Chapter 9

A Model-Based Response Surface Approach for Evaluating Climate Change Risks and Adaptation Urgency

Timothy R. Carter and Stefan Fronzek

Abstract We present a new approach to advance methods of climate change impact and adaptation assessment within a risk framework. Specifically, our research seeks to test the feasibility of applying impact models across sectors within a standard analytical framework for representing three aspects of potential relevance for policy: (i) sensitivity—examining the sensitivity of the sectors to changing climate for readily observable indicators; (ii) urgency—estimating risks of approaching or exceeding critical thresholds of impact under alternative scenarios as a basis for determining urgency of response; and (iii) response—determining the effectiveness of potential adaptation and mitigation responses. By working with observable indicators, the approach is also amenable to long-term monitoring as well as evaluation of the success of adaptation, where this too can be simulated. The approach focuses on impacts in climate-sensitive sectors, such as water resources, forestry, agriculture or human health. It involves the construction of impact response surfaces (IRSs) based on impact model simulations, using sectoral impact models that are also capable of simulating some adaptation measures. We illustrate the types of analyses to be undertaken and their potential outputs using two examples: risks of crop yield shortfall in Finland and impact risks for water management in the Vale do Gaio reservoir, Portugal. Based on previous analyses such as these, we have identified three challenges requiring special attention in this new modelling exercise: (a) ensuring the salience and credibility of the impact modelling conducted and outputs obtained, through engagement with relevant stakeholders, (b) co-exploration of the capabilities of current impact models and the need for improved representation of adaptation and (c) co-identification of critical thresholds for key impact indicators and effective representation of uncertainties. The approach is currently being tested for five sectors in Finland.

T. R. Carter (✉) · S. Fronzek
Finnish Environment Institute (SYKE), Helsinki, Finland
e-mail: tim.carter@syke.fi

S. Fronzek
e-mail: stefan.fronzek@syke.fi

Keywords Risk assessment • Probabilistic • Impact model • Shared socioeconomic pathways • Finland

Introduction

The Finnish Climate Act (no. 609/2015) specifies that the government should approve a national adaptation plan for climate change at least once every 10 years. The first adaptation plan to 2022 has the following three objectives (MMM 2014, p. 4): “(a) adaptation [should be] integrated into the planning and activities of both the various sectors and their actors, (b) the actors [should have] access to the necessary climate change assessment and management methods and (c) research and development work, communication and education and training [should enhance] the adaptive capacity of society, [develop] innovative solutions and [improve] citizens’ awareness on climate change adaptation”. A national risk assessment for key sectors was published in 2018 along with a governance model for organising future assessments (Hildén et al. 2018). This recommends that climate change risk assessments to support adaptation policies be integrated into existing assessments contributing to the National Security Strategy for Society. This planned enhancement of Finnish adaptation policy mirrors similar initiatives for regular risk assessments reported in other European countries (EEA 2018).

Impacts and Adaptation in a Risk Framework

In this short note, we propose a systematic method of climate change impact and adaptation assessment designed to be conducted at national or sub-national scale within a risk framework. Specifically, we seek to test the feasibility of applying impact models across sectors within a standard analytical framework for representing three aspects of potential relevance for policy: (i) *sensitivity*—examining the sensitivity of the sectors to changing climate for readily observable indicators; (ii) *urgency*—estimating risks of approaching or exceeding critical thresholds of impact under alternative scenarios to help determine urgency of response and (iii) *response*—determining the effectiveness of potential adaptation and mitigation responses. By working with observable indicators, the approach is also amenable to long-term monitoring as well as evaluation of the success of adaptation, where this too can be simulated.

Modelling Impacts and Adaptation

Numerical impact models are important research tools for evaluating climate change risks in support of decision-making. They are often deployed to quantify uncertainties in potential impacts across a range of climate projections and other scenario assumptions. However, their use in decision-making is still fairly limited, in part because of reluctance to engage stakeholders in the co-development of models in order to demonstrate a case for their applicability, salience and trustworthiness (EEA 2017).

This observation is of particular importance when simulating adaptation. A recent review found the treatment of adaptation in impact models intended for land use and water management to be fragmented and often simplistic, failing to recognise that adaptation is a complex human process framed by uncertainties and constraints (Holman et al. 2019). The review lists sixteen suggestions for future improvements in simulations of climate change adaptation (equally transferable to other sectors too). Four of these improvements are of especial relevance in the approach outlined below:

- embracing scenario uncertainty rather than seeking most likely futures for optimal solutions,
- working with stakeholders and decision-makers to better understand the triggers and goals of adaptation policies and measures,
- including adaptations that take advantage of climate change rather than simply responding to adverse impacts, and
- considering adaptation alongside mitigation within an integrated climate policy framework.

An additional aspect to highlight is the importance for model outcomes to relate to real-world evidence of adaptation (Berrang-Ford et al. 2011). This services a demand for monitoring and evaluation of adaptation by national and local policymakers and potentially for the Global Stocktake (Tompkins et al. 2018).

Objectives and Research Questions

The approach seeks to accomplish six aims. These are to:

- (1) Work with sectoral experts and stakeholders to co-select demonstration indicators that are observable and for which impacts and adaptation measures can be simulated using models,
- (2) Construct impact response surfaces (IRS—see section below) to depict the modelled sensitivity of indicators to climate and socioeconomic drivers across a plausible range of perturbations in different geographical regions, accounting for uncertainty where applicable,

- (3) Estimate the evolving likelihood of exceeding stakeholder-defined thresholds of impact and hence the urgency to act under alternative scenarios during the twenty-first century,
- (4) Simulate historical climate change impacts to compare to observed impacts and adaptation,
- (5) Examine the modelled effectiveness of adaptation and mitigation for ameliorating adverse impacts or exploiting beneficial impacts, and
- (6) Develop protocols for model analysis and for effective visualisation and dissemination of results to feed into national risk assessments.

To address these specific aims, a modelling methodology is being designed to ensure some commonality of approach between sectoral applications. This requires collective decisions to be agreed at an early stage of an assessment through a process of co-design across sectors and between researchers and stakeholders. Protocols can then be agreed that modellers can use to carry out the model simulations needed for addressing the major research questions, which include (in relation to the above objectives):

- (1) What impact indicators that are of relevance to stakeholders can be readily quantified and modelled using the IRS approach?
- (2) How sensitive are these indicators to changes in climate and other key driving variables?
- (3) By when and with what likelihood will critical thresholds of impact be exceeded in the future under alternative scenarios of socioeconomic and climate change?
- (4) Is there evidence that these thresholds have already been exceeded in the past?
- (5) How effective is adaptation and mitigation at reducing risks of exceeding critical thresholds?
- (6) Can a common approach to analysis be operationalised for use in national risk assessments?

Approach

Operationalising the IPCC Risk Framework

The approach builds on the premise that the IPCC Risk Framework can be operationalised by modelling impacts of climate change for key indicators co-selected with stakeholders across a range of sectors, relating these impacts to impact thresholds and simulating the effectiveness of adaptation and mitigation in ameliorating key risks. The IPCC risk framework depicts climate change risk, R , as

$$R = PI = f(H, E, V) \quad (9.1)$$

where H is the hazard, describing aspects of the climate that may induce adverse impacts (i.e. changes in the mean and/or variability, including extreme events). E

is exposure, which is the proximity of humans, ecosystems, infrastructures or other economic, social or cultural assets that could be adversely affected by the hazard. V is vulnerability, defined as the predisposition of the exposed elements to be adversely affected. The risk term, R , in Eq. (9.1) is sometimes interpreted in terms of potential impact, PI (IPCC 2014). Hence, risk (potential impact) is a function of the hazard posed by climate change (using climate model projections, for example, based on representative concentration pathways—RCPs), which can be moderated through mitigation, and of vulnerabilities (exposure, susceptibility and coping capacity) that are mediated by future socioeconomic trends (based, for example, on shared socioeconomic pathways—SSPs) and can be adjusted through adaptation.

Impact Models

The approach focuses on impacts in climate-sensitive sectors (e.g. water resources, forestry, agriculture, human health and winter recreation) and is built around simulations with a set of impact models. These models should be capable of simulating relevant indicators for the selected sectors and of incorporating options for adapting to climate change. They may operate at a variety of scales (e.g. site, catchment, regional, national) but can potentially be scaled up to the geographical units of relevance in the assessment.

Impact Response Surfaces

The method being applied for examining changing risk and the urgency for adaptation across different sectors involves the construction of impact response surfaces (IRSs) based on impact model simulations (Jones 2000). IRSs depict the response of an impact variable to changes in two explanatory variables as a plotted surface (see Fig. 9.1a). They can be used to evaluate responses to any scenario of the drivers that falls within the sensitivity range of the plot, hence providing a systematic, “scenario-neutral” analysis of impacts (Prudhomme et al. 2010) that does not rely on the arbitrary and opportunistic use of scenario simulations. While the approach may lack the internal consistency between variables that can be represented in detailed scenarios, our experience suggests that there are few cases where such simplification may produce radically different responses from those found for detailed scenarios, though such differences can of course be tested. IRSs also provide an opportunity to test model performance across a wide range of conditions, including those that may lie outside the conventional application of many models.

The IRS method has been increasingly applied during the past decade for illustrating impact model sensitivity to climate variables (e.g. temperature and precipitation) in sectors such as agriculture, hydrology and ecosystems (e.g. Poff et al. 2016; Fronzek et al. 2019). Pertinent to this study, IRSs have been combined with

Fig. 9.1 Features of impact response surfaces (IRSs) and their potential application in estimating climate change risks (see text for explanation)

probabilistic representations of future climate (e.g. Räisänen and Ruokolainen 2006) enabling estimates of the likelihood of certain pre-specified impact thresholds being crossed (Pirttioja et al. 2019). They have also been used to model responses to adaptation measures (e.g. Ruiz-Ramos et al. 2018).

Illustrative Results: Risk Assessment

Combining the IRS method with probabilistic projections of driving variables to estimate future climate-related risks is a novel approach with, as yet, limited uptake. Most applications have been in water resource management or agriculture, and we illustrate two such cases below using recent examples from Finland and Portugal. However, its practical merits have yet to be demonstrated for other sectors and are the subject of ongoing research.

Risks of Crop Yield Shortfall in Finland

In this example, results from a published site-based modelling study (Pirttioja et al. 2019) are schematised and extended to illustrate (hypothetically) how an IRS analysis can be used to estimate regional risk (Fig. 9.1). In A, yield sensitivity to temperature and precipitation perturbations relative to a reference climate (black dot) is shown as contours, with a threshold yield level indicated in red. Such a threshold yield could be determined with stakeholders. A probabilistic representation of projected climate at some time in the future is superimposed on the IRS (darker shades indicate higher

probability). The likelihood that the future climate would cause a yield shortfall can be estimated as the area on the climate surface where yields on the IRS lie below the threshold (B). Using similar estimates for several time periods into the future, a graph can be plotted showing the changing likelihood of crop failure (black line in D). The effectiveness of an adaptation measure under perturbed climate (e.g. changing to a different crop cultivar) can also be explored, by repeating the IRS analysis for the simulated adaptation (C) and constructing a new likelihood curve (blue line in D).

Impact Risks for Water Management in the Vale Do Gaio Reservoir, Portugal

The Vale do Gaio reservoir in the dry region of southern Portugal is used for irrigation of rice cultivation in the area. We constructed IRSs of the water inflow to the reservoir, the irrigation water demand for the current rice cultivation and the Water Exploitation Index (WEI; ratio between irrigation demand and runoff) with catchment-scale hydrological and irrigation models, and as adaptation options also for four other crops (winter wheat, olive trees, sunflower, corn) with a smaller water demand (Fronzek et al., in prep.). IRSs were then combined with probabilistic climate change projections similar to the crop yield example shown in Fig. 9.1. Results showed large risks of an inflow decrease throughout the twenty-first century and an increased risk of water scarce conditions from *extremely unlikely* (<5% probability) in the period 2011–2040 to *virtually certain* (>99% probability) for RCP8.5 by 2071–2100 under the current rice cultivation. Switching to crops with a smaller water demand, on the other hand, provided a potential even to increase the area under irrigation, but with an enhanced sensitivity to changes in rainfall compared to the current rice cultivation.

Regional Risks and the Urgency for Action

With appropriate data for model input, calibration and testing, the site-based approach to risk assessment can potentially be extended to national scale. We illustrate this for the same crop yield example (Fig. 9.1). A national analysis of the risk of yield shortfall might involve construction of equivalent likelihood curves for representative sites in different regions, and mapped for a given time period with the level of risk colour coded (E). This method of risk mapping shares characteristics with the reasons for concern used in the IPCC assessments (e.g. IPCC 2014) or traffic light warning systems for defining levels of risk and could be a useful device for indicating the level of urgency for action, whether by adaptation to ameliorate the risk or mitigation to avert the hazard. Note that estimates of likelihood can also be applied to climatic conditions already experienced historically, potentially allowing for comparison of risk estimates with actual observation of impacts being monitored in different regions.

The approach has an added advantage for regular risk assessments that it can be updated as new scenarios appear, without needing to re-run the underlying impact models.

Conclusions and Recommendations

Based on previous analyses such as those illustrated above, we conclude that there are three challenges requiring special attention in this new model-based approach to risk assessment: (a) ensuring the salience and credibility of the impact modelling conducted and outputs obtained, through engagement with relevant stakeholders, (b) co-exploration of the capabilities of current impact models and the need for improved representation of adaptation and (c) co-identification of critical thresholds for key impact indicators and effective representation of uncertainties. The approach is currently being tested in five sectors at national scale in Finland (<https://www.syke.fi/projects/adapt-first>).

Acknowledgements The authors acknowledge funding from the Adapt-FIRST project of the Academy of Finland (decision 330915) and the European Commission FP7 project IMPRESSIONS (Grant Agreement No. 603416).

References

- Berrang-Ford L, Ford JD, Paterson J (2011) Are we adapting to climate change? *Global Environ Change* 21:25–33
- EEA (2017) Climate change adaptation and disaster risk reduction in Europe: enhancing coherence of the knowledge base, policies and practices. 15/2017, Europ Environ Agency 172 pp
- EEA (2018) National climate change vulnerability and risk assessments in Europe, 2018. 1/2018, Europ Environ Agency 79 pp
- Fronzek S, Carter TR, Pirttioja N, et al (2019) Determining sectoral and regional sensitivity to climate and socio-economic change in Europe using impact response surfaces. *Reg Environ Change* 19:679–693
- Fronzek S, Pirttioja N, Honda Y, et al (in prep) Estimating impact likelihoods from probabilistic projections of climate and socio-economic change using impact response surfaces (in preparation)
- Hildén M, Haavisto R, Harjanne A, et al (2018) Climate resilient Finland—a governance model for organizing weather and climate risk assessments (in Finnish). Prime Minister’s Office, Publication 44/2018:67 pp
- Holman IP, Brown C, Carter TR, Harrison PA, Rounsevell M (2019) Improving the representation of adaptation in climate change impact models. *Reg Environ Change* 19:711–721
- IPCC (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri RK, Meyer LA (eds) Core writing team. Geneva, Switzerland, 151 pp
- Jones RN (2000) Analysing the risk of climate change using an irrigation demand model. *Climate Res* 14:89–100

- MMM (2014) Finland's national climate change adaptation plan 2022. Publications of the Ministry of Agriculture and Forestry 5b/2014, 40 pp
- Pirttioja N, Palosuo T, Fronzek S, Räisänen J, Rötter RP, Carter TR (2019) Using impact response surfaces to analyse the likelihood of impacts on crop yield under probabilistic climate change. *Agr Forest Meteorol* 264:213–224
- Poff NL, Brown CM, Grantham TE, et al (2016) Sustainable water management under future uncertainty with ecoengineering decision scaling. *Nat Clim Change* 6:25–34
- Prudhomme C, Wilby RL, Crooks S, Kay AL, Reynard NS (2010) Scenario-neutral approach to climate change impact studies: application to flood risk. *J Hydrol* 390:198–209
- Räisänen J, Ruokolainen L (2006) Probabilistic forecasts of near-term climate change based on a resampling ensemble technique. *Tellus* 58A:461–472
- Ruiz-Ramos M, Ferrise R, Rodríguez A, et al (2018) Adaptation response surfaces for managing wheat under perturbed climate and CO₂ in a Mediterranean environment. *Agric Syst* 159:260–274
- Tompkins EL, Vincent K, Nicholls RJ, Suckall N (2018) Documenting the state of adaptation for the global stocktake of the Paris agreement. *Wires Clim Change*. <https://doi.org/10.1002/wcc.545>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.