ClimateWise
Insuring a sustainable future

Physical risk framework

Understanding the impacts of climate change on real estate lending and investment portfolios

UNIVERSITY OF CAMBRIDGE
INSTITUTE FOR SUSTAINABILITY LEADERSHIP

ClimateWise

ClimateWise is a global network of leading insurers, reinsurers, brokers and industry service providers who share a commitment to reduce the impact of climate change on the insurance industry and society. It is a voluntary initiative, driven directly by its members and facilitated by the University of Cambridge Institute for Sustainability Leadership (CISL).

All members produce a detailed annual report providing evidence of action against the ClimateWise Principles. As of 2019, the ClimateWise Principles are fully aligned with the Task Force on Climate-related Financial Disclosures (TCFD) recommendations.

In 2016, the ClimateWise Insurance Advisory Council was established to lead research into ways the insurance industry can support the transition to a low carbon economy. The Council is formed by a group of C-Suite level executives from across the ClimateWise membership and is currently chaired by Dominic Christian, Global Chairman, Reinsurance solutions at Aon.

The University of Cambridge Institute for Sustainability Leadership

The University of Cambridge Institute for Sustainability Leadership (CISL) is a globally influential Institute developing leadership and solutions for a sustainable economy. We believe the economy can be 'rewired', through focused collaboration between business, government and finance institutions, to deliver positive outcomes for people and environment. For over three decades we have built the leadership capacity and capabilities of individuals and organisations, and created industry-leading collaborations, to catalyse change and accelerate the path to a sustainable economy. Our interdisciplinary research engagement builds the evidence base for practical action.

Rewiring the Economy

Rewiring the Economy is our ten-year plan to lay the foundations for a sustainable economy. The plan is built on ten interdependent tasks, delivered by business, government, and finance leaders co-operatively over the next decade to create an economy that encourages sustainable business practices and delivers positive outcomes for people and societies.

Publication details

Disclaimer
The opinions expressed here are those of the authors and do not represent an official position of their companies, CISL, the wider University of Cambridge or clients.

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The study design and editorial process was led by Dr Bronwyn Claire, Andrew Voysey, Rachel Austin, Emma Jillings, Dr Tom Herbstein, Amy Nicholass and with input from Adele Williams and James Cole of CISL.

The authors of this report were Mark Westcott, John Ward and Swenja Surminski (Vivid Economics) and Paul Sayers (Sayers and Partners LLP), with expert input provided by David Bresch (ETH Zurich). The authors are grateful for the guidance of the ClimateWise Insurance Advisory Council and for the advice and feedback received from members of the Advisory Panel which was established for this project. With special thanks to The Lighthill Risk Network for their support.

Vivid Economics
Vivid Economics is a leading strategic economics consultancy with global reach which strives to create lasting value for clients, both in government and the private sector, and for society at large.

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Copies
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Contact
To obtain more information on the report, please contact:
E: climatewise@cisl.cam.ac.uk
T: +44 (0)1223 768 850

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Executive summary

The changing climate poses new risks to investors and lenders.

The world is currently on track to see substantial climate change throughout the 21st century. As well as bringing higher temperatures, changes in precipitation and a range of other impacts, climate change will also influence the likelihood and intensity of extreme weather events. Collectively, these 'physical risks', threaten the interests of investors and lenders, especially those with interests in real estate and infrastructure assets.

This report shows how investors and lenders can make use of well-established insurance models, tools and metrics to improve their management of some of the physical risks of climate change. Natural catastrophe models have long been used by the insurance industry to assess and price extreme weather event risk, and hence help them and their clients manage these risks. This report shows how outputs from climate models can be used in combination with natural catastrophe models to assess some of the physical risks of climate change in different scenarios.

The physical risk framework is a practical guide containing an open, repeatable methodology which investors and lenders can follow, refining to suit their own needs. The methodology has the potential to become increasingly sophisticated over time as understanding of the impacts of climate change improves.

As an illustration, applying this methodology to a sample of 12 real estate portfolios – with a total market value in excess of £2 trillion, spread across Europe, North and South America and Asia – highlights some important preliminary findings:

1. Climate change is anticipated to have large impacts on the risk of losses from floods in the UK and tropical cyclones in North America and the Pacific Rim.
2. The estimated changes in risk, especially in the climate scenario most aligned with the current warming trajectory, raise important questions for investors, lenders, insurers and policymakers. They will need to consider how these expected increases in risk can be managed in the most cost-effective manner and, especially, the strategy of organisations set up to help address the insurance protection gap.
3. Not all investors and lenders are expected to be equally exposed. One of the most important ways that investors and lenders can influence their exposure to physical climate change risk is through both strategic location investment decisions (which region/country/continent) and local asset-siting decisions; although any changes should be done carefully, in a phased, managed way.
4. Adaptation measures can materially reduce losses from the physical risks of climate change, and these are proportionally most effective when combined with global efforts to reduce emissions.
5. There is a powerful opportunity for investors, lenders and policymakers, working with insurers, to target the uptake of adaptation measures in the most beneficial areas.

The collective understanding of the risks posed by climate change will be enhanced as more investors and lenders undertake similar analysis. This will allow investors and lenders to take better, more informed decisions.

ClimateWise members 2019

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Forewords

Dominic Christian

We convened the ClimateWise Insurance Advisory Council to help understand the increasingly complex nature of risk affecting the financial services sector. Our aim is to inform stakeholders of the true nature of the 'physical', 'transition' and 'liability' risks affecting our industry while identifying ways that insurance expertise can support other parts of the financial services sector in their response. The ClimateWise Physical risk methodology is the one of our first outputs.

Globally we are seeing increasing losses from physical risks, through both climate factors and the accumulation of assets in locations exposed to such hazards. Recent wild fires, typhoons and hurricanes demonstrate the impact of physical risks and the knock-on effect to the economy. In 2018, Swiss Re Institute estimated total economic losses from natural and man-made disasters of USD 155 billion, with insured losses from catastrophes being USD 79 billion, and more importantly claiming more than 11 000 victims. Different parts of the financial sector have differing abilities to respond to changes in the physical risk profile of assets. It is valuable to highlight the role of short-term insurance placements, and longer term asset holdings and adaptation measures.

Insurers have an opportunity and the responsibility to share knowledge and experience of managing risk with other stakeholders in order to build resilience within the financial sector and society more broadly. The industry's expertise with natural catastrophe modelling is perfectly placed to inform management of the physical risks associated with a changing climate. The open and repeatable methodology outlined in this report is designed for use by investors, lenders and supervisors to better understand exposure and consider adaptation. The model uses best current available climate science and provides transparency on the assumptions used. As climate projections become more accurate, the transparency of the model allows for quick updates to the analysis and assessments.

The insurance industry is called on to collaborate with other financial industry players to use our unique expertise across the industry and improve the financial resilience of the economy as a whole.

Dominic Christian,
Chair of ClimateWise and
Global Chairman,
Reinsurance Solutions at Aon

Russell Picot

Climate risk is a major societal risk, with an intergenerational quality that goes beyond traditional business strategy, decision and reporting horizons. The gap in current business assessment and response to climate change provides a possible first mover competitive advantage to adopting methodologies, such as outlined in this CISL report. The Bank of England's recent report finds that 30% of companies view climate change through the lens of corporate social responsibility, rather than taking a responsive or strategic approach.

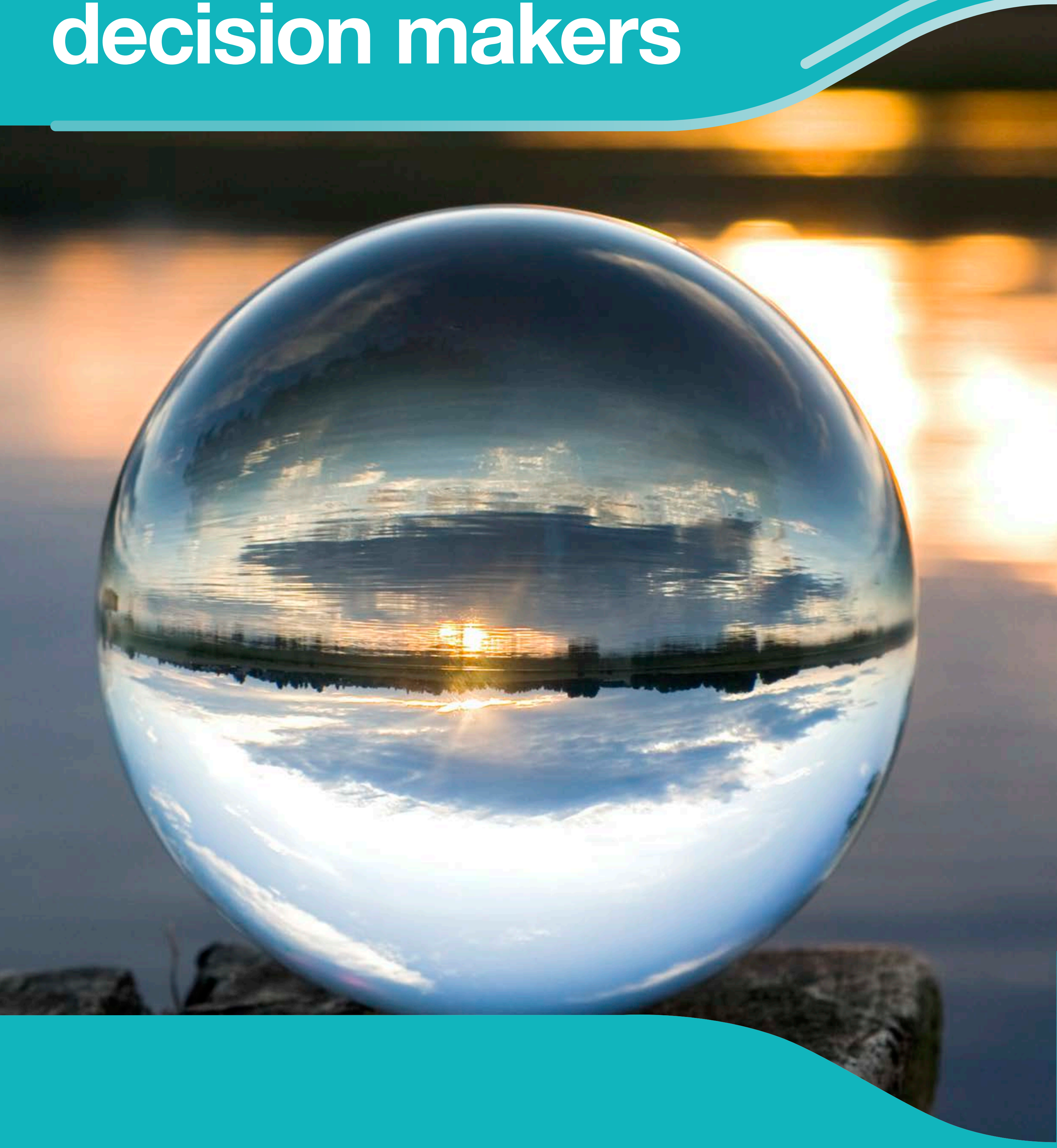
The conversations of senior executives and the boardroom have changed over the past few years, to reflect external and internal drivers of integrated thinking on climate change risks. The finance function provides key input on the exposure and forecast response to climate risks, including physical risk. The modern finance function needs to move beyond integrated reporting to integrated thinking on how a business assesses, reports and responds to physical climate risks. Taking integrated thinking into the mainstream of a business moves it towards leading practice.

The TCFD sees leading practice for assessing the resilience of portfolios as scenario analysis, with the recognition that the tools will be developed and improved over time as practice and enhanced data availability move the industry forward. The physical risk assessment methodology presented in this report is an important development in the range of scenario tools for business. The research highlights how different aspects of the financial services sector can benefit from working together to improve the management of the physical risks of climate change across investment, underwriting, lending and project finance. Also, the illustrative results highlight how pertinent it is for a business to assess its exposure to physical climate risks, and the role adaptation can play to mitigate exposure.

I would like to thank the ClimateWise Insurance Advisory Council for progressing the physical risk capabilities of the financial sector by expanding our response to climate risk beyond the insurance industry to the whole of the financial services sector.

Russell Picot,
Special Adviser to the FSB Taskforce on Climate-related Financial Disclosure
Board Chair of HSBC Bank (UK) Pension Scheme Trustee

Summary for decision makers



What are physical risks and why are they important for investors' and lenders' needs?

The changing climate poses new risks and challenges to investors and lenders. While much attention has focused on transition risk – the risks posed by rapid decarbonisation of the world economy – at present, political agreements to cut emissions have not been matched by equivalent action on the ground. Instead, the world is currently on track to see substantial climate change throughout the 21st century. This creates heightened risks to investors and lenders, the so-called 'physical risks' of climate change, which, among other impacts, may be seen in terms of higher temperatures, changes in flooding, drought or limited water availability, and sea level rise.

Regulators, investors and lenders are increasingly aware of the possible implications of physical risks across different parts of the financial system but they are also searching for practical, analytical approaches to guide their decision-making. The Financial Stability Board (FSB)'s Task Force on Climate-related Financial Disclosures (TCFD) has recommended inclusion of physical risk disclosures in organisations' annual filings. In addition, at least 18 regulators and central banks from across Europe, North America and Asia, including the Bank of England, De Nederlandsche Bank and Banque de France have recently drawn attention to the direct risk climate change poses to investors, as well as the potential for contagion to other parts of the finance sector.[1] However, while there is a general perception that this is important, there is still little understanding of how these risks can be assessed, and therefore reported, managed and, ultimately, reduced.

> Insurance can play a key role in helping to manage physical risks, especially of the most extreme events. But growing physical risks will also influence the future affordability and availability of insurance protection.

Climate change will influence the likelihood and intensity of extreme weather events, which threaten the interests of investors and lenders in real estate and infrastructure assets in particular. The Intergovernmental Panel on Climate Change (IPCC) reports that climate change will result, for example, in increased frequency and intensity of heatwaves; more heavy precipitation events, leading to a greater risk of flooding at the regional scale; and an increased frequency and intensity of extreme high sea levels, such as those caused by storm surges. The large year-to-year natural climate variability means that, even with further climate change, such events will not take place every year, even in more extreme scenarios. However, early signs of these risks materialising can be seen in more frequent heatwaves in most regions, a global increase in the frequency and intensity of heavy rainfall events and an increased risk of drought in the Mediterranean.[2] These changes pose particular threats to both infrastructure assets – for which global investment needs may exceed US$90 trillion by 2030 – and residential and commercial building stock – which is expected to grow by 13 per cent between 2017 and 2026.[3] For financial institutions lending against real estate and infrastructure assets, increases in the frequency and intensity of extreme weather events might increase the likelihood of defaults due to the increased financial losses borrowers face. For investors in real estate and infrastructure assets, such changes might lead to asset devaluation and reduced yields.

Insurance will likely play an important role in helping investors and lenders manage these increased risks, but insurance should not be used as a reason to ignore them. Insurance can play a key role in helping to manage physical risks, especially of the most extreme events. But growing physical risks will also influence the future affordability and availability of insurance protection. In their first-ever report on climate change, the UK's Prudential Regulation Authority noted that "increasing levels of physical risks could present challenges, both to market-based risk transfer mechanisms and to the underlying assumptions behind general insurance business models".[4] As such, investors and lenders need to be directly empowered to understand how these risks might influence them.

How can investors and lenders better understand physical risks?

This report shows how investors and lenders can use catastrophe modelling tools and associated metrics, refined by the insurance industry over decades, to better assess, manage, report and reduce their exposure to physical risks, particularly those from extreme weather events. Catastrophe models have long been used by the insurance industry to assess and price extreme weather event risk, and hence help them and their clients manage these risks. Recently the Geneva Association, the leading international insurance think tank, recommended that climate science projections should be used within natural catastrophe models to provide more forward-looking forecasts.[5] This report shows how, in practice, outputs from climate models and climate scientists can be used in combination with natural catastrophe models to assess risk under future climate scenarios. Used in this way, the insurance industry's catastrophe models are powerful tools that can be used by investors and lenders within their scenario analysis to help quantify the physical risks of climate change, while recognising the inherent uncertainty surrounding the future incidence of climate events.

Section 3 of the report outlines a four-step process that investors and lenders can follow to use these tools, as set out in Figure 1. Section 4 presents the results of an illustrative example of the process and the preliminary findings.

- First, investors and lenders need to collect data on the physical assets ('exposure') they are concerned about. As a minimum, this should include their geographic locations and some information on asset class, such as whether they are residential or non-residential property. The more detailed that property-level information can be – in terms of construction type and year, roof type, number of floors, occupancy and square footage – the more robust the associated results will be.
- Second, they need to decide which natural catastrophe model(s) to use for their analysis. A number of factors will play into this choice. A critical one will be whether the modelling will be undertaken in house or sub-contracted to a commercial model vendor. The former would require use of an open source model. This may allow for more bespoke analysis to be undertaken and provide greater understanding of what drives any results, but these models may not have received as much investment and will also require reasonable technical skills to be confident that the work is being undertaken accurately. The advantages and disadvantages reverse for vendor models. For models supplied by vendors, the extent and transparency of model documentation is another important factor, since this will enable investors and lenders to understand and review the assumptions that have been made in the modelling.
- The third stage involves choosing the climate scenarios to model and defining how those climate scenarios might influence the probability and severity of extreme weather events. In order to account for uncertainty about the extent of global action on reducing emissions, scenarios chosen should cover a wide range of plausible futures. The scope of potential ranges in temperature increases, typically expressed in terms of temperature increases by 2100 above a pre-industrial baseline, might range from 1.5°C, the temperature target 'aimed for' in the Paris Agreement, to 4°C or more, which broadly reflects the temperature increases that would be expected given the current trajectory of emissions. The relationship between these temperature changes and the severity and frequency of disaster events within a region should incorporate the latest peer-reviewed developments in climate science and acknowledge/account for the uncertainty around these relationships. Some models already include effects of climate change on the frequency and intensity of the perils within their models; otherwise, collaborations with academics or specialist climate change impact modellers may need to be sought out in consultation with the model developer. As climate models continue to develop, for example in their geographic fidelity, these developments can be incorporated into this stage of the analysis.
- The final stage is model execution and interpretation of the associated results. Catastrophe models can provide a wide range of different results of interest. Two of the most common outputs are Average Annual Loss (AAL) – the average losses from property damage experienced by a portfolio per year – and annual probability of occurrence – the probability that, over the period of one year, a given asset experiences an event of a given magnitude. Any results should be compared against a 'present day' climate scenario baseline and, where possible, these baseline results should be compared with and scrutinised against historical loss data. Forward-looking results should also be benchmarked against those from comparable studies, where available. When there is confidence that these results are robust, investors and lenders then have the option to convert the changes in expected losses into potential changes in asset values. They can also use the natural catastrophe model(s) to analyse how adaptation measures might reduce losses and asset value impacts.

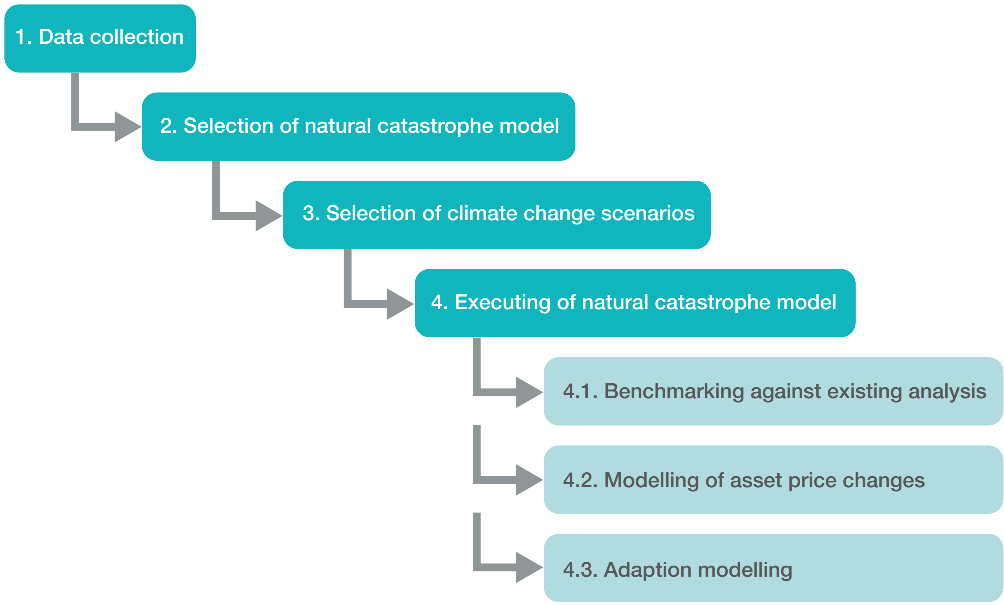


Figure 1. Key steps for investors and lenders to follow in modelling the physical risks of climate change

While an understanding of climate impacts on property portfolios represents one important implication from climate change, there are many other implications from climate change on lives and livelihoods, especially among developing countries, that are not captured in this approach.

What results emerge from an illustrative application of this methodology?

The report provides an illustration of how investors and lenders can follow this four-step process. In terms of data, this application analyses 12 real estate asset portfolios, consisting of assets in the UK, Europe, North America, South America and Asia. Seven of these portfolios consist of UK residential mortgage assets held by large UK retail banks and building societies, whilst five are real estate investment portfolios held by ClimateWise members. The latter portfolios mostly comprise offices and shopping centres, with assets across Europe, North America, South America and Asia. The analysis compares present day losses of the portfolios from extreme weather events to their expected losses in the 2050s. Financial institutions with long-term investments, including banks and building societies providing new 35-year mortgages today, will have exposure to risks in this time period.

The results derive from two natural catastrophe models that are characteristic of those used in the insurance industry. The application uses CLIMADA, an open source model developed by ETH Zurich, to explore European winter wind storm and tropical cyclone risks. A strong attraction of CLIMADA is that it is an open source model, which means that all assumptions behind the model are visible and, with modifications to the source code, can be adapted by advanced users. However, the sophistication of the modelling does not match that of the commercial vendors. The application also uses Future Flood Explorer (FFE), developed by an international team of academics and experts, to explore UK flood risk. The FFE was previously used as part of the 2017 Climate Change Risk Assessment for the UK government's Committee on Climate Change.

Financial institutions with long-term investments, including banks and building societies providing new 35-year mortgages today, will have exposure to risks in this time period.

The application explores expected losses in the 2050s in two climate change scenarios (acknowledging that this is just a sample of possible future climate change scenarios):

- The first scenario is consistent with 4°C of global warming by the end of the century, an outcome in line with the warming implied by current trajectories of climate action.
- The second scenario reflects the possibility that aggressive mitigation action and technological innovation leads to rapidly decreasing emissions levels and the global temperature rise being limited to 2°C by the end of the century.

The illustrative analysis uses results from climate models to map these changes in global average temperature increases into expected changes in the frequency and severity of floods and storms. It is recognised that this is an area subject to ongoing scientific enquiry, with the effects of climate change better understood for some extreme weather events such as UK flood, than others such as European wind storms. Furthermore, the changes in these events represent just a subset of future climate impacts.

The results show that, for these particular portfolios, climate change could have large impacts on the losses that investors and lenders face from floods in the UK and tropical cyclones in North America and the Pacific Rim, but that their increases in losses from European winter wind storms are likely to be lower. Under a 4°C warming scenario, the modelling suggests the AAL caused by UK floods to residential mortgage assets could increase by 130 per cent. It also suggests a 40 per cent increase in the number of residential properties exposed to significant flood risk (defined as a 1.3 per cent or 1 in 75 annual probability of flooding or above), equivalent to 180,000 properties within the portfolios examined. These results are for large, geographically well-diversified portfolios; more regionally concentrated lenders may see larger increases. For investment portfolios, in a 4°C warming scenario, the increase in AAL from flood risk across four UK portfolios is modelled to be 70 per cent higher in the 2050s than today. Across the two portfolios with assets in North America and the Pacific Rim, the analysis based on best evidence suggests that the equivalent expected increase from tropical cyclone risk is 80 per cent. The portfolios examined face much smaller increases in risk from European winter wind storms.

The analysis also suggests that losses faced by investors and lenders are lower, but still substantial, if global efforts to reduce emissions are successful. For the UK residential portfolios, AAL from floods would increase by only half the amount of a 4°C scenario, while the modelling suggests that the number of properties within the portfolios at risk of significant flooding (1.3 per cent or 1 in 75 annual probability or above) might only increase by 25 per cent. For investment portfolios in the UK, the increase in AAL is 40 per cent, which is similar to the potential increase in AAL from tropical cyclone risk. Table 1 summarises. These results reinforce that it is paramount for governments, business and society to try and keep warming as low as possible, as underlined by the most recent IPCC analysis.[2]

Peril	Asset type	Risk metric	2°C warming by end of century	4°C warming by end of century
UK flood risk	Residential mortgages	% increase in AAL by 2050s	61%	130%
		% increase in number of properties at significant risk of flooding (annual probability of 1.3% or above)	25%	40%
UK flood risk	Investment portfolios	% increase in AAL by 2050s	40%	70%
North America and Pacific Rim tropical cyclones	Investment portfolios	% increase in AAL by 2050s	43%	80%
European winter wind storms	Investment portfolios	% increase in AAL by 2050s	6.3%	3.6%

Table 1. Modelling shows increased losses are expected across all perils, but they are lower if global efforts to reduce emissions are successful

These findings align with those from earlier studies, including those from the insurance sector. For instance, JBA found a 25–30 per cent increase in AAL for UK residential properties in the 2040s,[6] while the UK's Climate Change Risk Assessment,[7] also using the Future Flood Explorer as in this analysis, found a 30–62 per cent increase in AAL in the 2050s for UK residential properties. The smaller increases in AAL found in these previous analyses are likely to reflect differences in assumptions around community-based adaptation and in the portfolios examined, while in the case of the JBA analysis, also differences in model set-up and time horizon. Similarly, the relatively modest increases in AAL from wind storms match the findings of research carried out on behalf of the Association of British Insurers (ABI) regarding the effect of climate change on wind storm losses to UK assets.[8] The ABI modelling exercise found the AAL from UK wind storms was expected to increase 11 per cent by the end of the century under a 1.5°C scenario and 25 per cent by the end of the century under a 4.5°C scenario. It is likely that differences to our analysis are largely attributable to the different time horizon and scenarios considered, as well as some differences in the model set-up and the underlying climate models used to drive the results.

What are the potential implications for investors and lenders, insurers and policymakers?

The potential increases in risk, especially in a 4°C scenario, raise important questions for investors, lenders, insurers and policymakers as to how they can be managed in the most cost-effective manner.

- In cases where commercially provided insurance policies are held in relation to these perils, policyholders might expect to see, on average, increases in premiums and insurance companies would need to purchase substantially more reinsurance to ensure solvency and in line with any increases in modelled uncertainty. For assets that have no insurance cover (such as some commercial properties), all of any increase in risk will be faced by investors and/or lenders.
- This also has important implications for the strategy of organisations set up to help address the insurance protection gap. In the specific case of the UK residential mortgage market, this applies particularly to Flood Re, whose role is to provide an affordable market for home insurance for properties built before 2009 that are at risk of flooding. It achieves this by offering fixed premiums according to council tax banding, with the funding gap between the premiums it charges and the risk-based price for insurance met through a levy imposed on the insurance industry (and, ultimately, its policyholders). This analysis suggests its funding gap could increase, reinforcing previous concerns about the sustainability of these arrangements. For example, although a formal assessment of when insurance availability for residential properties through normal market arrangements may become challenging has not been undertaken, a typical rule of thumb is that it can be challenging to provide affordable insurance in cases where the annual probability of flooding is 1.3 per cent or above. The modelling shows that, in a 4°C warming scenario, by the 2050s, the number of residential properties falling into this category could increase by 40 per cent to 180,000 properties across the portfolios examined. Scaled to the UK mortgage portfolio as a whole this could amount to an additional 250,000 properties, and compares with approximately who were benefiting from the Flood Re scheme during the most recently reported financial year.[a] Moreover, Flood Re is, by statute, to transition the UK residential market back to risk-reflective pricing, meaning that after 2039 premiums and excesses should, as well as being risk-reflective, remain affordable without the benefit of the levy: careful investigation will be required of whether and how Flood Re can achieve this in light of the projected increased risks arising from climate change.
- In the absence of Flood Re or for UK residential properties excluded from Flood Re (those built after 2009), the implications for both homeowners and mortgage providers could be more profound. It is possible that, in some cases, this increase in risk will mean that buildings insurance for residential properties may no longer be available for some homes at an affordable price (recognising that what is seen as an affordable premium can vary by household). A lack of access to affordable insurance would have adverse implications for homeowners living in those properties who may find that their properties suffer significant decreases in value, potentially leaving them in negative equity and either unable to sell their homes and/or unable to re-mortgage. This could have significant personal costs, as well as disrupting the liquidity and efficiency of the housing and mortgage markets. In turn, lenders may need to consider the increased risk of mortgage default, which is likely to be geographically concentrated, and ensure that their business strategies are robust to this risk.

A crucial next step from this work should be for national regulators to explore in more detail the interlinkages between flood risk, insurance availability and the residential property market – with a particular focus on how these interlinkages could evolve over time. In the UK, this would build on the concern expressed by the Bank of England regarding the possible crystallisation of financial risks from greater flood risk to the UK residential mortgage market if flood insurance would become unaffordable[9].

While there is expected to be a substantial overall elevation in physical risks in a 4°C scenario, not all lenders and investors are likely to be equally exposed. Especially in a 4°C warming scenario, the modelling finds significant differences in the risk of different portfolios of mortgage and investor assets. Under a 4°C warming scenario, the range of increase in expected losses across the seven UK residential mortgage portfolios varies between 108 per cent and 132 per cent. For the two portfolios of assets at risk of tropical cyclones in North America and the Pacific Rim, the range in the increase in losses is 17 percentage points, with much of this difference driven by the location of just a small number of assets. The modelling suggests that the spread in risk across different portfolios is substantially smaller if emission reductions are successful in moving the world onto a 2°C warming trajectory.

The potential increases in risk, especially in a 4°C scenario, raise important questions for investors, lenders, insurers and policymakers.

[a] It is recognised that the number of properties that Flood Re currently supports, 150,000 during the most recently reported financial year,[53] is significantly lower than the number of properties in the portfolios examined facing an annual probability of flooding of 1.3 per cent or higher, 445,000. Flood Re reports that: “benign weather and the decisions taken by insurers on which properties to cede have meant that the number of properties benefiting from the Scheme is below our expectations. As views of flood risk vary across the market and are reflected in ceding patterns, we have invested significantly in our understanding and modelling of flood risk to help us optimise the design of the Scheme and as a result benefit insurers and their customers.”[60]

This implies that one of the most important ways that investors and lenders can influence their risk is through both strategic location investment decisions (which region/country/continent) and local asset-siting decisions; although any such changes should be done carefully, in a phased, managed way. Capital providers to investors and lenders will likely want to understand how such location decisions, intermediated by insurance availability (discussed above) and adaptation action (discussed below), are taking account of the physical risks of climate change. To the extent that investors and lenders do alter location decisions, it will be much less disruptive to the real economy if this happens over a long period of time rather than as an abrupt response to one or a series of particular events.

Property-level adaptation measures can materially reduce climate change induced losses, and this is most effective when combined with global efforts to reduce emissions. The increase in losses identified above assumes relatively limited efforts to adapt to the impacts of climate change. In the UK, the modelling suggests that, under a 2°C scenario, around two thirds of the additional losses might be offset if half of at-risk households install flood protection measures. This includes measures to prevent flood ingress and measures to reduce damage if flood water does ingress, such as resilient flooring. Further reductions in losses, and a reduction in the number of properties at significant risk of floods (annual probability of flooding above 1.3 per cent), could be secured by increased community-level flood adaptation measures.[b] The analysis of tropical cyclone risk suggests that, in a 2°C temperature scenario, roof upgrades to properties at risk of tropical cyclones might offset around half of the increase in AAL. However, adaptation measures offset a smaller proportion of the increases in losses in higher temperature scenarios, when extreme weather events are expected to be more severe.[c] In other words, rather than considering adaptation as an alternative to efforts to reduce emissions, it is best thought as a complement to these efforts.

[b] The analysis assumes spending on construction and maintenance of river and coastal defences continues to be implemented as effectively as experienced in the recent past.

[c] As discussed in Section 3.4.3, adaptation measures provide only limited resilience against the most extreme events.

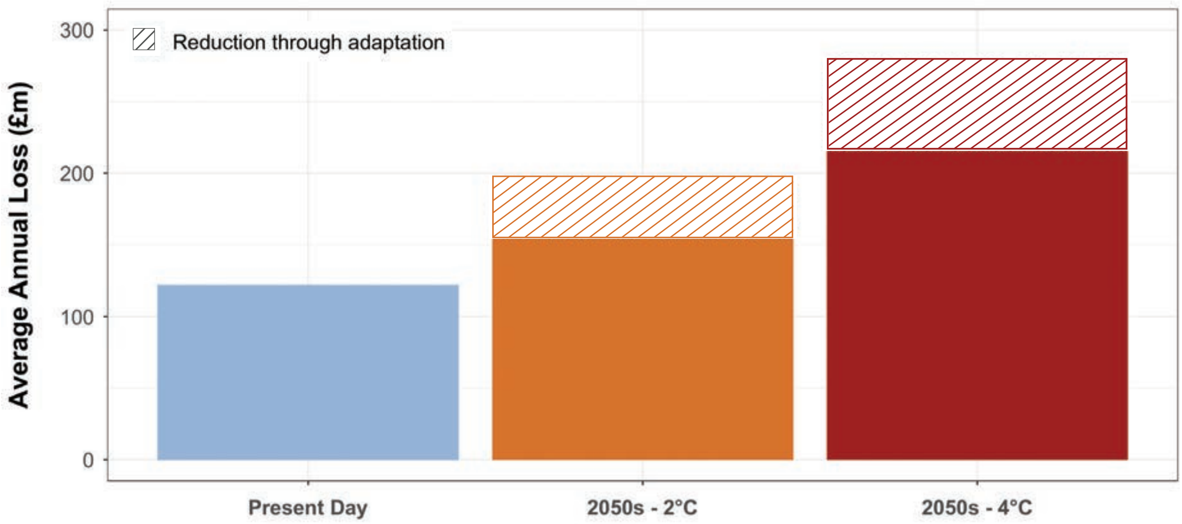


Figure 2. The modelling suggests that adaptation measures help reduce the Average Annual Loss from floods to properties in UK mortgage portfolios
Source: Vivid Economics, based on FFE

This illustrative analysis indicates there is a powerful opportunity for investors, lenders, the insurance industry and policymakers to target the uptake of adaptation measures in the most beneficial areas. Although it allows for rapid repricing of risk, the short time horizons created by the insurance industry's practice of one-year insurance contracts limits the ability for insurers to incentivise adaptation measures. However, investors and lenders, combined with policymakers, may find it easier to take a longer-term perspective. They could work in concert with insurers to encourage the uptake of adaptation measures, for instance, by making both loans and insurance contingent on the installation of relevant adaptation measures. These efforts could help overcome 'first-mover risks' whereby households may be unwilling to introduce adaptation measures that similar households do not have, for fear that their abnormality, and the signal that the property may be exposed to physical risks, might reduce the value of the property.

Advisory Group List

ClimateWise Insurance Advisory Council (2018)

Dominic Christian	Chair of ClimateWise and Global Chairman, Reinsurance Solutions at Aon
Jon Dye	CEO, Allianz UK
Stephen Catlin	Special Advisor to XL's Chief Executive Officer, XL Group plc
Charles Franks	Group CEO, Tokio Marine Kiln
Patrick Tiernan	Managing Director, Aviva Global Corporate & Specialty
William McDonnell	Chief Risk Officer, RSA Insurance Group
Rowan Douglas	CEO for Capital, Science and Policy Practice, Willis Research Network, Willis Group
Alex Hindson	Chief Risk Officer, Argo Group International Holdings, Ltd
Huw Evans	Director General, Association of British Insurers (ABI)
John Parry	Chief Financial Officer, Lloyds
Martyn Parker	Chairman Global Partnerships, Swiss Re
John Scott	Chief Risk Officer, Zurich Insurance plc
Simon Beale	CEO, MS Amlin
Ricard Wennerklint	Deputy CEO, If P&C
Steve Weinstein	Group General Counsel and Chief Compliance Officer, RenaissanceRe

With thanks to previous representatives of the ClimateWise Insurance Advisory Council:

Maurice Tulloch	Chair of ClimateWise (2015-2017), CEO International Insurance, Aviva
Scott Egan	Chief Financial Officer, RSA
Charles Philipps	previously CEO, MS Amlin

ClimateWise Physical Risk Advisory Panel

Elizabeth Cannizzo	Actuarial Analyst, Bank of England
Juan Duan	Risk Specialist – Catastrophe Risk, General Insurance Risk Specialists, Prudential Regulation Authority, Bank of England
Giorgis Hadzilacos	Technical Specialist – Catastrophe & Climate Risk
	General Insurance Risk Specialists, Insurance Division Bank of England
David Rochester	Head of Underwriting, Lloyds Banking Group
Jonathon Gascoigne	Senior Risk Adviser, Capital, Science & Policy Practice, Willis Towers Watson
Matthew Jupp	Principle, Mortgages, UK Finance
Miroslav Petkov	Director, S&P Global Ratings
Daniel Byrne	Chief Risk Officer, Flood Re
Dickie Whitaker	Chief Executive, Oasis Loss Modelling

Advisory Group Supportive Statements

"Flood Re welcomes this analysis which highlights the potential impacts of climate change on UK flood risk. Increasing the understanding of the potential climate change impact on future UK flood risk is an area of ongoing investigation. The direction of travel indicated by this analysis is clear, as is the corresponding threat to Flood Re's public purpose of transitioning to an affordable risk reflective home insurance market for those households most at risk of flood. Research and analysis, such as this report, will feed into Flood Re's medium and long-term plans, in particular the steps we are taking to assess and facilitate the take-up of adaptation measures.

Responding to the consequences of climate change and particularly the increased risk of flooding in the UK requires collaboration and action from a broad range of public and private stakeholders, including Government, insurers, mortgage providers, rating agencies and regulators. Flood Re therefore supports the the ClimateWise Principles and its work to draw together these various stakeholders, and looks forward to participating in future research and analysis to better understand and plan for the shifting landscape of UK flood risk."

Flood Re

"Lloyds Banking Group welcomes this research into the possible impact of climate change on properties in the UK. As a key mortgage lender, commercial lender, and home insurer, Lloyds has a significant interest in this issue from both a commercial and a customer point of view. Understanding the effects of climate change on UK homes, and responding to those consequences, is very important to us and to our customers. The key observation of this report – that we need to focus on both the mitigation of climate change, as well as adaptation to its effects – and that if we do both, we can maintain affordable insurance, is a positive message and one that Lloyds very much supports."

David Rochester, Lloyds Banking Group

"It's important that we keep pushing the boundaries of our understanding of a changing climate across a wide user base seeking answers to important questions. This study, which we are pleased to co-fund, provides an important step in demonstrating how metrics, historically mostly used by the (re)insurance market, have wider application across financial services. Work being pioneered by the (re)insurance industry on interoperability in models and data will further help bring new models and techniques to a wider audience at lower cost, helping society make more informed judgements on key risks."

Dickie Whitaker, Oasis

1. Introduction

This section explains the problem this work seeks to address, why this analysis has been carried out and the broader context that makes this contribution timely.

It also situates the work in the context of other recent studies exploring similar issues.

1.1 Why does physical climate risk matter to investors, lenders and their regulators?

The physical impacts of climate change (physical risks) will increase materially in the period to 2050, regardless of emission reduction efforts, with severe consequences for many parts of the world. Physical risks are those that result from climate variability, extreme events and longer-term shifts in climate patterns. 2018 saw a number of particularly severe climate-related extreme events across the globe, consistent with the Intergovernmental Panel on Climate Change (IPCC)'s findings that the frequency and severity of climate-related hazards are increasing due to climate change.[2] Evidence is emerging that these hazards have the potential to significantly affect lives, livelihoods and assets across the globe. The IPCC's Fifth Assessment Report[10] identifies, in particular:

- increased frequency and intensity of heatwaves
- increased frequency of heavy precipitation events, resulting in greater risk of flooding at the regional scale
- increased frequency and intensity of extreme sea level events, such as those caused by storm surges.

Climate change induced physical risks are combining with other trends to mean that losses from climate-related hazards will continue to rise unless significant risk management efforts are put in place. In the short term, increased losses will largely result from greater exposure and vulnerability arising from socioeconomic trends such as urbanisation, asset growth and population growth. For example, the population in coastline regions of the Gulf of Mexico in the United States increased by 150 per cent between 1960 and 2008.[11] However, these trends will be exacerbated by climate change, which will become an increasingly prominent driver of losses without substantial efforts to reduce emissions.

The physical impacts of climate change are direct and indirect, spreading through sectors, countries and value chains. While initial events are often localised, damaging or destroying real assets such as homes or infrastructure, their implications can spread across countries, markets and business value chains, creating knock-on effects that cascade through sectors. For example, the disruption caused by the Thai floods of 2011 resulted in the global price of hard drives doubling.[12]

The disruption and damage caused by physical risks has ramifications for investors and lenders. The financial service sector's exposure to physical climate risks varies depending on the type of operations, geographic location and portfolio composition. Recent reports show that physical impacts can adversely affect the market value of assets[13] and lead to increased corporate and sovereign credit risk.[14] Estimates suggest that US$2.5 trillion of financial asset value is at risk along a business-as-usual emissions path, potentially increasing to US$24.2 million (17 per cent of global financial asset value) if climate change is more damaging than expected.[15]

1.2 How are investors and lenders responding?

Investors and lenders are increasingly acknowledging the significance of physical risks. Back in 2010, the UK government's Foresight Project report on the impact of climate change on the UK financial services sector[16] concluded that many banks had little risk management and risk analytical expertise on the topic of climate change. Over the last few years, as Box 1 shows, banks, investors, regulators and other parts of the financial sector have increased efforts to understand the physical impacts of climate change. This has been driven by public policy, industry and public pressures, and influenced by concerns about potential financial losses and fiduciary duties. Physical risks disclosure by banks, investors and their clients/investees is seen as a key step to improve understanding of the possible implications of climate, as highlighted by the Task Force on Climate-related Financial Disclosures (TCFD's) recommendations or France's Article 173 disclosure requirement.[d] In assessing and responding to these risks, it is important to acknowledge the difference in the financial interests between investors – who have a focus on both upside and downside risks and generally have a greater risk appetite – and lenders – whose focus is more on protecting against downside risks materialising and who are typically more risk averse. Also, while the strategy of individual investors and lenders will vary significantly, lenders will also typically retain their financial interest in a specific asset for longer.

At present, the analytical ability to assess current and future physical risks, as well as assess opportunities, is generally limited. While the demand for physical climate risk analytics is increasing rapidly, largely in response to global initiatives such as the TCFD, the use of physical risk data and associated tools by investors and lenders remains very limited. Often, investment decisions proceed without any reflection of their exposure to physical risks.[17] This is particularly concerning given global infrastructure needs, estimated to be up to US$90 trillion by 2030.[18]

Implicit assumptions that insurance can cover any elevated physical risks may not be justified. Even today, the majority of natural disaster losses are not covered by insurance: Swiss Re estimates that the total economic losses from natural disasters have averaged US$180 billion annually in the last decade. Of this, around 70 per cent of risks from natural disasters remain uninsured, rising to 80–100 per cent in emerging markets.[19] Looking ahead, physical risks could influence the future affordability and availability of insurance protection. In their first-ever report on climate change, the UK's Prudential Regulation Authority noted that "increasing levels of physical risks could present challenges, both to market-based risk transfer mechanisms and to the underlying assumptions behind general insurance business models".[4] Increases in expected losses from extreme weather events are expected to raise the premiums needed to cover expected losses, making it harder to provide affordable insurance, and potentially making certain high-risk locations effectively uninsurable on commercial terms, with knock-on implications for property owners and mortgage providers.[20] In addition, increased levels of uncertainty might require insurers to hold more capital in order to meet solvency requirements.

Various other barriers also hold back investors and lenders in acquiring a detailed understanding of physical risks. In addition to any implicit assumption about insurance availability, businesses responsible for property construction often have no financial stake in the property beyond the point it is sold to a longer-term asset holder. This means that longer-term risks might be ignored when making critical non-reversible decisions which determine resilience to extreme weather. Often physical risks are disregarded in favour of other over-riding priorities, such as location or demand. However, a further key barrier is a perception among investors and lenders that there is a lack of access to analytical tools that enable investors and lenders (as well as regulators) to allow such assessments to be undertaken, particularly at the level of granularity that can inform effective decision-making.

[d] Article 173-VI of the Energy Transition for Green Growth Law requires asset owners and asset managers to explain the methodology and results of applying climate risk analysis. The law also requires the same stakeholders to report on their transition risk exposure.

1.3 How can the tools of the insurance industry help understanding of physical risks among investors and lenders?

The insurance industry can help build greater understanding of physical risks among investors and lenders. For a long time, insurers relied on loss experience and historic loss data to inform their risk underwriting decisions. Over the last two decades, however, the industry has increasingly turned to probabilistic computer models to understand the full distribution and scope of potential catastrophe losses. These models inform insurers' decisions on risk strategy, risk pricing and capital requirements. Mostly developed by private specialist companies who employ teams of scientists, mathematicians and engineers, the models are then licensed to insurance companies. This expertise has developed in the course of decades of underwriting and risk advisory activities. While initially only focused on current risk, given the 12-month underwriting cycle, methodologies have recently been advanced to also consider the longer-term impacts of climate change on catastrophe risk. The insurance industry body, the Geneva Association, recently endorsed and encouraged the incorporation of longer-term impacts of climate change, through the use of climate science analysis, into catastrophe risk modelling.[5]

In turn, greater clarity on the extent of current and future physical risks would allow investors and lenders to reconsider how these risks influence their decision-making, and how they might improve the resilience of their clients and society in general. An enhanced understanding of physical risks would allow lenders and investors, recognising that each group will have different interests and incentives, to engage with their clients and investee companies on their physical risk exposure, and realise business opportunities by supporting action to improve resilience. This could include developing ways to rate the resilience of different assets to physical risks.[23] Better sensitising major pools of capital to physical risks is a key first step to enhancing understanding about the (future) protection gap and empowering action such as adaptation.

The purpose of this report is to show how investors and lenders can make use of insurance industry catastrophe modelling tools and metrics to improve their management of the physical risks of climate change, especially by encouraging adaptation measures in targeted areas. It is structured as follows:

- **Section 2** provides an introduction to the insurance industry's natural catastrophe modelling tools and techniques that can be used to model extreme weather risks.[e]
- **Section 3** offers a practical guide as to how these tools can be used by investors and lenders to understand the physical risks of climate change, and shows how this guide has been applied in developing the results presented in this report.
- **Section 4** provides illustrative quantitative results from the new analysis of the physical risks to 12 real estate portfolios with a total market value in excess of £2 trillion.
- **Section 5** provides implications and conclusions for investors, lenders, insurers and policymakers.

Box 1. This report builds on existing work on physical climate change risks to the financial sector

A number of recent reports have helped contribute to greater understanding of the impact of physical climate change risks on investors and lenders and their investees/clients. This contribution builds on each of their foundations.

- **The Bank of England has highlighted the financial risks from climate change to the UK banking sector in a recent report.**[9] Although in the short term, the high penetration of insurance and the existence of Flood Re is expected to protect banks' exposures, the Bank of England reports that retail banks perceive flood risk to mortgaged properties to be one of the most significant climate risks facing retail banks, while the Bank recognises that these risks could 'crystallise' if, for example, insurance firms are unable to pay out against claims, insurance is withdrawn, or Flood Re is discontinued. However, the report does not include explicit modelling of the climate change risks to properties in banks' portfolios, nor discuss the extent to which adaptation measures might reduce these risks.
- **As part of a pilot project, 16 banks and the United Nations Environment Programme Finance Initiative (UNEP FI) have developed methodologies that aim to help the banking industry to understand and manage the physical risks and opportunities of climate change in their loan portfolios.**[21] The work draws together a range of different methodologies and climate change impact studies to develop 'impact metrics' that are applied to portfolios of agriculture, energy and real estate assets. While comprehensive in its coverage of climate risks, the report does not provide an explicit spatial analysis, explore the links between the insurance and banking sectors, nor look at how adaptation measures may offset increased physical risks.
- **The European Bank for Reconstruction and Development (EBRD) has issued recommendations on the disclosure of risk from physical impacts of climate change.**[22] These include the use of climate change scenarios, the types of risk metrics that should be used and the timescales that should be considered. An accompanying interactive web tool provides suggestions for how various business sectors should consider the relevance of physical risks. This report shows how the EBRD's recommendations can be implemented in practice, and the results that can emerge.

[e] This section is provided for those not familiar with these tools and techniques and may be skipped by those with experience of these tools.

2. A primer for investors and lenders on insurers' natural catastrophe models for extreme weather perils

This section describes the tools available to model extreme weather perils (Section 2.1) and the results they provide (Section 2.2).

It also explains how the change in probability and severity of these perils as a result of climate change can be incorporated into these tools (Section 2.3). In doing so, it recognises that while such (acute) events are one of the main ways in which climate change influences economic activity and the wider financial system, there are also other channels related to incremental changes in the climate (or chronic changes) such as rising temperatures or changes in precipitation patterns (see Appendix A for more discussion).

2.1 Introduction to the modelling of extreme weather perils

Catastrophe models estimate risks from extreme weather events. Catastrophe models are sophisticated computer models used to estimate the risk of physical damage and the financial costs of such damage ('losses') to a geographically specified portfolio of physical assets, typically buildings, caused by extreme weather events including tropical cyclones (hurricanes/typhoons), earthquakes, hail, winter wind storms, floods and wild fires.[f] Typically, the key output of a natural catastrophe model will be the distribution of possible losses, expressed in financial terms, to the portfolio.

Catastrophe models vary in detail but typically share the same key hazard, vulnerability and financial modules that are applied to a set of physical assets, referred to as exposures. As shown in Figure 3, these components work in combination to estimate the risk of financial losses to a portfolio of exposures. Where information is available, most models can also incorporate attributes about building type (modifiers) in relation to the exposures, and details on insurance arrangements for the purposes of calculating financial losses.

[f] This section serves as a short introduction to their key features; a comprehensive guide to natural catastrophe models can be found elsewhere.[33]

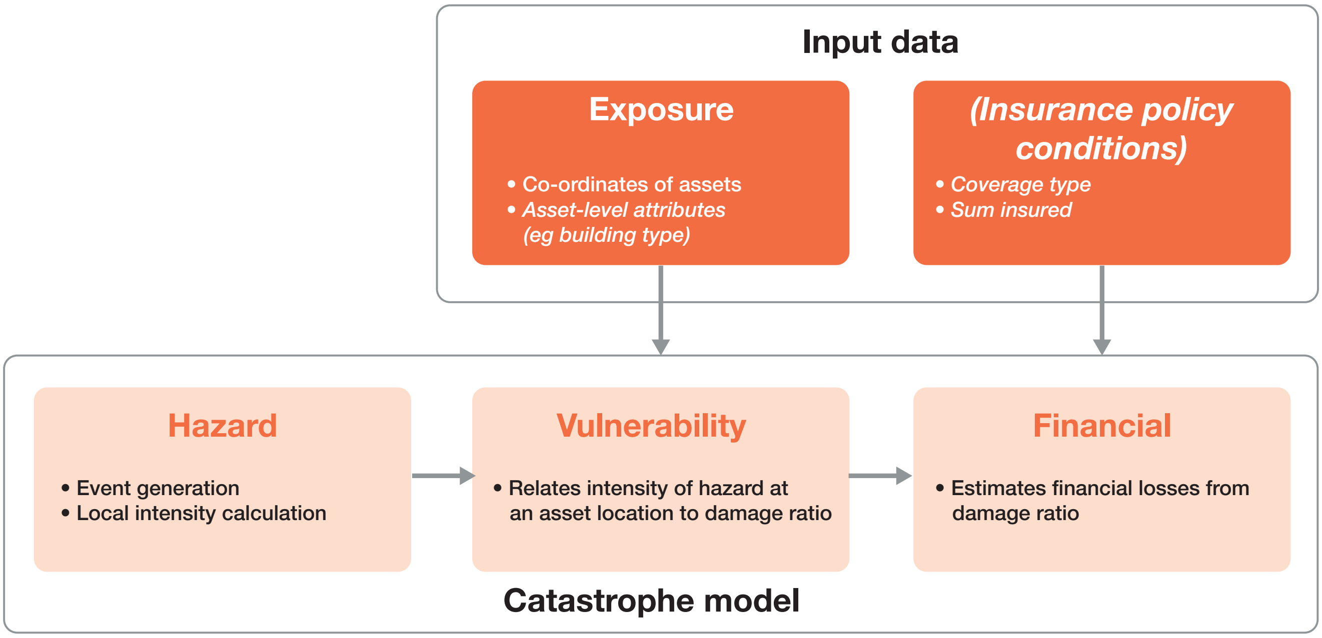


Figure 3. Catastrophe models comprise hazard, vulnerability and financial modules

The hazard element of a catastrophe model assesses the physical extent and intensity of physical perils – for example, hurricane or flood events. In order to provide a comprehensive view of future risk, a natural catastrophe model needs to model possible future extreme weather events. One method for generating this is to take a catalogue of historical events,[9] and make small, plausible modifications to each historical event's location or intensity to reflect what might happen in the future. At this stage, understanding of the impact of climate change on physical perils can be used to make modifications to the possible future extreme weather, for example, by incorporating any expected increases in intensity (as described in more detail in Section 2.3).

The vulnerability element estimates the physical damage caused by an extreme weather event. This normally uses damage curves, which relate the intensity of a hazard at a particular location to damage caused to assets at that location. For example, a damage curve for flood events describes the damage which would occur to assets at various flood depths. Damage is normally expressed in terms of a damage ratio, with a damage ratio of 100 per cent indicating total destruction of an asset.

Damage curves are generated either using observed data from historical events, or using analytic or experimental estimates. In the latter case, detailed characteristics such as building age, structural characteristics and building occupancy can be used to select an appropriate damage curve for a given exposure. Uncertainty around damage curves is a major source of uncertainty in natural catastrophe models.

The vulnerability element can be used to model impacts of adaptation. Many adaptation measures involve physical changes to real estate assets so as to reduce the damage done to assets by hazards of given intensities. This, in turn, reduces expected financial losses. Inside natural catastrophe models, the effects of this type of adaptation measure can be modelled by selecting a damage curve with a lower damage ratio at given intensities. A comparison of losses with a 'baseline' and 'adaptation' damage curve provides an estimate of the effect of adaptation.

[9] For example, the archival data of past hurricane events published by Unisys, or catalogue of European winter wind storms published by the EU's Copernicus Wind Storm Information Service.

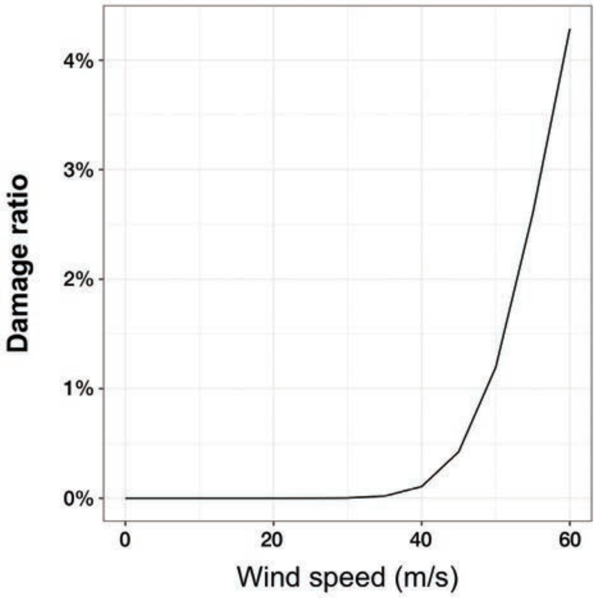


Figure 4. A damage curve relates hazard intensity to damage ratio
Source: CLIMADA

The financial element transforms physical damage to economic loss. By combining distribution of damage ratios with input data on replacement costs and any possible insurance contracts, the financial implications of the physical damage done by the event can be calculated.

In order to provide a comprehensive view of future risk, a natural catastrophe model needs to model possible future extreme weather events.

In many modelling approaches, this process is then repeated many thousands of times to help understand different scenarios of future losses. The precise frequency, severity and impacts of extreme weather events happening in the future are impossible to predict. To reflect this, many catastrophe models run thousands of simulations, in each case modelling a slightly different synthetic event. By calculating losses for each of the events in the synthetic event set and looking at the overall distribution of these losses, models with this feature are able to provide a comprehensive assessment of future risk, including information not just on the most likely (or expected) outcomes but also their likely distribution. As such, many catastrophe models can automatically embed, in a very sophisticated manner, an element of scenario analysis into the assessment of physical risks, as recommended by the TCFD.

2.2 Typical outputs from natural catastrophe models

Although natural catastrophe models vary in their implementations, they typically produce a common set of outputs including:

- *Average Annual Loss (AAL).* This expresses the average losses from property damage experienced by a portfolio per year. If insurance is available and priced commensurate with risk, the AAL provides a lower-bound estimate of the premium required to insure against the risk.[h] For illustration, Table 2 shows the calculation of AAL over a ten-year period for two scenarios. In both scenarios, total losses over ten years amount to £620 million, yielding an AAL of £62 million. However, the AAL metric provides no indication of whether losses are expected to be concentrated in a small number of years (as per Scenario 2) or spread more evenly through time (as per Scenario 1).
- *Annual probability of occurrence*. This measures the probability that, over the period of one year, a given asset (exposure) experiences an event of a given magnitude. For example, an asset might be at a 1 per cent chance of flooding at a depth of one metre or more in any given year.
- *Annual exceedance probability curve.* This shows the probability that any given threshold of losses will be exceeded in any given year. For example, the hypothetical exceedance probability curve in Figure 5 shows there is a 1 per cent chance of the portfolio experiencing a loss of £100 million or higher in any given year. AAL can be derived from an exceedance probability curve.
- *Return periods.* These are a way of describing the magnitude of an event. A flood with a 100-year return period has a 1 per cent chance of being exceeded by a higher-magnitude event in any year. Such a flood is expected to occur approximately, but not exactly, every 100 years.[24] Table 3 shows the relationship between return period and probability of exceedance at some frequently used values.

Year	Scenario 1 loss (£ million)	Scenario 2 loss (£ million)
2001	7	0
2002	0	0
2003	194	620
2004	125	0
2005	9	0
2006	21	0
2007	0	0
2008	14	0
2009	250	0
2010	0	0

Table 2. In both scenarios, the Average Annual Loss is £62 million but the pattern of losses in the two scenarios is very different

Note: In both scenarios, total losses over ten years are £620 million, yielding an Average Annual Loss of £62 million.

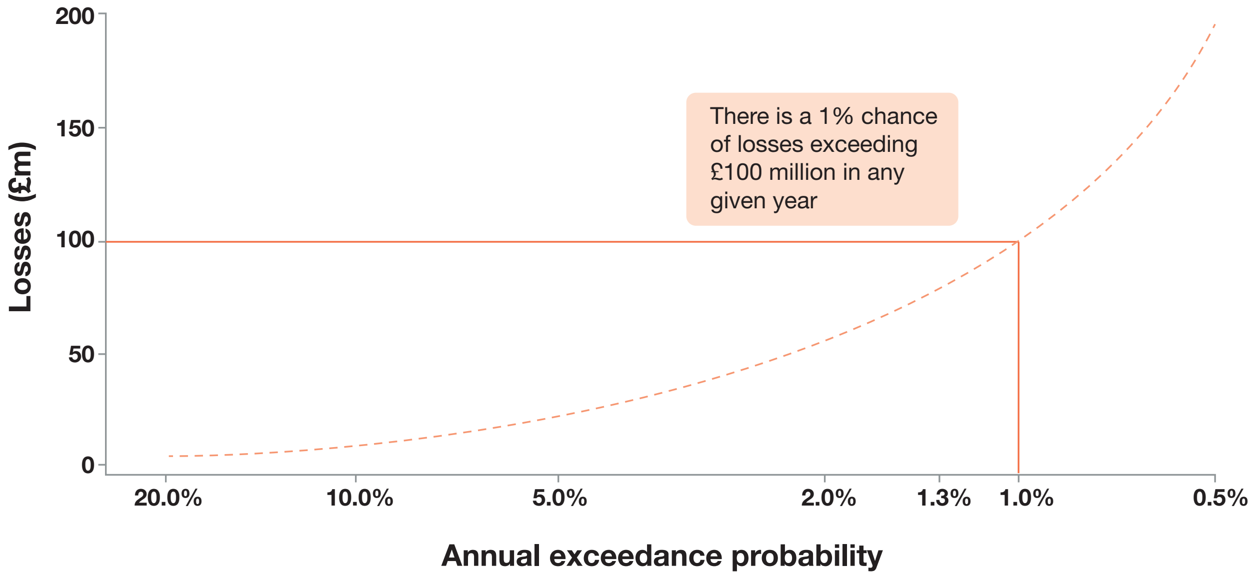


Figure 5. An exceedance probability curve shows the probability that different loss amounts will be exceeded in any given year

[h] Insurance premiums would be equal to the AAL in the absence of any administrative costs or profit in the insurance industry.

Probability losses are exceeded	Approximate return period
0.5%	200
1%	100
1.3%	75
2%	50
5%	20
10%	10
20%	5

Table 3. Return periods provide an alternative way to express exceedance probabilities

2.3 State of knowledge about climate change impacts on extreme weather risk

Climate change is expected to change the future frequency and intensity of extreme weather events, thereby altering the exposure of asset portfolios to physical risks. As a hypothetical example, it could mean that a property that was previously subject to a 1 in 100 annual probability of flooding (occurrence probability of 1 per cent) could see this probability increase to a 1 in 75 annual probability of flooding (occurrence probability of 1.3 per cent).

There is robust evidence that climate change is already under way. Each decade since 1980 has been warmer than any since 1850 (Figure 6). In turn, increases in atmospheric and ocean temperature have already reduced the amount of snow and ice and caused sea level rise. It is extremely likely that the predominant cause for these changes is the increase in greenhouse gas concentrations caused by human activity.[25]

It is very likely that climate change has already increased the frequency of some extreme weather events. The number of heatwaves in Europe has risen since 1950, with extreme temperatures estimated to already be ten times as likely as they were at the beginning of the 21st century. It is also likely that climate change has led to an increase in on-land heavy precipitation events.[2]

Further greenhouse gas emissions will cause future increases in global temperatures and associated changes in the climate system. The extent of these changes will be determined by the quantity of anthropogenic emissions. Current climate models predict that the increase in global mean temperatures relative to the pre-industrial period will be limited to around 2°C if global emissions are halved by 2050 relative to their 1990 levels. Even in this case, there will be substantial increases in the frequency and severity of many extreme weather events. However, under a 'business as usual' emissions pathway, global mean temperatures could increase by around 4°C by the end of the 21st century, leading to much more severe changes in some extreme weather events.

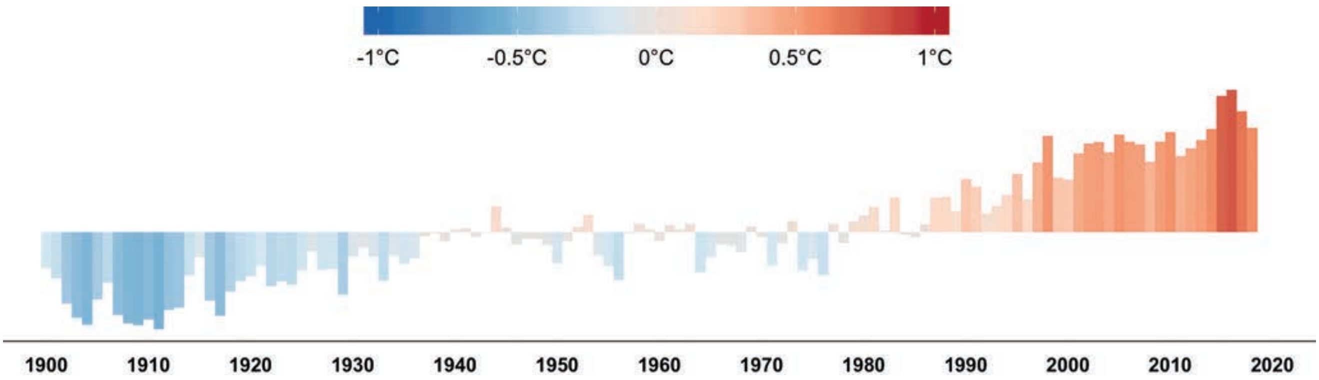


Figure 6. The global temperature record shows substantial warming in recent years
Note: The figure shows global mean temperatures in each year between 1900 and 2016 compared to a 1961–90 baseline.
Source: Climatic Research Unit, University of East Anglia

Climate models can be used to predict how climate change will influence the likelihood and severity of extreme weather events, although modelling some perils still represents a challenge. Drawing on evidence from the Intergovernmental Panel on Climate Change's Fifth Assessment Report, Table 4 shows how the scientific understanding of the physical relationship between climate change and perils varies. In general, extreme events related to temperature, such as extreme cold or heat, are better understood than complex meteorological phenomena such as storms and cyclones.

This report focuses on how climate change will lead to increases in physical risks from flooding in the UK, European winter wind storms caused by extratropical cyclones, and tropical cyclones in North America and the Pacific basin. The current understanding of, and confidence in, the link between these perils and climate change is as follows:

- **There is broad consensus that climate change will result in higher sea levels and more intense rainfall, raising the frequency of flood events in many geographies, including the UK.** By the end of the 21st century, global sea levels are expected to rise 53cm under a 2°C warming scenario and 74cm under a 4°C warming scenario (with a 66 per cent likelihood these will fall between 36–71cm and 52–98cm respectively).[26] The UK's 2017 Climate Change Risk Assessment concludes that "the impacts of flooding and coastal change in the UK are already significant and expected to increase as a result of climate change".[27]
- **The relationship between climate change and tropical cyclones is an area of active research.** The IPCC Fifth Assessment Report concludes that global warming is likely to result in fewer or an unchanged number of cyclones globally, but that the intensity of these cyclones is likely to increase.[28] Confidence in regional predictions is limited, but by the end of the 21st century, it is considered "more likely than not" that tropical cyclone intensity will increase in the western North Pacific and North Atlantic. However, there is low confidence in these predictions to the mid-21st century and some variance between models as to their predictions by the end of the 21st century.[28, i]
- **The effect of climate change on European winter wind storms is likely to be small, but the physical mechanisms linking climate change to European winter wind storms are still being investigated.** A recent review paper finds that most modelling studies expect more frequent and intense storms over Central and Western Europe, fewer storms in Southern Europe but that results are inconclusive for Northern and Eastern Europe.[29] Climate models do not always agree on the sign or magnitude of changes, and the biggest changes are expected only towards the end of the 21st century.

Despite these challenges, modelling physical risks provides important, valuable information for investors and lenders. While detailed understanding of the links between climate change and extreme weather events continues to evolve, the science makes clear that there are expected to be changes, many of which could be significant. Waiting for uncertainty in the climate science to resolve completely is likely to result in worse outcomes for both investors, lenders and society than working with the estimates that are available. Moreover, the modelling techniques identified in this report are flexible enough to account for the uncertainty in the relationship between climate change and extreme weather events, and can also be easily updated as the scientific evidence base improves.

	Likelihood of further changes by late 21st century	Region
Warmer and/or more frequent hot days and nights over most land areas	Virtually certain (99–100%)	Over most land areas
Increase in precipitation	Very likely (90–100%)	Arctic, Northern Europe, North America and Southern Hemisphere
Increases in intensity and/or duration of drought	Likely (66–100%)	On a global scale
Increase in intense tropical cyclone activity	More likely than not (50–100%)	In the western North Pacific (affecting eg China, Hong Kong, Macau, Japan, Korea, Philippines, Taiwan and Vietnam) and North Atlantic Ocean basins (affecting for example the Atlantic coast of the United States and Central America)
Increased incidence and/or magnitude of extreme high sea level	Very likely (90–100%)	Global
Small increases in winter wind speed extremes (European winter wind storms)	Likelihood not provided "Medium confidence" in change	Central and Northern Europe

Table 4. The impact of climate change is better understood for some perils than for others
Note: "Medium confidence" means scientists have either high agreement based on limited evidence; medium agreement based on medium evidence; or low agreement based on robust evidence.
Source: IPCC [30], and IPCC Chapter 14 and Chapter 23 [28], Table SPM.1, Chapter 14 and Chapter 23[28]

[i] The IPCC Special Report on Global Warming of 1.5°C reports that, in a 2°C warming scenario, a global-scale increased intensity and frequency of hot days and nights is very likely, that there is high confidence in increases in frequency, intensity and/or amount of heavy precipitation averaged over global land, that there is medium confidence in increased drought, dryness or precipitation deficits in some regions, that there is medium confidence in increased flood hazard in some regions and further increases in heavy precipitation associated with tropical cyclones.[2] Sea level rises are not assessed. An assessment of the capabilities of climate models to simulate perils and of the understanding of physical mechanisms that link climate change to changes in extreme events by peril is also available from the National Academy of Sciences.[92] However, this does not provide any quantification of the likelihood of future changes.

3. A practical guide for investors and lenders to repeat this methodology

This section sets out the steps that investors and lenders can follow to use natural catastrophe models to understand changing physical risks and the impacts on their portfolios.

Each of these four steps is described in general terms, with boxes then explaining how these steps have been applied in the illustrative analysis presented in this report. Figure 7 shows the outline of our methodology in terms of each element of a catastrophe model (as presented in Section 2.1): while assuming exposure (assets) remain constant over time, we model how climate change impacts the intensity and frequency of hazards, and how the vulnerability of exposures to those hazards can be changed through adaptation measures.

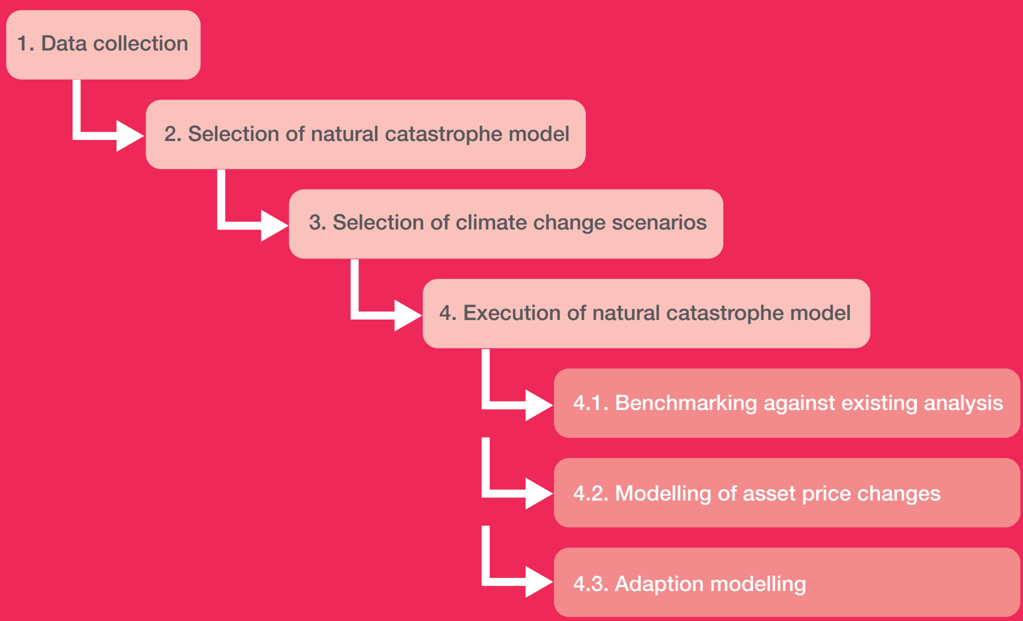


Figure 7. Key steps for investors and lenders to follow in modelling the physical risks of climate change

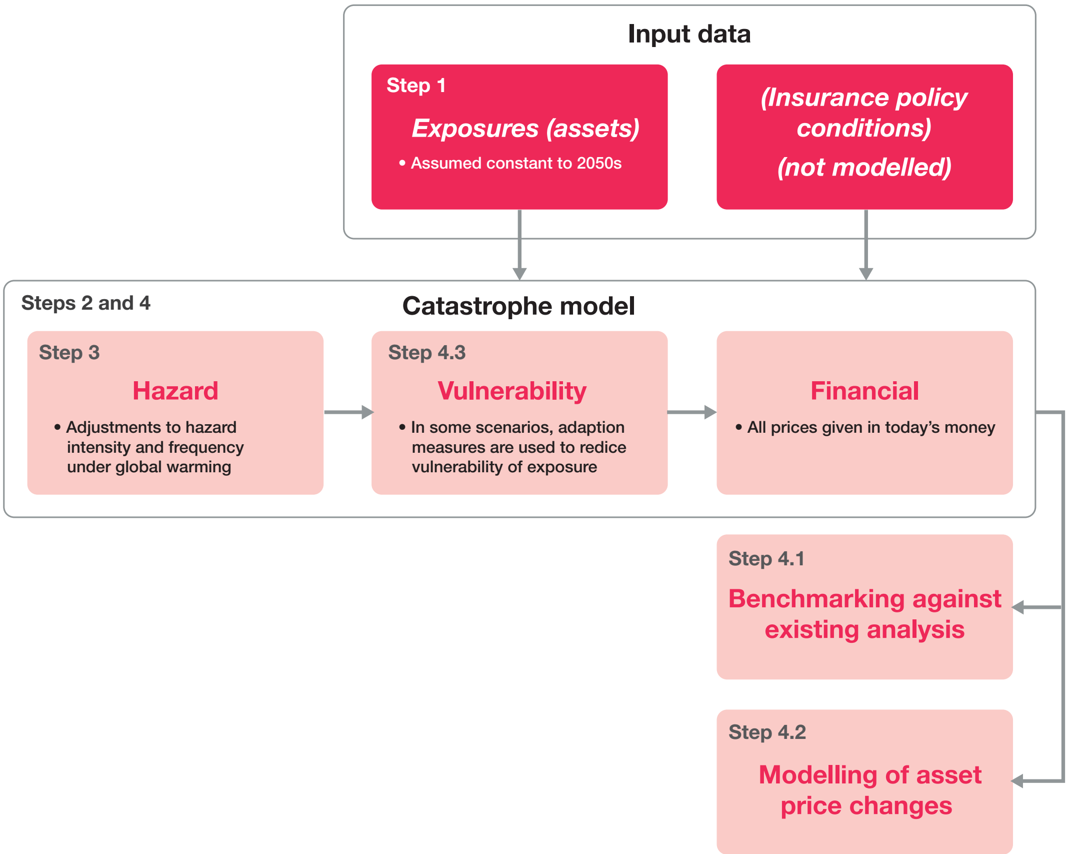


Figure 8. Model of the effects of climate change and adaptation measures on a given set of assets (exposures)
Note: Numbers refer to key steps in modelling process, as shown in Figure 7.

3.1 Data collection

The minimum data required by investors and lenders for input into catastrophe modelling is a set of physical assets ('exposures'), their geographic locations and some information on asset class, such as whether they are residential or non-residential property.

Modern natural catastrophe models run at a high spatial resolution and benefit from precise location data for each of the exposures. Flood models typically have a spatial resolution of between two and 50 metres, reflecting the geographic specificity of flood events; other perils might be modelled at lower resolutions. Most models require exposure location data to be provided in co-ordinate (latitude and longitude) form. Where co-ordinate data is not already available, 'geocoder' software can be used to convert a street-level address to co-ordinates. By looking up the address in a database, the geocoder converts the address '10 Downing Street, London, United Kingdom' to the co-ordinates 51.5034, 0.1276. Some natural catastrophe models have a geocoder built in; where they do not, there are a number of commercial services available. Since addresses are sometimes incomplete or ambiguous, it is often necessary to undertake a manual check of the plausibility of geocoder outputs. At minimum, this might involve checking that all co-ordinates returned by the geocoder are within the expected country/area. A more thorough review would 'reverse geocode' the co-ordinates returned by the geocoder back to addresses and make sure these match the original addresses provided.

Where detailed asset-level attribute data is available, this can provide a more representative view of risk by providing input for more advanced physical models. Such data might include property-level information on construction type and year, roof type, number of floors, occupancy and square footage. These additional property-level attributes are commonly known as 'modifiers'. Where precise information is not available, estimation techniques can be applied: commercial natural catastrophe models frequently incorporate databases which can be used to derive the most likely attributes for any given property.

Box 2. Modelling exercise: data collection

This analysis modelled risks from extreme weather events to 12 real estate portfolios. These 12 portfolios are in two distinct categories:

- Seven portfolios are collections of properties with outstanding mortgage loans to each of seven large UK retail banks or building societies. As mortgage providers, these financial institutions' focus is on devaluations and default risk over a period of up to 35 years.
- Five of these are direct investment portfolios held by ClimateWise members, insurers who hold real estate on their asset books, often as long-term investments. These relate to investments in commercial property, primarily offices and retail centres, but also including some residential property and industrial facilities. Data on these portfolios, which span the UK, the rest of Europe, Asia, North America and South America, were provided for analysis on a confidential basis. These are equity investments and so the investors have an interest in both upside and downside risk.

The analysis of the mortgage portfolios is facilitated by a commitment from the UK finance sector to improve transparency about lending locations. UK Finance publishes statistics on the total value of mortgage lending by each of ten United Kingdom lenders at the postcode sector level[j] on a quarterly basis.[31] Collectively, these lenders account for 70 per cent of the UK mortgage market. For the purposes of this analysis three lenders whose residential lending activity is heavily focused on Northern Ireland were excluded. The data covers lending to 9,007 postcode sectors as per the end of the third quarter of 2017.[k] For each postcode sector, across each lender, the data records the value (in GBP) of outstanding mortgage lending.

The data on the UK residential lending portfolios are not immediately suitable for inclusion in the natural catastrophe models; our analysis required transforming the data on outstanding lending levels into a property-level dataset. Figure 9 outlines the process. First, combining data on postcode-level lending with data on average loan-to-value ratios published by the estate agent Savills allows an estimation of the total value of mortgaged properties in each postcode sector.[l] Next, we collect and aggregate data published by HM Land Registry to calculate average house prices within each postcode sector. Dividing the total value of mortgage lending in each postcode sector by the average house price in the sector provides an estimate of the number of properties with outstanding mortgages for each lender in each postcode sector.[m] Finally, the analysis assumes that the mortgage portfolios are distributed in space throughout each postcode district in a similar way to all residential portfolios in that postcode district. Figure 10 shows the geographic distribution of assets resulting from these steps.

[j] The average size of a postcode sector is ten square miles. Because postcode sectors are drawn to include roughly equal numbers of households, they cover a considerably larger geographic area in rural areas than in towns or cities.
[k] A small number of postcode sectors are excluded from the data releases in order to preserve customer confidentiality.
[l] This data is published at the local authority level, so we first match each postcode sector to a local authority using lookup tables provided by the Office of National Statistics.
[m] It is thereby assumed that house prices in a postcode sector are similar between mortgaged and non-mortgaged properties.

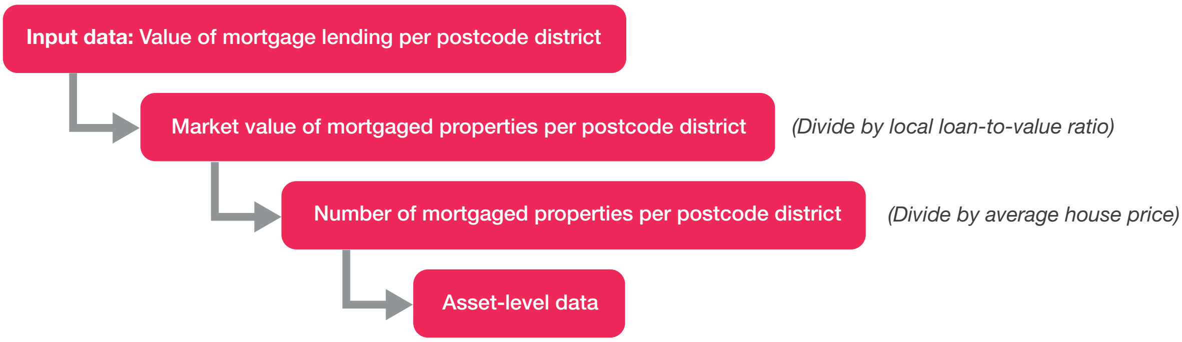


Figure 9. The analysis followed three steps to generate asset-level data for the mortgage portfolios

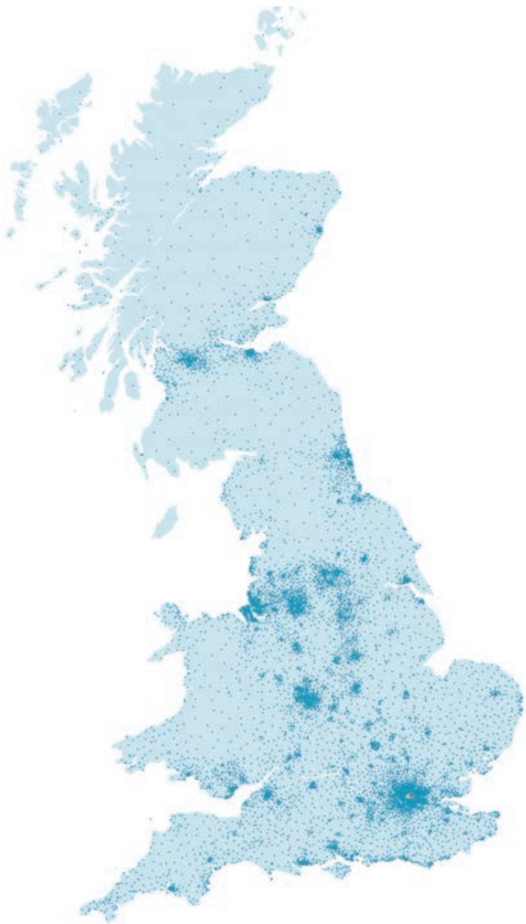


Figure 10. The geographic distribution of assets in the mortgage portfolios is heavily concentrated in urban areas

For the direct investment portfolios, data providers were asked to supply information on each of the assets in their portfolio in spreadsheet form with property addresses or postcodes. Because of the availability of property-level information, the transformations required for the residential lending portfolios was not required. Instead, the Google Maps geocoder service converted each asset's address into latitude and longitude co-ordinates, with a manual review to find co-ordinates for assets where the Google Maps geocoder returned multiple or no results. The analysis excludes assets where it was not possible to be confident that the co-ordinates returned by the geocoder were those of the underlying property. In some cases, data providers were not able to supply asset-level data for their portfolios; these portfolios were excluded from the analysis.

Replacement costs for each asset derive from research by the EU's Directorate General Joint Research Centre. Where a commercial asset owner was not able to provide either replacement cost or area estimates for their assets, we excluded the asset from our analysis. Where area data was available, the EU's Directorate General Joint Research Centre provides an estimate of 'maximum damage' per square metre for a number of different property types: residential, commercial and industrial, representing the full replacement cost per square metre of each asset type.[32] In order to express losses in terms of market value, data providers supplied market value data for each asset in the portfolio which were converted to current market value in GBP using exchange rate and inflation adjustments.

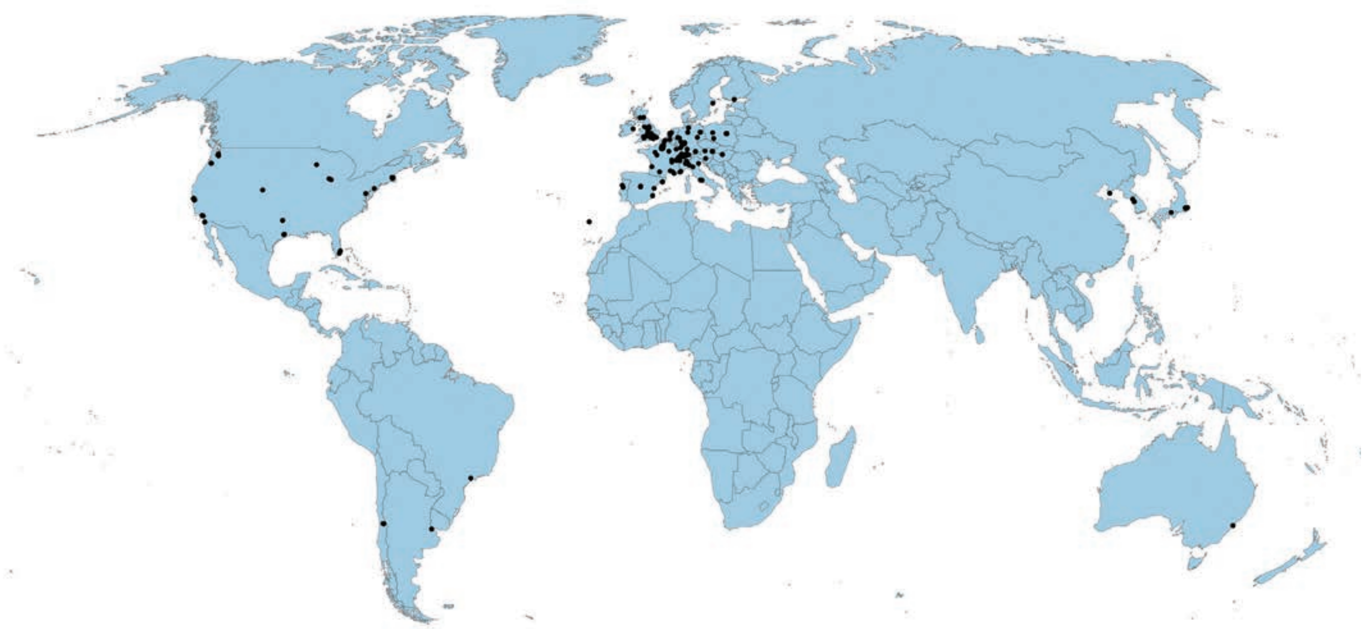


Figure 11. The distribution of assets in the direct investment portfolios covers Europe, North and South America and parts of Asia

3.2. Selection of natural catastrophe model

Investors and lenders can choose from a wide range of different catastrophe models. Box 3 provides a list of some commercial vendors, while Box 4 describes the Oasis Loss Modelling Framework, which is a platform designed to facilitate comparability across different model providers. When making a choice between models, investors and lenders need to consider a number of factors. A critical one will be whether the modelling will be undertaken in house or sub-contracted to a commercial model vendor. The former would require use of an open source model. This may allow for more bespoke analysis to be undertaken and provide greater understanding of what drives any results, but these models may not have received as much investment and will also require reasonable technical skills to be confident that the work is being undertaken accurately. The advantages and disadvantages reverse for vendor models. Other factors to consider include the range of perils modelled and the quality and resolution of those models, the ability of the model to integrate with existing systems and the computational demands of the model. For models supplied by vendors, the extent and transparency of model documentation is another important factor, since this will enable investors and lenders to understand and review the assumptions that have been made in the modelling.

Box 3. Natural catastrophe model vendors

A number of commercial vendors provide natural catastrophe models. The following list of vendors is provided by Mitchell-Wallace et al. 2017:[33]

- AIR Worldwide
- Ambiental
- CATRisk Solutions
- CoreLogic
- ERN
- Impact Forecasting
- JBA
- KatRisk
- KCC
- RMS

Box 4. Oasis Loss Modelling Framework

Oasis is an open source catastrophe modelling platform, providing tools for developing catastrophe models and running these models at scale (Oasis Loss Modelling Framework and Oasis ktools). Oasis defines a standard format that commercial model vendors, academics and research groups can use to distribute models of given physical hazards. In addition, Oasis defines a common format for exposures (assets). By defining open file formats and providing a common platform and calculation engine, Oasis makes it easier to compare and contrast outputs from various models. Oasis underpins ModEx, a multi-vendor catastrophe risk modelling platform.

Box 5. This analysis: natural catastrophe models

This analysis uses CLIMADA and the Future Flood Explorer to analyse how climate change impacts physical risks from three perils, as illustrated in Table 5 below.

				Includes assets exposed to:		
Portfolio	**Predominant asset class**	**Number of assets**	**Market value of assets (UK GBP)**	**UK flood (Future Flood Explorer)**	**European winter wind storms (CLIMADA)**	**Tropical cyclones (CLIMADA)**
UK retail FI 1	Residential			✓	✓	
UK retail FI 2	Residential			✓	✓	
UK retail FI 3	Residential			✓	✓	
UK retail FI 4	Residential			✓	✓	
UK retail FI 5	Residential			✓	✓	
UK retail FI 6	Residential			✓	✓	
UK retail FI 7	Residential			✓	✓	
Sub-total:		**7,200,000**	**2,093 bn**			
ClimateWise1	Commercial			✓		
ClimateWise2	Commercial			✓	✓	
ClimateWise3	Commercial			✓	✓	✓
ClimateWise4	Commercial			✓	✓	
ClimateWise5	Commercial				✓	✓
Sub-total:		**1,251**	**36 bn**			
Total		**7,200,000**	**2,129 bn**			

Table 5. Two catastrophe models are used to model flood and wind storm perils to seven portfolios of UK mortgage properties

Note: FI is short for financial institution. For confidentiality reasons, the number and value of assets in each individual portfolio are withheld. The number of assets in the UK retail bank and building society portfolios ranges between 138,000 and 2,200,000 properties, with associated market values of between £19 billion and £278 billion. The number of assets in portfolios held by ClimateWise members ranges between 23 and 608, with associated market values of between £320 million and £11 billion.
Source: Vivid Economics

CLIMADA is an open source global probabilistic risk modelling and adaptation platform developed by ETH Zurich that can estimate losses from European winter wind storms and tropical cyclones. It follows the same structure as commercial natural catastrophe models: a computation engine combines physical models of hazards, vulnerability calculations and financial data to produce estimates of the distribution of future losses caused by extreme weather events. These estimates can be made for present day conditions or, by making appropriate changes to CLIMADA's probabilistic hazard generation, for various climate change scenarios. CLIMADA is freely downloadable and, thanks to comprehensive documentation and user manuals, can be run without deep technical expertise.[n] It has been used for a number of academic publications.[34,35] While the physical sophistication of hazard models in CLIMADA does not match that of the commercial vendors, it has considerable value from being open source. This means all assumptions behind the model are visible and, with modifications to the source code, can be adapted as required by advanced users.

The Future Flood Explorer (FFE) is a flood model developed by a team of experts in flood risk management, led by Sayers and Partners. The FFE aims to understand how climate and socioeconomic changes effect flood risk and how adaptation measures can offset these changes. It was used as part of the 2017 Climate Change Risk Assessment for the Committee on Climate Change,[7] the assessment of flood disadvantage[36] and in support of the National Infrastructure Assessment 2018,[37] as well as for academic research. As set out in detail in these references, the FFE uses a combination of publicly accessible data (such as national flood maps published by UK governments) and licensed data to develop an efficient representation of the UK flood system and its response to climate change and investment in defences and other flood management measures (including property-level measures). In this analysis, the FFE is used to provide individual and combined estimates from coastal, fluvial and surface water floods to mortgage and non-mortgage assets in Great Britain.

Appendix B gives more details on the models and modelling approach.

[n] The source code and documentation for CLIMADA is available at https://github.com/davidnbresch/climada. It can be run inside MATLAB or GNU Octave, with a Python version forthcoming.

3.3 Selection of climate change scenarios and associated implications for perils

The third key issue for investors and lenders to address is which climate change scenarios to consider. This is a crucial component within the analysis, as it determines the range of impacts expected. It is typically expressed in terms of the expected increase in average global temperatures.[o] In order to account for uncertainty about the world's future emissions trajectory, scenarios chosen should cover a wide range of plausible futures. The scope of potential ranges in temperature increases, typically expressed in terms of temperature increases by 2100 above a pre-industrial baseline, might range from 1.5°C, the temperature target 'aimed for' in the Paris Agreement, to 4°C or more, which broadly reflects the temperature increases that would be expected given the current trajectory of emissions.

A related issue is how to map these changes in global temperature to changes in the severity and frequency of specific disaster events in a particular region. This should incorporate the latest peer-reviewed developments in climate science and acknowledge the uncertainty around these relationships, as discussed in Section 2.3. Some models already include effects of climate change on the frequency and intensity on the perils within their models; otherwise, collaborations with academics or specialist climate change impact modellers may need to be sought out in consultation with the model developer. It should be noted that, whilst catastrophe models normally operate at a very fine geographic resolution, outputs from climate models tend to be produced at a coarser level. As the science of climate modelling progresses, it is expected that the geographic resolution of climate models will come closer to that of natural catastrophe models. In the meantime a process referred to as 'downscaling' is required to apply outputs from climate change models to the natural catastrophe models.[p] In effect, this process provides a first way of understanding the localised impacts from the results emerging from climate science modelling.

Box 6. This analysis: climate change scenarios

This analysis considers two scenarios of future climate change: a 2°C and a 4°C rise in global mean temperatures, by 2100.[q] In 2015, world leaders committed to take measures to limit increases in global average temperature to "well below" 2°C below pre-industrial levels and to pursue efforts to limit temperature increases to 1.5°C. In October 2018, the IPCC presented its assessment of what would need to happen in order to reach this 1.5°C. However, current evidence suggests that neither a 2°, let alone a 1.5°C, temperature target are on course to being met. Independent scientific analysis by the Climate Action Tracker in November 2017 estimated that current global commitments to emissions reductions have only a 10 per cent chance of being sufficient to limit temperature rises to 2°C.[38] A recent sophisticated probabilistic analysis estimates that the most likely global mean temperature rise by the end of the 21st century is 3.2°C[39] and analysis by Schroders suggests that warming could reach 4°C.[40] The two scenarios used therefore span much, if not quite all, of the range of possible outcomes.

Climate models allow for an understanding of the links between global temperature scenarios and the frequency and severity of particular perils at the regional level. As noted above, these links are area of active scientific research and for which, at present, there remains considerable uncertainty, at least for certain perils. For the purposes of this study, the following is assumed:

- For UK floods, changes in sea level rise, extreme rain events and precipitation from the UK Climate Projections 2009 (UKCP09) drive changes in flood risk.[r]
- Changes in tropical cyclone risk in North America and the Pacific Basin are based on published academic research by Knutson, Sirutis, and Zhao.[41] This research paper provides estimates for the effects of global warming on tropical cyclones at the end of the 21st century under a greenhouse gas emissions scenario consistent with a 4°C warming scenario. CLIMADA's tropical cyclone module scales the effects on intensity and frequency to the 2050s (and where required for a 2°C warming scenario) based on the total concentration of greenhouse gases expected in the atmosphere.
- For European winter wind storm risk, an ensemble of EUROCORDEX regional climate models is used to predict regional changes to storm intensity and extreme wind speed.

A fuller discussion of these choices is provided in Appendix B. It is recognised that a fuller assessment would explore the links between temperature change and frequency and intensity of perils in more detail, especially for tropical cyclone and European winter wind storm risk where uncertainty is greatest.

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[o] Sometimes, scenarios relate to the expected concentration of greenhouse gases in the atmosphere. The IPCC has developed a series of 'Representative Concentration Pathways' (RCPs) that are often used as the starting point for modelling climate impacts.

[p] Downscaling is the general term for procedures which take outputs known at large scales and use them to make predictions at more local scales.[93]

[q] Climate change scenarios are sometimes defined in terms of emissions scenarios (for example the use of Representative Control Pathways in IPCC reports). In using climate change scenarios based on global mean temperature rises, we are following the recommendations of the UK Committee on Climate Change (UKCCC)'s Climate Change Risk Assessment 2017. As well as providing flexibility to use outputs of various climate models, stakeholder feedback to the UKCCC indicated that this description of climate scenarios is more easily understood by readers. 2°and 4° warming correspond to the mean predicted increase in temperatures from the CMIP5 ensemble of climate models in the RCP4.5 and RCP8.5 emissions scenarios, respectively.

[r] Updated climate projections were released in late 2018 ('UKCP18'), including projections at a higher spatial resolution and better modelling of extreme rainfall events. These outputs were not available at the time of analysis. The Met Office recommended continued use of UKCP09 until UKCP18 outputs were made public.

3.4 Model execution

After preparing input data, choosing a natural catastrophe model and climate change scenarios, model execution can begin. Typically, each scenario will require a separate execution step, starting with the 'present day' climate scenario. Where possible, model outputs from this scenario should be compared with historical loss data. Where results differ, these differences should be explored and scrutinised. Following this, future climate change scenarios can be run. Again, results should be compared to the analyst's expectations and, where differences arise, scrutinised.

3.4.1 Benchmarking against other analyses

Where possible, model outputs from future scenarios should be checked for plausibility by comparison with other analyses. This could involve applying a different catastrophe model to the same input data and comparing results. In some cases, analysis of the climate change risks of the perils and in the geography of interest will already be available from public sources. If outputs are similar between models, this can provide more confidence in the outputs of any one.

Box 7. This analysis: benchmarking against other analyses

Recent research by JBA has estimated that the Average Annual Losses (AAL) to UK residential properties will increase 25–30 per cent by 2040.[6] Although this is somewhat smaller than the increase in AAL to UK residential mortgage portfolios found by this analysis (an increase of 60 per cent in a 2°C warming scenario in the 2050s), the difference is relatively small, and likely to reflect differences between the models (in particular, differences in assumptions made around community-level adaptation) and differences in the portfolios modelled. The JBA analysis also only focuses on 2040 whereas this analysis looks at 2050, by which point floods are expected to become more common and more severe.

Also using the Future Flood Explorer, the UK Climate Change Risk Assessment estimated a 30 per cent increase in AAL to residential properties in the 2050s in a 2°C warming scenario and 62 per cent in a 4°C scenario.[7] Differences to the results presented here reflect different assumptions around natural flood management, sustainable urban drainage, coastal management, the future ability of forecasting and warning, and the portfolios modelled.

Research carried out on behalf of the Association of British Insurers estimated that AAL from UK wind storms are expected to increase 11 per cent by the end of the century under a 1.5°C scenario and 25 per cent by the end of the century under a 4.5°C scenario. The differences to the results presented here are likely largely due the different time horizon and scenarios considered, as well as some differences in the model set-up and the underlying climate models used to drive the results.

3.4.2 Impact of climate change on asset values

An optional stage in any analysis by investors and lenders is to explore how the changes in losses caused by physical risks might influence asset values. There is good evidence that natural catastrophe risk has a material impact on residential property values. For example, properties in New York which were newly classified as being at risk of flooding after Hurricane Sandy experienced 18 per cent price reductions,[42] and properties in the United States exposed to sea level rise sell for around 7 percent less than equivalent properties without such exposure.[43] In the UK, analysis of house prices has shown that a property at risk of flood can be expected to sell for 1.5 per cent less than an otherwise similar property which is not at risk of flooding. After a flood hits, properties in affected areas can see further reductions in prices which last for a period of two to three years.[44] These effects will be realised at different time scales depending on the asset. For properties which are occupied by their owners, reduced values will first have financial ramifications at the point of sale. However, for properties which are rented, adjustments to rental yields might take place more rapidly.

Box 8. This analysis: impact of climate change on asset values

This analysis focuses on the effect of changed risk due to climate change on the prices of UK residential mortgage properties. This reflects where the data within this project is richest, although a similar analysis could be applied to other asset types.

It uses a simple asset value model. Under this approach, asset prices are assumed to reflect the present value of benefits that they provide. An increase in the Average Annual Loss (AAL) reduces these benefits, either directly or through higher insurance premiums, and therefore reduces the value of the asset. The approach assumes that buyers of property are aware of risks and respond rationally to them. Technically, the pricing equation can be expressed as follows:

$$\text{Change in asset price= Present value of increase in AAL} = \sum_{t=p}^{\infty} \frac{(AAL_t - AAL_p)}{(1+d)^{t-p}}$$

where AAL_t refers to AAL in future period, AAL_p refers to AAL at the present day and d stands for a discount rate, assumed to be 10 per cent.

This modelling exercise provides a very conservative view of price changes. In assuming that asset prices change to reflect AAL, it implicitly assumes either that insurance is available and priced at the level of AAL or that households are able and willing to accept financial losses in years in which they occur (technically, that insurance is available at a risk-neutral risk rate, without allowances for overheads and profit within the insurance sector, or that households are risk neutral). In reality, households want to protect themselves against losses before they occur by purchasing insurance (in other words, they are risk averse) and insurance premiums are likely to be some multiple of the AAL. This implies that the assets would see larger changes in value than those modelled here. Further, the model does not account for changes in desirability caused by flood risk or flood events, or changes in local economic activity caused by floods. For instance, through business interruption, flood can result in unemployment, depressed incomes and therefore reduced demand for housing. As such, any estimates derived from this approach should be considered as the lower bound of possible change in asset values; however, the evidence base on how much higher impacts might be is not yet available.

3.4.3 Adaptation modelling

The flexibility provided by natural catastrophe models' vulnerability modules can allow investors and lenders to understand the effect of some adaptation measures on expected losses. Adaptation measures aim to reduce the impacts of climate change and allow households and communities to become more resilient to climate change. Many are physical interventions which reduce the damage done to assets by hazards of given intensities and thus reduce expected financial losses. The effectiveness of such interventions will depend on the effectiveness of the measures themselves and the extent to which measures are taken up. Inside natural catastrophe models, their effects can be modelled by selecting a damage curve with a lower damage ratio at given intensities. A comparison of losses with a 'baseline' and 'adaptation' damage curve provides an estimate of the effect of adaptation. Adaptation damage curves can be calibrated using data on historic losses for properties with adaptation measures or through engineering estimates of the effectiveness of the measures at given hazard intensities.

Box 9. This analysis: adaptation modelling

Property-level adaptation measures have been incorporated into our analysis. The focus is on property-level adaptation as this is where there is the greatest scope for investors and lenders to encourage adaptation. There is also a crucial role for 'community-level adaptation' in reducing losses, especially for flood risk. This term refers to measures which provide loss reduction benefits to multiple properties or whole communities and includes, for example, sea walls or more frequent dredging of rivers.

UK flood

Flood adaptation measures include devices for preventing the ingress of flood waters into buildings (such as waterproof doors, windows and airbricks) and measures that reduce damage if flood waters do ingress (such as resilient flooring, plastic kitchens and raised power sockets). The analysis models a package of measures to prevent flood ingress and measures to reduce damage if flood water does ingress, for example, resilient flooring. A cost–benefit analysis of these measures is beyond the scope of this analysis, but estimated capital costs for the package of measures modelled range between £5,100 and £14,000.[37]

These measures can be effective at preventing damage caused by floods up to a depth of around 60cm, but are less effective for deeper floods.[45] Inside the FFE, this is captured by reducing the percentage reduction in damage from low-return period events more than for more extreme (and deeper) events, as shown in Table 6.

Return-period of event (years)	Reduction in damage (coastal)	Reduction in damage (fluvial)	Reduction in damage (surface water)
2	0%	80%	80%
5	80%	80%	80%
10	80%	80%	80%
25	40%	40%	80%
50	0%	25%	40%
100	0%	0%	20%
> 200	0%	0%	0%

Table 6. The adjustments to the damage curve for adaptation measures within the FFE take account of the fact that adaptation is less effective for more extreme events
Source: Future Flood Explorer

Take-up of adaptation measures is frequently low, even when they might be cost effective. As well as being reluctant to make capital investments with uncertain or longer-term returns, property owners can be reluctant to install outwardly visible measures which signal that the property is at risk of flooding[46-47] and/or that look aesthetically unappealing. This analysis assumes that 50 per cent of households on flood plains install adaptation measures. This figure is high relative to recent experience but, with appropriate incentivisation or requirements, is considered to be achievable.

In the UK, a large base of flood defences (including flood walls and embankments, pumping stations, barriers, sluices and outfalls) also reduce flood risk. Spending on maintaining and improving these defences exceeds £400 million a year.[48] Any modelling exercise of future flood risk requires an assumption about how defences will be managed in the future. This analysis assumes that current flood defence policies continue to be implemented as effectively as they are today,[s] but that there are no changes in natural flood management, sustainable drainage systems or coastal alignment measures.

[s] In some areas where the cost–benefit case is weakest, the standard of protection provided by flood defences is assumed to reduce as investment fails to keep pace with climate change. Areas with the highest standards today (such as the Thames Estuary) continue to be well protected and standards are assumed to remain maintained into the future. The majority of defence systems are assumed to be maintained at their current standards, but in areas where the condition grade is already low, the case for continued maintenance or improvement is assumed weak and assumed to deteriorate further with time.

Tropical cyclones and European winter wind storms

Typically, building codes in developed countries specify that, at the point of construction, buildings must be designed and constructed in order to withstand all but the most extreme winds they are expected to face. When implemented, such codes are effective: for example, properties built in Florida after the introduction of a state-wide building code experienced lower losses during the 2004–05 hurricane season than those built before the code was introduced.[49] Construction options such as resilient walls, load-bearing structures and advanced materials can ensure that buildings meet the requirements set out in building codes.

A number of building-level adaptations can be retrofitted to properties after their construction to increase wind resilience. Three main categories of adaptations are roof reinforcement, anchoring to create a continuous load path from roof to the foundations, and reinforcing windows and doors.[50] Costs vary widely between properties depending on details of initial construction. For buildings with a primary structural framing of steel, concrete or reinforced masonry, the United States Federal Emergency Management Agency (FEMA) estimates that such adaptation measures are cost effective when costing less than 10 per cent of the building's replacement cost.[51] If climate change increases the expected frequency or intensity of events, then adaptation measures might be cost effective in an even wider range of situations.

Our analysis illustrates the potential of adaptation to reduce the effects of climate change on tropical cyclones and European winter wind storms by modelling roof reinforcement. Roof cover damage is among the most frequent kinds of wind damage and is usually followed by water intrusion leading to significant damage to the interior.[52] By improving the roof cover, reinforcing the roof structure, or anchoring the roof better to the rest of the building, it is possible to increase the wind resilience of a building. In order to model this adaptation measure, the analysis applies an adjustment to the default damage curve within CLIMADA's tropical cyclone and European winter wind storm vulnerability models. This adjustment reflects the expectation that adapted buildings will suffer less damage for given wind speeds than buildings which have not been adapted. The magnitude of the adjustment at various wind speeds is calculated based on FEMA's evidence on the effectiveness of adaptation measures (Hazus Hurricane Model). This suggests that roof upgrades are more effective at reducing expected damage from relatively less extreme events. Figure 12 shows the adjustment to the damage curve for tropical cyclone damage.

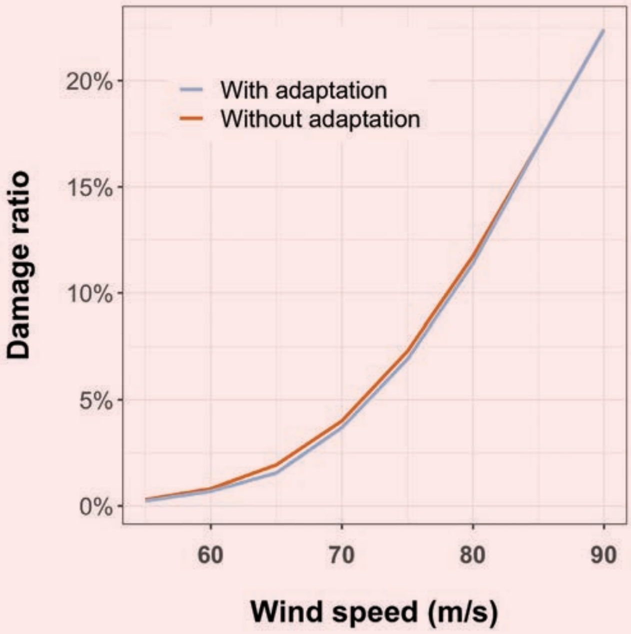


Figure 12. Inside CLIMADA, adaptation measures are modelled by a shift in the damage curve
Source: Vivid Economics based on CLIMADA and FEMA

4. Illustrative results

This section presents illustrative results from applying the methodology set out above to 12 real estate portfolios with total market value in excess of £2 trillion.

Seven of these are mortgage portfolios held by UK retail banks and building societies, the rest are portfolios of direct investments held by ClimateWise members in the UK, the rest of Europe, Asia, North America and South America. The analysis quantifies the increase in physical risks from floods (UK assets only), European winter wind storms and tropical cyclones by comparing expected outcomes in the 2050s to today under two warming scenarios. While the specific results reflect the geographic distribution of assets in these portfolios, there are a number of key results suggested by the modelling:[t]

- Flood risk could increase materially for UK mortgage portfolios both in terms of the number of properties at 'considerable' risk of flooding[u] (potentially increasing by 25–40 per cent) and the Loss (AAL) expected from flood (potentially increasing by 61–128 per cent). The AAL refer to the modelled yearly averages – natural variation in the climate means that actual losses in any given year might be substantially higher or lower.
- These losses are likely to be geographically clustered around coastal locations and mortgage providers with a disproportionate focus in these areas will see greater risk increases.
- The worst affected properties might see increases in AAL of around £2,500, which would imply value impairments of £25,000 or more.
- Property-level adaptation can play a key role in reducing this increase in risk (possibly offsetting between 54 per cent and 65 per cent of the increase in losses); the modelling suggests that adaptation is proportionately more effective if global emission reduction efforts are successful.
- For the particular commercial portfolios with UK assets examined in this analysis, the increase in the number of properties exposed to a high risk of flooding is modest. However, even without many properties falling into this 'high risk' category, the increase in expected AAL could be between 40 per cent and 70 per cent.
- European winter wind storm risk, both in the UK and the rest of Europe, might increase only modestly for the portfolios under consideration.
- Among the two properties with assets exposed to tropical cyclone risk, losses could increase by between 43 per cent and 80 per cent, but with one third to one half of this increase potentially offset by adaptation.
- The tropical cyclone results also illustrate how for portfolios with a small number of large-value assets, overall portfolio impacts can be driven by the location of just a small number of assets.

[t] In all cases, the ranges cited in this list refer to the results from 2°C and 4°C warming scenarios.
[u] Defined here as a 1.3 per cent (or 1 in 75) annual probability of flooding.

There are a number of reasons why these results may underestimate the increase in physical risks. These include that the analysis only focuses on some of the additional physical risks that climate change will create, an assumption that there will be no further assets constructed in areas most exposed to physical risks in the future and a focus only on the direct damage to assets, excluding knock-on impacts such as business interruption or the potential that the local economy will be weakened. These and other reasons are discussed further in Appendix A.

Sections 4.1 and 4.2 present results from UK flood modelling, Section 4.3 provides results from European winter wind storm modelling and 4.4 from tropical cyclones. In comparing the results across perils, it is important to bear in mind the differing levels of confidence that can be attached to how different climate change scenarios will influence the probability and severity of extreme events, as discussed in Section 2.3 (which notes that the confidence is generally higher for UK flood risk than for tropical cyclones or European winter wind storms).

15% properties currently at risk of flooding

4.1 UK flood risk: residential mortgage properties

The UK flood risk analysis for mortgage portfolios focuses on the climate change induced flood risk to 7.2 million residential properties in seven bank and building society mortgage portfolios. Of these properties, the baseline modelling suggests that 1.1 million (15 per cent) are currently at risk of flooding (that is, their annual probability of flooding is 0.1 per cent or above, a common threshold for defining properties at 'some' risk of flooding). This modelling also suggests more properties are at risk of surface water flooding (500,000) than of fluvial (288,000) or coastal flooding (350,000), but Average Annual Losses tend to be larger for coastal flooding (around £48 million) and fluvial flooding (around £55 million). This reflects that coastal floods tend to be deeper and more damaging than surface water floods.

Across these portfolios, climate change might increase the number of properties at a 1.3 per cent (or 1 in 75) annual probability of flooding or more by around 25–40 per cent. The 1.3 per cent annual probability threshold has traditionally been the level at which properties have been considered at 'considerable' risk of flood.[8] The modelling suggests that, of the 7.2 million properties in the portfolios, 445,000 (6.1 per cent) currently have an annual probability of flooding of 1.3 per cent or above. As shown in Figure 13 below, this could rise by 111,000 to 556,000 by the 2050s in a 2°C warming scenario and by 180,000 to 626,000 in a 4°C warming scenario, potential increases of 25 per cent and 40 per cent respectively.[v] This compares to 150,000 properties Flood Re at the end of the 2017/2018 financial year.[53]

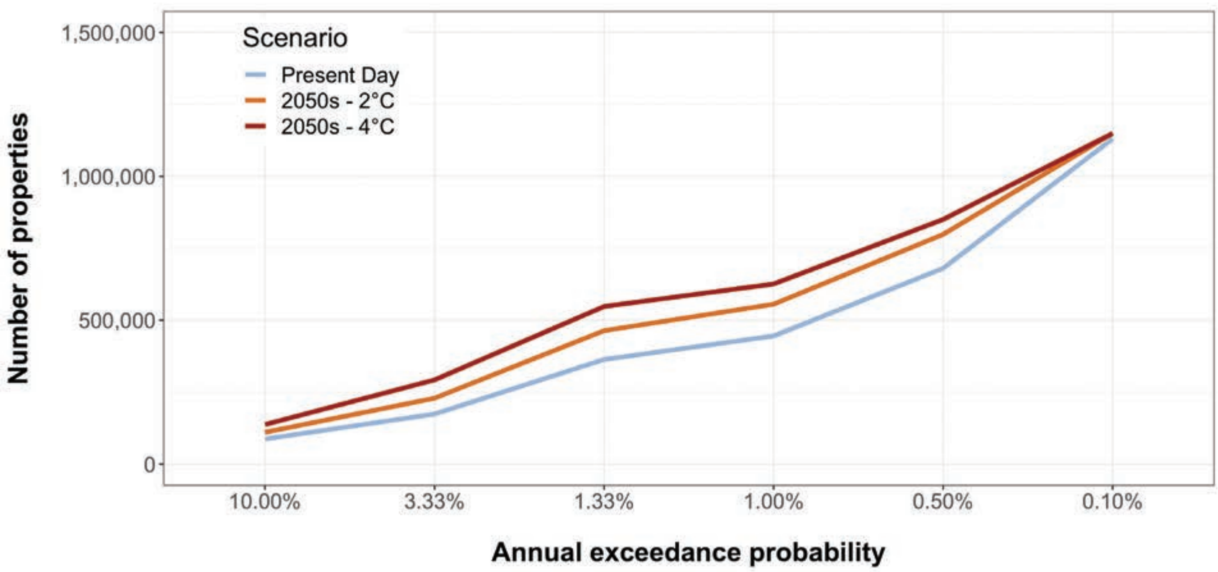


Figure 13. Warming scenarios might increase the number of properties at risk of floods at all but the most extreme exceedance probabilities
Source: Sayers and Partners and Vivid Economics, based on FFE

[v] The number of properties at risk of 'some' flooding, as defined by having an annual probability of flooding of 0.1 per cent or above, does not change in our model. This is because it is assumed the spatial extent of the floodplain (as notionally defined by a 1 in 1,000 year storm event given an absence of defences) is not affected by climate change: only the frequency of flooding within the floodplain changes. This is considered a reasonable assumption for the range of climate scenarios considered here and given the assumption of continued development of community-level flood defences.

Similarly, for properties within these portfolios, AAL from floods could increase by between 61 per cent and 128 per cent (2°C and 4°C, respectively), with losses from all types of floods increasing. Currently, the modelling suggests that AAL from flood to properties in the lending portfolios are around £122 million.[w] This could rise by around 60 per cent to £196 million in the 2050s in a 2°C warming scenario and by 128 per cent to £279 million in the 2050s in a 4°C warming scenario, expressed in today's prices. This is a modelled yearly average – natural variation in the climate means that actual losses in any given year might be higher or lower. Figure 14 shows that the modelling indicates that the proportion of losses caused by different types of flood events are expected to stay broadly similar to today in both 2°C and 4°C scenarios.

These results broadly align with those from previous studies. As noted in Box 7, these results are broadly consistent with those found in previous analysis: JBA[6] found a 25–30 per cent increase in AAL for UK residential properties in the 2040s while the UK's Climate Change Risk Assessment,[7] also using the Future Flood Explorer as in this analysis, found a 30–62 per cent increase in AAL in the 2050s for UK residential properties. The smaller increases in AAL found in these previous analyses are likely to reflect differences in assumptions around community-based adaptation and in the portfolios examined, while in the case of the JBA analysis, also differences in model set-up and time horizon.

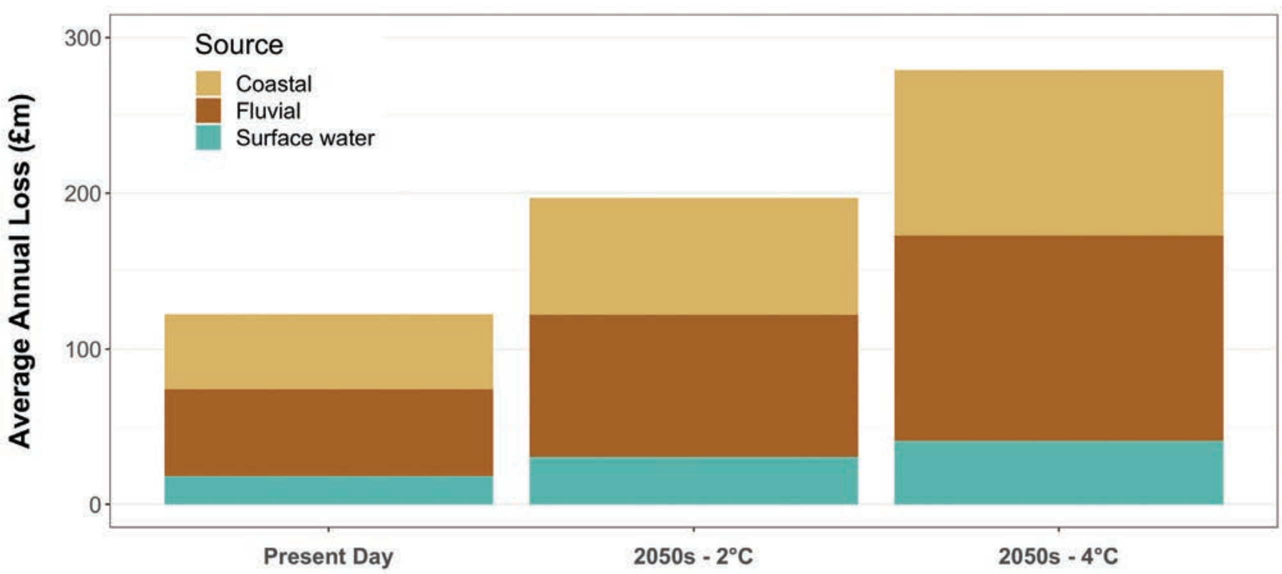


Figure 14. All flood types are expected to contribute to the increase in Average Annual Loss seen in both 2°C and 4°C scenarios
Source: Sayers and Partners and Vivid Economics, based on FFE

[w] The total market value of assets in the portfolio is £2,093 billion.

The modelling suggests significant differences in the increases in AAL faced by different UK retail banks/ building societies, especially in a 4°C scenario. Figure 15 shows the possible variation in increases in Average Annual Losses by lender. In a 4°C warming scenario, the AAL are estimated to be between 2.1 and 2.3 times their baseline, depending on the portfolio. In a 2°C scenario, the modelling suggests significantly less variation in the change in AAL, with the increases clustered around 1.6 times.

Similarly, the modelling indicates significant variation across portfolios as to the change in the number of properties at considerable risk of flooding. As shown in Figure 16, in a 4°C scenario, the least adversely affected lender might see only a 32 per cent increase in the number of properties at a 1.3 per cent (1 in 75) annual probability of flood or more, whereas the equivalent increase for the worst affected lender could be 42 per cent. In a 2°C scenario modelled differences are less pronounced but still important: the least affected lender might face a 21 per cent increase in the number of properties that exceed this probability, compared to 25 per cent for the most adversely affected lender.

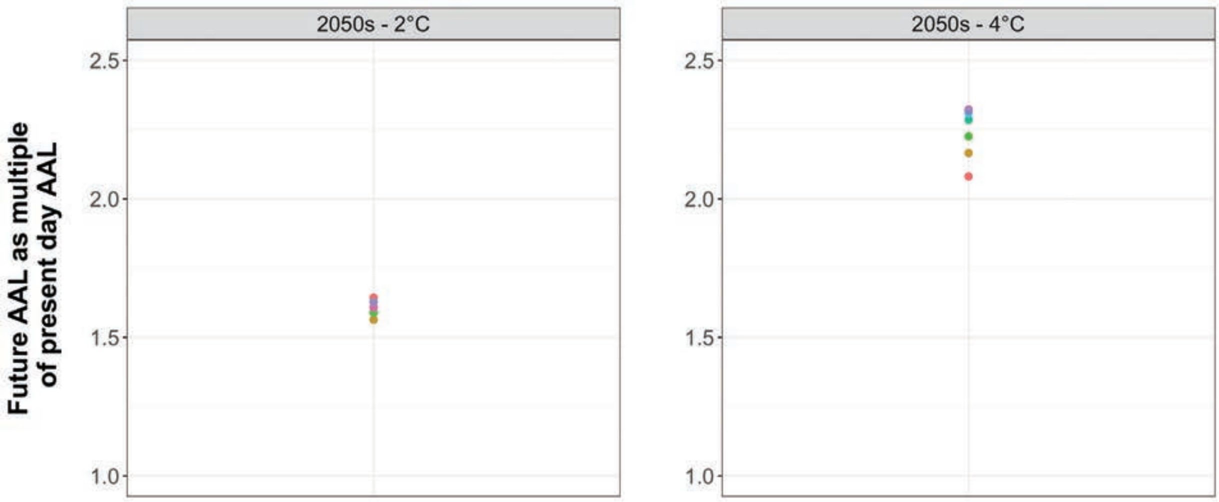


Figure 15. The modelling suggests that the variation in the increase in Average Annual Losses across UK retail banks and building societies is more apparent in a 4°C scenario
Note: Each coloured dot represents a different UK retail bank or building society mortgage portfolio.
Source: Sayers and Partners and Vivid Economics, based on FFE

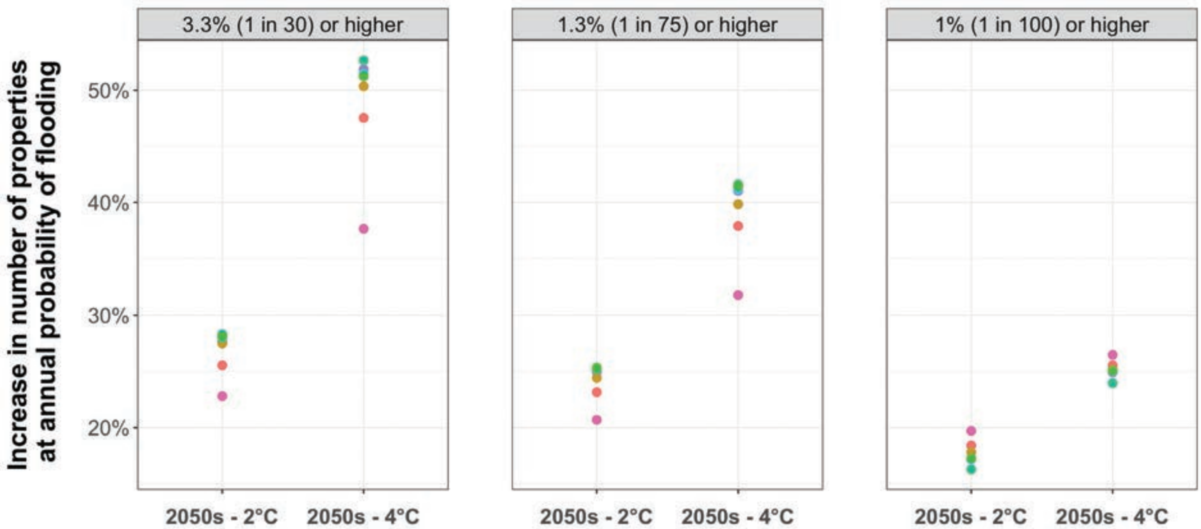


Figure 16. The modelling finds significant variation across portfolios in the increase in the number of properties at key exceedance probabilities
Note: Each coloured dot represents a UK retail bank or building society mortgage portfolio.
Source: Sayers and Partners and Vivid Economics, based on FFE

The potential differences in AAL increase across the portfolios are largely driven by likely differential exposure to coastal flooding risk. Figure 17 shows how AAL could change between the present day and the 2050s for each flood type and each portfolio. In a 4°C scenario, one portfolio potentially sees coastal flooding losses in the 2050s that are 2.3 times their current level, compared to 1.9 times for the least exposed. By contrast, in the same scenario, changes in AAL for fluvial and surface water floods are expected to be much more tightly clustered. This is further reinforced by Figure 18 which maps the possible annual average ten-year losses from floods as a share of outstanding mortgage lending.[x] This shows that concentration of flood risk in coastal areas is already apparent under present day conditions, but that the modelling indicates it is likely to become more apparent in a 2°C scenario, and even more so in a 4°C scenario. Indeed, in some coastal postcode sectors, the modelling suggests that AAL in a 4°C scenario could increase by as much as £2,500. Even in a 2°C warming scenario, AAL are predicted to increase by £1,400 per property in the coastal postcode sectors most heavily impacted by climate change.

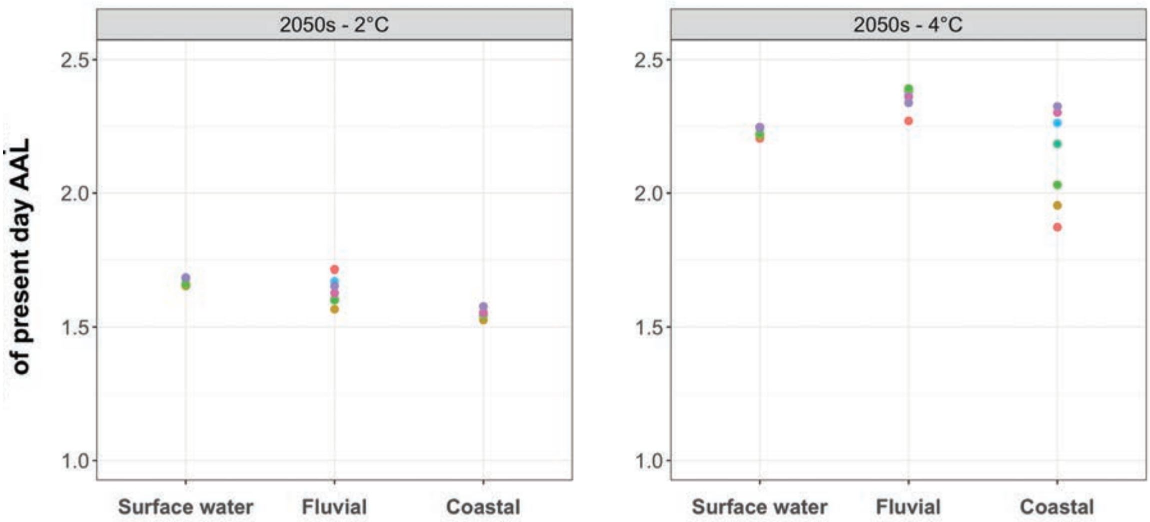


Figure 17. The modelling finds that, in a 4°C scenario, there are significant differences in the risks from coastal flooding across the mortgage portfolios

Note: Each coloured dot represents a UK retail bank or building society mortgage portfolio.
Source: Sayers and Partners and Vivid Economics, based on FFE

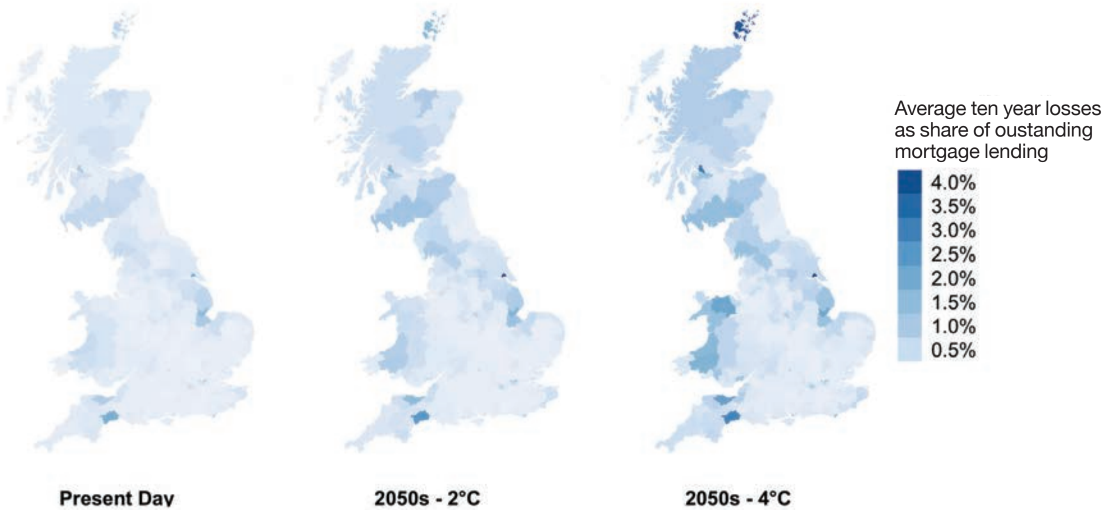


Figure 18. The modelling suggests that climate change will increases the geographic concentration of risk around coastal regions

Note: This map shows how ten-year average losses from flood vary across local authority districts in Great Britain. Ten-year average losses are expressed in terms of outstanding mortgage lending.
Source: Sayers and Partners and Vivid Economics, based on FFE

[x] The average duration of a UK residential mortgage is 25 years, so the average mortgage can be expected to have 12 years of repayments outstanding. The annual ten-year loss therefore represents the losses that might be expected to occur over the life of a mortgage.

Properties in the most heavily affected areas may face average value impairments of at least £25,000 in a 4°C scenario. In the most heavily affected postcode district, the modelling suggests that AAL might increase by £2,500. Applying the simple value impairment model described in Section 3.4.2 would mean that these properties could see value impairment of £25,000, with actual impacts potentially much higher.[y] Value impairment of this magnitude could increase the probability of mortgage defaults. There are a further 15 postcode districts where the modelling suggests AAL could increase by £1,000 or more, implying modelled value impairment of over £10,000.

Adaptation is likely to be more effective at reducing losses in a 2°C scenario than in a 4°C scenario,[z] as shown in Figure 19**.** This reflects the lesser effectiveness of property-level adaptation measures to protect properties from more extreme events – events that become relatively more likely in higher warming scenarios. Specifically, as shown in Figure 20, in a 2°C scenario, property-level adaptation measures are very effective at offsetting fluvial and surface water floods, potentially mitigating 72 per cent and 85 per cent of the increased losses respectively, compared to just 24 per cent of the increase in coastal-flooding related losses. By contrast, in a 4°C scenario, the modelling finds that the measures are much less effective at protecting against increased fluvial and surface water risk, with just 49 per cent and 62 per cent of the possible AAL increase being offset.

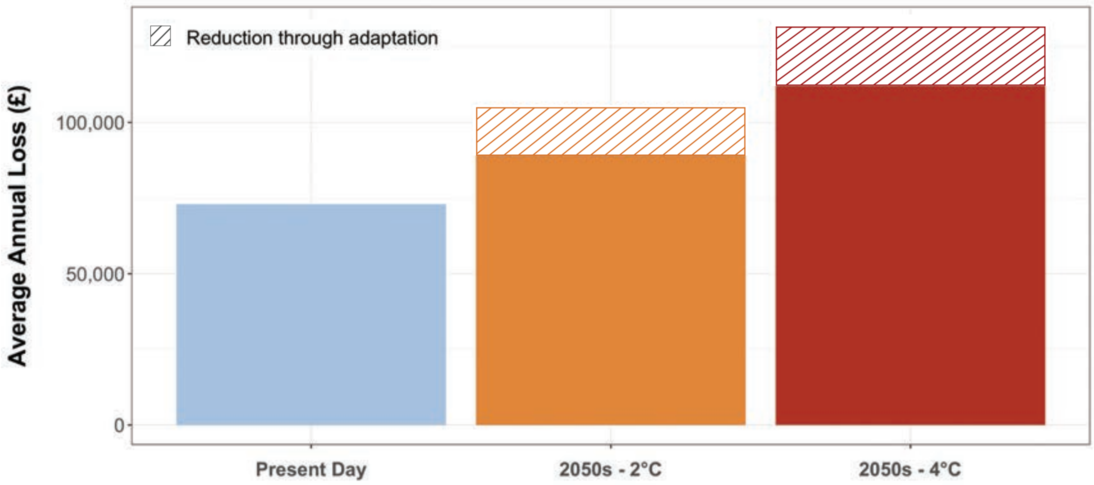


Figure 19. Adaptation measures may help reduce the increases in Loss (AAL) among properties in the UK mortgage portfolios
Source: Sayers and Partners and Vivid Economics, based on FFE

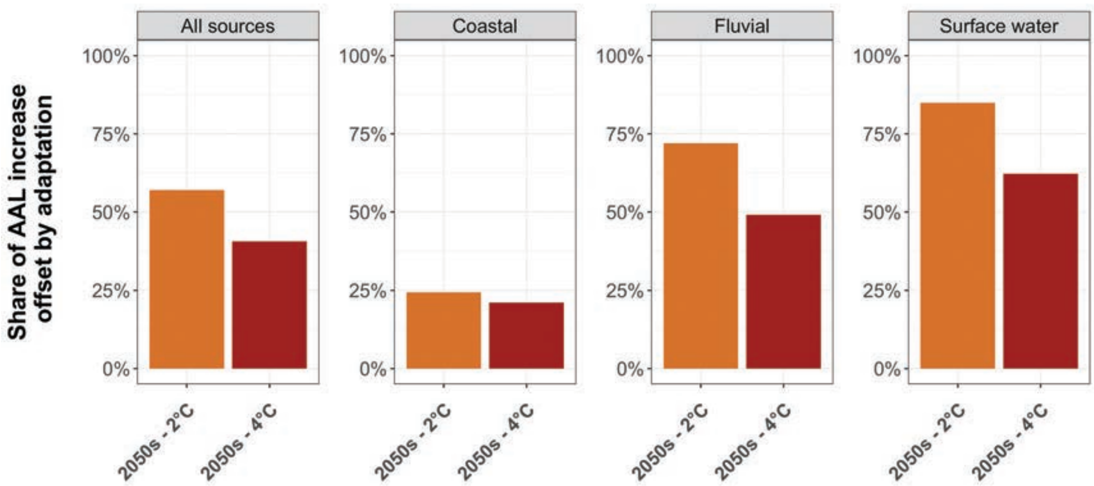


Figure 20. Adaptation measures can mitigate the impact of all flood types, but is markedly less effective for coastal floods
Source: Sayers and Partners and Vivid Economics, based on FFE

[y] AAL is expressed in present day prices. In nominal terms, losses will be higher in the 2050s due to inflation. If inflation in goods and services needed for flood repairs is lower than inflation in house prices, as per recent experience, the overall effect of inflation will be to lower losses in real terms.

[z] Although adaptation offsets less of the effect of 4°C warming than of 2°C, the effectiveness of adaptation in terms of losses reduced per pound spent is higher in a 4°C scenario, due to the larger climate change impacts.

4.2 UK flood risk: commercial assets

The analysis of flood risk on commercial assets covers 551 properties across four commercial portfolios. In contrast to the mortgage portfolio results in Section 4.1, these assets represent a small sample of commercial properties and it is therefore much more difficult to reliably extrapolate to assets beyond these portfolios. Figure 21 shows the geographic distribution of the assets modelled.

The modelling suggests that the average probability of flooding for assets in these portfolios could increase from its baseline level of 1.8 per cent to 2.4 per cent under 2°C warming and 3.3 per cent in a 4°C warming scenario. In the examined portfolios, current flood risk is predominantly surface water flooding risk (with a modelled average of 1.5 per cent), reflecting that many of these assets are in urban areas, with coastal and fluvial floods only providing minimal risk (0.08 per cent) and (0.15 per cent). As shown in Figure 23, this distribution is not expected to change under either warming scenario.

For these portfolios, climate change is not expected to have a significant impact on the number of properties at significant flood risk, defined as a 1.3 per cent (1 in 75) or more annual probability of flooding. Figure 22 shows that, currently, 189 (3.8 per cent) of these properties are estimated to have an annual probability of flooding at or above this threshold. By the 2050s, the modelling suggests that this increases to 194 in a 2°C scenario and 204 in a 4°C scenario.

There is significant variation in baseline risk across the portfolios. At present, the average annual flood probability to assets in each portfolio is estimated to range from 1.7 per cent in the portfolio with the lowest risk to 3.2 per cent for the portfolio most at risk. Compared with the residential mortgages, this estimated variation in baseline risk illustrates how it can be more difficult for smaller portfolios of larger assets to benefit from geographic diversification that limits exposure to physical risks.

However, across these portfolios, there is expected to be much less variation in the additional risk caused by climate change. Across the portfolios, average annual flood probabilities are modelled to increase by between 38 per cent and 45 per cent in a 2°C scenario and 83 per cent and 94 per cent in a 2°C scenario. For most portfolios, the modelled number of properties at annual risk of flooding of 1.3 per cent or more remains unchanged; for others, it changes by at most 4 per cent. For these portfolios, at least, the best predictor of future flood risk is today's flood risk.

Figure 21. The direct investment assets included in UK flood analysis are predominantly in the south and south east of England

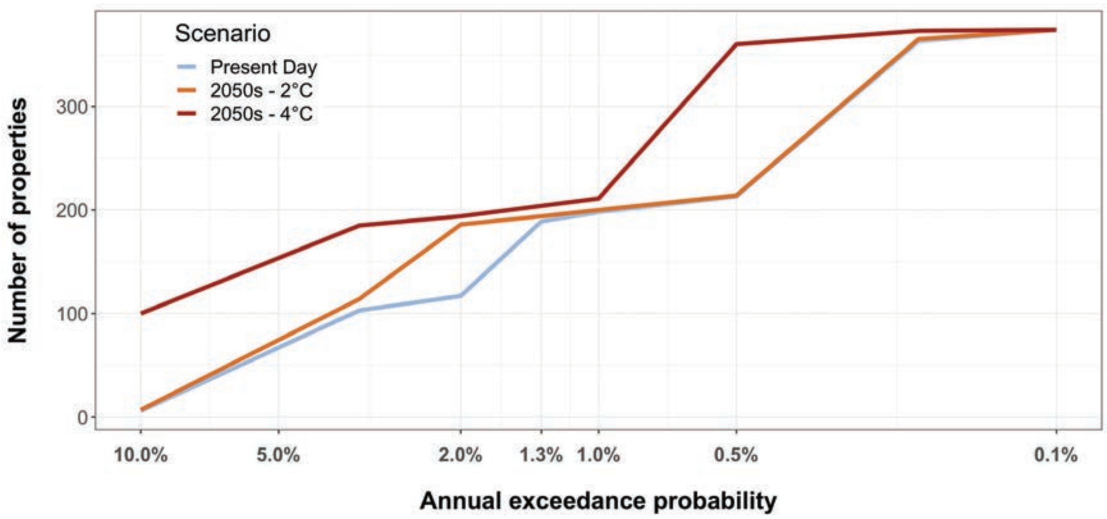


Figure 22. Among the portfolios examined, the expected number of commercial properties at different exceedance probabilities is notably higher in a 4°C scenario than in a 2°C scenario
Source: Sayers and Partners and Vivid Economics, based on FFE

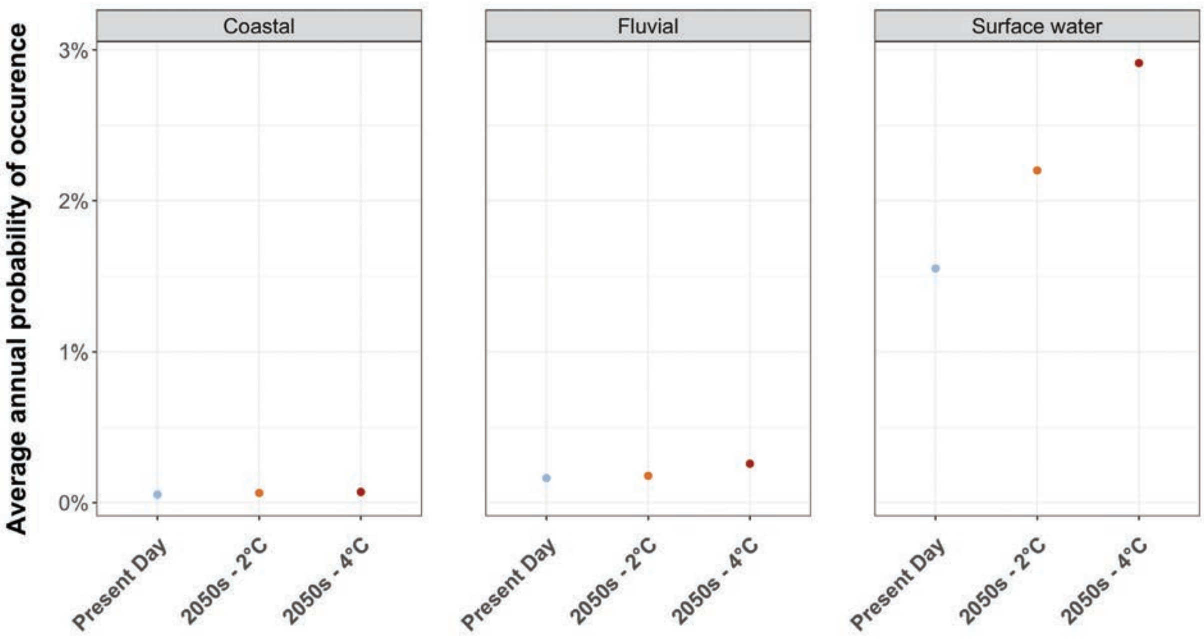


Figure 23. Surface water is expected to represent the largest risk to UK assets in the commercial asset portfolios examined, both under present day and future climate scenarios
Source: Sayers and Partners and Vivid Economics, based on FFE

Data limitations mean that it is only possible to calculate the possible change in AAL for a subset of three investment portfolios, accounting for 40 assets. The large majority of these assets are at a low baseline risk of flood; the estimated changes in AAL presented here might not be representative of other portfolios. In combination, AAL might increase 40 per cent from present day to the 2050s in a 2°C warming scenario and 70 per cent in a 4°C warming scenario, as shown in Figure 24. The possible variation in AAL increase across portfolios is between 32 per cent and 40 per cent in a 2°C warming scenario and 58 per cent and 72 per cent in a 4°C warming scenario. The modelling suggests that adaptation measures might completely offset these increases, although this may reflect the low baseline risk of assets in these portfolios. Again, it should be stressed that these are modelled yearly averages – natural variation in the climate means that modelled losses in any given year might be higher or lower.

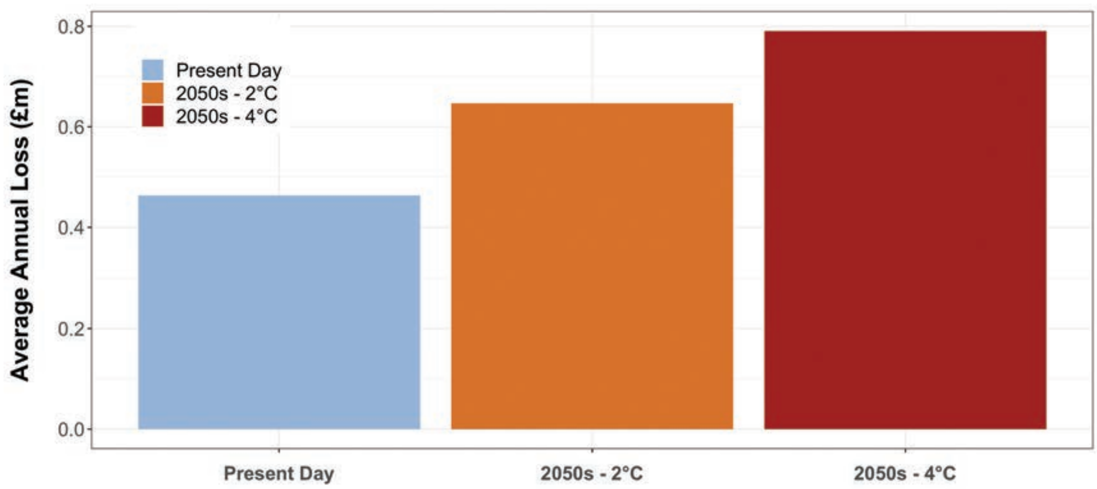


Figure 24. There are significant increases in the expected Average Annual Loss from UK floods among the commercial property portfolios reviewed, albeit from a low baseline
Source: Sayers and Partners and Vivid Economics, based on FFE

4.3 European winter wind storms

The present day risk to UK mortgaged properties from wind storms is considerably lower than that of flood risk. Currently, average ten-year losses are estimated to be around 1.2 per cent of outstanding mortgage lending on the Atlantic coast, where risk is concentrated, and average ten-year losses across the portfolios as a whole are estimated to be 0.04 per cent. This compares with estimated current average ten-year losses from floods of 2.1 per cent in the most risky areas and 0.12 per cent across the portfolios as a whole.

Furthermore, the expected increase in losses to UK residential properties are expected to be small. In a 2°C warming scenario, losses from European winter wind storms might increase by 5.6 per cent. Under a 4°C scenario, predicted decreases in wind storm intensity in the south of England mean that losses could be lower than today (falling by 2.5 per cent).[a1]

Across the commercial asset portfolios reviewed, the impacts from climate change on European winter wind storm risk might also be modest. The modelled increase in AAL is 6.3 per cent in a 2°C warming scenario and 3.6 per cent in a 4°C warming scenario, with the smaller increase in a 4°C scenario again reflecting expectations of reduced extreme wind speeds in the south of England as well as in other areas of Northern Europe. These increases might be limited to 4.7 per cent and 2.6 per cent respectively by the uptake of adaptation measures, although given the moderate increases caused by climate change, such measures may not be cost effective.

These results are similar to those in previous analysis undertaken by the insurance industry. The relatively modest increases in AAL from wind storms match the findings of research carried out on behalf of the Association of British Insurers (ABI) regarding the effect of climate change on wind storm losses to UK assets.[8] The ABI modelling exercise found AAL from UK wind storms was expected to increase 11 per cent by the end of the century under a 1.5°C scenario and 25 per cent by the end of the century under a 4.5°C scenario. It is likely that differences to our analysis are largely attributable to the different time horizon and scenarios considered, as well as some differences in the model set-up and the underlying climate models used to drive the results.

Collectively, these results suggest that, in the UK, climate change impacts from European winter wind storm losses may be lower than from flooding. This demonstrates that climate change is not expected to have a uniform effect on all peril types. While understanding of the climate change impacts on winter wind storms will improve over time, and natural variation in the climate means that actual losses in any one year could be much higher, this result, if replicated in subsequent analysis, suggests that decision-makers might consider deprioritising winter wind storm risk when considering incentivisation of adaptation measures.

4.4 Commercial investment: tropical cyclones

The analysis of tropical cyclone risk focuses on two portfolios. Within these two portfolios, there are nine assets at risk of tropical cyclones: five assets located in the Pacific Rim and four assets on the east coast of the United States.[b1] The assets are a mix of commercial and industrial properties.

Among the two portfolios reviewed, losses from tropical cyclones might increase by 43 per cent in a 2°C warming scenario and 80 per cent in a 4°C warming scenario (Figure 25).[c1] Similarly, losses at an exceedance probability of 1 per cent might nearly double in a 4°C warming scenario (a 97 per cent increase), but increase by just 54 per cent in a 2°C warming scenario (Figure 26).

There is variation in the expected increase in losses across the two portfolios caused by variation in asset locations between the two portfolios (Figure 27). While the expected increases in losses are 43 per cent (2°C) and 80 per cent (4°C) for one portfolio, they are 50 per cent (2°C) and 197 per cent (4°C) for the other. The portfolio with larger losses is at increased risk due to properties with high replacement costs in the most vulnerable location to climate change impacts, the Florida coast. This shows that, especially for portfolios with a small number of relatively large-value investments, investors might find themselves increasingly exposed to physical risks from decisions over just a relatively small number of assets.

As with other perils, adaptation measures have the potential to play an important role in reducing physical risks for these portfolios, especially in a 2°C warming scenario. The modelling suggests that retrofitting of more resilient roofs might moderate around 49 per cent of the additional risk in a 2°C warming scenario, but only 33 per cent in a 4°C warming scenario.

[a1] Figure 32 in Appendix B shows a map of these changes.
[b1] Tropical cyclones do not pose a risk to assets on the west coast of the United States.
[c1] The same caveat as expressed in the discussion for other perils – namely that the natural variation in the climate means that actual losses in any one year could be higher or lower than the modelled Average Annual Losses.

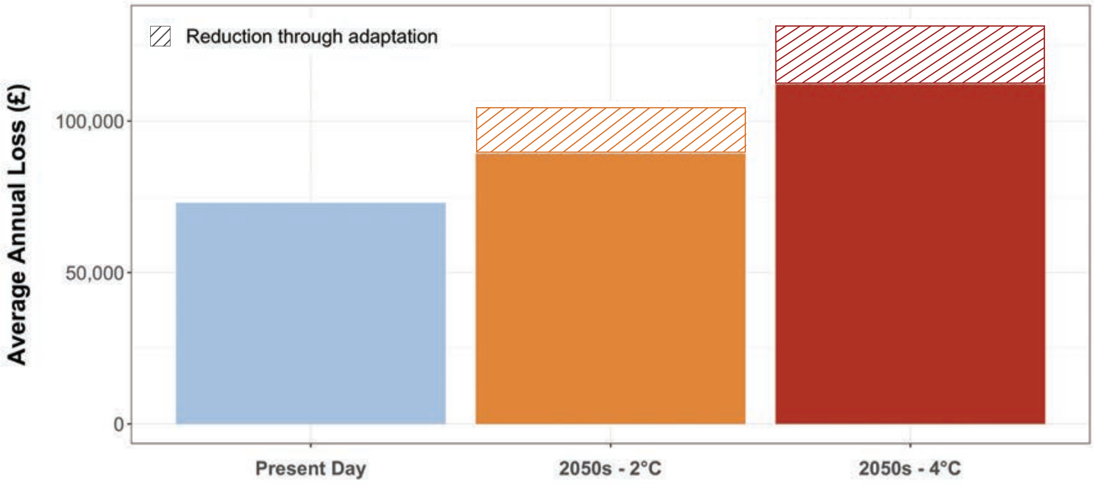


Figure 25. For tropical cyclone risk, among the two portfolios examined, the modelling suggests that adaptation offsets a greater proportion of the increase in losses in a 2°C scenario than in a 4°C scenario
Source: Vivid Economics, based on CLIMADA

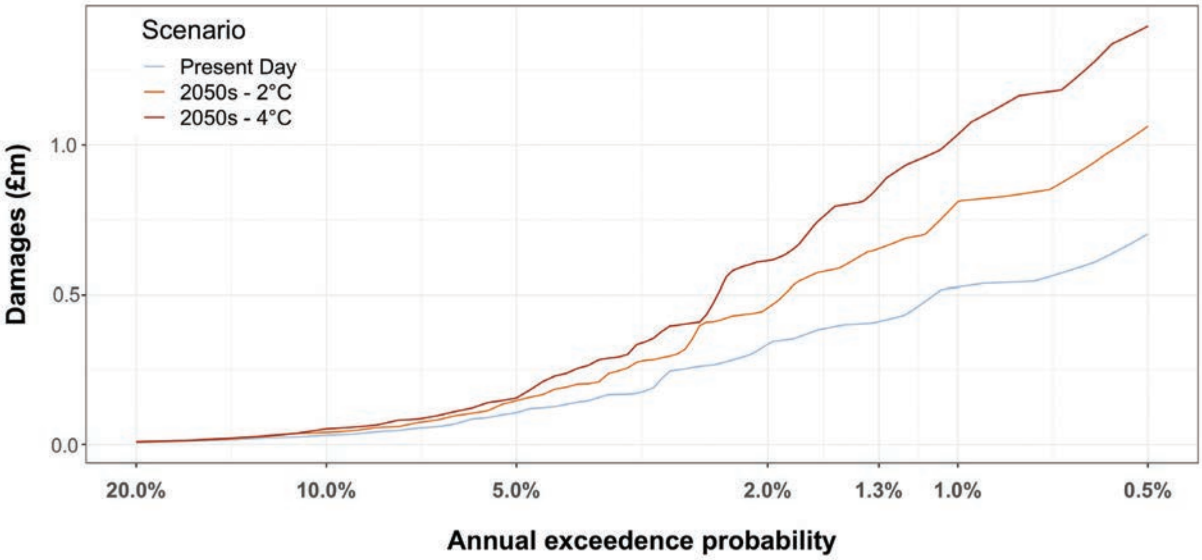


Figure 26. The modelling suggests that, for these portfolios, the exceedance probability curve becomes much steeper in a 4°C scenario
Source: Vivid Economics, based on CLIMADA

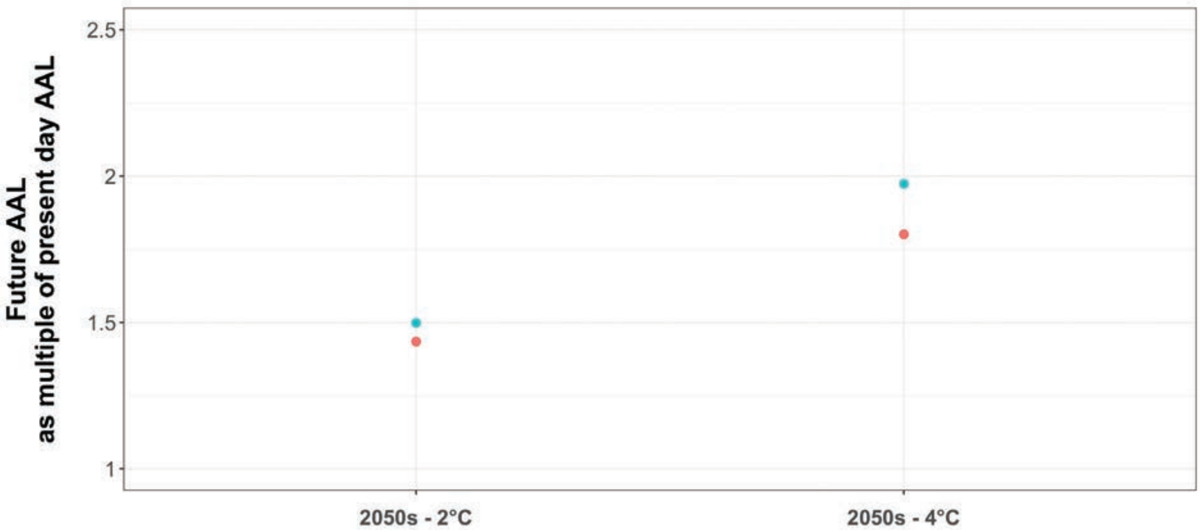


Figure 27. The modelled increase in Average Annual Loss (AAL) from tropical cyclone risk for the two portfolios examined are notably higher in a 4°C scenario
Source: Vivid Economics, based on CLIMADA

5. Conclusions and associated implications

5.1 Investors and lenders can make use of insurance data and catastrophe models to improve their management of the physical risks of climate change

There is increasing focus among investors and lenders, driven both by increased general awareness of materiality and specifically by the Task Force on Climate-related Financial Disclosure (TCFD), on the financial risks posed by the physical impacts of climate change. Globally, weather-related financial losses in 2017 exceeded US$325 billion, the highest level on record.[54] Partly in response to these challenges, an updated report on the implementation of the TCFD, published in September 2018, reported that more than 500 public and private sector organisations supported the TCFD's recommendations in reporting on these physical (and transition) risks, including global companies, banks, insurers, asset managers, stock exchanges and governments.[55]

But while there is growing recognition of the importance of physical risks, there is considerable uncertainty among investors and lenders, and more broadly, about how these may be best understood and quantified in practice, so as to inform strategic decision-making. For instance, the TCFD update report notes that banks, in their disclosures, focus more heavily on transition risks than physical risks. Similarly, it notes that the examples of risk management behaviour identified by asset owners focus on reducing greenhouse gas emissions and improving energy efficiency. A report exploring the implications of physical risks for banks found that one of the key barriers to improved strategic decisions in relation to physical risks was a perceived lack of "spatial data on future changes in extreme weather and climate events".[21]

A failure to take account of these risks could be damaging both for individual investors and lenders, but also for the financial system and the economy as a whole. The likelihood that physical risks are not being properly accounted for when investors and lenders make strategic decisions increases the likelihood that these decisions will increase exposure to such risks. If large enough, this could have negative implications for the wider financial system. It is no surprise that a growing number of regulators across the world are exploring the impacts that physical risks might pose for financial stability.

Tools and metrics from the insurance industry can play a vital role in advancing the understanding of investors and lenders of physical risks. These tools were originally developed in the context of extreme weather events with insurers and their service providers seeking to understand historic trends and current in order to determine probable loss calculations to inform underwriting decisions. However, more recently, they have started to consider the implications of changes in hazard, exposure and vulnerability, including the impact of climate change. While a number of uncertainties remain, primarily reflecting uncertainties around how climate change will affect different physical risks, these tools nonetheless offer important insights for investors and lenders into current and future risk trends. By looking at physical risks in scenarios consistent with 2°C and 4°C warming[d1] from flood, European winter wind storm and tropical cyclone risk for a series of 12 portfolios of assets, with a market value in excess of £2 trillion, this report provides an illustration of how investors and lenders can make greater use of these tools and metrics.

[d1] This relates to an increase in warming of 4°C above a 1961–90 baseline by 2100. The analysis looks at the change in risk implied by this temperature increase in the 2050s.

5.2 The illustrative results suggest that some physical risks may increase considerably, raising important questions for investors, lenders, insurers and policymakers

5.2.1 Climate change may lead to a large increase in losses from floods in the UK and tropical cyclones in North America and the Pacific Rim

In the UK, under a 4°C warming scenario, UK residential mortgage portfolios might see an increase in Average Annual Loss (AAL) from floods of 130 per cent, and the number of properties at considerable risk of flood (1.3 per cent or 1 in 75 annual probability above) could increase by 40 per cent (180,000 within the portfolios). If global efforts to reduce emissions in line with a 2°C temperature target are successful then these losses are expected to fall substantially: AAL might only increase by 61 per cent and the number of properties at considerable risk of flood might increase by only 25 per cent. These results stem from an analysis of seven large, relatively well geographically diversified mortgage portfolios and take account of coastal, fluvial and surface water flooding. It is an assessment of how much additional damage today's portfolios might face under the climatic conditions expected in the 2050s, assuming a continuation of trends in the recent past regarding community-based adaptation.[e1]

Beyond the UK residential mortgage market, the results suggest increases in flood risk for investors with UK assets and in tropical cyclone risk for investors with assets in North America and the Pacific Rim. These relate to investments in commercial property, primarily offices and shopping centres. In the UK, in a 4°C warming scenario, the increase in AAL from flood risk across three portfolios may be approximately 70 per cent higher in the 2050s than today; and across the two portfolios with assets in North America and the Pacific Rim, the equivalent increase from tropical cyclone risk is expected to be around 80 per cent. These potential increases are significantly lower in a 2°C warming scenario, 40 per cent and 43 per cent respectively. These results are based on the analysis of a small number of portfolios and are unlikely to be transferable to other portfolios with different geographic distributions of assets.

In contrast to flood and tropical cyclone risk, the analysis suggests that investors and lenders in the reviewed portfolios face smaller increases in risk from European winter wind storms under different climate change scenarios. This reflects that climate change is currently expected to make only small changes in the frequency and severity of such events. However, there remains considerable uncertainty regarding the underlying climate science in relation to this type of event, while portfolios of assets with a different geographic distribution to those analysed in this study might experience different, possibly larger, increases in risk.

5.2.2 The changes in risk, especially in the scenario most aligned with the current warming trajectory, raise important questions for investors, lenders, insurers and policymakers on how increased risk can be managed in the most cost-effective manner

The likely increase in risk will have significant knock-on effects. Insurance premiums will rise proportionately to the increase in AAL. Correspondingly, insurers will also need to purchase more reinsurance. In the residential property market, lenders may need to factor higher insurance premiums into mortgage affordability assessments, and potentially take a more pro-active stance than at present, to ensure that insurance protection is maintained for the duration of the mortgage term.

Bodies tasked with closing the protection gap may need to factor these changes into their medium-term operational and funding strategies. Across the world, a range of innovative institutional structures have been developed to try and ensure that more communities and assets benefit from insurance. Their focus is to close the so-called 'protection gap' – the losses from disasters that are not insured.[56] These institutions will need to consider how to take account of the increased physical risks that climate change will cause.

This need is likely to be particularly prominent for residential properties. Properties that are unable to acquire buildings insurance for flood or other events aggravated by climate change could see a significant fall in property value. This would have adverse implications for homeowners living in those properties who may find themselves in negative equity and hence either unable to sell their homes and/or unable to re-mortgage. This would have significant personal costs, as well as disrupting the liquidity and efficiency of the housing and mortgage markets. It would also have knock-on impacts to lenders, who would need to consider the increased risk of mortgage default, which is likely to be geographically concentrated, and ensure that their business strategies are robust to this risk.

In the UK, there are specific implications for Flood Re. As discussed in Box 10, Flood Re's role is to provide an affordable market for home insurance, for properties built before 2009 that are at risk of flooding. Although home insurance affordability in the UK has not been formally assessed in this work, a typical rule of thumb is that it can be challenging to provide insurance cover for residential properties which have more than a 1.3 per cent or 1 in 75 annual probability of flooding: in the UK, in a 4°C warming scenario, 180,000 additional properties in the portfolios examined might fall into this category by the 2050s. This compares with an estimated 445,000 properties at present, and 150,000 properties that Flood Re protected during the most recently reported financial year.[53] These findings reinforce previous concerns about the sustainability of these institutional arrangements.[57] Any increase in risk will need to be carefully factored into Flood Re's corporate and funding strategy, and especially its Transition Plan to manage the transition of the UK residential market to risk-reflective pricing, meaning that after 2039 premiums and excesses should, as well as being risk-reflective, remain affordable without the benefit of the levy.

[e1] As such, it does not take account of the possibility that lenders will change their portfolios between now and the 2050s nor of additional socio-economic changes, such as additional urbanisation, which might increase surface run-off and hence increase flood risk. The role of individual property adaptation is discussed in Section 5.2.4 below.

Box 10. Flood Re

The UK has a long tradition of flood insurance with penetration rates estimated to be as high as 95 per cent in England.[58] This has been supported by a series of informal and formal arrangements between the government and the insurance industry. Up until 2013, insurers considered flood risk to be not significant for properties at less than a 1.3 per cent or 1 in 75 annual probability of flooding and made flood insurance available to these properties as part of standard household insurance, while offering insurance for properties at a significant risk of flood as long as the Environment Agency committed to reducing the risk for those properties.[8] However, rising flood losses and recent improvements in risk analysis technologies such as data mapping led to increasing concerns that flood insurance would become unaffordable for those in high-flood-risk areas once their risk could be properly ascertained by insurers.[59] Socially vulnerable populations are particularly at risk.[36]

In response, the insurance industry and government developed Flood Re, a not-for-profit reinsurance initiative launched in 2016. It seeks to satisfy the dual objectives of market autonomy and insurance affordability by formalising cross-subsidies between low and high-risk homeowners to avoid a sudden affordability crisis in the wake of floods. As a reinsurance pool owned and operated by the insurance industry, Flood Re gives insurers the option of reinsuring high-risk policies at a subsidised price; insurers can pass on their own cost savings to policyholders and thus make flood insurance more affordable, even for those at high risk. The subsidised price is based on the council tax banding of the relevant property; the higher the banding, the more expensive it is to reinsure. Flood risk levels are not considered in the Flood Re pricing approach, and properties built after 1 January 2009 are not eligible. In the event of extreme losses and pressure on the scheme's solvency, Flood Re can make a levy 2 call on insurers for additional funding. Importantly, there is no formal public back-up mechanism for Flood Re. Flood Re has underwritten 150,051 policies in the financial year of 2018[53] and 90 per cent of the home insurance market offers the scheme.[60]

Flood Re is intended to be a transitional measure to make way for risk-reflective pricing by 2039, in the expectation that flood risk management will have improved significantly by then. In this light, Flood Re has committed to considering what role it can play to incentivise homeowners to adopt property-level risk-reduction measures.[60]

A crucial next step from this work should be to explore in more detail the interlinkages between climate change risk and insurance availability. For example, in the UK, this could build on the concern expressed by the Bank of England regarding the possible crystallisation of financial risks from greater flood risk to the UK residential mortgage market if flood insurance became unaffordable.[9] Similar studies in other countries would also be valuable.

5.2.3 There is significant variation in the risks that different investors and lenders face

As regulators increasingly scrutinise efficacy of action in this area, discrepancies across investors and lenders in their risk to climate change impacts will matter. Regulators will necessarily focus their attention, and any possible interventions, on areas where risks are concentrated.

Especially in a 4°C warming scenario, there are likely to be significant differences in the risks faced by different portfolios of mortgage and investor assets. The potential range of increase in expected losses across the seven UK residential mortgage portfolios reviewed in this analysis varies between 108 per cent and 132 per cent. For the two portfolios of assets at risk of tropical cyclones in North America and the Pacific Rim, the possible difference in the increase in expected losses is 17 percentage points. The spread in risk across different portfolios is substantially smaller if emission reductions are successful in moving the world onto a 2°C warming trajectory.

In the UK residential mortgage market, a fuller assessment could reveal even larger differences in risk across portfolios. The analysis of UK residential mortgages focused on the seven largest – and hence most diversified – lenders. Other lenders, especially regional building societies, may well have less diversified portfolios, some of which are likely to be concentrated in regions particularly exposed to flood risk.

130% increase in Average Annual Losses from floods under a 4°C warming scenario

This implies that one of the most important ways that investors and lenders can influence their exposure to physical risks is through both strategic location investment decisions (which region/country/continent) and local asset-siting decisions, although any transition in the approach to capital allocation should happen smoothly. Capital providers to investors and lenders will likely want to understand how such location decisions, intermediated by insurance availability (discussed above) and adaptation action (discussed below), are taking account of the physical risks of climate change. To the extent that investors and lenders do alter location decisions, it will be much less disruptive to the real economy if this happens over a long period of time rather than as an abrupt response to one or a series of particular events.

5.2.4 Adaptation measures can have a material role in reducing risks, but are less effective in higher temperature scenarios

The implementation of adaptation measures offers the potential to substantially reduce the physical risks of climate change that investors and lenders face. The increase in losses identified above assume relatively limited efforts to adapt to the impacts of climate change. In relation to UK flood risk, they assume flood defences continue to be maintained and improved as effectively as experienced in the recent past. In relation to tropical cyclone risk, it assumes no change from the status quo in relation to either property-level or community-based protection measures. By contrast, for UK flood risk, if, in addition to the community-based adaptation in the baseline, a package of adaptation measures[f1] is installed to 50 per cent of households, then under a 2°C warming scenario, around 57 per cent of the expected increase in losses might be offset. For UK commercial properties, in the same warming scenario, the modelling suggests that all of the additional losses in the portfolios assessed can be offset (although this partly reflects the low baseline risk in these portfolios). Finally, the modelled adaptation measures for tropical cyclone risk might offset around half of the expected increase in losses in a 2°C warming scenario. Further reductions in losses, and a reduction in the number of properties at significant risk of floods, could be secured by increased community-level adaptation measures.

However, property-level adaptation is likely to be less effective in a 4°C warming scenario. For the UK flood results, while the modelling results suggest that adaptation might offset 57 per cent of the increase in AAL under a 2°C warming scenario, this falls to 41 per cent in a 4°C scenario. The equivalent figures for tropical cyclone risk are that a 49 per cent modelled offset in a 2°C scenario falls to 33 per cent in a 4°C scenario.

This suggests an important opportunity for investors and lenders to work in conjunction with insurers, as well as government, in order to encourage the uptake of adaptation measures. For UK residential properties, existing efforts to encourage adaptation will need to be enhanced significantly to realise the 50 per cent penetration rate assumed in this analysis. Joint efforts between lenders, insurers and the government are likely to be critical: the short time horizons created by the (capital-efficient) industry practice of insurers only writing one-year contracts appears unlikely to provide sufficient incentive for household-level adaptation by itself.[61] If efforts were co-ordinated at an industry or government level, this could help overcome 'first-mover risks' whereby households may be unwilling to introduce adaptation measures that similar households do not have, for fear that their abnormality, and the signal that the property may be exposed to physical risks, reduce the value of the property.

For investors in real estate and infrastructure assets the commercial incentive to undertake adaptation is currently still limited, and any current efforts are likely to be driven by building codes and planning regulation rather than business strategy. However, with rising risk levels the demand for risk reduction measures is likely to rise. More public information about what adaptation measures are likely to be cost effective would be valuable. Importantly, as discussed above, adaptation measures are proportionally more effective while temperature increases are still somewhat limited, implying it is important to start considering adaptation early and not to delay decisions and investments.

The analysis also suggests that investors, lenders and insurers have a common interest in advocating both for enhanced community-level adaptation and to support the emission reductions needed to keep temperature increases to a level where adaptation can be most effective.

For UK residential properties, existing efforts to encourage adaptation will need to be enhanced significantly to realise the 50 per cent penetration rate assumed in this analysis.

[f1] Adaptation measures include a mix of measures to prevent flood ingress and measures to reduce damages if flood water does ingress, eg resilient flooring.

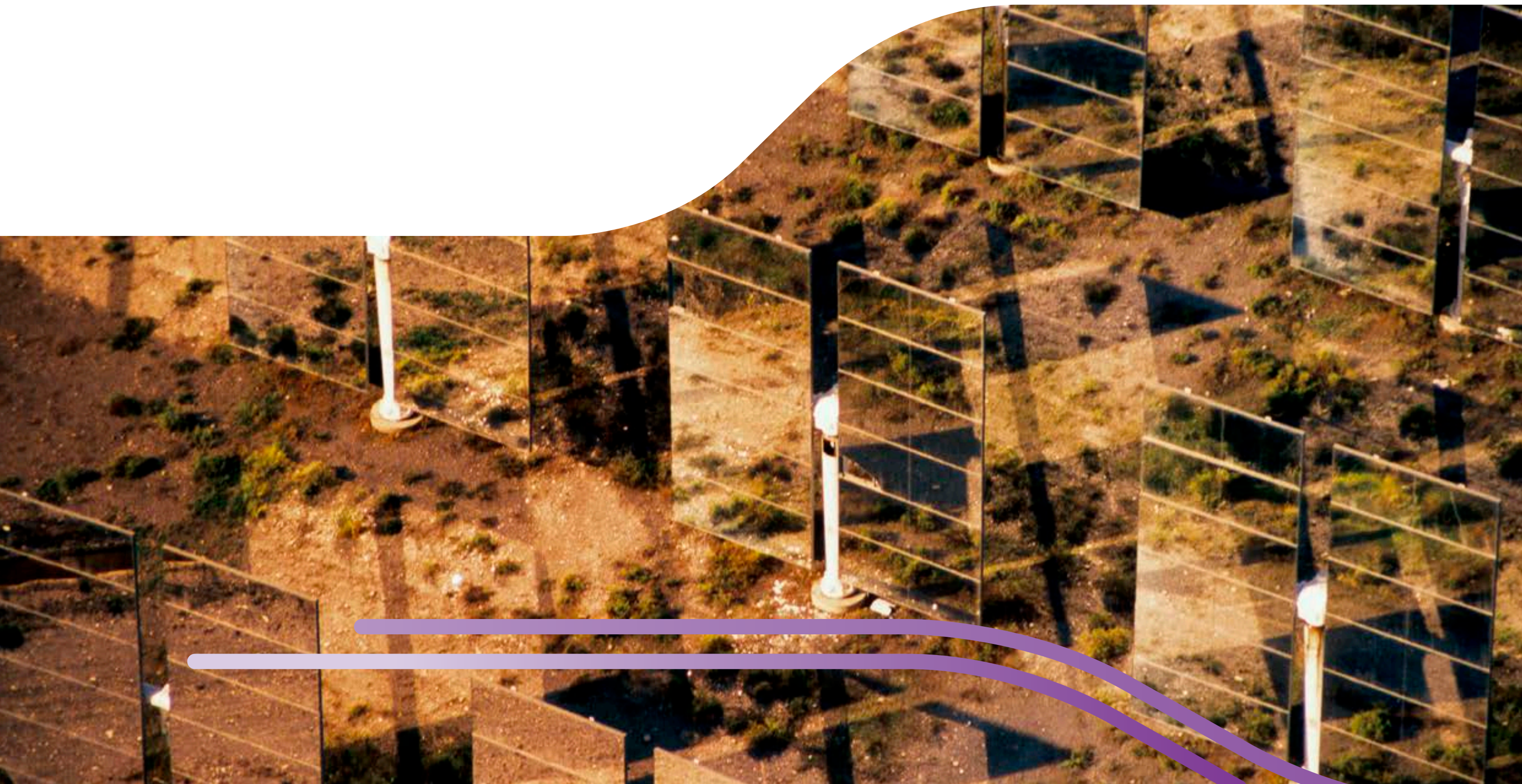
5.3 This report provides a practical guide containing an open, repeatable methodology to empower investors and lenders to undertake similar analysis

This report provides an initial demonstration of how investors and lenders can use insurance tools and metrics to help inform – as a first step to managing and reducing – the physical risks they face. Investors and lenders can build on this initial analysis to undertake more comprehensive assessments, exploring more risks, using similar and more detailed tools and models, and taking account of the specificities of their portfolios. As explained in this report, investors and lenders might either undertake this work themselves and/or work with commercial and academic partners to help them do so.

Additional work can further increase the efficacy of these tools:

- **For investors and lenders, a crucial requirement to make effective use of these tools is to collect good exposure data.** The data-collection exercise undertaken for this report illustrated substantial differences in the quality of exposure data held by investors and lenders, and the ease with which they could access it. Information management systems should be used to keep centralised records about assets' locations and attributes; including property age, number of floors, footprint, and construction type.
- **For those developing tools, further work can allow these tools to be applied to more types of physical risk and for a wider set of assets.** At present, these tools and metrics are more effective at supporting the understanding of the impacts from the increased likelihood and severity of (some) extreme weather events, such as floods, winter wind storms and tropical cyclones, and for assets with a defined location such as real estate and infrastructure assets. This is an important, but limited, subset of both the impacts of climate change and the assets that will be affected. More work, adapting either these tools or making use of others, will be needed to support understanding of slow onset climate change impacts (such as temperature increases) and to explore financial assets that are related to defined locations, but do not record such links systematically, such as tradeable securities.

Nonetheless, the expectation to understand, report and manage physical risks is growing; investors and lenders that use the tools described in this report can lead this race and gain a competitive advantage. Scrutiny on how physical risks might affect financial stability has increased significantly in the last few years. This will only continue as the physical risks of climate change become more apparent. Investors and lenders who best understand these risks will be best placed to manage them, and by demonstrating this to the market can gain a competitive advantage over their peers. By using the methodologies set out in this report, investors and lenders can make an important contribution both to making specific portfolios more resilient to climate change, and building the resilience of the financial system as a whole.



6. Glossary

Annual exceedance probability curve: a graph which 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 the period of one year, a given asset experiences an event of a given magnitude. For example, an asset might face a 1 per cent chance of flooding at a depth of one metre or more in any given year.

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

Coastal flood: flooding from the sea when tidal surge, wave action or a combination overflows the shoreline boundary.

European winter wind storm: wind storms caused by extra-tropical cyclones, most commonly affecting countries in Northern Europe.

Exposure: physical assets exposed to extreme weather events.

Fluvial flood: flooding that occurs when water from an established river or drainage channel spills onto the floodplain.

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

Protection gap: the difference between the amount of insurance that is economically beneficial and what is actually purchased.

Replacement cost: the cost of fully reinstating an asset after total damage.

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

Surface water flood: flooding from a rainfall event prior to the generated run-off reaching an established river or drainage channel.

Tropical cyclone: intense circular storm originating over warm tropical oceans. Known as hurricanes when forming in the Atlantic Ocean and typhoons in the Pacific Ocean.

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Appendix A

A conservative approach

There are a number of reasons why the estimates of losses provided in Section 4 might underestimate the true increase in physical risks faced by investors and lenders.

Hazard

This analysis focuses on future changes in the likelihood and intensity of extreme weather events. This is one important physical effect of climate change, but not the only one. 'Chronic' changes in the system are also a major risk to investors and lenders. For example, sea level rises put properties and infrastructure at risk of inundation and coastal erosion, which could result in significant financial losses.[62] In this analysis, although the impact of sea level rise on flooding is modelled in the Future Flood Explorer, impacts on coastal erosion are excluded. Steady increases in average temperature might reduce agricultural output and reduce labour productivity, with knock-on impacts for investors and lenders, while, similarly, changes in annual rainfall patterns will influence agricultural productivity and water availability.

The analysis does not model the impact of all 'acute' perils on investors and lenders. Some examples of excluded perils include the substantial additional flood risk for most of Central and Western Europe[63] and in North America,[62] whereas this analysis only looks at flood risk in the UK. In addition, increased frequency of drought events is expected to lead to increased subsidence risk.

Climate models which drive predictions of extreme weather events may not be capable of capturing tipping points in the climate system. Tipping points refer to thresholds around which small changes in a variable might lead to rapid changes in another. For example, small changes in the extent of Arctic summer sea ice might rapidly amplify warming[64]. If such tipping points are crossed, faster global warming might lead to increased losses for investors and lenders.

Exposure

The seven modelled UK residential mortgage portfolios represent 70 per cent of mortgage lending, but smaller lenders might have higher risk than these. The UK mortgage market is also served by a large number of smaller lenders, including some regionally focused building societies.[65] These are likely to have less geographically diverse portfolios. To the extent that these are located in areas of particular risk of flood (for example in coastal regions), they might suffer higher losses than the larger, more geographically diverse, portfolios.

Increased urbanisation and demand for new housing might result in new buildings in high-risk locations. For example, in the UK, between 2001 and 2014, 23,000 new homes were built in areas with a high chance of flooding.[66] This analysis assumes that lenders do not change their portfolios between now and the 2050s whereas in practice these patterns of new construction are likely to lead to increased flood risk for many portfolios. In addition, new buildings built around existing building stock might increase flood risk for existing properties: by reducing the ability of the ground to absorb surface water, they might increase the risk of surface floods for existing properties.

Scope of losses

The analysis models direct damage to physical assets caused by extreme weather events and the financial losses associated with that damage, but there are a range of non-direct impacts that investors and lenders may face that are excluded. Physical damage to assets is also likely to cause business interruption and supply chain interruptions. In the UK, drought, flooding and storms are estimated to account for 10–35 per cent of delays and interruptions of service to electricity, road and rail infrastructure.[67] These indirect losses might be more difficult to insure.

The analysis assumes that labour and materials required to repair damage to assets are available at their normal market rates. After major natural catastrophe events, local increases in demand for labour and materials might increase the cost of reinstating assets.

As suggested by the Bank of England, flood events might also have adverse effects on the local economy, making it more difficult for customers to service their loans.[9] Business interruption caused by flood damage can cause reductions in demand for local goods and services and cause unemployment.[91] If businesses are unable to insure properties, such effects could lead to permanent economic malaise and associated value impairments, even to properties which are not directly affected. When modelling changes to prices of UK residential properties, we do not consider such local economy effects.

This has been shown, for example, in the case of 2015 floods in Calderdale, Yorkshire.[94]

Appendix B

Technical details

Technical details: UK flood

Flood is a major peril to UK assets. Across the UK the most significant sources of flooding today are fluvial (river) flooding (contributing £560 million/40 per cent of total UK flood risk), coastal flooding (contributing £320 million/24 per cent), surface water flooding (contributing £260 million/20 per cent) and groundwater (contributing £210 million/16 per cent). [7] If current levels of adaptation continue flood risks are projected to increase significantly by the 2080s (50 per cent under a 2°C climate change projection, 150 per cent under a 4°C climate change projection, and sixfold under the H++ scenario, *ibid*). When projections of population growth are included the risks increase further (*ibid*).

The Future Flood Explorer (FFE) is used here to model future changes in flood risk taking into account the influences of climate change and adaptation. In doing so, the FFE builds upon lessons from past national scale studies undertaken in the UK[24-68] and insights from international studies (eg[69-70] to provide an innovative emulation of the system response. The UK FFE uses available data on flood hazard, exposure and vulnerability to develop a credible representation of the behaviour of the UK flood risk system (that takes account of the flood defences where they exist). This approach was scrutinised as part of the UK Climate Change Risk Assessment and subsequent national studies, and shown to provide credible and useful insights.[7-36-37]

The underlying spatial resolution of the flood hazard data used within the UK FFE varies from 2m to 50m (depending upon flood source – coastal, fluvial or surface water and location). The data on exposure is based on residential point datasets (and hence has the resolution of a single property). The influence of flood defences (overtopping and breach) are included, with data on defence location, condition grade and standard of protection used). The concept of the 'neighbourhood' is used to provide a locally aggregated spatial unit that brings together flood hazard and exposure with census-based social vulnerability data. The spatial scale of 'neighbourhoods' varies across the UK and is based upon census Lower Super Output Areas (LSOAs) in England and Wales, Super Output Areas (SOAs) in Northern Ireland and the Data Zones (DZs) in Scotland (as defined in the 2011 Census). This definition yields a total of 42,619 neighbourhoods with the average population in each varying slightly by country: 1,600 in England, 760 in Scotland, 1,600 in Wales and 2,000 in Northern Ireland. For each Census Calculation Area, an Impact Curve is generated relating the return period of a current or future flood event to the magnitude of the impact (eg economic damage or the number of properties that would be flooded), as shown in Figure 28. The Impact Curves are then manipulated to quantify the influence of climate change as well as adaptations on flood risk.

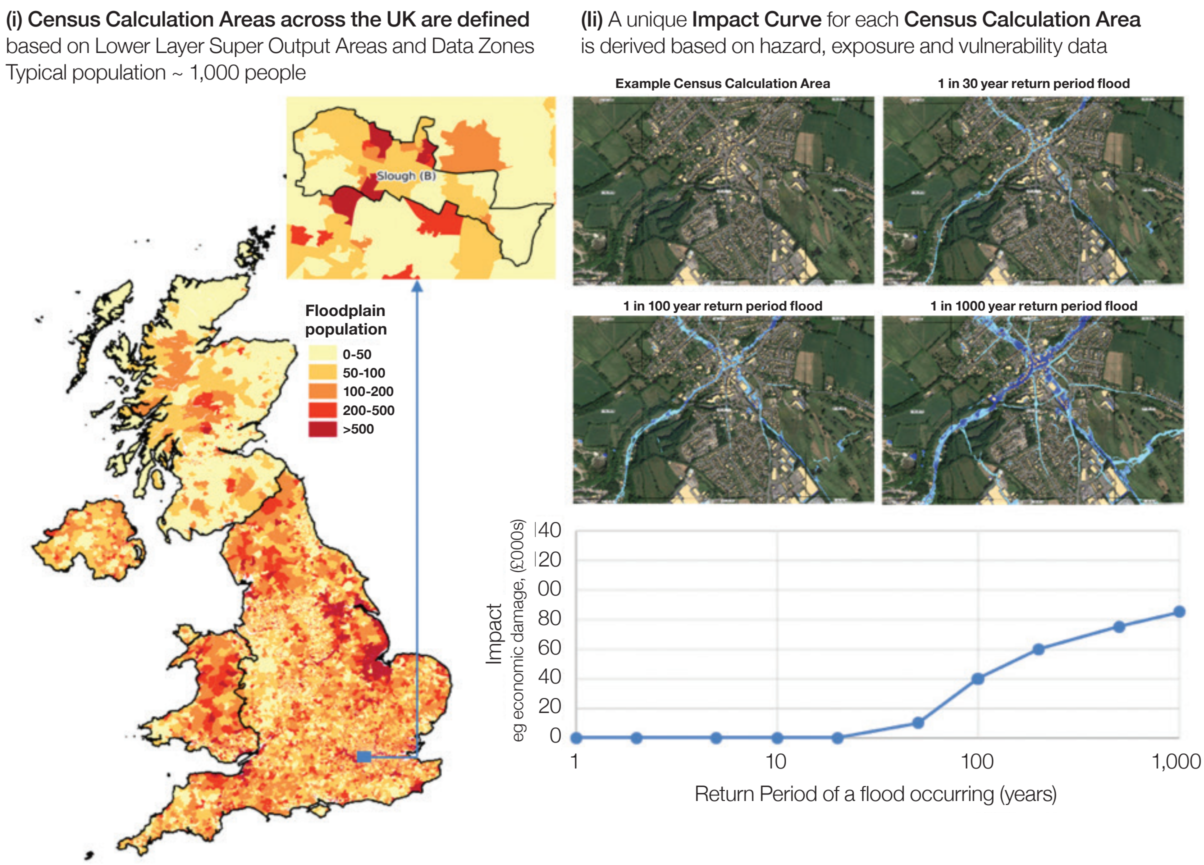

Figure 28. The FFE is based on Impact Curves developed for each Census Calculation Area
Source: Sayers, Penning-Rowsell, et al. 2018[36]

For both 2°C and 4°C scenarios, climate change is represented through spatially varying changes in:

- **Sea level rise.** Wave conditions around much of the UK coast are depth limited.[71] Because of this, relative Sea Level Rise (rSLR) has a dominant influence on coastal flooding (increasing both wave-driven overtopping, the chance of a breach and overflow) and is used here as a proxy for all other climate-related changes at coast. The impact of rSLR is taken forward into the analysis through its influence on the Standard of Protection (SoP) of coastal defences. This is done based upon the relationships derived between rSLR and the change in the SoP afforded by a given coastal defence established during the Foresight Future Flooding Study.[68] The supporting evidence for the values of relative SLR used to represent each climate scenario is provided in Table 7. An illustration of the influence of rSLR on SOP is provided in Figure 29.
- **River flows and water levels.** The influence of climate change on fluvial flows and water levels is included in the FFE through two mechanisms: (i) Changes in peak flows (using evidence from national analysis, Table 8); (ii) Associated changes in the SoP of a fluvial defence, based on the relationship between a change in flow and a change in the probability of that flow being exceeded, determined using regional growth curves to translate a change in flow to a change in return period and hence a change in the SoP of a defence.
- **Surface water run-off.** This is assessed by first considering changes in the intensity of short duration rainfall and then translating this to a change in the return period of the run-off generated. The assumed changes in intense rainfall (sub-daily rainfall < 6 hours' duration) used here are based on research by UKWIR.[72-73] These effects are shown in Table 9.

	2 Degrees			4 Degrees		
Region	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
England and Wales (based on Deakin et al, 2001)						
Lincolnshire (East coast)	0.03	0.13	0.26	0.14	0.37	0.64
Dungerness (South-east coast)	0.03	0.14	0.26	0.14	0.37	0.64
Lyme Bay (South-west coast)	0.03	0.15	0.28	0.15	0.38	0.66
Swansea (Mid-west coast)	0.03	0.13	0.25	0.14	0.36	0.63
Flyde (North-west coaast)	0.02	0.11	0.21	0.14	0.34	0.59
Scotland (locations based on Crew, 2012)						
Edinburgh	0.02	0.08	0.17	0.13	0.32	0.55
Aberdeen	0.02	0.09	0.18	0.13	0.32	0.56
Wick	0.02	0.11	0.21	0.14	0.34	0.59
Lerwick	0.04	0.16	0.30	0.15	0.39	0.67
Ullapool	0.02	0.09	0.18	0.13	0.32	0.56
Stornaway	0.02	0.11	0.22	0.14	0.34	0.59
Tobermory	0.02	0.08	0.16	0.13	0.31	0.54
Millport	0.02	0.08	0.16	0.13	0.31	0.54
Northern Ireland						
NI - All	0.02	0.09	0.17	0.13	0.32	0.55

Table 7. Climate change is expected to increase sea level rise differentially across the UK
Source: Sayers 2015[7]

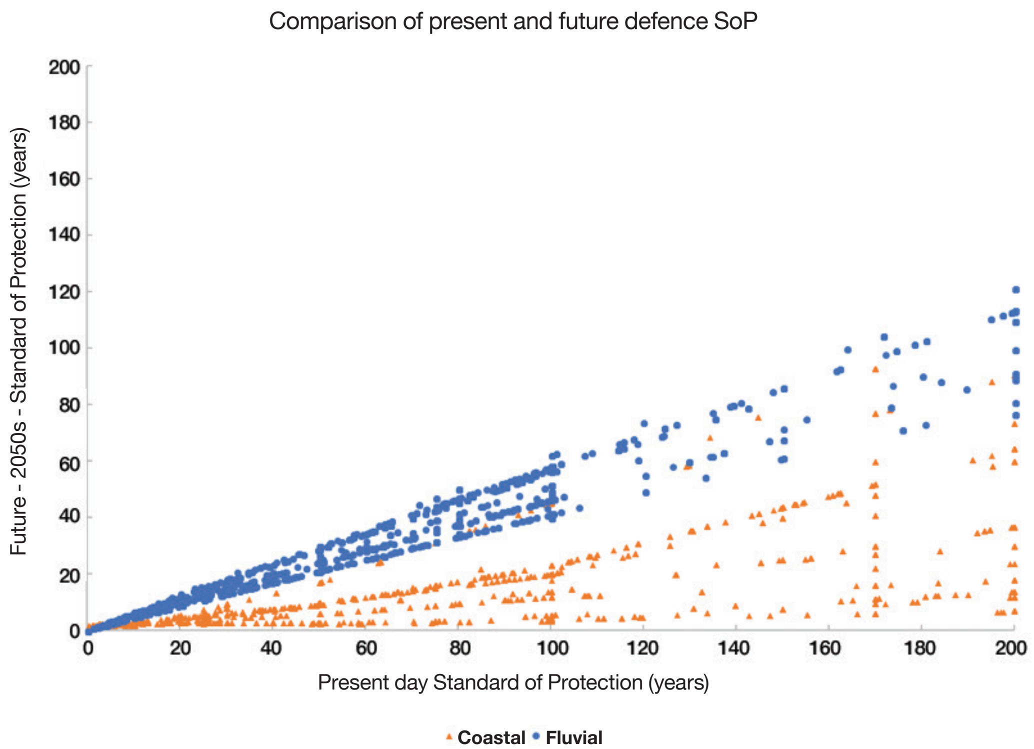

Figure 29. Climate change impacts defence standards
Note: Figure shows influence of climate change on defence standard (figure shown is for defences in England and under a 4°C scenario).
Source: Sayers et al. 2018[37]

Country	Region	2050s – 2°C	2050s – 4°C
England and Wales	Northumbria	8	21
	Humber	8	21
	Anglian	3	24
	Thames	3	24
	South East	8	33
	South West	10	28
	Severn	8	28
	Dee	8	21
	North West	15	26
	Solway	18	26
	Tweed	13	26
	Western Wales	8	24
Scotland	Orkney and Shetland	19	22
	North Highland	13	19
	West Highland	21	30
	North East Scotland	9	11
	Argyll	21	30
	Tay	11	17
	Clyde	14	23
	Forth	12	19
	Solway	13	21
	Tweed	10	15

Table 8. Climate change is expected to increase peak river flows differentially across the UK
Source: Sayers 2015[7]

Climate change factor	Scenario	Change by 2050s
Lower	2°C	+10%
Medium	4°C	+20%

Table 9. Climate change is expected to increase the incidence of intense rainfall across the UK
Source: Sayers 2015[7]

Flood risk is best managed through a portfolio of measures implemented through a continuous process of adjustment.[68-74] This is reflected in much of the UK flood risk management policy.[75] For the purpose of this study, however, the adaptation assumptions are more constrained, reflecting the focus of the analysis on the financial sector and insurance industry. Two primary adaptation assumptions are made:

- **No property-level adaptation:** A central discussion in any analysis of future risk is the assumptions made regarding community-level adaptation. For this study it is assumed that flood defences continue to be maintained and improved as effectively as experienced in the recent past (ie achieving the same outcomes as in recent years). This does not imply the same level of investment (because of course investment is not static) and does not imply maintaining the standard of protection in line with climate change because this would be unrealistic from a technical perspective and would require a significant acceleration in the increase in investment.[76] Concretely, we assume that in some areas where the cost–benefit case is weakest (as inferred from a low present day standard) the standard of protection provided reduces as investment fails to keep pace with climate change. In areas with a robust cost–benefit case (as inferred from the highest standards of protection today, such as the Thames Estuary) investment keeps pace with climate change and standards are maintained into the future. A similar assumption is made for condition grade (which influences the chance of a defence breach). In areas protected by defences with a condition grade of 4 or better (a typical target condition grade maintained by the Environment Agency) the case for continued maintenance is strong, whereas with defences with a condition grade of 5 (poor) today the case for improvement is assumed weak and with time they deteriorate further. In the context of the baseline assumed for this study, no other adaptations are included.

- **Property-level adaptation measures:** Several policy measures encourage individual property owners to protect themselves and their property from flooding. The Environment Agency's Flood and Coastal Erosion Risk Management Strategy[77] and Defra's partnership funding policies encourage local communities to contribute towards their risk reduction, not least by implementing property-level adaptation measures. Local authority enforced Building Regulations have been strengthened in recent years to promote property-level adaptation measures, and subsidies and grants are often made available for those in flood-affected areas to install certain property-level adaptation measures. At the same time, the availability of these measures is increasing from a wide range of companies, including installing 'Kitemarked' devices for preventing the ingress of flood waters into properties and installing fixtures and fittings that are less susceptible to flood damage should a property be flooded (eg plastic kitchen fittings).

There are barriers to the uptake of property-level adaptation measures. Property owners are often reluctant to implement risk-reducing measures which demonstrate to the wider public that their properties are at risk, such as external flood gates[46-47] it argues that people sometimes put what Giddens calls their ontological security above their physical security. Preferring to think of their homes as places that are innately safe, they reject the idea of defending them; preferring to think of nature as a positive moral force, they hesitate to view it as a source of real danger; and preferring to think of society as a competent protector of last resort, they are reluctant to accept the need to protect themselves. Being central to ontological security, such social representations (of 'home,' 'nature,' 'society' etc. Furthermore, adaptation measures are only likely be an efficient response where the frequency of flood events is high,[78] and are only likely to be effective when the external flood depth is less than 60cm.[45] They also often rely upon neighbourhoods acting to prevent flood waters penetrating through party walls and shared roof spaces. At flood depths greater than this, or in the absence of the collective action that may be necessary, it is likely that resistance measures (ie external flood boards and similar products) will be overtopped or will be of insufficient strength to withstand the loading of large depths of the flood water. Additionally, not all measures implemented will be successful. An evaluation of post-installation effectiveness commissioned by Defra concluded that: "of the 11 Environment Agency responses received, 6 schemes had been tested and Property-level Protection measures deployed but only 4 provided further detail. The information provided showed that for 79 per cent of properties, Property-level Protection measures either prevented flood water ingress or served to reduce the impact and level of flooding experienced, whilst 21 per cent found that it made no difference at all".[78]

Analysis by Flood Re in 2018 considers evidence for property-level adaptation measures and discusses current uncertainties around their precise impacts.[79] It also calls for a collation of data from relevant agencies, such as local authorities and water companies, regarding implemented schemes which could enhance the evidence base regarding: (i) the real cost of property-level adaptation measures including barriers and resilience measures; (ii) the performance of implemented schemes; and (iii) the locations of properties with measures.

The FFE includes representation of the effectiveness of reducing damage through property-level actions varying according to the return period of the flood event, whilst acknowledging the above uncertainty. The relationship is based on expert evidence and suggests that such measures are likely to be effective at reducing damage in more frequent events (and shallower depths) and less so in more extreme events (with greater depths). [74] This is illustrated by Table 6 in the main text.

The take-up rate of adaptation measures is a key consideration. Take-up is currently low and evidence suggests even lower in vulnerable communities than in the population as a whole. This reflects several difficulties that are characteristic of more socially vulnerable neighbourhoods, including rented tenure and low income as well as the need for collective action demanded by the nature of the housing stock, for example to provide flood resistance to terraced housing. For the purpose of this study, however, a more ambitious assumption of 50 per cent take-up is assumed. This, in part, seeks to reflect an ambitious but credible assessment of the potential of the property-level measures when appropriately incentivised.

Technical details: European winter wind storms

European winter wind storms are the costliest natural hazard in a number of European countries. Over the period 1970 to 2006, 70 severe wind storm events in Europe caused damages of approximately US$ 50 billion[34] nature and dynamics of storms, (ii. Losses from Windstorm Friederike, the most severe storm of the 2017–18 season, are estimated at between EUR 1.3 and 2.6 billion.[80]

European winter wind storms are normally caused by extra-tropical cyclones originating in North America, following an eastward track and passing through environments with growth conditions (eg strong north–south temperature gradient and high baroclinicity).[81] Most storms follow a track which curves northwards and hit land in northern European countries such as the United Kingdom and countries in Scandinavia, but under certain conditions storms travel southwards, affecting countries such as France, Germany and Switzerland.[82]

There is considerable decadal variability in storm frequency, intensity and location. To date, such variability has dominated any underlying long-term trends caused by climate change. This has led the European Environment Agency to conclude that there is no recent increase in storm damage which can be attributed to climate change.[83]

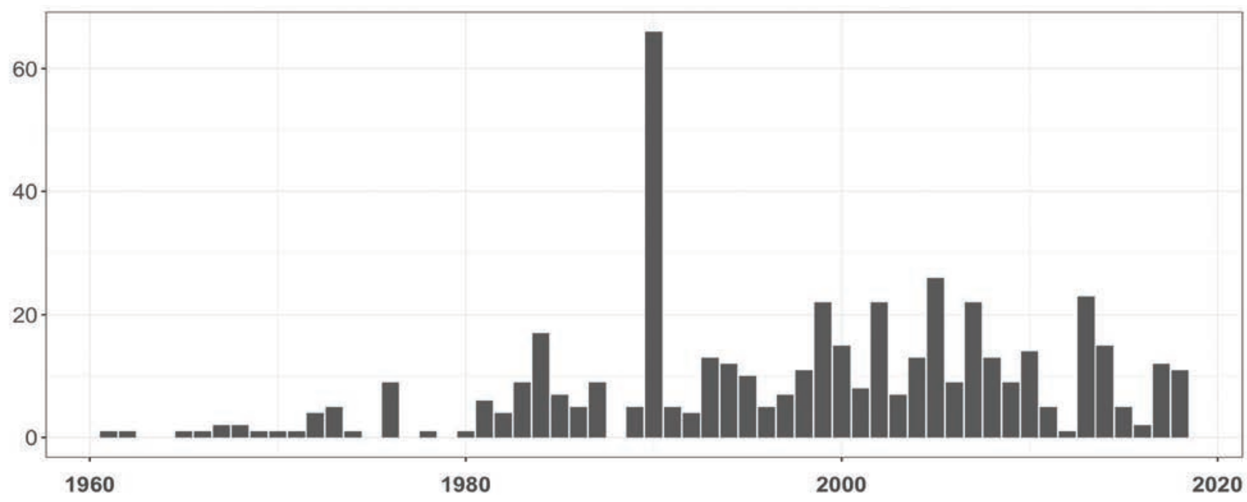

Figure 30. Number of European winter wind storms causing financial losses or deaths per year
Source: Vivid Economics, based on EM-DAT[84]

CLIMADA's European winter wind storm model is based on tracks and footprints of historic storms extracted from the EU's Copernicus Wind Storm Information Service (WISC). This is a comprehensive catalogue of wind storms occurring over the European area from 1940 onwards. The catalogue estimates the geographic footprint of each historic storm at a resolution of 4.4km; this footprint indicates maximum three-second gust speed in metres per second over a 72-hour period.

CLIMADA applies a perturbation process to create a synthetic event sent from this set of historic storms. For each historic storm, CLIMADA creates a large number of 'daughter' storms. These daughter storms are created from the historical storm set using a Monte Carlo method applying rigid motion and wind field intensity alteration. In this way, the synthetic set of storms closely mirrors the historical set in terms of intensity distribution. This is verified by calculating the storm severity index (SSI) for both historical and synthetic storms and comparing their distributions. As shown in Figure 31, these distributions match very closely.

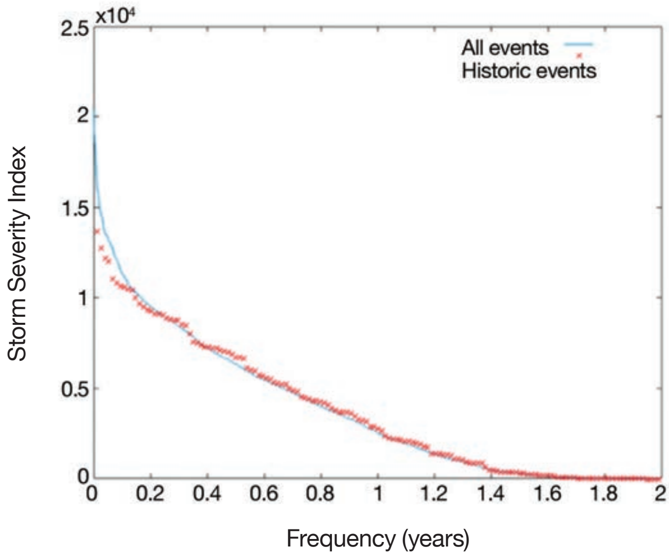

Figure 31. The distribution of storm intensity in CLIMADA's synthetic event set closely matches that of the historical record
Source: CLIMADA

CLIMADA's vulnerability module embeds a European winter wind storm damage curve which is applied to all assets. This represents a simplification relative to commercial natural catastrophe models, where damage curves typically vary by country, building type and building attributes. CLIMADA's damage curve is derived from historical claims data from 1987 and 1990 storm events in the UK.[34]

The relationship between future climate change and European winter wind storm frequency and intensity is complex. Important factors determining the effects of global warming on extra-tropical cyclones are the distribution of near-surface temperature changes and the increased moisture in the atmosphere[34] nature and dynamics of storms, (ii. At least two factors work to make the mean frequency of cyclones less likely in a warmer climate. First, polar regions are expected to warm faster than the tropics, reducing the equator-to-pole surface temperature differential, which should lead to an overall decrease in cyclone activity.[85] Second, the atmosphere is expected to become moister as it warms which, through changes in the equator-to-pole transport of latent heat, should again reduce mean activity. However, despite the potential for an overall decrease in mean cyclone activity, increased atmospheric humidity might favour an increase in the number of stronger extra-tropical cyclones (and therefore storms).

In order to incorporate climate change impacts, we adjust CLIMADA's synthetic storm hazard set in accordance with projections on extreme winds from EUROCORDEX regional climate models. EUROCORDEX is a high-resolution regional climate change ensemble for Europe, providing outputs from a number of regionally downscaled climate models on a large number of climatic variables on a 12.5km resolution at a daily time period.[86] Broadly following the methodology provided in Donat et al. 2011,[87] we use outputs from EUROCORDEX to estimate how the 99th percentile maximum daily wind speed during the months of October to March changes between present day and future climate change scenarios. For each individual member of the EUROCORDEX ensemble we calculate the 99th percentile maximum daily wind speed during the months of October to March at each 12.5km grid cell for the time period 2000–15, which is taken to represent present day conditions. We repeat the procedure for RCP4.5 and RCP8.5 emissions scenarios over the period 2045–55, as proxies for 2°C and 4°C scenarios. For each grid cell location and each ensemble member, we subtract the 99th percentile daily maximum wind speed under future scenarios from the present estimate. Finally, we average across all models, resulting in a prediction of the change in extreme wind speed for each grid cell, as shown in Figure 32. By interpolating the EUROCORDEX grid to that of WISC, we apply this spatially explicit adjustment to each of the synthetic storm footprints generated by CLIMADA. Although this methodology does not explicitly model the frequency of storms, it increases the frequency of more extreme storms by shifting the entire distribution of wind speeds.

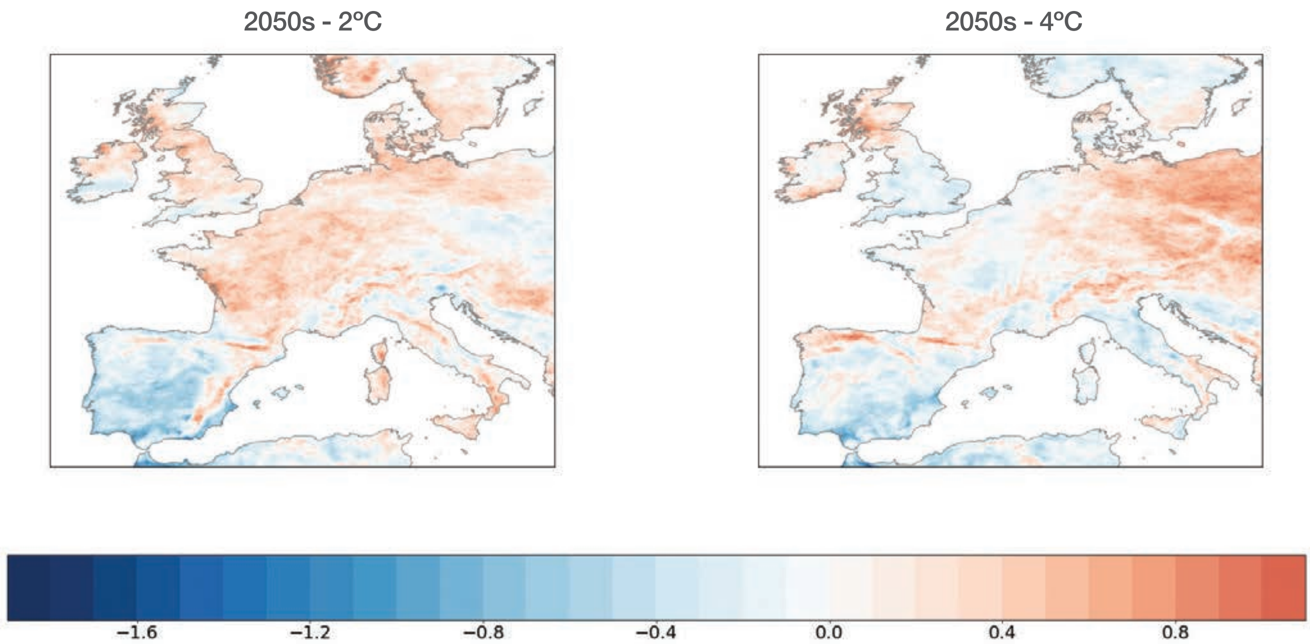

Figure 32. Change in 99th percentile daily maximum wind speed (m/s) relative to present day
Source: Vivid Economics, based on EUROCORDEX downscaling of global climate models

Technical details: Tropical cyclones

Tropical cyclones are low-pressure systems with thunderstorm activity and circulating winds. They can be up to 400 miles wide and move at between 15mph and 40mph. Tropical cyclones are known by other names depending on their location: hurricanes in the Atlantic and eastern North Pacific and typhoons in the western North Pacific.[88]

There have been statistically significant trends in the recent tropical cyclone record. Kossin, Emanuel and Vecchi 2014 found that tropical cyclone tracks moved northward in the period between 1982 and 2012,[89] and an upward trend in the maximum lifetime intensity of storms since 1970 has been identified in North Atlantic and western North Pacific basins.[90] However, it is still debated whether these trends reflect a response to climate change or internal climate variability.

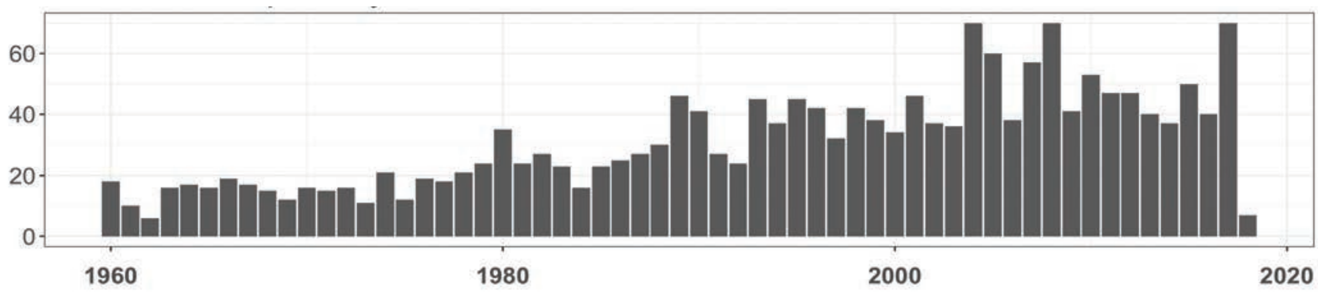

Figure 33. Tropical cyclones causing financial loss or death per year
Source: Vivid Economics, based on EM-DAT[84]

There have been statistically significant trends in the recent tropical cyclone record. Kossin, Emanuel and Vecchi 2014 found that tropical cyclone tracks moved northward in the period between 1982 and 2012,[89] and an upward trend in the maximum lifetime intensity of storms since 1970 has been identified in North Atlantic and western North Pacific basins.[90] However, it is still debated whether these trends reflect a response to climate change or internal climate variability.

CLIMADA's tropical cyclone hazard model produces a synthetic event set based on a comprehensive archive of hurricane tracks maintained by Unisys. For each event in the historical record a set of synthetic 'daughter' events is generated by applying a directed random walk process to the historical track. This random walk process perturbs the wind speed and track such that the synthetic event varies from the historic. In order that the probabilistic tracks exhibit realistic wind speeds overland, a wind speed decay function calibrated against historic data is applied to the synthetic track. Finally, the Holland windfield function is used to generate a footprint from each synthetic storm track.[91] The synthetic event has been validated against the historic events by comparing the probability distribution of intensity at select locations in the historic versus synthetic event set.

CLIMADA's tropical cyclone vulnerability module applies a single damage curve to all asset types. This is a simplification relative to commercial models, which might embed damage curves that vary by property type and geography. CLIMADA's tropical cyclone damage curve has been generated by estimating the relationship between wind speed and damage using data on historic storm events and their associated losses. It is considered to provide conservative estimates of the damage caused by tropical cyclones.

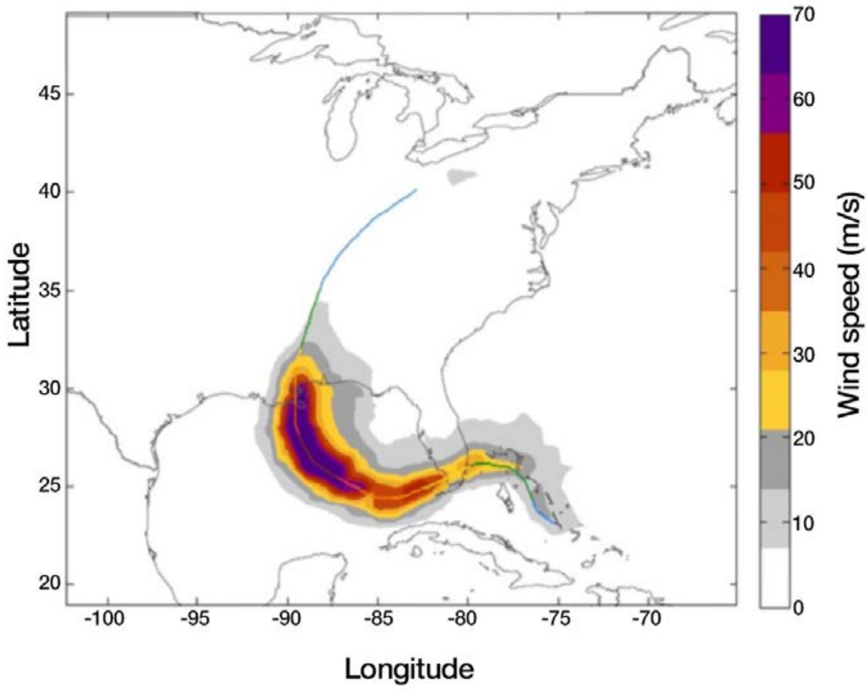

Figure 34. Footprint of a synthetic storm event created on the basis of Hurricane Katrina
Source: CLIMADA

Modelling the impact of climate change on future tropical cyclones provides a particular challenge for climate models. This is because global and regional climate models are generally unable to simulate the formation of tropical cyclones in the Atlantic. Nonetheless, most modelling studies predict a global decrease in the frequency of tropical cyclones, but there is considerable disagreement across models when making predictions for frequency across individual basins. There is also broad consensus that the intensity of strong storms will increase, that storms will be accompanied by more intense rainfall and that higher sea levels will increase the risk from storm surge. However, outputs from modelling studies vary due to technical differences in downscaling approaches, in projected changes of large-scale conditions and in physics and tracking algorithms.[90]

In order to incorporate climate change impacts, we use functionality within CLIMADA's tropical cyclone hazard module which adjusts the synthetic tropical cyclone event set in line with the predictions of the impact of climate change on tropical cyclones by Knutson et al. 2015.[41] This model produces global projections of changes in intense tropical cyclone activity based on the Geophysical Fluid Dynamics Laboratory (GFDL) Hurricane Model for an RCP4.5 emissions scenario and the late 21st century. In order to produce predictions for 2°C and 4°C warming scenarios, CLIMADA scales these effects on intensity and frequency to the 2050s in proportion to total radiative forcing of the RCP4.5 and RCP8.5 scenarios. The synthetic tropical cyclone event set is then adjusted according to these scaled predictions, resulting in geographically explicit changes in cyclone intensity and frequency as shown in Figure 35.

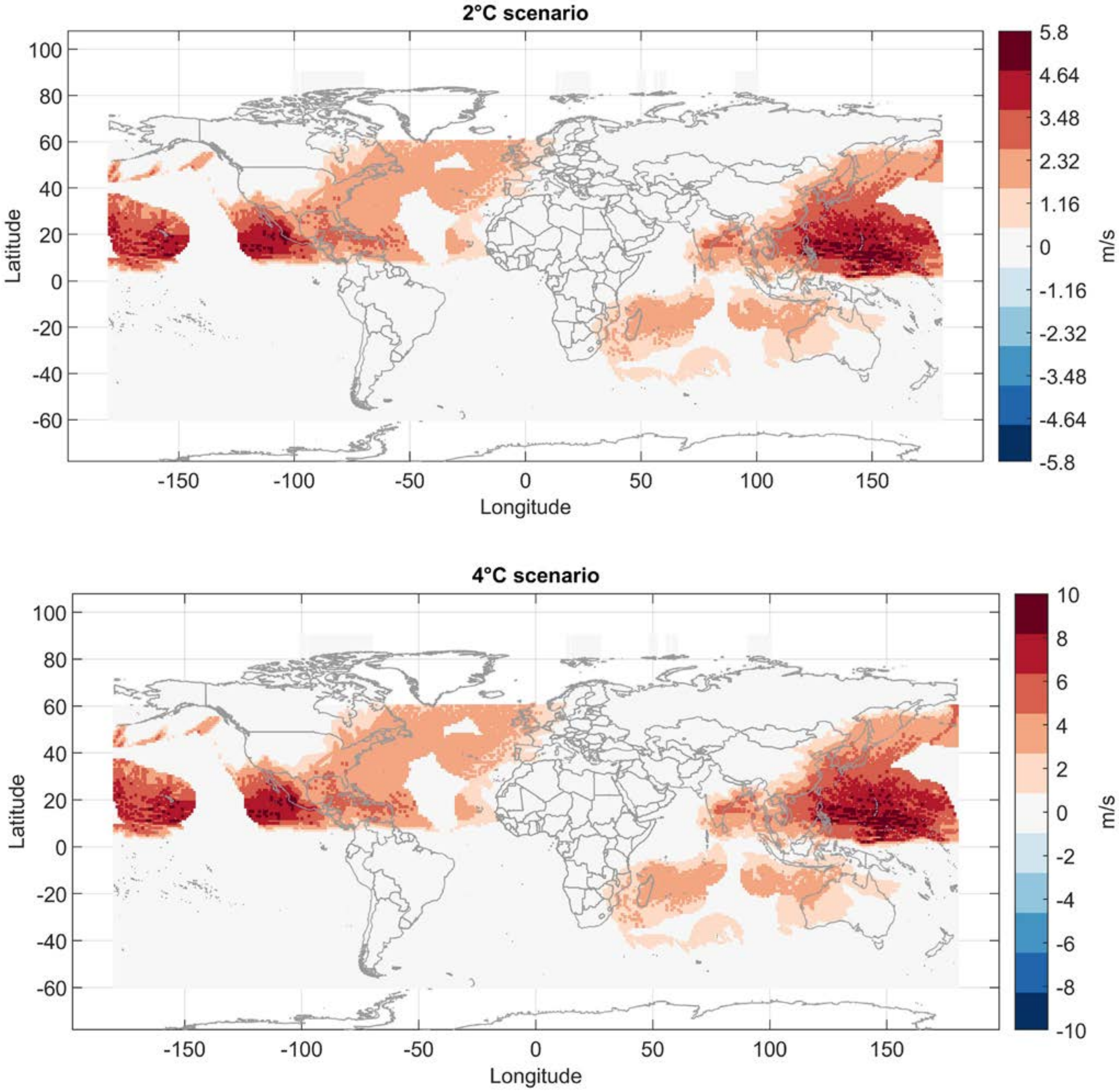

Figure 35. Change of intensity of tropical cyclones between present day and 2050s
Note: Changes in tropical cyclone intensity for 2°C scenario (top) and 4°C scenario (bottom).
Source: CLIMADA

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Head Office
1 Trumpington Street
Cambridge,
CB2 1QA,UK
T: +44 (0)1223 768850
E: info@cisl.cam.ac.uk

EU Office
The Periclès Building
Rue de la Science 23
B-1040 Brussels, Belgium
T: +32 (0)2 894 93 19
E: info.eu@cisl.cam.ac.uk

South Africa
PO Box 313
Cape Town 8000,
South Africa
T: +27 (0)82 829 6852
E: info.sa@cisl.cam.ac.uk

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