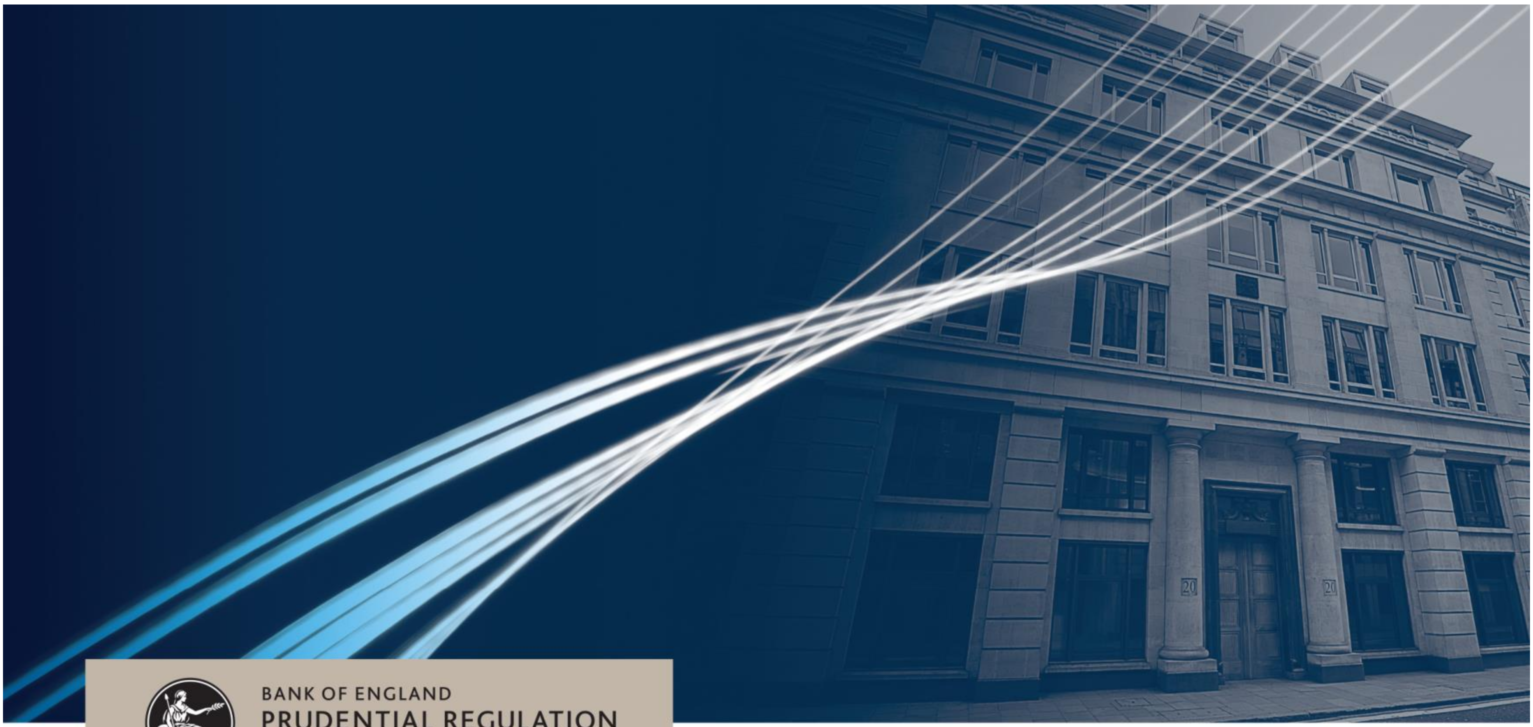

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A framework for assessing financial impacts of physical climate change

A practitioner's aide for the general insurance sector

May 2019

This report was written by a cross-industry working group

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Acknowledgements to the working group

In July 2018 the Bank of England facilitated the creation of an industry-wide working group comprising experts drawn from the (re)insurance industry, with a particular focus on assessing impacts from physical climate risk and extreme weather modelling (natural catastrophe). The aim was to develop a framework, identify good practice, and provide case studies that might help practitioners to assess the potential financial impact on liabilities from physical climate change.

Given the uncertainties inherent in the emergence of the physical consequences of climate change, and in society's transition to a low-carbon climate-resilient economy, the working group recognises the difficulties and limitations involved in seeking to quantify financial risk impacts on insurance liabilities. Nonetheless, the lessons and disciplines that can emerge from seeking to answer these questions, using existing tools, have a crucial role to play over the coming years.

A six-stage framework was created by the working group through a series of focused workshops which ran from July 2018 to March 2019. This report reflects the hard work of all those who participated in the workshops and shows how the framework can be used in practice for different business decisions and time horizons, and through the use of different tools. This would not have been possible without the invaluable contributions of the working group members, authors, editors and reviewers and, for this reason, we would like to thank those who participated in the process.

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Foreword

Climate change, and society's response to it, presents financial risks to insurers. While these risks will crystallise in full over the coming decades, they are already becoming apparent. The PRA expects insurers to take a strategic approach to addressing the risks from climate change, and from my recent discussions, many insurers are keen to make progress in developing a strategic approach. However, they highlight the practical challenges of developing scenarios, strategies and risk management approaches to climate change risk beyond the usual planning horizon.

In response to this, the Bank of England convened a joint working group in July 2018 with representatives across the general insurance market tasked with providing practical assistance to those looking to assess financial risks from physical changes in the climate. Assessing financial risks from climate change is not trivial given the inherent uncertainty of long-term climatic model predictions, the lack of data, and the limitations of existing tools. We know from our supervision of general insurers that they are well placed to contribute towards this assessment by drawing on their expertise in modelling extreme weather risk. Harnessing this expertise can unlock the shift from awareness to action.

This report is the product of the joint working group's thinking. It sets out a six-stage framework that insurers can follow, using existing tools and associated metrics to better assess, manage and report exposure to physical climate risks related to extreme weather events which in turn will lead to action. A number of case studies illustrate how the proposed framework can operate in practice. These examples display how consideration of financial impacts from physical climate change can better inform insurers' risk management decisions.

I encourage firms and practitioners to read this report alongside the PRA's Supervisory Statement 3/19 that sets out expectations for how banks and insurers should approach the financial risks from climate change, including that the response is led by the board, that it is embedded within existing financial risk management practice, that it uses (long-term) scenario analysis to inform strategy setting and risk assessment, and that it includes disclosure.

I would like to thank the specialists in the working group who pulled together existing knowledge and expertise in this topic to share it with the wider industry, to accelerate the shift from awareness towards action. To further deliver on this objective, the working group will welcome feedback that advances the debate with those involved in this rapidly evolving field.

David Rule

Executive Director of Insurance Supervision, PRA, and sponsor of the working group

Executive summary

Changes to the global climate will pose an increasing risk to the general insurance industry over the coming decades. This cross-industry specialist working group has sought to address an element of physical risk to insurance liabilities from climate change risk: weather-related events changing in response to different future climate conditions. It is aimed at practitioners working with or at general insurance firms who are looking to assess the financial impacts to the liability side of the firm's balance sheet caused by future climate change.

The paper outlines a framework for practitioners to use to assess this risk, using tools that are already available within the general insurance sector. The framework is intended as a possible starting point for firms to assess the impacts in the context of their business decisions and disclosure requirements. Although the results from such an analysis will have inherent uncertainty, the insurance industry is uniquely placed to manage this due to its existing expertise in dealing with uncertainty when assessing climatic extremes. Several case studies are also provided which illustrate how different stages of the framework could be used.

The framework has six stages:

1. **Identify business decision(s).** A physical climate change study would typically aim to inform a business decision or activity. This stage of the framework will decide the time horizon and metrics that need to be considered.

2. **Define materiality.** This stage enables the firm to focus on the business areas where the physical risk from climate change could have a material impact on business decisions.

3. **Conduct background research**. The firm will need to review existing scientific publications to understand better how climate change could influence the relevant areas identified. The likely outcome is a range of projected changes in frequencies or intensities for specific perils.

4. **Assess available tools.** A decision will need to be made on which catastrophe tool(s) will provide the most suitable analysis.

5. **Calculate impact.** This stage involves using the tools selected to assess the financial impact from the projected changes to the perils in question. Key considerations could include the appropriate communication of both the output and the uncertainty in the results.

6. **Reporting and action.** Output from the use of the framework needs to be communicated to decision makers in a manner that can inform the business decision(s) in question, highlighting the limitations and uncertainty related to the analysis.

While this report acknowledges that tools assessing physical climate change risk are evolving rapidly, it puts emphasis on outlining the tools and methodologies that are currently available to the general insurance sector to assess the potential impact of climate change on their insurance liabilities. The advantages and disadvantages of each of the tools are discussed.

This report also sets out recommendations for how the catastrophe analytics industry can contribute further, suggesting that it can play an important role in interpreting existing scientific studies and, combined with existing tools, assess the financial impacts from physical climate change while making recommendations for improving both future research and catastrophe tools development.

1 Introduction

Climate change poses increasing risks and challenges to the financial services industry (PRA, 2018). Many regulatory and industry initiatives are already raising public awareness of these risks on different parts of the financial system (PRA, 2019). Key initiatives include the creation of the Financial Stability Board (FSB) Task Force on Climate-related Financial Disclosures (TCFD) and the joint PRA/FCA Climate Financial Risk Forum.

Climate change presents a particular threat to the insurance industry, which in turn creates a further risk to society, given the role of the insurance industry in helping to mitigate the aftermath of natural disasters. Consequently, equipping the insurance industry with practical and analytical approaches to assess financial impacts from climate change can help:

- (re)insurance companies to proactively manage the related increasing financial risks; and

- broader society to increase resilience by better assessment and management of its impact.

The (re)insurance industry is ideally placed to develop techniques to assess and manage changing physical risk (Lloyd’s, 2014). The industry has a long history of using risk assessment tools – for example, expert judgement, event footprints, hazard maps, and probabilistic models – to price extreme weather risk; while these tools will require some adjustment, they can be adapted to allow for climate change, avoiding the need for firms to deploy new methodologies or tools in their day-to-day business. Use of these tools to compare future climate to current climate risk for a given peril is also likely to be transferable to other sectors, although this is beyond the scope of this report.

However, there remains a lack of practical, analytical approaches to assess financial impacts from climate change and facilitate reporting, management and mitigation (ClimateWise, 2019a). This paper addresses the lack of practical or analytical approaches by demonstrating how the tools already used in the insurance industry can help assess financial impacts – and specifically the risk of increasing weather-related losses – from climate change, while recognising the inherent uncertainty implicit in such estimates. Throughout the report the term ‘physical climate change risks’ is used to refer to this risk of increasing losses – as opposed to other risks from climate change and society’s response to it (such as a fall in the value of assets).

Who this report is for and what it contains

This report is relevant to all general insurance firms, reinsurance firms and groups, including the Society of Lloyd’s and managing agents. Specifically, the report is aimed at practitioners in the field of climate and natural catastrophe risk assessment, and the wider catastrophe analytics industry comprising specialists within firms, catastrophe model vendors, academia, brokers, and consultants.

The report sets out a proposed framework for assessing financial impacts on the liabilities side of the balance sheet from physical climate change risk and the relevance of these impacts to a wide range of business decisions. The particular business issue being addressed will help to determine whether the focus of analysis is on short, medium, or long-term change, and whether the firm is more interested in changes to expected losses or to losses in extreme circumstances. The framework supports a sound risk management strategy in the context of long-term climate change and recognises resource constraints by using existing available tools and knowledge to project future losses. It deliberately focuses on losses as a pragmatic step forward, while acknowledging the importance of other forms of climate change risk - such as transition risk - or the relevance of climate change risks to the asset side of balance sheets of both life and general insurers (ClimateWise, 2019a and ClimateWise, 2019b).

Context – current capabilities

Climate change, and society's response to it, presents prudential, systemic financial risks (PRA, 2015). General insurance firms have developed significant expertise over the last three decades in the quantification of natural catastrophe risk. However, to date, development has focused on assessing the current risk from weather related natural catastrophes; adapting this work to reflect changing climate is in its infancy with varying levels of sophistication exhibited in the market.

The working group recognises that the framework put forward in this report is a first step; it is expected that over time firms' approaches will mature and evolve further.

Why is physical climate change risk relevant to general insurance firms' liabilities?

Physical risks from climate change manifest themselves in changes to both the frequency and severity of specific weather events (such as heatwaves, floods, wildfires and storms) and, in the longer term, broader shifts in climate such as changes in precipitation and extreme weather variability, sea level change and rising average temperatures (IPCC, 2014).

Losses related to physical risk factors directly affect insurance firms' liabilities through higher claims, and physical risks may extend beyond the immediate impact of natural catastrophes, for example through the disruption of supply chains.

The report recognises the challenge of assessing these financial impacts on general insurers' liabilities. Weather-related risk estimates under current climatic conditions already contain significant uncertainty; this uncertainty is exacerbated when estimates are projected to reflect possible future climatic conditions. This report takes as a key premise that business decisions that are impacted by climate change can be informed by attempts to assess related risks despite the implicit uncertainty.

Who wrote this report?

The working group comprises representatives from UK insurers, global reinsurers, a reinsurance intermediary, a rating agency, the Society of Lloyd's, and catastrophe modelling vendors, along with the PRA's internal specialists ('we' in the report refers to the working group). We developed the framework and applied it to a number of case studies which are summarised in this report. We are grateful to the many external reviewers who helped shape the final version of this report.

How to use this report

This report can be used as a starting point for practitioners and firms to develop their own assessment of financial impacts of physical climate change risk on liabilities in order to understand the impact on specific business decisions. This report deliberately focuses on physical climate change risk impacts without discussing the interaction with other factors such as exposure growth changes or construction practices (such as buildings becoming more resistant to wind damage); this report's approach permits assessment of the impact of climate change assuming all other variables remain constant. Therefore, readers should keep in mind the focused scope of climate change assessments when interpreting the case studies in this report. Firms may wish to incorporate in the proposed framework other financial impacts from climate change such as those described above. Impact to assets or transition risk are not covered in this report.

Suggestions for applying the framework to other areas are set out in Chapter 5.

Report Structure

Chapter 2 of this report outlines the proposed framework, which offers a practical approach to developing scenarios and assessing physical climate change risk. This is not intended to be prescriptive, and practitioners and firms are encouraged to build on the framework to develop their own view of physical climate change risk.

Chapter 3 provides more detail on a range of currently available tools which can be used to assess physical climate change risk and explains when it may be appropriate to use one tool rather than another; these tools range from expert judgement to catastrophe models.

Chapter 4 of the report includes a number of case studies which have been developed to illustrate how to adopt the framework. These demonstrate how each stage of the framework applies in practice using existing tools and available resources to develop climate change scenarios, and should make the process easier to follow. Note, however, that the case studies are illustrative and although specific tools are being put forward for particular scenarios, it is not suggested that those are the only tools that could be used in that particular situation.

Finally, in Chapter 5, we give some recommendations for the future development of tools and processes necessary to assess the financial impacts from climate change risk beyond property, physical climate change risk, and insurance.

Feedback and next steps

The working group is keen to get comments and views on the framework. The PRA has set up an email address for responses, which it will monitor so that emails are shared with the working group for discussion. Responses are requested by Friday 22 November 2019. Please send any comments or enquiries to: PCCriskframework@bankofengland.co.uk. We may not respond to individual emails, however, we will consider how we collate and share feedback received.

2 Framework for assessing physical climate change risk

This chapter describes a framework designed to assess physical climate change risk for the general insurance sector. It aims to be practical and should help answer the question: how could the decision/business process be impacted given a range of possible climate outcomes?

2.1 Introduction to the framework

2.1.1 Why a framework is needed

This report recognises that there is a wide range of possible impacts from climate change on general insurance firms' liabilities. Consequently, there is no single climate change scenario that can assess this impact effectively across all firms and across all business decisions. Instead, each firm should be able to develop its own assessment of the impact in the context of its own risk profile and the range of business decisions it needs to take.

There is currently no widely accepted process for assessing financial impacts from physical climate change risk. The tools, techniques, and methodologies used by insurance risk practitioners to assess physical climate change risk vary in their maturity across the sector. A framework to guide the development of physical climate change risk impact assessments should improve the ability of firms to respond to this emerging risk and reduce potential duplication of effort across the insurance sector.

A widely adopted framework would also help to ensure a minimum level of consistency – and hence quality – is achieved in developing scenarios. To the extent that firms utilise this proposed framework consistently, stakeholders such as investors, regulators and rating agencies can gauge the market-wide response more clearly.

This framework is intended to be used as a guide rather than being a prescriptive standard. We believe that use of the framework will provide further insight to functions such as risk management, underwriting, risk transfer, exposure management, and capital modelling into how climate change could affect future risk and profitability, and thus influence their decisions.

2.1.2 How the framework could operate

This section sets out some key considerations regarding implementation.

- *Who within the organisation might have responsibility for the framework?*

  The framework is presented from a risk practitioner's viewpoint rather than from a wider business perspective. It is envisaged that the framework operates within the wider context of a (re)insurance firms' risk operation. It is therefore likely to be owned by someone with an ability to embed the outputs of the framework in the overall firm operations and with sufficient authority to ensure that the outputs inform decisions. The implementation of the framework needs to be undertaken by a team that is sufficiently versed in the assessment of climate risk, such as in exposure management, catastrophe modelling and/or actuarial.

- *What is the relationship between the framework stages?*

  The framework is comprised of six stages that are depicted in Figure 1 below to be sequential, although iteration between stages will often be necessary. For instance, the research stage may reveal elements of physical climate change risk that were not previously considered and materiality might have to be reconsidered.

Nevertheless, each stage of activity informs the next stage. The description below does not prescribe output specifications for each stage as those might differ depending on the particular business decision. The case studies in Chapter 4 will provide examples of those outputs.

- *Does this framework apply to insurance firms of all sizes?*

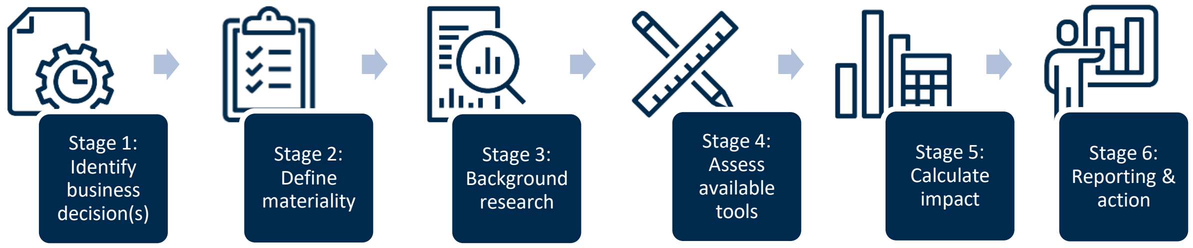
  The stages comprising this framework are deliberately generic to make them applicable to most firm types. However, the firm size will inform the emphasis to be given to each of the different stages. For example, a larger insurer that has access to climate specialists will be able to dedicate its own resources to the background research whilst a smaller syndicate might choose to outsource a significant part of that effort.

In all cases, the framework is put forward as a first step for firms to undertake their own assessment. Over time, it is envisaged that practitioners and firms will develop and customise the framework to reflect their own requirements.

2.1.3 Overview of framework stages

This section provides an overview of each of the six stages; further detail is in sections 2.2.1 to 2.2.6.

Figure 1: Schematic to illustrate the framework. Firms may decide not to progress through all stages for all business decisions, for example if a particular peril is found not to have a material impact on a firm's risk profile.



Stage 1: Identify business decision(s) – establishes the context for the analysis. This might be a firm's desire to disclose climate-related risk or a specific business decision (such as the reinsurance purchase decision) or process (such as capital model validation). Time horizons over which impacts are to be assessed are defined. Given the relatively short-term nature of non-life (re)insurance liabilities, the impact of climate change on catastrophe perils may be small or may be very difficult to distinguish from natural variability. As such, over a short horizon the impact of climate change may be dwarfed by other factors such as interest rate movements, natural climate variability or changes in exposure. An impact assessment over a longer time horizon can pick up trends and can serve to illustrate any costs of inaction, or can help inform the firm's growth and/or risk management strategy.

Stage 2: Define materiality – focuses the analysis on areas of the business (such as a line of business, portfolio or region-peril(s)) where climate change could have a material impact on the firm's risk, and therefore could have an effect on the decision or process agreed in Stage 1. For instance, for a global (re)insurer, US hurricane risk is one region-peril that is impacted by climate change; although the effect is likely to be modest in the short term, this could have a financial impact that influences business decisions. In order to undertake the materiality assessment, firms need to understand the likely climate change impact on natural perils and should take account of existing research.

Stage 3: Conduct background research – involves searching existing publications to identify and analyse current scientific understanding of how climate change could lead to changes in the frequency, severity and correlation of weather-related perils. The outcome of this stage is likely to be a range of projected changes in frequencies and/or hazard intensities for specified climate scenarios over specified timeframes. The results can then be used as a basis to assess loss impacts.

Stage 4: Assess available tools – sets out that firms need to decide which catastrophe tools would best suit the analysis, given the findings from the background research. Where this may involve acquiring or investing in new tools, the framework acknowledges that a firm may have resource constraints in this stage. Readily available catastrophe risk assessment tools might include in-house or vendor probabilistic catastrophe models, hazard maps, footprints, and expert judgement. These are described in more detail in Chapter 3. All the tools described have pros and cons; for example, hazard maps cannot be used for event accumulation and footprints do not provide information on changes to average annual loss (AAL) or specific parts of the exceedance probability curve. These should be considered carefully when the tools are used.

Stage 5: Calculate impact - applies the tools selected in Stage 4 to the firm's exposures. The effort dedicated to this stage will vary depending of the materiality of the business decision in question and the influence physical climate change risk may have on its outcome. Key considerations are to ensure that:

- The metrics used in communicating the outcome of the exercise should be driven by the decision they are meant to inform, and their familiarity. Metrics such as 1-in-X years return period, AAL or aggregate exceedance probability (AEP) may be easiest to communicate.

- The results of the analysis should capture uncertainty where possible (such as using different tools to assess the same physical climate change risk question, or presenting results as a range). Qualitative assessments can, in some cases, complement and support analysis given the uncertainty in current knowledge of climate change impacts for some material perils.

Stage 6: Reporting and action – communicates quantitative and/or qualitative loss results to decision makers. This is arguably the most important stage and could take the form of a recommendation to 'act' or 'monitor' based on the results presented. The results will need to include a clear indication of the extent to which loss estimates can be relied upon, and appropriate caveats will be necessary to manage the risk of misinterpretation; for instance, 'these results are intended to illustrate loss sensitivity to climate change and do not constitute a prediction or forecast'.

Successful use of the framework should result in specific actions being taken by the firm.

2.2 Framework stages

2.2.1 Stage 1: Identify business decision(s)

Consideration of time horizons and metrics

When considering the analysis of physical climate change risk, the first step is to be clear about what business decision(s) the analysis is designed to support, such as business strategy, product development, underwriting and pricing, or risk appetite setting. As explained in the introduction, this is likely to mean defining both the time horizon and whether to focus on expected losses or extreme (tail) losses.

For the purposes of this framework, in the context of general insurance operations, the time horizons will be defined as follows:

- Short term: 1-5 years, which is the period during which boards typically operate to develop risk appetite, strategy and business plans.

- Medium term: 5-10 years, which is the period that the viability of new products would need to be tested against.

- Long term: 10-years or more.

This report recognises that the relevant time horizons for a firm will vary based on their operation strategy (for instance, a mutual insurer compared to a Lloyd's syndicate) and the above time horizons should be read as indicative.

Similarly, we can think of the loss metrics indicated by the business decisions to be either:

- expected losses – typically AAL or median losses to show how average losses might change; or

- tail losses – showing how the losses that might be expected in an extreme year could move as a result of climate change, although whether the particular metric considered is specifically the 1-in-30, 1-in-200, or other loss will reflect the risk appetite and needs of the firm.

Applying the principles

The relevance and materiality of physical climate change risk and the time horizon over which its impact needs to be assessed will depend on the specific insurance products, territories, perils, and strategies being considered. With respect to general insurance business for example, consideration of these risks in the underwriting and pricing processes as well as determination of an insurer's risk transfer strategy will usually be based on a relatively short time horizon. The focus for pricing reviews might be on average expected losses, whereas capital considerations may include looking at potential extreme (tail) losses.

When developing a new product, considering the potential costs and benefits of mergers and acquisitions, or development of the overall business plan, insurers may need to consider the impact of climate change on these risks over the medium term, depending on the portfolio. Such a consideration of forward-looking climate risks is in line with a strategic approach that considers how actions today affect future financial risks. Other firm activities, such as risk management, risk appetite setting and public reporting could require a medium to long-term view to be taken. Again, general pricing for products may focus on expected losses, whereas risk management may need to look also at how extreme losses could change under different climate conditions.

Finally, when developing a public policy engagement strategy, or considering disclosure, a longer-term view of the physical effects of climate change may be needed. This could take account of potential adaptation measures to mitigate issues of future insurability or affordability. Both average and extreme losses may be needed to inform the business decisions in this case.

Table 1 suggests the time horizons and areas of focus for a number of business decisions to help illustrate the above issues.

Table 1: Example business decisions, firm functions impacted and the time horizons over which they are considered.

Motivation to undertake climate change analysis	Time horizon	Example of firm functions impacted
Disclosure: TCFD[1] related	Long	Corporate and Social Responsibility, Finance and Risk, Finance, Actuarial, Sales, Marketing, Exposure Management
Disclosure: Public reporting (eg shareholders)	Medium, Long	Finance, Actuarial, Exposure Management, and Risk
Disclosure: Public policy advocacy	Long	Corporate and Social Responsibility, Finance, and Risk
Business decision: Underwriting and pricing	Short	Sales, Marketing, Underwriting, Finance, Exposure Management, and Actuarial
Business decision: Capital	Short	Claims, Finance, Actuarial, Exposure Management, and Risk
Business decision: Outwards risk transfer (eg reinsurance purchase)	Short	Underwriting, Finance, Actuarial, Exposure Management, and Risk
Business decision: Product development	Medium, Long	Sales, Marketing, Underwriting, Claims, Finance, Actuarial, Exposure Management, and Risk
Business decision: Business Plan	Medium	Sales, Marketing, Underwriting, Finance, Actuarial, Exposure Management, and Risk
Business decision: Risk management, including risk appetite setting	Medium, Long	Underwriting, Finance, Actuarial, Exposure Management, and Risk

2.2.2 Stage 2: Define materiality

Assessing physical climate change risk across the entirety of the insured portfolio is not a trivial task. (Re)insurers are encouraged to apply the principle of proportionality and focus on the material exposures that are most likely to be impacted by physical climate change risk. The materiality exercise should consider the following four elements.

1) *Peril materiality in the context of the business decision(s)*

Given current portfolio exposure aggregates, rank the region/peril exposure combinations by materiality in the context of the business decision in question (refer Stage 1) and determine the most relevant financial metric. For instance, if the exercise is to quantify impact on capital requirements, then a metric such as 1-in-200 year AEP could be suitable, whereas AAL might be an appropriate metric for pricing analysis.

2) *Susceptibility of peril to climate change*

For the climate-related perils that affect the portfolio, determine which are most likely to alter as a result of climate change during the time frame in question (as defined in Stage 1). Note that peril/territories that might be considered as immaterial under current climate conditions may, under future conditions, become more material. For instance, wildfire, drought or subsidence might currently be of low materiality to a particular portfolio, but that might change by 2030. Care also needs to be taken for perils that have limited current scientific evidence to indicate significant change under future climatic conditions (such as hurricanes and tornadoes – see Figure 2). For those

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[1] Task Force on Climate-related Financial Disclosures (2017) – see Appendix 3 ‘Bibliography’.

perils, materiality might be high because the aggregated exposure for that firm's portfolio is significant and even a small change in peril characteristic might materially affect the firm.[2]

To assess the susceptibility of each peril to climate change, some preliminary background research on existing published material will be necessary (refer to 'Iterative nature of materiality assessment' on page 12).

Figure 2: The most material perils in a typical general insurance portfolio might not necessarily have the strongest available evidence to support the peril/territory materiality assessment. Source: Union of Concerned Scientists (2012) based on Intergovernmental Panel on Climate Change (IPCC) 2012 report.

Table 2 provides a matrix for evaluating two aspects of importance in determining materiality: the x-axis categorises the perils according to the strength of scientific evidence suggesting a change in hazard (positive or negative) under climate change; the y-axis categorises the exposures for a given territory/peril as material or otherwise to the portfolio.

Table 2: Exposure versus peril materiality evaluation matrix.

		How strong is the scientific evidence for climate change having an impact on the hazard?	
		Limited scientific evidence	Strong scientific evidence
Is the peril/territory exposure aggregate material under current climatic conditions?	Peril/territory exposure aggregate is material	Consider undertaking background research to establish if the scientific evidence suggests that climate change might impact risk unfavourably	Include this exposure in subsequent stages of the analysis
	Peril/territory exposure aggregate is immaterial	Consider as immaterial for climate change assessment	Estimate physical activity threshold at which peril/territory would become material

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[2] For further discussion on the statements on agreement and evidence of climate change, the reader is referred to the discussion in the Technical Summary of the Fifth Assessment Report (AR5) of IPCC 2013 Technical paper (Box TS.1, Figure 1) – see Appendix 3 'Bibliography'.

3) Interconnectivity and second-order impacts

The simplified matrix presented in Table 2 does not take into consideration the interconnectivity between perils or climatic scenarios, which is an added dimension that (re)insurance firms might want to consider. For instance, if background research indicates that the impact of El Niño years may be more pronounced in future, then the materiality of both Australian bushfire and California flood may require analysis alongside each other since they are aligned to El Niño.

Furthermore, there could be a potential feedback loop from changes in technology, policy, or consumer behaviour to the liabilities of a general insurer's book of business. For instance, innovative property-level flood defences may reduce the impact of increased flood risk. These aspects of the analysis are deliberately not considered in this report, but firms are encouraged to consider them in their overall climate change analysis and assess where interconnectivity between peril/territories or second-order impacts may alter the materiality assessment based on the simple matrix shown above.

4) Iterative nature of materiality assessment

Some preliminary background research is likely to be necessary to understand the impact of physical climate change risk on different perils over different time horizons; that is, in order to answer the question along the x-axis of Table 2. While the Intergovernmental Panel on Climate Change (IPCC) reports provide an initial view, more thorough background research (as described in the subsequent stage of the framework) may reveal other perils that previously were not thought to be significant, such as subsidence. Some iteration between Stages 2 and 3 might be necessary.

2.2.3 Stage 3: Background research

We use the term 'background research' to refer to investigations a firm carries out into available scientific research, rather than to primary scientific research itself. Most firms to which this report is relevant will not be in a position to undertake primary scientific research, and there is no expectation that they will do so. However, there is a wide body of literature available covering primary scientific research into climate change, including modelling of potential future climates and the effects of such climates. Researching the available scientific literature and leveraging relevant outputs from this is encouraged, as is the commissioning of experts to carry out specific research into areas of materiality for a firm, or pooling of resources between firms to address any specific research gaps.

Undertaking background research on what is available and relevant to the decisions of a firm can be a challenging task in itself. Firms undertaking an evaluation of their potential risk from climate change need to be aware of the latest relevant scientific findings, both for assessing materiality and for informing loss estimates. Scientific literature includes government reports, review articles, and primary research articles. These vary in their levels of authoritativeness, reliability and frequency of update, and firms will have to consider how best to fit this research within resource constraints, and whether there are any opportunities to pool resources.

Where to start?

A good starting place for general background research into climate change science is to use government commissioned studies such as the IPCC's Working Group Assessment Reports. The IPCC was established in 1988 by the United Nations Environment Program (UNEP) and World Meteorological Organization (WMO). Its remit is not specifically business focused, but it periodically collects, organises and synthesizes the works of thousands of scientists across 195 member countries into assessment reports that may be useful to business users. These assessment reports contain easy to understand summaries for the non-specialist, including sections on regional extreme weather impacts and an assessment of likely future climate outcomes based on scenarios of varying concentrations of greenhouse gas emissions. The IPCC provides information centred on four Representative Concentration Scenarios (RCPs) of future global gas concentrations and aerosol emissions (IPCC, 2014) that correspond to different levels of future radiative forcing, from RCP2.6 (closely related to the Paris Agreement) to RCP8.5 (limited to no action taken), that can be directly related to changes in global mean surface temperature (Table 3).

As can be seen in Table 3, academic research such as that produced by the IPCC can have fairly long time horizons, potentially longer than those relevant for business decisions. Nevertheless, assessing climate change risk over longer horizons could inform changes expected over shorter horizons, especially if impacts are expected in one direction in the future. For example, if quantification done over a long time horizon for a particular metric is X then over a shorter horizon the impact may be less than X. Furthermore, given quantification uncertainties, the use of multiple scenarios could yield a result that is more qualitative and/or indicates directional impacts.

Table 3: Projected changes in global mean surface temperature for 2080-2099 compared to 1860-1899. *Source*: Humphrey and Murphy (2016).

RCP Scenario	Change in global mean surface temperature
RCP2.6	1.4 - 3.2°C
RCP4.5	2.1 - 4.2°C
RCP6.0	2.5 - 4.7°C
RCP8.5	3.4 - 6.2°C

In addition to the IPCC, national governmental bodies periodically publish reports similar in scope and intention but specific to local impacts. Two examples are the Climate Science Special Report published by the US Global Change Research Program with a focus on US impacts, and the UK Climate Projections published in partnership between government departments, the Met Office Hadley Centre and Environment Agency with a focus on the UK. These national reports may be more appropriate or more recently updated documents for those countries where they exist.

Firms with a specific interest in a particular peril/territory that has material impact for them may need to delve further into the literature directly relevant to the impact of changing climate on that peril/territory. Two approaches can be taken.

1) *Approach an expert*

Professionals with an academic background, including those working in the (re)insurance industry, may already possess a thorough knowledge of the scientific research available regarding a particular topic. Commissioning such expertise can be an effective way to undertake background research on a specific topic. Firms that choose to consult with experts should provide clear guidance regarding what is material to their business; for example, the timeframe for which decisions will be made.

2) *Investigate the literature*

Firms who prefer to do this work in-house may benefit from gaining a wider general knowledge around the subject area, which may be relevant not only to climate change, but also to understand current climate risk better. Firms that wish to go deeper into the research could examine two additional sources:

- Studying a review article as the next level of detailed background research. These are peer-reviewed summaries of multiple primary research articles which can give a view on the level of agreement that exists on a certain topic and where are the greatest uncertainties. The publication date of a review article should be noted by the researcher as the article may not necessarily include the most recent research. An example is shown in Figure 3.

- Individual primary research articles in peer-reviewed journals may be considered. The findings in these papers contain only the results of a single study though this could represent a consensus view. Primary studies can be further stratified by the quality of the institution or impact factor of the journal (eg Scimago Journal & Country ranking are given here: www.scimagojr.com).

Finally, an investigation of the literature may be used to identify the key individuals with whom the firm wishes to consult to find out more information, or commission to carry out further research.

Outputs of the background research

The outputs of an investigation into climate change literature are likely to be, for a specific peril and/or region of interest:

- key drivers influencing the severity of a given peril;
- impact of climate change on those drivers;
- historic trends and/or potential future trends impacting these drivers;
- a measure of uncertainty in the current climate and the strength of climate change signal that will be distinct from inherent natural variability in today's climate;
- change in likelihood of events (or event drivers) of a given severity;
- change in geographic areas impacted by a given peril; and
- the relation of the information above to greenhouse gas emission projection(s), recognising that research outcomes are based on a range of IPCC model outputs.

The information presented is unlikely to match exactly the information the firm requires, notably in relation to:

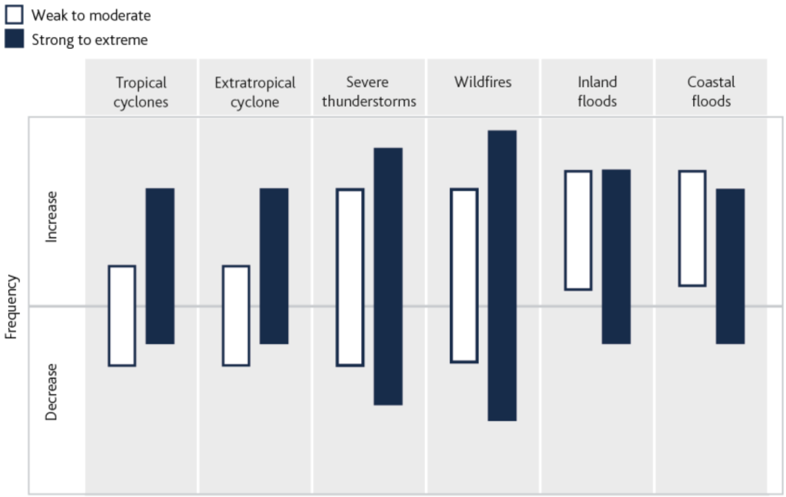
- The timeframe considered by the research – academic studies may focus on change over a period of many future decades rather than business-relevant timeframes, which typically may be somewhat shorter.
- The spatial resolution of the region considered by the research – many climate studies consider change at regional, continental, or even global level. Significant regional differences may exist within the area considered and require further investigation.

An example of the sort of high-level information that may be available is given in Figure 3, which shows the likelihood of increasing or decreasing frequency of a low and moderate severity event for a range of perils globally. The diagram is useful in understanding and comparing the impacts across perils and illustrating the range of uncertainty in predictions – for example, it is clear that the likelihood of wildfire events of all sizes may either increase or decrease. Despite its usefulness, further research would be needed before being applicable to the climate change study, because it:

- considers a single fixed timeframe that may not be relevant to decisions to be undertaken by a firm, such as change by 2100; and

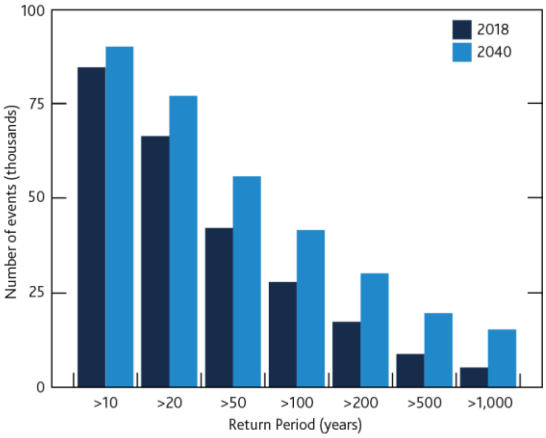
- provides an indication of changes in frequency of each peril at a global level, which is inevitably a broad average of many different effects and in its current form cannot be extrapolated down to a regional level. In addition, the global level information provided is not weighted by regional variability in insurance exposure so is of limited practical value.

Figure 3: Summary of climate change impacts from AIR (2017) showing a likelihood of increases or decreases in frequency of weak-to-moderate intensity events (with a 2- to 10-year return period) and strong to extreme events (50 to 1-in-250 year return period) for different weather-related phenomena by the end of the 21st century. Length of bar indicates degree of uncertainty. Note that the relative positions of the bars represent globally-averaged estimates; significant regional differences may exist and would need to be considered separately.



Higher resolution data, specific to particular perils, may therefore be more useful to firms than a global view. An example of such information is in Figure 4, which shows the number of river flood events exceeding return period thresholds for present-day and future climate in the UK. At a high level this information supports that presented in Figure 3 for inland floods, but it also provides further detail; it highlights that for the UK there is an increasing number of events of all severities, and quantifies the increase in a way that could be directly used by a firm. It is also possible to drill down further and see that there is a larger magnitude change in the number of extreme events (>1-in-200 year return period) compared with more frequent events. Such information may enable firms to incorporate scientific information more easily into their decision making for a specific perils/regions, but firms using information such as this must be careful to check that the source of the data or modelling work is credible, to fully understand the uncertainties associated with such estimates, and the underlying greenhouse gas emission scenarios and time horizons for which they are applicable. An understanding that modelling work is not a prediction for the future is essential to the proper use of model outputs such as these.

Figure 4: Schematic showing the number of river flood events that generate a flow in excess of a given severity (expressed as a return period of the flow under today's climate). A comparison between present-day (dark blue) and future (light blue) climates is shown. Source: JBA Risk Management Limited.



What to do with the outputs of the background research?

The activity a firm wishes to take next will depend on the research findings, the business decisions being considered, peril materiality, among others.

For example, if research into a specific peril of interest concludes there is not likely to be a significant change in its severity and frequency, a firm may decide to review the scientific literature in 3-5 years to monitor that more recent work continues to show this to be the case. Conversely, if there is a scientific consensus (even at a less granular level and longer timescale than is relevant to the firm) that a particular peril will increase in frequency and severity, the firm is likely to wish to undertake further investigation. Using the example in Figure 3 above, a firm with a material exposure to inland and coastal flood may deem those findings sufficient to undertake a further level of analysis. The next step in this case would likely be further investigation into existing literature on climate change impacts at regional level in those areas to which the firm has a material level of exposure.

Interpretation

A certain amount of interpretation of the outputs may be needed by the firm and/or the firm may be able to adjust its approach to reflect the fact that the research findings do not match the exact needs of the firm.

For example, if a firm finds that the frequency of a certain event is set to double by 2100, it may choose to assess its relative exposure to the 2100 scenario and work to those parameters because it can do so without there being an adverse impact on the business – potentially a conservative approach for a decision that has impact, for example over a 10-year timeframe. Alternatively, it may decide to assess its exposure under current and future climate and interpolate between the two to obtain an estimate of the situation for the time horizon it requires, perhaps with a further adjustment for uncertainty.

When interpreting trends from multiple climate model outputs, a range of potential future greenhouse gas emission scenarios and time horizons should be assessed. Any trends identified that impact business decisions should be statistically significant; in particular any observed trend should be consistent across a number of models and model runs so that it is unlikely to be a result of a particular model development, so that the projected change from the current position outweighs any model uncertainty.

There are many uncertainties to be aware of when interpreting climate change studies. Chief among them are the greenhouse gas emission scenarios used in climate projections. Future greenhouse gas emissions are unknown, since they will be driven by global economic development, emissions-limiting policies and technological advances. As part of its work the IPCC creates optimistic and pessimistic emission scenarios which are used in future projections. Firms are encouraged to inform their decision of choice of emission scenarios considering how current levels of greenhouse emissions compare with IPCC's optimistic and pessimistic scenarios. Other key uncertainties arise from the quality of the historic observations and the accuracy of the climate models.

End point of background research

At the end of the background research stage, firms should be in a better position to assess the materiality of climate change for each peril/territory, and for each material peril/territory the firm should have qualitative or quantitative information that describes the severity of those impacts. In turn, that information will form an input to the tools discussed in the next stage of the framework. Firms can use this information (or lack thereof) to prioritise areas in which they need to undertake either further research or take action (section 2.2.4 onwards).

Further research

Climate change projections for the different perils have inherent uncertainty. Firms are encouraged to use the output of their background research whilst taking this uncertainty into account. However, there will be cases where the resulting information from the background research investigation is deemed inadequate or insufficiently clear to justify carrying out impact assessments at this stage and firms may decide to undertake or commission further research or to wait and monitor future developments.

2.2.4 Stage 4: Assess available tools

The tools and methodologies that may be used to assess physical climate change risks will be classified into four categories in this report: i) expert judgement; ii) hazard maps; iii) event footprints; and iv) catastrophe models. These tools have been used in the general insurance sector for assessing extreme weather-related risks over the past 20-30 years. While most of these tools are not explicitly built to assess climate change risks, they can serve as a foundation for physical climate change analysis. Application of these tools is discussed in Chapter 3.

Expert judgement: Expert judgement enables a firm to assess the impact of climate change without the use of more formal tools such as hazard maps, footprints, and catastrophe models. It will generally involve qualitative assessment by those with knowledge of the nature of and losses arising from weather events. Expert judgement will also be necessary when using the other types of tools discussed here, such as when translating scientific results into impacts on peril frequency and severity.

Hazard maps - identify areas that are exposed to a given peril at a given recurrence interval. Hazard maps do not represent the geographic limits of a potential individual event but rather depict the area impacted by an envelope of events that have a similar probability of occurring at an individual location. Hazard maps can therefore be used to examine climate change impact for individual policies or at individual location, but not for a portfolio unless further assumptions are made. Catastrophe models or footprints can act as complementary tools to support event geographic limits.

Footprints - are maps that show the extent and severity of individual catastrophe events. A number of different types of footprint are used in the industry:

- **Historic events** either as they occurred, or perturbed; for example, a stronger or weaker variation of the event, or an actual historic event moved to a different location.

- Single **stochastic events** extracted from a stochastic event catalogue (typically taken from a catastrophe model).

- **Synthetic events** designed to meet a specific set of criteria (for example, a 1-in-100 year hazard intensity impacting specific named cities); such footprints are often developed by determining a realistic impact extent and return period of interest and extracting event severity information from the corresponding hazard map.

Comparisons of event severities described by event footprints that represent current and future climate scenarios are useful tools to assess physical climate change risks at the portfolio level, as described in Chapter 3.

Catastrophe models - are the most detailed of the various tools that can be used to understand the potential impacts of climate risks on insurance and reinsurance portfolios (Geneva Association, 2019). They incorporate information regarding event frequency, extent and severity in a stochastic event set and hence enable users to calculate the expected loss to a portfolio for a given peril and region (or combination of perils and regions), providing an exceedance probability curve and event and/or annual loss tables. Typically built to describe the likelihood of perils for today's climate conditions, catastrophe models may also be adjusted to represent future climates and hence enable assessment of climate change impacts as described in section 2.2.2.

Each of these tools has pros and cons, and different tools give different analytical flexibility to assess physical climate change risks (Table 4). The tools can be simple or complex. However, that is not the same as ease or difficulty of assessing physical climate change risks which depends more on the research that underpins how the tool is used.

Table 4: Pros and cons associated with the various option available to assess physical climate change.

Tools	Pros	Cons
Expert judgement	• Ease of implementation • Can be applied to non-modelled risks • Can be applied using actuarial techniques across frequency or severity separately • Transparent	• Less sophisticated • May be difficult to explain and/or justify • Consistency may be difficult to achieve • May not be quantitative
Hazard maps	• Enable assessment of impact for insurance portfolios for risk selection or pricing	• Building new climate change conditioned maps may require extensive development or be subject to significant uncertainty • Do not consider event-based accumulation • Limited application beyond primary insurance as frequency and severity are combined and cannot be isolated
Footprints	• Enable assessment of impact at level where event-based accumulation is required • Easy to communicate	• Uncertainties in footprint selection need to be clearly understood and communicated • No consideration of frequency for deterministic event selection so results only apply for that event and cannot be extrapolated to exceedance probability curve or AAL • Interpreting research on 'baseline' conditions to the catastrophe model built on recent climate may be difficult
Catastrophe models	• May enable assessment of multiple metrics • Most sophisticated • Ease of implementation if model exists or only a change in frequency required	• Significant efforts are often needed to develop climate change conditioned catastrophe models • Uncertainties in modifying the catastrophe model outputs need to be clearly understood and uncertainties could be compounded when moving from a single event to probabilistic output

The following questions should be considered when selecting a tool:

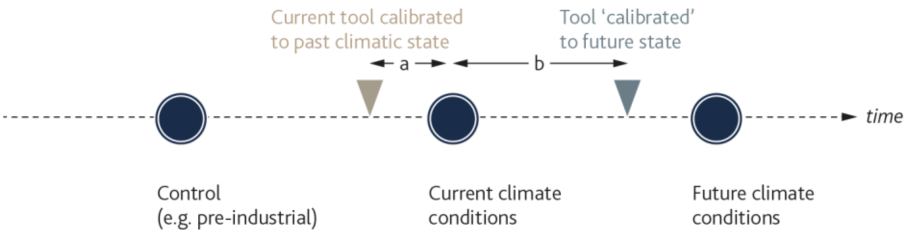
Business decision(s): If a firm is going to assess physical climate change risks at the portfolio level (such as looking at risk appetite or business strategy), footprints and catastrophe models might be more appropriate. If a firm is going to assess the physical climate change risk at the individual risk level (such as looking at underwriting and pricing), hazard maps might be more appropriate.

Resources available: Firms with more resources or exposure to more significant risks might decide to use or develop more complex tools.

Peril/region considered: For peril/regions that are non-modelled, simple tools might be appropriate and easy to implement. For peril/regions that are well studied, firms might decide to use more sophisticated tools.

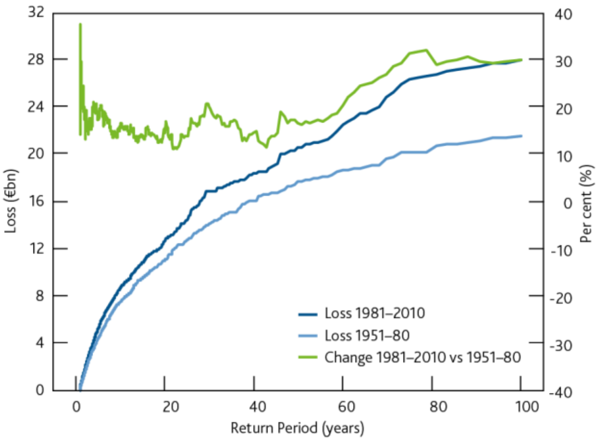
When assessing the appropriateness of tools, users should consider to what degree climate change has already occurred as far as the assessment tool is concerned. In other words, users should understand which climate state the tool they are planning to use has been calibrated against. For instance, a catastrophe model that is using a historical time series to base its stochastic catalogue generation will represent a specific climate state that may – or may not – accurately represent current climate conditions (Figure 5).

Figure 5: The selected climate risk assessment tool represents a past climatic state that may – or may not – accurately represent current climate conditions (a). Consequently, the assessment of a future climatic state might require users to consider both the impact of future climate change and differences already experienced since the climatic state that the selected tool was calibrated against (a+b).



Consequently, when attempting to assess the financial impact of physical climate change risk for a future climatic state, the assessment has to consider that the assessment tool might represent a past climatic state. In other words, the historical dataset used to inform the tool may already be inappropriate if the underlying climate is shifting. The significance of appropriately assessing how current tools have interpreted historic information to base their modelled loss estimation is illustrated in Figure 6.

Figure 6: Difference in modelled losses occurrence exceedance probability (OEP) for the same portfolio when two different subsets of climatic data (in this case UK wind data) are used showcases the potentially underlying shift in risk over time (Dixon et al., 2018).



The use of historic claims experience to help identify potential trends of emerging patterns from climate change can provide useful information to validate the tools outlined above. Such an approach is more applicable for perils with high frequency characteristics (such as wildfire, precipitation-induced flooding or tornados). To undertake such an exercise, attribution of climate change to the claims pattern is necessary.

2.2.5 Stage 5: Calculate climate change impact

This stage assesses loss impacts (where possible) using the tools outlined in Stage 4. Proxy assumptions will most likely be needed in translating hazard changes into loss impacts. Practitioners may decide to exercise their expert judgement or, where resources permit, consult model developers and academic authors of referenced studies on the implications of these proxy assumptions. Some examples of challenges faced in this stage are how to translate:

- a basin-wide projection of tropical cyclone activity into regional landfall activity;
- a wind-speed change into a wind loss change;
- a rainfall rate change into a flood loss change; and
- sea level change and wind-speed intensity change into a storm surge severity change.

In many cases, the degree of uncertainty in these assumptions will be as large as, or even larger than, the signal itself. Given the high degree of uncertainty in results, it is essential to illustrate the sensitivity to different assumptions. The aim should be a range of outcomes which consider potential alternatives. Practitioners may wish to assess impacts under various climate scenarios, such as the IPCC's Representative Concentration Pathways (RCPs), and for a range of assumptions used to translate hazard impacts into potential loss impacts. Single figure loss quantification may in fact be misleading and qualitative 'range of impact' assessments could be more useful.

2.2.6 Stage 6: Report and action

It is important that the results of the assessment are adequately and honestly communicated to the interested parties, which could be both external and internal. Results of analysis must be communicated clearly, with particular reference to the timeframe considered. A modest annual change can have a substantial compounded impact; for instance, a 7% per year increase in losses for 10 years doubles the overall loss.

The various users of those impact estimates may need different levels of detail. The results reported should include the expected impact and how this could develop in the future. It is important for users to understand whether or when the impact of climate change could become material and therefore to what extent it may need to be incorporated into business decisions. Given the uncertainty inherent in these projections, reporting should include detailed description of the key assumptions, the rationale for their choice and the sensitivities of the projections to alternative assumptions. The degree of uncertainty may be communicated best by showing how projections and results change if different methods, assumptions and tools are used, as well as alternative scenarios.

In many cases, the background research will identify several findings that are related – for instance, in the case of tropical cyclones: frequency impacts, sea level changes, rainfall rate increases, genesis changes, and activity changes. Combining these findings based on several highly sensitive hazard-to-loss assumptions can lead to uncertain results. In these situations, modellers may wish to consider each impact in isolation or limit their analysis to those impacts they consider most significant given available knowledge. In this way, decision makers will be able to see the loss impacts of each change separately, preferably for the same future scenario for consistency, thus gaining deeper understanding of the relative importance of model assumptions.[3]

To ensure results are relevant to the decision considered, stakeholders should be consulted to determine which metrics are most useful to them. While 1-in-100 year return period, 1-in-200 year return period, 1-in-250 year return period, OEP/AEP, and AAL are common metrics, practitioners and firms may have preferences as to:

- overall impact on the firm's profit and loss and/or capital position;
- loss impacts versus alternative measures, such as policyholders affected and claims volumes;
- additional metrics such as line of business loss ratios, underwriting margins, and solvency ratios;
- region/peril impacts for hydro-meteorological models only versus region/peril impacts for all models (eg including non-hydro-meteorological models such as earthquake).

In addition, the metrics used may depend on the choice of method.

The full range of projections that can be produced may have many users in different functions: risk management, strategy, pricing, and reinsurance protection. For example, the materiality and uncertainty of the projections could indicate to risk management a need to update risk appetites and risk limits related to natural catastrophe exposure, and whether and how to incorporate these into the board risk report. Similarly, pricing managers may use this information to decide whether it is necessary to incorporate climate change explicitly into their assessments, and if so, what additional tools/models are necessary for the pricing process.

The same points may need to be considered when designing the appropriate reinsurance protection. Finally, the strategy function should be informed about potential changes in the natural catastrophe market landscape. For example, some types of risks could become uninsurable or too expensive to insure, which may need to be reflected in the strategic direction of the firm. Alternatively, new opportunities may develop in lines of business for which the exposure to natural catastrophe could significantly increase, or when new industries emerge (such as agricultural developments) and therefore create higher demand for insurance protection.

Externally, such assessment could be included in insurers' TCFD reporting or any other relevant external reporting requirements, where insurers need to outline how climate change may impact their operations and financial performance. Also, this information should be useful to regulators and rating agencies to assess the materiality of physical climate change risk relative to insurers' risk profiles and how these physical risks should be incorporated in their assessments.

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[3] Loss impacts are only comparable if hazard impacts were based on a similar RCP scenario and a comparable set of climate models.

3 Tools for assessing physical climate change risk

This chapter details the four categories of tools that can be used to assess physical climate change risk, providing an overview of how they might be used to aid assessments of the impact of climate change. Examples demonstrating the use of these tools are shown in Chapter 4.

3.1 General comments

The tools available today to help insurers quantify catastrophe risk largely reflect a view of the past climate that may – or may not – depict the current climate conditions. Adjustments are necessary if they are to be used to help assess the impact of climate change. Such adjustments may be made by the provider of the tools (often a model vendor) or by the user, who can often adjust model outputs in order to reflect potential future climates. In many cases a collaborative approach between the provider and user will prove to be the ideal approach.

Firms must first consider which future time period is of interest to them, which will depend largely on the business questions they need to answer. The uncertainties involved in just assessing catastrophe risk under the current climate are significant, meaning that the climate change signal might not exceed the current level of uncertainty in the near term. Assessment of impacts for a time window further into the future may appear to be more useful to the firm, but will suffer from greater uncertainty regarding how climate change unfolds.

Modelling future climate projections and the impact of these on catastrophe risk is an uncertain science in all aspects. Projections of future greenhouse gas concentrations rely on assumptions about the impact of political decisions as well as modelling work. Even given the same inputs, different climate models will return a range of estimates of global average temperature and different climates. The estimate of changes to extreme events rather than quantities like average global temperature is yet more because climate models typically do not capture information at a sufficient temporal or spatial resolution to model extremes explicitly. Downscaling to a useful resolution for insurance estimates can be done but involves another level of modelling and assumptions. Before using tools to try to quantify possible changes, it is vital that the user has a thorough understanding of the uncertainties in each part of the modelling chain.

As a result of these uncertainties, it is generally unwise to focus on a single prediction, but rather to develop a set of representative predictions that define a plausible range of future outcomes.

3.2 Expert judgement

Expert judgement as a tool for assessing risk has a long history in the actuarial profession. It can be defined as a judgement on a specific set of criteria by persons possessing the relevant knowledge and understanding of those criteria. Expert judgement is relevant to all aspects of modelling, including the choice of a model, but becomes critical when there is a lack of data or modelling work available to enable other kinds of evaluation. In the Solvency II context, Article 2 of the Delegated Regulation requires insurance and reinsurance firms to use the expertise of persons with relevant knowledge, experience and understanding of the business risks when making assumptions relating to the solvency capital requirements, minimum capital requirements, and investment rules. The limitations and degree of reliability of any assumptions should then be communicated to all internal users (subject to proportionality). Case study F provides an example of applying expert judgement to assess climate change impacts for Germany hail.

Several papers provide guidance on best practice[4] and a structured process for conducting expert judgement (eg Ashcroft et al. 2016, Hora 2009). It is likely that firms regulated by the PRA will have expert judgement policies in place, particularly if they are using an internal model for Solvency Capital Requirement calculations. Among other matters, the policy should address the governance structure, definition of responsibilities, links with associated policies such as those on materiality, a clear description of standards, and the documentation required, and frequency of review.

Ashcroft et al. (2016) recommend a five-step process for conducting expert judgement:
i) preliminary assessment; ii) definition of the problem; iii) obtaining expert input; iv) making the decision; and v) ongoing monitoring. The preliminary assessment reviews the materiality of the decision to determine the appropriateness of using expert judgement. In defining the problem a statement of the judgement needed should be clearly articulated and terminology defined. Expert input can be obtained through written responses or interviews, but should be documented in either case. The decision makers are unlikely to be the experts themselves and any decisions should face appropriate challenge and governance before being accepted. Finally, after a decision has been made, there should be a system in place to regularly monitor and review how the expert decision outcome compares with observations.

The quality of expert judgement can be negatively influenced by a number of cognitive biases. A good overview of biases in actuarial work is given by Tredger et al. (2015). They include:

- **Anchoring**: using an initial piece of information to make a judgement regardless of its relevance.
- **Availability**: using information that first or most readily comes to mind.
- **Framing**: bias introduced by the way the question is asked and use of a small sample.
- **Extrapolating**: from too limited information.

Organisers of an expert judgement process should consider these biases and take appropriate steps to mitigate them.

These general principles will need some adaptation in this climate change risk assessment framework. Firms may have weather and/or climate experts employed internally, but in the majority of cases this is unlikely. Conclusions from scientific literature can be thought of as standing-in for an expert individual. However, the exact question and timeframe a firm would like to address, and the metrics they wish to use are unlikely to be matched exactly in research papers. So there is likely to be a need to implement assumptions and methods, themselves based on expert judgement, in order to interpret findings presented in the scientific literature.

3.2 Hazard maps

Hazard maps provide location-level information on the extent or severity of a peril for a given return period. This information may be linked to a distribution of likely claims values to enable calculation of a technical price for flood; hence maps are used by primary insurers to inform pricing and underwriting decisions.

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[4] For Internal Model firms, refer to EIOPA (2015) and PRA (2016).

Hazard maps are typically based on historical or prevailing climate conditions and reflect today's climate. In a limited number of examples, maps adjusted to represent future climates may be available. Where this is not the case, firms may apply expert judgement and carry out mapping adjustments themselves, using government and academic climate science sources and individual research.

The IPCC scenarios outlined in section 2.2.3 provide warming scenarios that can be used as the basis for map adjustments. Having chosen a suitable climate scenario, examination of the scientific literature can identify the likely impact of that scenario on the severity and frequency of the peril of interest. In some territories government advice on certain perils may be available. An example for river flood in the UK is given in Case Study D 'Flood pricing' in Chapter 4.

Once the new relationship between hazard frequency and severity under a future climate scenario is identified, a future climate hazard map can be created by adjusting current hazard intensities in the current map accordingly. Adjustments may also be carried out when hazard risk is expressed numerically using simpler scoring data derived from the maps. This approach works well for perils that impact all areas (such as wind) but has limitations for perils that have a limited extent (such as flood) since it does not easily enable extension of mapping into areas that are unaffected in today's climate but may become exposed in a future climate. An alternative approach to creating new maps is to use available maps to represent alternative future climates.

Attempting to assess the financial impacts from physical climate change risk at a single location is a challenging task given the related uncertainty, so climate-adjusted hazard maps are more likely to be used for assessing the change in a firm's aggregate exposure to the chosen peril as the law of large numbers reduces some of the uncertainty tied to a single location. Portfolio data can be overlaid on the maps to ascertain the hazard severity for a particular return interval, then vulnerability functions used to associate that severity with a damage estimate. Comparison of the result for current and future climates can reveal the change in exposure. Such comparisons might be carried out for:

- a whole region (such as a country or province), thereby providing the change in exposure to a peril for a given return period, but without constraining that exposure to the extent of a single event; or

- for an area that corresponds to a realistic event extent. Such analysis will need to take into consideration whether the geographic extent of an event might change as a result of climate change (for instance, the area affected by flood may be greater if rainfall levels increase).

Hazard maps can also be used to develop future underwriting strategies; for example, a firm may choose to write more business in an area that will see a less severe (or even improved) change in risk rather than in areas that are likely to see more severe changes. The maps may also be used to develop flood footprints as described in section 3.4.

Box 1: Example of how to use government advice in adjusting maps to account for climate change.

In the UK, the 2008 Climate Change Act requires the Government to publish UK Climate Change Risk Assessments (UK CCRA) every five years. The latest relevant publication is the UK CCRA 2017. The risk assessments are related back to IPCC work, so for example, the 2°C warming scenario from the UK CCRA 2017 is related to RCP2.6 from the IPCC AR5 scenarios. The risk assessments provided by the Government then provide a number of different metrics that can be used to assess the impact of climate change with respect to different hazards such as:

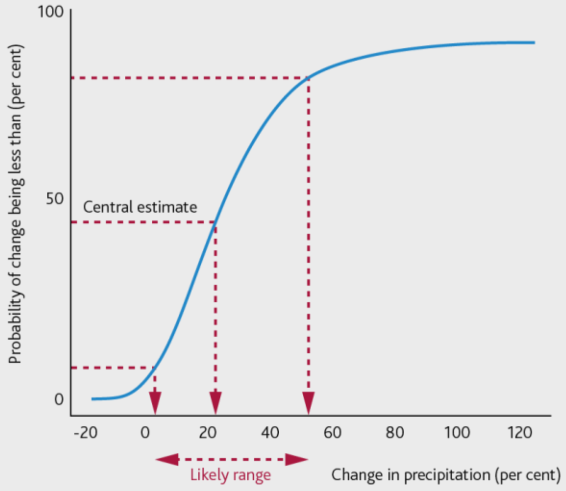
- Rainfall (surface water) – UK Climate Projections 2009 offers a percentage change in the 'wettest day of the season' at 25km resolution.

- River flow – UK CCRA 2017 river flow allowances quantify the projected percentage change in peak river flows for each scenario and time period.

- Sea level (coastal surge) – UK CCRA 2017 coastal allowances represent relative sea level rise along different sections of the UK coastline.

Figures such as these, where available, may be used to re-map directly a particular peril for a chosen climate scenario. The metrics include a central estimate and a likely range of variability around that central estimate, therefore it is possible to model a low- , average-, and high-impact estimated outcome relating to each starting climate scenario.

Figure 7: Cumulative distribution function (CDF) showing the probability of precipitation increasing by less than the values on the x-axis by 2100. Dotted lines represent the 10th, 50th and 90th percentiles. The likely change in precipitation, represented by the 80% confidence interval of possible changes, will be an increase in precipitation of between 5% and 55%.



3.4 Footprints

Assessment of possible risk change for a pre-selected event may be obtained by generating event footprints under current and climate-adjusted conditions. The chosen footprint will represent only one possible event occurrence from many possible eventualities, while the climate-adjusted footprint will represent only one representation of a possible future climate (see section 3.1).

Firms may choose to adopt existing footprints (from third parties) or develop their own (such as by adapting from those developed for own risk and solvency assessment (ORSA) purposes). When choosing a footprint against which to study the potential impact of climate change, firms should assess which regions have material exposure to the peril in question, remembering that some exposures that are not material today may become so under a future climate.

The footprints used to assess changing event exposures might be events from a stochastic event set, representations of key historic events, synthetic events that correspond to a particular description (such as a 1-in-100 year event in location X) or might be generated using data selected from a hazard map for an area corresponding to a realistic event extent.

When selecting stochastic events corresponding to scenarios, firms should caution that the degree of closeness between the similar stochastic event and the scenario can depend on the number of events in the region of interest similar to the scenario. This aspect alone could influence conclusions drawn by this exercise. Therefore, choosing multiple representations of the scenario rather than one (such as multiple representations of the current historical instead of one) helps account for this uncertainty. An analogy of this uncertainty in current catastrophe model use is the difference between losses using the hazard of historical/real time events and those obtained using similar stochastic events.

When an event can be described according to its physical parameters, then it is possible to adjust these parameters to represent a future climate and regenerate the historic event footprint for that future climate. Such adjustments might be carried out in two places.

(i) If an event is mapped in terms of its hazard intensity, then the hazard intensity can be adjusted for each location to represent the possible intensity under a future climate. The level of adjustment required might be based on the IPCC scenarios but for an individual peril will need to be ascertained based on research and expert judgement. Firms may be able to make such adjustments themselves.

(ii) If an event is described in terms of its input parameters (such as river flow or rainfall intensity in the case of flood), then these parameters may be adjusted in a similar way and the event regenerated. Firms may need to work in collaboration with modelling companies to do this in cases where they use a hazard map or event modelled by a third party.

3.5 Catastrophe models

Traditionally, catastrophe models have been used to understand risk in the current climate, and only recently have they started to be used to understand the impact of future climate change. In a limited number of cases (for instance, Case Study B ‘UK flood’ in Chapter 4), modelling companies provide two versions of a model, one for today’s climate and one for a future climate scenario and time horizon. However, in most cases, a future climate version will not be available and firms wishing to use a model for assessing risk under a future climate must consider how best to adjust the current model.

Before considering such adjustments, firms must assess whether a model already contains climate change or climate variability signals. Models are built using observed climate and damage data, and statistical methodologies to represent climate extremes and their impacts. The amount of observed climate data available varies by region and peril. For example, reliable data is available on land-falling hurricanes in the continental US from around 1900, while reliable wind-speed observations in Europe are only available from around the 1970s or later depending on the country: in both cases this data provides a limited record of the full natural hazard risk volatility.

Catastrophe models are typically built using as much relevant reliable data as is available to improve precision, but developers must decide whether it is necessary to adjust some of the data to reflect current climate conditions. For temperature and sea level change, it is often reasonably straightforward to justify such adjustments, since historic climate trends in observations are relatively easily identified, whereas for other climate variables the trends and variability may be difficult to quantify or poorly understood, for example due to inter-annual natural variability. If a model is built using data from a certain period without adjustment for long-term trends, then the model will represent the average climate over that data period. Even models that make allowance for change over the period reflected in the data, may not represent exactly the present day climate, and may require further calibrating to current conditions adjustment even before the process of adjusting for future climate change begins.

A firm must also decide if it wishes to adjust only the hazard component of the model, or also to adjust exposure, vulnerability and secondary modifiers in the model. These components may change alongside climate in the future, and potentially to an extent that impacts model results more than climate change itself.

Having determined the time period which is implicit in a model, firms must determine the future time horizon for which they wish to obtain comparisons. It is then possible to adjust the model to reflect a future climate in two ways.

1) Rebuilding the model

A catastrophe model can be completely or partially rebuilt to reflect an adjusted climate, using different input variables and parameters. This is typically achieved by adjusting frequency and/or severity of events in the stochastic event set. This approach is the most scientifically robust, but requires considerable research effort and time. It is typically only possible for the original model developers to rebuild a model in this way and therefore may require pooling of market-wide resources.

An example of how this can be done is illustrated in Case Study C (Chapter 4), where a European windstorm model is generated using General Circulation Models (GCMs) that simulate climate conditions and resulting weather patterns. Input parameters to these models (such as sea surface temperatures) may be adjusted for future climates under different greenhouse gas emissions scenarios. The input is perturbed through a range of values to yield multiple versions of the future, known as an ‘ensemble’. Stochastic events should be selected to match characteristics of the ensemble as closely as possible. This can be done, for example by altering characteristics of existing events (such as tracks or intensities) so that the stochastic catalogue has characteristics matching those found under different emissions scenarios. Firms must bear in mind that the output from such an approach represents only one in many possible future climate scenarios.

2) Adjusting model outputs

Catastrophe model outputs such as the event loss table (which includes event losses and rates) for events and years in a model can be adjusted without having to rebuild the model. In this case, modifications are done using only the information available in the loss output, and hence, for example, frequency adjustments can only be made to events already in the catalogue rather than creating new events as in point 1) above. These adjustments can be calculated once and then applied to any set of results from the original model, making this method very efficient. The challenge is to derive a reasonable set of adjustments to make, a process that is likely to involve considerable research and use of expert judgement.

Case Study A ‘US surge’ describes the partial rebuild of a model using an adjusted climate to create a new event set, as an example of rebuilding the model. This new event set is then used to derive adjustments to losses for every event in the original event set, as an example of adjusting model outputs.

3.6 Tool limitations

Losses arising from catastrophe events depend on hazard, exposure, vulnerability and financial structures. The tools described above outline some of the more common techniques that may be used to adjust estimates of hazard as an indication of the physical impact of climate change on insurance portfolios. They do not discuss, however, the ways in which exposure and vulnerability may change. Comparison of current and future event outcomes based on the same exposure data and assumptions does not account for other changes that will occur in parallel with the likely increase in severity and/or frequency of natural peril events. Some of these changes will be driven by factors unrelated to climate change (for example, rise in property values over time) whereas others will relate to the underlying peril or even climate change itself (for example, changes in planning laws and improvements in flood defences to protect against expected rises in flood hazard). Insurers are advised to consider the impact of factors such as these in parallel with consideration of changes to hazard driven directly by climate change itself.

Climate change assessments using the tools discussed above give an illustration of what changes a future climate might cause if all other variables are kept equal. The results of applying the framework therefore provide an important input to a wide range of business decisions. This report is not, however, suggesting that those results alone should be extrapolated to draw specific conclusions about the impact of climate change on the overall exceedance curve or annual average loss. Climate change may have opposite impacts on different parts of the exceedance probability curve; stress testing a single event cannot capture this behaviour but can provide some useful information on where to focus future analysis efforts. Equally, the results obtained by running a different event or climate scenario may lead to a different conclusion, and should not be understood as attributing the occurrence of a single event to climate change; in many cases, the same event may also occur in the absence of climate change, albeit perhaps with a different probability of occurrence. Firms and practitioners are encouraged therefore to test not only a range of different events but also the impact of a range of climate scenarios on these events, and to explore the uncertainty in the results in order to gain deeper insight into climate change impacts.

4 Case studies

This chapter provides six case studies that illustrate the application of aspects of the proposed framework.

The case studies have been created based on scenarios provided by the working group members. They have been developed to cover a range of different hypothetical business decisions, time horizons, metrics, and the use of different tools. They are provided for illustrative purposes of how aspects of the framework might apply in practice, and are not suggested to constitute best practice, but rather illustrate the potential challenges and solutions that practitioners and firms may consider. The case studies were selected based on material developed before the working group was set up, and that could be shared by each of the working group members. The business cases related to each case study have been developed to retrofit the scientific work undertaken by the working group members. As such, no case study is an example of a complete physical climate change impact assessment but rather illustrates aspects of the six stages of the framework.

The case studies deliberately contradict each other in some aspects of the framework to illustrate that firms might take different views on materiality of perils depending on their exposure and business need. For instance, Case Study B 'UK flood' assesses that the climate change signal for UK windstorm is not material, while Case Study C 'UK windstorm' looks specifically at this peril.

Case studies A, B and C are based on individual peril/territories, and case studies D, E and F are based on multiple peril/territory combinations. The latter group is designed around a common context (such as business decisions, time horizons, exposure, or analysis metrics used), but reflect different responses to each constituent event (such as different underlying research or tools used). Some case studies are based on climate change conditioned catastrophe models or hazard maps which are not currently readily available but will emerge over time; others are based on expert judgement and footprints that firms can implement using the available sources themselves.

Outline of case studies

Case study	Business Decision & Horizon	Territory/Peril	Assessment tools used	Provided by	Pages
A	Pricing by 2030	US Surge component of US Hurricane	Catastrophe model	RMS	31-36
B	Underwriting by 2040	UK Flood	Catastrophe model	JBA	37-40
C	Public policy engagement by 2079	UK Windstorm	Catastrophe model	AIR	41-44
D	Pricing and risk selection by 2040	UK Flood, US Flood	Hazard maps	Ambiental, Fathom, JBA	45-49
E	Risk appetite by 2040	Japan Typhoon and flood	Footprints	AIR	50-57
F	Strategic decision making by 2030 and 2100	Wind flood and surge components of US Hurricane; Germany hail and California wildfire	Catastrophe model, expert judgement and footprint	SCOR, KatRisk, Guy Carpenter	58-70

Case Study A ‘US surge component of US Hurricane’

Provided by RMS

Stage 1 Business decision

A London Market insurer is looking to capitalise on potential deregulation of the US flood insurance market and expand its lines on flood risk in the high value residential and commercial segments. This requires building the analytical capability and tools to price policies efficiently and quantify risk on the portfolio. The Underwriting Property Committee is expecting the new and expanded business lines to mature over the next 7-15 years. In an initial study to identify risks, the Committee found that physical climate change posed a potentially significant risk to their business plan. It approached the exposure management team to help them answer the following questions:

(i) Would the technical price be affected from physical climate change?
(ii) Is there a risk of the technical premium increasing above a level which is affordable for policyholders?

Stage 2 Materiality

The insurance firm already has expertise in the US East Coast and a growing portfolio of high value residential and commercial properties. As such, the exposure management team has decided to answer the questions posed by the Underwriting Property Committee using sections of that coastline as a case study. The current contractual wording covers the risk of flooding from both inland and coastal flood mechanisms, but in most of the candidate US east coast locations inland flooding is insignificant compared to the storm surge component. As such, the materiality analysis identified storm surge as the dominant peril.

Stage 3 Background research

Baseline

Using 2010 as the baseline, the findings were that sea level is projected to increase over the US East Coast with different levels of magnitude and uncertainty depending on location. The 2010 baseline was deemed to be similar to the baseline assumed by the current view of US storm surge risk adopted by the firm.

Methodology

The exposure management team undertook the background research by dedicating five work-days to perform in-house background research followed by a 15 day consultation exercise with their catastrophe model vendor. The internal background research reviewed articles on the topic, mainly focusing on sea level rise (SLR) and understanding the 7-15 year time horizon implication.

From this exercise it became clear that impacts of physical climate change risk to coastal hazard along the east coast are not straightforward. If meaningful conclusions are to be drawn with the available resources, the background research has to focus on specific sections of the coastline. By limiting the domain in this way, an analysis could be performed that is detailed enough to address the questions of the Underwriting Property Committee making the most of the limited available resources.

Two areas were chosen as case studies: a selection of postcodes in New Castle county, Delaware, and a selection of postcodes in Portsmouth and Norfolk counties, Virginia. Portsmouth and Norfolk are situated at the entrance to Chesapeake Bay. New Castle was chosen because it lies on the Delaware River to the north of Delaware Bay and is therefore further from the open ocean than Portsmouth and Norfolk. For this study, the team used a representative exposure of residential and commercial lines of business (LoB), with a combined TIV of $136 billion in Portsmouth and Norfolk, and $88 billion in New Castle. The spatial resolution of the exposure is approximately 100m at the coast.

The background research focused its attention on SLR which was deemed to have most material impact on flood risk, as the increase in mean sea level can contribute to an increase in frequency and severity of coastal flooding from storm surges.

The external model vendor provided information that was derived from participating in the 2014 Risky Business Project (riskybusiness.org), which quantified the impact of climate change on coastal flood risks in the US using projected SLR ranges taken from Kopp et al. (2014). These projections were provided at a local level in the US and were derived by combining formal expert elicitation, expert assessment, and process modelling. Using the year 2010 as the baseline, for this exercise the external model vendor recommended that the SLR in Delaware and Virginia should be taken from the median of the projected SLR range for 2030, using a blend of RCP8.5, RCP4.5 and RCP2.6 future climate scenarios.

Limitations and uncertainty

This exercise assumes that the selected case study areas can be viewed as representative of the wider US east coast and provide answers to the questions posed by the Underwriting Property Committee. However, SLR varies significantly across the coastline due to local factors and it is difficult to extract conclusions for the whole portfolio using these locations as samples.

The SLR projections themselves contain uncertainty due to many contributing factors such as the behaviour of ice sheets, or changes in ocean processes in a different future climate. Given that uncertainty in the SLR estimates can be as large as the year-to-year variability in local sea level, some caution is required when drawing conclusions from the results.

Interaction between inland and coastal flooding was not included in the background research as it was deemed to have minimal impact for the postcodes in question, and was too complex for the level of study.

It is noted that by limiting the study to SLR only, the team is excluding possible impacts of climate change on hurricane intensity and frequency, as well as any projected adaptation measures such as improved defences. However, this also means that the loss impacts are driven purely by the projected SLR in the specified climate change scenario, allowing a more straightforward interpretation of the results.

Stage 4 Assess tools

For the eastern US coastline there are catastrophe models available with sufficient resolution to assess impacts of SLR on surge losses in the study locations. Also, the firm’s view of risk is a direct output of the external vendor catastrophe model. The exposure management team therefore consulted with the model vendor who provided a bespoke modification of the hazard component for their North America hurricane model. This modification incorporates SLR by increasing water depths across all events, which was also the approach adopted for the Risky Business Project.

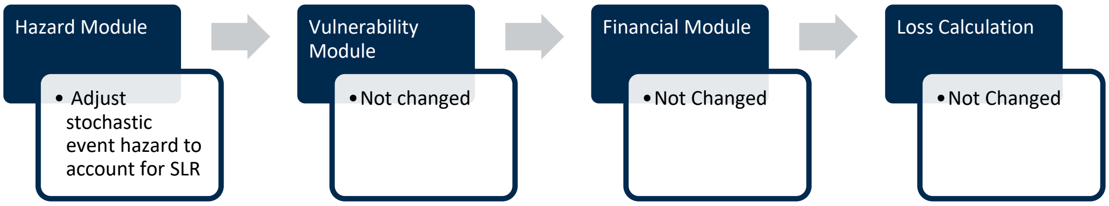
The alternative, of building new scenarios within the stochastic model set, was explored but deemed to be too time consuming and resource-intensive for this study.

Stage 5 Calculate impact

The external model vendor provided the exposure management team with two approaches to adjust the default model.

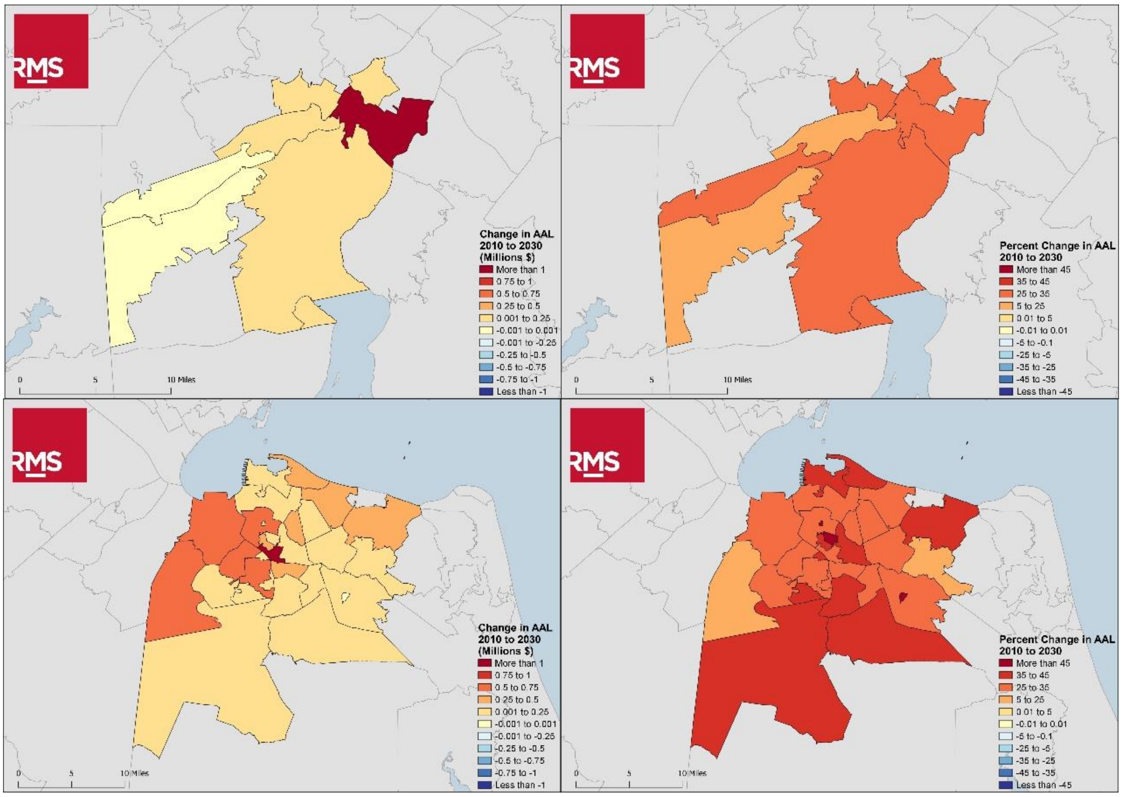
Approach 1

The flow chart below indicates the changes applied to the model in the first approach.



The model vendor adjusted the hazard module by increasing modelled sea level from the 2010 baseline to account for climate change in a specific decade, which was in this case 2030. No other part of the model was changed.

Figure A1: Combined residential and commercial surge only AAL change in $ million from 2010 to 2030 in a) Delaware (DE) and c) Virginia (VA). Corresponding percentage changes are shown in b) DE and d) VA



The impact of adjusting sea level in the two study areas can be seen in the change maps of average annual loss (AAL) shown in Figure A1. The losses shown are for the storm surge peril only; wind losses are not included. In both study areas the percentage change in AAL from 2010 to 2030 is mostly in the 25%-50% band. This information can be used in part to answer the questions raised by the Underwriting Property Committee; how could pricing change given physical climate change?

The impact on AAL and occurrence exceedance probability (OEP) losses are shown in Tables A1 and A2 below for the storm surge peril only. The results show ground up loss rather than gross loss, as the flood policy terms themselves might be a lever used to control the risk due to SLR identified in the study.

Table A1: AAL and OEP losses in $ million for the Portsmouth and Norfolk, VA study area

	Loss Increase from 2010 Baseline	
	($)	(%)
AAL	9 M	32%
OEP 50	141 M	34%
OEP 100	241 M	25%
OEP 200	366 M	23%
OEP 500	467 M	21%

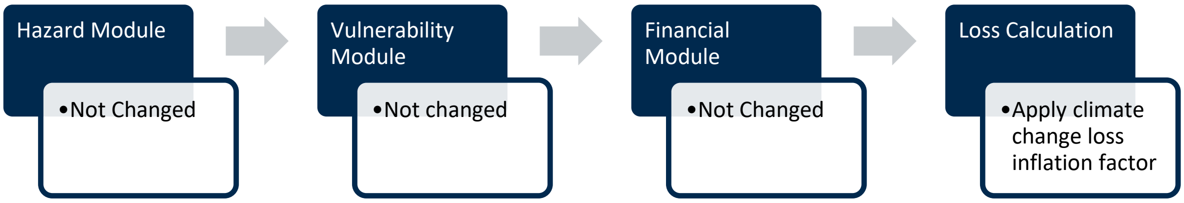
Table A2: AAL and OEP losses in $ million for the New Castle, DE study area

	Loss Increase from 2010 Baseline	
	($)	(%)
AAL	2 M	30%
OEP 50	15 M	33%
OEP 100	35 M	34%
OEP 200	56 M	27%
OEP 500	88 M	20%

The OEP results indicate that the greatest change comes at lower return periods. This is because the damage caused by a rare event with high surge might not be significantly impacted by adding less than 30cm of SLR. However, smaller events where surge depths were not high enough to overtop defences or enter buildings in the baseline climate may now do so with the addition of only a modest SLR, leading to greater loss.

Approach 2

The flow chart below indicates the changes applied to the model in the second approach.



In this example, the model itself remains unchanged from the baseline. Instead of altering the model, for a given future climate scenario a pre-calculated loss inflation factor can be supplied by postcode for each event. These factors inflate event losses from the baseline catastrophe model to account for physical climate change, and are calculated in-house by the external model vendor using the climate adjusted model described in approach 1. This approach allows the exposure management team to combine existing event loss tables (ELTs) with a look up table of loss inflation factors, to quickly analyse and price new risks as they attach. The inflation factors also allow the team to quickly extend the view beyond the initial medium term period of 2010-2030, to look at the longer-term sustainability for 2050 and beyond.

Below is a sample Table (A3) for five stochastic events showing their SLR loss amplification factor for one zip code in New Castle, DE.

Table A3: Future climate loss inflation factors in a given zip code for five sample events using 2030, 2050, 2080, and 2100 SLR scenarios

	SLR Loss Amplification Factor (by decade)			
EventID	2030	2050	2080	2100
0001	x11.3	x18.3	x29.1	x35.4
0002	x1.6	x2.5	x3.9	x4.7
0003	x1.3	x1.7	x2.5	x3
0004	x1.2	x1.5	x2.1	x2.5
0005	x1.2	x1.3	x1.6	x1.8

The team notes the first event in the table has much higher loss inflation factors for all future climate scenarios compared to the other four events. This event has a relatively low loss in the baseline year (2010) and a small increase in water inundation level, therefore disproportionately increasing loss. This could be due to SLR now causing overtopping of defences which were not overtopped in 2010, or water depths are now high enough to enter elevated buildings where they would not have done so before. The events with lower inflation factors already have relatively high losses in 2010 and adding the same SLR in these locations does not have as much impact.

Upon further consultation the model vendor provided separate loss inflation factors for residential and commercial lines, allowing the team to look in more detail at large commercial accounts in the locations of the study.

The team notes that the impact of SLR on the portfolio 1-in-200 year return period loss and portfolio AAL is similar for both locations assessed – they both increase – but varies spatially at a local level.

Stage 6 Report findings

With respect to physical climate change impacts on the business, the exposure management team makes the following recommendations to the Underwriting Property Committee.

Pricing:

- Sea level change is expected to drive a small increase in risk over the 7-15 year time horizon. This risk should be gradually reflected in the pricing of property on the east coast of the US or managed through policy conditions.
- Large commercial accounts should include a climate change loading in their assessment when pre-bound.

Business planning:

- There is a low risk of the technical premium becoming unaffordable for policy holders in the medium term.
- SLR driven increases in the technical premium over the medium term might be greatest in areas which are currently lower risk for storm surge.

Next Stages:

- Obtain localised risk loadings for SLR by applying the work to the whole US coastline.
- Expand the work to investigate the impact of physical climate change on
- other potential perils affected by physical climate change risk.

Case Study B ‘UK flood’

Provided by JBA

Stage 1 Business decision

A primary insurer’s personal lines Property Underwriting Committee seeks to understand the impact of physical climate change on long-term underwriting limits at a portfolio level for each of its UK branches. The findings will inform the firm’s overall long-term business strategy for the period to 2040.

The Underwriting Committee has assigned the exercise of investigating impacts from physical climate change risk to the actuarial function, as that is the team responsible for developing technical pricing.

Stage 2 Materiality

The insurer is mainly exposed to property catastrophe risk in the UK. An earlier, high-level physical climate change risk study had concluded that there is no clear physical climate change risk signal for windstorm and any future analysis should focus on inland and coastal flood impacts as a first step.

Stage 3 Background research

The actuarial team has decided to focus on two areas in the UK to allow them to undertake a deep dive given limited resources. The areas of focus are the branches of Yorkshire and East England. These regions have been identified by the Committee as being targeted for most growth potential under the current draft strategy. Additionally, Government research suggests climate change may impact these two areas differently (such the change in peak river flow, Figure B1) and this offers an insight into the potential range of impacts.

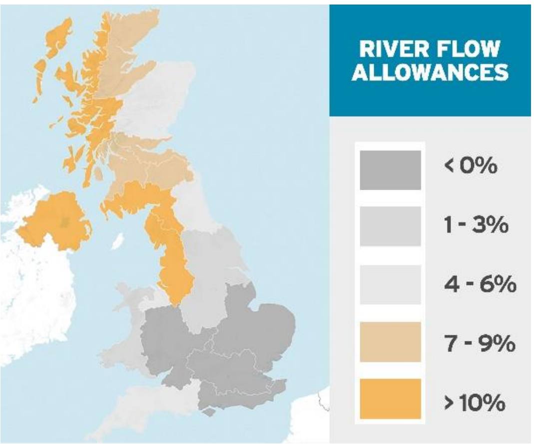
Baseline

The background research team defined the baseline as the climate in 2018.

Methodology

The background research component of the exercise involved firstly undertaking a literature review to understand the expected changes to inland and coastal flooding by 2040. This background research identified that the UK Government climate data sources (UK Climate Change Risk Assessment Report 2017 and UK Climate Projections 2009) published by Defra (Defra 2017; Defra 2009) offer sufficient reliable information on changes to future rainfall, river flow and sea level risk by 2040 for this work and no further background research was undertaken.

Figure B1: Projected changes to peak river flows, termed climate change allowances, per catchment area as defined by the UK CCRA 2017



Limitations and Uncertainty

The UK Government Study acknowledges the range of future climate conditions but puts forward a most likely outcome. This is not a forecast and remains an uncertain outcome. Basing the analysis on a single climate scenario requires appropriate disclaimers and communication to the final report recipients.

Stage 4 Assess tools

The criteria for selecting an appropriate tool is one that: (i) can provide granular analysis at postcode level as a minimum; (ii) can most closely depict the background research findings; (iii) covers all types of flood risk across the UK; and (iv) is readily available and can be procured within the set budget.

As the exercise is mainly addressing the impact of climate change risk on pricing, the tool to be used would need to provide technical premium (AAL) at property level, so both catastrophe models and flood hazard maps were considered. The background research team assessed five different providers of flood hazard maps or catastrophe models and selected a model that provided a close match to the set criteria by incorporating physical climate change projections in its event set, comprising both inland flood and storm surge.

The selected third party provider has adjusted the rainfall data in its stochastic catalogue by adopting the UK Climate Projection 2009 (UKCP09) wettest day of season. This is available at 25km resolution and is defined as the 99th percentile of daily maximum precipitation. The peak river flows and relative sea level are adjusted using the data available from the UK CCRA 2017 (Defra, 2009).

Each event in the stochastic event set is defined in terms of the return period of the hazard intensity (of river flow, rainfall or sea level) at all affected gauges. To estimate the return period in years of a given hazard intensity, a probability distribution is fitted to the flow, rainfall or sea level data at each modelled location, using the peaks-over-threshold method.

To obtain the climate change adjusted return period for a given hazard intensity, the probability distribution fitted at each modelled location is adjusted using the allowance value for that location by classifying each gauge into one of the UK CCRA 2017 or UKCP09 regions (depending on flood type), based on the gauge’s physical location (Defra, 2009).

Stage 5 Calculate impact

The analysis was carried out using the selected model vendor’s industry portfolio, comprising data on the number, type and total sums insured of residential properties. The industry portfolio was run by the external catastrophe model provider with results produced in a csv file. The results contained outputs from current climate and future climate conditions which permitted a direct comparison.

The metrics used to assess impact were AAL and AEP. Tables B1 and B2 below illustrate those results.

Table B1: AAL results for 2018 and 2040, for the two sample regions, with the relative difference between modelled outputs.

County	Current (2018) mean loss	Future (2040) mean loss	Difference
East England	£27,827,461	£24,979,911	-10%
Yorkshire	£32,985,753	£42,175,786	28%

Table B2: The relative difference in 2018 and 2040 AEP mean loss per return period for Yorkshire and East England.

Return period (years)	Yorkshire	East England
2	66%	-17%
5	40%	-15%
10	34%	-13%
20	28%	-11%
50	23%	-10%
100	26%	-10%
250	23%	-8%
500	17%	-5%
1,000	14%	3%

The AEP results for Yorkshire show an increase in loss at all return periods. However, the relative difference in mean loss reduces with event severity. Conversely, for East England, the model projects a decrease in losses across most return periods by 2040, apart from a 1-in-1,000 year event, when losses are expected to increase by approximately 3% (Table B2). The range in relative difference is larger for Yorkshire (+14% to +66%) than East England (+3% to -17%). The two regions therefore highlight how areas may be affected differently by climate change. In Yorkshire, the risk to flood is predominantly projected to increase, whereas in East England there is expected to be a reduction in flood risk.

Stage 6 Report findings

The recommendations to the Underwriting Committee by the team are:

- The potential of climate change impact to flood risk may vary geographically and impacts can be significant.
- There is scope to consider long-term portfolio management and diversification opportunities.
- There is merit in undertaking a more detailed analysis covering the full geographic extent of the UK and expanding the analysis to commercial lines.

The caveats to this analysis, communicated to the Underwriting Committee, are:

- This analysis looks only at current personal lines policies.
- This view is restricted to the modelling methodology the catastrophe model vendor applied. Only sources of flooding included in their model are accounted for.
- The results offer one possible view of changes to flood risk.

Case Study C 'UK windstorm'

Provided by AIR

Stage 1 Business decision

A UK primary insurer would like to assess the physical effects of climate change on its long-term public policy engagement strategy. The firm wants to know whether potential adaptation measures should be taken now in order to mitigate the likely increase in some risks and perils becoming either uninsurable or unaffordable. The firm would like to undertake a pilot study for UK windstorm and will extend the study to other perils in the future.

Stage 2 Materiality

The area of focus is the UK. UK windstorm is the material peril in this case as it has been selected for the case study. The firm has exposure in all parts of the UK which have experienced significant windstorm damage in the past.

Stage 3 Background research

The firm worked with the UK Met Office to complete a climate change study on UK windstorms. Details of the research are summarised below.

Baseline

The future states represented are RCP 4.5 and 8.5 which represent mid-range mitigation and high greenhouse gas emissions respectively. The research focused on the temperature scenario 3°C corresponding to RCP 8.5 (2070-2079). A historical time period of 1995-2004 was used as the baseline to calculate any changes in the future storm track.

Methodology

In order to assess the change in frequency of UK windstorms, storm track density statistics were calculated that show the mean storm track and the related uncertainty for the three projected temperature increases. The storm track density indicates the number of times per winter (December-February) that a windstorm passes through points on a grid.

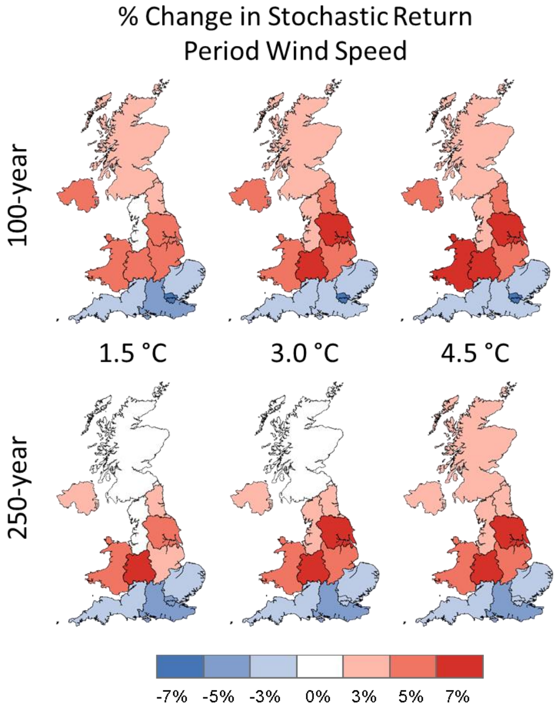
Following the approach in Zappa et al. (2013), the mean storm track density is estimated by averaging the mean of the multi-simulation CMIP5 model track densities. In other words, if multiple simulations were available within a CMIP5 model, then those track densities were first averaged for each temperature scenario, and then these CMIP5 model-average track densities were used to estimate the average storm track density over all CMIP5 models. This ensures that each CMIP5 model is equally weighted within the analysis irrespective of the number of model runs. Track densities are analysed on a 4°x4° grid covering the UK and surrounding areas. The storm tracks provide the position of the storm at 6-hourly intervals. It was this information that was used to create the storm track density plots.

To create the climate change conditioned catalogue, individual storm tracks were either removed or perturbed spatially in order to increase or decrease the local value of storm track density or intensity. This process was performed iteratively using varying degrees of perturbation. The final scenarios used in this analysis were those that resulted in the smallest root mean squared error (RMSE) when compared to the three temperature scenarios provided by the Met Office.

The Met Office's findings on track density change are as follows. 'Under a global temperature increase of 1.5°C, the number of storms over the UK generally decreases with the largest decrease in storm occurrence over the southwestern UK. Under a global temperature increase of 3.0°C and 4.5°C, the number of storms over the UK generally increases by up to 15% of the CMIP5 baseline. An exception to this is over southern UK where we see a decrease which gradually lessens with increasing temperature. In general, the activity over the UK increases between subsequent climate change scenarios.'

Corresponding changes in the climate conditioned catalogue on a return period wind speed basis are shown below.

Figure C1: Changes in return period wind speeds for three CMIP5 scenarios



The climate change conditioned catalogue (aka *future)* was then run over AIR's industry exposure database for the UK and losses compared between the *current* and *future* catalogues.

Limitations and uncertainty

The climate system is intrinsically non-linear. Small changes or errors in the modelling can result in large changes in the final results. This is especially true in this case, where losses can be quite sensitive to small changes in the magnitude and location of future wind speeds. The range of uncertainty seen in the CMIP5 ensembles with respect to both track density and storm intensity is large, with the 5-95% confidence intervals ranging between positive and negative values (see Figure C1). Additional analysis suggests at least some sensitivity to both the choice of reference period and individual CMIP5 model ensemble members.

There are many aspects of the changing risk not addressed in the methodologies described. It should also be noted that the analysis performed by the Met Office for this study looked at UK windstorms independent of their relative strengths, whereas by virtue of being a catastrophe model, the stochastic model used by AIR is intended to examine the strongest of these events.

Further limitations include the need to assess changes in storm clustering, global teleconnections (such as the NAO), construction practices, exposure growth, and many others to fully quantify future effects.

Stage 4 Assess tools

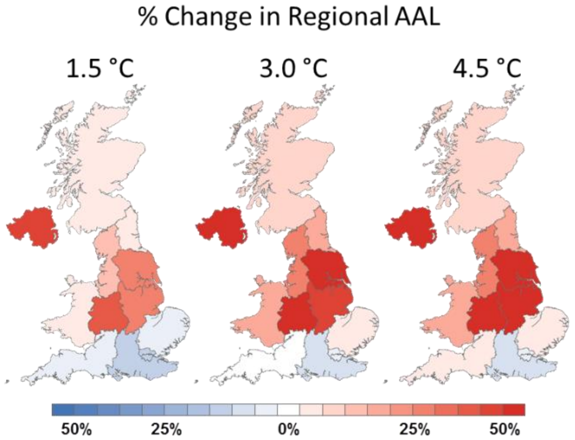
A catastrophe model is used for this case study. This is because a catastrophe model is available for UK windstorm that allows multiple factors such as track and intensity changes to be accounted for explicitly and to alter the entire catalogue. In this way, competing effects where some components/regions show different directions of change can be more readily quantified. Other quantification approaches such as scenarios looking at individual events may help give insight into specific conditions but cannot quantify changes across the exceedance probability curve/AAL and often not at the level of geographic granularity that can be done with climate change conditioned catalogues.

Stage 5 Calculate impact

The climate change conditioned catalogue was run over the firm’s portfolio and losses compared between the current and future catalogues. Results show an increase in UK windstorm losses in both AAL and 1-in-200 year return period as shown in Figure C2 below.

Figure C2: Percent changes in regional AAL relative to the stochastic baseline

	3.0°C
AAL	23%
1-in-100 yr Aggregate	27%
1-in-200 yr Aggregate	38%



Stage 6 Report findings

Results of the study show that the public policy engagement strategy would need to take account of the physical effects of climate change. Potential adaptation measures should be taken now to mitigate the increase in the UK windstorm risk in the long term. Nevertheless, given the long time horizon and size of the climate change impacts, it is likely that factors such as exposure changes, changes to building codes and so on could outweigh climate change risk. However, potential adaptation measures could be taken now to mitigate the increase in the UK windstorm risk in the long term. Impacts could be lower over a shorter time horizon.

Further study is needed to understand the likely increase in other risks and perils.

Case Study D ‘Flood pricing’

Provided by Ambiental (UK flat portfolio), Fathom (US), JBA (UK regional analysis)

Stage 1 Business decision

A direct insurer with an international portfolio seeks to understand the potential impact of physical climate change on risk selection and pricing to personal lines. Where government pools are involved, this includes ceding impact given current ceding rules. The Underwriting Committee wants to stress test its current pricing strategy for climate change and decides to undertake a sensitivity test for the 2040 horizon that aligns with the business plan climate-change stress-testing undertaken by the board in response to TCFD.

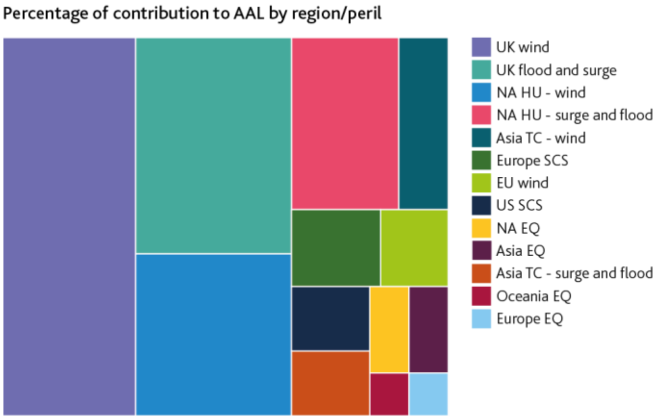
The Underwriting Committee has assigned the exercise of investigating impacts from physical climate change risk to the actuarial function as that is the team responsible for developing technical pricing.

Stage 2 Materiality

The materiality analysis involved, as a first stage, assessing the contribution of the different peril/territories to the personal lines portfolio using current climate assumptions (Figure D1 below). In considering the material perils, the background research team considered:

- IPCC perils that have been identified as having a clear impact under climate change conditions. This process excluded UK wind as the climate projections by 2040 did not provide a clear signal in terms of windstorm change of geographical focus, frequencies or intensities.
- It was decided to focus on perils that have high spatial resolution as the study scope includes risk selection. As such, the team decided to focus on flood as a first investigatory stage of the study.
- Material exposure for flood was deemed to be primarily in the UK, addressing combined flood risk (river, surface water and surge). For the US, it was recognised that tropical cyclone-induced inland flood and surge are major contributors to the risk and those need to be looked as part of a dedicated North Atlantic hurricane study. Instead, this effort focused on non-tropical cyclone induced flooding in the West Coast (California) where the portfolio has been growing significantly in the last two years and is projected to increase further.

Figure D1: Illustrative breakdown of overall portfolio by AAL that indicates potential materiality by peril/territory



Stage 3 Background research

Background research was split in two geographic regions: UK and California.

Baseline

The background research team defined the baseline as the current climate in 2018.

Methodology

UK Flood

The background research component of the exercise was first to undertake a literature research to understand the expected changes in inland and coastal flooding by 2040. The literature research identified that the UK Government climate data sources published in 2017 offer sufficient and reliable information on changes to future rainfall, river flow and sea level risk by 2040. UK Climate Projections (UKCP09), produced by the Met Office and supported by BEIS and Defra (Defra, 2009), provide climate information designed to help those needing to plan how they will adapt to a changing climate. The background research team felt that this piece of research presents the most up-to-date assessment of climate change over the 21st century (soon to be updated with UKCP18).

US (California) Flood

The background research team found that a range of potential changes in flood magnitude was inferred from modelled changes to extreme rainfall, outlined in the Climate Change Impacts in the United States: The Third National Climate Assessment report.[5] Future multiplier changes in heavy precipitation events are outlined for two different RCP scenarios for the 2090 time horizon and expert judgement was applied to scale that projection back to 2040.

Limitations and uncertainty

The UK Government Study acknowledges the range of future climate conditions but puts forward a most likely outcome. This is not a forecast and is still an uncertain outcome. Basing the analysis on a single climate scenario requires appropriate disclaimers and communication to its final recipients.

For both UK and California, the data retrieved by the background research are flood hazard maps. The underlying assumption is that the relationships between probabilistic hazard layers and impact/losses, defined under current climate studies can be used as a proxy for future damage.

Stage 4 Assess tools

The criteria for selecting an appropriate tool is that it should be compatible with the currently-used pricing tools and can be linked with the background research findings. As a result, flood hazard maps were chosen as the preferred tool.

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[5] McKibben, B. Climate change impacts in the United States: the third national climate assessment. (New York Review 1755 Broadway, 5th Floor, New York, NY 10019 USA, 2014).

Stage 5 Calculate impact

UK Flood

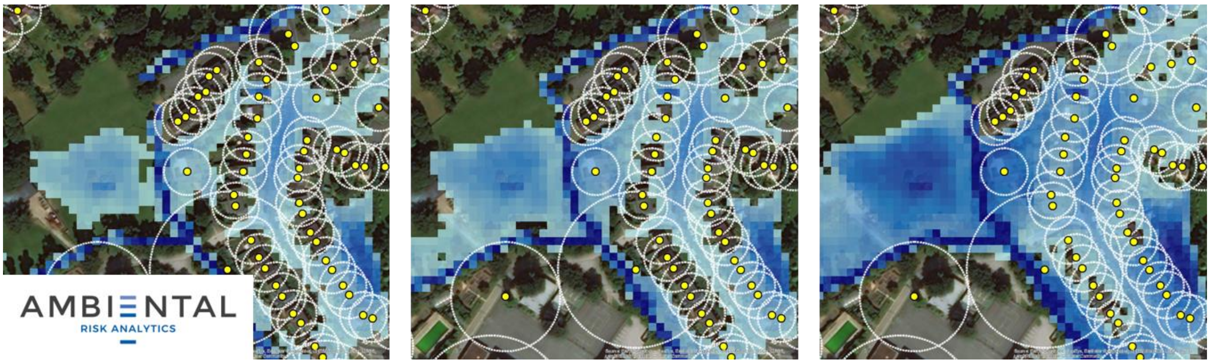
Two sets of analyses were undertaken to quantify the impact of physical climate change to pricing.

The first analysis looked at a sample of 100,000 policies across the portfolio and attempted to quantify the relative change to AAL given a baseline of the current AAL estimate. Using an external provider's flood maps, three different climatic scenarios were investigated as depicted in the UKCP09 publication (Defra, 2009). The analysis used hazard maps with conditioned hydrologic inputs accordingly to reflect UKCP09 assumptions. Maximum flood depths from all sources (fluvial, pluvial and tidal) and climate change scenarios (2050s Low, Medium and High emissions) were extracted from the flood hazard maps to all properties in the portfolio using a buffer representing the footprint of each building. The results for these sample 100,000 properties indicate that for a UKCP09 horizon that is closer to 2040, there is a potentially significant pricing uplift in AAL (Table D1).

Table D1: Maximum flood depths for the 2050s Low, Medium and High emissions.

Scenario	Uplift (%)
2050s Low	8%
2050s Med	32%
2050s High	88%

Figure D2: Image showing the increase in pluvial flooding to the sample portfolio for the 2050s Low (left image), Medium (middle image) and High (right image) emissions scenarios at a focussed location near Haywards Heath, West Sussex.



The second analysis looked into the ceding strategy for Flood Re. The analysis looked at two regions of the UK by developing a flat portfolio: a hypothetical portfolio containing the same type of risk (same structure type, total sums insured), for every full postcode in the two areas of interest. The flat portfolio was sent to the external catastrophe model provider who processed it using two catastrophe models: one for present-day and another adjusted for climate change. Calculating the potential change between future and current climate conditions was deemed to be a more efficient method than re-mapping the entirety of the two sample areas for all three flood types. As such, climate-change conditioned flood maps based on this potential change, along with a comprehensive breakdown of results (in a csv file), were provided.

The two regions highlight how areas may be affected differently by climate change. In Warrington (Figure D3), the risk to flood is predominantly projected to increase, whereas in Cambridge (Figure D4) there is expected to be a reduction in flood risk or, in some locations, no change at all.

The change in relationship between future and current climate conditions informed the actuarial technical pricing model. Using the current flood premiums for the active policies in the current portfolio, a cost inflation (or deflation) was applied based on the catastrophe modelling results. This permitted the pricing team to understand whether the climate change-impacted technical flood premium would go beyond the threshold above which ceding to Flood Re would be likely.

Figure D3: Map showing the projected relative change in flood risk across Warrington.

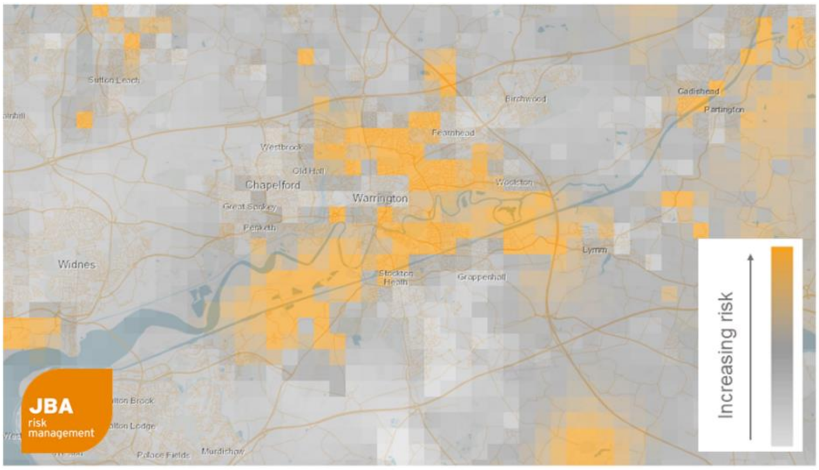
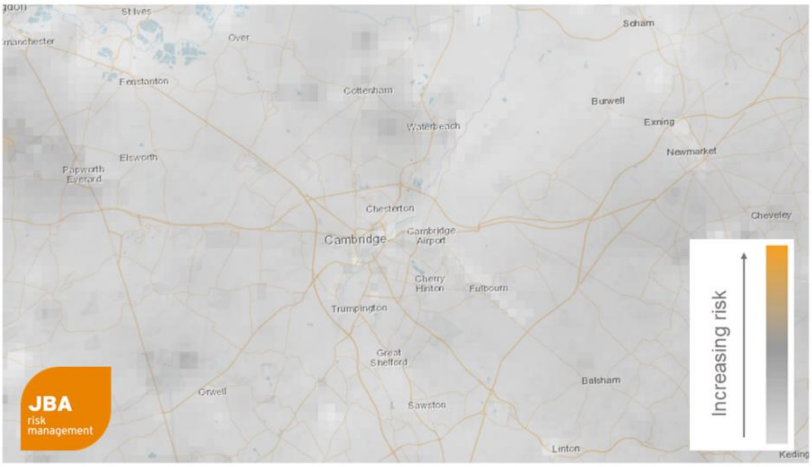


Figure D4: Map showing the projected relative change in flood risk across Cambridge.



Given the caveats outlined in the section below, the insurer could expect to experience less than 5% change in the proportions of ceded properties across the two combined areas, broken down regionally with 31% increase in Warrington but a 6% reduction in Cambridge (Table D2).

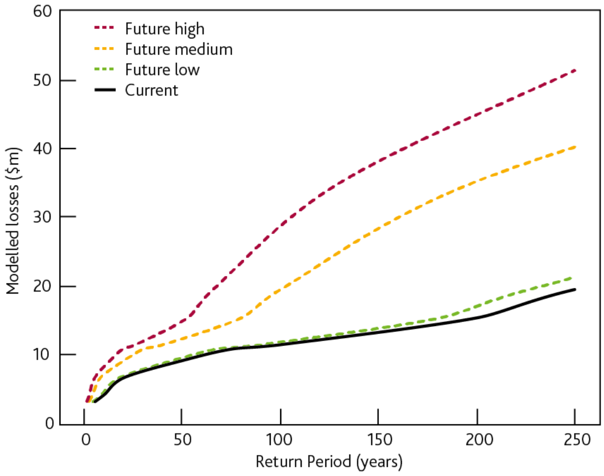
Table D2: Regional difference in insurer's levels of ceded properties.

Area	% Ceded 2018	% Ceded 2040	Relative change
Warrington	4.07%	5.34%	31%
Cambridge	0.63%	0.59%	-6%

US (California) Flood

A subset of the active California portfolio was used to assess the potential impact of climate change on pricing. Hazard maps that have been adjusted in line with the research results were used to assess the potential impact to losses. These hazard maps provided water depths at each property location and the same vulnerability curve was used as for current conditions to provide a comparison. Figure D5 below illustrates the potential impact to losses for the sample portfolio in the tail of the distribution.

Figure D5: AEP for the sample portfolio comparing modelled losses across different climate scenarios



Stage 6 Report findings

The results offer an indication of the potential impact to pricing for the different case studies: (i) UK-wide sample portfolio; (ii) UK Flood Re ceding strategy for two regions; and (iii) California sample portfolio looking at the overall change in flood risk. In all cases, the potential for climate change to change pricing and/or risk selection and ceding to national pools was found to be notable.

The caveats to this analysis communicated to the Property Underwriting Committee were:

- These results use sample portfolios/regions and only provide an indication of the potential impact of climate change. The analysis is informative and not conclusive.
- The analysis looks primarily at technical premium (AAL) based using flood hazard maps and does not consider other components to pricing and risk selection. All other pricing/risk selection/Flood Re ceding decisions are outside this analysis.
- The view is limited by the modelling methodology adopted by the flood map external provider. Only sources of flooding included in their model are taken into account.
- This view does not reflect the insurer’s future ceding strategy. Under a revised strategy, this view may underestimate or overestimate ceding levels.
- The results offer one possible view of changes to flood risk.

The Underwriting Committee recognises that physical climate change risk has the potential to change underwriting limits in different directions allowing the firm to shape the portfolio growth plan capitalising on regional and local opportunities. As such, the Committee requested that a subsequent analysis is undertaken to look at flood risk using the full portfolio rather than a subset.

Case Study E ‘Japan typhoon and flood’

Provided by AIR

Stage 1 Business decision

A Japan primary mutual provides typhoon and flood coverage in the prefectures of Osaka, Kyoto, Shiga, Nara, and Mie. The Risk Management Committee would like to assess the potential adequacy of its current risk appetite for typhoon and flood by 2040. The Committee issued an internal study to assess whether the ORSA scenarios driving the risk appetite for typhoon and flood will materially differ in the future.

Stage 2 Materiality

The mutual covers policy holders for Osaka, Kyoto, Shiga, Nara, and Mie prefectures. These areas experienced a number of damaging typhoon and flood events historically, such as Typhoon Vera (1959). The materiality analysis identified that the surge component of typhoon is less relevant as the mutual has underwriting rules that prohibit acceptance of risks affected by surge risk. As such material risks are wind and inland flood, which match the ORSA scenarios.

Stage 3 Background research

Baseline

Typhoon Vera was used as the baseline to calculate physical climate change impacts to the wind component of typhoon by 2019 and the flood component of typhoon by 2040.

Methodology

Wind component of typhoon

Researchers at Kyoto University found that historical typhoons, namely Vera (1959), Mireille (1991) and Songda (2004), when simulated under climate change conditions reach greater intensity at maturity (Mori and Takemi, 2016; Takemi et al., 2016b; Ito et al., 2016). This finding is consistent with other modelling studies which expect tropical cyclone intensities to increase by the end of this century (IPCC, 2012).

Typhoon Vera's (1959) wind and surge impacts led to over 5,000 fatalities and was the costliest weather-related disaster in Japan's history (AIR, 2017). The eye of Vera made landfall with a central pressure (CP) of 930 mb at co-ordinates (135.5°, 35.5°). While the local levee systems have been significantly upgraded since 1959, a similar but more extreme version of Vera occurring this century could result in a significant loss to the insurance industry.

The CMIP5[6] atmosphere-ocean models provided Takemi et al. (2016a) with the SST, surface air temperature (SAT) and temperature lapse rate (TLR) in the Northwest Pacific basin for the year 2100 under an RCP 8.5 scenario. Four Pseudo-Global Warming (PGW) climates were derived from the ensemble mean SST (PGW0) and the three clustered SST patterns (PGW1-3) of Mizuta et al. (2014).

Using a Global Climate Model (GCM) with a coupled nest, Takemi et al. (2016a) simulated Typhoon Vera under the original 1959 climate and the four PGW climates. Their model is hereon referred to as the PGW model. In a 1959 climate, the PGW model produced versions of the original Vera that had a landfall CP of 926.2-932.7 mb and longitude of 135.1-135.7°. These versions acted as a control in their study to understand the effect of climate change. In the four PGW climates, the PGW model produced versions of a future Vera that had a landfall CP of 912.7-929.5 mb and longitude of 133.8-134.9°. In summary, if Typhoon Vera were to occur again at the end of this century, it would likely make landfall to the west of the original Vera with a lower landfall CP.

The landfall CP and longitude ranges provide criteria to select similar events from AIR's stochastic catalogue. The stochastic events catalogue of AIR's typhoon model for Japan is a 10k year catalogue based on the 1951-2006 historical record. The control ensemble had to satisfy the following criteria:

- landfall CP of 926.2 to 932.7 mb; and
- landfall longitude of 135.1 to 135.7°.

The PGW ensemble had to satisfy:

- landfall CP of 912.7 to 929.5 mb; and
- landfall longitude of 133.8 to 134.9°.

Both ensembles had to satisfy two additional criteria:

- the first landfall is on the islands of Shikoku or Honshu; and
- the landfall angle, measured from North, is positive.

Landfall CP and longitude are chosen as criteria because they are key determinants of typhoon damage. The PGW model can adequately reproduce the landfall CP and longitude of the original Typhoon Vera (Mori and Takemi, 2016), so extrapolation under PGW climates is valid. Four stochastic events were found for the control ensemble, and five were found for the PGW ensemble. Figure E1 shows the landfall CP and location of the nine stochastic events and Vera (1959). The control events are numbered C1-C4 from west to east. Their CP range is 927.0-929.8 mb with a median of 928.3 mb. The PGW events are number P1-P5. Their CP range is 919.5-929.1 mb with a median of 925.8 mb.

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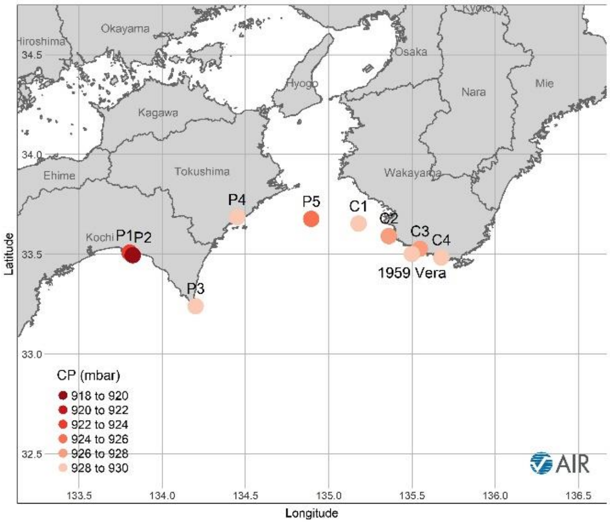
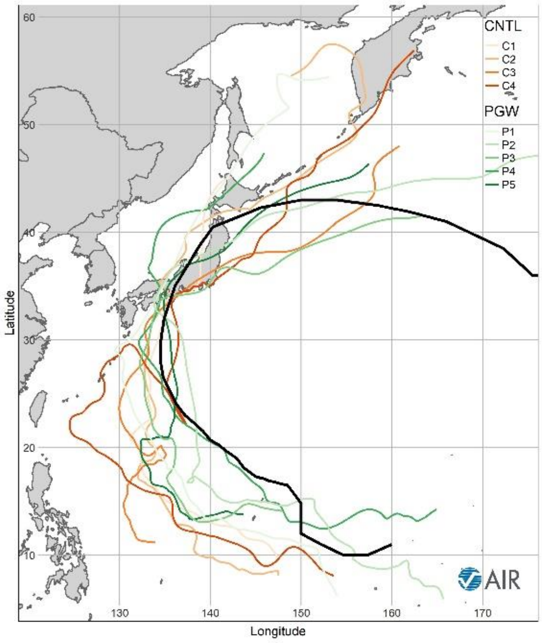
[6] Coupled Model Intercomparison Project Phase 5.

Figure E1: Map showing the location and central pressure (CP) of the four control events (C1-C4) that represent Typhoon Vera under September 1959 conditions and five PGW events (P1-P5) which represent Vera under pseudo-global warming conditions in the year 2100. The original Typhoon Vera (1959) is also shown.



All control events make landfall on Honshu but only one PGW event (P5) does so. Events P1-P4 make landfall on Shikoku. Figure E2 shows the tracks of the nine stochastic events plus the original track of Vera (1959). The diversity of the track shapes is much greater than that simulated by the PGW model because the tracks were selected on landfall characteristics only.

Figure E2: Map showing the tracks of the four control (oranges) and five PGW (greens) stochastic events and the original track of Typhoon Vera in 1959 (black).

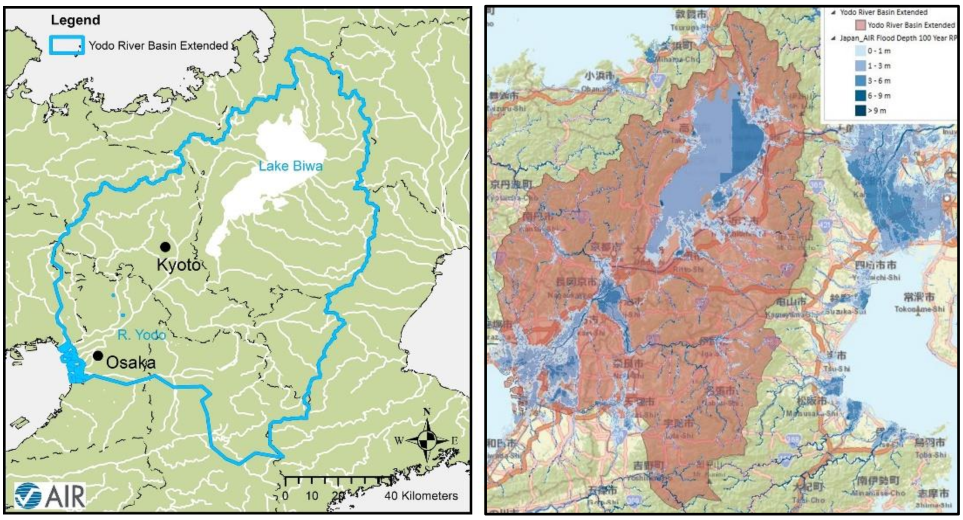


Flood

The Yodo river basin is the seventh largest basin in Japan. The Yodo river exits into Osaka Bay at Osaka, a major port city, which has the second largest metropolitan area in Japan, after Tokyo. The cities of Kyoto and Otsu also reside in the basin which is home to 9% of Japan's population (Ibbitt et al., 2002). The Yodo basin experienced exceptional flooding in 1959 due to Typhoon Vera and it has been the focus of several climate change studies to date (Takemi et al, 2016).

Figure E3 (left) shows an extended Yodo basin, created by extending, by-hand in ArcGIS (ESRI, 2014), a freely-available shapefile of the Yodo basin (CEO Water Mandate, 2016). Figure E3 (right) shows the 1-in-100 year flood hazard map for the Yodo basin in AIR's Touchstone platform (AIR, 2017). AIR's flood hazard maps for Japan show the extent and depth of on-plain flooding due to typhoon and non-typhoon precipitation for a given return period. Figure E3 (right) shows the flooding that would occur if every affected river in the Yodo basin simultaneously carried the 1-in-100 year flow. In practice, this scenario would never occur, but the map can be used to accumulate exposure at risk of flooding. The 1-in-100 year return period is the target safety level in Japan.

Figure E3: The extended Yodo River basin (left) and AIR's 1-in-100 year flood hazard map (right).



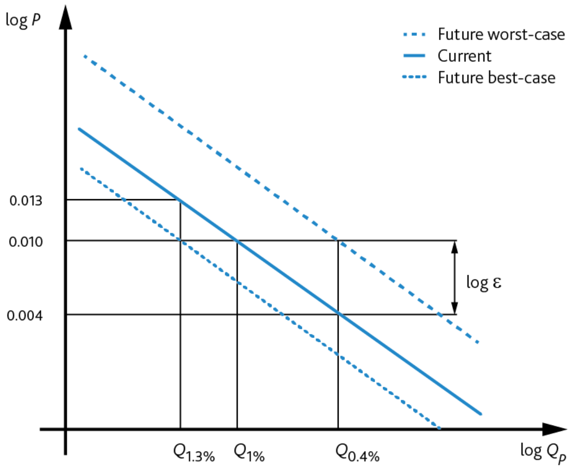
The SRES A1B scenario, proposed by the IPCC, envisages continued rapid economic growth with emissions peaking in the middle of the 21st Century and reaching 850 ppm of CO2-equivalent by the year 2100 (IPCC, 2008). By running climate models under the A1B scenario, Japan's National Institute for Land and Infrastructure Management (NILIM) calculated the median change in the likelihood of the 1-in-100 year river flow (as-of 2004) by the years 2040 and 2100 (NILIM, 2013). This ratio, denoted by ε, is used here to develop a tool for quantifying the impact of climate change on Japan flood risk.

The current 1-in-100 year flow in the NILIM study is for the year 2004 since it is based on 1979-2003 precipitation data. Using 2015-2039 simulated precipitation data, the NILIM study found that the likelihood of exceeding the current 1-in-100 year flow in the Yodo basin in the year 2040 is expected to be 0.7-3.0 times as large as that in the year 2004 (NILIM, 2013). This means ε varies between 0.7 and 3.0.

AIR’s 1-in-100 year flood hazard map is assumed to represent the hazard in the year 2015 since it is based on 1979-2014 precipitation data. To apply NILIM’s findings to AIR’s map, ε is assumed to change linearly between the years 2004 and 2040. Interpolating to the years 2015-2040 to be consistent with AIR’s hazard maps gives the future likelihood of exceeding the current 1-in-100 year flow to be 0.8-2.4 times than that of today, a range smaller than the 2040 to 2004 comparison.

To determine the 1-in-100 year flood map of 2040, several simplifying assumptions have been made. The exceedance probability (P) and river flow (QP) relationship is assumed to follow a power law such that the P-QP curve is linear on a log-log plot and this flood frequency relationship holds for the entire basin (as opposed to individual catchments). An alternative assumption, not used here, is that P-QP is a log-linear relationship. The (Q1%, 1%) point on the curve can be translated by ε where $0.8 \leq \varepsilon \leq 2.4$ to obtain the future (Q1%, 1%) point. In the absence of additional information, it is assumed that the main body (50-500 year) of the current curve can be translated by the same ε values to obtain the future curves. Figure E4 illustrates how the current and future P-QP relationships could change. To a first-order approximation, the 1-in-100 year flood map of 2040 is at best today’s 80-year and at worst today’s 240-year. Readily available are the 1-in-50 year and 1-in-250 year flood hazard maps, which act as proxies to represent the 1-in-100 year flood risk in 2040.

Figure E4: Schematic graph showing how the current and future relationships between exceedance probability (P) and river flow (Q_P) may change by the ratio ε.



Footprints for the 50, 100 and 1-in-250 year return periods are made by intersecting the extended Yodo basin with AIR’s corresponding flood hazard maps. Damage ratios can be input for each flood depth bin. The gross accumulated amount in each flood footprint can be calculated in Touchstone’s Geospatial Module by accumulating the exposure in each flood depth bin, scaling by the corresponding damage ratios and applying policy terms.

The accumulated amount in the 50 and 1-in-250 year footprints provide estimates for the best and worst-case 1-in-100 year gross accumulated amount in the year 2040.

Limitations and uncertainty

Wind component of typhoon

The selected stochastic events do not reflect the full range of landfall CPs simulated by the PGW model. None of the events have a landfall CP of less than 919.5 mb. Future studies should consider selecting from larger catalogues such as 100,000 years in length.

Events with more eastward landfall angles will have their fastest winds farther offshore. Future studies may wish to put a stricter constraint on the landfall angle criterion. An alternative to selecting by landfall characteristics would be to select by wind speed footprints. Takemi et al.(2016a) did not present these, so it was not appropriate for the present study.

Flood

The relationship between hazard maps made under current climate conditions and future maps made under a changed climate is highly uncertain. Climate models provide a best guess of what the future climate might be. To apply the findings of climate models to this case study required several simplifying assumptions. Future studies should test the sensitivity of these results to the assumptions made.

Stage 4 Assess tools

Wind component of typhoon

The method 'stochastic IDs' was chosen given the resources available (the IDs), published information and relatively low level of effort.

Flood

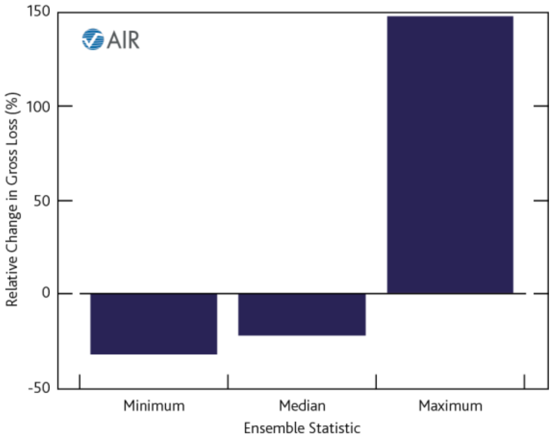
The method of developing footprints from hazard maps was chosen given the resources available (flood hazard maps), access to relevant research, and the relatively low amount of effort required.

Stage 5 Calculate impact

Wind component of typhoon

Figure E5 shows the relative change in the minimum, median and maximum wind-only gross losses between the two ensembles. The median wind-only gross loss of the PGW ensemble is 21% lower than that of the control ensemble. This suggests that despite having a lower landfall CP, future versions of Vera are expected to cause lower wind-only losses to the portfolio, one of the contributing factors being the sensitivity of losses to location of exposure relative to the event. However the maximum gross loss increases by almost 147% suggesting that a future version of Vera could significantly increase losses. Smaller losses could be due to storms making landfall farther to the west and south, where there is less exposure, lower vulnerability and other factors.

Figure E5: Relative change in minimum, median and maximum gross loss from the control ensemble to the PGW ensemble.



Flood

In this study, only the hazard was changed. Vulnerability and financial modules were not altered.

By the year 2040, the best-case scenario is that the total gross accumulated loss from a 1-in-100 year flow in the Yodo river basin is 12% lower than the amount from the current 1-in-100 year flow. In the worst-case it is 17% higher. Table E1 shows a summary of the changes in number of risks and gross loss in the footprints.

Table E1: Best and worst-case changes in total gross loss due to a 1-in-100 year flow in the Yodo River basin in the year 2040, relative to the current values.

	Change in gross loss (%)
Best-case 2040	-12%
Worst-case 2040	17%

Combined wind and flood impact

One modification made when considering the results together was to adjust the time horizon difference between these two scenarios. As the business decision in the case study focuses on 2040, the result for typhoon was scaled down from 2100 to 2040 by assuming the loss increases linearly over time.

Considering the wind and inland flood scenario loss changes together showed a decrease in future scenario loss for this scenario under climate change.

Stage 6 Report findings

Given that the wind and inland flood analyses both show a decreased loss in the future scenario, the Risk Management Committee could review the risk appetite for wind and flood by 2040, and consider writing additional risks. However, uncertainty in the analysis needs to be considered as the results only reflect a limited number of realisations of the whole spectrum of possible outcomes.

Challenges faced when merging the two separate analyses into Case Study E

Challenge	In this case study, one challenge of merging these two perils in a single scenario is the different time horizon used in the background research. Conclusions regarding wind and flood were based on research studying the climate change impact for different time horizons with typhoon by 2100 and flood by 2040.
Solution	This case study used a scenario which merged two perils, Japan typhoon and Japan flood, and estimated the overall impact of climate change on wind and flood PML. The merging methodology is relatively simple in this case because the two events included in the scenario were developed creating extreme 'footprints' for these two perils and the analysis results showed how much the scenario loss from combining these two perils would change. One modification we made when considering the results together was to adjust the time horizon difference between these two perils. As the business decision in the case study focuses on 2040, we scaled the result for typhoon down from 2100 to 2040 by assuming the loss increases in a linear fashion over time.
Residual limitations	In this case study, climate change impact was assessed using 'footprints'. By definition, the two approaches within this tool, footprints and stochastic IDs, both create possible extreme scenarios. One limitation of this tool is that the results only reflect a limited number of realisations of the whole uncertainty spectrum and do not show changes in AAL and exceedance probability curve losses. As such, uncertainties, eg in the interpolation, the robustness of the scenarios, and the validity of adding wind and flood losses from different methods in the analysis need to be clearly understood when interpreting the results.

Case Study F 'Global book of business, including North Atlantic hurricane'

Provided by: NA Hurricane by KatRisk, Junaid Seria and Christopher Melhauser of SCOR; Germany Hail analysis by Guy Carpenter; and California Wildfire by the PRA

Stage 1 Business decision

The Board Risk Committee of a global reinsurer, headed by the Group CRO, seeks to investigate the impact of climate change on extreme weather events that could have a material impact on decision-making over two time horizons: 2030 and 2100.

Three questions are posed, which the Catastrophe Risk Modelling team is asked to help answer:

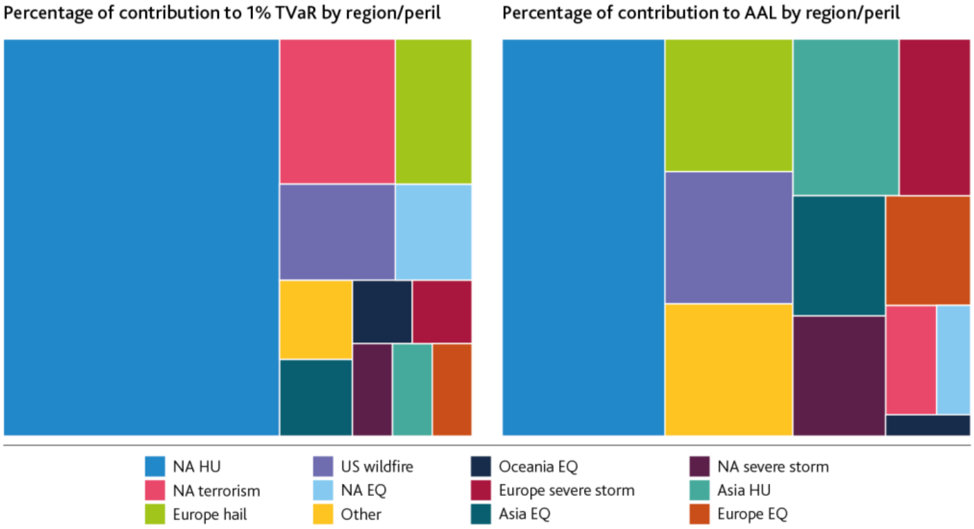
(i) Which region-perils and LoBs are most likely to be affected by climate change and where are their impacts likely to be most material?
(ii) Is there enough scientific evidence of the link between climate change and catastrophe perils to influence how catastrophe risk is priced and/or set catastrophe capacities?
(iii) Which risk management decisions could benefit from a climate change risk assessment?

Stage 2 Materiality

Hydro-meteorological perils contribute 75% of the current portfolio 1-in-100 year TVaR. By far the largest single contributor is US hurricane. This is followed by European hail and US wildfire, using as metrics the 1-in-100 year TVaR and AAL (refer to Figure F1). In terms of assessing materiality in the context of the framework (refer to Figure 2 in Section 2.2.2), the selection of hydro-meteorological perils that are material are based on the y axis (the peril/territory exposure aggregates that are most material to the business decision).

The materiality analysis further isolated exposure hotspots that would drive the three material hydro-meteorological perils: continental US exposure for US hurricane (US HU), California exposure for US wildfire (CA WF), and German exposure for European hail (DE HL).

Figure F1: Illustrative breakdown of overall portfolio by 1% TVaR (left) and AAL (right) that indicates potential materiality by peril/territory



Stage 3 Background research

Baseline

For US hurricane, the storm-surge baseline was set to 2015 sea-level; for the flood analysis, the precipitation data is catchment dependent, with all data after 1979 used for calibration and validation, and for wind, 1900-2012 HURDAT2 data was used to define rates. For DE hail, the baseline period was set as 1971-2000. For US wildfire the year 2016 was set as a baseline. All research was based on IPCC reports.

Methodology

US hurricane

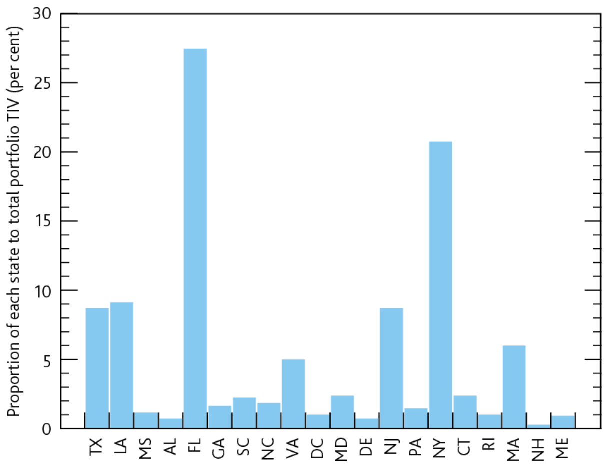
The background research team comprised catastrophe modellers and scientists from the firm who undertook a detailed review of the latest academic literature on the impact of climate change for the three territory/perils over various time horizons and IPCC climate scenarios. Over 30 research papers were reviewed with a focus on research that provided insight into how key hazard parameters could be adjusted due to climate change. Academic authors were contacted to better understand how to translate the hazard impacts into loss impacts. Key findings are summarised in Table F1.

Table F1: Summary of technical findings from the firm’s scientific literature review on the potential impacts of climate change on North Atlantic hurricanes/tropical cyclones (NATC).

Possible future hurricane enhancements	Estimated impact for NA basin by late 21st century relative to current climate
Surge severity due to projected sea level rises and increases in hurricane intensity	Combined loss impact of 11%-20% increase in AAL (based in RCP8.5) – in this case projection by 2030
Rainfall rates	+18% increase within 100km of storm centre for NATC (RCP4.5)
Hurricane intensity	+4.5% increase in maximum wind speeds of hurricane strength storms (RCP4.5)
Frequency of Cat 4 & Cat 5 hurricanes	+42% Cat 4-5hurricanes (not statistically significant) (RCP4.5)
Frequency of TCs	-9.4% decrease for TC (not statistically significant) (RCP4.5)
Storm size	+11% increase in median storm size (RCP4.5)
Rapid intensification	60 knot/24hrs: change in RP from 1:100 to 1:20-1:30 (using current TC frequency assumptions to isolate RI changes) (RCP8.5)
TC Genesis, LMI latitude and landfall changes Observed changes*/GCM projection**	Eastward migration of TC genesis (increase frequency in tropical East NA, reduced frequency in tropical West NA)** Equatorward migration of TC genesis (-110km/decade) (*not statistically significant*)* ~25% TC landfall rate flat over time* LMI latitude: essentially flat (95% 2-side CI): +7km/decade (98km) for IBTrACs, -12km/decade (126km) for ADT-HURSAT*

A hypothetical coastal portfolio is used for the US Hurricane climate change analysis which is comprised of 900,000 locations along the US east and gulf coasts (Figure F2) with a total insured value (TIV) of USD 650 billion. The portfolio is 60% building, 30% contents, and 10% Business Interruption. All primary characteristics are assumed unknown.

Figure F2 – TIV breakdown by state of the hypothetical coastal portfolio



To isolate the impact of climate change from the impact of exposure changes, the exposure is not trended with present day values, wind and flood insurance conditions, and flood defences.

Germany hail

Background research was conducted by the reinsurer into the scientific literature, first consulting major governmental reports such as the IPCC, then looking at review papers and then at individual studies. Overall, there is low confidence that a localised severe weather phenomena such as hail and thunderstorms are well observed because of historical events occurring in rural areas are often missed due to the lack of monitoring systems and reduced population density (IPCC, 2013). As an alternative, proxies such wind shear and the Convective Available Potential Energy (CAPE) from climate reanalysis simulations (and observations where available) are often used to investigate spatiotemporal changes in hail occurrence over the last few decades. In addition, observations of lightning flashes and radar reflectivity are also a good proxy for convective activity, and available datasets can span several decades with a high level of spatial homogeneity.

Two studies were found of most relevant to assess changes in the annual hail frequency. Because robust trends are often difficult to estimate for near-term time horizons, long-term trends can be used. Kapsch et al. (2012) uses multiple 15-year periods at different instances during the 21st century relative to 1986-2000. Mohr et al. (2015) investigates changes over the 2021-2050 future period relative to 1971-2000. The background research team estimated long-term trends by computing differences between averages of future periods and the reference period, and normalised the change to reflect the number of years elapsed between the two periods.

California wildfire

Wildfires predominantly affect the west, north west and south east of the continental US. Focusing on the west, research team used historical records since the 1970s to investigate any changes in the frequency and intensity of wildfires in California. The results show that the average length of a wildfire season in the early 1970s was 5 months, and that this has now increased to over 7 months today. However, the background research team found that the frequency of wildfires has not changed significantly over the past four decades. What seems to have incrementally changed is the intensity and the acres burned during these fires.

Research from IPCC shows that under a high emissions scenario, the mean area burned by the end of the century could increase by 63% compared to 1976-2005. The maximum area burned state-wide could increase by 178% and extreme wildfires (> 25,000 acres) could become 50% more frequent. Not all areas are expected to be affected in the same way. For example, the area burned in the Pacific North West Forest is expected to increase at a rate twice that of the Rocky Mounty Forest, which in turn is expected to increase at a rate twice that of Desert Southwest ecoregions. The background research team undertook two analyses for the San Bernardino and Sierra Foothills areas on wildfire risk. Using the literature review findings, for the Sierra Foothills area, the average area burned annually was projected to be doubled by mid-century, under a business as usual greenhouse gas emission scenario, and then double again by the end of the century. In San Bernardino area, the climate models used in this analysis show a minor impact on the average annual acres burned in this area.

As a result of the background research, to assess the physical climate change impacts on the study area, it was decided to expand the wildfire footprints by on average 60% in the northern area, as suggested by the Sierra Foothills study, and by 1% in the southern area, as suggested by the San Bernardino study. This range reflects the literature review findings that the impact of physical climate change to wildfire risk is highly dependent on a range of factors and hence

Limitations and uncertainty

US hurricane

Several papers agreed that given the high degree of inter-annual and decadal variability observed, it is difficult to detect a statistically significant signal that can be attributed to human-induced climate change. It is unclear how each of the enhancements listed in Table F1 would interact with each other and whether the relative contribution of these enhancements could change and/or interact over different time horizons.

Given the low climate change signal-to-noise ratio for North Atlantic tropical cyclones and uncertainty as to the interaction of these hazard parameters the background research team felt it did not have enough confidence in climate model projections to adjust current pricing (AAL) of US hurricane risk or change the way to segment region-perils for accumulation management. However, the team was encouraged to be proactive and, concluded that a quantitative approach was possible based on current modelling tools available and the level of scientific understanding.

The team considered the guidance of the Task Force for Climate Related Financial Disclosures (TCFD) and proposed a series of sensitivity tests to illustrate the impacts of climate change. As an example, for the future climate storm severity scenario, the team would independently calculate the change in storm surge losses (at mean and PML) due to projected increases in sea levels on the US East Coast, projected increases in hurricane wind speeds, and projected increases in precipitation intensity.

Germany hail

The primary limitation of trying to quantify the impact of climate change on hailstorms is that the current generation of climate models are too coarse for simulating localised convective storms. As noted above, this means that scientists must use proxies such as CAPE and wind shear from the models in order to estimate future hailstorm activity. The consequence of this is that there is often a wide spread in future projections of convective activity from different models (ie the uncertainty is large). In addition, the direction of change is not always the same, with some models predicting increases in future activity, and others predicting decreases (Martius et al. 2018).

The impact of climate change on hailstorms is difficult to assess given that the majority of hail generation factors will be affected by climate change but the direction of change is not always the same (Martius et al. 2018). Rising temperatures and increasing evaporation will most likely promote increases in CAPE, helping hailstones to form. However, projected decreases in wind shear may reduce their likelihood (Brooks, 2013). Aerosols are not greenhouse gases but they often have an anthropogenic source and their use and impact may increase in the future. The influence of these particles is highly uncertain with studies reporting conflicting results (see for example, Noppel et al. 2010, Khain et al. 2011, LLotoviz and Khain, 2016).

Future climate projections are usually conducted using global and regional climate models and are run at relatively coarse resolution for long periods. This means that, as in the observational record, hail events cannot be directly represented in these models and projections rely on proxies. Model-based studies for central Europe show some agreement that hailstorm frequency will increase in the future (EEA, 2017). Uncertainties however are large, which are reflected in large differences across climate models.

California wildfire

The findings of the impact of climate change on Californian wildfires are possible projections of what future scenarios might look like (Perry, 2013). However, the results are highly uncertain and different studies show a variety of results (Allianz, 2015).

With regard to historical research, there are few sources that track the number of wildfires and acres burned over the years. So it is necessary to rely on a single NIFC doing so (NIFC, 2018).

There seems to be a consensus on the causes underlying changes in wildfire trends (SwissRe, 2018) and therefore these views are considered appropriate to include in background research. However, the findings are based on analyses carried out by different individuals or organisations (including

UC Regents/Berkeley, 2018; Westerling et al., 2006) and as such different views on these may arise (State of California, 2018).

Stage 4 Assess tools

US hurricane

The background research team opted for a quantitative probabilistic approach. While more complex than other available approaches, the depth of scientific research available and sophistication of commercial US hurricane models allows for a more sophisticated assessment. As argued earlier, given the high degree of uncertainty in hazard projections, sensitivity/scenario testing was chosen rather than attempting to produce a climate change loss forecast.

Hurricane cat models are built using historical weather and climate data and are therefore well-suited for testing the sensitivity of insurance losses to variations in climate parameters – more so than deterministic footprint analyses, use of hazard maps or qualitative expert assessments.

The firm partnered with KatRisk, a catastrophe modelling vendor to perform the sensitivity analyses. KatRisk was chosen because its North America model includes tropical cyclone (TC) wind, storm surge, and inland flooding from TC and non-TC (frontal, convective) sources in a common event set. Further, it has functionality that allows users to sensitivity test the loss impact of future sea-levels, alter flood hazard intensities, and customise damage functions.

Several meetings were held between the background research team and KatRisk to agree the scenario design based on the background research team's literature review.

Germany hail

The firm's current hail pricing is based on actuarial techniques with the expectation that the reinsurance program will cover extreme events. As such, the firm does not have access to deterministic or probabilistic catastrophe models for hail risk and will need to rely on expert judgement. The firm has an expert judgement framework already in place that it uses to assess risks for which data does not exist; for example, in the operational risk component of the internal model.

As the firm has prioritised the focus of its specialist scientific staff on US HU, an actuary performed the background research exercise, using experience pricing for weather risks. The expert judgements to be used will consist of the numerical projections taken from the appropriate scientific literature.

California wildfire

The firm used bespoke footprints to represent the area burned by fires in the current climate scenario and in the future scenario. Footprints were considered appropriate for this scenario since information on the area burned historically by fires was readily available on different websites and it was possible to emulate these areas by drawing footprints of the fires in the selected scenario on a map. The method also lent itself well to creating future scenarios as it was possible to expand the existing footprints by a certain percentage to represent the increase in acres burnt by future wildfires, as suggested by research.

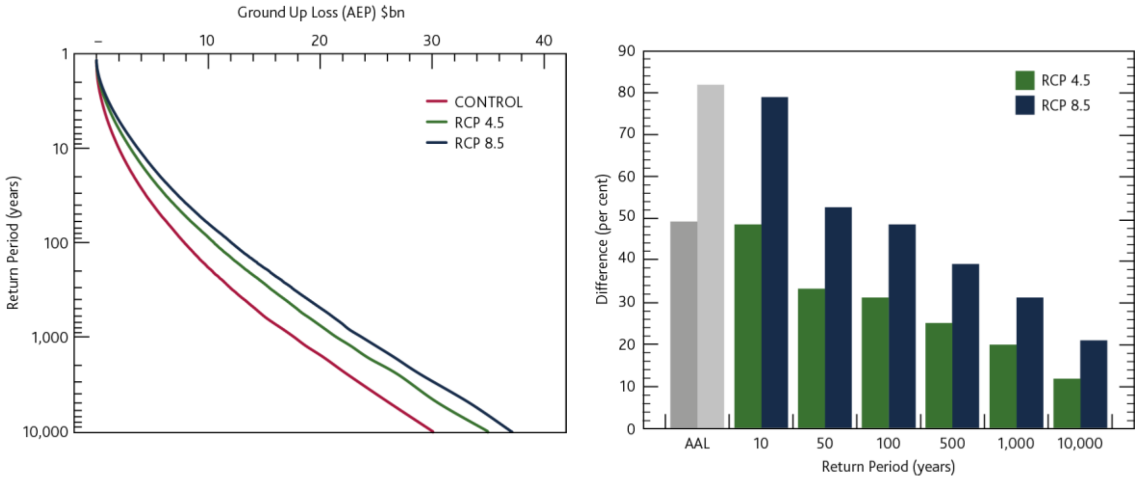
Stage 5 Calculate impact

US hurricane

Four tests were undertaken to illustrate the relative sensitivity of independently altering various hazard or vulnerability parameters based on RCP4.5 and RCP8.5 (storm surge only) IPCC scenarios and the impact on insurance losses to these future changes in hurricane risk. We focus on the statistically significant climate signals at 2100 for storm surge, tropical cyclone induced flooding, and wind speed.

Test 1 – Sea Level Rise: This test considered an increase in storm surge risk due to sea level rise (SLR). Landfall frequency and wind intensities were unchanged. The SLR by 2100 for IPCC RCP4.5 (0.4m SLR) and RCP 8.5 (0.6SLR) scenarios were considered with the base sea level increased by the projected average change along the US east coast; regional differences were not considered. The projected changes were added to the base surge heights, changing the storm surge height, but the storm surge extent remains unchanged.

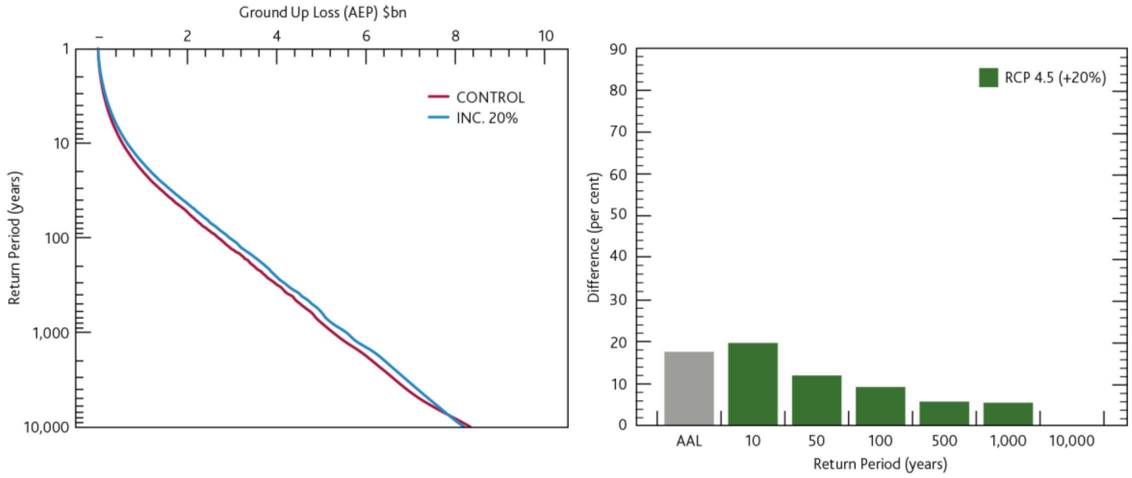
Figure F3: (Left) The OEP AEP impact for increasing losses considering present (CONTROL; red) and increases in sea-levels in-line with an intermediate IPCC RCP4.5 (green) and RCP8.5 (blue) climate change scenarios by 2030 (red) and 2100 by 2100 (green); (right) the percent difference in AAL and AEP metrics between control and IPCC RCP4.5 (dark grey AAL; green PML) and RCP8.5 (light grey AAL; blue PML).



There is a 50% increase in the surge AAL by 2100 for RCP4.5 and an 80% for RCP8.5, with a smaller impact of 30% and 50%, respectively, at the 1:100 (Figure F3). The impact on short return periods is larger than in the tail because the relative change in flood depths is most pronounced for smaller events. The projected changes in SLR will have a larger relative impact on earnings compared to capacity allocation, especially for the RCP 8.5 scenario.

Test 2 – Increased Precipitation resulting to inland flood: This test estimated the loss impact of potential future increases in rainfall rates. Knutson et al. (2015), finds a statistically significant increase of ~20% in TC rainfall rates (or 17% for hurricanes) within 100km of the storm centre under RCP4.5, by the late 21st century for a downscaled CMIP5 ensemble. Landfall frequency and wind intensity were unchanged. The team approximated the increased rainfall rates by increasing the return period of local flood depths by 20%. Thus, a storm that causes a 1-in-100 year level of inundation would now generate flooding at about a 1-in-125 year level. For simplicity, this was done for all rainfall events, not just TC induced rainfall events. Additionally, this assumes that rainfall rate changes translate proportionally to flood depth return period changes.

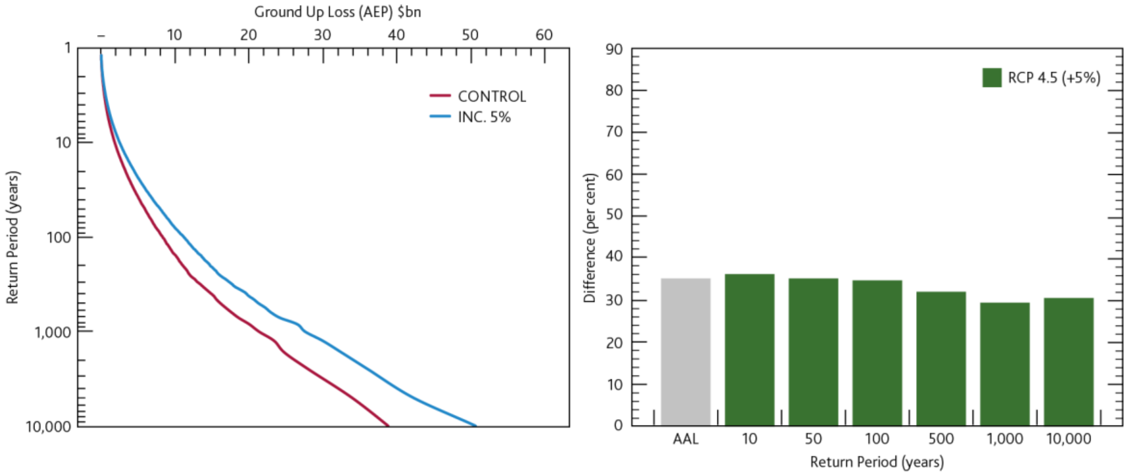
Figure F4: (Left) AEP losses considering present (CONTROL; red) and the projected (INC. 20%; blue) 20% increase in precipitation rate for RCP4.5 by 2100; (right) the percent difference in AAL and AEP metrics between present and IPCC RCP4.5 (light grey AAL; green PML).



By 2100, for the RCP4.5 climate change scenario, the overall impact is to increase the inland flood AAL by 18% and the 1-in-100 AEP by 9% (Figure F4). The impact is greatest at short return periods because the contribution of flood losses relative to wind is greater for weaker storms in the KatRisk model. Recall this is a coastal portfolio, thus the relativities between inland flood and storm surge may be different given the exposure distribution.

Test 3 – Increase in Wind Intensity: This test estimated the loss impact of potential future increases in windspeed for all hurricanes in the North Atlantic Basin. Based on a series of downscaling experiments for CMIP5 multi-model ensembles, Knutson et. al., (2015) estimates a (statistically significant) 4.5% increase in Lifetime Maximum Intensity (LMI) windspeeds for hurricane strength storms by the end of the 21st century, relative to control (1980-2008), based on RCP4.5. The increase in TC wind intensity was approximated by increasing the wind speed vulnerability to give a mean damage ratio corresponding to a 5% increase in wind speeds. It is assumed that the increase projected in LMI is seen across the storm.

Figure F5: (Left) AEP losses considering present (CONTROL; red) and the projected (INC. 5%; blue) increase of 4.5% in hurricane strength from the IPCC RCP4.5 by 2100; (right) the percent difference in AAL and AEP metrics between control and IPCC RCP4.5 (light grey AAL; green PML).



By 2100, for RCP4.5, there is a proportional increase across the AEP curve of approximately 35% (Figure F5), with both the AAL and AEP metrics showing uniform increases. The methodology for this sensitivity test is highly dependent on the shape of the underlying vulnerability curves. For the given primary characteristics (unknown) of the hypothetical exposure, a relatively consistent increase in damage for the given 5% increase in wind speed is observed.

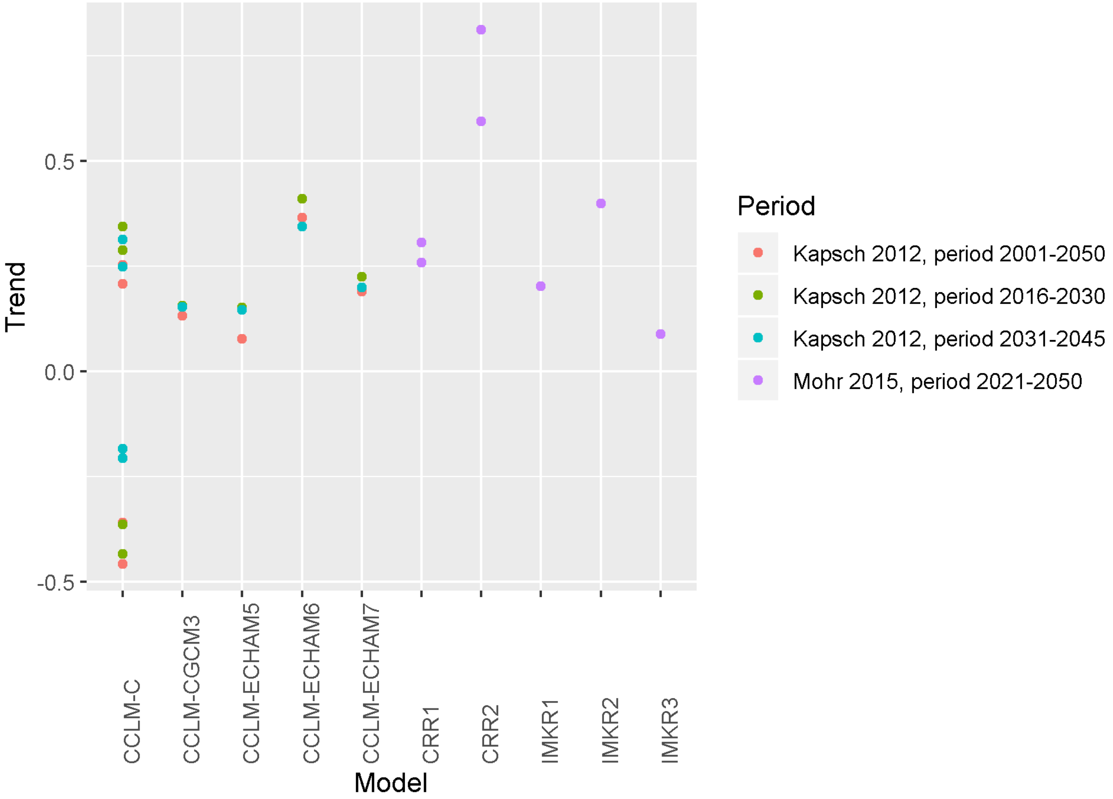
Test 4 – Tropical Cyclone Frequency: For the North Atlantic, projected frequency changes in Knutson et al. (2015) are not statistically significant, however an earlier study by Knutson et al. (2013) finds marginally statistically significant projected decreases of 20% in overall TC count and a 45% projected increase in Category 4-5 hurricane counts for the North Atlantic by the end of the 21st century.

Given the limited number of coupled atmosphere-ocean models at high atmospheric resolution capable of making projections of intense hurricanes, caution was advised when interpreting loss results, thus a qualitative assessment of loss will be discussed. KatRisk implemented a series of tests where the frequency was adjusted to explore the high uncertainty of impact of climate change to hurricane frequencies. The tests (20% reduction in all TC frequency in conjunction with a 45% increase in Category 4-5 hurricane frequency) were implemented outside the model by altering the frequencies of simulated years in the year-loss table in order to achieve the desired frequency changes. This method preserved the temporal integrity of events within simulated years. At very short return periods (1-in-2 OEP) a small reduction in wind losses is found which is hypothesized to be due to the reduction in the rates for tropical and Category 0-3 storms. However, wind losses increase for all other return periods due to the increase in rates for Category 4 and 5 hurricanes.

Germany hail

Both Mohr et al. (2015) and Kapsch et al. (2012) find positive trends between 0.1%-0.6% per year in increased frequency of hail days (Figure F5). The only exception is one model run in Kapsch et al. (2012) which exhibited a strongly negative trend; however, the author expressed reservations regarding these model results as they showed an unrealistic discontinuity in the time series of some relevant parameters. Thus, for the purpose of this study this run was excluded from the calculations. The difference in projections between models was found to be larger than the difference between emission scenarios.

Figure F6: Trends in annual hail frequency are found to be mostly positive for most models used by Mohr et al (2015) and Kapsch (2012)



The results suggest that the trend is of 0.2% per year (estimated as the median and excluding one model run with a highly negative trend) leading to a 1.0%-2.0% increase in the number of hail days in the next 5-10 years. Since only the frequency and not the severity distribution is assumed to change, these percentages can be applied directly to the AAL and 1-in-200 year return period values.

California wildfire

The scenario, which is comprised of 9 current and 11 future large wildfire footprints across California, was created by looking at historical wildfires maps across California and identifying the areas most likely to be affected by this peril applying expert judgement. The number of footprints considered is a mix of 'current climate' and 'future climate' scenarios, biased for the latter by increasing the duration of the wildfire season by roughly 3 weeks by 2050, which in turn is expected to increase wildfire frequency in a given year.

The footprints developed were based on the size and shape of historical fire footprints. Once the 'current climate' and 'future climate' footprints were created, the insurance exposure was overlaid to the footprints in order to estimate the percentage of properties and vehicles in the area affected by the wildfire (eg Figure F7). Then, using the TSI for that area it was possible to calculate the insured losses for each individual fire under 'current' and 'future' climate conditions The calculated increase of potential losses under the 'future climate' from this analysis was 130%.

Figure F7: Pollock Pines fire, current (shaded) and future (outline) footprint.

Stage 6 Report findings

The key findings communicated to the Board Risk Committee were:

- Out of the three material perils assessed, US HU continues to be the driver of the global reinsurer's modelled loss tail and it is the main contributor to PCCR-related decision making.
    - SLR and inland flood have a clearer signal impacting PCCR than wind for US HU.
    - US TC-induced flood impacts are more likely to erode earnings than generate major capital eroding events.
    - Material increases in the frequency of intense hurricane should inform reinsurance/retrocession design.
- Since the sea-level-rise, DE Hail and wildfire climate change impact to losses appears to be incremental, it is recommended that this should be considered as part of the annual pricing process.
- The California wildfire loss profile appear to have significant potential to increase given projected climate change impacts.

Specific to the medium and long time horizons, the three recommendations proposed to the Board Risk Committee were:

Risk appetite and tolerance setting

- Limited reliance is placed on projections for intense hurricanes given the high levels of uncertainty. The team recommended the firm continue to monitor academic research.
- TC rainfall flooding and surge flooding signals are more credible, however projected changes are not expected to invalidate how the firm currently estimates wind-driven USHU PMLs. However, the team recommended the firm actively monitor flood-wind aggregation potential, particularly since TC-driven flood is not widely modelled explicitly in the industry.
- Given the potential for impact by DE hail and California wildfire, the firm is recommended to include metrics for these perils in order to better monitor if and when risk appetite needs to be revisited.

Business planning

- Given the projected changes in hurricane-driven flood, flood as a peril is likely to have a higher profile in the minds of the public purchasing insurance. This is likely to be accentuated by deregulation in the US flood market. A similar issue is expected with regard to hail for specific European portfolios.
- In assessing the firm’s US flood and US wildfire strategy, the team recommends the firm should actively consider how climate change could influence regional US flood and wildfire losses over the next decade, to inform medium-term portfolio steering decisions.

Corporate citizen/opportunities

- The cost of not adapting to climate change is significant. The firm should leverage its technical expertise to seek out opportunities to partner with cities in their adaptation planning, and potentially develop risk transfer solutions to help cities accelerate their adaptation strategies.

Challenges faced when merging the two separate analyses into Case Study F

Challenge	Will perils that currently are non-peak become more material under future climate conditions?	Given limited resources, how can we apply proportionality to the effort dedicated in assessing physical climate change risk to a range of hydro-meteorological perils affecting the current portfolio?	How can I compare US hurricane wind, surge and inland flood results when the underlying climate scenarios are different?
Solution	IPCC has identified hydro-meteorological peril-territories with higher propensity to be impacted by physical climate change risk. When those peril-territories are included in the current portfolio, it raises the question of whether their materiality might significantly change from current levels (see Chapter 2). In this case study, the US hurricane contribution to the 1-in-100 TVaR (Tail Value at Risk) has been far more material than EU hail and US wildfire. Instead of completely disregarding EU hail and US wildfire, this case study assessed the physical climate change risk of EU hail and US wildfire – by undertaking a relatively quick analysis – when compared to the detailed analysis of US hurricane. The analysis showed that EU hail or US wildfire loss contributions are unlikely to increase to a level material enough to include in the final recommendations to the Board Risk Committee.	Depending on the business question at hand, peril-territory materiality is established. In this case, US hurricane is dominant and the allocation of resource between US HU and EU hail, US wildfire reflects materiality. For instance, more academic papers were reviewed for US hurricane than for EU hail and US wildfire. Equally, the choice of tools reflects proportionality: for US hurricane, a catastrophe model was modified to assess physical climate change risk; for US wildfire; simple footprints were drawn; and for EU hail, expert judgement to estimate loss change was adopted.	The background research is often based on IPCC future climatic projections and assumptions reflecting future climatic states. Those projections and assumptions are rarely the same across studies. So, it is difficult to compare or aggregate physical climate change risk assessment results to formulate an overall view across the portfolio that will inform the business decision. In this case study, the background research focused on a 'medium' climatic projection across the different perils when that was available. The comparison across perils was done even when there was not a perfect alignment of the climatic model projections, acknowledging and reporting the limitations and assumptions behind such assessment.
Residual limitations	The IPCC analysis is generic and does not reflect portfolio specifics. Expert judgement needs to be applied to assess whether some particular peril-territory combination requires further analysis. For instance, this particular case study did not consider EU windstorm as the physical climate change risk signal under future climatic projections was deemed to be non-significant by the analysts working on this project. This view might be challenged when undertaken by a different firm.	There is a level of subjectivity applied in deciding how the limited resource pool should be split across the different peril-territory combinations. That decision needs to be made in context of the relevant business decision(s). For this case study, given the audience is the Risk Committee, materiality in terms of insolvency and risk appetite was measured at 1-in-100. If the same study was done for pricing purposes only, then the AAL metric might have demonstrated different materiality s for the same peril-territory combinations.	Differences across future climatic conditions are particularly pertinent at longer time horizons (such as 2100). For shorter time horizons, the differences in climatic projections are less divergent. In this case study, SLR adopted a NOAA-only view rather than considering other SLR scientific resources. It is difficult to attribute with confidence a set increase in inland precipitation given the selected 'medium' climatic projection.

5 Conclusions and recommendations for future development

This report sets out a practical framework that can be used to assess financial impacts from physical climate change risk for general insurance firms. Such assessments can leverage existing tools already in use by the insurance industry. This report has demonstrated how expert judgement, hazard maps, footprints, and catastrophe models can be tailored to address practitioners' needs, depending on the data available, the business need in question and the required output metrics.

This framework provides a robust starting point for practitioners and firms to assess the financial impacts from physical climate change risk in the context of business decisions and disclosure requirements. The general insurance industry has a particular advantage in assessing the financial losses caused by physical risks due to its expertise in modelling weather perils and dealing with the related uncertainty.

A measure of success from using this framework will be to see action coming as a result of analysis that addresses the risks from climate change and contributes to the insurance industry shift from awareness towards action.

Where should the general insurance industry focus its efforts?

As the general insurance industry looks to understand, assess, and manage better the financial risks posed by climate change, there are areas where those experienced in catastrophe risk modelling can add particular value.

First, while the quantification of the impact of physical climate change on insurance liabilities is currently in the early stages of development, there are many studies investigating the impact of climate change on natural disasters. The sheer volume of information can make it difficult to assimilate and understand which reports are most important. The catastrophe analytics industry can play an important role in consolidating, distilling, and highlighting the most compelling research. This information can be provided to general insurance firms to allow them to generate credible assumptions to apply in subsequent assessment methodologies.

Second, there is a larger role that should be played in terms of providing accessible tools to allow the assessment and contextualisation of these risks. To date, catastrophe models have used historical data to develop stochastic event sets. When considering the impact of climate change, where the future may differ from the past, changes to historical data should be accounted for. The catastrophe analytics industry is well placed to develop stochastic event sets to reflect future climatic states, such as using output from GCMs, which better take into consideration the forward-looking impact of climate change. Such event sets could also be linked to IPCC climatic conditions (for instance, models reflecting an RCP8 scenario). These tools could then be made available within existing catastrophe models to allow users to easily investigate climate change impacts on particular insurance portfolios.

The evolution of current climate risk models to incorporate future climate states is a clear area for development where those with expertise can extend the scope of their existing products to enable investigation of these issues.

Using the framework to address climate change adaptation

Beyond assessing the financial impact to general insurance liabilities, other industries could benefit from an enhanced understanding of the financial risks posed by climate change and the potential subsequent losses (ClimateWise, 2019a). The proposed framework can be used to help develop products that support climate change adaptation. For instance, robust and systematic assessment of climate change risk can indicate easier risk transfer mechanisms for infrastructure projects seeking to manage this risk (such as flood levee construction). The framework can also be used in industries seeking to identify financial impacts from climate change risk to property such as asset managers.

Appendices

Appendix 1: Abbreviations

AAL: Annual average loss

AEP: Aggregate exceedance probability

CCRA: Climate change risk assessments

CDF: Cumulative distribution function

CMIP5: Coupled Model Inter-comparison Project Phase 5

CRO: Chief risk officer

GCM: General circulation models

HNW: High net worth

IPCC: Intergovernmental Panel on Climate Change

LoB: Line of business

NAO: North Atlantic Oscillation

NFIP: National Flood Insurance Programme

NOAA: National Oceanic and Atmospheric Agency

OEP: Occurrence exceedance probability

ORSA: Own risk and solvency assessment

PRA: Prudential Regulation Authority

RCP: Representative Concentration Pathway

RMSE: Root mean squared error

RP: Return period

SJR: Scimago Journal & Country Rank

SLR: Sea level rise

SS: Supervisory statement

TCFD: Task Force on Climate-Related Financial Disclosures

UNEP: United Nations Environment Programme

PML: Probable Maximum Loss

TVaR: Tail Value at Risk

Appendix 2: Glossary

Annual exceedance probability curve: a graph that shows the probability that a given threshold of losses will be exceeded in any one year. Average annual losses can be derived from an exceedance probability curve.

Annual probability of occurrence: this measures the probability that, over a period of one year, an event of a given magnitude occurs. For example, a particular insured property might have face a 1% chance of flooding at a depth of one metre or more in any given year.

Assessment reports: in the context of the Intergovernmental Panel on Climate Change (IPCC)'s Working Group Assessment Reports, these are analytical summaries of peer-reviewed academic publications relating to climate change.

Average annual loss (AAL): the average losses from property damage experienced by a portfolio per year.

Catastrophe models: a computerised system that generates a robust set of simulated events and estimates of magnitude, intensity, and location of a catastrophe event such as hurricane or earthquake. This is used to determine the amount of damage and calculate the insured loss as a result of the event.

Climate change adaptation: a response to climate change that seeks to reduce the vulnerability of social and biological systems to relatively sudden change and so as to offset the effects of global warming.

Climate specialists: professionals who specialise in the study of the natural climate system, including the statistics of the Earth's temperature and precipitation.

Coupled General Circulation Model: this is a type of climate model. It employs a mathematical model of the general circulation of a planetary atmosphere or ocean.

Envelope of events: the furthest outline from multiple footprints each representing a plausible natural climatic extreme event.

Event: a distinctly defined occurrence of a hazard (eg hurricane), implicitly with a start- and end-point in time.

Event footprints: the furthermost physical geographic outline of a natural event stemming from maximum intensity of the event hazard (eg flood depth) over the defined period of the event.

Event loss table (ELT): the output from a catastrophe model, comprising loss statistics for every loss generating event in the catastrophe model.

Exceedance probability curve: describes the probability that various levels of loss will be exceeded. For example, if we simulate 10,000 years of hurricanes, the highest loss shown will have a 0.01% chance of being exceeded. Please refer to annual exceedance probability curve and occurrence exceedance probability curve.

Exposure: physical assets (ie insured properties or other possessions) exposed to extreme weather events.

Extreme weather event: the occurrence of an event for which a particular variable weather measure is above (or below) a threshold value near the upper (or lower) ends of the range of its observed values in a specific region.

Fluvial flooding: flooding that occurs when water from an established natural or artificial river course or drainage channel spills onto the natural or man-made floodplain. Usually occurs as a result of rainfall occurring upstream of the point of flood.

Hazard maps: a map that highlights areas that are affected by or are vulnerable to a particular hazard such as flood depths, 3-sec gust wind speeds, peak ground acceleration.

Market-based risk transfer mechanisms: the process of moving risk from one party to another (eg policyholder to insurer, insure to reinsurer, reinsurer to retrocessionaire) or alternative risk transfer, via a contract and in exchange for a premium.

Natural catastrophe model: a sophisticated computer model used to estimate the risk of financial losses to portfolios of assets.

Occurrence exceedance probability (OEP): the probability of a single event loss in a year exceeding a certain level.

Peak river flow: the maximum instantaneous discharge of a stream or river at a given location**.**

Peaks-over-threshold (POT) method: a practical method for extreme value analysis. It relies on extracting, from a continuous record, the peak values reached for any period during which values exceed a certain threshold (or fall below a certain threshold).

Physical climate change risk: the potential for changes in climate to affect extreme weather events and their impacts on the natural physical environment.

Pluvial flooding: Flooding caused directly by extreme rainfall (ie not from rivers). Sometimes called ‘off-flood plain’ flooding in the context of catastrophe model building.

Primary scientific research/studies: a document or paper which was written or created during the time being studied and is the result of original scientific research or observation.

Probable Maximum Loss (PML): the value of the largest loss that is considered likely to result from an event.

Probabilistic models: these incorporate random variables and probability distributions into a mathematical model that describes an event or phenomenon. Catastrophe models are examples of these.

Systemic financial risk: risk of collapse of a significant part of a financial system or market, as opposed to risk associated with any one individual entity, group or component of the system that can be contained or managed without harming the entire system.

Representative concentration pathway (RCP): in the context of this publication this is defined as a projected greenhouse gas concentration trajectory to a particular point in time in the future adopted by the IPCC for its fifth Assessment Report in 2014**.**

Return period: a way of describing the magnitude of an extreme weather event. An event with a 1-in-100 year return period has a 1% chance of being exceeded by a higher magnitude event in any year.

Root mean squared error (RMSE): measure of the differences between values (sample or population values) predicted by a model or an estimator and the values observed.

Sea level rise (SLR): long-term average sea-level rise relative to the local land level, as derived from coastal tide gauges.

Scenario: a representation of a possible (catastrophic) event based on scientific, industry, and other expert knowledge.

Scoring data: in the context of this report, these are analytical point estimates of hazard propensity for a particular natural catastrophe based on the outputs of a hazard or catastrophe model.

Stochastic event: a single realisation from a stochastic event catalogue (refer to definition below) that describes one plausible occurrence of an extreme natural event (eg flood, windstorm).

Stochastic event catalogue: a compiled list of a large number of events (eg n>10,000) with associated probabilities, to reflect the range of what is possible in practice, and relative likelihood of each such event.

Supply chain: the sequence of processes involved in the production and distribution of a commodity.

Synthetic event: an event generated from, but extrapolated beyond, the historical record. In the context of this report this is a plausible natural catastrophe event that fits insured loss or natural peril loss propensity specifications for a particular portfolio.

Temporal or spatial resolution: the precision of a measurement with respect to time and space.

Time horizons: a fixed point of time in the future at which point certain events/processes will be evaluated or assumed to end.

Vulnerability function: a function relating to a hazard metric (eg water depth) indicating the damage ratio that applies to a particular risk or set of risks in order to calculate ground-up insured loss.

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