The global-scale impacts of climate change: the QUEST-GSI project

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1 Introduction

In each successive assessment of the Intergovernmental Panel on Climate Change (IPCC) there has been a substantial increase in the numbers of studies investigating the potential impacts of climate change, in an increasingly diverse number of sectors and places. However, the vast majority of these studies have been undertaken at the local and regional scales, and there remain few assessments of the potential consequences of climate change at the global scale: this was the case even in the IPCC's Fifth Assessment Report (IPCC 2014). Most of the published global-scale assessments concentrate on one sector (Table 1), and different studies have used different scenarios and assumptions. This makes it difficult to compare impacts across places, sectors and scenarios. The few published global multi-sectoral studies use either a single climate model (Hayashi et al. 2010) or a small number of climate models (Piontek et al. 2014).

The QUEST-GSI project¹ was established to undertake a consistent assessment of the potential range in impacts of climate change across the global domain in several sectors. It uses multiple climate models to characterise plausible climate futures with consistent baseline climate and socio-economic data and consistent assumptions, together with a suite of global-scale sectoral impacts models; one component of the project used catchment-scale hydrological models in a set of catchments around the world with consistent scenarios and assumptions.

The QUEST-GSI project developed from the UK 'Fast Track' assessments, which were initially designed to estimate rapidly the impacts of climate change associated with the latest versions of UK Met Office Hadley Centre climate models. The first phase of the Fast Track

¹QUEST was the UK Natural Environment Research Council (NERC) research programme on Quantifying Uncertainty in the Earth System; GSI is a part of QUEST exploring the Global Scale Impacts of climate change.

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used HadCM2 with IS92 emissions scenarios (Parry et al. 1999a; Hulme et al. 1999; Table 1) and some early stabilisation scenarios (Arnell et al. 2002), whilst the second focused on HadCM3 and the SRES emissions and socio-economic scenarios, incorporating in some sectors several other climate models (Parry 2004; Arnell et al. 2004; Table 1). Two key lessons were learnt from the Fast Track assessments. First, the estimated global impacts were strongly dependent on the assumed spatial pattern of change in climate, and use of just a few climate models could give a misleading indication of the potential range of future impacts. Second, it was not possible to seek to construct generalised relationships between amount of forcing and climate impact through meta-analysis of studies using different emissions and socio-economic scenarios because it was impossible to separate out the effects of time on the magnitude of impacts. The QUEST-GSI project addressed these two lessons through the use of multiple climate models, and through its experimental design based on pattern-scaling climate model output.

This Special Issue of *Climatic Change* includes a series of papers presenting some of the major findings of the QUEST-GSI project. This paper provides an overview of the project and its methodology, describes how the results and approach have been used in subsequent assessments, and identifies some lessons learnt from the project as a whole.

2 Objectives and project approach

The project had two overall objectives:

- (i) to estimate the impacts of specified emissions pathways on impacts in several sectors across the global domain;
- (ii) to develop a capacity to rapidly assess impacts under different emissions pathways or temperature trajectories.

The first objective is relatively traditional, except in its focus on harmonised multi-sectoral impacts. The second addresses the challenge of how to extrapolate from scenario-based assessments to estimate impacts under other scenarios – for example, scenarios representing

Table 1 Global-scale assessments of the impacts of climate change

Water resources and river flooding	Alcamo et al. (2003; 2007), Arnell (1999 ^a , 2004 ^b), Arnell et al. (2011), Doll (2009), Doll and Zhang (2010), Hirabayashi et al. (2008; 2013), Rockstrom et al. (2009), Fung et al. (2011); Hanasaki et al. (2013); Schewe et al. (2014)
Agriculture and food	Parry et al. (1999b; 2004 ^b), Fischer et al. (2005; 2007), Tubiello and Fischer (2007), Tebaldi and Lobell (2008), Hertel et al. (2010), Deryng et al. (2011); Rosenzweig et al. (2014)
Terrestrial ecosystems	White et al. (1999 ^a), Cramer et al. (2001), Leemans & Eickhout (2004); Levy et al. (2004 ^b), Scholze et al. (2006), Schaphoff et al. (2006), Gonzalez et al. (2010), Heyder et al. (2011); Friend et al. (2014)
Human health	Martens et al. (1999 ^a), van Lieshout et al. (2004 ^b)
Coastal zones	Nicholls et al. (1999 ^a), Nicholls (2004 ^b), Li et al. (2009); Hinkel et al. (2014)

^a part of the Fast Track first phase

^b part of the Fast Track second phase

different potential climate mitigation policies. This second objective was tackled firstly by streamlining the assessment procedure to allow impacts to be estimated rapidly for new emissions scenarios, and secondly by developing force-response functions (similar to Fussel et al. 2003) relating generalised measures of impact to global temperature change.

All the impact models used a consistent set of climate and sea level scenarios, the same baseline climatology (CRU TS3.1: Harris et al. 2013) and the same socio-economic scenarios (from the IMAGE 2.3 characterisations of the four SRES storylines (van Vuuren et al. 2007)) to produce a harmonized global-scale impact assessment.

Climate and sea level rise scenarios were produced by pattern-scaling climate model output, and then rescaling the results to match specified changes in global mean temperature (Osborn et al. 2015). Patterns for change in climate variables and sea level rise were constructed from 21 and 9 CMIP3 climate models (Meehl et al. 2007) respectively, although not all models were used in all impact sectors. A pattern-scaling approach was used rather than simply extracting the appropriate time period from climate model output for two primary reasons. First, it filters out the effect of year-to-year climatic variability and thereby allows clearer comparisons between emissions, models, and years. Second, it allows spatial and seasonal patterns of change in climate and sea level to be estimated for forcings that have not been explicitly simulated by climate models.

Two types of climate scenarios were constructed from the pattern-scaled climate and sea level patterns. The first represents changes under the four SRES (IPCC 2000) emissions pathways, and the second represents changes under prescribed changes in global mean surface temperature. These prescribed change scenarios were used to construct relationships between climate forcing (global mean surface temperature) and impact. The climate scenarios (emissions-based or prescribed) were applied to the CRU TS3.1 1961–1990 baseline climatology (Harris et al. 2013) using the delta method. Patterns of sea level rise were applied to the estimated average 1961–1990 sea level (Brown et al. [this issue](#)).

The impact models all operated across the global domain at a spatial resolution of $0.5^\circ \times 0.5^\circ$ or coastal segment (average length 85 km). Table 2 summarises the sectors considered and lists

Table 2 QUEST-GSI global-scale sectors and indicators

Sector	Description of indicators
Water	Change in runoff Exposure to water resources scarcity Exposure to change in river flood risk
Agriculture and food	Crop productivity Suitability for crop production Exposure of cropland to drought Exposure to undernourishment
Coastal zone	Exposure to change in coastal flooding Change in wetland extent
Terrestrial ecosystems	Soil organic carbon stocks Ecosystem productivity
Human health	Childhood stunting Storm surge mortality
Built environment	Residential heating and cooling energy demand

some of the indicators of impact. Most of the sectors used established models, but in some cases these were implemented in novel ways (e.g., through use of high-throughput computing: Gosling et al. 2010) or were implemented with new parameterisations (e.g., crop productivity: Osborne et al. 2012). Some new models were developed in the QUEST-GSI project (Lloyd et al. 2011; 2015; Dawson et al. 2014).

Impacts are characterised by different indicator metrics, appropriate to each impact sector, and no attempt is made to aggregate impacts across sectors to produce a single indicator representing the sum or aggregated impact of climate change at a place or in a region. This is because the metrics are expressed in different units, and even if they were made dimensionless (e.g., as quantiles from their distribution across space) any aggregation would involve subjective weighting.

Finally, although most of the analysis was undertaken at the global scale, one part of the project involved the application of a set of catchment-scale hydrological models in different geographic environments, with emissions-based and prescribed climate scenarios from the same seven climate models (Todd et al. 2011). This allowed a comparison of impacts under the same scenarios in the different geographic settings (studies in different catchments have typically used different climate models and approaches to construct scenarios, making comparisons difficult), and also provided an element of ‘ground truthing’ for the global scale hydrological assessments (Gosling et al. 2011).

3 Generalisation and development

The QUEST-GSI project assessed the impacts of climate change across a range of sectors at the global scale for a set of SRES emissions scenarios and prescribed change scenarios (Table 3), and also developed a framework for assessing the implications of different emissions scenarios. One application of this framework has been through the AVOID project² (www.avoid.net), which builds on climate research to understand the causes, effects, and consequences of different climate policies. Within the AVOID project, the QUEST-GSI framework has been used to estimate the impacts (across a subset of sectors) under a series of emissions pathways representing different hypothetical emissions policies with different rates of reduction in emissions, and compared these impacts with those under ‘business-as-usual’ pathways (Arnell et al. 2013). In this application, climate scenarios were constructed by scaling the CMIP3 climate model patterns to changes in global mean temperature implied by the emissions pathways – an application of the ‘streamlined’ framework. Another application of the streamlined framework estimated impacts under pathways describing increases in global mean surface temperature which reached 2, 3 and 4 °C above pre-industrial levels by 2100 (Arnell et al. 2015) to provide evidence to support the production of the UK’s fifth carbon budget under the 2008 Climate Change Act (Committee on Climate Change 2015). The framework has also been applied in the water sector (Arnell and Lloyd-Hughes 2013) with the new CMIP5 climate models forced by Representative Concentration Pathways (RCPs: Moss et al. 2010; Taylor et al. 2012) and new socio-economic scenarios (O’Neill et al. 2014).

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Table 3 QUEST-GSI papers

Sector	Papers
Multi-sectoral	Arnell et al. (2013; this issue a, b)
Scenarios	Osborn et al. (2015)
Water	Arnell et al. (2011), Gosling and Arnell (2011), Gosling et al. (2010); Haddeland et al. (2011); Arnell and Gosling (2013), Arnell and Gosling (this issue), Gosling and Arnell (this issue)
Catchment-scale	Gosling et al. (2011), Arnell (2011), Hughes et al. (2011), Kingston and Taylor (2010); Kingston et al. (2011); Nobrega et al. (2011); Singh et al. (2010); Thorne (2011), Todd et al. (2011), Xu et al. (2011)
Agriculture and food	Fraser et al. (2008; 2011; 2013); Osborne et al. (2012); Simelton et al. (2009; 2012); Dawson et al. (2014)
Coastal zone	Nicholls et al. (2011); Brown et al. (this issue)
Terrestrial ecosystems	Gottschalk et al. (2012)
Human health	Lloyd et al. (2011); Lloyd et al. (2015)

4 Lessons learnt

An interdisciplinary, multi-sectoral impact assessment using harmonised data and assumptions generates a number of operational challenges. These include the necessity to clarify the details of the experimental design (including such mundane issues as naming conventions) early in the process, the importance of defining transparent priorities for analysis (distinguishing between a ‘core set’ and an ‘extended set’, for example), and the need for early consultation on the specific attributes of climate and socio-economic scenarios that are required by different sectors. The QUEST-GSI project also identified two significant technical issues which are more conceptual: how to validate global-scale impacts models, and how to present impacts across sectors and regions in a clear manner, given the uncertainty in the regional pattern of climate change as defined by different climate model scenarios. The validation issue is particularly challenging for the socio-economic impact models because these either estimate exposure to impact rather than actual direct impacts, or estimate actual impacts making generalised assumptions about current and future adaptation measures: the estimated current impacts cannot therefore readily be compared with observations of ‘real’ impacts (which are in any case often very sparse). Where validation data are not available, global-scale impact models therefore need to be evaluated on the basis of their conceptual underpinnings.

The second conceptual issue - relating to the presentation of results - is more challenging. For a specific sector and in a specific region, it has become common practice in the impacts research community to present the range in, or distribution of, potential impacts across different climate scenarios (for a given level of climate forcing and socio-economic scenario), and often to characterise the overall magnitude of impacts by the ensemble mean or median. However, comparing means (or medians) reduces the variability between regions and sectors, and indeed it is unlikely that any one plausible scenario of regional climate change produces the average change everywhere and for all sectors. Similarly, it is unlikely that the most extreme impacts would occur simultaneously everywhere and in all sectors. One way to resolve this is to construct coherent spatially-variable, multi-sectoral stories from individual climate model scenarios (as in Arnell et al. ([this issue a](#))), but in order to represent uncertainty it is necessary to build many stories. One major lesson learnt in the QUEST-GSI project from

presentations to different audiences is that different audiences have different requirements so results need to be presented in a wide variety of ways. Some audiences are more concerned with the ranges of potential impacts and are not concerned with whether the extremes can occur at the same time; others are more concerned with synchronous impacts in different places or sectors. Some audiences - typically policy audiences - are keen to see impacts categorised into a small number of classes (for example, low, medium and high), but others - typically science audiences - are sceptical of what are seen to be arbitrary class boundaries.

There are, of course, a number of areas where further research is necessary in order to produce more robust assessments of the potential impacts of climate change across sectors, under different plausible climate futures. Three are particularly important. First, in most sectors, the range of potential impacts is large due primarily to uncertainty in the regional distribution of changes in temperature, precipitation, and other relevant dimensions of climate. The more recent CMIP5 generation of climate models does not necessarily reduce the range for a given indicator much (see Arnell and Lloyd-Hughes 2013 and Gosling and Arnell [this issue](#), for examples), so reducing the range in estimates will involve the development of ways of combining climate model output with scientific understanding of potential plausible changes - particularly in atmospheric dynamics (Shepherd 2014). Second, the QUEST-GSI project used one impact model and a small range of impact indicators for each sector. Other models and indicators are available, and incorporating more may allow more robust interpretations of risks. The ISI-MIP project (Warszawski et al. 2014) involves the intercomparison of different impact models, but the effects of using different indicators for a given sector also needs to be evaluated. Third, most of the indicators used in the QUEST-GSI project did not incorporate the effects of adaptation, and the two that did - for coastal and crop productivity impacts - out of necessity made generalised assumptions about how adaptation was implemented and actually worked.

5 The papers in this issue

The first paper (Osborn et al. 2015) presents an overview of the pattern-scaling approach used to construct climate scenarios for the QUEST-GSI project, summarising the method and its assumptions. The following papers present impacts in individual sectors, considering in turn water resources (Gosling and Arnell [this issue](#)), river flooding (Arnell and Gosling [this issue](#)), coastal flooding (Brown et al. [this issue](#)) and crop productivity (Rose et al. [this issue](#)). They describe the methods used, and present regional and global results. The next two papers focus on two new global-scale impacts models developed in the QUEST-GSI project (simulating malnourishment (Dawson et al. 2014) and coastal flood mortality (Lloyd et al. 2015), and present some initial results. The final two papers are multi-sectoral. The first (Arnell et al. [this issue a](#)) summarises the regional and global scale impacts across sectors, synthesising the results presented in the sectoral papers. The second (Arnell et al. [this issue b](#)) presents global and regional functions relating impact to change in global mean surface temperature.

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