, downscaling to the spatial and temporal scales relevant to decision-makers, and then translation into quantities of interest. The veracity of this approach cannot be tested, and it faces in-principle challenges. Alternatively, numerical weather prediction models in a hypothetical climate setting can provide tailored narratives of high-resolution simulations of high-impact weather in a future climate. This 'tales of future weather' approach will aid in the interpretation of lower-resolution simulations. Arguably, it potentially provides complementary, more realistic and more physically consistent pictures of what future weather might look like.
DOI: 10.1038/nclimate2450

Sensitivity of climate change detection and attribution to the characterization of internal climate variability

Imbers, J., Lopez, A., Huntingford, C. and Allen, M. (2014) *Journal of Climate,* 27, 3477-3491

The Intergovernmental Panel on Climate Change's (IPCC) "very likely" statement that anthropogenic emissions are affecting climate is based on a statistical detection and attribution methodology that strongly depends on the characterization of internal climate variability. In this paper, the authors test the robustness of this statement in the case of global mean surface air temperature, under different representations of such variability. The contributions of the different natural and anthropogenic forcings to the global mean surface air temperature response are computed using a box diffusion model. Representations of internal climate variability are explored using simple stochastic models that nevertheless span a representative range of plausible temporal autocorrelation structures, including the short-memory first-order autoregressive [AR(1)] process and the long-memory fractionally differencing process. The authors find that, independently of the representation chosen, the greenhouse gas signal remains statistically significant under the detection model employed in this paper. The results support the robustness of the IPCC detection and attribution statement for global mean temperature change under different characterizations of internal variability, but they also suggest that a wider variety of robustness tests, other than simple comparisons of residual variance, should be performed when dealing with other climate variables and/or different spatial scales.
DOI: 10.1175/JCLI-D-12-00622.1

Insuring future climate catastrophes

Kunreuther, H., Michel-Kerjan, E. and Ranger, N. (2013), *Climatic Change,* 118, 339–354

The combined influences of a change in climate patterns and the increased concentration of property and economic activity in hazard-prone areas has the potential of restricting the availability and affordability of insurance. This paper evaluates the premiums that private insurers are likely to charge and their ability to cover residential losses against hurricane risk in Florida as a function of (a) recent projections on future hurricane activity in 2020 and 2040; (b) insurance market conditions (ie, soft or hard market); (c) the availability of reinsurance; and (d) the adoption of adaptation measures (ie, implementation of physical risk reduction measures to reduce wind damage to the structure and buildings). We find that uncertainties in climate projections translate into a divergent picture for insurance in Florida. Under dynamic climate models, the total price of insurance for Florida (assuming constant exposure) could increase significantly by 2040, from $12.9 billion (in 1990) to $14.2 billion, under hard market conditions. Under lower bound projections, premiums could decline to $9.4 billion by 2040. Taking a broader range of climate change scenarios, including several statistical ones, prices could be between $4.7 and $32.1 billion by 2040. The upper end of this range suggests that insurance could be unaffordable for many people in Florida. The adoption of most recent building codes for all residences in the state could reduce by nearly half the expected price of insurance so that even under high climate change scenarios, insurance premiums would be lower than under the 1990 baseline climate scenario. Under a full adaptation scenario, if insurers can obtain reinsurance, they will be able to cover

100 per cent of the loss if they allocated 10 per cent of their surplus to cover a 100-year return hurricane, and 63 per cent and 55 per cent of losses from a 250-year hurricane in 2020 and 2040. Property-level adaptation and the maintenance of strong and competitive reinsurance markets will thus be essential to maintain the affordability and availability of insurance in the new era of catastrophe risk.

DOI: 10.1007/s10584-012-0625-z

Robustness of pattern scaled climate change scenarios for adaptation decision support

Lopez, A., Smith, L.A. and Suckling, E.B. (2014) *Climatic Change,* 122 (4), 555-566

[Based on Technical Paper 13, Dec 2011]

Pattern scaling offers the promise of exploring spatial details of the climate system response to anthropogenic climate forcings without their full simulation by state-of-the-art Global Climate Models. The circumstances in which pattern scaling methods are capable of delivering on this promise are explored by quantifying its performance in an idealized setting. Given a large ensemble that is assumed to sample the full range of variability and provide quantitative decision-relevant information, the soundness of applying the pattern scaling methodology to generate decision-relevant climate scenarios is explored. Pattern scaling is not expected to reproduce its target exactly, of course, and its generic limitations have been well documented since it was first proposed. In this work, using as a particular example the quantification of the risk of heat waves in Southern Europe, it is shown that the magnitude of the error in the pattern scaled estimates can be significant enough to disqualify the use of this approach in quantitative decision support. This suggests that future application of pattern scaling in climate science should provide decision-makers not just a restatement of the assumptions made, but also evidence that the methodology is adequate for purpose in practice for the case under consideration.

DOI: 10.1007/s10584-013-1022-y

Do probabilistic expert elicitations capture scientists' uncertainty about climate change?

Millner, A. , Calel, R., Stainforth, D.A. and MacKerron, G. (2013) *Climatic Change,* 116:427-436

This paper shows that existing expert elicitation studies – which have become important barometers of scientific knowledge about future climate change - may qualitatively understate the extent of experts' uncertainty about climate change. The authors designed a choice experiment that allows them to empirically determine whether experts' knowledge about climate sensitivity (the equilibrium surface warming that results from a doubling of atmospheric CO^2 concentration) can be captured by subjective probabilities. The results show that, even for this much-studied and well understood quantity, a non-negligible proportion of climate scientists violate the choice axioms that must be satisfied for subjective probabilities to adequately describe their beliefs. Moreover, the cause of their violation of the axioms is the ambiguity in their knowledge. The authors expect these results to hold to a greater extent for less understood climate variables, calling into question the veracity of previous elicitations for these quantities. The experimental design provides an instrument for detecting ambiguity, a valuable new source of information when linking climate science and climate policy which can help policy-makers select decision tools appropriate to our true state of knowledge.

DOI: 10.1007/s10584-012-0620-4

Scientific ambiguity and climate policy

Millner, A., Dietz, S. and Heal, G. (2013) ***Environmental and Resource Economics,*** **55(1), 21-46**

[Based on Technical Paper 4, December 2010]

This paper focuses on current (and improved) handling of ambiguity in climate mitigation policy. Economic evaluation of climate policy traditionally treats uncertainty by appealing to expected utility theory. Yet our knowledge of the impacts of climate policy may not be of sufficient quality to be described by unique probabilistic beliefs. In such circumstances, it has been argued that the axioms of expected utility theory may not be the correct standard of rationality. By contrast, several axiomatic frameworks have recently been proposed that account for ambiguous knowledge. In this paper, the authors apply static and dynamic versions of a smooth ambiguity model to climate mitigation policy. They obtain a general result on the comparative statics of optimal abatement and ambiguity aversion, and then extend the analysis to a more realistic, dynamic setting, where scientific ambiguity is introduced into the well-known DICE model of the climate-economy system. For policy-relevant exogenous mitigation policies, the authors show that the value of emissions abatement increases as ambiguity aversion increases, and that this "ambiguity premium" can in some plausible cases be very large. In these cases the effect of ambiguity aversion on welfare is comparable to that of other much studied welfare parameters. Thus ambiguity aversion may be an important neglected aspect of climate change economics, and seems likely to provide another argument for strong abatement policy.
DOI: 10.1007/s10640-012-9612-0

Normalizing Economic Loss from Natural Disasters: A Global Analysis

Neumayer, E. and Barthel, F. (2011) ***Global Environmental Change,*** **21 (1), 13-24**

[Based on Technical Paper 6, November 2010]

Climate change is likely to lead to an increase in the frequency and/or intensity of certain types of natural hazards, if not globally, then at least in certain regions. All other things equal, this should lead to an increase in the economic toll from natural disasters over time. Yet, all other things are not equal, since affected areas become wealthier over time and rational individuals and governments undertake defensive mitigation measures, which requires normalizing economic losses if one wishes to analyse trends in economic loss from natural disasters for detecting a potential climate change signal. In this working paper, we argue that the conventional methodology for normalizing economic loss is problematic since it normalizes for changes in wealth over time, but fails to normalize for differences in wealth across space at any given point of time. We introduce an alternative methodology that overcomes this problem in theory, but faces many more problems in its empirical application. Applying, therefore, both methods to the most comprehensive existing global dataset of natural disaster loss, in general we find no significant upward trends in normalized disaster damage over the period 1980 to 2009 globally, regionally, for specific disasters or for specific disasters in specific regions. Due to our inability to control for defensive mitigation measures, one cannot infer from our analysis that there have definitely not been more frequent and/or more intensive weather-related natural hazards over the study period already. Moreover, it may still be far too early to detect a trend if human-induced climate change has only just started and will gain momentum over time.
DOI: 10.1016/j.gloenvcha.2010.10.004

Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments

Ranger, N. and Niehörster, F. (2012) *Global Environmental Change,* 22, 703-712

[Based on Technical Paper 8, July 2011]

Current projections of long-term trends in Atlantic hurricane activity due to climate change are deeply uncertain, both in magnitude and sign. This creates challenges for adaptation planning in exposed coastal communities. We present a framework to support the interpretation of current long-term tropical cyclone projections, which accommodates the nature of the uncertainty, and aims to facilitate robust decision making using the information that is available today. The framework is populated with projections taken from the recent literature to develop a set of scenarios of long-term hurricane hazard. Hazard scenarios are then used to generate risk scenarios for Florida using a coupled climate-catastrophe modelling approach. The scenarios represent a broad range of plausible futures; from wind-related hurricane losses in Florida halving by the end of the century, to more than a four-fold increase due to climate change alone. We suggest that it is not possible, based on current evidence, to meaningfully quantify the relative confidence of each scenario. The analyses also suggest that natural variability is likely to be the dominant driver of the level and volatility of wind-related risk over the coming decade; however, under the highest scenario, the superposition of this natural variability and anthropogenic climate change could mean notably increased levels of risk within the decade. Finally, we present a series of analyses to better understand the relative adequacy of the different models that underpin the scenarios and draw conclusions for the design of future climate science and modelling experiments to be most informative for adaptation.
DOI: doi:10.1016/j.gloenvcha.2012.03.009

A preliminary assessment of the impact of climate change on non-life insurance demand in the BRICS economies

Ranger, N. and Surminski, S. (2013), *International Journal of Disaster Risk Reduction,* 3, 14-30

[Based on Technical Paper 12, September 2011]

Over the past decade, the increase in insurance demand in the BRICS has been a key driver of global non-life premium growth. Current forecasts suggest that these markets will continue to be areas of significant expansion. For example, based on a simple model, we project that gross premium volumes in the BRICS economies could increase at a rate of between 5.4 and 12.3 per cent per year over the coming decade, depending on the country. We consider how climate change may influence these trends in the period to 2030. We argue that the influence of climate change will be more multifaceted, complex and regionally variable than portrayed in the past. We suggest five pathways of influence: wealth; willingness to pay for insurance; policy and regulation; changes to the supply of insurance; and new opportunities associated with adaptation and mitigation. We conclude that, with the exception of policy and regulation, the influence of climate change on insurance demand to 2030 is likely to be small when compared with the expected growth due to rising incomes, but is not insignificant. For example, we expect the impact on premium volumes mediated through wealth to be small; less than a 0.4 per cent adjustment in the annual growth rate to 2030. But, we also conclude that the scale of the risks and opportunities will depend partly on (re)insurer responses to the challenges of climate change. We outline five actions that could pave the way for future opportunities.
DOI: doi:10.1016/j.ijdrr.2012.11.004

"Better communication of uncertainty in today's science, improved science education in the use of simulation modelling that values scientific understanding of the entire system, and the communication of all (known) varieties of uncertainty will both improve how science handles uncertainty in the future and improve the use of science in support of sound policy-making today."

(Smith and Stern, 2011)

Uncertainty in science and its role in climate policy

Smith, L.A. and Stern, N. (2011), *Phil. Trans.* R. Soc. A, 369, 1-24

Policy-making is usually about risk management. Thus, the handling of uncertainty in science is central to its support of sound policy-making. There is value in scientists engaging in a deep conversation with policy-makers and others, not merely "delivering" results or analyses and then playing no further role. Communicating the policy relevance of different varieties of uncertainty, including imprecision, ambiguity, intractability and indeterminism, is an important part of this conversation. Uncertainty is handled better when scientists engage with policy-makers. Climate policy aims both to alter future risks (particularly via mitigation) and to take account of and respond to relevant remaining risks (via adaptation) in the complex causal chain that begins and ends with individuals. Policy-making profits from learning how to shift the distribution of risks towards less dangerous impacts, even if the probability of events remains uncertain. Immediate value lies not only in communicating how risks may change with time and how those risks may be changed by action, but also in projecting how our understanding of those risks may improve with time (via science) and how our ability to influence them may advance (via technology and policy design). Guidance on the most urgent places to gather information and realistic estimates of when to expect more informative answers is of immediate value, as are plausible estimates of the risk of delaying action. Risk assessment requires grappling with probability and ambiguity (uncertainty in the Knightian sense) and assessing the ethical, logical, philosophical and economic underpinnings of whether a target of '50 per cent chance of remaining under +2°C' is either 'right' or 'safe'. How do we better stimulate advances in the difficult analytical and philosophical questions while maintaining foundational scientific work advancing our understanding of the phenomena? And provide immediate help with decisions that must be made now?

DOI: 10.1098/rsta.2011.0149

Probabilistic skill in ensemble seasonal forecasts

Smith, L.A., Du, H.L., Suckling, E.B. and Niehörster, F. (2014) *Quarterly Journal of the Royal Meteorological Society,* DOI:10.1002/qj.2403

[Based on Technical Paper 20, February 2014]

Operational seasonal forecasting centres employ simulation models to make probability forecasts of future conditions on seasonal to annual lead times. Skill in such forecasts is reflected in the information they add to purely empirical statistical models, or to earlier versions of simulation models. An evaluation of seasonal probability forecasts from the DEMETER and the ENSEMBLES multi-model ensemble experiments is presented. Two particular regions are considered (Nino3.4 in the Pacific and Main Development Region in the Atlantic); these regions were chosen before any spatial distribution of skill were examined. The ENSEMBLES models are found to have skill against the climatological distribution on seasonal time scales; for models in ENSEMBLES which have a clearly defined predecessor model in DEMETER the improvement from DEMETER to ENSEMBLES is discussed. Due to the long lead times of the forecasts and the evolution of observation technology, the forecast-outcome archive for seasonal forecast evaluation is small; arguably evaluation data for seasonal forecasting will always be precious. Issues of information contamination from in-sample evaluation are discussed, impacts (both positive and negative) of variations in cross-validation protocol are demonstrated. Other difficulties due to the small forecast-outcome archive are identified. The claim that the multi-model ensemble provides a "better" probability forecast than the best single model is examined and challenged. Significant forecast information beyond the climatological distribution is also found in a probability forecast based on persistence. On seasonal time scales, the ENSEMBLES simulation based probability forecasts add significantly more information to empirical probability forecasts than on decadal scales. It is suggested most skillful operational seasonal forecasts available would meld information both from simulation models and empirical models.

DOI: 10.1002/qj.2403

Towards improving the framework for probabilistic forecast evaluation

Smith, L.A., Suckling, E.B., Thompson, E.L., Maynard, T. and Du, H.L., *Climatic Change,* in press, 2015

The evaluation of forecast performance plays a central role both in the interpretation and use of model simulations, and in model development. Different evaluation measures (scores) are available, each often quantifying different characteristics of forecast performance. The properties of several scores for probabilistic forecast evaluation are first considered in an abstract sense and then used to interpret decadal probability hindcasts of global mean temperature. The Continuous Ranked Probability Score, Proper Linear score, and IJ Good's logarithmic score (also referred to as Ignorance) are compared; although information from all three may be useful, the logarithmic score has an immediate interpretation and is not insensitive to forecast busts. Benchmark forecasts from simple empirical models like Dynamic Climatology are employed to place the scores in context. Comparing scores for forecast systems based on physical models (in this case HadCM3, from the CMIP5 decadal archive) against such benchmarks is more informative than internal comparison systems based on similar physical simulation models with each other. It is shown that a forecast system based on HadCM3 out performs Dynamic Climatology in decadal global mean temperature hindcasts; Dynamic Climatology previously outperformed a forecast system based upon HadGEM2 and reasons for these results are suggested. Forecasts of aggregate data (five-year means of global mean temperature) are, of course, narrower than forecasts of annual averages due to the suppression of variance; while the average "distance" between the forecasts and a target may be expected to decrease, little if any discernible improvement in probabilistic skill is achieved.

Mapping climate change in European temperature distributions

Stainforth, D.A., Chapman, S.C. and Watkins, N.W. (2013) *Environmental Research Letters,* 8 (034031)

This paper presents a translation of observations of weather into observations of climate change at local scales. The paper shows how the distributions of daily temperatures have changed shape over the last half century. Such information is likely to be valuable in planning adaptation measures.
DOI: 10.1088/1748-9326/8/3/034031

An evaluation of decadal probability forecasts from state-of-the-art climate models

Suckling, E.B and Smith, L.A. (2013), *Journal of Climate,* 26 (23), pp. 9334-9347 (2013)

[Based on Technical paper 19, October 2013]

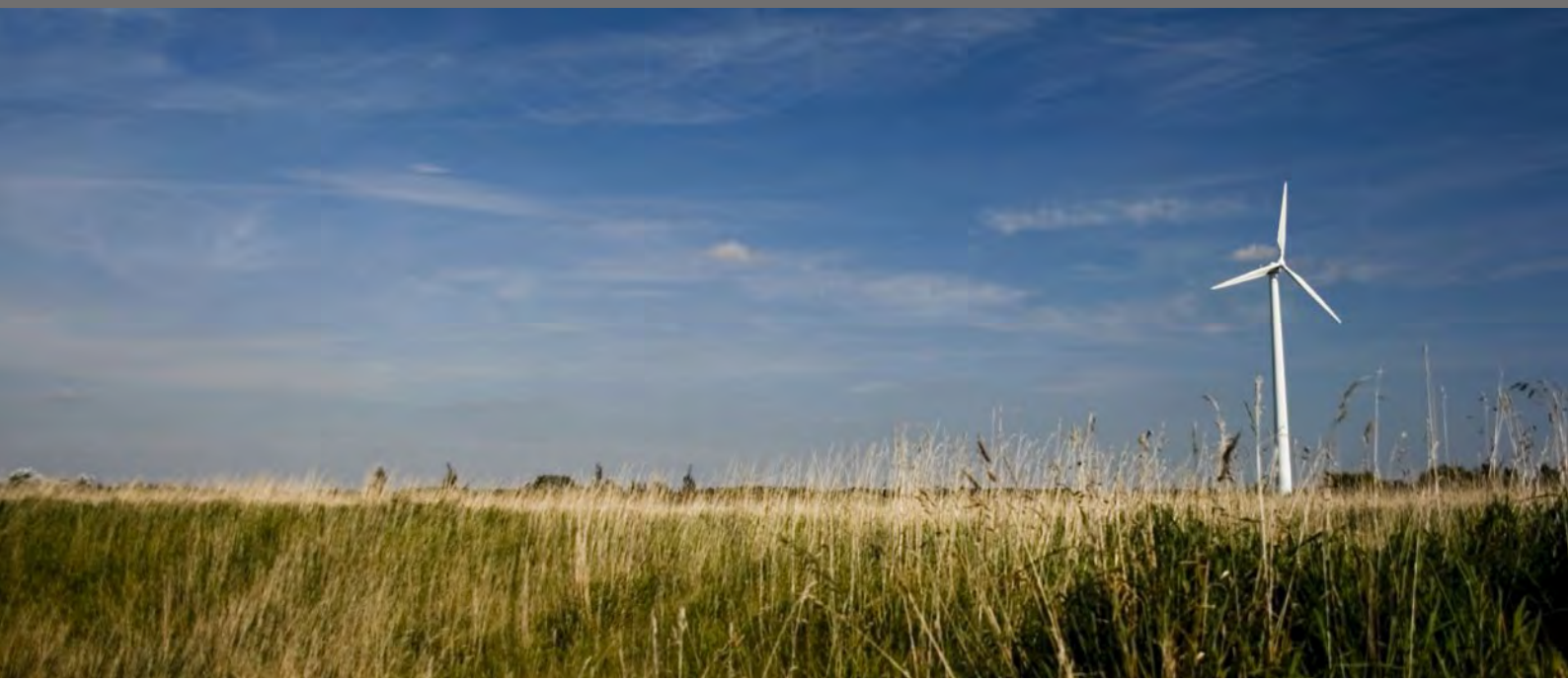
While state-of-the-art models of Earth's climate system have improved tremendously over the last 20 years, nontrivial structural flaws still hinder their ability to forecast the decadal dynamics of the Earth system realistically. Contrasting the skill of these models not only with each other but also with empirical models can reveal the space and time scales on which simulation models exploit their physical basis effectively and quantify their ability to add information to operational forecasts. The skill of decadal probabilistic hindcasts for annual global-mean and regional-mean temperatures from the EU Ensemble-Based Predictions of Climate Changes and Their Impacts (ENSEMBLES) project is contrasted with several empirical models. Both the ENSEMBLES models and a "dynamic climatology" empirical model show probabilistic skill above that of a static climatology for global-mean temperature. The dynamic climatology model, however, often outperforms the ENSEMBLES models. The fact that empirical models display skill similar to that of today's state-of-the-art simulation models suggests that empirical forecasts can improve decadal forecasts for climate services, just as in weather, medium-range, and seasonal forecasting. It is suggested that the direct comparison of simulation models with empirical models becomes a regular component of large model forecast evaluations. Doing so would clarify the extent to which state-of-the-art simulation models provide information beyond that available from simpler empirical models and clarify current limitations in using simulation forecasting for decision support. Ultimately, the skill of simulation models based on physical principles is expected to surpass that of empirical models in a changing climate; their direct comparison provides information on progress toward that goal, which is not available in model-model intercomparisons.
DOI: 10.1175/JCLI-D-12-00485.1

Natural catastrophe insurance in China: policy and regulatory drivers for the agricultural and the property sectors

Surminski, S. (2013) in Orie, M. and Stahel, W.R. (eds.) *The Geneva Reports Risk and Insurance Research: Insurers' contributions to disaster reduction – a series of case studies*, No. 7, 2013. The Geneva Association: Geneva, Switzerland.

While insurance cover against catastrophe and natural disaster has long been in place for agriculture in China, its availability remains limited for individuals and small to medium-sized businesses. In the case of agriculture, insurance is seen as an effective way to achieve overall public policy aims; no such driver has yet developed for the property-owning sector. The rapidly growing urbanisation of the Chinese population and its concentration along the eastern coastal regions, which are particularly exposed to the potential effects of sea level rise and extreme weather events such as typhoons, has greatly increased exposure to risk and this may trigger more public policy support for new risk management measures in the property sector. The liberalisation of the Chinese economy could encourage the greater participation of the private insurers, but an optimal balance between public and private involvement has yet to be found.
DOI: 10.1016/j.ijdrr.2013.10.005

Appendix 1: Papers and posters



Policy indexes as tools for decision-makers – the case of climate policy

Surminski, S. and Williamson, A. (2014) *Global Policy,* 5 (3), 275-285

[Based on Technical Paper 14, September 2012]

The last two decades have witnessed an explosion in the publication of country indexes that measure and rank the relative policy performances of governments. Whilst there is a well understood audience for such rankings amongst policy-makers and the media, much less is known about their use and applicability to business users and business planning. In this study, we explore if and how policy indexes can assist business decision-making, and compare and contrast the strength and weaknesses of using indexes between their current target audience of government decision-makers and business planners. We focus on one particular area – climate policy – where several of these types of indexes have been developed, all with different aims, varying in methodology applied and data used. Our analysis is supported by an investigation of the information content of these climate change indexes and by a number of stakeholder interviews with business representatives. Despite several challenges and limitations to the use of policy indexes by business leaders, we suggest that the need for data and information to support business planning and market entry decisions is strong – particularly in emerging markets and in sectors that face political uncertainty.
DOI: 10.1111/1758-5899.12121

Ambiguity and insurance: robust capital requirements and premiums

Walker, O. and Dietz, S. in revise and resubmit mode with the *Journal of Risk and Insurance*

[Based on Technical Paper 16, November 2012]

Many insurance and reinsurance contracts are contingent on events such as hurricanes, terrorist attacks or political upheavals whose probabilities are not known with precision. There is a body of experimental evidence showing that higher premiums are charged for these "ambiguous" contracts, which may in turn inhibit (re) insurance transactions, but little research analysing explicitly how and why premiums are loaded in this way. In this paper we model the effect of ambiguity on the capital requirement of a (re)insurer whose objectives are profit maximisation and robustness. The latter objective means that it must hold enough capital to meet a survival constraint across a range of available estimates of the probability of ruin. We provide characterisations of when one book of insurance is more ambiguous than another and formally explore the circumstances in which a more ambiguous book requires at least as large a capital holding. This analysis allows us to derive several explicit formulae for the price of ambiguous insurance contracts, each of which identifies the extra ambiguity load.
www.cccep.ac.uk/Publications/Working-papers/Papers/110-119/WP115-ambiguity-insurance-capital-premiums.pdf

ii) Academic papers related to the Munich Re Programme

Each of the 33 papers listed in this section derived significant benefit from research and personnel of the Munich Re Programme. While their primary source of funding was not the Programme, the Munich Re Programme created the environment in which they were created, and often the material and circumstances without which they would not have been written.

Model Error and Ensemble Forecasting: A Cautionary Tale

Bradley, S., Frigg, R., Du, H.L and Smith, L.A. (2014) in Guichun C. Guo and Chuang Liu (eds.) *Scientific Explanation and Methodology of Science,* Singapore: World Scientific, pp. 58-66

This paper provides examples and illustrations, in a controlled mathematical context, of how model inadequacy can cause predictions to break down. In particular, a simple nonlinear system is show to yield seriously misleading probability forecasts in cases where the system being forecast is another mathematical model, and thus the "model error" is known and known to be "small" by any common measure.
DOI: 10.1142/9789814596640_0005

The Clean Development Mechanism and CER Price Formation in the Carbon Markets

Carmona, R. and Fehr, M. (2011), in *Seminar on Stochastic Analysis,* Random Fields and Applications VI, Progress in Probability, Volume 63, 2011, 341-383

The goal of this paper is to propose an equilibrium model for the joint price formation of allowances issued by regulators in the framework of a cap-and-trade scheme and offset certificates such as CERs generated within the framework of the Clean Development Mechanism (CDM) or the Joint Implemenation (JI) of the Kyoto Protocol. Thereby we consider a system of cap-and-trade schemes, such as, eg, the EU ETS and a possible American Market (US ETS) or Japan ETS, which are linked indirectly by the Clean Development Mechanism and for which banking is allowed. Besides deriving equilibrium price formulas for the joint price dynamics of these linked markets, the main thrust of the paper is to explain the spreads between European emission allowances (EUAs) and CERs as observed historically.
DOI: 10.1.1.380.962

Parameter estimation using ignorance

Du, H.L. and Smith, L.A. (2012) *Physical Review* E, 86: 016213

Dynamical modeling lies at the heart of our understanding of physical systems. Its role in science is deeper than mere operational forecasting, in that it allows us to evaluate the adequacy of the mathematical structure of our models. Despite the importance of model parameters, there is no general method of parameter estimation outside linear systems. A relatively simple method of parameter estimation for nonlinear systems is introduced, based on variations in the accuracy of probability forecasts. It is illustrated on the logistic map, the Henon map, and the 12-dimensional Lorenz96 flow, and its ability to outperform linear least squares in these systems is explored at various noise levels and sampling rates. As expected, it is more effective when the forecast error distributions are non-Gaussian. The method selects parameter values by minimizing a proper, local skill score for continuous probability forecasts as a function of the parameter values. This approach is easier to implement in practice than alternative nonlinear methods based on the geometry of attractors or the ability of the model to shadow the observations. Direct measures of inadequacy in the model, the "implied ignorance", and the information deficit are introduced.
DOI: 10.1103/PhysRevE.86.016213

Pseudo-orbit Data Assimilation Part I: The Perfect Model Scenario

Du, H.L and Smith, L.A. (2014) *Journal of the Atmospheric Sciences,* DOI: 10.1175/JAS-D-13-032.1

This paper introduces a concrete, constructive approach toward embracing model error within the simulation of large nonlinear models. This first part sets the mathematical stage by considering a new approach to data assimilation, illustrated in the perfect model scenario. This perfect model scenario is often assumed but rarely justified in medium-range, seasonal, decadal and climate model data assimilation. The foundations laid in this paper provide the context for understanding quantitatively how to measure the strengths and limitations of using geophysical models for decision support.
DOI: 10.1175/JAS-D-13-032.1

Pseudo-orbit Data Assimilation Part II: Assimilation with Imperfect Models

Du, H.L and Smith, L.A. (2014) *Journal of the Atmospheric Sciences,* DOI: 10.1175/JAS-D-13-033.1

This paper builds on the foundations of Part I to illustrate how data assimilation can be generalized to imperfect models, as are all geophysical models. By adopting a search for pseudo-orbits with respect to the limitations of our models, this approach encourages both better simulation in practice and examination of the strengths and limitations in the fidelity of a given model. Such information allows better risk management, as well as clarifying the immediate aims of model development.
DOI: 10.1175/JAS-D-13-033.1

Modelling the Impact of Climate Change on Water Resources

Fai Fung, C., Lopez, A. and New, M. (eds.), Wiley, 2010

The quantitative assessment of the impact of climate change on water availability and water resources management requires knowledge of climate, hydro(geo) logical and water resources models, and particularly the relationships between each of them. This book brings together world experts on each of these aspects, distilling each complex topic into concise and easy to understand chapters, in which both the uses and limitations of modelling are explored. The book concludes with a set of case studies using real-life examples to illustrate the steps required and the problems that can be faced in assessing the potential impacts of climate change on water resource systems.
DOI: 10.1002/9781444324921.fmatter

Storage costs in commodity option pricing

Fehr, M. and Hinz, J. (2010), *Siam Journal on Financial Mathematics,* Vol. 1: 729-751

Unlike derivatives of financial contracts, commodity options exhibit distinct particularities owing to physical aspects of the underlying. An adaptation of no-arbitrage pricing to this kind of derivative turns out to be a stress test, challenging the martingale-based models with diverse technical and technological constraints, with storability and short selling restrictions, and sometimes with the lack of an efficient dynamic hedging. In this work, we study the effect of storability on risk neutral commodity price modeling and suggest a model class where arbitrage is excluded for both commodity futures trading and simultaneous dynamical management of the commodity stock. The proposed framework is based on key results from interest rate theory.
DOI: 10.1137/090746586

Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen

Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer C. and Muir Wood, R. (2011), *Climatic Change,* 104, 113-137

This study illustrates a methodology to assess the economic impacts of climate change at a city scale and benefits of adaptation, taking the case of sea level rise and storm surge risk in the city of Copenhagen, capital of Denmark. The approach is a simplified catastrophe risk assessment, to calculate the direct costs of storm surges under scenarios of sea level rise, coupled to an economic input-output (IO) model. The output is a risk assessment of the direct and indirect economic impacts of storm surge under climate change, including, for example, production and job losses and reconstruction duration, and the benefits of investment in upgraded sea defences. The simplified catastrophe risk assessment entails a statistical analysis of storm surge characteristics,

geographical-information analysis of population and asset exposure combined with aggregated vulnerability information. For the city of Copenhagen, it is found that in absence of adaptation, sea level rise would significantly increase flood risks. Results call for the introduction of adaptation in long-term urban planning, as one part of a comprehensive strategy to manage the implications of climate change in the city. Mitigation policies can also aid adaptation by limiting the pace of future sea level rise.
DOI: 10.1007/s10584-010-9978-3

A global ranking of port cities with high exposure to climate extremes

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., and Chateau, J. (2011), *Climatic Change,* 104, 89-111

This paper presents a first estimate of the exposure of the world's large port cities (population exceeding one million inhabitants in 2005) to coastal flooding due to sea-level rise and storm surge now and in the 2070s, taking into account scenarios of socio-economic and climate changes. The analysis suggests that about 40 million people (0.6 per cent of the global population or roughly 1 in 10 of the total port city population in the cities considered) are currently exposed to a 1 in 100-year coastal flood event. For assets, the total value exposed in 2005 across all cities considered is estimated to be US$3,000 billion; corresponding to around 5 per cent of global GDP in 2005 (both measured in international USD) with USA, Japan and the Netherlands being the countries with the highest values. By the 2070s, total population exposed could grow more than threefold due to the combined effects of sea-level rise, subsidence, population growth and urbanisation with asset exposure increasing to more than ten times current levels or approximately nine per cent of projected global GDP in this period. On the global-scale, population growth, socio-economic growth and urbanization are the most important drivers of the overall increase in exposure particularly in developing countries, as low-lying areas are urbanized. Climate change and subsidence can significantly exacerbate this increase in exposure. Exposure is concentrated in a few cities: collectively Asia dominates population exposure now and in the future and also dominates asset exposure by the 2070s. Importantly, even if the environmental or socio-economic changes were smaller than assumed here the underlying trends would remain. This research shows the high potential benefits from risk-reduction planning and policies at the city scale to address the issues raised by the possible growth in exposure.
DOI: 10.1007/s10584-010-9977-4

The costs and benefits of reducing risk from natural hazards to residential structures in developing countries

Hochrainer-Stigler, S., Kunreuther, H., Linnerooth-Bayer, J., Mechler, R., Michel-Kerjan, E., Muir-Wood, R., Ranger, N., Vaziri, P. and Young, M. (2011). Working Paper 2011-01. Wharton Risk Management and Decision Processes Center.

This paper examines the benefits and costs of improving or retrofitting residential structures in highly exposed low- and middle-income developing countries such that they are less vulnerable to hazards during their lifetime. Since it is misleading to assess the benefits of prevention using deterministic models, the challenges for cost benefit analyses are to express avoided losses in probabilistic terms, evaluate and assess risk, monetize direct and indirect benefits and include dynamic drivers such as changing population, land use and climate. In detail, we examine structures exposed to three different hazards in four countries, including hurricane risk in St. Lucia, flood risk in Jakarta, earthquake risk in Istanbul and flood risk within the Rohini River basin in Uttar Pradesh (India). The purpose in undertaking these analyses is to shed light on the benefits and costs over time, recognizing the bounds of the analysis, and to demonstrate a systematic probabilistic approach for evaluating alternative risk reducing measures. http://opim.wharton.upenn.edu/risk/library/WP2011-01_IIASA,RMS,Wharton_DevelopingCountries.pdf

Testing the robustness of the anthropogenic climate change detection statements using different empirical models

Imbers, J., Lopez, A., Huntingford, C. and Allen, M. (2013) ***Journal of Geophysical Research: Atmospheres,*** **118 (8), 3192-3199**

In this paper the authors aim to test the robustness of the detection and attribution of anthropogenic climate change using four different empirical models that were previously developed to explain the observed global mean temperature changes over the last few decades. These studies postulated that the main drivers of these changes included not only the usual natural forcings, such as solar and volcanic, and anthropogenic forcings, such as greenhouse gases and sulfates, but also other known Earth system oscillations such as El Niño Southern Oscillation (ENSO) or the Atlantic Multidecadal Oscillation (AMO). The authors consider these signals, or forced responses, and test whether or not the anthropogenic signal can be robustly detected under different assumptions for the internal variability of the climate system. They assume that the internal variability of the global mean surface temperature can be described by simple stochastic models that explore a wide range of plausible temporal autocorrelations, ranging from short memory processes exemplified by an AR(1) model to long memory processes, represented by a fractional differenced model. The authors conclude that, in all instances, human-induced changes to atmospheric gas composition are affecting global mean surface temperature changes.
DOI: 10.1002/jgrd.50296

Risk Management and Climate Change

Kunreuther, H., Heal, G., Allen, M., Edenhofer, O., Field, C.B. and Yohe, G. (2013) ***Nature Climate Change*** **3, 447-450**

The selection of climate policies should be an exercise in risk management reflecting the many relevant sources of uncertainty. Studies of climate change and its impacts rarely yield consensus on the distribution of exposure, vulnerability, or possible outcomes. Hence policy analysis cannot effectively evaluate alternatives using standard approaches such as expected utility theory and benefit-cost analysis. This perspective highlights the value of robust decision-making tools designed for situations, such as evaluating climate policies, where generally agreed-upon probability distributions are not available and stakeholders differ in their degree of risk tolerance. This broader risk management approach enables one to examine a range of possible outcomes and the uncertainty surrounding their likelihoods.
DOI: 10.1038/nclimate1740

Integrated Risk and Uncertainty Assessment of Climate Change Response Policies

Kunreuther, H., Gupta, S., Bosetti, V., Cooke, R., Dutt, V., Ha-Duong, M., Held, H., Llanes-Regueiro, J., Patt, A., Shittu, E. and Weber, E. (2014) ***Intergovernmental Panel on Climate Change, Chapter 2, Working Group III to the Fifth Assessment Report of the IPCC*****, November 26, 2014.**
http://opim.wharton.upenn.edu/risk/library/IPCC-AR5-WG3-Ch02_Integrated-Risk+Uncertainty-Assessment-of-Climate-Change-Response-Policies_2014oct.pdf

Warming of the Oceans and Implications for the (Re)insurance Industry

Niehörster, F., Aichinger, M., Murnane, R., Ranger, N. and Surminski, S. (2013), A Geneva Association Report, June 2013

Executive summary: There is new, robust evidence that the global oceans have warmed significantly. Given that energy from the ocean is the key driver of extreme events, ocean warming has effectively caused a shift towards a “new normal” for a number of insurance-relevant hazards. This shift is quasi irreversible – even if greenhouse gas (GHG) emissions completely stop tomorrow, oceanic temperatures will continue to rise. In the non-stationary environment caused by ocean warming, traditional approaches, which are solely based on analysing historical data, increasingly fail to estimate today’s hazard probabilities. A paradigm shift from historic to predictive risk assessment methods is necessary. Due to the limits of predictability and scientific understanding of extreme events in a non-stationary environment, today’s likelihood of extreme events is ambiguous. As a consequence, scenario-based approaches and tail risk modelling become an essential

part of enterprise risk management. In some high-risk areas, ocean warming and climate change threaten the insurability of catastrophe risk more generally. To avoid market failure, the coupling of risk transfer and risk mitigation becomes essential.
www.genevaassociation.org/media/616661/ga2013-warming_of_the_oceans.pdf

Climate simulation, uncertainty, and policy advice: The case of the IPCC

Petersen, A.C. (2011), in Gramelsberger, G., Feichter, J. (Eds.). Climate Change and Policy: *The Calculability of Climate Change and the Challenge of Uncertainty* 91-111. Dordrecht: Springer.

The Intergovernmental Panel on Climate Change (IPCC) is a body of the United Nations established in 1988 which has the responsibility to provide policy-relevant assessments of knowledge pertaining to climate change. While the IPCC does not advise on which climate policies should be agreed upon by the world's nations, it does provide succinct Summaries for Policymakers (SPMs) on the state of knowledge on the causes and effects of human-induced climate change, on mitigation of the causes and on adaptation to the effects. If we are interested in how climate-simulation uncertainty is dealt with in policy advice, the IPCC is a prime location for study.
DOI: 10.1007/978-3-642-17700-2_3

Simulating Nature: A Philosophical Study of Computer-Model Uncertainties and Their Role in Climate Science and Policy Advice

Petersen, A.C. (2012), 2nd ed., CRC Press.

Computer simulation has become an important means for obtaining knowledge about nature. The practice of scientific simulation and the frequent use of uncertain simulation results in public policy raise a wide range of philosophical questions. Most prominently highlighted is the field of anthropogenic climate change – are humans currently changing the climate? Referring to empirical results from science studies and political science, Simulating Nature: A Philosophical Study of Computer-Simulation Uncertainties and Their Role in Climate Science and Policy Advice, Second Edition, addresses questions about the types of uncertainty associated with scientific simulation and about how these uncertainties can be communicated. The author, who participated in the United Nations' Intergovernmental Panel on Climate Change (IPCC) plenaries in 2001 and 2007, discusses the assessment reports and workings of the IPCC. This second edition reflects the latest developments in climate change policy, including a thorough update and rewriting of sections that refer to the IPCC.
www.crcpress.com/product/isbn/9781466500624

Adaptation in the UK: a decision-making process

Ranger, N., Millner, A., Dietz, S., Fankhauser, S. and Ruta, G. (2010) GRI/CCCEP Policy Brief

Climate change is one of the most significant challenges we face. It will impact the UK population, environment and economy in many ways; including health, water supplies, food, ecosystems and damages from extreme weather. While reducing emissions of greenhouse gases is crucial to prevent long-term effects, adapting to climate changes is the only way to limit nearer-term impacts. This policy brief focuses on the planning process for adaptation measures; in particular, how good adaptation decisions can be made with the information available today. We apply a framework with an explicit treatment of the role of risk information and decision factors to four adaptation case studies: flooding, the water sector, the food sector, and ecosystems/biodiversity. The analysis of the four case studies shows that while each present unique challenges in terms of risk identification and decision factors, they also exhibit similarities that can be used to draw out general rules for decision-making.
lse.ac.uk/GranthamInstitute/publication/adaptation-in-the-uk-a-decision-making-process/

An assessment of the potential impact of climate change on flood risk in Mumbai

Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., Herweijer, C., Pohit, S. and Corfee-Morlot, J. (2011), *Climatic Change,* 104, 139-167

Managing risks from extreme events will be a crucial component of climate change adaptation. In this study, we demonstrate an approach to assess future risks and quantify the benefits of adaptation options at a city-scale, with application to flood risk in Mumbai. In 2005, Mumbai experienced unprecedented flooding, causing direct economic damages estimated at almost two billion USD and 500 fatalities. Our findings suggest that by the 2080s, in a SRES A2 scenario, an "upper bound" climate scenario could see the likelihood of a 2005-like event more than double. We estimate that total losses (direct plus indirect) associated with a 1 in 100-year event could triple compared with the current situation (to $690-$1,890 million USD), due to climate change alone. Continued rapid urbanisation could further increase the risk level. The analysis also demonstrates that adaptation could significantly reduce future losses; for example, estimates suggest that by improving the drainage system in Mumbai, losses associated with a 1-in-100 year flood event today could be reduced by as much as 70 per cent.
We show that assessing the indirect costs of extreme events is an important component of an adaptation assessment, both in ensuring the analysis captures the full economic benefits of adaptation and also identifying options that can help to manage indirect risks of disasters. For example, we show that by extending insurance to 100 per cent penetration, the indirect effects of flooding could be almost halved. We conclude that, while this study explores only the upper-bound climate scenario, the risk-assessment core demonstrated in this study could form an important quantitative tool in developing city-scale adaptation strategies. We provide a discussion of sources of uncertainty and risk-based tools could be linked with decision-making approaches to inform adaptation plans that are robust to climate change.
DOI: 10.1007/s10584-010-9979-2

Multi-year contracts to improve risk management culture?

Ranger, N. and Maynard, T. (2013), *Asia Insurance Review.* February 2013

In this extract from The Geneva Papers on Risk and Insurance, Trevor Maynard and Nicola Ranger talk about using the multi-year insurance contracts to help bring about improved individual and societal risk management.
lse.ac.uk/CATS/Publications/Publications%20PDFs/Maynard&Ranger-AsiaInsuranceReview-Feb2013.pdf

Disaster resilience and post-2015 development goals: the options for economics targets and indicators

Ranger, N. and Surminski, S., April 2013, Policy paper, Centre for Climate Change Economics and Policy, Leeds and London, UK.

In 2015, the Millennium Development Goals (MDGs) expire. Detailed discussions are already underway to inform the post-2015 development goals. This paper seeks to inform discussions around appropriate economics targets and indicators for inclusion in the post-2015 framework, recommending a single economic target with an accompanying "basket" of indicators.
lse.ac.uk/GranthamInstitute/wp-content/uploads/2014/03/PP-disaster-resilience-post-2015-development-goals-economics.pdf

Broad range of 2050 warming from an observationally constrained large climate model ensemble

Rowlands, D.J., Frame, D.J., Ackerley, D., Aina, T., Booth, B.B.B., Christensen, C., Collins, M., Faull, N., Forest, C.E., Grandey, B.S., Gryspeerdt, E., Highwood, E.J., Ingram, W.J., Knight, S., Lopez, A., Massey, N., McNamara, F., Meinshausen, N., Piani, C., Rosier, S.M., Sanderson, B.M., Smith, L.A., Stone, D.A., Thurston, M., Yamazaki, K., Yamazaki, Y.H. and Allen, M.R. (2012), *Nature Geoscience,* 5, 256-260.

Incomplete understanding of three aspects of the climate system – equilibrium climate sensitivity, rate of ocean heat uptake and historical aerosol forcing – and the physical processes underlying them lead to uncertainties in our assessment of the global-mean temperature evolution in the 21st century. Explorations of these uncertainties have

so far relied on scaling approaches, large ensembles of simplified climate models, or small ensembles of complex coupled atmosphere–ocean general circulation models which under-represent uncertainties in key climate system properties derived from independent sources. Here we present results from a multi-thousand-member perturbed-physics ensemble of transient coupled atmosphere–ocean general circulation model simulations. We find that model versions that reproduce observed surface temperature changes over the past 50 years show global-mean temperature increases of 1.4-3 K by 2050, relative to 1961-1990, under a mid-range forcing scenario. This range of warming is broadly consistent with the expert assessment provided by the Intergovernmental Panel on Climate Change Fourth Assessment Report, but extends towards larger warming than observed in ensembles-of-opportunity typically used for climate impact assessments. From our simulations, we conclude that warming by the middle of the twenty-first century that is stronger than earlier estimates is consistent with recent observed temperature changes and a mid-range 'no mitigation' scenario for greenhouse-gas emissions.
DOI: 10.1038/ngeo1430

Variations on reliability: connecting climate predictions to climate policy

Smith, L.A. and Petersen, A.C. (2014), in Boumans, M., Hon, G. and Petersen, A.C. (ed.) *Error and Uncertainty in Scientific Practice,* London: Pickering & Chatto.

[Extract from Introduction:] This chapter deals with the implications of uncertainty in the practice of climate modelling for communicating model-based findings to decision-makers, particularly high-resolution predictions intended to inform decision-making on adaptation to climate change. Our general claim is that methodological reflections on uncertainty in scientific practices should provide guidance on how their results can be used more responsibly in decision support. In the case of decisions that need to be made to adapt to climate change, societal actors, both public and private, are confronted with deep uncertainty. In fact, it has been argued that some of the questions these actors may ask 'cannot be answered by science'. In this chapter, the notions of 'reliability' are examined critically, in particular the manner(s) in which the reliability of climate model findings pertaining to model-based high-resolution climate predictions is communicated.
lse.ac.uk/CATS/Publications/Publications%20PDFs/Smith-Petersen-Variations-on-reliability-2014.pdf

The role of insurance risk transfer in encouraging climate investment in developing countries

Surminski, S. (2013) in Dupuy, P-M., Viñuales, J.E. (eds.) *Harnessing foreign investment to promote environmental protection.* Cambridge University Press, Cambridge, UK, 228-250

[Extract from Introduction:] Environmental change has profound effects on economies, wider society, individuals and ecosystems. Responding to threats such as pollution, loss of biodiversity or climatic changes requires public policy intervention, as well as private action and significant new capital investments. Under the caption of "sustainable development" more and more private companies and national governments pledge to balance the economic, social and environmental effects of growth. Innovative solutions are being developed and tested, especially in the context of financing the required action. One particular area that receives increasing attention is how best to foster public and private investments in environmental protection. This is especially relevant for low-income countries: often those most exposed to environmental changes are least capable to respond to the threats, and require financial and technical support from developed countries and donors. Most commentators have focused on the role of public policy in facilitating the required environmental investments. Conversely, the application of financial instruments such as insurance is still under-researched.

Insurance risk transfer has been used for centuries as a tool to manage the risk of uncertain losses. In its most basic form insurance is a mechanism where risks or part of a risk are transferred from one party (the insured) to another party (the insurer) in return for a payment (the premium). The insurer pays out a previously agreed amount if the insured experiences a loss, or if a predefined event occurs. In other words, the insured pays a certain premium to reduce the risk of an uncertain loss. This reduction in uncertainty is widely seen as an important mechanism driving our economic systems: without insurance many activities and processes would be deemed too risky and would not be undertaken. Moreover, in the event of a loss, those affected might struggle to recover. In economic

terms the justification for any insurance is derived from the welfare function, which means that the provision of insurance can increase the expected utility of individuals, companies or society.
DOI: 10.1017/CBO9781139344289

Private-sector adaptation to climate risk

Surminski, S. (2014), *Nature Climate Change,* 3, 943-945

A small but growing number of companies are addressing climate risks; however, a range of barriers limit wider private-sector adaptation efforts, particularly in developing countries.
DOI: 10.1038/nclimate2040

Observations on the role of the private sector in the UNFCCC's Loss and Damage of climate change work programme

Surminski, S. and Eldridge, J., 2015, International *Journal of Global Warming,* in press.

Private sector engagement, particularly in relation to public policy based action and strategy, has become a buzz word in most policy areas, but this is often accompanied by a lack of clarity on roles and responsibilities between public and private sector. We investigate this for the new United Nations Framework Convention on Climate Change (UNFCCC) work stream on addressing loss and damage (L&D) from climate change. This paper presents evidence gathered from official submissions by Parties and other bodies to the UNFCCC, the small but growing L&D literature, and experience from the related fields of Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA).

The results from the study show: a degree of "vagueness" when it comes to outlining the role the private sector, but expectation that they will support the emerging L&D framework through knowledge, skills and resource. Private sector engagement is mainly seen in the context of utilizing private sector expertise based in developed countries, rather than assessing current and future impacts on the growing private sector in developing countries. Unclear conceptual boundaries of L&D, DRR and CCA are posing a challenge for stakeholders.
While evidence of existing engagement in the L&D debate is noticeable for the insurance industry, there remains only a limited understanding on how to actually measure the effectiveness of such private sector engagement. Creating greater clarity on expectations of, and the ability to deliver by, the private sector would be important tasks for the UNFCCC to focus on.
lse.ac.uk/GranthamInstitute/publication/observations-on-the-role-of-the-private-sector-in-the-unfcccs-loss-and-damage-of-climate-change-work-programme-working-paper-142/

The concept of Loss and Damage of climate change – a new challenge for climate decision-making? A science perspective

Surminski, S. and Lopez, A. (2014) *Climate and Development,* DOI:10.1080/17565529.2014.934770

Loss and damage (L&D) of climate change is a relatively new work stream of the international climate change regime. Lacking a clear official definition, L&D has triggered a debate about framing the topic, incorporating technical aspects of disaster risk reduction (DRR) and climate change adaptation as well as political considerations such as the idea of compensation for vulnerable countries. This paper reviews the implications of L&D for decision-making with a special focus on the role of climate science. We identify three broad policy goals embedded in the discussion: creating awareness about the sensitivity of human and natural systems to climate change; developing risk reduction and risk management approaches to enhance adaptation, reduce vulnerability and build resilience and informing compensation mechanisms. For all of these, an understanding of the current and future climate-related L&D is needed. Existing decision-making frameworks can help deal with uncertainties and avoid a "wait and see" mentality for most L&D decisions. The compensation component of L&D, however, offers a different dimension to the climate change discussion. While recognizing the political and moral reasons driving the debate around compensation, an increased focus on the complex and possibly unsolvable attribution question might put on

hold efforts to integrate adaptation to climate change with wider development aims and DRR, blocking necessary action.
DOI: 10.1080/17565529.2014.934770

Building effective and sustainable risk transfer initiatives in low- and middle-income economies: what can we learn from existing insurance schemes

Surminski, S. and Oramas-Dorta, D. (2011) Policy Paper, Centre for Climate Change Economics and Policy Grantham Research Institute on Climate Change and the Environment, Leeds and London, UK.

Negotiators for Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are exploring if and how risk transfer solutions could enhance adaptation efforts in those countries that are most vulnerable and exposed to the impacts of extreme weather events that are expected to be affected by climate change. One concept that is being investigated is a climate insurance facility.

This paper is intended to inform the UNFCCC's discussions about 'Loss and Damage' by providing evidence-based information about existing risk transfer schemes in developing countries. It examines 123 natural hazard risk transfer initiatives from the Disaster Risk Transfer Compendium collated by the ClimateWise insurance initiative.
lse.ac.uk/GranthamInstitute/publication/building-effective-and-sustainable-risk-transfer-initiatives-in-low-and-middle-income-economies-what-can-we-learn-from-existing-insurance-schemes/

Flood insurance schemes and climate adaptation in developing countries

Surminski, S. and Oramas-Dorta, D. (2014) ***International Journal of Disaster Risk Reduction,*** **Volume 7, March 2014, 154-164**

Risk transfer, including insurance, is widely recognized as a tool for increasing financial resilience to severe weather events such as floods. The application of this mechanism varies widely across countries, with a range of different types and schemes in operation. While most of the analytical focus has so far been on those markets that have a long tradition of insurance, there is still a clear gap in our understanding of how this mechanism works in a developing country context. This paper assesses 27 insurance schemes that transfer the risk of economic losses arising from floods in low- and middle-income countries, focusing on the linkages between financial risk transfer and risk reduction. This aspect is important to avoid the effect of moral hazard and has gained particular relevance in the context of the climate change adaptation discourse, where some scholars and practitioners view insurance as a potential tool not just for current risks, but also to address projected future impacts of a changing climate by incentivizing risk reduction. We therefore look beyond the pure financial risk transfer nature of those 27 insurance schemes and investigate any prevention and risk reduction elements. Our analysis suggests that the potential for utilizing risk transfer for risk reduction is far from exhausted, with only very few schemes showing an operational link between risk transfer and risk reduction, while the effectiveness and implementation on the ground remains unclear. The dearth of linkages between risk reduction and insurance is a missed opportunity in the efforts to address rising risk levels, particularly in the context of climate change. Rising risk levels pose a threat to the insurability of floods, and insurance without risk reduction elements could lead to moral hazard. Therefore a closer linkage between risk transfer and risk reduction could make this a more sustainable and robust tool.
DOI: 10.1016/j.ijdrr.2013.10.005

Climate change and extreme weather events in developing countries. Future Risk: climate change and energy security – global challenges and implications

Surminski, S., June 2012, Chartered Insurance Institute, *Centenary Future Risk Series: Report 3*. Chartered Insurance Institute, London, UK
www.cii.co.uk/media/2300239/c12j_7194_environmental_report_2012_web.pdf

Adaptation Planning and Implementation

Surminski, S., contributing author to Mimura, Pulwarty et al. (2014) Chapter 15 in Fields, C. et al. (eds.) *IPCC WP2 5th Assessment Report – Impacts, Adaptation and Vulnerability.* Intergovernmental Panel on Climate Change
https://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap15_FINAL.pdf

Detecting instabilities in tree-ring proxy calibration

Visser, H., Büntgen, U., D'Arrigo, R. and Petersen, A. C. (2010), *Climate of the Past* 6(3), 367-377

Evidence has been found for reduced sensitivity of tree growth to temperature in a number of forests at high northern latitudes and alpine locations. Furthermore, at some of these sites, emergent subpopulations of trees show negative growth trends with rising temperature. These findings are typically referred to as the "Divergence Problem" (DP). Given the high relevance of paleoclimatic reconstructions for policy-related studies, it is important for dendrochronologists to address this issue of potential model uncertainties associated with the DP. Here we address this issue by proposing a calibration technique, termed "stochastic response function" (SRF), which allows the presence or absence of any instabilities in growth response of trees (or any other climate proxy) to their calibration target to be visualized and detected. Since this framework estimates confidence limits and subsequently provides statistical significance tests, the approach is also very well suited for proxy screening prior to the generation of a climate-reconstruction network.

Two examples of tree growth/climate relationships are provided, one from the North American Arctic treeline and the other from the upper treeline in the European Alps. Instabilities were found to be present where stabilities were reported in the literature, and vice versa, stabilities were found where instabilities were reported. We advise to apply SRFs in future proxy-screening schemes, next to the use of correlations and RE/CE statistics. It will improve the strength of reconstruction hindcasts.
DOI: 10.5194/cp-6-367-2010

Inferences on weather extremes and weather-related disasters: a review of statistical methods

Visser, H. and Petersen, A. C. (2012), *Climate of the Past* 8(1), 265-286

The study of weather extremes and their impacts, such as weather-related disasters, plays an important role in research of climate change. Due to the great societal consequences of extremes – historically, now and in the future – the peer-reviewed literature on this theme has been growing enormously since the 1980s. Data sources have a wide origin, from century-long climate reconstructions from tree rings to relatively short (30 to 60-year) databases with disaster statistics and human impacts.

When scanning peer-reviewed literature on weather extremes and its impacts, it is noticeable that many different methods are used to make inferences. However, discussions on these methods are rare. Such discussions are important since a particular methodological choice might substantially influence the inferences made. A calculation of a return period of once in 500 years, based on a normal distribution will deviate from that based on a Gumbel distribution. And the particular choice between a linear or a flexible trend model might influence inferences as well.

In this article, a concise overview of statistical methods applied in the field of weather extremes and weather-related disasters is given. Methods have been evaluated as to stationarity assumptions, the choice for specific probability density functions (PDFs) and the availability of uncertainty information. As for stationarity assumptions, the outcome was that good testing is essential. Inferences on extremes may be wrong if data are assumed stationary while they are not. The same holds for the block-stationarity assumption. As for PDF choices it was found that often more than one PDF shape fits to the same data. From a simulation study the conclusion

can be drawn that both the generalized extreme value (GEV) distribution and the log-normal PDF fit very well to a variety of indicators. The application of the normal and Gumbel distributions is more limited. As for uncertainty, it is advisable to test conclusions on extremes for assumptions underlying the modelling approach. Finally, it can be concluded that the coupling of individual extremes or disasters to climate change should be avoided.
DOI: 10.5194/cp-8-265-2012

On the relation between weather-related disaster impacts, vulnerability and climate change

Visser, H., Petersen, A. C. and Ligtvoet, W. (2014) *Climatic Change* 125(3-4), 461-477

Disasters such as floods, storms, heatwaves and droughts can have enormous implications for health, the environment and economic development. In this article, we address the question of how climate change might have influenced the impact of weather-related disasters. This relation is not straightforward, since disaster burden is not influenced by weather and climate events alone – other drivers are growth in population and wealth, and changes in vulnerability. We normalized disaster impacts, analyzed trends in the data and compared them with trends in extreme weather and climate events and vulnerability, following a 3 by 4 by 3 set-up, with three disaster burden categories, four regions and three extreme weather event categories. The trends in normalized disaster impacts show large differences between regions and weather event categories. Despite these variations, our overall conclusion is that the increasing exposure of people and economic assets is the major cause of increasing trends in disaster impacts. This holds for long-term trends in economic losses as well as the number of people affected. We also found similar, though more qualitative, results for the number of people killed; in all three cases, the role played by climate change cannot be excluded. Furthermore, we found that trends in historic vulnerability tend to be stable over time, despite adaptation measures taken by countries. Based on these findings, we derived disaster impact projections for the coming decades. We argue that projections beyond 2030 are too uncertain, not only due to unknown changes in vulnerability, but also due to increasing non-stationarities in normalization relations.
DOI: 10.1007/s10584-014-1179-z

Adaptation to Climate Change: Linking Disaster Risk Reduction and Insurance

Warner, K., Ranger, N., Surminski, S., Arnold, M., Linnerooth-Bayer, J., Michel-Kerjan, E., Kovacs, P. and Herweijer, C. (2009) *Report for the United National International Strategy for Disaster Reduction Secretariat (UNISDR)*, June 2009

This paper is an initial attempt to consider the role in adaptation of insurance and related risk sharing and risk transfer methods, in the context of a comprehensive approach to risk reduction and risk management. It is the result of informal conversations at Poznan between members of the United Nations International Strategy for Disaster Reduction Secretariat (UNISDR) and the Munich Climate Insurance Initiative (MCII).

It offers a preliminary analysis, produced in the short time required to provide a timely input to the June 2009 negotiations in Bonn. It is neither conclusive nor comprehensive, but aims to provide a useful contribution to the ongoing conversation on the role of insurance in adaptation and reducing disaster risk.

This paper is the work of the authors alone, as a group, and does not necessarily represent the policies or views of the UNISDR or MCII or their partner organizations.
www.preventionweb.net/files/9654_linkingdrrinsurance.pdf

iii) Munich Re Technical Papers

In all, 20 Technical Papers were produced as part of the Programme. These were intended to stimulate discussion within the research community and among users of research. They appeared online quickly and were very effective in stimulating discussion, often with new contacts. Most of these papers were subsequently submitted to academic journals, and most of those which have not yet appeared in the peer reviewed literature have clear offspring in that literature, or are still under review. The details of each Technical Paper are given below, as in the previous two sections, with one exception: where a Technical Paper evolved into a journal paper, and the abstract is identical to that of the journal paper given in section (i) above, the abstract is not repeated in this section.

Economic policy when models disagree

P. Barrieu (with Sinclair-Desgagné), Technical Paper 1, July 2009

This paper proposes a general way to conceive public policy when there is no consensual account of the situation of interest. The approach builds on an extension and dual formulation of the traditional theory of economic policy. It does not need a representative policymaker's utility function (as in the literature on ambiguity), a reference model (as in robust control theory) or some prior probability distribution over the set of supplied scenarios (as in Bayesian model-averaging). The method requires instead that the willingness to accept a policy's projected outcomes coincide with the willingness to pay to correct the current situation. Policies constructed in this manner are shown to be effective, robust and simple in a precise and intuitive sense.
www.cccep.ac.uk/Publications/Working-papers/Abstracts/1-9/Abstract_5.aspx

A more recent version is at:
http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1366989

High impact, low probability? An empirical analysis of risk in the economics of climate change

S. Dietz, Technical Paper 2, Sep 2009
www.cccep.ac.uk/Publications/Working-papers/Abstracts/10-19/Abstract_10.aspx

Properly designed emissions trading schemes do work!

M. Fehr (with R. Carmona and J. Hinz), Technical Paper 3, Nov 2009

Emissions trading markets have been touted as the most efficient mechanism to achieve environmental goals at least cost. Whether in the form of voluntary markets or in a mandatory framework like in the first phase of the European Union (EU) Emission Trading Scheme (ETS), the regulator sets a cap on the emissions which can occur without penalty, and provides emissions allowances accordingly. The recipients are free to use these emission certificates to cover their emissions, or to sell them to the

firms which are expected to emit more than what they can cover with their original allocations.

As observed in most existing programmes, cap-and-trade systems can fail to reach their emission targets as too generous an allocation of pollution permits serves as a disincentive for emissions reductions and deflates pollution prices. Moreover, the implementation of the first phase of the EU ETS has been widely criticized on one more sensitive account: providing significant (some went as far as calling them obscene) windfall profits for power producers.

Here we weight on this debate with the results of a rigorous quantitative modelling undertaking, providing insight into what went wrong in the first phase of the EU ETS, and proposing alternative reduction schemes with provable advantages. Using market equilibrium models and numerical tools, we demonstrate that properly designed market-based pollution reduction mechanisms can reach pre-assigned emissions targets at low reduction cost and windfall profits, while being flexible enough to promote clean technologies. In the present article, we illustrate our claims with the results of a hypothetical cap-and-trade scheme for the Japanese electricity market. www.cccep.ac.uk/Publications/Working-papers/Abstracts/10-19/abstract-WP14.aspx

Ambiguity and climate policy

A. Millner and S. Dietz (with G. Heal), Technical Paper 4, Aug 2010

www.cccep.ac.uk/Publications/Working-papers/Abstracts/20-29/abstract-28.aspx

A Trend Analysis of Normalized Insured Economic Damage from Natural Disasters

E. Neumayer and F. Barthel, Technical Paper 5, Nov 2010

www.cccep.ac.uk/Publications/Working-papers/Abstracts/40-49/WP40-abstract.aspx

Normalizing Economic Loss from Natural Disasters: A Global Analysis

E. Neumayer and F. Barthel, Technical Paper 6, Nov 2010

www.cccep.ac.uk/Publications/Working-papers/Abstracts/40-49/WP41-abstract.aspx

Integrated EUA and CER price modelling and application for spread option pricing

P. Barrieu and M. Fehr, Technical Paper 7, March 2011

www.cccep.ac.uk/Publications/Working-papers/Abstracts/50-59/eua-cer-price-modelling.aspx

Deep uncertainty in long-term hurricane risk: scenario generation and implications for future climate experiments

N. Ranger and F. Niehörster, Technical Paper 8, July 2011

www.cccep.ac.uk/Publications/Working-papers/Abstracts/60-69/uncertainty-hurricane-risk-climate-predictions.aspx

Scientific Uncertainty: A User's Guide

S. Bradley, Technical Paper 9, Aug 2011

There are different kinds of uncertainty. This paper outlines some of the various ways that uncertainty enters science, focusing on uncertainty in climate science and weather prediction. The paper goes on to show how we cope with some of these sources of error through sophisticated modelling techniques. The paper shows how to maintain confidence in the face of error. www.cccep.ac.uk/Publications/Working-papers/Abstracts/60-69/scientific-uncertainty-users-guide.aspx

A representation result for choice under conscious unawareness

O. Walker and S. Dietz, Technical Paper 10, Sep 2011

There are many examples in policy-making, investment and day-to-day life where the set of contingencies the decision-maker can conceive of does not resolve all uncertainty about the consequences of actions. In such circumstances, the decision-maker may nevertheless reason that there exist certain aspects of the "full" state space of which she is unaware; that is, she may think it is possible she is unaware of something. We call this type of belief "conscious unawareness" and claim that its presence may lead to a violation of Savage's Sure Thing Principle. We then specify a choice setting in which the decision-maker has preferences over a set of actions stated naturally in English, and over a set of caveats. A caveat maps from the set of permutations

– the product space of the set of contingencies she can conceive of (her subjective state space, S) and the set of payoff assignments to the actions – to a space of consequences. We obtain a representation result under which she prefers action a to a... By endowing the decision-maker with beliefs over the set of payoff assignments, we make choice in cases where conscious unawareness is a major concern (eg, climate change policy) tractable by means of some of the standard analytical tools of risk and ambiguity analysis. The representation also allows us to characterise the decision-maker's attitude towards perceived payoff uncertainty arising from factors she is unaware of. Using the same framework, we are able to state a more general representation that allows us to capture source preference in examples where the decision-maker is consciously unaware.
www.cccep.ac.uk/Publications/Working-papers/Abstracts/60-69/choice-conscious-unawareness.aspx

Forecasting non-life insurance demand in the BRICS economies: a preliminary evaluation of the impacts of income and climate change

N. Ranger and A. Williamson, Technical Paper 11, Sep 2011

Insurance demand is driven by many factors, but for the emerging economies, one of the most significant historical drivers of growth has been income per capita. Based on a simple forecasting approach, we project that insurance penetration in the BRICS economies could increase at a rate of between 1.6 and 4.2 per cent per year over the coming decade, depending on the country, due to rising per capita income. When other factors are included, this broadens to between 0.1 and 4.3 per cent per year. This equates to a rate of increase in gross premium volumes of between 5.4 and 12.3 per cent per year. The largest growth in insurance penetration and premium volumes is expected in China, closely followed by India and Russia. A concern for (re)insurers is how climate change may impact these growth paths. Based on current projections, we expect the impact on growth mediated through income to be small; less than a 0.4 per cent adjustment in the annual growth rate in premium volumes to 2030.
www.cccep.ac.uk/Publications/Working-papers/Abstracts/70-79/insurance-brics-economies-climate.aspx

A preliminary assessment of the impact of climate change on non-life insurance demand in the BRICS economies

N. Ranger and S. Surminski, Technical Paper 12, Sep 2011
www.cccep.ac.uk/Publications/Working-papers/Abstracts/70-79/climate-change-non-life-insurance-brics.aspx

Pattern scaled climate change scenarios: are these useful for adaptation?

L.A. Smith, A. Lopez and E.B. Suckling, Technical Paper 13, Dec 2011
www.cccep.ac.uk/Publications/Working-papers/Abstracts/80-89/pattern-scaled-climate-change-scenarios.aspx

Policy indexes – what do they tell us and what are their applications? The case of climate policy and business planning in emerging markets

S. Surminski and A. Williamson, Technical Paper 14, Sep 12
www.cccep.ac.uk/Publications/Working-papers/Abstracts/100-109/policy-indexes-climate-policy-business-planning-in-emerging-markets.aspx

The roles of public and private actors in the governance of adaptation: the case of agricultural insurance in India

S. Fisher and S. Surminski, Technical Paper 15, Sep 2012

Climate change adaptation is an increasingly important field and will involve a range of actors from national governments to private companies, communities and households. There is a growing policy discourse supporting the involvement of the private sector in adaptation. However, there is little empirical examination to show how the sector might be involved and how adaptation might be governed. This paper uses evidence from the field of risk governance and insurance and analytical frameworks from the wider governance literature to draw important findings for the governance of adaptation. We use the recently published *Compendium of Disaster Risk Initiatives in the Developing World* and a case study of agricultural insurance in India to argue that the role of the private sector is increasing, but so far within a particular model of engagement. In the context of

climate change, how the public-private relationships are constructed is key to how adaptation can be leveraged from such an arrangement. The evidence in this paper suggests that due to commercial viability and other concerns, there will continue to be a role for the public sector alongside the private sector to ensure adaptation measures address vulnerability. In conclusion, we argue that the type of relationship between the public and the private actors has a significant influence on the adaptation outcomes. The question is not purely about involving the private sector, which is how this is currently framed within policy and academic work on adaptation, but how the private actors are engaged. Governments seeking to engage private actors need to build those relationships with the desired adaptation outcomes in mind.
www.cccep.ac.uk/Publications/Working-papers/Abstracts/100-109/public-private-actors-governance-adaptation-agricultural-insurance-in-india.aspx

Ambiguity and insurance: robust capital requirements and premiums

O. Walker and S. Dietz, Technical Paper 16, Nov 2012
www.cccep.ac.uk/Publications/Working-papers/Abstracts/110-119/ambiguity-insurance-capital-premiums.aspx

Laplace's Demon and climate change

R. Frigg, S. Bradley, H.L. Du and L.A. Smith, Technical Paper 17, Jan 2013
www.cccep.ac.uk/Publications/Working-papers/Papers/120-129/WP121-laplaces-demon-climate-change.pdf

Do flood insurance schemes in developing countries provide incentives to reduce physical risks?

S. Surminski and D. Oramas-Dorta, Technical Paper 18, Jul 2013
www.cccep.ac.uk/Publications/Working-papers/Papers/130-139/WP139-flood-insurance-schemes-developing-countries.pdf

An evaluation of decadal probability forecasts from state-of-the-art climate models

E.B. Suckling and L.A. Smith, Technical Paper 19, Oct 2013
http://www.cccep.ac.uk/Publications/Working-papers/Abstracts/160-169/An-evaluation-of-decadal-probability-forecasts.aspx

Probabilistic skill in ensemble seasonal forecasts

H.L. Du, L.A. Smith, E.B. Suckling and F. Niehörster, Technical Paper 20, Feb 2014
www.cccep.ac.uk/Publications/Working-papers/Abstracts/160-169/Probabilistic-skill-in-ensemble-seasonal-forecasts.aspx

iv) Posters from the Munich Re Programme

Traditionally, papers and talks have dominated the communication of new ideas in our field. In the 21st century a wide range of new pathways of dissemination are available; among these new approaches, the "poster" is making a comeback. Always effective in real-time, online archives and search engines enhance the poster's longevity. Seven posters were produced under the Munich Re Programme. The abstracts are collected below. The posters themselves can either be found below or elsewhere in this report. And, of course, online.

Skill of Ensemble Seasonal Probabilistic Forecast

H.L. Du, F. Niehörster, R. Binter and L.A. Smith, 2009

The skill of probability forecasts of the temperature at Nino 3.4 based upon the ENSEMBLES seasonal simulations is considered and contrasted with those of the DEMETER simulations. This poster addresses the problem of interpreting probability forecasts based on these multi-model ensemble simulations; the distributions considered are formed by kernel dressing the ensemble and blending with the climatology. The sources of apparent (RMS) skill in distributions based on multi-model simulations is discussed, and it is demonstrated that the inclusion of "zero-skill" models in the long range can improve RMS scores, casting some doubt on the common justification for the claim that all models should be included in forming an operational PDF. It is argued that the rational response varies with lead time.
The poster can be found on page 72.
www.lse.ac.uk/CATS/Publications/Posters%20PDFs/Skill-of-ensemble-seasonal-probabilistic-forecast.pdf

Small-number statistics, Common Sense and Profit: Challenges and Non-challenges for Hurricane Forecasting

A.S. Jarman and L.A Smith, 2011

When making only one forecast per year, or per decade, it can take some time to establish statistical confidence in the skill of a given forecast scheme. Must a risk tolerant decision-maker wait decades until skill is "proven" if that decision-maker believes the system to have value? What of a risk neutral decision-maker? A methodology is illustrated to demonstrate there are imperfect forecast systems which almost certainly have nontrivial value long before one might establish that their skill was statistically significant. The poster can be found on page 28.
lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/EQUIP_Jarman_2011%2001%2019.pdf

A preliminary assessment of the impact of climate change on non-life insurance demand in the BRICS economies

N. Ranger and S. Surminski, (2013), International Journal of Disaster Risk Reduction, 3, 14-30
[Based on Technical Paper 12, September 2011]

See abstract in Appendix 1, page 49.
The poster can be found on page 33.
lse.ac.uk/CATS/Publications/Posters%20PDFs/Surminski-and-Ranger-BRICS-poster-LLoyds-landscapeA1-(FINAL).pdf

All models are wrong: Which are worth paying to look at? A case study for Global Mean Temperature

E.B. Suckling and L.A. Smith, 2011

Dynamical simulation models (GCMs), often used to provide decision support in the context of climate variability and change, typically have complex structures, rendering them computationally intensive to run and expensive to develop. In extrapolation the models which "capture the physics" must justify their cost to users by demonstrating that they outperform simpler statistical models by placing significantly more probability mass on the verification. But do today's "best available" models do so? An approach is presented towards a robust measure of the in-sample skill of ensemble forecasts and the performance of a set of decadal simulations from ENSEMBLES for global mean temperature is assessed against a benchmark statistical model based on the random analogue prediction method. The ensemble forecasts are expressed as probability distributions through the kernel dressing procedure and their quality quantified according to the Ignorance skill score.
The poster can be found on page 92.
lse.ac.uk/CATS/Publications/Posters%20PDFs/All-models-are-wrong-Which-are-worth-paying-to-look-at.pdf

Distinguishing between skill and value in hurricane forecasting

A.S. Jarman and L.A. Smith, 2012

Significant improvements in hurricane forecasts are sometimes said to be of little value, as the time required to establish the skill of these improvements would be decades or more. It is argued that this mistaken view comes from a confusion of skill with value, often coupled with the use of naïve statistical tests. When making only

Skill of Ensemble Seasonal Probabilistic Forecast

Hailiang Du[1], Falk Niehoerster[1], Roman Binter[1] and Leonard A. Smith[1,2]

[1] Centre for the Analysis of Time Series, London School of Economics, [2] Pembroke College, Oxford

Email: *lenny@maths.ox.ac.uk*, *h.l.du@lse.ac.uk*

Abstract

The skill of probability forecasts of the temperature at Nino 3.4 based upon the ENSEMBLES seasonal simulations is considered and contrasted with those of the DEMETER simulations. This poster addresses the problem of interpreting probability forecasts based on these multi-model ensemble simulations; the distributions considered are formed by kernel dressing the ensemble and blending with the climatology. The sources of apparent (RMS) skill in distributions based on multi-model simulations is discussed, and it is demonstrated that the inclusion of "zero-skill" models in the long range can improve RMS scores, casting some doubt on the common justification for the claim that all models should be included in forming an operational PDF. It is argued that the rational response varies with lead time

1 From Simulation to a PDF

A given ensemble of simulations is translated into a probability distribution function by a combination of kernel dressing and blending with climatology [4]. Given an N member ensemble at time t, $X_t = [x_t^1, ..., x_t^N]$, and treating ensemble members under the same model as exchangeable, kernel dressing defines the model-based component of the density as:

$$p(y : X, \sigma) = \frac{1}{N\sigma} \sum_i^N K\left(\frac{y - x^i - u}{\sigma}\right), \quad (1)$$

where K is a kernel. Here we take

$$K(\zeta) = \frac{1}{\sqrt{2\pi}} exp(-\frac{1}{2}\zeta^2), \quad (2)$$

where y is a random variable corresponding to the density function p. In this case each ensemble member contributes a Gaussian kernel centred at $x^i + u$, where u is an offset accounting for systematical bias. The kernel width, σ, is simply the standard deviation of the Gaussian kernel.

For any finite ensemble, the verification may lie far from the ensemble members even if the verification is selected from the same distribution as the ensemble itself. Blending the most relevant climatological distribution of the system with the model-based distribution yields a probability forecast usually superior to that obtained without blending. The eventual forecast distribution is then:

$$p(\cdot) = \alpha p_m(\cdot) + (1 - \alpha) p_c(\cdot) \quad (3)$$

where p_m is the density function generated by dressing the ensemble and p_c is the estimate of climatological density.

To produce the forecast distribution requires estimation of the kernel width σ the shifting parameter u and the weight α assigned to the model. We fit these three parameters simultaneously by optimising the Ignorance score, introduced below, by leave one out cross validation [1].

2 Contrasting ENSEMBLES & DEMETER

The performance of forecast distributions is evaluated primarily using the "log p score" (Ignorance Score [2]). The Ignorance Score is defined by:

$$S(p(y), Y) = -log(p(Y)), \quad (4)$$

where Y is the verification. Ignorance is the only proper local score for continuous variables [1,3]. In practice, given K forecast-verification pairs $(p_t, Y_t, t = 1, ..., K)$, the empirical average Ignorance skill score is:

$$S_{Emp}(p(y), Y) = \frac{1}{K} \sum_{i=1}^{K} -log(p_i(Y_i)) \quad (5)$$

We evaluate the ENSEMBLES & DEMETER seasonal models [5] by their empirical Ignorance score. From Fig 1. In general, both IFS(ECMWF) model and HadGem2(UKMO) model tend to outperform other models in the ENSEMBLES project. ECHAM5(INGV) model seems doing very well in the DEMETER project. By looking at the relative Ignorance between ENSMEBLE and DEMETER model outputs, it seems except the ECHAM5(INGV) model, all other three models have made improvement in terms of Ignorance.

[1]As only 42 years data are provided, the estimation of these two parameters is lack of robustness. If one has 4000 years data, one can draw multiple 42 years data set from them and estimate the parameters for each sample set. The variation of the estimates is large.

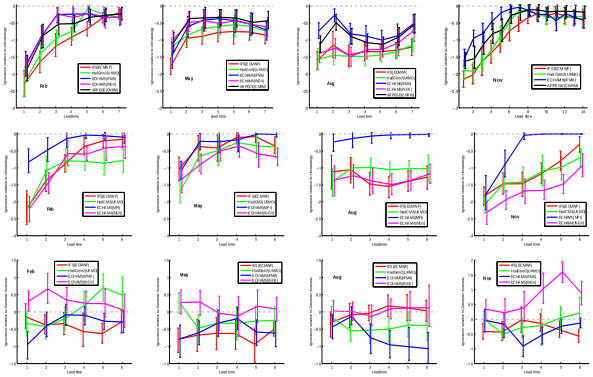


Fig 1: Ignorance score of each model forecast of SST in the nino3.4 region as a function of lead time. The uncertain bars are the 90 percent bootstrap re-sampling bounds, calculated from 512 bootstrap re-samples. Figures in the first row represent Ignorance of each model from ENSEMBLES project relative to climatology, each picture corresponding each launch date; the second row represents Ignorance of each model from DEMETER project relative to climatology; the third row shows the Ignorance score of ENSEMBLES forecast relative to corresponding DEMETER model forecast (ECHAM5(IFMK) is compared with ECHAM5(MPI)).

3 The meaning of the (ensemble) mean and value of large ensembles

It is often said that the ensemble mean outperforms the best model. The right panel in Fig. 2 shows that at large lead times merely decreasing the variance of the IFS(ECMWF) forecast improves the RMS skill. In this case including zero skill forecasts (with zero mean error) would appear to improve the score! While at short lead times (where the ensemble has more significant skill) decreasing the variance increases the RMS error. This casts doubt on the utility of RMS error measures. The left panel in Fig 2. suggests that multi-model ensemble really does contribute skill.

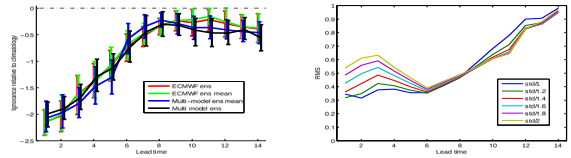


Fig 2: a) Ignorance score of i) IFS(ECMWF) ensemble ii) IFS(ECMWF) ensemble mean iii) Multi-model (Including the four models in Fig 1) ensemble mean iv) Multi-model ensemble, forecast for Nov launch, relative to climatology. b) RMS error for the forecast using IFS(ECMWF) ensemble mean with their variance shrunk.

The seasonal ensembles within the ENSEMBLES project each consist of nine members, decreasing the ensemble degrades forecast skill, as shown in Fig. 3 where skill of two member (red) and four member (green) ensembles are shown relative to the full nine member ensemble.

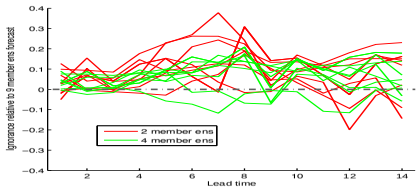


Fig 3: Ignorance score of IFS(ECMWF) model forecast of SST in the nino3.4 region as a function of lead time. The green lines represents the Ignorance of 4 member (random drawn from the original 9 member ensemble) ensemble forecasts relative to 9 member ensemble forecast; the red lines 2 member ensemble forecasts

4 Constructing PDFs from multiple models

Each model provides a distribution of simulations: how do we best combine them without over-fitting given that we have only 50 independent launches? Fig. 4 illustrates that that such combinations will be lead-time dependent. At shorter lead times, where the better models have significantly more skill, combining only one or two of the best models does well, while including all models does poorly in months one to eight, and then arguably outperforms the other combination in months ten through fourteen.

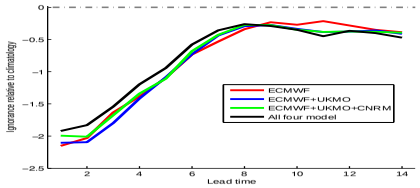


Fig 4: Ignorance score of multi-model forecasts of Nino3.4 SST as a function of lead time. Multi-model forecasts are constructed by assigning equal weights on each model forecast PDF.

Summary

The current generation of seasonal forecasts will retire before the forecast-verification archive gets significantly larger: seasonal verification data is precious. ENSEMBLES-based PDFs have skill at 14 months lead-time, a skill significant improvement on the DEMETER models. Different skill scores can obscure real skill from proper scoring rule from mere statistical effects reflected in RMS scores. The evidence of skill at long lead-times is of nontrivial value in various applications, and distinguishing the limitations of this skill for decision making from the limitations of our current skill scores will prove of great value.

References

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[2] G.W. Brier, Verification of forecasts expressed in terms of probabilities. *Mon. Wea. Rev.*, **78**, 1C3, (1950).

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[4] J. Brocker and L.A. Smith, From ensemble forecasts to predictive distribution functions, *Tellus A*, 60, 663-678 (2007).

[5] A. Weisheimer, F. J. Doblas-Reyes, T. N. Palmer, A. Alessandri, A. Arribas, M. Deque, N. Keenlyside, M. MacVean, A. Navarra, and P. Rogel, ENSEMBLES: A new multi-model ensemble for seasonal-to-annual predictionsSkill and progress beyond DEMETER in forecasting tropical Pacific SSTs, *Geophys. Res. Lett.*, 36, L21711 (2009).

one forecast per year, it may well take a substantial length of time to establish statistical confidence in the skill of a given forecast scheme. While, of course, the degree of statistical uncertainty increases with decrease in sample size (time duration) there is a fundamental difference between the skill of a forecast and its value. Hurricane numbers appear to reflect slowly changing hydro-meteorological conditions (eg, the Atlantic multi-decadal oscillation) and the evaluation of both skill and value is complicated by long timescales. It is argued that these factors do not compel a risk tolerant decision-maker to wait decades until skill is "proven". The case of a risk neutral decision-maker is discussed. Forecasts may well have statistical skill without adding any value for decision-makers. At the same time, imperfect forecast systems can possess non-trivial value long before one might establish that their skill was statistically significant. Relationships between forecast skill and value given imperfect models and the statistical uncertainty in both are also discussed.

The poster can be found on page 20.
lse.ac.uk/CATS/Publications/Posters%20PDFs/Distinguishing-between-skill-and-value-in-hurricane-forecasting.pdf

What do we really know about US Hurricane Risk in 2020?

N. Ranger and F. Niehörster, 2012

How will the frequency and intensity of Atlantic tropical cyclones change, on average, over the next ten years and what does this mean for insured losses? These are important questions for long-term business strategy. But, even for the most fundamental metrics, such as the frequency of landfalling hurricanes, still even the most recent state-of-the-art studies give contradictory results. How can the insurance industry prepare for climate change given this level of uncertainty?

The poster can be found on page 18.
lse.ac.uk/CATS/Publications/Publications%20PDFs/Posters%20PDFs/2013-Ranger-and-Niehörster---What-do-we-really-know-about-US-hurricane-risk-in-2020.pdf

Forecasting the Probability of Tropical Cyclone Formation: the reliability of NHC forecasts from the 2012 hurricane season

A.S. Jarman and L.A. Smith, 2013

Atlantic tropical cyclones are responsible for some of the world's greatest economic losses due to natural hazards. Short-term (48 hour) probabilistic forecasting has become an integral part of the prediction of these events. Forecasters from the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center (NHC) post subjective probability tropical cyclone forecasts out to 48 hours during each hurricane season. Reliability diagrams provide an immediate indication of the quality of a probabilistic forecasting system by illustrating the degree of correspondence between the observed frequencies of an event and the forecast probabilities assigned to it. In their most common format, however, reliability diagrams fail to provide a truly representative measure of reliability, as they do not clearly indicate the variability expected even in a perfectly reliable forecast system. A revised format (J. Broecker and L. A. Smith, *Weather and Forecasting*, 22(3), pp 651-661, 2007) aids the visual evaluation of the likelihood of the observed relative frequencies of tropical cyclones during the 2012 hurricane season. This is done by indicating the variability expected under the assumption that the NHC's probability forecasts were genuinely reliable. The strengths and weaknesses of the 2012 forecasts are examined. For most categories, the forecast probabilities are consistent with the observed frequencies of tropical cyclones. The verisimilitude of forecasts of very high probability and very low probability (including forecasts of "zero" probability) are discussed. In addition, relationships between "time until event" and forecast probability are analysed. In 2012, forecasts of a probability of 70 per cent or more were each followed by events (52 out of 52). It is interesting to note the distribution of time of onset of these events within the 48 hour window. It is hoped that these observations may suggest ways to improve the utility and evaluation of operational tropical cyclone forecasts. **The poster can be found on page 30.** lse.ac.uk/CATS/Talks%20and%20Presentations/EGU-AJ-poster-2013.pdf

Appendix 2: Insurance industry briefs

Insurance briefs were intended to get information gleaned from state-of-the-art research into the insurance sector quickly. Two insurance industry briefs were produced. Each explored an aspect of climate change with significant implications and consequences for the insurance sector, and was intended to be of interest to a wide range of professionals within the insurance industry, as well as policymakers and regulators.

Trends in economic and insured losses from weather-related events: A new analysis

Robert Ward and Nicola Ranger, November 2010

This insurance industry brief describes the role of normalisation studies in contributing to the understanding of trends in economic and insured losses from weather-related events, and outlines the results of new analyses.
www.cccep.ac.uk/Publications/insurancBriefs/economic-trends-insured-losses.pdf

Munich RE

Centre for Climate Change Economics and Policy

INSURANCE INDUSTRY *brief*

The Munich Re Programme of the Centre for Climate Change Economics and Policy

TRENDS IN ECONOMIC AND INSURED LOSSES FROM WEATHER-RELATED EVENTS: A new analysis

Robert Ward and Nicola Ranger — November 2010

Summary

- Global economic losses from reported weather-related events increased between 1980 and 2009 by US$2.7 billion per year in real terms (when merely the effects of inflation are taken into account).
- Normalisation methods allow loss data to be adjusted for one or more components, such as population growth, increasing wealth or changes in vulnerability, so that any remaining trends can be studied.
- Conventional normalisation methods have explored the contribution of inflation, changes in wealth per capita, and changes in population over time to the trends in economic losses, but do not take into account variations in wealth per capita and population between locations.
- A new normalisation method has been devised by researchers in the Munich Re Programme at the Centre for Climate Change Economics and Policy which takes into account spatial variations in wealth per capita and population, although it suffers from greater problems than the conventional method in terms of practical application.
- The new normalisation method has been applied to economic losses from global weather-related events over the past 30 years, during a period when there appears to have been an increase in the reported number of weather-related loss events.
- The most likely explanation for the simultaneous findings of, on the one hand, the absence of upward trends in reported global losses (recorded by either the conventional or new method) and, on the other hand, the dramatic increase in recorded weather-related loss events, is the implementation of defensive mitigation measures, particularly in some developed countries, which has reduced vulnerability to weather related damage.
- Other possible explanations for the absence of upward trends include data limitations, bias in the reporting of losses, problems in the measurement of the areas affected by loss events, or a decrease in the intensity of weather-related loss events over time.
- The first ever analysis of global insured losses has been carried out using the conventional normalisation method, but indicates no statistically significant trend for total weather-related events over the past 19 years.
- However, the new analysis shows that there has been a statistically significant increase in insured losses from weather-related events in the United States over the past 37 years, and in Germany over the past 29 years.
- Statistically significant upward trends in normalised insured losses are found for total weather-related events, convective events, flooding, all storm events, and tropical cyclones in the United States, and for total weather-related events, winter storms and all storm events in Germany.

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LSE The London School of Economics and Political Science

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Aiming for a 2°C goal: What does it mean for the insurance industry?

Nicola Ranger and Robert Ward, May 2010

This brief explores the importance of adaptation to the impacts of climate change, particularly in managing near-term changes in risk that cannot be avoided through reductions in greenhouse gas emissions. The brief also considers the role that the insurance industry can play in adaptation.
www.cccep.ac.uk/Publications/insuranceBriefs/aiming-for-2degree-goal.pdf

Munich RE

Centre for Climate Change Economics and Policy

INSURANCE INDUSTRY *brief*

The Munich Re Programme of the Centre for Climate Change Economics and Policy

AIMING FOR A 2°C GOAL: What does it mean for the insurance industry?

Nicola Ranger and Robert Ward — May 2010

Summary

- Many countries now agree on the need to limit global warming to no more than 2°C above pre-industrial levels.
- A warming of 2°C would not be 'safe'. In a world that is 2°C warmer, we are very likely to experience changes to the types and characteristics of extreme weather in many regions, as well as a global trend towards more intense weather-related events, including droughts, floods, storms and heat waves.
- It is clear that changes in extreme events will put additional stress on risk management procedures, particularly where exposures and vulnerabilities to extreme weather are high.
- Climate change means increased ambiguity over long-term risks. The impact on the insurance industry will depend upon its ability to anticipate and respond to changing levels of risk.
- Adaptation can have immediate benefits. Without adaptation to the impacts of climate change, the viability of weather related insurance markets and products in some areas will be put under pressure.
- The insurance industry can play a leading role in promoting and supporting adaptation to climate change, with benefits from protecting and extending the market for property and casualty insurance.

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Appendix 3: Theses

The Munich Re Programme funded one doctoral research student directly – Dr Alex Jarman's PhD thesis is a direct outcome of our cooperation. Two other doctoral theses were significantly influenced by work in the Programme, even though the primary funding of the student originated from another source. One of these was by Dr Fabian Barthel (in Geography and Environment) the other by Dr Seamus Bradley (in Philosophy). Each thesis is available online. Their abstracts are presented below.

i) Munich Re Programme PhD thesis

Alex Jarman (2014) 'On the provision, reliability, and use of hurricane forecasts on various timescales'

Available at: http://etheses.lse.ac.uk/943/

Abstract: Probabilistic forecasting plays a pivotal role both in the application and in the advancement of geophysical modelling. Operational techniques and modelling methodologies are examined critically in this thesis and suggestions for improvement are made; potential improvements are illustrated in low-dimensional chaotic systems of nonlinear equations. Atlantic basin hurricane forecasting and forecast evaluation methodologies on daily to multi-annual timescales provide the primary focus of application and real world illustration. Atlantic basin hurricanes have attracted much attention from the scientific and private sector communities as well as from the general public due to their potential for devastation to life and property, and speculation on increasing trends in hurricane activity. Current approaches to modelling, prediction and forecast evaluation employed in operational hurricane forecasting are critiqued, followed by recommendations for best-practice techniques. The applicability of these insights extends far beyond the forecasting of hurricanes. Hurricane data analysis and forecast output is based on small-number count data sourced from a small-sample historical archive; analysis benefits from specialised statistical methods which are adapted to this particular problem. The challenges and opportunities arising in hurricane statistical analysis and forecasting posed by small-number, small-sample, and, in particular, by serially dependent data are clarified. This will allow analysts and forecasters alike access to more appropriate statistical methodologies. Novel statistical forecasting techniques are introduced for seasonal hurricane prediction. In addition, a range of linear and non-linear techniques for analysis of hurricane count data are applied for the first time along with an innovative algorithmic approach for the statistical inference of regression model coefficients. A real-time outlook for the 2013 hurricane season is presented, along with a methodology to support a running (re)analysis for National Hurricane Center 48 hour forecasts in 2013; the focus here is on whether, and if so how, to improve forecast effectiveness by "recalibrating" the raw forecasts in real time. In this case, it is revealed that recalibration does not improve forecast performance, and that, across years, it can be detrimental. In short, a new statistical framework is proposed for evaluating and interpreting forecast reliability, forecast skill, and forecast value to provide a sound basis for constructing and utilising operational event predictions. This novel framework is then illustrated in the specific context of hurricane prediction. Proposed methods of forecast recalibration in the context of both a low-dimensional dynamical system and operational hurricane forecasting are employed to illustrate methods for improving resource allocation distinguishing, for example, scenarios where forecast recalibration is effective from those where resources would be better dedicated towards improving forecast techniques. A novel approach to robust statistical identification of the weakest links in the complex chain leading to probabilistic prediction of nonlinear systems is presented, and its application demonstrated in both numerical studies and operational systems.

ii) Related PhD theses

Fabian Barthel (2011) 'Spatial dependence in dyadic data: the cases of double taxation treaties, official development assistance, and asylum migration'

Available at: http://etheses.lse.ac.uk/336/

Abstract: The thesis analyses spatial dependence in dyadic data by the means of three applications. These have in common that they concern bilateral international relations or flows between two countries with a particular focus on the relationship between developing and developed countries. While the first chapter provides a general introduction to spatial dependence with a focus on dyadic datasets, the second chapter looks at double taxation treaties (DTTs) and analyses whether strategic interaction among capital importing countries can explain the widespread conclusion of double taxation treaties between an industrialised and a developing country. This is important since upon entering such a treaty, the net-capital importer can lose a significant amount of tax revenues from foreign direct investment (FDI), while the net-capital exporter is better off. The analysis reveals that a country is more likely to enter a DTT if competitor countries for FDI also negotiated such a DTT, providing evidence for the hypothesis that the group of net-capital importers finds itself in a situation which can be described as a prisoners' dilemma: individually they would be better off if they refused to negotiate a treaty, but collectively they have an incentive to sign such a tax treaty. The third chapter is on official development assistance and deals with the question of whether a specific donor tends to dedicate a larger share of its aid budget to a certain recipient if other donors give money to the same beneficiary. A considerable degree of spatial dependence is found in the form that donors tend to allocate their money to the same recipients. Donors particularly follow the example of the most important aid donors. This behaviour has negative implications for aid effectiveness, contributes to harmful aid volatility and leads to aid darlings and orphans. However, there is no evidence that donors strategically interact with each other in order to pursue their military strategic and economic goals. Spatial dependence in asylum migration is the third application, discussed in the fourth chapter. It is well documented in the literature that personal networks of migrants reduce the risk of migration and facilitate transition to the host country. So far it has always been assumed that these personal networks only exist for fellow countrymen. The empirical analysis, however, shows that the positive effects also operate across borders and that also migrants from other geographically close source countries make asylum migration from a given source country more likely. Furthermore, it is shown that a more restrictive asylum policy in one destination country provides a negative externality for other destinations. This is because asylum seekers are deflected by a tighter asylum regime and encouraged to lodge their application in more liberal target countries.

Seamus Bradley (2012) 'Scientific uncertainty and decision-making'

Available at: http://etheses.lse.ac.uk/606/

Abstract: It is important to have an adequate model of uncertainty, since decisions must be made before the uncertainty can be resolved. For instance, flood defences must be designed before we know the future distribution of flood events. It is standardly assumed that probability theory offers the best model of uncertain information. I think there are reasons to be sceptical of this claim. I criticise some arguments for the claim that probability theory is the only adequate model of uncertainty. In particular I critique Dutch book arguments, representation theorems, and accuracy based arguments. Then I put forward my preferred model: imprecise probabilities. These are sets of probability measures. I offer several motivations for this model of uncertain belief, and suggest a number of interpretations of the framework. I also defend the model against some criticisms, including the so-called problem of dilation.
I apply this framework to decision problems in the abstract. I discuss some decision rules from the literature including Levi's E-admissibility and the more permissive rule favoured by Walley, among others. I then point towards some applications to climate decisions. My conclusions are largely negative: decision-making under such severe uncertainty is inevitably diffcult. I finish with a case study of scientific uncertainty. Climate modellers attempt to offer probabilistic forecasts of future climate change. There is reason to be sceptical that the model probabilities offered really do reflect the chances of future climate change, at least at regional scales and long lead times. Indeed, scientific uncertainty is multi-dimensional, and difficult to quantify. I argue that probability theory is not an adequate representation of the kinds of severe uncertainty that arise in some areas in science. I claim that this requires that we look for a better framework for modelling uncertainty.

Appendix 4: Press releases

Global warming of 2˚C will put insurance markets under stress

Press release 29 June 2010 of the Munich Re Industry Brief 'Aiming for a 2°C Goal: What does it mean for the insurance industry?' (Ranger and Ward 2010, MRe IB1).

International efforts to limit global warming to no more than 2˚C above pre-industrial levels will not be enough to prevent changes in extreme weather events that will put the risk management procedures of the insurance industry under stress and could threaten the insurability of people and their property in some areas, according to a new report (http://www.cccep.ac.uk/Publications/insuranceBriefs/home.aspx) published today (29 June 2010) by the Centre for Climate Change Economics and Policy at the London School of Economics and Political Science and the University of Leeds.

The report, written by Nicola Ranger and Bob Ward for the Centre's Munich Re Programme, warns that while the Copenhagen Accord calls for reductions in global emissions of greenhouse gases to limit warming to no more than 2˚C, such an increase in the average temperature "would not be 'safe'".

It states: "In a world that is 2˚C warmer, we are very likely to experience changes to the types and characteristics of extreme weather in many regions, as well as a global trend towards more intense weather-related events, including droughts, floods, storms and heat waves".

It adds: "It is still not possible to predict exactly how hazards will change, particularly at a regional or local level; in fact, due to their localised and rare nature, changes in extreme weather are amongst the most difficult impacts of climate change to predict."

But the report points out: "It is clear that changes in extreme events will put additional stress on risk management procedures, particularly where exposures and vulnerabilities to extreme weather are high.

"From an industry perspective, long-term solvency could depend on the ability of insurers and reinsurers to anticipate and respond rapidly to changing levels of hazard and risk in relation to hurricanes and other extreme weather events. Risk managers could see benefits from incorporating flexibility into long-term strategies to allow for the rising ambiguity in hazard and risk on decadal timescales."

The report also highlights the threat to insurability that could result if there is inadequate adaptation to the impacts of climate change that would be associated with a rise in global average temperature of 2˚C.

It states: "The impact of such changes in hazard on the global risk of extreme weather events will depend on the effectiveness of adaptation, in particular, the extent to which reductions in exposure and vulnerability limit risks associated with weather-related hazards. If such reductions do not occur or are inadequate, risks will increase, and the number of people and properties that are considered uninsurable could grow."

"In addition, with continued migration of populations to coastal regions, insurers and reinsurers could be exposed to potentially growing accumulations of risk. Without adaptation by limiting exposure and vulnerability of insureds, such increases in expected losses, uncertainty and capital demands could have profound consequences for future affordability and availability of insurance cover."

The report acknowledges that "the traditional response to changing levels of risk by the insurance industry has been adjustments to insurance premiums, policy conditions and coverage", but draws attention to "recent evidence from the United States where major and rapid changes in policies offered by private insurers to cover homeowners' properties can create negative public and political reactions that may affect other lines of business".

It adds: "An alternative response by insurers and reinsurers may be to guide and contribute to public policies that reduce exposure and vulnerability in order to promote insurability."

The report concludes: "The insurance industry can play a leading role in promoting and supporting adaptation to climate change, with benefits from protecting and extending the market for property and casualty insurance."

"Promoting and supporting societal adaptation could increasingly become a strategic imperative for the insurance industry."

The report also notes that the reductions in greenhouse gas emissions by 2020 listed by countries in the Copenhagen Accord collectively fall short of the level required to create a 50 per cent chance of avoiding a rise in global temperature of more than 2˚C. The report states: "Any delay in global emissions reductions is likely to mean greater costs of action to achieve the same goal, or a greater chance of higher levels of warming."

New research shows rise in wealth is driving increase in global economic losses from extreme weather by US$2.7 billion per year

Press release 23 November 2010 of the Munich Re Technical Paper 'Normalizing Economic Loss from Natural Disasters: A Global Analysis', (Neumayer and Barthel 2010, MRe TP6), and the related Industry Brief 'Trends in economic and insured losses from weather-related events: A new analysis' (Ward and Ranger 2010, MRe IB2).

Global economic losses from reported weather-related events have been increasing in real terms by about US$2.7 billion per year since 1980, mainly because of the rise in the amount of wealth that is accumulating in areas that are exposed to potential damage, according to new findings by researchers in the Munich Re Programme at the Centre for Climate Change Economics and Policy, which are published today (23 November 2010).

A new journal paper, by Eric Neumayer and Fabian Barthel of the London School of Economics and Political Science (LSE), describes a new method for studying which factors have been contributing to the rise in economic losses, by taking into account inflation as well as differences in wealth between different locations and changes in wealth over time.

The researchers applied this new "normalization" method, together with a conventional method that does not take into account differences in wealth and population between poor rural areas and rich urban areas, to the most comprehensive database of economic losses from worldwide weather-related events since 1980, which has been compiled by the reinsurance company Munich Re.

They report their results in a new paper published online today as a corrected proof for the journal *Global Environmental Change*. Only one previous study has ever been published on the normalization of global economic losses.

The researchers found that the conventional method, which takes into account changes in wealth and inflation, produced results that showed no detectable trend in global economic losses from extreme weather between 1980 and 2009.

When the researchers applied their new method, they found a statistically significant downward trend in normalized losses from global reported weather-related events between 1980 and 2009. This downward trend was also found in losses for developed countries, but not developing countries. However, they also noted that the number of recorded weather-related events over the past 30 years has apparently increased markedly.

The researchers concluded that the lack of an upward trend in economic losses once inflation and changes in wealth were taken into account could best be explained by the implementation of risk-reduction measures, such as flood defences and building codes, which reduce vulnerability to damage by extreme weather over time.

They also indicated that other explanations, apart from risk reduction measures, could include data limitations, bias in the reporting of losses, problems in the measurement of the areas affected by loss events, or, much less likely, a decrease in the intensity of weather-related loss events over time.

A new report for the insurance industry by Robert Ward and Nicola Ranger, also published today, points out that when inflation is excluded, economic losses from weather-related events around the world have been increasing by an average of US$2.7 billion a year in real terms over the past 30 years. The findings by Professor Neumayer and Mr Barthel indicate that these losses can be attributed to the increase in the amount of wealth that is exposed to weather-related events. Professor Neumayer and Mr Barthel also warned against inferring from their results that climate change had not affected economic losses from extreme weather. Professor Neumayer said: "The absence of upward trends in our results for economic losses is fully compatible with a possible rise in the frequency or intensity of extreme weather events. Adaptation and defensive measures may well prevent us from detecting an exposure to elevated weather hazards."

He added: “Whatever the reason, one thing is clear. Any adaptive response which may be limiting losses by reducing vulnerability is being completely outpaced by the massive increase in the amount of wealth, in the form of homes, business and infrastructure, that is exposed to damage by extreme weather events.”

Commenting on the new research results, Lord Stern of Brentford, who chairs the Centre, said: “A plausible explanation for the apparent absence of upward trends in normalized economic losses over the past 30 years, even though there is a marked apparent rise in the number of reported weather-related events, is the implementation of defensive mitigation measures, which has reduced vulnerability to weather-related damage. Some of this may result from greater risk bringing greater awareness and learning and thus more careful decision-making. Increasing relative risk aversion may also be important in interpreting these results: if climate risk were constant then the rising risk aversion would lead to lower normalized losses, because as people become more wealthy they take more precautions with any given fraction of their wealth.”

Lord Stern added: “So what we may be seeing is rising risk due to climate change, resulting in the apparent increase in recorded weather-related loss events, which when combined with increasing relative risk aversion and greater learning leads to the absence of observable change in normalized losses.”

Appendix 5: Events and dissemination

Dr Nikolaus von Bomhard and Lord Nicholas Stern at the press conference for the opening of the Grantham Research Institute on Climate Change and the Environment, LSE, 6th October 2008.

i) Events

Summaries of the events organized as part of the Munich Re Programme are given on the following pages (in chronological order).

Inaugural lecture: 'A Global Deal for Climate Change'

6 October 2008

This formed part of the formal launch of the Grantham Research Institute, the Centre for Climate Change Economics and Policy, and the Munich Re Programme. The lecture was chaired by LSE Director Howard Davies and involved Professor Lord Nicholas Stern, first chair of the Grantham Research Institute and Centre for Climate Change Economics and Policy, and holder of the IG Patel Chair in Economics and Government at LSE; Dr Nicolaus von Bomhard, chairman of the board of management of Munich Re; Jeremy Grantham, chairman and co-founder of GMO and trustee of the Grantham Foundation for the Protection of the Environment; and ESRC Chief Executive Ian Diamond.

Symposium 1: Interpreting models in a climate change context

Munich Re offices, London, 20 July 2009

This first academic-industry symposium of the Munich Re Programme brought together experts in a range of different modelling techniques relevant to issues of climate and climate change risk management. It was attended by over 80 participants. By discussing the various approaches to interpreting model results, it explored how models are best used to improve decision-making and risk assessment.

The objectives of the symposium were:

- To explore how different types of models – climate, economic and risk models – are interpreted in the context of today's climatic conditions.
- To discuss the role of today's models in decision-making in politics and the insurance business under current climatic conditions.
- To discuss how models impact on planning and insurance-related risk assessment in the context of future climate change.
- To summarise the status of models utilised in climate change assessments.
- To identify approaches to future model development and interpretation that could improve their utility in the context of planning for future climate change.

Background: Models, particularly computer-based models, are now widely used in strategic, political and economic decision-making, as well as in the insurance sector. Yet different disciplines relate to, and utilise, models in very different ways. In some sectors they are seen as indicators of potential sensitivities. In others, they are sometimes interpreted as providing detailed deterministic or probabilistic predictions. The relationship between models and the real world, and how this is perceived by researchers, policy-makers and industry, is critical in achieving robust decisions and minimising future risks. Decisions in the context of climate change provide a particularly substantial challenge because of the time frames involved. The multi-decadal character of the problem limits the possibility of learning from experience in terms of adapting and improving both the models and the decision-making frameworks which use them.

There is nevertheless a substantial opportunity to learn from the way different types of models are interpreted and applied.

The programme and some presentations of the symposium can be found at: www.cccep.ac.uk/Events/Past/2009/munich-re-symposium-1.aspx

Roundtable: How can Climate Change Science and Economics Better Support the Insurance Industry?

Munich Re offices, London, 26 May 2010

Eighteen representatives of the insurance industry attended this roundtable and engaged in discussions with the aim of helping improve LSE's understanding of the needs of the insurance industry related to climate change science and economics. The afternoon was also used to present an industry brief, produced as part of the Munich Re Programme, by Nicola Ranger and Bob Ward: 'Aiming for a 2°C Goal: What does it mean for the insurance industry?' (see Appendix 2).

Delegates at the insurance industry roundtable, May 2010

Symposium 2: Quantification and interpretation of trends in economic and insured nat cat losses. How can climate change affect the frequency and severity of natural disasters?

Industry symposium, Munich, 23 November 2010

Nick Stern gave a keynote speech covering:

- Climate change impacts and consequences for policymakers.
- Expected effects of global warming on natcat losses in the next decades.
- The value of cooperation with Munich Re.
- Activities since Copenhagen and outlook for the Climate Change negotiations in Cancún in December 2010.

Eric Neumayer and Eberhard Faust presented new research results of normalised natural catastrophe loss trends for insurance and their interpretation. They discussed problems with loss normalisation, a review of existing studies, and results of new analyses by LSE and Munich Re.
www.cccep.ac.uk/Events/Past/2010/trends-economic-insured-nat-cat.aspx

Symposium 3: The Study of Economic Loss from Natural Disasters

Science symposium, London, 30 November 2010

Invited experts from across the world discussed findings and compared competing methodologies for normalising disaster losses. The symposium provided an opportunity for presentations of latest findings and open and progressive discussion on methodologies and the relevance of this research area to risk management planning more generally. For a summary report of the event see:
www.cccep.ac.uk/Events/Past/2010/economic-loss-natural-disasters.aspx

Symposium 4: Hurricane Forecasting: Skill and value

Academic symposium, LSE, London 15 May 2012

Held as part of research stream D, this academic symposium on Hurricane Forecasting focused on questions relating to the construction, evaluation and use of hurricane forecasts on seasonal scales. The aim of the symposium was to present the findings from LSE's work in this area as part of the Munich Re Programme, to stakeholders and other users. Participants from the climate research and forecast user communities included representatives from the UK Met Office, UCL, Imperial College, KNMI, the Bermuda Institute of Biological Sciences, the William J Clinton Foundation, Christian Aid, as well as members of the Munich Re Programme at LSE and Munich Re itself. Various aspects of the end-to-end process of forecast production and implementation - such as lead time, forecast targets, and good practice in forecast verification - were covered in detail. The principle focus was on the skill and value of Atlantic basin hurricane forecasts, but other areas of extreme weather risk, such as floods, landslides, and drought, were also presented and discussed.

LSE research in this area continues to be shaped by the requirements of forecast users and the knowledge and capabilities of forecast providers. Participants were invited to share knowledge to assist LSE in their understanding of the needs of decision-makers when communicating uncertainty, and distinguishing between forecast skill and value.

The full report from the meeting can be found at:
www.cccep.ac.uk/Events/Past/2012/May/report-hurricane-forecasting.pdf

Symposium 5: Insurance in emerging markets: determinants of growth and the case of climate change?

LSE, London, 21 November 2012

This symposium on Insurance in Emerging Markets brought together a small group of leading academics and practitioners to discuss the different determinants of insurance growth. Participants from the following organisations attended: University of California, Berkeley, European Bank for Reconstruction and Development (EBRD), Financial Services Authority (FSA), Inter-American Development Bank (IADB), LSE, Ludwig-Maximilians-

Universitaet, Munich Re, TERI University, World Bank, and the University of Würzburg.

The workshop provided an open exchange on latest findings, considering evidence from emerging markets and developed markets, as well as comparing tools and methods for evaluation. The symposium provided an opportunity to present the findings under the LSE-Munich Re Programme research stream E, while inviting a discourse on how best to link the topic of climate change with general insurance economics.

Further details and the Proceedings from the meeting are available at:
www.cccep.ac.uk/Events/Past/2012/November/insurance-markets-growth-climate-change-symposium.aspx

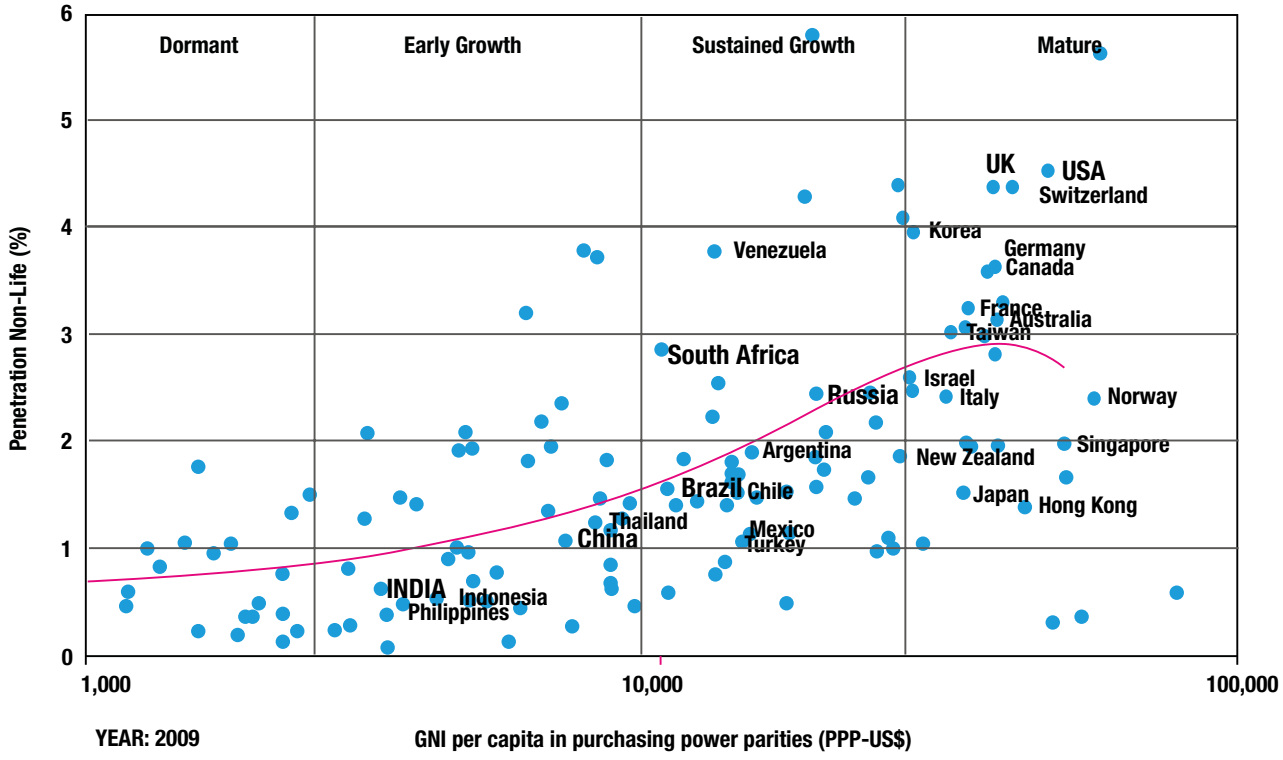
Final event: Frontiers in climate change economics and policy research: Taking stock, moving forward

Royal Society, London, 24 September 2013

On 24-25 September 2013 a two-day event was held at the Royal Society, London, to mark the end of phase I of the Centre for Climate Change Economics and Policy (CCCEP), including the Munich Re Programme. The event began with an afternoon dedicated to the Munich Re Programme, with speakers from both LSE and Munich Re, and Professor Howard Kunreuther (Munich Re Programme visiting professor). In the evening a keynote talk was given by Professor Lord Nicholas Stern.

This concluding event of the programme was geared towards the aim of making the research accessible to broader stakeholders. A wide range of industry representatives and policy-makers attended the event and contributed to the discussion of the key findings showcased, which were disseminated further via an audio recording of the event which continues to be accessible online:
www.cccep.ac.uk/Events/Multimedia/podcast-economics-climate-risks-insurance-munich-re.aspx

The day's programme can be found at:
www.cccep.ac.uk/Events/Past/2013/Sep/economics-climate-risks-insurance-munich-re-research.aspx



The relationship between gross national income (GNI) per capita (expressed in purchasing power parities, PPPs) and the penetration of non-life insurance (% of GDP) in 2009 for around 200 countries. The red line is known as the 'Global Trend Line' (GTL). GNI per capita is shown logarithmically, giving the characteristic' s-curve'. Source: data provided by Munich Re. Ranger, N. and S. Surminski (2011).

ii) Dissemination activities

Presentations and talks given by Programme staff, along with various other collaborative activities, played a key role in communicating findings to a broader range of stakeholders. We detail below a selection of these key activities.

IARU Scientific Congress, Climate Change: Global Risks, Challenges and Decisions

Copenhagen, March 2009

Nicola Ranger gave a presentation 'Adaptation and Insurance: Reducing Risk and Maintaining the Insurability of People and Property in the Face of Rising Hazards'.

ABI Climate Change Data Seminar

London, 27 August 2009

Leonard Smith (with David Stainforth, Ana Lopez and Edward Tredger) gave a presentation entitled 'Climate Models and their Information Content for the Insurance Industry'.

Germanwatch – MCII joint workshop: Addressing the most vulnerable people in a Copenhagen climate deal: Technical alternatives from risk management approaches?

Bonn, Germany, 17 September 2009

Nicola Ranger gave a presentation entitled 'Identifying the Most Vulnerable'.

SAMSI 2009-10 Program on Space-time Analysis for Environmental Mapping, Epidemiology and Climate Change, Opening workshop on Climate Change

13-16 September 2009

Leonard Smith gave a presentation entitled 'Experimental Design and Interpretation of Policy-relevant Climate Model Ensembles'.

Talk by Visiting Professor Howard Kunreuther

LSE, London, 14 October 2009

'At War with the Weather and Other Extreme Events: Managing Large-scale Risks in a new Era of Catastrophes'. Further details available at: www.cccep.ac.uk/Events/Past/2009/munich-re-war-weather.aspx

Understanding the Role of Insurance and Disaster Risk Reduction in Adaptation

Bonn, Germany, October 2009

Nicola Ranger with Munich Re colleagues organised this half-day academic workshop. The output from the workshop was used for informing the MCII on disaster and insurance in developing countries.

Challenging the European Climate-Energy package in the UK and in France

Paris, November 2009

Nicola Ranger prepared a presentation for policymakers on climate science needs for managing risks from extreme events in Europe: 'Managing Extreme Events in a Changing Climate: Key Questions in the Context of UK and EU Adaptation Policy'

ENSEMBLES symposium

Exeter, UK, November 2009

Hailiang Du and Leonard Smith presented a poster entitled 'Skill of Ensemble Seasonal Probabilistic Forecast' (Du, Niehörster, Binter and Smith), at the final ENSEMBLES symposium at the Met Office, Exeter, UK. The abstract and a link to the poster can be found in Appendix 1(iv).
http://ensembles-eu.metoffice.com/meetings/GA6_Exeter_2009/FinalSymposium.html

Nicholas Stern press briefing with Munich Re, at COP15

Copenhagen, December 2009

Lord Stern spoke at the MCII press-briefing, alongside Peter Höppe, in support of the MCII and promoting the importance of disaster risk management within the international negotiations on a future global deal for climate change.

7th Insurance Linked Securities (ILS) Summit

New York, January 2010

Leonard Smith presented 'Examining Uncertainties in Climate Models: Forecasting the Impact of Best and Worst Case Climate Scenarios on the Future of the ILS Market'.

Handling Uncertainty in Science

Royal Society London, 22 March 2010

Leonard Smith and Nicholas Stern presented 'Uncertainty, Ambiguity and Risk in Forming Climate Policy'. The abstract can be viewed at: http://www.lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/SmithAndStern_Uncertainty_RS__Mar2010.pdf

The interpretation of long-term hurricane projections for decision-support

'Town Hall meeting' workshop, New York, 11 March 2010

Nicola Ranger co-hosted a "town hall" meeting/workshop in New York with Wharton Business School (Professor Howard Kunreuther and colleagues) to discuss the interpretation of long-term hurricane projections for decision-support. Attendees included Eberhard Faust of Munich Re along with other leading hurricane researchers.

Industrial-Academic Forum on Commodities, energy markets, and emissions trading, the Fields Institute

Toronto, 9-10 April 2010

Max Fehr gave a talk entitled 'Option Pricing in the European Union's Emission Trading Scheme'. See: www.fields.utoronto.ca/programs/scientific/09-10/finance/forums/trading/index.html

Collaboration with GFDL and MIT

April 2010

In April 2010, LSE collaborated with scientists at the Geophysical Fluid Dynamics Laboratory (GFDL) and MIT to develop a framework for producing robust scenarios useful for decision-making.

2nd ILS Summit Europe

London, 26-28 April 2010

Leonard Smith and Pauline Barrieu presented 'Examining Uncertainties in Climate Models: Forecasting the Impact of Best and Worst Case Climate Scenarios on the Future of the ILS Market'.

LSE academic workshop with the Wharton Risk Centre

May 2010

Workshop facilitated by Professor Howard Kunreuther to explore the implications for insurance systems in Florida and linkages with adaptation.

AMS conference on Hurricane meteorology

Tuscon Arizona, 11 May 2010

Falk Niehörster presented a paper entitled 'Interpretation of decadal tropical cyclone forecasts for decision-support: application to insurance and disaster risk reduction along the US Gulf Coast and the Caribbean' (N. Ranger, L. Smith, F. Niehörster, R. Muir-Wood, and H. Kunreuther).

Abstract: We present preliminary results of a collaborative project, between the industry and academia, that develops a framework for interpreting the range of available tropical cyclone activity projections under climate change with the goal of informing the development of robust climate change adaptation strategies by individuals, the insurance industry and public policymakers.

Predictions of changes in tropical cyclone characteristics with climate change (both natural and anthropogenic) are notoriously uncertain. Firstly, the relatively short length and data quality issues in observational records make the detection and attribution of trends in tropical cyclone characteristics problematic. Secondly, the small-scale physics

involved in tropical cyclone formation and evolution make adequate simulation in global climate models impossible at present; with different climate models giving divergent results. However, there is information in past records and future projections, if interpreted with full account of the uncertainties.

Here, we present a framework for interpreting current tropical cyclone projections for decision-support, which accommodates uncertainty and facilitates robust decision-making using the information available today. This framework is used to construct an envelope of plausible future risk scenarios (a future "risk space") using a coupled climate-catastrophe modelling approach. We will present preliminary results demonstrating the application of this framework to assess how climate change could affect losses and insurance systems in Florida and the Caribbean.

A prime objective of this research is to identify possible adaptive responses by individuals, the insurance industry and public policymakers that cost-effectively manage future risks and are robust under the deep uncertainties in current long-term forecasts
http://ams.confex.com/ams/29Hurricanes/techprogram/paper_168804.htm

Seminar by Arthur Petersen, Munich Re Programme Visiting Professor

LSE, London, 13 May 2010

Arthur Petersen presented a seminar entitled 'Improving the IPCC's uncertainty management in assessing climate change, impacts and responses'. The abstract can be viewed at:
www.cccep.ac.uk/Events/Past/2010/munich-re-seminar-IPCC.aspx

ESF workshop 'Exploring Epistemic Shifts in Computer Based Environmental Sciences'

Aarhus University, Denmark, 10-12 June 2010

Arthur Petersen presented a workshop paper 'Reframing the Reliability of Models: Moving from Error to Quality for Use' (jointly authored with Leonard Smith). The paper can be viewed at:
www.lse.ac.uk/CATS/Talks%20and%20Presentations/Visitor%20talks/Petersen_Smith_Aarhus.pdf

24th European Conference on Operational Research, Euro XXIV

Lisbon, 11-14 July 2010

Max Fehr and Pauline Barrieu organized two sessions for the 'Energy and Emissions Markets' stream of the Euro XXIV conference. Fehr also gave a talk 'Option Pricing in the European Union's Emission Trading Scheme'. The abstract can be viewed at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/Fehr_option_pricing.pdf

11th International Meeting on Statistical Climatology (IMSC)

Edinburgh, 12-16 July 2010

Several CATS members, including Leonard Smith, Dave Stainforth, Nicola Ranger, Falk Niehörster, Ana Lopez, Milena Cuellar, Joe Daron and Alex Jarman, gave presentations at the 11th International Meeting on Statistical Climatology. They included: 'When is a model relevant?' (Smith); 'Understanding the relevance of climate model simulations to informing policy: an example of the application of MAGICC to greenhouse gas mitigation policy' (Ranger); 'The inapplicability of traditional statistical methods in climate ensembles' (Stainforth); 'Comparing Cloud Feedbacks in Perturbed-Physics Ensembles from two different GCMs' (Niehörster); 'SVD on ICE – On the linearity of climate change simulation with GCMs' (Niehörster); 'Climate model evaluation and models of natural variability' (Lopez); 'Analysis of long-term persistence in a perturbed physical ensemble' (Lopez); and 'Are Current Flaws in Bayesian Approaches to Climate Projection Fatal?' (Smith). Abstracts of all these presentations can be found at: lse.ac.uk/CATS/Talks%20and%20Presentations/IMSC_Conference.aspx

MCII side event, UNFCCC negotiations

Bonn, Germany, 4 August 2010

Nicola Ranger contributed at this MCII side event and delegate dinner.

Workshop: insurance demand, development and climate change

Munich, November 2010

Swenja Surminski and Nicola Ranger collaborated with Munich Re colleagues on understanding the links between insurance demand, development and climate change.

AOSIS negotiators meeting

St. George's, Grenada, November 2010

Nicola Ranger contributed to the AOSIS (Alliance of Small Island States) negotiators meeting.

AGU Fall Meeting 2010

San Francisco, 13-17 December 2010

Nicola Ranger presented 'Revisiting the Generation and Interpretation of Climate Information for Adaptation Decision-making' at the AGU Fall Meeting 2010. Slides are available at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/NicolaRanger_AGU2010.pdf

VU University-LSE-KNMI-PBL workshop

January 2011

Professor Arthur Petersen hosted a joint VU University Amsterdam/LSE/KNMI/PBL workshop on uncertainties in weather extremes.

Equipping society for climate change through improved treatments of uncertainty

Leeds, January 2011

Alex Jarman presented his poster entitled 'Small-number statistics, common sense and profit: challenges and non-challenges for hurricane forecasting'. (See poster page 26) www.equip.leeds.ac.uk/annual-conference-455.html

Cat Risk Management Modelling: measuring, managing and mitigating cat risk

London, February 2011

Swenja Surminski gave a presentation, entitled 'Cat Risk Management: An academic perspective' which illustrated the Munich Re Programme with its different applications.

Economics of Natural Disasters – Bridging Disaster Risk Reduction and Climate Adaptation Efforts and Strategies

Venice, February 2011

Swenja Surminski gave a talk entitled 'Adaptation to climate extremes: investigating the role of the private sector – the case of the insurance industry'.

Law and Economics of Natural Hazards Management in a Changing Climate

Innsbruck, February 2011

Swenja Surminski gave a talk entitled 'The Implications of Climate Model Uncertainty for Insurance and Adaptation Decision-making'.

Risk Prevention Initiative (RPI), Bermuda Institute of Ocean Science (BIOS)

March 2011

Falk Niehörster gave an invited talk entitled 'Towards decision relevant hurricane risk scenarios'.

'All Models Are Wrong' workshop

Groningen, Netherlands, 14-16 March 2011

Leonard Smith gave a talk entitled 'All models are wrong but some are dangerous: Philosophical aspects of statistical model selection', and presented a poster with Emma Suckling entitled 'All models are wrong: Which are worth paying to look at? A case study for Global Mean Temperature'. (For abstract see Appendix 1iv).
See poster on page 92.

BusinessGreen.com Sustainable Business Lecture Series

LSE, London, March 2011

Swenja Surminski gave an invited talk entitled "Insuring the uninsurable" at 'Preparing for stormy weather – identifying and managing climate risks'.

Presentation to Scottish Government

March 2011

Simon Dietz presented work based on his paper with Anthony Millner and Geoffrey Heal, 'Ambiguity and climate policy', to the Scottish Government.

World Bank Experts Roundtable on Urban Flood Risk Management

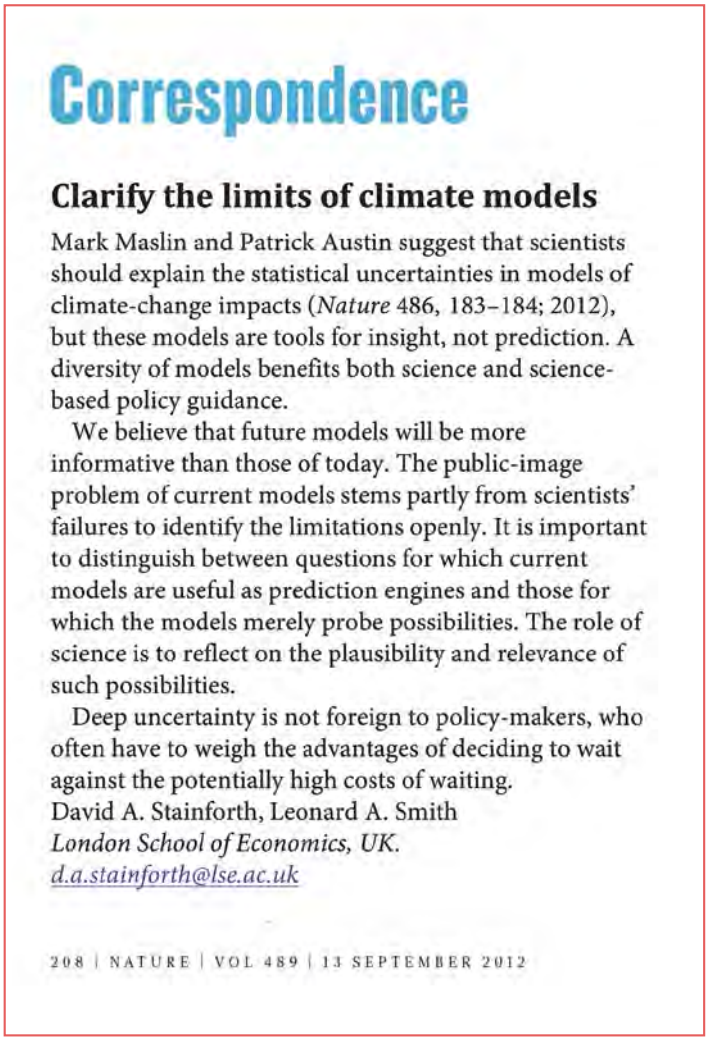
March 2011

Nicola Ranger presented a talk 'The role of climate change in urban flood risk management today' at this roundtable, hosted by the East Asia Disaster Risk Management team.

Workshop, Munich Re

Munich, March 2011

Swenja Surminski and Nicola Ranger conducted a mini-workshop discussing the latest findings on insurance demand with colleagues at Munich Re.



Correspondence

Clarify the limits of climate models

Mark Maslin and Patrick Austin suggest that scientists should explain the statistical uncertainties in models of climate-change impacts (*Nature* 486, 183–184; 2012), but these models are tools for insight, not prediction. A diversity of models benefits both science and science-based policy guidance.

We believe that future models will be more informative than those of today. The public-image problem of current models stems partly from scientists' failures to identify the limitations openly. It is important to distinguish between questions for which current models are useful as prediction engines and those for which the models merely probe possibilities. The role of science is to reflect on the plausibility and relevance of such possibilities.

Deep uncertainty is not foreign to policy-makers, who often have to weigh the advantages of deciding to wait against the potentially high costs of waiting.

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All models are wrong: Which are worth paying to look at?

A case study for Global Mean Temperature

Emma Suckling and Leonard A. Smith

Centre for the Analysis of Time Series, Department of Statistics, London School of Economics, UK

http://www2.lse.ac.uk/CATS

Introduction

Dynamical simulation models (GCMs), often used to provide decision support in the context of climate variability and change, typically have complex structures, rendering them computationally intensive to run and expensive to develop. In extrapolation the models which 'capture the physics' must justify their cost to users by demonstrating that they outperform simpler statistical models by placing significantly more probability mass on the verification. But do today's 'best available' models do so?

An approach is presented towards a robust measure of the in-sample skill of ensemble forecasts and the performance of a set of decadal simulations from ENSEMBLES for global mean temperature is assessed against a benchmark statistical model based on the random analogue prediction method. The ensemble forecasts are expressed as probability distributions through the kernel dressing procedure and their quality quantified according to the Ignorance skill score.

Can we determine where simulations win?

The performance of decadal predictions over global mean temperature is initially considered since in the absence of second order effects, simulation models are expected to perform better over larger spatial and temporal scales. It is then essential to understand how the performance (as well as the value in terms of providing decision support) of complex models will change against simple data-based models moving from global annual averages to local daily extremes.

Figure 1 illustrates the simulated global mean temperature (as a 2 year running mean) for the HadGEM2 model, containing 3 initial condition ensemble members, over the full set of decadal predictions from ENSEMBLES, which are initialised to observations for a series of November launch dates [1]. HadCRUT3 observations and ERA40 reanalysis data have been treated in an identical manner and are also shown.

Even at global scales, the raw model forecasts are seen to differ somewhat from the target observations.

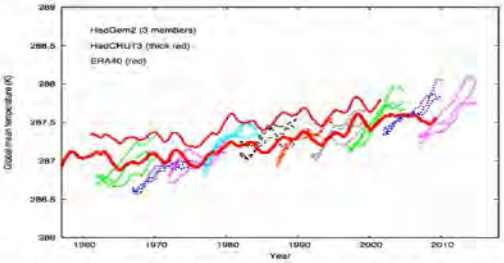


Figure 1: Global mean temperature (2 year running mean applied) for the HadGEM2 model of the ENSEMBLES decadal forecasts. HadCRUT3 observations and ERA40 reanalysis are included.

Figure 2 shows the forecast distributions for a subset of the simulations. While the pattern of temperature change is captured well over some individual forecasts, in several instances the verification falls within the tail of the distribution even after a complicated bias correction procedure is applied, which is based on the mean forecasts error as a function of lead time (figure 3).

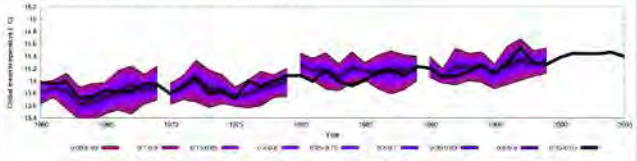


Figure 2: Predictive distributions (percentile ranges as indicated) of global mean temperature for the HadGEM2 model from the ENSEMBLES decadal simulations for launch dates at 10 year intervals.

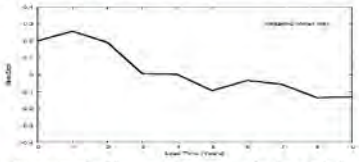


Figure 3: Mean forecast error for global mean temperature as a function of lead time (T(obs)-T(model)).

References

[1] A. Troccoli and T. N. Palmer, Phil. Trans. R. Soc. A **365**, 2179-2191 (2007).

[2] L. A. Smith, *The Maintenance of Uncertainty*, Proc. International School of Physics "Enrico Fermi", Course CXXXIII, pg 177-246 (1997).

[3] J. Bröcker and L. A. Smith, Weather and Forecasting, **22** (2), 382-388 (2007).

[4] H. Du, F. Niehoerster and L. A. Smith, *Improvement in Full Probability Forecasting at Seasonal Lead-times*, submitted.

Random Analogue Prediction model

The random analogue prediction model (RAP) [2] provides a simple reference for comparison against the performance of complex simulation models since it contains few model structure assumptions but is expected to be more skilful than climatology. A set of forecasts are produced for the RAP model, initialised to the observations.

Figure 4 illustrates this approach, in which an ensemble is built from available analogue states over the full time series using the direct method (so that a forecast for lead time, n, is produced by considering the full set of nth differences, leaving out the forecast year itself).

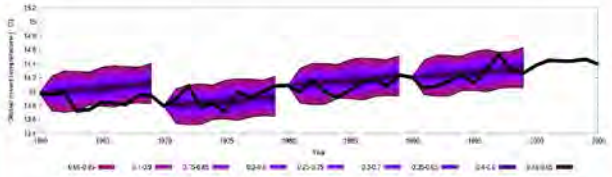


Figure 4: Predictive distributions for global mean temperature using the direct RAP model.

Ensemble forecast evaluation

Figure 5 shows a comparison between the performance as a function of lead time for the HadGEM2 and RAP models. A measure of the information contained in each ensemble of model forecasts is quantified by transforming the forecasts into a continuous probability distribution function through the kernel dressing procedure [3]. Gaussian functions are applied to each ensemble member with optimised kernel mean and spread as a function of lead time that are obtained by minimising a cost function based on the Ignorance skill score, defined as $I=-\log_2(p(x))$, where $p(x)$ is the probability assigned to the verification, x. The mean is taken over a set of forecast-verification pairs using a leave-one-out cross validation methodology.

RAP performs to a similar quality as HadGEM2 over some lead times, although a small sample size of forecast-verification pairs in the ENSEMBLES simulations leads to large uncertainties. The blue line illustrates a true leave-one-out methodology, pointing to the importance of careful cross validation in decadal forecasting [4].

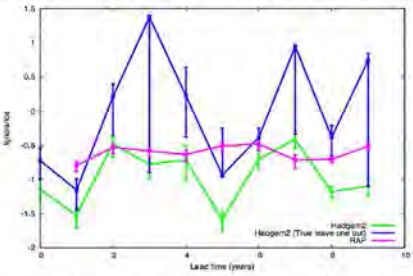


Figure 5: Ignorance as a function of lead time for the HadGEM2 and RAP models. The uncertainty bars are the 70th percentile from re-sampling from the forecast set. Lower Ignorance values indicate better skill.

While statistical models such as RAP are not expected to capture changes due to previously unobserved physical feedbacks, current simulation models may or may not capture such feedbacks. An important question therefore arises as to how a model may be deemed fit for purpose in decision support tasks in the longer range. At decadal scales, direct comparisons can be made as illustrated here.

Outlook

The performance of decadal forecasts from ENSEMBLES has been contrasted with a simple benchmark model. It is found that at some lead times simulations outperform RAP (~1 bit), placing twice the probability mass on the verification. Small sample sizes, however, lead to large uncertainties in terms of computing skill.

Given the practical limitations in terms of producing ensemble forecasts, establishing statistical significance for any model requires clear experimental design, including prior specification of which predictions will be evaluated.

Under EQUIP, this methodology will be used to determine the user-value derived by employing GCMs in addition to statistical forecasts.

Acknowledgements

The support of the Economic and Social Research Council (ESRC), as well as NERC under the EQUIP project is gratefully acknowledged.

Predictability + School on Data Assimilation, NORDITA

Stockholm, 25-27 May 2011

Leonard Smith, Arthur Petersen and Hailiang Du attended this summer school; Smith gave a talk entitled 'Things they didn't tell you last week: DA in Maths, Physics, and Decision Support'.

Current Challenges in Climate Modelling 2011

University of Uppsala, 26 May 2011

Leonard Smith gave an invited talk entitled "What (and who) do ensembles of climate models inform".

18th annual conference of the European Association of Environmental and Resource Economists

Rome, June 2011

Inaugural conference of the American Association of Environmental and Resource Economists

Seattle, June 2011

Antony Millner, Simon Dietz and Geoffrey Heal presented work based on their paper 'Scientific ambiguity and climate policy' at these and a number of other international conferences.

28th International Conference on Mathematical Geophysics Modelling Earth Dynamics: Complexity, Uncertainty and Validation

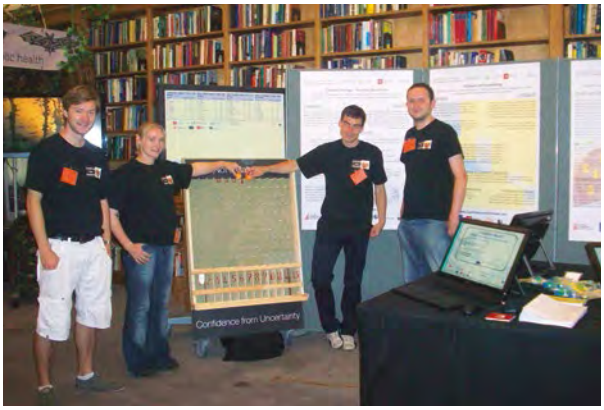
Pisa, Italy, 5-9 June 2011

Leonard Smith gave an invited talk, 'Extracting Insight from Predictions of the Irrelevant: Can the Diversity in Our Models Inform Our Uncertainty of the Future?' at the special session 'Can our models only predict the irrelevant?' held in memory of Professor Tarantola.

Confidence from uncertainty, Royal Society Summer Science Exhibition

July 2011

David Stainforth led an exhibit that aimed to explore how predictions are made and communicated, how and when probabilities can be deduced, and the role of computer models in these processes. It involved interactive computer-based probability games and hands-on physical games to do so.



Members of LSE CATS with the Royal Society exhibit, July 2011

Decisions, Games, and Logic

Maastricht, 8 July 2011

Oliver Walker presented a talk entitled 'Reasoning about Unawareness: A Decision Theoretic Account'.

Insurance Demand, Climate Change and the BRICS Economies

Munich and London, 2011

Ranger and Surminski participated in a number of discussions and workshops on Insurance demand and climate change in the BRICS economies in Munich and London during 2011.

Climate science and climate change: Epistemological and methodological issues, SPS side event of the 14th Congress of Logic, Methodology and Philosophy of Science

Nancy, July 2011

Leonard Smith gave an invited talk entitled 'Insight or Numbers? Distinguishing Climate Science from Climate Modelling'.

ICIS workshop 'Verification, Validation and Uncertainty Quantification Across Disciplines'

Park City, Utah, 6-13 August 2011

Leonard Smith gave a talk entitled 'Scientific Support for Climate Policy: Is a VVUQ analysis of today's models helpful? And where not: what then?'

European Association of Mutual Insurers AMICE's seminar 'Tomorrow's emerging risks'

Copenhagen, 22 September 2011

Swenja Surminski gave an invited talk on climate change and the insurance industry.

MIRC-hosted expert workshop on insurance demand and behavioural aspects

Munich, December 2011

Swenja Surminski participated in this workshop.

Invited lecture: 'Coupled dynamic modelling of the economy and of the climate system'

LSE, London, March 2012

Professor Michael Ghil gave an invited lecture at LSE, as part of the Munich Re Programme. lse.ac.uk/CATS/talksPresentations/Coupled-dynamic-modelling-of-the-economy-and-of-the-climate-system.pdf

European Commission expert workshop

Brussels, March 2012

Swenja Surminski was an invited participant at this workshop on 'Developing the EU Adaptation Strategy: Dealing with disaster risk and climate change adaptation responses.

Colloquium on disaster risk transfer and adaptation at the French Senate

Paris, March 2012

Swenja Surminski was invited to take part in a panel discussion at the Colloquium. She outlined insurance and adaptation examples from developing countries and the developed world. Partners: French Senate, French insurance industry.

EGU 2012

Vienna, April 2012

Swenja Surminski gave a presentation entitled 'The impact of climate change on the BRICS economies: The case of insurance demand', at EGU, Vienna, April 2012. Alex Jarman gave a talk entitled 'Misleading estimates of forecast quality: quantifying skill with sequential forecasts' which presented research on the effects of serial dependence on estimating the skill of a forecast system.

OECD Adaptation Workshop

May 2012

Surminski gave an invited presentation on private sector adaptation at the OECD Adaptation Workshop.

Adaptation Futures Conference

Arizona US, May 2012

Susannah Fisher gave a presentation based on the technical paper (co-author Swenja Surminski) 'The roles of public and private actors in the governance of adaptation: the case of agricultural insurance in India' [MRe TP#15].

32nd Annual International Symposium on Forecasting

Boston, 25 June 2012

Leonard Smith was a featured speaker ('Editor's Choice') at the 32nd Annual International Symposium on Forecasting, Boston. His talk was entitled 'Predictability and Insight: Contrasting the achievable aims of forecasting in weather like cases and climate like cases'.

8th IEEE International Conference on eScience

Chicago, 8-12 October 2012

Leonard Smith gave a keynote speech entitled 'Predictability and Understanding of Our Climate Risk: Approximations, Bugs and Insight'. The abstract can be viewed at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/eScience-2012---Predictability-and-Understanding-of-Our-Climate.pdf

Climate Risk and Insurance meeting

Zurich, December 2012

Swenja Surminski gave an invited presentation on 'risk engineering' at the Meeting of the Working Group of the Climate Risk and Insurance (CR+I) Project of the Geneva Association, Zurich. Partner: industry.

AGU Fall Meeting

San Francisco, 3-7 December 2012

Leonard Smith gave an invited talk entitled 'Queuing the wrong U?' The abstract can be viewed at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/2012-L-Smith-Queuing-the-Wrong-U.pdf and slides at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Slides/Smith%202012-12-05%20AGU%20Q%20Wrong%20U%20SFS.pdf Munich Re Research Officer Emma Suckling presented 'Increasing the relevance of GCM simulations for Climate Services'. The abstract can be viewed at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Abstracts/2012-L-Smith-and-E-Suckling-Increasing-the-relevance-of-GCM-simulations-for-Climate-Services.pdf And slides are at: lse.ac.uk/CATS/Talks%20and%20Presentations/Talk%20Slides/Smith%202012-12-06%20AGU%20Climate%20Services%20SFS.pdf

European Climate Change Adaptation (ECCA) conference

Hamburg, 18–20 March 2013

Swenja Surminski chaired two sessions at this conference (http://eccaconf.eu/index.php/page/ECCA):

i) 'Addressing uncertainties in national adaptation strategies', in which David Stainforth and Nicola Ranger were panelists; ii) 'Challenges to respond to loss and damage of climate Change', in which Ana Lopez presented a talk. A synthesis report is available at: lse.ac.uk/CATS/Events/EventsDocs/ECCA-Synthesis-paper-Loss-and-Damage-final.pdf

Facts on climate change in Russia

Munich, 1 March 2013

Swenja Surminski collaborated with Munich Re experts, which led to a joint analytical article for *Geo Topics:* Natural catastrophes 2012 – Analyses, assessments, positions.

Dutch Government Expert Panel on Uncertainty Communication in the IPCC AR5 WG I SPM

PBL Netherlands Environmental Assessment Agency, Bilthoven, 17-18 June 2013

At the invitation of Professor Arthur Petersen, Leonard Smith, David Stainforth and Erica Thompson joined this expert panel discussing and refining the official questions and requests for clarification regarding the AR5 report to be submitted by the Dutch government. www.pbl.nl/en/news/newsitems/2013/bridging-the-gap-between-stakeholders-and-climate-modellers

Above: Arthur Petersen, Leonard Smith, David Stainforth, Erica Thompson and Ewelina Sienkiewicz amongst other members of the expert panel.

Brazilian Insurance Association

Rio de Janeiro, Brazil, June 2013

Swenja Surminski gave a presentation based on the Munich Re Programme research stream E work to industry leaders.

The Roles of Climate Models: Epistemic, Ethical, and Socio-Political Perspectives

Eindhoven, October November 2013

Erica Thompson gave a talk entitled 'Assessing the evidence: How decision-makers could gain useful insight from climate model results'. Details of the event can be found at: http://enviroethics.org/2013/09/04/workshop-roles-of-climate-models/

Appendix 6: Awards and prizes

It is true to say that the Munich Re Programme was literally “Award Winning”. In addition to this official recognition, papers under the Programme have already received well over 100 citations in the Thomson Reuters’ Web of Science. All of the peer reviewed papers produced are, of course, still rather young as the academic pace tends to be a bit less intense than the pace in industry.

Lloyd's Science of Risk Prize 2012

Nicola Ranger's paper with Falk Niehörster 'Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments' was shortlisted for the Lloyd's Science of Risk Prize. Nicola gave a presentation entitled 'What do we really know about US Hurricane Risk in 2020?' at the prize event on 29 November 2012. (See Appendix 1 for details of both the paper and presentation poster.) lse.ac.uk/CATS/prizes/Lloyds-Science-of-Risk-Post-conference-booklet-2012-(3).pdf

Lloyd's Science of Risk Prize 2014

The Ranger and Surminski paper on non-life insurance demand (Ranger and Surminski 2013) was shortlisted for the Lloyd's Risk Prize in 2014, recognizing the academic as well as the broader policy and industry relevance of this work. See poster page 31.

EAERE award for Outstanding Publication 2013

The paper 'Scientific Ambiguity and Climate Policy' (Millner, Dietz and Heal) has had a significant impact on research into climate change economics. It appeared first as a working paper as part of the prestigious working-paper series of the US National Bureau of Economic Research. Subsequently it was published in *Environmental and Resource Economics*, the official journal of the European Association of Environmental and Resource Economists (EAERE), and won the EAERE award for Outstanding Publication in the journal in 2013 and has been highly cited.

AGU 2013 Charney Lecture

Leonard Smith was invited to present the prestigious AGU Charney Lecture in San Francisco in December 2013. His title was "Probability in Weather and Climate". http://atmospheres.agu.org/awards/jule-charney-lecture/

Appendix 7: Programme personnel

Personnel who worked on the Munich Re Programme, both at LSE and at Munich Re, are all listed here.

i) at LSE

Pauline Barrieu is Professor of Statistics at the London School of Economics and Political Science, where she is also Deputy Head of the Statistics Department and co-Director of the Centre for the Analysis of Time Series (CATS). She joined the Department of Statistics in 2002 having obtained two doctorates: a PhD in Finance with highest honours, Doctorat H.E.C., France, H.E.C. Graduate Business School, awarded in October 2002; and a PhD in Applied Mathematics with highest honours, Laboratoire de Probabilités et Modéles aléatoires, University of Paris VI, France, awarded in December 2002.

Fabian Barthel was a research student at LSE, gaining his PhD in Human Geography in 2011. His thesis was entitled 'Spatial dependence in dyadic data: the cases of double taxation treaties, official development assistance, and asylum migration'. He worked on the Munich Re Programme with Professor Eric Neumayer. He is currently a consultant with the Boston Consulting Group.

Seamus Bradley studied BSc Mathematics and Philosophy at the University of Warwick before moving to the University of Bristol for an MA in History and Philosophy of Science. He completed his PhD at LSE in 2012. His thesis was entitled 'Scientific Uncertainty and Decision-Making'. He worked on the Munich Re Programme with Professor Roman Frigg. He is currently a postdoctoral fellow at the Ludwig-Maximilians-Universität München.

Raphael Calel completed a PhD in Environmental Economics at the LSE, having previously studied Economics at the University of Cambridge. He has now moved to the Department of Agricultural and Resource Economics at the University of California, Berkeley.

Umut Cetin is Associate Professor in the Department of Statistics at LSE. His research interests are in stochastic calculus, theory of martingales and Markov processes, liquidity risk and credit risk modelling, aysmmetric information in financial markets, and carbon finance. He attained his PhD in Applied Mathematics from Cornell University, Ithaca, New York.

Simon Dietz is Co-Director of both the Grantham Research Institute on Climate Change and the Environment, and the Centre for Climate Change Economics and Policy. Simon joined LSE in 2006, having previously worked at the UK Treasury, as a policy analyst on the 'Stern Review on the Economics of Climate Change'. Simon holds a starred first class honours degree in Environmental Science from the University of East Anglia, and Masters and PhD degrees from LSE, specialising in environmental policy and economics. He is co-editor of the *Handbook of Sustainable Development* (2007, with Giles Atkinson and Eric Neumayer) and *The Political Economy of the Environment: an Interdisciplinary Approach* (2011, with Jonathan Michie and Christine Oughton).

Hailiang Du received his PhD in statistics from LSE in June 2009. His thesis was entitled 'Combining Statistical Methods with Dynamical Insight to Improve Nonlinear Estimation'. He is a research officer in the Centre for the Analysis of Time Series (CATS) at LSE, though currently he is on secondment as a Research Scientist within the Center for Robust Decision-making on Climate and Energy Policy (RDCEP) at the University of Chicago. He worked on the Munich Re Programme with Professor Leonard Smith.

Max Fehr was a research assistant on the Munich Re Programme, working with Pauline Barrieu and Umut Cetin. Max holds a PhD from the Institute for Operations Research, Mathematics Department, ETH Zurich for a thesis entitled 'Market Design for Emission Trading Schemes', for which he was awarded the ETH Medal (the medal is awarded to the top five PhD theses at ETH). He was also awarded the "Walter Saxer-Versicherungs-Hochschulpreis" prize from ETH for his PhD. The prize is awarded for research in insurance mathematics or related fields, by a consortium consisting of Generali Assurances, Pricewater houseCoopers, Swiss Life, Swiss Re, Winterthur Insurance, and Zurich Financial Services.

Roman Frigg is Director of the Centre for Philosophy of Natural and Social Science (CPNSS), Associate Professor of Philosophy in the Department of Philosophy, Logic and Scientific Method, and Co-Director of the Centre for the Analysis of Time Series (CATS) at LSE. He is a Visiting Professor in the Munich Centre for Mathematical Philosophy of the Ludwig-Maximilians-University Munich and has held visiting appointments at the Universities of Utrecht, Sydney, and Barcelona. He holds a PhD in Philosophy from the University of London and Masters degrees both in theoretical physics and philosophy from the University of Basel, Switzerland.

Lyn Grove is Centre Manager of the Centre for the Analysis of Time Series at LSE, and was responsible for the administration of the Munich Re Programme. Lyn has

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Alex Jarman graduated with a Physics degree from the University of Auckland, followed by a Masters in Applied Meteorology at the University of Reading where he was awarded a NERC studentship. Alex undertook his PhD at LSE as part of the Munich Re Programme. He successfully defended his PhD thesis, 'On the Provision, Reliability, and Use of Hurricane Forecasts on all Timescales' in May 2014. His research interests include forecast evaluation and decision-making with forecast information, nonlinear time series analysis, and the physics and predictability of weather and climate.

Howard Kunreuther is the James G. Dinan Professor; Professor of Decision Sciences and Business and Public Policy at the Wharton School, and co-director of the Wharton Risk Management and Decision Processes Center. He has a long-standing interest in ways that society can better manage low-probability, high-consequence events related to technological and natural hazards. Dr Kunreuther was a member of the World Economic Forum's Global Agenda Council on Insurance and Asset Management for 2011-2012, and in 2009-2010 served as co-chair of the Forum's Global Agenda Council on Leadership and Innovation for Reducing Risks from Natural Disasters. He is a member of the National Research Council's panel on Increasing National Resilience to Hazards and Disasters and serves the Intergovernmental Panel on Climate Change (IPCC) as a chapter lead author of the IPCC's 5th Assessment Report on Integrated Risk and Uncertainty Assessment of Climate Change Response. He is a Fellow of the American Association for the Advancement of Science, and a Distinguished Fellow of the Society for Risk Analysis, receiving the Society's Distinguished Achievement Award in 2001.

Ana Lopez is a Research Officer in the Centre for the Analysis of Time Series at LSE, and is also a stipendiary college lecturer at University College Oxford. She has expertise in probabilistic climate change projections and their use in the quantification of future impacts and adaptation to climate change. Her previous experience includes research in theoretical physics in different universities in the USA, Argentina and the UK, and as a Tyndall Research Fellow at Oxford University, where she explored different approaches to identify the difficulties and potentialities of using large ensembles of climate models to project impacts of climate change, quantify their uncertainty, and extract robust and relevant information to develop adaptation pathways in different systems, with a focus on water resource management and biodiversity.

Antony Millner is a Senior Research Fellow in the Grantham Research Institute on Climate Change and the Environment at LSE. He works on a variety of issues in economics, with a focus on applications to environmental problems. His current research projects include work on climate change economics, discounting, and the political economy of policy choice. Antony completed his PhD at Oxford University in 2010, and spent two years as a Ciriacy-Wantrup Postdoctoral Scholar in the Department of Agricultural and Resource Economics at the University of California, Berkeley. He also has a Master's degree in Theoretical Physics and Applied Mathematics from Cambridge University and the University of Cape Town.

Eric Neumayer is Professor of Environment and Development at LSE. Eric joined the Department of Geography and Environment in 1998, having been an academic assistant at the Centre for Law and Economics at the University of Saarbrücken, Germany. An economist by training, he is the co-editor of the *Handbook of Sustainable Development* (with Giles Atkinson and Simon Dietz. Edward Elgar, 2007), the author of *Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms* (Edward Elgar, 1999; Second Revised Edition 2003; Third Revised Edition 2010), *Greening Trade and Investment: Environmental Protection Without Protectionism* (Earthscan, 2001) and *The Pattern of Aid Giving – the impact of good governance on development assistance* (Routledge 2003), as well as numerous journal articles. His teaching focuses on neoclassical environmental and ecological economics.

Falk Niehörster is an expert on climate change and catastrophic risk with a background in mathematics, physics and climatology. He has a track record of successfully interfacing between science and decision-making in the context of insurance and politics. Building on his expertise in system theory and uncertainty, he is providing reliable information and applicable strategies for management, adaptation and mitigation of risk from extreme events. Falk is currently working as a Director at Risk Management Solutions (RMS) on Model Strategy

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Delioma Oramas-Dorta is a Catastrophe Analyst at Guy Carpenter, the leading international Reinsurance broker, having joined GC in 2012. She is part of the Catastrophe Model Development team, tasked with development of Catastrophe Risk models, and has been involved in the development of flood and hail models. Before joining Guy Carpenter, Delioma worked as a researcher in projects dealing with Catastrophe Risk insurance in developing economies, at LSE and Oxford University. She holds an MPhil in Geographical Information Systems and Remote Sensing from Cambridge University and a PhD in Volcanic Hazard from Coventry University.

Arthur Petersen is Professor of Science, Technology and Public Policy at UCL's Department of Science, Technology, Engineering, and Public Policy. He joined UCL STEaPP full time in September 2014 after more than 13 years' work as scientific adviser on environment and infrastructure policy within the Dutch Government. Most recently he served as Chief Scientist of the PBL Netherlands Environmental Assessment Agency (2011–2014). Arthur is also Adjunct Professor of Science and Environmental Public Policy at the VU University Amsterdam (since 2011) and Research Affiliate at the Massachusetts Institute of Technology (since 2009), and has been Visiting Professor at LSE (2009-2014) and at UCL STEaPP (January-August 2014). Arthur studied physics and philosophy, obtained doctorate degrees in atmospheric sciences (Doctor of Philosophy – PhD, Utrecht University, 1999) and philosophy of science (Doctor of Public Administration – DPA, VU University Amsterdam, 2006), and now also finds disciplinary homes in sociology and political science. Most of his research is about managing uncertainty.

Nicola Ranger is an Advisor for Climate and Natural Hazards at the Department for International Development (DfID). She is a climate scientist with expertise in the science, economics and policy of disaster risk management and climate change. She has more than ten years' experience working in government, industry and academia. She was a Senior Research Fellow at the Grantham Research Institute on Climate Change and the Environment at LSE from 2009-2014. She previously worked at RMS and Defra.

Judith Rees is Vice-Chair of the Grantham Research Institute on Climate Change and the Environment at LSE. She is also: President of the Royal Geographical Society; Member of the UN Secretary General's Advisory Board on Water and Sanitation; External Strategic Advisor, Climate & Development Knowledge Network (CDKN); and Member Scientific Advisory Committee Energy Climate House, CEPS, Brussels. Judith was Director of the Grantham Research Institute on Climate Change and the Environment and the ESRC Centre for Climate Change Economics and Policy from 2008 until 2012. She was Deputy Director of LSE from 1998 to 2004, and Acting Director from May 2011 until September 2012. Judith has acted as advisor and consultant to a number of international organisations, government departments and NGOs including the World Bank, UNDP and the EC/ Rio Group, CPRE and Friends of the Earth. The advice has covered a range of water and environment related topics including the regulation of public and private water utilities, the provision of urban water and sanitation, sustainable development, pricing, institutional design and regulatory regimes in environmental management. She was member of the Technical Advisory Committee of the Global Water Partnership from 1996 until 2009. Judith was awarded the title of a Commander of the Order of the British Empire (DBE) in 2006 and Dame Commander of the Order of the British Empire (DBE) in 2013.

James Rydge is the Lead Economist for the Global Commission on the Economy and Climate. James was lead author of the Economics of Change chapter of the Global Commission's *Better Growth, Better Climate* report, released on 16 September 2014. Prior to joining the Global Commission, James was the Dahrendorf Research Fellow at the Grantham Research Institute on Climate Change and the Environment at LSE. In this role he worked closely with Lord Nicholas Stern, collaborating across a wide range of research areas, including on the economics of the low-carbon transition. James has a PhD in Economics and a Master's in Finance from the University of Sydney. Previously, he worked at the Bank of New York Mellon in London and PricewaterhouseCoopers in Sydney.

Appendix 7: Programme personnel

Leonard A Smith is Director of the LSE Centre for the Analysis of Time Series (CATS) and a Professor of Statistics. He is also Senior Research Fellow (mathematics) of Pembroke College, Oxford. He was the Principal Investigator of the Munich Re Programme, as well as a Co-investigator of the Centre for Climate Change Economics and Policy (CCCEP). From 2007 to 2008 he was leader of the LSE Climate Change Research Network. Leonard has been awarded the Royal Meteorological Society's Fitzroy Medal for his contributions to applied meteorology, a Selby Fellow of the Australian Academy of Science, a SAMSI Fellow, and the 2013 AGU Charney Lecturer. His graduate degrees (Phd, MPhil, MA) are in Physics from Columbia University. Leonard's current research focuses on better understanding of nonlinear dynamical systems, both mathematical and observed, prediction and predictability, the role of probability in informed decision support, and disentangling the effects of imprecise observation and model inadequacy when relating mathematical structures to reality.

David Stainforth is a Principal Research Fellow in the Grantham Research Institute at LSE. He is a physicist by training and has many years' experience of climate modelling. While a researcher at Oxford University he co-founded and was chief scientist of the climateprediction.net project, the world's largest climate modelling experiment. He has been both a NERC Research Fellow and a Tyndall Research Fellow at Oxford University. His current research interests focus on how we can extract robust and useful information about future climate, and climate related phenomena, from modelling experiments. This includes issues of how to design climate modelling experiments and how to link climate science to real-world decision-making in such a way as to be of value to industry, policy-makers and wider society.

Nick Stern is IG Patel Professor of Economics and Government at the LSE, and has been Chair of the Grantham Research Institute since it was founded in 2008. Lord Stern was adviser to the UK Government on the Economics of Climate Change and Development from 2005-2007, where he was Head of the Stern Review on the Economics of Climate Change, published in 2006. He was Head of the Government Economic Service from 2003-2007; Second Permanent Secretary to Her Majesty's Treasury from 2003-2005; Director of Policy and Research for the Prime Minister's Commission for Africa from 2004-2005; and Chief Economist and Senior Vice President at the World Bank from 2000-2003. During his time as Chief Economist of the European Bank for Reconstruction and Development, and Visiting Professor of Economics at LSE, he was one of the founding forces behind the Asia Research Centre, formally becoming its director in 2007.

Emma Suckling is a postdoctoral research scientist within NCAS-Climate at the Department of Meteorology, University of Reading, where she is involved in developing empirical prediction systems for European climate variables on seasonal-to-decadal time scales as part of the EU-funded SPECS project. Prior to that she was a Research Officer in CATS at LSE where she worked on the NERC EQUIP project and the Munich Re Programme. She is a physicist by training, having pursued both her undergraduate degree and a PhD in theoretical nuclear physics at the University of Surrey.

Swenja Surminski is a Senior Research Fellow at the Grantham Research Institute on Climate Change and the Environment at LSE, as well as a member of the Centre for Climate Change Economics and Policy (CCCEP). She is Programme Leader for the 'climate risk, insurance and private sector' work-stream at the institute, overseeing research projects from a multi-disciplinary field. Her research focuses on climate adaptation and disaster risk reduction with a special interest in the role of the private sector, particularly insurance and public-private partnerships as well as adaptation policy. Swenja is leading the institute's research under the EU's FP7 ENHANCE project, currently conducting an analysis of the London Climate Change Partnership as well as investigating UK flood insurance developments. She was recently appointed lead author for the business and industry chapter of the UK Climate Change Risk Assessment. Swenja is the lead academic for a World Bank project on the benefits of Disaster Risk Management (DRM), working with the Overseas Development Institute to explore how the co-benefits of DRM measures can strengthen the economic case for investment. She has published widely and works closely with industry and policy-makers at a global level, in a developing country context, across the EU and within the UK.

Erica Thompson is a Research Officer in the Centre for the Analysis of Time Series at LSE. Her research interests focus on how to identify meaningful and useful projections of future climate, how different types of model output can be used to inform these projections, and how to think

about uncertainty. She looked at some of these questions in the context of North Atlantic storms for her PhD at Imperial College London. Her background is in the physical sciences, having studied physics and mathematics at Cambridge University. Erica has also worked for the UK Energy Research Centre on an assessment of global oil depletion and for the Grantham Institute at Imperial College as a research assistant in climate policy; she is also interested in climate and energy policy and the role of scientific advice in policy-making. Recently she has worked on the DECC Global Calculator and is currently working with the UK Met Office as the Knowledge Integrator for the AVOID2 research programme.

Oliver Walker holds a doctorate from the Economics Department at the University of Oxford, and has worked as a University Lecturer at Cambridge University, a post-doctoral researcher at the Grantham Research Institute, LSE, and a college lecturer at Corpus Christi College, Oxford. He currently works as an economic consultant at NERA, and is the author of the *Rough Guide to Economics*, which was published in March 2014.

Andrew Williamson is currently the Global Leader of the Country Insight Solutions team at Dun & Bradstreet, providing clients with timely advice and research on operational risks internationally, with a special focus on the risks faced by companies' individual supply chains. Andrew recently spent a couple of years furthering his interest in the theories of environmental economics, policy drafting and environmental impact assessment, by undertaking an MSc in Environmental Policy and Regulation at LSE. He worked subsequently for just over a year at the Grantham Research Institute on Climate Change and the Environment, specialising in research on the opportunities and risks posed by climate change to the financial sector. Previous to this Andrew held a number of roles at the Economist Intelligence Unit including Global Director of Economic Research and Deputy Director of Country Forecasting. He began his career at the Foreign and Commonwealth Office.

Other contributors at LSE

The following staff at LSE also contributed to the Munich Re Programme:

Roman Binter, Alex Bowen, Sam Fankhauser, Susannah Fisher, Cameron Hepburn, George McKerron, Alessandro Tavoni, Bob Ward

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Hans-Jörg Beilharz is Professor of Economics at the University of Applied Science in Bad Honnef (Germany). He earned his PhD in the field of economic policy at the University of Heidelberg. Thereafter, he worked as a consultant for utility companies and as an economist for Munich Re where he did research on the economics of climate change and natural disasters.

Jan Eichner. Within Munich Re's Geo Risks Research division Jan Eichner is head of NatCatSERVICE, the largest global loss database on natural hazard loss events. His expertise covers loss data statistics as well as hazard-related aspects of atmospheric risks, risks from space, emerging risks and risks of change. Jan holds a PhD in theoretical physics with a focal point on the applicability of extreme value statistics in complex systems. Prior to joining Munich Re in 2009 he has worked for Risk Management Solutions in the development of natural catastrophe risk models for various perils such as convective storm, hurricane and storm surge.

Eberhard Faust is head of the risk research branch within the Geo Risks Research/Corporate Climate Centre division of Munich Re. The perils he is monitoring expand beyond atmospheric hazards and natural variability/anthropogenic change of the climate also into geophysical hazards such as geomagnetic disturbances. He has (co-)authored numerous scientific publications, and is lead author for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). He holds a diploma (MSc.) of Environmental Sciences/meteorology from the University of Bayreuth, and also a doctorate (PhD) of Theology from the University of Heidelberg where his research focused on ancient social history/culture.

Philipp Hasenmüller is a corporate responsibility consultant at Munich Re. He graduated in business administration and earned a master's degree in environmental sciences as well as a doctorate in the field of sustainability management. From 2004 until 2009 he worked as a research associate for the Centre for Sustainability Management (CSM) at Leuphana University Lueneburg. At Munich Re he was the project manager responsible for the collaboration between Munich Re and LSE's CCCEP from 2009 until 2012.

Peter Höppe is head of the Munich Re division 'Geo Risks Research/Corporate Climate Centre'. Before joining Munich Re in 2004 Professor Hoeppe has worked in different university institutes. His academic education is in meteorology (Masters and PhD) and human biology (PhD). Currently his research focus is on trends of natural catastrophes and their drivers as well as on climate change effects on insurance industry in general. Professor Höppe is member of many scientific societies and advisory boards. He is founder and Chairman of the Munich Climate Insurance Initiative and Chair of the "Finance-Forum: Climate Change".

Michael Menhart has been Chief Economist at Munich Re (Group) since 2007. Prior to joining Munich Re in 2005, Dr Menhart worked for McKinsey & Company, specialising in the insurance and financial services industry. Dr Michael Menhart holds a PhD and a diploma in economics from the University of Augsburg/Germany as well as an MA. in economics from Wayne State University in Detroit/USA.

Other contributors at Munich Re

A number of other staff across Munich Re also contributed to the Programme, including:

Ernst Rauch, Eva Loesch, Petra Loew, Angelika Wirtz, Wolfgang Kron, Werner Teichert, Ulrich Trumpp, Peter Müller, Steven Chang.

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