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THE FINANCIAL RISKS OF CLIMATE CHANGE

Examining the financial implications of climate change using climate models and insurance catastrophe risk models

Report by AIR Worldwide Corp. and the Met Office
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AIR WORLDWIDE

Met Office

EXECUTIVE SUMMARY

Key findings

This study makes several groundbreaking advances in the area of climate impact assessment by using state-of-the-art modelling techniques combined with expert knowledge in the fields of climate, meteorology, hydrology and actuarial science. The report provides a detailed analysis of the potential impact from a changing climate on insured risk for insurers and other stakeholders through its effects on precipitation-induced inland floods in Great Britain, winter windstorms in the United Kingdom, and typhoons in China.

Potential impacts on pricing, required minimum capital under Solvency II and supplemental capital requirements are also discussed. The main findings, expressed in 2008 £ values and focusing solely on the impact of climate change[1], are:

- The inland flood component of insurance premiums could increase by around 21% across Great Britain assuming a global temperature rise of 4°C.
- The average annual insured flood losses in Great Britain could rise by 14% to £633 million assuming a global temperature rise of 4°C.
- The insured inland flood loss in Great Britain occurring on average once every 100 years could rise by 30% to £5.4 billion. The insured inland flood loss occurring on average once every 200 years could rise by 32% to £7.9 billion. The estimates assume a global temperature rise of 4°C.
- The average annual insured wind losses in the UK could rise by 25% to £827 million assuming a 1.45° southward shift in storm track across the UK.
- The insured wind-related loss from winter season windstorms in the UK occurring on average once every 100 years could rise by 14% to £7.3 billion. The insured wind loss occurring on average once every 200 years could rise by 12% to £9.7 billion. The estimates assume a 1.45° southward shift in storm track.
- Within Great Britain, the results vary by region. For example, while the average annual insured flood losses for Great Britain as a whole could rise by 14%, regional increases range from less than 10% to nearly 30%, assuming a global temperature rise of 4°C.
- The average annual insured losses from typhoons affecting China could increase by 32% to £345 million; the 100-year loss could increase by 9% to £838 million, and; the 200-year loss could increase by 17% to £1.1 billion. The estimates assume a global temperature rise of 4°C**.**

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[1] Section 4 of this study has examined the effects of changes in GDP and the stock of insured assets; the numbers cited in Key Findings and elsewhere in the main body of the report are without these effects.

Introduction

This ground-breaking study couples climate models with insurance catastrophe models to examine the financial implications of climate change through the effects of global temperature increases of 2, 4 and 6°C on precipitation-induced floods, windstorms, and typhoons. In particular, the study assesses the potential influence of a changing climate on insured risk from two dominant natural hazards in the UK — namely, inland flooding and winter windstorms — and from typhoon activity in China.

Although many climate models allow the possibility of large, rapid and widespread climate change, some of the key processes driving such changes are highly uncertain and they have the potential to significantly alter the projections of global climate change. Such potential processes are discussed in Appendix 3, Question 6. The modelling presented in this report takes a conservative approach by not considering such extreme shifts in climate.

Approach

The climate scenarios that were used to model projected changes in risk were developed by the Met Office using an approach of combining results from recent climate model output, diverse published data, and scientific literature. A robust relationship between UK precipitation and global mean temperature change was identified. When considering UK windstorms however, no clear dependence on global temperature was found. The projected changes in windstorm activity are provided in the form of a change in storm track, which incorporates impacts from natural variability. The projections thus reflect a wide spectrum of potential changes in storm tracks, as described in greater detail in Section 2. The assessment of changes in China typhoon risk shows a similar pattern, where changes in precipitation associated with these storms are related to increased global temperatures, but no clear dependence is found for typhoon wind intensity. Therefore, the study uses variations in wind intensity as a sensitivity for possible changes in typhoon risk.

The approach taken to define climate change impacts allows the timing of the change to be removed from the discussion. Nevertheless, it is informative to know approximately when various levels of global warming might be reached. As a best estimate, 2°C of global warming would be reached in the 2040s if any of the IPCC's main SRES scenarios are followed (A1B, A2, A1FI etc). The UK's Committee on Climate Change (CCC) scenario of 4% annually reduced global emissions starting in 2016 would keep the warming close to 2°C, even beyond 2100. If certain feedbacks in the climate system are strong, 2°C warming could be reached earlier, perhaps as soon as 2030. However the benefits of mitigation are still clear. In the CCC scenario, the probability of exceeding 4°C is much smaller than in the SRES scenarios. In the worst case considered, the SRES A1FI scenario, the best estimate is that 4°C warming would be reached in the 2070s, or as early as 2060 if feedbacks are strong, with further warming thereafter. Present understanding suggests that such strong feedbacks are unlikely.

To assess the financial impact of climate change on the selected perils and regions, AIR Worldwide applied the climate scenarios provided by the Met Office to its catastrophe models for Great Britain Flood, UK Extratropical Cyclones and China Typhoons. In that process, AIR developed "climate conditioned" catalogues of potential future events and compared the resulting insured losses with losses associated with today's climate, which is representative of the baseline risk.

The study uses three key metrics to measure the financial impacts. These are:

- *Average annual loss (AAL)*: AAL refers to the aggregation of losses that can be expected to occur per year, *on average*, over a period of many years. Clearly, significant events will not happen every year; thus it is important to emphasise that AAL reflects the *long-term* average.
- *The 100-year loss:* The 100-year loss has a 1% probability of occurring in any given year; that is, it is the loss that can be expected to occur or be exceeded on average once every 100 years.
- *The 200-year loss:* The 200-year loss has a 0.5% probability of occurring in any given year; that is, it is the loss that can be expected to occur or be exceeded on average once every 200 years.

Note that the financial metrics discussed above are defined in the context of a given climate regime. That is, the 100-year loss in the current climate regime, which defines the baseline, may be different from the 100-year loss in a future climate regime, in particular when the loss is sensitive to changes in climate.

Results

The impact of the climate scenarios on catastrophe model output and, in particular, on the three selected financial metrics is presented below.

United Kingdom

Average annual losses from the two dominant natural hazards in the UK (inland flooding and windstorm) could increase significantly with globally rising temperatures and changes in storm tracks as specified by the Met Office. With respect to the more extreme events — namely, losses occurring on average once every 100 or 200 years — rising temperatures could bring about significant changes to the risk landscape. Losses in the UK are also examined on a regional level, since even a uniform change in precipitation and/or wind can produce a non-uniform response in the distribution of wind or flood risk.

Focusing solely on the impact of climate change, the impacts values on the three key financial metrics are as follows (in 2008 £):

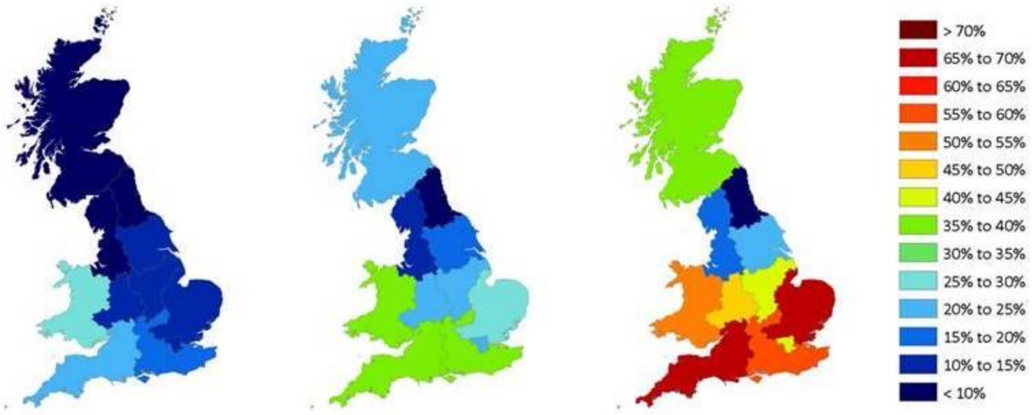
- Average annual insured losses from inland flooding in Great Britain could rise by 14% to £633 million and average annual insured UK wind losses could rise by 25% to £827 million. At the regional level, increases range from less than 10%

to 29% for inland flood losses and from 17% to 29% for insured wind losses. In the South West, for example, the average annual insured flood losses could rise by 29% and insured wind losses by 24%. Note that the inland flood losses assume a global temperature rise of 4°C, and wind losses assume a 1.45° southward shift in storm track.

- The insured inland flood 100-year loss could rise by 30% to £5.4 billion and the 200-year loss could rise by 32% to £7.9 billion. Regional variations range from less than 10% to 39% for the 100-year loss, and from less than 10% to 51% for the 200-year loss. The regional response for Wales, for example, indicates that the insured flood 100-year loss could increase by 39%; in the South West, the inland flood 200-year loss could increase by 51%. The estimates assume a global temperature rise of 4°C.
- The wind-related insured loss from winter season windstorms in the UK occurring once every 100 years could rise by 14% to £7.3 billion, and the loss occurring once every 200 years could rise by 12% to £9.7 billion. Regional variations range from below 10% to 16% for the 100-year loss and below 10% to 17% for the 200-year loss. For the North West, for example, the 100-year loss due to windstorms could increase by 16%; the 200-year loss for London could increase by 17%. The estimates assume a 1.45° southward shift in storm tracks.

All of the above results are significantly different (at the 95% level of confidence) from the baseline representative of today’s climate conditions. Figure 1 below shows the regional variations in 100-year flood losses for temperature rises of 2, 4 and 6°C (left to right). As can be seen, the South West, South East and Wales face the highest percentage changes for a temperature increase of 4°C.

Figure 1 Regional response of the 100-year flood loss for a 2, 4 and 6°C increase in temperature



Note: Values shown reflect percentage increases relative to the baseline (current climate) risk.

China

With the projected changes in global mean temperature, average annual insured losses from winds and precipitation-induced floods caused by typhoons affecting China could also increase significantly by 32% to £345 million assuming a global temperature rise of 4°C and slightly more intense typhoons. In percentage terms, the 100-year and 200-year loss do not increase as dramatically. This reflects the high frequency of loss-causing typhoons in China (about ten each year in the current climate), and the importance of losses which accumulate over the course of the year rather than from a single event. Still, as the climate warms, a 200-year loss in China could increase significantly to £1.1 billion. Again, these results are also statistically different (at the 95% level of confidence) from the baseline representative of the today's climate.

Implications for insurers and policymakers

The loss estimates discussed above were derived by conditioning the results of fully probabilistic catastrophe models based on a range of climate scenarios. Further sensitivity analyses were conducted to explore possible implications for insurers and policymakers. Pricing and capital requirements, for example, were found to be sensitive to the assumed underlying climate scenarios and climate-conditioned event catalogues. It should be emphasised, however, that the projected impacts represent future possibilities only to the extent that the climate and modelled events actually occur as presented and that the industry responds as discussed in Section 4.

The loss estimates derived from the catastrophe models and presented in Section 3 isolate the effects of climate change by holding all other parameters constant. However, in practice, other parameters will not remain constant. Nevertheless, the findings highlight the benefits of adaptation and mitigation policies such as flood defences and changes in building codes, as well as other policies intended to reduce the impacts of a 4°C rise in global temperatures.

Economic growth

As an example, a conservative long-run estimate of annual GDP growth for the UK and China (based on annual real growth of 2.5% and 6% respectively) could be adopted as a proxy for increases in the number of insured properties resulting from population growth and increases in the total sums insured resulting from increased wealth.

Assuming a 4°C increase in temperature and ten years of GDP growth at 2.5%, insured 100-year Great Britain flood losses could rise by 38% compared with a possible rise of 30% if GDP growth were not taken into account. Assuming a 4°C increase in temperature and ten years of GDP growth at 6%, insured 100-year China typhoon losses could rise by 16% compared with a possible rise of 9% if GDP growth were not taken into account.

Insurance pricing

In order to estimate how insurance pricing could be impacted by climate change, a typical loss cost pricing algorithm was applied to the modelled average annual losses.

The implications for pricing based on the modelled climate scenarios are as follows (assuming no GDP growth):

- The inland flood component of insurance premiums could increase by around 21% across Great Britain if a global temperature rise of 4°C is assumed.
- The wind component of insurance premiums could increase by around 37% across the UK if a southward shift in storm tracks is assumed.
- The typhoon-induced flood and wind components of insurance premiums could increase by around 48% across China assuming a global temperature rise of 4°C.

Insurance capital

Solvency II’s 99.5% requirement that a company should remain solvent for the coming 12 months justifies using the 200-year loss to represent Required Minimum Capital for the purposes of a sensitivity study. Note however that increases in predicted large loss costs do not necessarily equate directly to increased individual company capital required. The response of individual companies will depend, for example, on how diversified their book is.

- Assuming a global temperature rise of 4°C, a further £1.9 billion would need to be added to the £5.9 billion capital currently required to cover insured inland flood losses in Great Britain.
- Assuming a southward shift in storm tracks, a further £1 billion would need to be added to the £8.6 billion capital currently required to cover insured wind losses in the UK.

In addition to increasing prices and holding more capital, insurers may also reduce capacity in response to increased risks arising from climate change. Similarly, where the price of insurance is not set appropriately or insurers do not hold sufficient capital, a reduction in the availability of insurance is likely to be the result.

A note on the approach

The study focuses on the financial impacts due to climate change from windstorms and inland flood in the UK and from typhoons in China. Coastal flooding is not considered. Given the fact that sea levels are likely to rise with increasing global mean temperatures, a future study addressing this aspect could be of interest. Likewise, future studies could consider the impacts from other natural hazards that have not been included in the current study since they are expected to contribute to the changes in financial risk as well.

AIR’s catastrophe risk assessment methodology is based on both physical and statistical models that represent real-world systems. As with all models, these representations are not exact. The simulated windstorms and flood events generated by the AIR models do not represent events that have occurred, but rather events that could occur in the future with a given likelihood. The insured loss estimates provided in this study are intended to function as one of several tools for use in analysing and managing risk.

The assumptions that AIR and the Met Office used in generating the results of this study may not constitute the exclusive set of reasonable assumptions and methodologies, and different assumptions and methodologies adopted by other climate and catastrophe models could yield different results.

Whilst scientific uncertainty has been accounted for in this study, other potential sources of uncertainty were not. For this study, the impact of climate change on financial risk is isolated by modifying the frequency or intensity of the perils of interest according to the requirements set forth by the climate model results. All other parameters - such as the geographic distribution of populations, insurance take-up rates, flood defences, building codes, etc are held constant. However, it may be that the historical population growth in areas of high hazard (growth that has been largely responsible for the observed upward trend in catastrophe losses over the last several decades) may actually reverse under a changing climate; that is, populations may in fact migrate *away* from high risk areas, which would reduce exposure. Similarly, as the wind climate grows more extreme, construction practices may change such that the wind resistivity of structures increases. Building codes may change as well in the face of increased hazard, and government investment in flood defences could accelerate. On the other hand, take-up rates in China could grow dramatically as that insurance market continues to grow. Whilst this study has advanced the knowledge of climate impacts, all of these factors must be considered and balanced in a well-conceived approach to risk management.

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CONTENTS

1.0 INTRODUCTION

Earth's climate system, comprised of the atmosphere, the oceans, the cryosphere and continental land masses, is constantly changing. Not only do changes to each component of the system influence the risk of natural catastrophes, but the interactions between them bring about an inherent uncertainty surrounding how climate will evolve in the future. Dependable historical data is limited and deficiencies and inaccuracies in the historical record present an added challenge for scientists to separate natural variability from trends induced by the anthropogenic emission of greenhouse gases.

Over the past several decades, dynamical modelling techniques have paved the way for an improved understanding of climate and the impacts of climate change on various forms of exposure, including life and property. The fidelity of *climate models*, for example, has been improved in both resolution and representation of physical processes, allowing investigators to quantify the influence of greenhouse emissions on the climatological factors known to generate extreme weather events. These models can be used to study, for example, the sensitivity of storm frequency and intensity to significant changes in key climate mechanisms such as increasing ocean temperatures.

Similarly, since the late 1980s, *catastrophe models* have combined the latest findings in atmospheric science with sophisticated engineering and financial models to estimate the damage from extreme weather events. By combining such damage estimates with complex insurance and reinsurance terms, insured loss can be computed to quantify risk to insurers. Such an analysis can be used to gauge the risk to a range of assets from an individual property such as an industrial facility to a worldwide portfolio of residential and commercial properties.

Using future climate scenarios, catastrophe models can be applied in a "what if" mode to estimate how an assumed future climate scenario might cause the risk to differ from the risk as we know it today. For this study, the impact of climate change on financial risk is found by modifying only the frequency or intensity of the perils of interest according to the requirements set forth from the climate model results. All other parameters are held constant (such as exposures, insurance uptake rates, building codes, etc). Because catastrophe models are "probabilistic" by nature, they can measure not only the expected impact of a projected climate, but also the level of confidence surrounding such expectations.

This study couples projections from state-of-the-art climate research and model results with risk estimation techniques from catastrophe models to measure the potential influence of a changing climate on insured exposure in the UK and in China. For the UK, the study focuses on two important natural hazards, namely flooding borne from extreme precipitation and wind damage resulting from mid-latitude (extratropical) cyclones. Extratropical cyclones tend to be strongest during the winter months when the contrast in temperature between the poles and the equator is largest. Thus winter season extratropical cyclones, often referred to simply as winter storms, are the focus of this study. For China, the results reflect potential changes in typhoon risk as represented by the wind and flood damage caused by tropical cyclones.

2.0 CLIMATE MODEL RESULTS

The Met Office, tasked with assessing how increasing global temperatures may influence UK wind and flood activity as well as China typhoon activity, have taken a ground-breaking approach. By combining the results of Hadley Centre climate models, recently published scientific techniques, and a comprehensive review of the scientific literature, Met Office climate scientists have developed a set of plausible "climate scenarios" reflecting projected changes in risk.

Given climate science is evolving quickly, many questions naturally arise in an application study such as this. The authors have anticipated several of these questions in advance, and responded to them in detail in Appendix 3. When appropriate, the reader will be referred to that Appendix for more detailed information in these important topic areas.

2.1 Background

The aim of the climate change research component is to quantify the impacts of a changing climate to three major perils impacting the insurance industry:

- Frequency and intensity of precipitation events on inland flood risk in Great Britain;
- Frequency and intensity of extra-tropical cyclones on wind risk in the UK; and
- Frequency and intensity of China typhoons on wind risk in China.

A methodology has been sought that will, taking into account and communicating relevant uncertainties, allow the combination of very diverse published data and models within a single framework under different climate scenarios. The method should also allow for future scientific developments to be included, and be reviewed independently from the scientists undertaking the research.

The output of the research has been specified in terms of perturbations to current climate – leading to a *perils matrix* of climate scenario versus a change to the current risk. This approach allows the area where there is the most experience and understanding (past climate risk) to be used as a basis and associated, through current understanding of future climate changes in published literature and models, with future climate risk.

2.2 Methodology

Use of climate models for the quantification of the impacts of climate change within specific regions and time periods is a nascent science. Whilst the case for the global impacts of greenhouse gases has been made by the IPCC and others, the specification of changes in regional and extreme phenomena has more uncertainty and less consensus, especially where natural climate variability is concerned (e.g., El Niño and the North Atlantic Oscillation).

One approach to the question is to seek consensus in a common diagnostic of climate change for each of the perils, and estimate changes in hazard risk from the consensus by adjusting loss probability functions accordingly (e.g., in terms of the mean and other moments of the probability function). Consensus in this sense does not suggest that there is scientific certainty, but suggests that there is agreement around the level of current understanding. The question of whether these scientific results will be superseded is later addressed in **Question 8**.

The approach taken has been to assess the correlation between a change in global surface temperature and the peril of interest. The approach allows one to take account of all climate scenarios (e.g., the SRES scenarios used in the IPCC analysis) and removes the timing of the change from the discussion, thus removing one of the key uncertainties. The method assumes that the relationship between local changes in perils and global temperature do not change, and are unaffected by the choice of climate emissions scenario under which they are reached. A 2°C of warming can then be said to be relevant to any baseline time period under examination. As a best estimate, 2°C of global warming would be reached in the 2040s if any of the IPCC's main SRES scenarios are followed (A1B, A2, A1FI etc). The UK's Committee on Climate Change (CCC) scenario of 4% annually reduced emissions starting in 2016 would keep the warming close to 2°C, even beyond 2100. If certain feedbacks in the climate system are strong, we could reach 2°C warming earlier, perhaps as soon as 2030. However the benefits of mitigation are still clear. In the CCC scenario the probability of exceeding 4°C is much smaller than in the SRES scenarios. In the worst case considered, the SRES A1FI scenario, the best estimate is that 4°C warming would be reached in the 2070s, or as early as 2060 if feedbacks are strong, with further warming thereafter. Present understanding suggests that such strong feedbacks are unlikely. An analysis of when 2°C and 4°C of global warming is likely to be reached is discussed in more detail in **Question 1**.

The structure of the risk matrix for each peril is dependent on the risks under examination. Where there is little or no consensus in the degree of change in terms of global temperature, a range of risks is sampled since one published methodology cannot, *a priori*, be favoured or discounted in lieu of another method.

Limitations: In addition to the core of the work, a range of detailed questions have been presented to show the current scientific consensus on a range of topics and aid decision making. In particular, a discussion of the current major uncertainties in climate modelling and likely future changes in results from the science is presented in **Question 6** and **Question 8**.

2.3 Data sources

The data used to create the perils matrix come from a variety of different sources and includes the following: data from papers published in peer reviewed literature, data from the Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC FAR, 2007), data from the Met Office Hadley Centre QUMP ensembles (Murphy et al., 2004), and to a lesser extent data from as yet unpublished literature.

It is worth mentioning that whilst *global climate models* (GCMs) variously include physics and dynamics of the atmosphere and ocean, sea and land ice, land surface, vegetation, atmospheric chemistry and ocean bio-geochemistry to various degrees, currently they are all of relatively low resolution – covering the globe in boxes of approximately 100km to 300km square. To overcome this, *regional climate models* (RCMs) are used to add geographic detail with resolution from 50km to 25km over a bounded geographic region. These RCMs inherently require conditions at their boundaries supplied from GCMs, thus linking their projections.

Computer resources do limit climate experiments, and whereas high-resolution *coupled* models – models that include both an interactive ocean and atmosphere – are desired to capture various climate processes such as El Niño (Roberts et al. 2009), some studies are based on uncoupled models run at higher resolution. This has implications for the results for some perils analysed.

Whilst researching the data for this project it becomes readily apparent that there is a lack of consistency amongst papers as to which statistics are being reported. This makes data pooling difficult (see discussion below on UK wind storms). This suggests that there would be benefit in agreeing on a set of metrics to aid comparison across the scientific community on these significant perils.

In addition, some papers have made use of the same base model (e.g. for regional model boundary conditions). As such, there is some commonality between some model results, and this has been noted where relevant.

2.4 Met Office Hadley Centre Ensembles

The Met Office Hadley Centre has a variety of global climate models with grid resolutions of the order 150 to 300 km. Many important climate processes take place at a finer scale like, for example, cloud formation. These *sub-grid processes* cannot be modelled explicitly so are estimated using a mixture of observations, theory and simulations – also known as parameterisation.

Parameterisation can lead to a range of equally reasonable estimates, leading to different, but still plausible, climate projections. A single climate model does not enable these different parameterisations to be studied. However, an *ensemble* – a collection of climate projections, run using different parameterisation schemes – enables a more detailed analysis of the climate modelling uncertainty. The GCM that was used in this analysis was the HadCM3 model with 17 ensemble members (Murphy et al., 2004). In addition, the CO_2 was increased year over year using prescribed scenarios (often called transient climate simulations). The collection of 17 ensemble members will be referred to hereafter as TQUMP.

A resolution of 300km is too coarse to accurately simulate the variability of climate in relatively small regions like the United Kingdom. The Met Office Hadley Centre Regional Climate Model (RCM), known as HadRM3, has a grid resolution of 25km and a domain covering the whole of Europe. This higher resolution means that the topography and land surface of the UK can be represented more accurately than in a GCM. In addition, finer-scale climatic features are better resolved. Eleven of the transient GCMs were used to drive the RCMs, enabling an 11-member ensemble of transient RCMs to be derived, hereafter referred to as RQUMP.

Great Britain Flood (GBF)

This study analyses precipitation that can lead to both fluvial and pluvial flooding, as analysed in the current literature derived from GCMs and RCMs. A discussion is provided in **Question 4**. Although the impacts from storm surges have not been assessed, a description of the current scientific consensus on sea-level rise is provided in **Question 2**.

The changes assessed in regional precipitation within the IPCC AR4 summary are dependent on the time of year. The models agree on the sign of the change for winters, being wetter, with warmer air and water temperatures leading to more evaporation and heavier rainfall. Whilst there is less consensus, summer rainfall is likely to decrease over much of the UK. For both summer and winter, it is possible that extreme rainfall will increase more than average rainfall, with more intense events occurring more frequently. These results are consistent with the recently published UKCP09 results, and this research makes use of the same underlying models.

After a review of the full literature base, changes in the 1-in-5 year return value for daily winter (December to February) precipitation and changes in the corresponding mean precipitation have been chosen as a common risk diagnostic for analysis (see figures 2 and 3), derived from research into the global climate sensitivity (the level of warming expected from a doubling of CO_2).

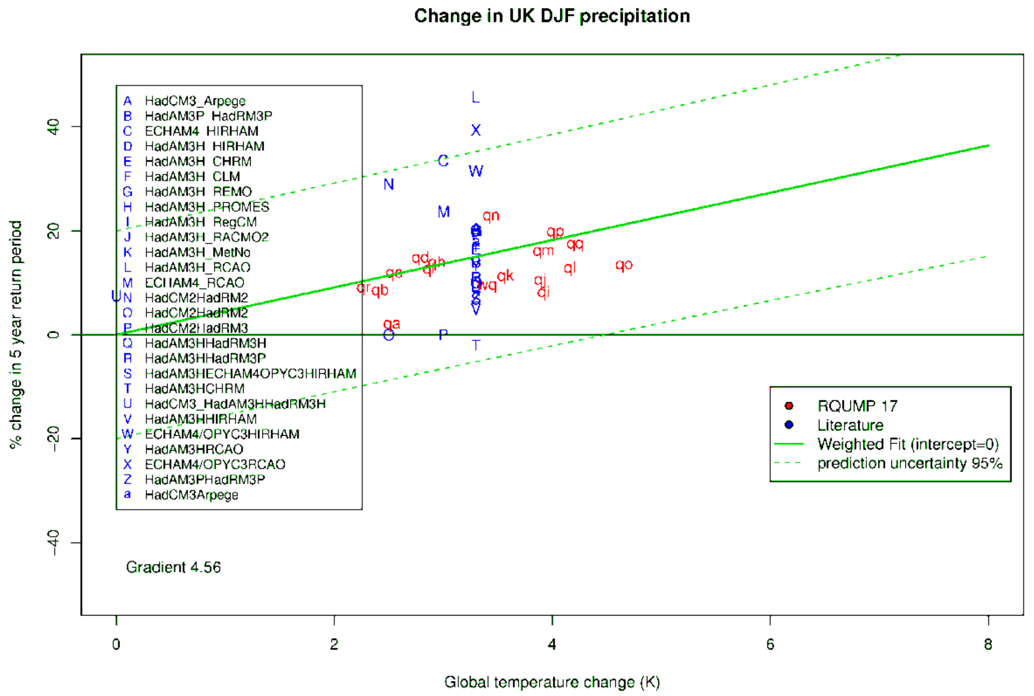
A robust relationship with global mean temperature change was found for both parameters, thus allowing for projections. This would be expected as there is a strong relationship between air temperature and potential moisture content, well known via the Clausius-Clapeyron relationship. The relationship is calculated from a linear regression through published values and new analysis of published model data, with an intercept fixed at zero (figures 2 and 3). Extreme rainfall is calculated using data from RCMs, whereas the global mean temperature is determined from the GCM that provides the boundary forcing for the RCM concerned.

For this risk matrix, published data mostly included output from three global models that were used for the boundary conditions to drive the various RCMs, reducing sampling uncertainty. Additionally, changes in the mean were not widely reported in the literature, and so only the RQUMP ensemble data have been analysed. The results are similar compared to the more extreme 1-in-5 year events, and so are assumed to be consistent. Note that where ensemble data has been used to assess the changes at 2°C, 4°C and 6°C, a median or "best estimate" value from the ensemble has been used (i.e., not the worst case scenario).

Limitations: Note that, for the 1-in-5 year return period changes (figure 2), the gradient is insensitive to the removal of the published literature and the use of the RQUMP data on their own. This gives support to the analysis in figure 3, where no other published data is available.

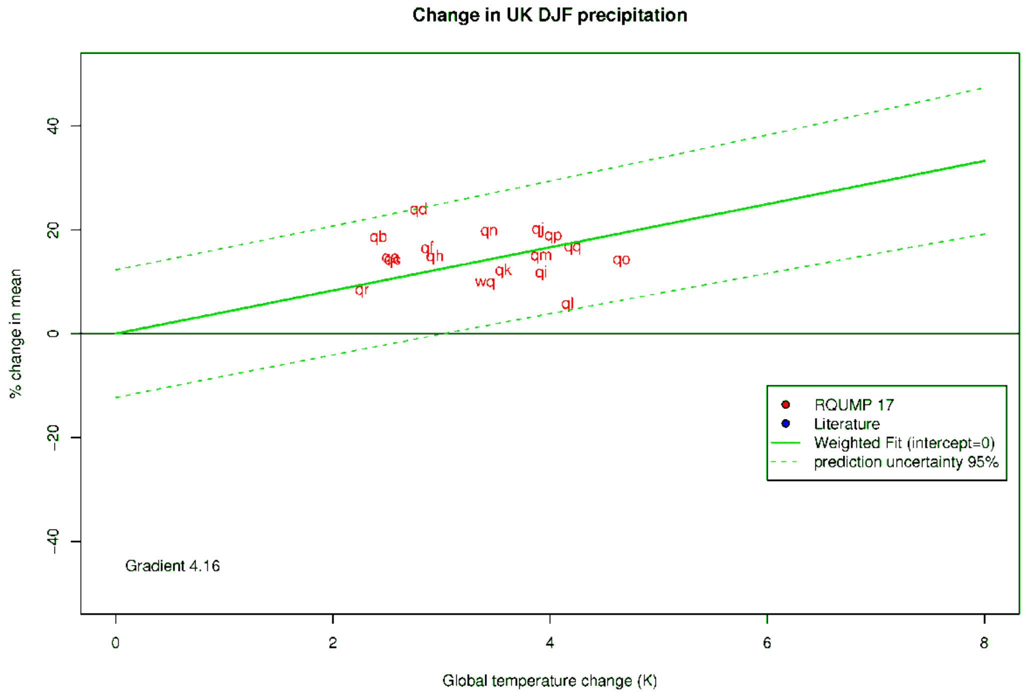
Impacts on natural climate variability have not been assessed directly in this study, although more discussion on this topic is provided in **Question 5**.

Figure 2 Change in UK 1-in-5 year return period precipitation



Note: Change in 1–in-5 year return period daily (December-February) precipitation. Capital blue letters represent published GCM-RCM couplet results for a wide range of climate models. Red lower-case letters represent analysis from RQUMP model output. A gradient of 4.56% change per degree of global warming is used in the matrix of perils.

Figure 3 Change in mean winter UK precipitation



Note: Change in mean winter (December-February) precipitation. Limited published literature was available for this quantity. Red lower-case letters represent analysis from RQUMP model output. A gradient of 4.16% change per degree of global warming is used in the matrix of perils.

United Kingdom Windstorm (UKW)

The climate of damaging extratropical wind storms in Europe is dominated by natural fluctuations in the position of the winter storm track. Whilst the IPCC AR4 suggests a northerly trend in the position of the storm track throughout the northern hemisphere, any signals related to climate change would need to be significant in comparison to the large variability in natural processes detected locally. Periods of increased and reduced storminess and their associated winds have been observed historically, however there is no consistent view of the local impacts of climate change on European winter storms – either in intensity, frequency or location. This is largely because of significant natural variability related to the North Atlantic Oscillation which to date has not been well captured by climate models. As such, the published material on the topic was found to be too diverse in methods and metrics to allow assimilation in any quantitative way. For this study, scenarios for this peril are therefore not dependant on global warming, but on the position of the storm track.

The future exposure of the UK to windstorms is a function of storm track changes and changes in storm strength. Published literature generally does not separate these two effects and so a reported change could be due to track change, strength change, or both. Changes in storm track have been chosen to overcome this, as this will effect a change in winds experienced at a given location, thus allowing any future improvements in our understanding of storm strength to be incorporated at a later date. This approach also allows us to incorporate the impacts from the natural variability in storm track.

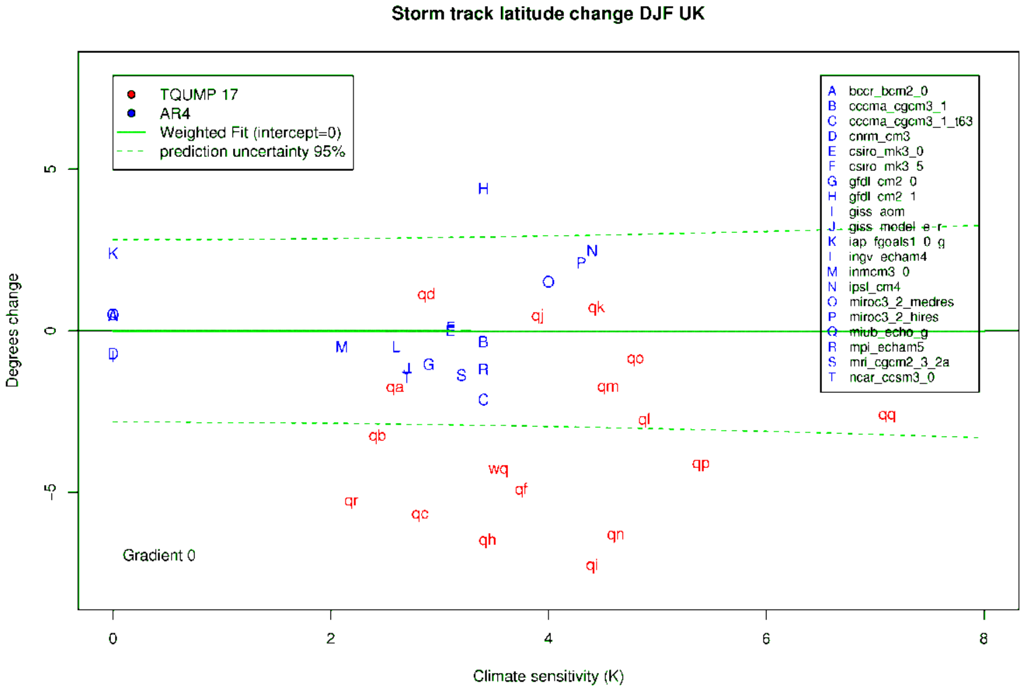
For this study, data from the IPCC AR4 multi-model ensemble archive and the Met Office Hadley Centre TQUMP ensembles of 17 models have been analysed to provide values for this peril. The storm track for the UK was derived from daily mean sea level pressure which has been filtered so that only variability on 2 to 6 day timescales is retained. Such an approach identifies areas of high variability associated with synoptic systems and is commonly termed band-pass filtered analysis. Although usually performed at a height of 500 hPa and a large scale diagnostic, it is applied here to surface pressure as that is the only common diagnostic available for all models. It has limitations in that it does not identify individual storms but rather areas of high variability on synoptic timescales.

The maximum of a parabola fitted to the mean band-pass filtered fields at 0° longitude has been taken to be the latitude of the storm track affecting the UK. This is repeated for future data and changes in the latitude of the parabola maximum are taken as a change in storm track.

No dependence on global temperature/climate sensitivity has been found for the changes in storm track by this measure (figure 4), and we therefore provide the maximum, the minimum, and the central value between these derived from the joint ensemble of results. Therefore, the perils matrix for UKW reflects a wide spectrum of potential changes in storm tracks rather than changes directly associated with rising global temperatures. Note that the approximate location of the observed annual mean storm track is near 57°N, with a standard deviation in the annual mean of the storm track of ±3° latitude (provided by AIR Worldwide and discussed later). This is of the order of the changes seen in the climate models and so the changes from current climate change projections can be considered as having a similar magnitude as from natural variability.

Limitations: Recent modelling work suggests that the ability of climate models to resolve the natural variability over the North Atlantic may be improved with the inclusion of a stratosphere – allowing teleconnections to El Niño and the Pacific Ocean. This process is not included in the current generation of climate models, and may allow for improvement in the modelling of natural processes in the future.

Figure 4 Changes in the storm track



Note: Changes in the storm track derived from 2-6 day band-pass filtered mean sea level pressure. IPCC AR4 models are in capital blue letters. TQUMP are in red letters. There is no current relationship between global temperature and the position of the European storm track in climate models.

China Typhoon (ChT)

As with the other perils, the literature was found to be very diverse in its approach and analysis of tropical cyclone activity in the Pacific. **Question 3** provides a summary of recent global research in this field, especially focussed on the Atlantic sector.

A parameter which has been widely published and can be derived for most models is the large scale cyclogenesis parameter (Royer et al, 1998). It has components of cyclonicity, vertical shear, and latent heat release from rainfall, and is a large scale indicator of tropical storm genesis. The metric is robust and has been shown to reproduce global tropical storm activity. The Royer metric is calculated for the region

0°N to 30°N,100°E to 180°E for both present and future, coupled and uncoupled IPCC AR4 and QUMP data.

For the Royer parameter in the coupled and uncoupled IPCC AR4 and TQUMP models (figure 5), no clear relationship was found, with the potential for future increases and decreases. Closer analysis of the data indicates the possibility of a structural error. Genesis parameters from pairs of coupled and uncoupled models which share the same atmosphere are not in agreement, indicating that the coupling of the atmosphere to the ocean may have a significant impact on the potential future genesis of tropical storms.

To analyse this further, figure 6 shows the published results. Most studies use high resolution atmospheric models (uncoupled), and show a reduction in tropical cyclone activity.

Thus there is a quandary as to whether one data subset may be in error. Are the low resolution models with poor representation of tropical storms, but coupled and so capturing an important feedback process with the ocean, unable to represent storm changes? Or, are the high resolution (but uncoupled) models failing to capture the feedbacks from the ocean surface that have an important influence on future storm changes? Currently there is no clear answer.

Therefore, as a sensitivity study for the perils matrix, we provide estimates of possible future intensities of tropical cyclones using methodology and results adapted from Emanuel et al., (2008) – more details are provided in Appendix 2.

Here, the winds in future tropical cyclones are scaled by a single factor which can be applied to the cumulative distribution function (CDF) of damaging winds from tropical cyclones. Using values derived from the seven GCMs reported in Emanuel et al. (2008), the mean +/- two standard deviations are provided as three plausible changes in tropical wind intensity.

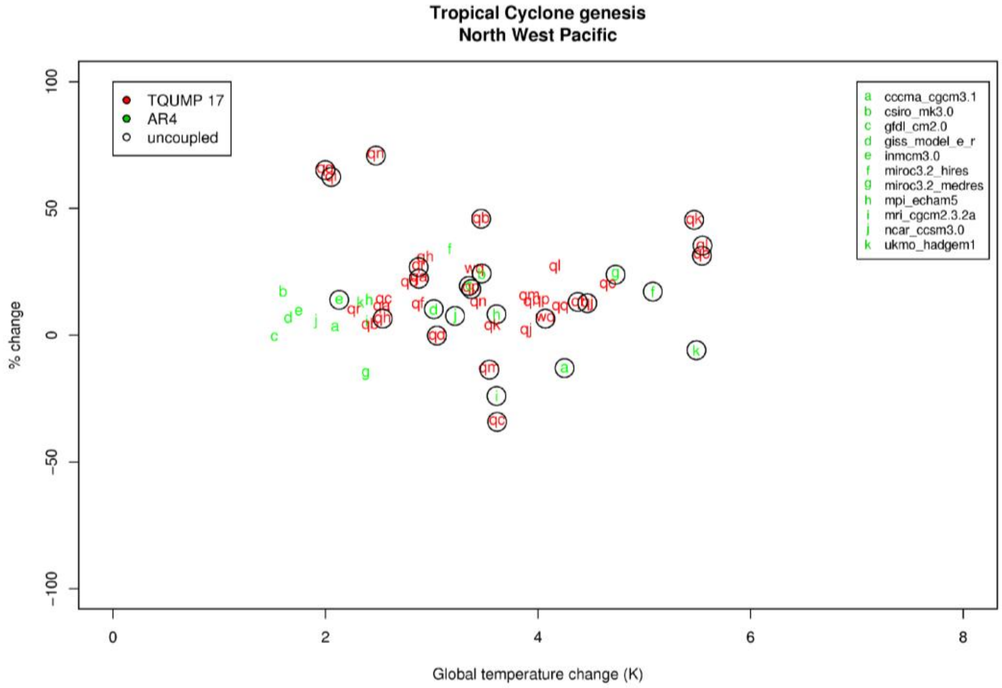
In addition, precipitation changes associated with tropical cyclones is also provided. Here, there is much more consistency within the published literature with increases in extreme precipitation found for all modelling studies (not shown). The maximum water-carrying capacity of the atmosphere is determined by the temperature of the air, and has been calculated by the Clausius-Clapeyron relation. Although increases in extreme precipitation simulated by climate models have not generally seen the full increase implied by simulated temperature increases, it is thought that given the extreme environmental conditions found within tropical cyclones this is more likely to be realised. Therefore precipitation increases calculated for 2, 4 and 6 °C global mean temperature increase follow the Clausius-Clapeyron relation.

Limitations: Potentially the greatest factor affecting the impact of climate change on tropical storm damage for China may come from changes in the track and likelihood of tropical cyclone landfalls. It is well known that landfall for this region is strongly affected by factors such as El Niño and future climate changes in the Pacific have been shown to include “ENSO like” effects on cyclone changes in the North West Pacific

(Yokoi and Takayabu 2009). Yet changes in likelihood of landfall are not taken into account in this study. The reason for this is that the necessary modelling – that of high resolution coupled simulations where individual storms can be tracked – is not available. Further, only a handful of studies have directly related changes in climate factors to landfall probability and are generally focused on the Atlantic (e.g., Dailey et al 2009).

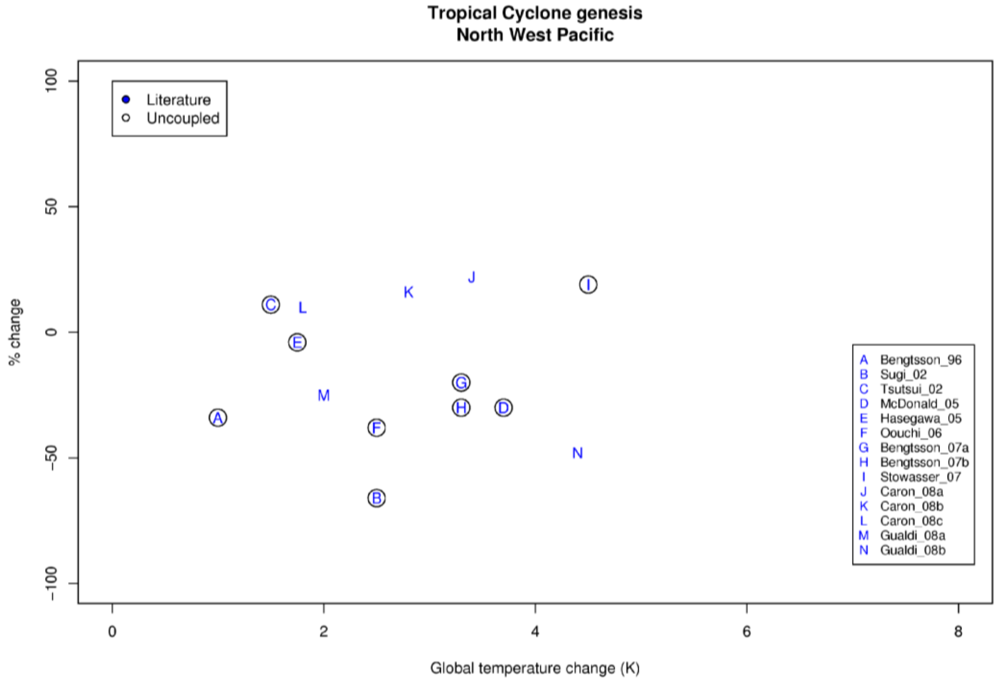
The results herein emanate from one study, although seven different GCMs were considered. The scaling of winds in this way will enhance the damaging winds of severe storms more than those of weaker storms, given wind energy increases with the cube of wind speed. As such, all the assessed models show an increase in intensity but by taking the mean and providing a scenario range of the mean plus and minus two standard deviations produces a “low end” scenario of intensity reduction. No information is provided in this approach on the changing structure of tropical cyclones with intensity or their lifetime characteristics.

Figure 5 **Tropical cyclone genesis in the North West Pacific as a function of global surface temperature change**



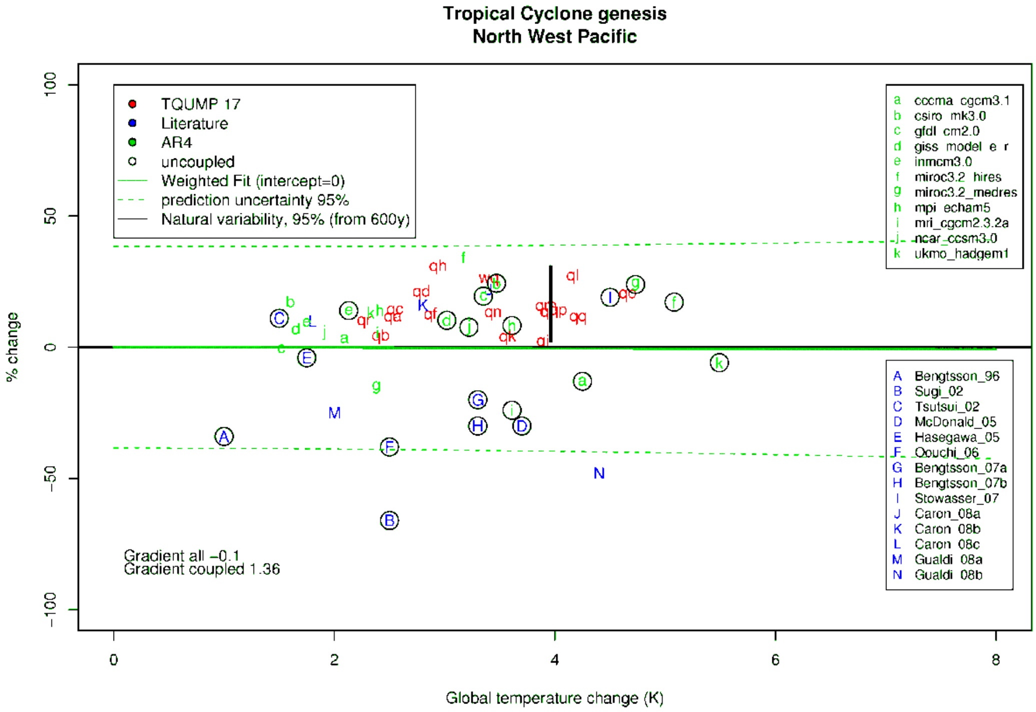
Note: No published models beyond the IPCC AR4 and TQUMP ensemble were available. Here green letters indicate IPCC AR4 models, red letters are from the TQUMP ensemble, and circled letters are using uncoupled models (atmosphere only models with prescribed sea surface temperatures).

Figure 6 **Published literature analysis for cyclogenesis of tropical storms in the North West Pacific**



Note: Caron 2008 results (J, K, L) are large scale Royer type metrics as per figure 4.

Figure 7 **Complete analysis including both large scale Royer parameter and published literature for both coupled and uncoupled climate models of tropical storms in the North West Pacific**



Note: Red letters are for TQUMP models, blue letters are published analyses, green are for IPCC AR4 models, and circled letters are for uncoupled models. A line showing the 95% confidence interval of natural variability in the percentage change is shown (derived from a 600 year climate control experiment).

3.0 CATASTROPHE MODEL RESULTS

AIR Worldwide was tasked with assessing the insurance impacts of the various climate scenarios put forth by the Met Office. Using state-of-the-art catastrophe models, AIR has developed “climate conditioned” catalogues of potential future events and compared the resulting insured losses based on projected climate scenarios with the baseline risk associated with today’s climate.

Changes in risk are measured by way of several key metrics, in particular, the average annual loss (AAL) reflecting the expected annual insured loss aggregated over an entire year, the 1.0% exceedance probability (100-year) loss, and the 0.5% exceedance probability (200-year) loss. AAL refers to the loss that can be expected to occur per year, *averaged* over a period of many years. Clearly, significant events will not happen every year, so it is important to emphasise that AAL is a long-term expected loss. The 100-year loss is the loss that can be expected to occur or be exceeded on average once every 100 years. Note that the 100 year loss in the current climate regime, which defines the baseline, may be different from the 100-year loss in a future climate regime. Similarly, the 200-year loss is the loss that can be expected to occur or be exceeded once every 200 years.

Making use of UK government economic regions, changes are also reported at a regional scale. Confidence intervals associated with the baseline risk are used to evaluate the statistical significance of each climate scenario.

As can be expected from both the baseline and the climate adjusted catalogues, the majority of catalogue entries consists of events that cause low to medium losses; there are considerably fewer tail events with very large losses (such as the 100-year losses or larger). Due to the relatively small number of tail events, the confidence interval gets wider for the 0.5% probability loss than for 1% probability loss, i.e. the uncertainty around the largest event losses is larger. By the same token the confidence intervals for UK regional risk are wider than for the UK overall.

3.1 Methodology

Catastrophe models for the insurance industry, pioneered by AIR Worldwide in the late 1980s, integrate science related to natural hazards (meteorology, seismology, hydrology and the like) with engineering relationships to produce estimates of property damage expected under various scenarios. By computing the damage over a portfolio of insured risks or, in the case of this study, over the entire industry stock of insured buildings, one can quantify the financial impacts of natural (and man-made) catastrophes. Catastrophe models have been used for over 20 years to prepare for hazards ranging from hurricanes to earthquakes to terrorism, and have recently proven useful to quantify the sensitivity of risk to climate (e.g., Dailey et al. 2009).

In the case of meteorological hazards, catastrophe models can accurately compute the underlying “climatological” (baseline) risk by subjecting buildings to a full spectrum of severe weather events as they might occur in the current climate. This is accomplished by simulating the effects of a large catalogue of events—representing thousands of scenario-years of plausible weather activity—based on the current climate. Potential events are simulated in accordance with their relative probability of occurrence; thus the catalogue comprises many weak, fewer strong, and even fewer extreme events.

In this study, AIR has applied three of its catastrophe models to the problem of risk brought about by climate change. The AIR Inland Flood Model for Great Britain quantifies the risk of inland flooding brought about by heavy precipitation over Great Britain. The AIR Extratropical Cyclone (Winter Storm) Model for Europe captures the wind risk from winter season mid-latitude (extratropical) cyclones over the UK and continental Europe. Finally, the AIR Typhoon Model for China quantifies the impact of intense tropical cyclones on China's growing insurance market. Each of these models is discussed in more detail in Appendices 6, 7, and 8, respectively.

By taking as input the climate scenarios discussed in Section 2, and comparing the output of the catastrophe models to the baseline risk (defined as the risk under today's climate), one can assess the sensitivity of insured losses to projected future climate. Of course, there is significant uncertainty associated with both the climate projections and the impacts of those projections on insured property loss. Here is where the probabilistic qualities of catastrophe models can be quite useful. Specifically, the large catalogue of event scenarios contained within each catastrophe model can be used to quantify both the financial impact and level of confidence surrounding the results.

3.2 Great Britain Inland Flood (GBF)

The results of the research conducted by the Met Office show a significant increase in rainfall over Great Britain, in terms of both the average annual precipitation as well as the 1-in-5 year rainfall event. The conclusion of the climate model and literature assessment indicates the following impacts corresponding to 2°C, 4°C, and 6°C increases in global temperature (hereafter, the climate conditions and resulting losses associated with the future climate warmed by 2°C, 4°C, and 6°C will be called CS1, CS2, and CS3 respectively):

Table 1 Projected increase in GB Flood 5-year precipitation as specified by the Met Office

% Change in 5-yr return period	9.1%	18.2%	27.4%
Global temperature change	CS1 (2°C)	CS2 (4°C)	CS3 (6°C)

Note: See Figure 2.

Table 2 Projected increase in GB Flood mean precipitation as specified by the Met Office

% Change in average	8.3%	16.6%	25.0%
Global temperature change	CS1 (2°C)	CS2 (4°C)	CS3 (6°C)

Note: See Figure 3.

These projections can be interpreted as follows. When global temperatures rise by 2°C, annual precipitation which induces flooding in Great Britain is expected to increase by 8.3%, and precipitation associated with more extreme events occurring once every five years is expected to rise by 9.1%. Correspondingly, more dramatic increases in global temperatures induce a more dramatic atmospheric response of 25.0% and 27.4%, respectively.

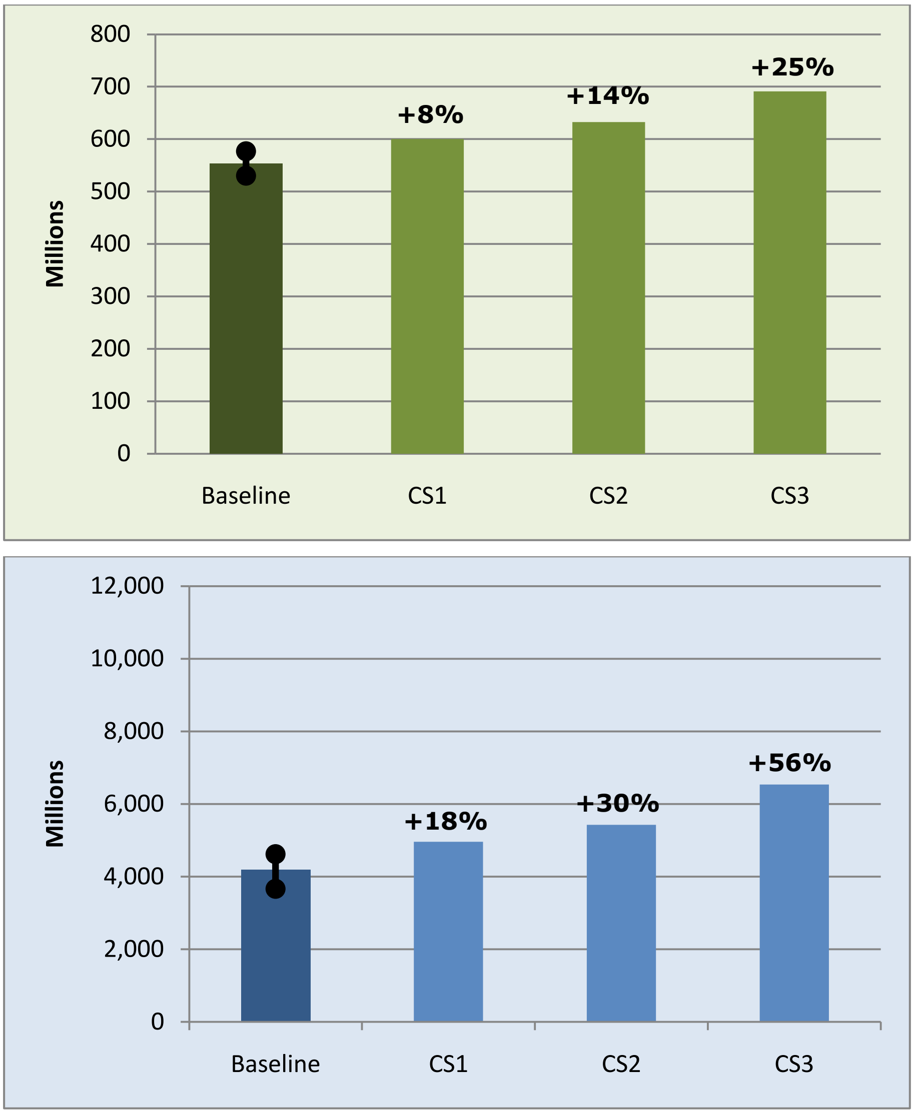
GBF countrywide impact

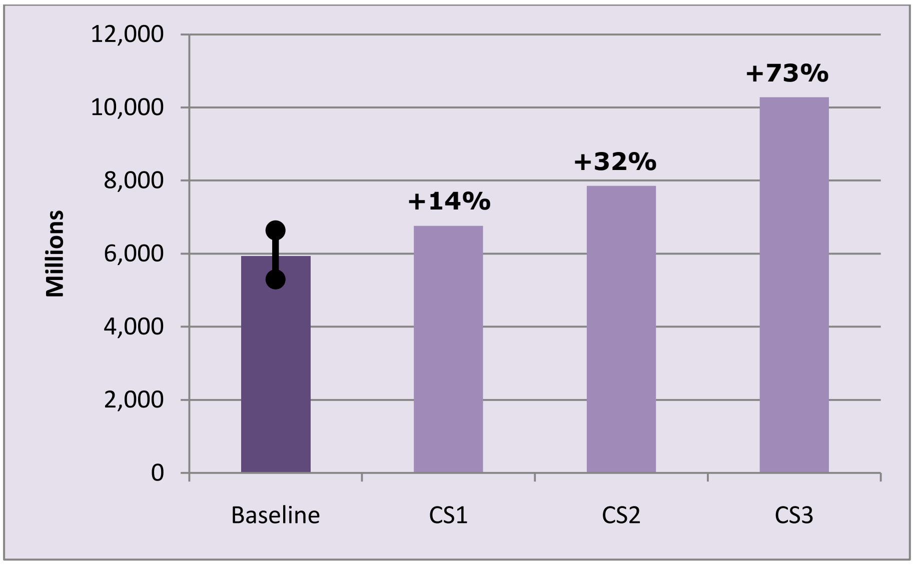
Making use of the AIR Worldwide Inland Flood Model for Great Britain, these changes in mean and 1-in-5 year precipitation were applied to the model's representation of the current climate, resulting in a "climate conditioned" (re-sampled) catalogue of events, one for each climate scenario. A complete description of the sampling techniques used throughout this study, along with the climate conditioned hazard distributions are provided in Appendix 5.

Unless specifically noted, all catastrophe model results reflect expected deviations from a climatological (current climate) baseline risk under some future climate scenario. Reported are "ground-up" losses, which represent total insured damages, including deductibles, but before the application of retention or reinsurance.

The targeted adjustments to mean and 1-in-5 year precipitation as set by the Met Office were precisely met in the climate conditioned catalogues for CS1, CS2, and CS3. In response to more plentiful annual precipitation and more frequent extreme precipitation events, insured losses are expected to increase. The results for Great Britain are shown in Figure 8. The first panel shows changes to average annual loss (AAL), the second shows changes to an expected 100-year loss, and last panel shows changes to an expected 200-year loss.

Figure 8 Countrywide average annual loss (top), 100-year loss (middle) and 200-year loss (lower) in response to expected increases in precipitation (in 2008 £ values)





Note: The baseline risk is shown on the far left of each panel indicating loss expectations in today's climate. Losses associated with CS1, CS2, and CS3 correspond to precipitation-induced flooding expected as global temperatures rise by 2°C, 4°C, and 6°C respectively.

Source: AIR Worldwide Corp.

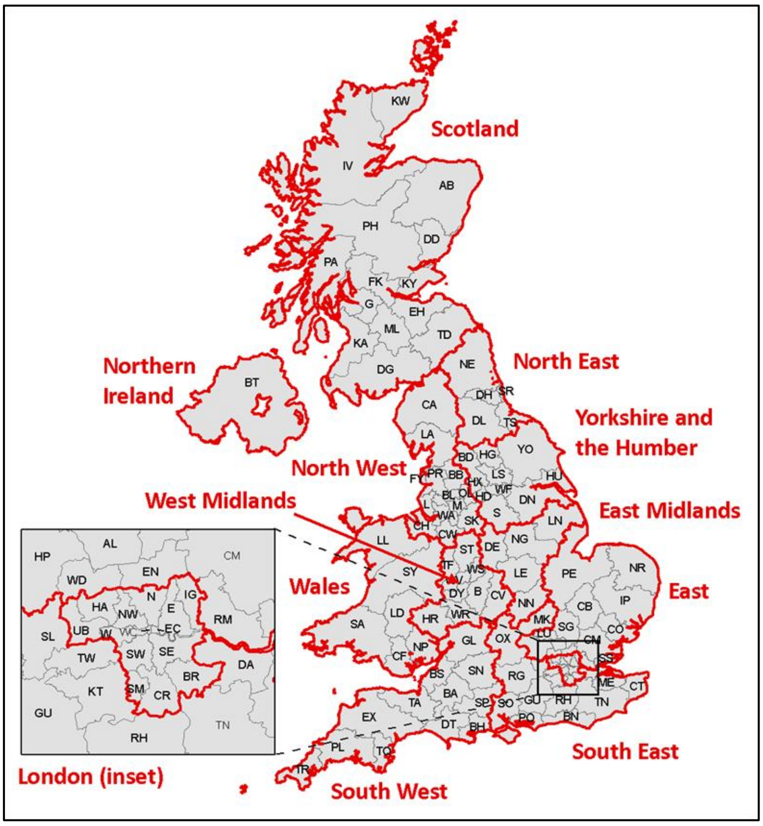
A 95% confidence interval is placed on the baseline risk for each loss metric to illustrate confidence in the calculation of expected losses with respect to today's climate. When a climate scenario falls within the 95% confidence bound, as does CS1 for the 100-year and 200-year loss, it can be argued that the risk cannot be statistically distinguished from today's climate with confidence.

When climate scenario losses fall outside the 95% confidence interval, it can be argued with confidence that when these levels of global warming are reached, insured risk will increase beyond a level that can be explained by natural variability occurring in the contemporary climate. Thus, climate scenarios tied to strong global "forcing", like that of CS2 and especially CS3, reflect significantly higher risk than is apparent in the baseline.

GBF regional impact

In this study, UK government economic regions are used to stratify results to a finer spatial scale. To take the results to the scale of individual postal codes is impractical given the limitations of GCMs noted earlier, so we have chosen to portray the results at the same scale as the UK Government Office regions, hereafter referred to as *economic regions*. This categorisation will also facilitate the next discussion on socio-economic impacts. A mapping of postal code to these regions, and their names, is shown in Figure 9.

Figure 9 Regional definition used in this study



Note: UK Government Office regions will in this study be referred to as "UK Economic Regions", and are mapped to Postal Codes as shown.

While precipitation may not increase uniformly across the whole of Great Britain, such an assumption is made here because the resolution of the GCMs used to project climate is insufficient to resolve variability within the UK at a finer scale. However, because even a uniform distribution of rainfall produces a non-uniform runoff and flood risk, one can still measure how increasing precipitation amounts across the larger region may bring about non-uniform changes in regional risk.

The maps in Figures 10, 11, and 12 show the regional response, as a percentage increase relative to the baseline, for each of the economic regions. Note that although Northern Ireland is not modelled for flood risk, it will later be included in the wind risk assessment.

The first series of maps show the regional response of AAL to CS1 (left), CS2 (middle), and CS3 (right). The second and third series show the same, but for the 100-year and 200-year loss, respectively. Because some regions are more highly exposed, both physically (risk of runoff is regionally higher) and/or monetarily (more valuable and more dense exposures), the response may be greater than for Great Britain as a whole.

Figure 10 **Regional response of average annual loss to CS1 (left), CS2 (middle) and CS3 (right)**

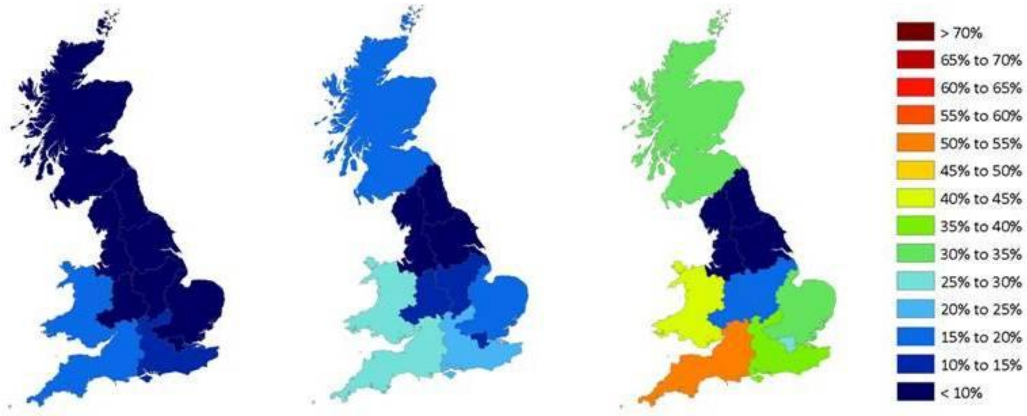


Figure 11 **Regional response of the 100-year Loss to CS1 (left), CS2 (middle) and CS3 (right)**

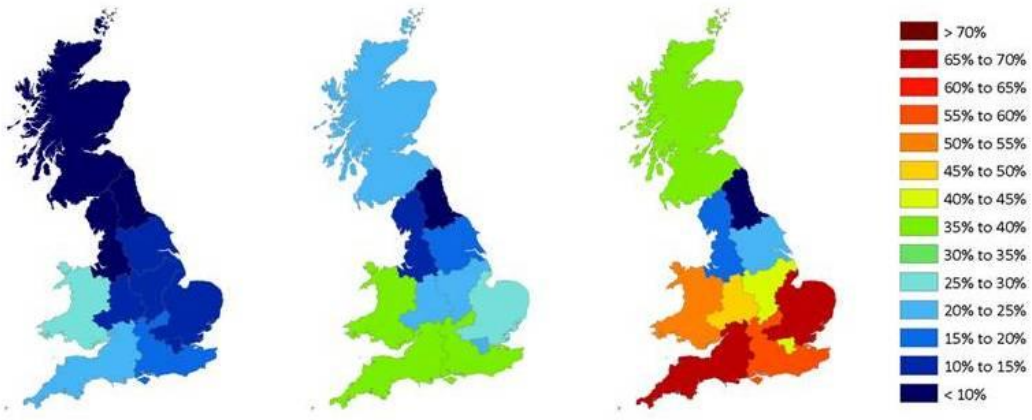
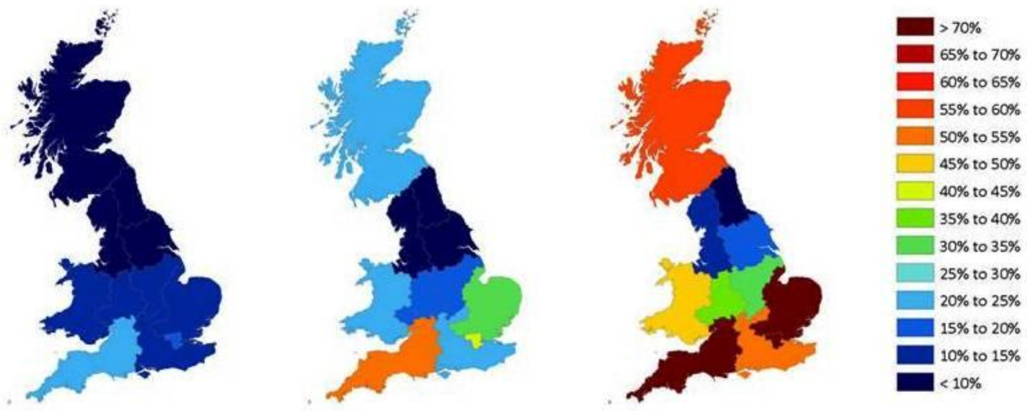


Figure 12 **Regional response of the 200-year Loss to CS1 (left), CS2 (middle) and CS3 (right)**



Note: Values shown reflect percentage increases relative to the baseline (current climate) risk.

Source: AIR Worldwide Corp.

In summary, with regards to **GBF**, the Met Office scenarios result in higher levels of precipitation and runoff, leading to increased flood risk. The increased flood hazard brought about by up to 2°C warming results in about 8% higher AAL for Great Britain as a whole. The influence at the regional scale varies. As warming increases to 4°C, the more dramatic change in precipitation results in about 14% higher AAL. Finally, increased precipitation brought about by 6°C rise in temperatures results in 25% higher AAL.

The impact on the 100-year and 200-year insured loss (with annual probabilities of 1.0% and 0.5% respectively) is more dramatic, with impacts across all scenarios ranging from about 18% to 56% for 100-year losses and about 14% to 73% for 200-year losses depending on the climate scenario. For example, a 6°C rise in global temperatures could increase the 200-year loss by as much as 73%.

3.3 United Kingdom Windstorm (UKW)

The results of the research conducted by the Met Office show an inconclusive response in extratropical cyclone activity as a result of warming global temperatures. However, it is expected that warming will lead to changes in the dynamics that cause winter windstorms to form and intensify, and we have chosen to measure the sensitivity of wind risk to changes in the mean track taken by winter storms.

The Met Office summarises the research and climate model results with three climate conditions, referred to as Sensitivity A, B, and C. Sensitivity B reflects a shift in future storm tracks of -1.45 degrees latitude, where the reduction in mean track latitude reflects a southward (towards the equator) shift. Scenarios A and C represent more extreme (low probability) shifts to the north (A = +4.4 degrees) and to the south (C = -7.28 degrees) quantified as the maximum and minimum around the mean change indicated by scenario B from the Met Office’s joint ensemble results. Whilst the large northward or southward shifts are not very plausible, they allow one to gauge the sensitivity of loss to the spatial distribution of storm frequency.

Table 3 Shift in UK windstorm track latitude as specified by the Met Office

Degrees change	4.40°	-1.45°	-7.28°
Climate sensitivity	(A)	(B)	(C)

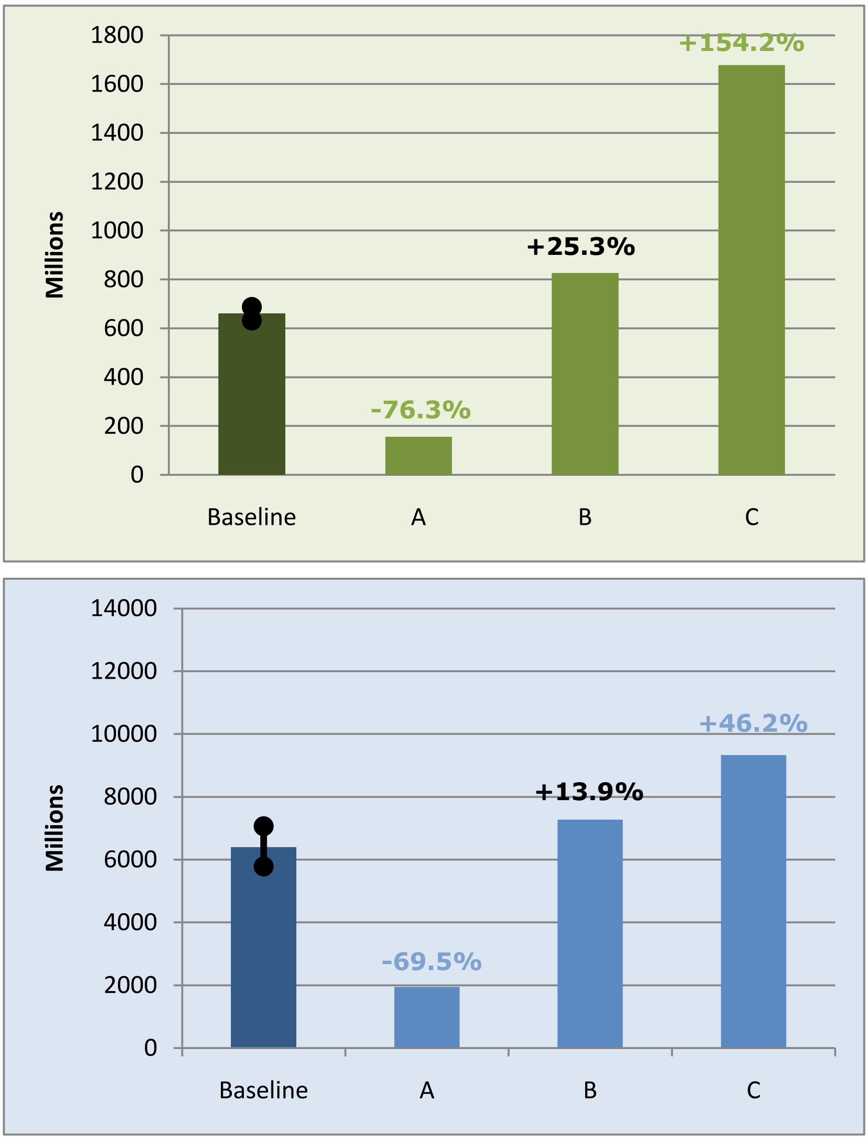
Note: See Figure 4.

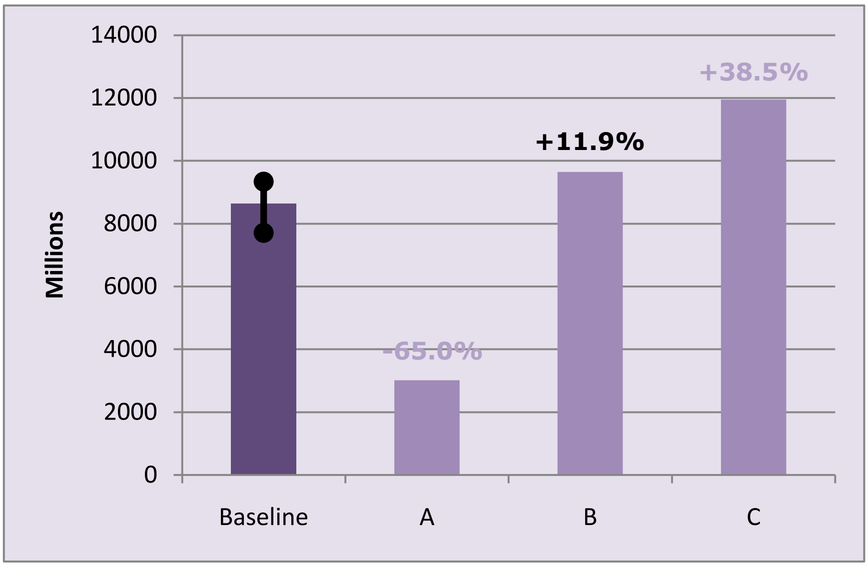
These shifts in storm track are tied in part to a climate signal called the *North Atlantic Oscillation* (NAO). The NAO is known to influence the steering of UK winter storms. A detailed discussion of this and other climate influences on windstorm activity is provided in Appendix 3, **Question 5**.

UKW countrywide impact

Making use of the AIR Extratropical Cyclone Model for Europe, these changes in mean track latitude were applied to the model's representation of the current climate, resulting in a "climate conditioned" catalogue of potential events, one for each climate scenario. Because these scenarios are not directly associated with increases in global temperature (as in GBF), they are designated Sensitivity A, B and C instead of CS1, CS2 and CS3.

Figure 13 Countrywide average annual loss (top), 100-year loss (middle) and 200-year loss (lower) in response to changes in the mean windstorm track affecting the UK (in 2008 £ values)





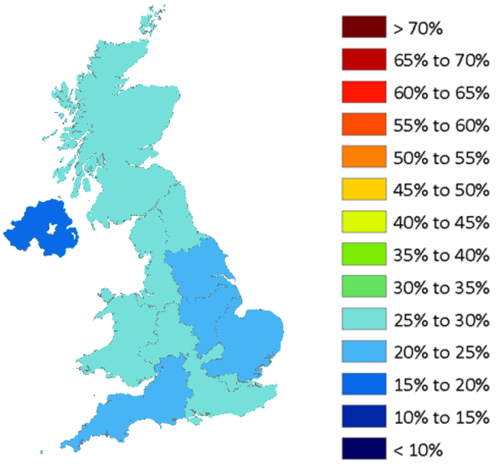
Note: The baseline risk is shown on the far left of each panel indicating loss expectations in today's climate. Losses associated with track shifts A, B, and C correspond to fundamental changes in tracks of storms passing over the UK. Sensitivity Experiments A and C are low probability scenarios reflecting extreme track shifts.

Source: AIR Worldwide Corp.

UKW regional impact

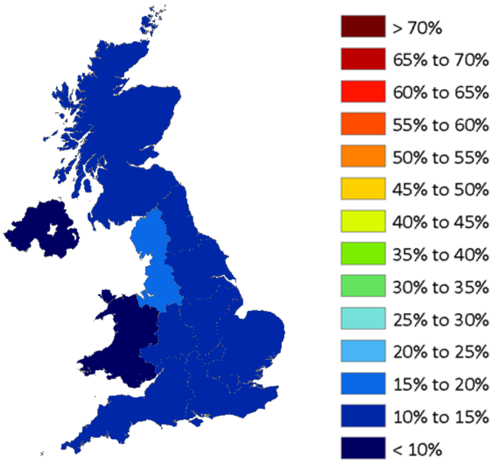
As in the case of GBF, economic regions are used to stratify UKW loss results to a finer spatial scale. Again here, even a systematic shift in the track of storms affecting all of Europe will have a non-uniform impact on relative risk within the UK. The results are shown in Figures 14, 15, and 16 for Sensitivity B which reflects a 1.45 degree southerly shift in mean track.

Figure 14 Regional response of average annual loss to a 1.45 degree southward shift in the mean track of windstorms



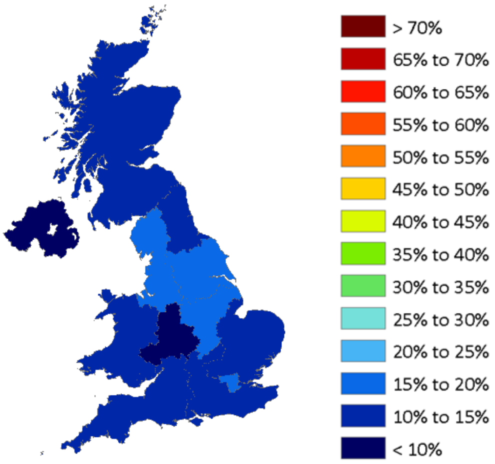
Source: AIR Worldwide Corp.

Figure 15 Regional response of a 100-year loss to a 1.45 degree southward shift in the mean track of windstorms



Source: AIR Worldwide Corp.

Figure 16 Regional response of a 200-year loss to a 1.45 degree southward shift in the mean track of windstorms



Note: The above three figures correspond to Sensitivity B. Values shown reflect percentage increases relative to the baseline (current climate) risk.

Source: AIR Worldwide Corp.

In summary, with regards to **UKW**, the scientific research is insufficient to pinpoint a change in frequency or intensity as global temperatures continue to rise. One of the postulated sensitivities (Sensitivity B) shows a southward shift of 1.45° latitude. This could play a significant role in defining future risk because it would tend to increase the passage of storms over the more populated (and therefore more risk-exposed) regions of the UK.

Even the modest change in storm track represented by Sensitivity B, while holding the overall frequency and intensity of European winter storms constant, could bring about a rise in average annual losses of around 25% and increases in 100-year and 200-year losses of around 14% and 12%, respectively. Overall, regional differences are observed but are not as variable as for GBF.

3.4 China Typhoon (ChT)

The results of the assessment of intensity changes associated with Pacific tropical cyclones are not conclusive. However, as with UKW, the expectation is that as the climate warms, wind intensity in typhoons affecting China will increase modestly by 3.7%. Because the research is not very mature, in particular with regard to landfalling typhoons, the Met Office has provided two additional scenarios for sensitivity testing, one reflecting a small intensity decrease of 0.5% and the other reflecting a more substantial increase of 7.9%. As in the UKW experiments, these scenarios which are not directly associated with increasing global temperatures, are referred to as Sensitivity A, B, and C.

Table 4 Projected change in China Typhoon wind intensity as specified by the Met Office

% change	-0.5%	3.7%	7.9%
Climate sensitivity	(A)	(B)	(C)

The results of the Met Office assessment show a more significant increase in rainfall associated with tropical cyclones affecting China which can be more directly tied to varying levels of global warming. The conclusion of the model and literature assessment indicate increased precipitation rates of 13%, 26% and 39% corresponding to 2˚C, 4˚C, and 6˚C increases in global temperature, respectively.

Table 5 Projected increase in China Typhoon mean precipitation as specified by the Met Office

% Change in average	13.0%	26.0%	39.0%
Global temperature change	CS1 (2˚C)	CS2 (4˚C)	CS3 (6˚C)

ChT Countrywide Impact

Making use of the AIR Typhoon Model for China, changes in mean tropical cyclone precipitation combined with three sensitivities to wind intensity were applied to the model's representation of the current climate, resulting in an ensemble of nine climate conditioned catalogues, one for each combination of intensity change (A-B-C) and global temperature increase (2-4-6˚C).

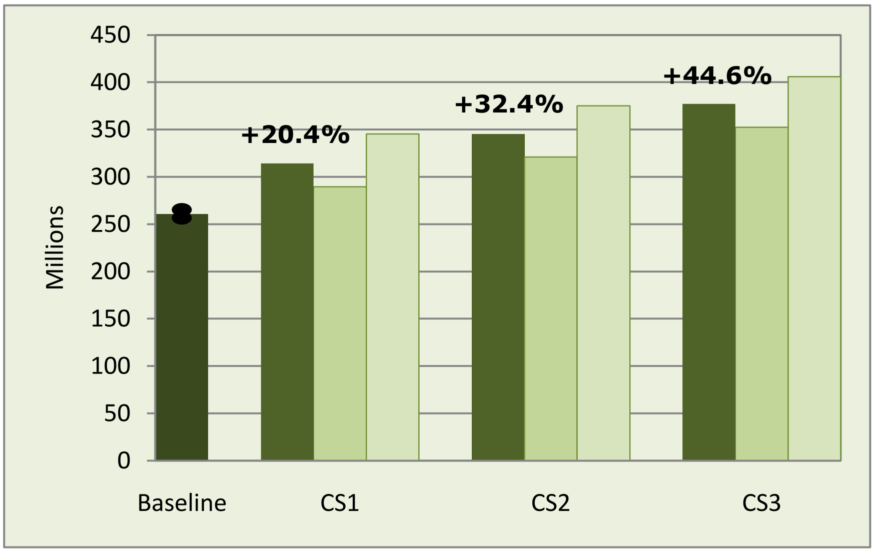
The results indicate a statistically significant increase in average annual losses, from 20% to over 40% with increasing temperature forcing. The results are shown in Figure

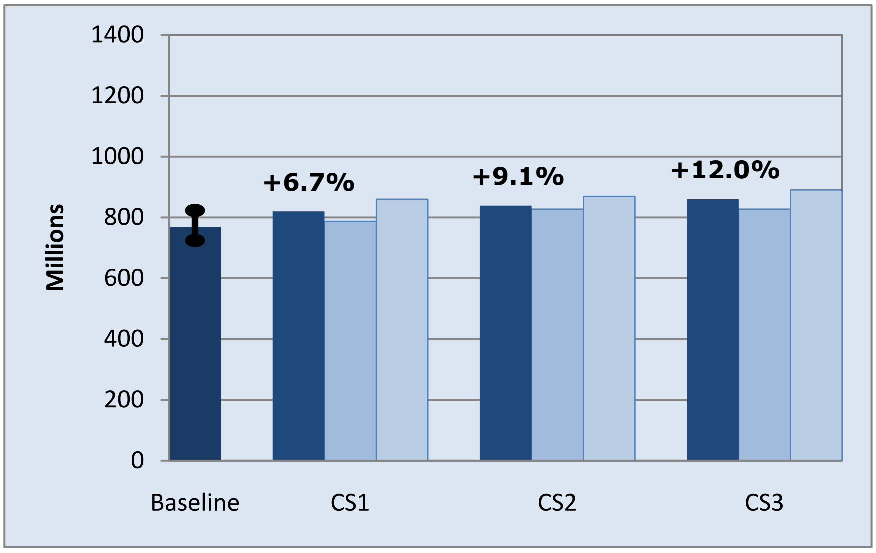
17. For all charts in Figure 17, the first bar in each group of three corresponds to the expected intensity change, or Sensitivity B. The second and third bars in each group of three correspond to intensity changes for Sensitivities A and C, reflecting two standard deviations from expected. The overall typhoon risk in China is much more sensitive to increases in precipitation than to changes in wind intensity. This is apparent from historical loss experience where a larger portion of total loss is due to flooding.

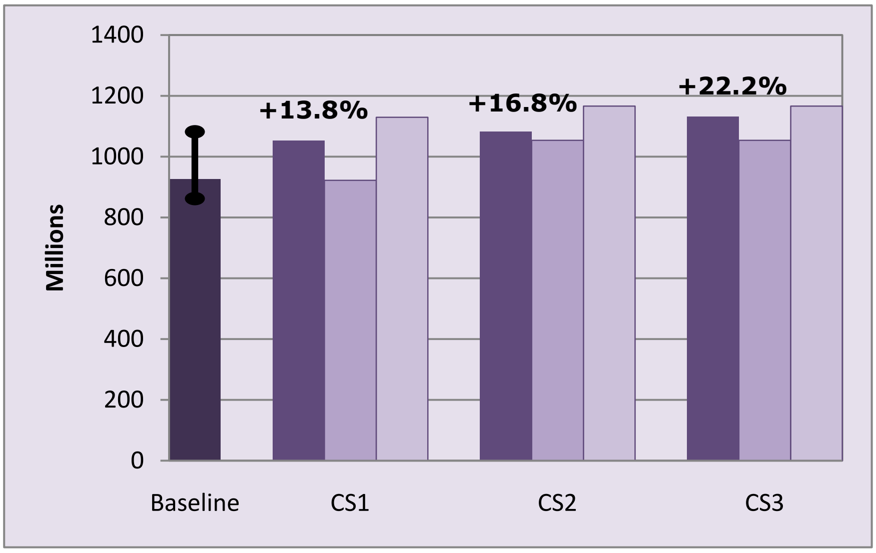
In percentage terms, the results indicate a smaller impact on the 100-year and 200-year losses. This can largely be explained by the fact that China experiences losses from about 10 typhoons in a typical year. Thus, the loss from any one event is secondary to the aggregate losses experienced over the course of the year. This does not mean that China cannot experience a single dominant event, but rather that the larger impact of climate change on total annual losses is of fundamental importance. Still, the 200-year loss is estimated to rise by more than 20% under climate scenario CS3, while average annual losses could rise by about 45% under the same climate conditions.

Just as important as the rising risk, China's insurance market is growing rapidly, making it even more important to understand how the insurance landscape will respond to even small increases in the risk. This topic will be expanded upon in the following section of the report.

Figure 17 Countrywide average annual loss (top), 100-year loss (middle) and 200-year loss (lower) in response to changes in the mean precipitation and wind intensity affecting China (in 2008 £ values)







Note: The baseline risk is shown on the far left of each panel indicating loss expectations in today's climate. Losses associated with increased precipitation are shown for CS1, CS2, and CS3. 95% confidence intervals are indicated for each baseline. For each climate scenario, intensity changes associated with Sensitivity B (expected), A, and C are shown in that order. Percent changes are linked to the expected intensity change corresponding to Sensitivity B. Units are British Pounds (using a currency conversion of 0.091), and losses have been converted to insured assuming a countrywide effective insurance take-up rate, weighted by line of business, equal to about 22%.

Source: AIR Worldwide Corp.

In summary, with regards to **ChT**, the main impact of the Met Office climate scenarios on typhoon activity is to increase precipitation-induced flood damage, with a more modest increase in wind damage. AAL increases range from around 20% to around 45% across the 2°C, 4°C, and 6°C temperature rise scenarios. The percentage change in 100-year and 200-year losses is more modest, due at least in part to the fact that China experiences losses from around 10 events per year. Therefore, the influence of global warming does not manifest itself significantly on the maximum loss event in a year, but rather on the annual aggregate risk in this growing insurance market.

4.0 ISSUES FOR INSURERS AND POLICYMAKERS

Examining the impact of future climate scenarios on selected risk metrics derived from catastrophe models is an important first step. Determining how these changes might impact important aspects of insurers' operations needs to be examined as well. Of particular interest are the potential impacts on pricing, risk measurement and management, regulator's requirements for minimum capital, the amount of additional capital that insurers may need, and supplemental capital requirements.

This section concludes with a brief discussion of some prudent prevention, loss mitigation and adaptation steps that could be taken now to counter some of the possible increases in key risk metrics.

4.1 Insurance industry climate change impacts

The catastrophe model results presented in the previous Section, i.e. the AAL and the 100-year and 200-year losses, are important input for the purpose of examining the potential impacts on various other metrics of interest to insurers, which are examined in more detail in this section. The selected climate scenarios' potential impacts on pricing and capital issues, including the impact on minimal capital that may be required by regulators as well as additional capital to absorb shock losses, can all be explored using fully probabilistic catastrophe loss distributions.

The loss estimates presented in Section 3 isolate the effects of climate change by holding all other parameters constant. In examining the potential impact on insurers' operations in this section, projected 10 year GDP growth is considered alongside an assumption of no growth. The GDP projections are meant to serve as a proxy for combined increases in the number of insured properties resulting from population growth and increases in the total sums insured resulting from increased wealth. However, it does not take into account increased take-up of insurance which is likely to be an important factor, particularly for China.

For the perils of Great Britain Flood (GBF) and UK Extratropical Cyclone (UKW), an annual trend growth rate of 2.5% is assumed (+28% over ten years), which is assumed at the low end of a range of published estimates. For China, a 6% annual GDP growth (+79% over ten years) is assumed, which is also at the lower end of a range of published estimates.

Pricing

It should be noted that all discussions about pricing in this Section relate solely to the catastrophe component of the cost of insurance that is being considered across the risk transfer chain. The price of insurance that is ultimately charged to the policyholder cannot be predicted by a simple review of the modelled loss distributions as set forth in this analysis for a number of reasons, not least of which is that individual insurers will make their own individual pricing decisions as to what rates to use. These decisions may be based in part upon market conditions as well as on their own analyses and estimates of expected catastrophe losses. Decisions may also be based on various fixed and variable expenses, including the costs of their chosen forms of risk transfer alternatives, and their individual company's uniquely established risk appetite and risk tolerance levels. In some circumstances, the pricing may even be influenced by political considerations.

Nevertheless, certain simplified assumptions about how the event catalogues may generally impact overall insurance prices can be made by examining modelled average annual losses (AAL) in conjunction with some conservative assumptions.

The possible pricing impact can be estimated by beginning with a typical pricing formula and examining how a change in AAL due to climate change might change the price level. A typical primary insurer's loss cost pricing formula would reflect estimates of loss, expenses and profit components for the catastrophe portion of the price of insurance, as follows:

- *Modelled catastrophe losses.* These are usually in the form of AAL, including a proper understanding of the impact of uncertainty.
- *Fixed expenses*. Fixed expenses (including a small allowance for reinsurance, other risk transfer costs and associated capital costs) related to the most volatile portions of the modelled loss distribution, which could be represented through a multiplier to the portion of AAL for the more volatile and uncertain ceded losses; a *very* conservative assumption would be that this serves to increase modelled AAL by 10% (i.e. 0.1).
- *Variable expenses and profit load.* Profit load would reflect on the volatility and uncertainty of the losses to account for risk and could be considered a portion of variable expenses that are typically set as a percentage of the price charged, including commissions, taxes, licenses and fees; a conservative assumption is that variable expenses and profit load are 25% (i.e. 0.25) of an adequate risk-appropriate premium.

By way of this example, then, the potential impact in price could be expected to be (1+0.1)*AAL/(1-0.25), or 1.47 times the observed increase in AAL. In other words, each 1% increase in modelled AAL attributable to climate change could be expected to increase prices by at least 1.47%. Of course, individual insurers' situations could suggest the use of alternative percentages for the various pricing components and change those assumed in the example for the industry.

Tables 6, 7 and 8 below show the possible pricing impact for each of the climate scenarios pertaining to GBF, UKW and ChT, both without and with projected growth.

Table 6 Potential pricing changes (%) for Great Britain Inland Flood

No Growth			With Growth		
CS1	CS2	CS3	CS1	CS2	CS3
12	21	37	16	27	47

Note: Potential percentage change in insurance pricing calculated from a typical loss cost pricing formula, based on countrywide AAL in response to expected increases in precipitation over Great Britain. Losses associated with CS1, CS2, and CS3 correspond to precipitation-induced flooding expected as global temperatures rise by 2°C, 4°C, and 6°C, respectively. Where indicated, an annual GDP growth of 2.5% is assumed.

Table 7 Potential pricing changes (%) for UK Wind

No Growth	With Growth
37	48

Note: Potential percentage change in insurance pricing calculated from a typical loss cost pricing formula, based on countrywide AAL in response to changes in the mean windstorm track affecting the UK. Losses associated with Sensitivity B were used. Where indicated, an annual GDP growth of 2.5% is assumed.

Table 8 Potential pricing changes (%) for China Typhoon

No Growth	With Growth
48	85

Note: Potential percentage change in insurance pricing calculated from a typical loss cost pricing formula, based on countrywide AAL in response to expected increases in Sensitivity B (intensity) and CS2 (precipitation). Where indicated, an annual GDP growth of 6% is assumed.

Measurement and management of tail risk

Insurers typically analyse the more volatile events in the tail of the modelled catastrophe loss distribution to determine how the results compare to their respective company's chosen risk appetite, risk tolerance and business plans, strategies, and tactics.

The 100-year and 200-year losses are important risk metrics which are often requested by rating agencies. Careful review of increases of these key tail risk measurements due to climate change could be important to insurers. Furthermore, although not provided in this study, an understanding of the impact climate could have on even more extreme losses would also be of use to insurance risk managers. Whilst expected actions by individual insurers cannot be predicted because they would depend on each company's individual economic capital situation and chosen risk appetite and tolerance levels, generally it can be said that as the measured risk increases fewer numbers or risks and/or lower values per risk are possible to insure. This could have significant impact on insurability and how much of the risk might need to be eliminated, reduced, or transferred to others, including to the insured.

The consequences of insurers exceeding their risk appetites and tolerances due to incorrect assessment of climate change related risks could include the following:

- Restrict coverage or increase risk retention by the insured (via deductibles, coinsurance and limits)
- Limit the number and/or average insured values in high risk areas
- Broker blocks of existing business
- Purchase reinsurance
- Participate in securitised risk instruments, such as catastrophe bonds
- Ensure pricing adequacy to accommodate the additional cost of reinsurance and catastrophe bonds or other risk transfer alternatives
- Reduce capacity
- Speed up collection of more accurate information on risk location, construction and consider resilience/mitigation measures

To show the impact of the various climate scenarios on risk measurements of interest to both insurers and rating agencies, Tables 9, 10 and 11 recall from Section 3 the potential percentage increase in expected 100-year (or 1% exceedance probability) and 200-year (or 0.5% exceedance probability) losses. Also shown is the impact of GDP growth on each of these metrics.

Table 9 Change (%) in tail risk measurement for Great Britain Flood for 0.5% threshold loss

No Growth			With Growth		
CS1	CS2	CS3	CS1	CS2	CS3
14	32	73	18	41	94

Note: Tail Risk Measurements, such as the 200-year loss, are often examined by insurance company risk managers as Probable Maximum Loss events to be managed relative to the company's uniquely defined risk appetite and tolerance. Table shows percentage change in the countrywide 200-year loss in response to expected increases in precipitation. The baseline risk (not shown) indicates loss expectations in the current climate. Losses associated with CS1, CS2 and CS3 correspond to precipitation-induced flooding expected as global temperatures rise by 2°C, 4°C and 6°C, respectively. Where indicated, an annual GDP growth of 2.5% is assumed.

Table 10 Change (%) in tail risk measurement for Great Britain Flood for 1.0% threshold loss

No Growth			With Growth		
CS1	CS2	CS3	CS1	CS2	CS3
18	30	56	24	38	72

Note: Tail Risk Measurements, such as the 100-year loss, are often examined by insurance company risk managers as Probable Maximum Loss events to be managed relative to the company's uniquely defined risk appetite and tolerance. Table shows percentage change in the countrywide 100-year loss in response to expected increases in precipitation. The baseline risk (not shown) indicates loss expectations in the current climate. Losses associated with CS1, CS2 and CS3 correspond to precipitation-induced flooding expected as global temperatures rise by 2°C, 4°C and 6°C, respectively. Where indicated, an annual GDP growth of 2.5% is assumed.

Table 11 Change (%) in tail risk measurement for UK Wind

0.5% Threshold Loss		1.0% Threshold Loss	
No Growth	With Growth	No Growth	With Growth
12	15	14	18

Note: Tail Risk Measurements, such as 100-year or 200-year losses, are often examined by insurance company risk managers as Probable Maximum Loss events to be managed relative to the company's uniquely defined risk appetite and tolerance. Table shows percentage change in the countrywide 200-year (left) and 100-year (right) losses in response to changes in the mean windstorm track affecting the UK. The baseline risk (not shown) indicates loss expectations in the current climate. Losses associated with Sensitivity B were compared to the baseline and are shown in this Table. Where indicated, an annual GDP growth of 2.5% is assumed.

Table 12 Change (%) in tail risk measurement for China Typhoon

0.5% Threshold Loss		1.0% Threshold Loss	
No Growth	With Growth	No Growth	With Growth
17	30	9	16

Note: Tail Risk Measurements, such as 100-year or 200-year losses, are often examined by insurance company risk managers as Probable Maximum Loss events to be managed relative to the company's uniquely defined risk appetite and tolerance. Table shows percentage change in the countrywide 200-year (left) and 100-year (right) losses in response to expected increases in Sensitivity B (wind intensity) and CS2 (precipitation) compared to the baseline risk (not shown), which indicates loss expectations in today's climate. Where indicated, an annual GDP growth of 6% is assumed.

Potential change in regulated required minimum capital

Estimating potential changes in future government-required minimum capital is important in that insurers may be required to hold increased amounts of capital that otherwise might be invested for higher returns. The recent economic downturn and regulatory actions associated with Solvency II may lead to increased regulatory oversight over the long-run and higher levels of required minimum capital for insurers.

It is assumed here that the 200-year loss (0.5% exceedance probability) could be representative of the required minimum capital for insurance companies under Solvency II and that any addition to the 200-year loss resulting from climate change would represent a change in required minimum capital.

Tables 13 and 14 show the potential changes in the required minimum capital resulting from climate change for GBF and UKW. Results (in millions of £) are shown with and without trended growth in GDP.

Table 13 Potential change (£m) in required minimum capital (probability at 99.5%) for Great Britain Flood due to climate change

No Growth			With Growth		
CS1	CS2	CS3	CS1	CS2	CS3
832	1,920	4,346	1,065	2,457	5,563

Note: Potential change (in millions of £, in 2008 values) in the countrywide 200-year flood loss in response to expected increases in precipitation. The 200-year losses are expected to be identified in Solvency II as representative of the Required Minimum Capital to be retained by insurers. Countrywide 200-year losses are in response to expected increases in response to changes in the global temperature rises affecting rainfall in the UK. Losses associated with CS1, CS2 and CS3 correspond to precipitation-induced flooding expected as global temperatures rise by 2°C, 4°C and 6°C, respectively. These are compared to the baseline, identified as the required minimum capital for today's climate (not shown). A significant portion of the Required Minimum Capital is reflected in the exposure already included in the baseline risk. Where indicated, an annual GDP growth of 2.5% is assumed.

Table 14 Potential change (£m) in required minimum capital (probability at 99.5%) for for UK Wind due to climate change

No Growth	With Growth
1,023	1,310

Note: Change (in millions of £, in 2008 values) in the countrywide 200-year wind loss in response to expected increases in precipitation. The 200-year losses are expected to be identified in Solvency II as representative of the Required Minimum Capital to be retained by insurers. Countrywide 200-year losses associated with Sensitivity B are in response to changes in the mean windstorm track affecting the UK. A significant portion of the Required Minimum Capital is reflected in the exposure already included in the baseline risk, identified as the required minimum capital for today's climate (not shown). Where indicated, an annual GDP growth of 2.5% is assumed.

Whilst it is not anticipated that such increases in required minimum capital will be a significant burden on insurers at the risk levels presented in this study, they could become problematic under more extreme scenarios or in light of other uncertainties.

Potential increase in capital requirement

Whilst the government is generally expected to establish the 200-year loss as required minimum capital for insurers, a higher capital standard might be of interest to insurers—one that would reflect the extreme losses in the tail of the loss distribution. Here, supplemental capital requirement is defined as the additional capital needed to cover shock losses in the tail of the distribution above a certain threshold. There are many higher losses that fall beyond the 0.4% exceedance probability (250-year) portion of the modelled loss distribution. Tail Value at Risk, or TVar, is the probability weighted average of all simulated event losses beyond some specified probability (such as 0.4%). By looking beyond individual points on the loss distribution and instead considering a *portion* of the curve, such as TVar 0.4%, estimates of supplemental capital requirement reflect a broader range of shock losses. The additional amount based upon the average of all such higher shock losses is more reflective of capital that could be needed to pay claims for those losses should they occur.

The potential additional capital needed (i.e. the supplemental capital requirement) is represented by the change in (TVar 0.4% – AAL) driven by the given climate change scenarios. The difference of the extreme shock loss average over the AAL is the amount for which additional capital might be needed to cover the more volatile losses introduced by climate change scenarios.

It should be mentioned that whilst this process yields an approximate amount of additional capital that might be needed, it does not get at either the actual cost of such capital or the actual amount of additional capital that will be needed. Cost of capital is generally a function of volatility and uncertainty. It is ultimately established by the marketplace, based upon competing investments with similar risk. The additional amount of capital required for each company will only be determined after a review of total enterprise risk, and perceived consequences of falling below certain levels.

Tables 15 and 16 provide the calculated additional capital potentially needed for GBF and UKW for each of the climate scenarios provided by the climate model, both with and without overall growth.

Table 15 Potential additional supplemental capital requirement (£m) for Great Britain Flood due to climate change (difference between TVar 0.4% and AAL)

No Growth			With Growth		
CS1	CS2	CS3	CS1	CS2	CS3
1,604	3,753	8,545	2,053	4,804	10,938

Note: Supplemental Capital Requirement is defined as the difference between Tail Value at Risk at the 1-in-250 probability of exceedance and Average Annual Loss (AAL). Losses associated with CS1, CS2 and CS3 correspond to precipitation-induced flooding expected as global temperatures rise by 2°C, 4°C and 6°C, respectively (at 2008 value). A significant portion of the supplemental capital requirement is reflected in the exposure already included in the baseline, or current climate (not shown). Where indicated, an annual GDP growth of 2.5% is assumed.

Table 16 Additional supplemental capital requirement (£m) for UK Wind due to claimte change (difference between TVar 0.4% and AAL)

No Growth	With Growth
1,258	1,610

Note: Supplemental Capital Requirement is defined as the difference between Tail Value at Risk at the 1-in-250 probability of exceedance and Average Annual Loss (AAL). Losses associated with Sensitivity B were compared to the baseline and are in response to changes in the mean windstorm track affecting the UK (at 2008 value). A significant portion of the supplemental capital requirement is reflected in the exposure already included in the baseline, or current climate (not shown). Where indicated, an annual GDP growth of 2.5% is assumed.

4.2 Issues for policymakers

For the purposes of this study, the impact of climate change on financial risk was isolated by modifying only the frequency and intensity of the perils of interest according to the requirements set forth by the climate model results whilst keeping all other parameters unchanged. Subsequently, for the purposes of discussing the potential impacts on insurers' operations, growth trends representing both increases in the number of insured risks and total sums insured were also considered.

Many other factors could also come into play that could either exacerbate or mitigate risk in the decades ahead. For example, it may be that the historical population growth in areas of high hazard (growth that has been largely responsible for the observed upward trend in catastrophe losses over the last several decades) may actually reverse under a changing climate; that is, populations may in fact migrate *away* from high risk areas, which would reduce exposure. Similarly, construction practices may change such that the resistance of structures increases. In addition, building codes are likely to change—becoming more stringent—in the face of increased hazard, and government investment in flood defenses may accelerate. On the other hand, insurance take-up rates in China could grow dramatically, which would increase industry exposure to catastrophe risk in that country. Nevertheless, some steps toward prevention, mitigation, and adaptation could be taken to counter or prepare to respond to the expected increases in catastrophe risk brought about by climate change. Whilst climate change is global, prevention, mitigation, and adaptation often requires local action plans with national leadership and support. Things that could be done now include the following:

- Actions to limit greenhouse gas emissions
- Implementation of effective and adequately enforced risk responsive land use planning and management
- Implementation of mandatory risk-appropriate building codes and adequate enforcement standards so that new and existing structures are built to resist the expected increases in the frequency and intensity of wind and flood events

Other considerations include:

- Governments can take a variety of actions, including: continue to encourage and invest in assessment of the risk for people and property who have or will locate on floodplains or in coastal regions and in other regions at risk from severe windstorms; continue to adequately invest or accelerate investment in protection; invest in appropriate levels of protection and redemption efforts to ensure that adequate infrastructure and critical response facilities will be operational in the face of future extreme events; consider similar issues relating to other perils, especially those that may be correlated with flooding and severe windstorms; to invest in advance planning for rapid response following disasters to facilitate recovery of an affected region, to get the infrastructure and services restored, people back into their homes, and businesses and the economy back to normal as quickly as possible, and; develop advance weather monitoring and warning systems as part of effective risk and response plans that could include mandatory and voluntary evacuations.
- Governments along with other stakeholders could carefully consider the impact that the aging of their populations may have during mandatory and voluntary evacuations, long periods of displacement, and increased levels of stress and anxiety following significant flooding and wind events; other at-risk groups include the poor and infirm; potential challenges include how to deal with and dispose of potentially significant amounts of debris, which may include hazardous materials.
- Public private partnerships could be pursued to increase the awareness and understanding of all stakeholders about the risks and what can be done about

them; with respect to the insurance industry, conducting advanced discussions with key stakeholders to seek solutions to the challenges posed by potential increases in future losses from flooding, severe windstorm, and other perils, specifically with regard to premium increases and affordability, availability, and insurability. Waiting until losses deteriorate to a point where the insurance environment were to become difficult to sustain without increased government financial supports could mean that the solutions would become both more costly and disruptive.

- Individuals and businesses could take actions to control losses to their property and ensure the continuation of its use, including actions to limit their own greenhouse gas emissions and to support businesses that do likewise; embrace risk responsive land use planning and building codes reflective of the winds, flooding, and other perils to which their location is exposed; and to realise that protection and preventative efforts can fail or their designed levels be exceeded such that they make prudent choices as to where to locate and then invest in mitigation efforts.

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A2 PERILS MATRIX

GB Flood 5-Yr Precipitation[1]

9.1%	18.2%	27.4%
(2°C)	(4°C)	(6°C)

GB Flood Mean Precipitation[2]

8.3%	16.6%	25.0%
(2°C)	(4°C)	(6°C)

UK Windstorm Track Latitude[3]

4.40 °	-1.45 °	-7.28 °
(A)	(B)	(C)

China Typhoon Wind Intensity[4]

-0.5%	3.7%	7.9%
(A)	(B)	(C)

China Typhoon Mean Precipitation[5]

13.0%	26.0%	39.0%
(2°C)	(4°C)	(6°C)

Legend

Scenarios of climate change are presented for different perils. The columns correspond to projected scenarios of global temperature rise for GB Flood and China Typhoon precipitation. For UK windstorm events, and China typhoon intensity, scenarios A-B-C represent a plausible range of change from current climate modelling and literature. See text and references for further details.

___%	___%	___%
(2°C)	(4°C)	(6°C)

Footnotes

1. Change in 5 year return value for whole of Dec/Jan/Feb daily accumulation distribution
2. Change in mean for whole of Dec/Jan/Feb daily accumulation distribution
3. Change in the centre of the storm track at 0° longitude. Derived from parabola fitted to the daily band pass filtered 500hPa height data at 0° longitude
4. Intensity changes are taken from Emanuel et al 2008 as an illustrative sample of changes that might occur. Matrix values are the reported intensity changes converted to a wind speed scaling factor for all winds. The range reflects the mean change from 7 GCM ± 2 standard deviations
5. Change in extreme rainfall derived from Clausius-Clapeyron and global mean temperature change

A3 KEY QUESTIONS RELATED TO MODELLING CLIMATE CHANGE

A3.1 Q1. What are the likely timescales of SRES / government policy scenarios reaching 2ºC and 4ºC of global warming?

The timescales of reaching 2°C and 4°C of global warming for a given emissions scenario depend on the rate of rise of greenhouse gas concentrations and the consequent response of global temperatures. The range of possibilities can be estimated using ensembles of climate models which synthesise current understanding and its associated uncertainties.

The IPCC SRES scenarios cover a wide range of plausible emissions trajectories arising from plausible future socioeconomic storylines which encompass a range of assumptions affecting greenhouse gas emissions but do not include climate mitigation policy. More recently, the UK government Climate Change Committee (CCC) proposed a scenario of mitigation policy represented by a peak in global emissions in 2016 followed by a reduction in emissions of 4% per year. Here we use a subset of SRES scenarios and the CCC 2016:4% scenario to address the question posed above.

It is important that projections of climate change consider the uncertainties in the response of global temperature to a given change in CO2 concentration ("climate sensitivity"), and the uncertainties in translating emissions scenarios into concentrations. Most previous climate modelling studies have relied on the assumption that the relationship between CO_2 emissions and the change in atmospheric concentrations (the "airborne fraction" of emissions) would remain at the present-day level. There is now a large body of evidence which suggest that this is a poor assumption, and that the airborne fraction could be expected to increase because current land carbon sinks are projected to become weaker as a consequence of climate change.

Although the IPCC 4th Assessment Report (AR4) presented climate change projections for some SRES scenarios using Ocean-Atmosphere General Circulation Models (GCMs), which allow uncertainties in climate sensitivity to be considered, these models did not cover the upper end of the SRES scenarios and, more importantly, neglected feedbacks between climate change and the carbon cycle. Moreover, the CCC scenario has not been used in studies with GCMs. Therefore here we use a simple climate model, MAGICC, tuned to represent the behaviour of the AR4 GCMs and also accounting for the range of strengths of the climate-carbon cycle feedback as assessed by the Coupled Climate Model Intercomparison Study (C4MIP) cited in AR4. This method is consistent with that employed by the IPCC in generating the likely range of global warming by 2100, as presented in the IPCC AR4 Working Group 1 Summary for Policymakers.

We examine the SRES scenarios A1FI, A1B and B2. A1FI is a scenario of intensive fossil fuel use, giving the highest emissions of all the major SRES scenarios, B2 is a relatively low emissions scenario, but not the lowest of SRES and still features ongoing increases in emissions. A1B is similar to A1FI initially, but becomes similar to B2 at the end of the 21st Century. We also examined the CCC 2016:4% scenario, which gives lower emissions than all SRES scenarios after 2016.

For each scenario, we performed an ensemble of 729 simulations with MAGICC, exploring the range of uncertainties in both climate sensitivity and climate-carbon cycle feedback strength. Here we discard both the upper and lower extreme 10% of simulations in order to avoid less plausible outliers. We present our results for the dates at which 2°C and 4°C of global warming are reached (relative to pre-industrial), for both the 10th and 90th percentiles as described above, and the median. The 10th percentile shows the date by which 10% of the simulations have reached the particular temperature threshold. These results are shown in tables A1 and A2.

It should be noted that we do not attach the term "likely" to this range of projections, as this term has previously been used by IPCC to represent outcomes with a 66% or higher chance of occurring. We regard the range of 10th to 90th percentiles as a plausible range of outcomes.

For each scenario, the threshold of 2°C and 4°C were passed on a range of dates, reflecting the uncertainties in climate sensitivity and climate-carbon cycle feedbacks. The ranges of dates for reaching 2°C are similar in all 3 SRES scenarios and the 10th percentile for CCC 2016:4% is also similar to that of the SRES scenarios. This reflects the fact that the climate system is relatively slow to respond to emissions, so differences in emissions scenarios are not reflected in differences in the rate of climate change for some years – and this includes the effect of emissions cuts if feedbacks are strong.

However, it is important to note that the median date of passing 2°C in CCC 2016:4% is 2079, nearly 40 years after the median date for all SRES scenarios studied. This suggests that if feedbacks and climate sensitivity are not as strong as some models suggest, cutting emissions could still significantly delay the time at which 2°C is reached. The 90th percentile for the *CCC 2016:4%* scenario does not reach 2°C by the end of the simulation in 2200.

This implies that considerable further climate change has therefore already been committed to at the present day, and if feedbacks are strong then we may still reach 2°C even with 4% per year emissions cuts after 2016, but if feedbacks are weak then 2°C may be avoidable with this level of emissions cuts.

The range of dates for passing 4°C varied more between the SRES scenarios, with the B2 scenario only reaching 4°C in the 10th percentile of the ensemble. Moreover, the 2016:4% scenario never reached 4°C even in at the 10th percentile. This shows that differences in emissions scenarios, especially emissions cuts, can determine if and when 4°C is reached. The median projections for A1B and A1FI reached 4°C at 2100 and 2070 respectively, and the 10th percentile projections reached 4°C at 2070 in A1B and 2060 in A1FI.

Work by Parry et al. 2009 also shows that the timing of reductions is important for adaptation. For example, if we would wish to adapt to 90% of the risk implied by delaying mitigation until 2035, we should be planning to adapt to at least 4°C of warming. This paper also highlights the long recovery process of many environmental systems – with sea levels likely to continue to rise for some decades after the land has begun to cool. It may thereafter take centuries for a stable climate to be achieved.

Scenario	2 ºC		
	10%	median	90%
SRES B2	2035	2048	2065
SRES A1B	2035	2042	2055
SRES A1FI	2035	2042	2048
CCC 2016:4%	2037	2079	N/A

Table A1. Summary of years in which global temperatures reach 2 ºC above preindustrial values, for the 10th and 90th percentiles and median of a 729-member ensemble for each scenario. The SRES simulations were run to 2100, and the CCC 2016:4% simulation was run to the year 2200. N/A indicates that 2 ºC warming was not reached by the end of the simulation.

SRES Scenario	4 ºC		
	10%	50%	90%
B2	2082	N/A	N/A
A1B	2070	2100	N/A
A1FI	2060	2070	2087
CCC 2016:4%	N/A	N/A	N/A

Table A2. Summary of years in which global temperatures reach 2 ºC above preindustrial values, for the 10th and 90th percentiles and median of a 729-member ensemble for each scenario. The SRES simulations were run to 2100, and the CCC 2016:4% simulation was run to the year 2200. N/A indicates that 2 ºC warming was not reached by the end of the simulation.

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A3.2 Q2. What are the major changes and updates on sea-level rise research since the IPCC 4th assessment report was released?

The tide-gauge record of sea level for the 20th century show that global average sea levels rose at an average rate of approximately 1.7 mm yr^{-1}. Altimetry data from satellites have been available since the early 1990s, which show that global sea levels have risen at about 3 mm yr^{-1} over this period. This value is supported by coastal tide gauge measurements, although it is not certain whether this represents the start of a long-term acceleration or natural variability. Sea level rise around the world is not uniform, owing to the differences in ocean circulation and non-uniform changes in temperature and salinity. These regional variations in sea level rise can be substantial with, for example, one study (Yin et al. (2009)) finding that mean sea level for New York City could increase by around 20cm more than the global mean. From the perspective of impacts it is important to also include the rise and subsidence of the land. During the period 1993-2003, for which more accurate data are available, thermal expansion of the surface of the oceans and melting of land ice each accounted for about half of the observed rise in sea levels, although there is some uncertainty in the estimates.

Global sea level rise is projected to continue during the 21st century and this is very likely to be at a greater rate than observed during the 20th century. The AR4 gives a range of 0.18 m to 0.59 m for increases between 1990 and 2095, depending on the choice of SRES emission scenario used. Thermal expansion will contribute the majority of this rise, with the rest from melting of glaciers and ice caps on land, and a small contribution from the ice sheets of Antarctica and Greenland. A major source of uncertainty originates from the contribution of the ice sheets of Greenland and Antarctica. For example, increased precipitation over Antarctica and Greenland would act to increase the ice mass, whereas acceleration of glacier flow or melting would decrease the land ice mass. Most importantly, the AR4 Synthesis Report concluded that an upper bound for sea level rise during the 21st century could not be established.

Since AR4, statistical techniques have also been used to estimate future sea level rise (e.g., Rahmstorf (2007) and Grinsted et al. (2009)). Briefly, functions relating past temperature changes and past sea level rise in the late 19th and 20th century are constructed, and then combined with projections of temperature change to estimate future sea level rise. However, this approach implicitly assumes that the balance of processes (thermal expansion, melting of ice and glacier flow rates) during the 20th century will remain the same during the 21st century. The relative contributions of ice sheets and thermal expansion in the future are highly uncertain. Hence, these statistical methods are of limited use for projecting future sea level rise.

Since the publication of the AR4 reports, new satellite data have become available which show that glacier flow rates have increased in some areas (e.g. in parts of Antarctica). Gravity measurements have been used to estimate the loss of ice from Greenland between 1995 and 2007, which in turn has contributed to a sea level rise between 0.5 and 0.9 mm yr^{-1} (Mernild, 2009). However, other evidence has been presented showing a slowdown in the flow rates of a number of glaciers in Greenland (Kerr, 2009). It is unclear whether the recent changes in ice sheets are a short-term change, or a systematic acceleration. Hence, it is uncertain whether the recent acceleration in glacier outflow and sea level rise will continue throughout the 21st century. Other historical data and process models have also been used to study ice sheet dynamics and place an upper limit on future sea level rise. The most pessimistic view is taken by Hansen (2007) who expects sea level rise to be of “the order of metres” by 2100, because strong feedbacks and non-linearities, such as the melting of ice shelves where glaciers meet the oceans, are not currently included in models. However, counter to this argument, a recent study of glaciers in Greenland by Pfeffer et al. (2008) examined the fluxes and discharges of ice that would be necessary to produce prescribed sea level rises. These authors assumed that the velocity of glaciers could not exceed the upper limit of current observations. They suggest a likely rise in sea levels of 0.8 m by 2100, and an upper limit of 2 m. Another study of glacier flow by Nick et al. (2009) examined a single glacier in Greenland. Their study concluded that an acceleration of the glacier’s flow rate could be followed by a reduced flow rate, so that extrapolating recently observed flow rates may not produce reliable sea level rise estimates. Furthermore, Rohling et al. (2008) have examined changes in sea levels around 100,000 years ago during the last interglacial period. Ice masses and the size and shapes of the ice sheets had some similarity to those of today. Rohling et al. estimate the maximum sea level rise during the last interglacial period to be roughly 1.6 m per century.

Katsman et al. (2008) combined observations and model results from the IPCC AR4 and additionally considered the impact of changes in ocean dynamics and the earth’s gravity field resulting from the melting of land-based ice to estimate sea level rise in the north-east Atlantic Ocean. These authors estimated a rise between 0.30 and 0.55 m for a temperature rise of 2 ºC, and a rise between 0.40 and 0.80 m for a temperature rise of 4 ºC for 2100. They also showed that changes in the Antarctic ice mass are more important for sea level rise in the extratropical oceans of the northern hemisphere than the Greenland ice sheet.

The UKCP09 marine science report found that model projections of regional variations in sea level suggest similar changes in UK mean sea level over the 21st century to the global mean. The approach taken to UK sea level rise in this UKCP09 report was to present two projections. The first was based on the current generation of climate models and predicted 12-76cm of UK coastal absolute sea level rise (not including land movement) for 2095, based on the 5th percentile low emissions scenario to the 95th percentile high emission scenario. The second, so called High++ scenario, used evidence such as that mentioned above, to estimate the amount of sea level rise that can not yet be completely ruled out. However, based on current understanding this rise of 93cm to 1.9m should be considered unlikely to occur during the 21st century.

In addition to trends in regional and global sea level under the influence of global warming, local sea level can undergo short lived increases driven by atmospheric pressure gradients and winds. Such surge events can substantially increase sea level above the normal tidal range if they occur near a high tide. For the UK, an example is the extreme storm surge that occurred during the winter of 1953 and caused considerable loss of life and damage to property. For recent decades, trends in high water levels around the UK have been linked to increases in the underlying regional mean sea level rather than any increases in wind and pressure gradient driven contributions.

The UKCP09 marine science report considered potential storm surge increases in local high water for the 21st century, using an ensemble of model projections. They found that the size of surge expected to occur on average about once in 50yr is expected to increase by less than 0.9 mm/yr (additional to projected changes in mean sea level and any local effects from subsidence or uplift of land). The largest surge trends around the UK were projected to be in the Bristol Channel and Severn Estuary. The UKCP09 analysis also provided a high-end "High++" range of surge increases which, as for the mean sea level changes for this scenario, are thought to be improbable but cannot be completely ruled out. These high-end projections were obtained using the largest estimated increase in UK storminess as given by current generation climate models (developed by different international groups). High++ surge contributions to sea level increase over the 21st century of up to 0.95m were given for the Thames Estuary.

Thus, the recent work summarised above suggests that for the UK and western Europe sea level rise by 2100 will not exceed 2 m, and is likely to be much smaller. However, the dynamics of ice sheets, and the possible effects of freshwater from ice melt on ocean circulation are still not fully understood. The additional effects of increased storm surges around the UK are likely to be small relative to the mean sea level changes, although increases of up to 0.95m in the Thames Estuary cannot be ruled out. Finally, sea level rise will continue for many centuries beyond 2100, even if greenhouse gas concentration are stabilised, because of the ongoing uptake of heat by the oceans. This implies that adaptation measures will be required even if stringent mitigation targets of limiting warming to 2 deg C are implemented (Nicholls and Lowe, 2004).

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A3.3 Q3. What does the research say about the relationship between tropical cyclones and climate change?

"Tropical cyclone" is the generic term for a low-pressure system over tropical or subtropical waters, with intense convective activity (e.g. thunderstorms) and winds circulating in a cyclonic (anticlockwise) direction in the northern hemisphere (clockwise, in the southern hemisphere). A tropical storm is a tropical cyclone with maximum sustained surface wind speeds of at least 39 miles per hour, and a hurricane is a very intense tropical cyclone with wind speeds of more than 73 miles per hour. Generally these storms can form in environments with (1) warm ocean waters (> 26.5°C), (2) an unstable atmosphere, (3) a moist mid-troposphere, (4) sufficient distance from the equator, (5) near-surface spin and convergence of the air, and (6) low values of vertical wind shear (Shepherd and Knutson, 2007).

The tropical cyclone (hurricane) seasons of 2004 and 2005 in the North Atlantic were particularly active, with 15 and 28 tropical cyclones recorded respectively with a number making landfall, resulting in widespread destruction, including the particularly damaging Hurricane Katrina in August 2005. The relatively unusual nature of these seasons raised questions around whether anthropogenic climate change was influencing the number and/or intensity of tropical cyclones.

A number of studies have been conducted in recent years examining the influence of the warming climate on tropical cyclones around the world (Shepherd and Knutson, 2007). Some of these studies have examined the historical record to determine if any changes in frequency or intensity of tropical cyclones have been observed in recent years. An issue associated with many of these investigations is the quality of the historical dataset being examined (Trenberth et al., 2007; Shepherd and Knutson, 2007). Some researchers maintain that the influence of climate change on tropical cyclones is detectable within the observations, albeit mainly those occurring in the Atlantic basin (e.g. Emanuel 2005; Webster et al. 2005; Hoyos et al., 2006; Mann and Emanuel, 2006; Santer et al., 2006; Trenberth and Shea, 2006; Holland and Webster, 2007; Kossin et al, 2007; Elsner et al., 2008 and Vecchi and Knutson 2008). The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) states "there are indications that the average number of Category 4 and 5 hurricanes per year has increased over the past 30 years" (Meehl et al., 2007). Other climate scientists (e.g. Landsea, 2005; Michaels et al., 2005; Klotzbach, 2006 and Landsea et al., 2006) argue that the historical record is too inhomogeneous in quality to enable meaningful analysis, despite attempts to homogenise the observations.

A likely important additional factor affecting tropical storm and hurricane frequency in the North Atlantic in given periods of decades ahead is the state of the superimposed multidecadal sea surface temperature and vertical wind shear fluctuations associated with the Atlantic Multidecadal Oscillation (AMO) (e.g. Goldenberg et al, 2001, Knight et al, 2006). In future, variations of the AMO could be both natural and anthropogenically forced. (IPCC Fourth Assessment Report, Chapter 10).

In addition to examining the effect of climate change on hurricanes up to the present day, climate models have also been used to project the frequency and intensity of tropical cyclones throughout the 21st century. Within the IPCC AR4, the conclusion reached from a study of coarse-resolution climate models (50 to 100 km grid spacing) alongside finer-scale projections (down to ~9 km grid spacing) was that climate change could lead to future tropical cyclones having increased peak wind intensities and more intense precipitation, particularly towards the centres of the storms (Meehl et al., 2007). However, many of these studies also projected fewer tropical storms occurring globally, and with varying degrees of change to cyclone intensities (Sugi et al., 2002; McDonald et al., 2005; Chauvin et al., 2006; Oouchi et al., 2006; Yoshimura et al., 2006; Bengtsson et al., 2007; Caron and Jones 2008). The results of downscaling data from seven global climate models (Emanuel et al., 2008) also indicate a reduction in global frequency and increased intensities in some basins. Hence the IPCC's AR4 stated "A synthesis of the model results to date indicates that, for a future warmer climate, coarse-resolution models show few consistent changes in tropical cyclones, with results dependent on the model, although those models do show a consistent increase in precipitation intensity in future storms. Higher resolution models that more credibly simulate tropical cyclones project some consistent increase in peak wind intensities, but a more consistent projected increase in mean and peak precipitation intensities in future tropical cyclones. There is also a less certain possibility of a decrease in the number of relatively weak tropical cyclones, increased numbers of intense tropical cyclones and a global decrease in total numbers of tropical cyclones" (Meehl et al., 2007).

Within the North Atlantic basin, the projections of the numbers of future tropical cyclones are highly dependent on the model used. A study by Oouchi et al. (2006) showed rises of up to 34% in the number of storms experienced in the basin, whereas a number of other studies demonstrate either decreases in the frequency of tropical storms in the North Atlantic (e.g. McDonald et al., 2005; Gualdi et al.,2008 and Knutson et al., 2008) or no change in frequency (e.g. Bengtsson et al. 2007; Emanuel et al. 2008). Some studies project increases in the intensity of associated precipitation (e.g. Gualdi et al., 2008; Knutson et al., 2008) or increased wind speed intensity (e.g. Oouchi et al., 2006). The decreases in the numbers of storms projected is believed to be related to increases in the stability of the atmosphere and also increased vertical wind shear – both offsetting the impact of rising local sea surface temperatures in the tropical Atlantic (pers. comm. Kim, J.-H., Met Office Hadley Centre, 2009). Smith et al. (2007) have shown that the probability of hurricanes making landfall is reduced during the warm phase of the ENSO cycle, and the probability of landfall along the east coast area is also reduced during the neutral phase before the La Niña part of the ENSO cycle. Dailey et al. (2009) showed that U.S. hurricane landfall risk is sensitive to the SSTs but that sensitivity varies by region and intensity. They also concluded that hurricane landfalls may react not only to warm-SST conditions, but also to the effect of ocean temperature anomalies on the atmosphere's general circulation.

As is evident from this review, there is still no consensus on the impact of climate change on tropical cyclone frequency and intensity. There is still skepticism within the modelling community about the process of tropical cyclogenesis (formation of the storms) within the low resolution climate models, with the models also demonstrating substantially weaker storms in hindcasts (model runs of past years intended to assess the ability of the climate model to replicate the observations) compared to the historical record. Although the simulation of storms improves in higher resolution climate models (Bengstsson et al. 2007; Vitart et al. 2007) very high resolution models are required to simulate accurately the intensity of tropical storms. However, low resolution climate models do show skill in predicting tropical storm numbers in the Atlantic when they are used for seasonal forecasting (Vitart et al. 2007).

The feedbacks between tropical storms and the ocean form an important part of the mechanisms of changes in tropical storms (e.g. Pasquero and Emanuel, 2008). These feedbacks are missing from atmosphere-only climate models that are frequently used for tropical cyclone studies because they are cheaper to run at high resolution. This adds to the uncertainty of the future predictions.

Further investigations are required to determine the relationships that control tropical cyclone formation, particularly in the North Atlantic, with a more dynamic-based appreciation of the tropical atmosphere being necessary to develop a better understanding of the frequency and intensity of tropical storms throughout the 21st century.

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A3.4 Q4. How might climate influence temperature and precipitation extremes?

The IPCC AR4 reports high confidence for increases in the frequency and intensity of heat extremes in almost all parts of the world. However, regionally the magnitude of such changes is expected to vary considerably as a result of changes in the land surface. Regions with expected extensive soil drying and ice melt, for example are likely to have the greatest warming. Current indications show the largest increases are likely over Southern Europe, parts of North America, the Amazon region of South America and parts of East Asia. Uncertainties, arising from variations in models' handling and prediction of land surface changes are considerable, indicating that very large increases in extreme temperatures cannot be ruled out. Extreme cold events are generally expected to become rarer and less cold.

An analysis of projections of precipitation extremes in the IPCC AR4 showed that such extremes are expected to increase in the future. Although summer rainfall is projected to decrease in many areas, it is expected to be concentrated into more intense events with longer dry periods in between. Precipitation extremes are related to changes in mean precipitation. Wet extremes become more severe in areas where mean rainfall increases but can also become more severe where mean rainfall decreases. Estimating changes in extremes at specific locations is often difficult due to model uncertainty and to natural climate variability. Natural climate variability can make it difficult to quantify or can even obscure any underlying change in extremes and to model uncertainty.

There have been several studies on temperature extremes since the publication of the AR4. A major advance is the establishment of the link between extremes and the ENSO and NAO. Kenyon and Hegerl (2008) have shown that temperature extremes are strongly influenced by both the North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO). Scaife et al (2008) showed that changes in the NAO over the period 1960-1990 are likely to be responsible for much of the observed change in the frequency of heavy winter precipitation, the numbers of frost days, and cold minimum temperatures over Europe and extratropical North Africa. In particular, the changes in extreme winter minimum temperatures caused by the NAO are similar in magnitude to projections of changes in future extremes.

The risk of a hot European summer similar to 2003 has been at least doubled owing to the human influence on climate (Jones et al., 2008) though the current developing warm North Atlantic phase of the Atlantic Multidecadal Oscillation is offsetting this temporarily by moderately favouring cyclonic, less warm north west European summers (Knight et al, 2006, Folland et al, 2009). However a future cold phase, as predicted under anthropogenic warming and through natural variability (Knight et al, 2005) would reinforce the risk of hot summers. European summers of the 2040s are thus likely to be at least as warm as 2003 50% of the time. Washington et al. (2009) have estimated the potential benefits of mitigation of emissions on extreme hot temperatures. These authors showed that if CO_2 levels were stabilised at 450 ppm by 2100 with no overshoots, the intensity of heat waves would be reduced by over 50% compared to a non-mitigation scenario, with the biggest reductions in heat waves seen over much of Europe and Russia, and also Canada and the western USA.

Daily minimum and maximum temperatures have warmed since 1950 in most regions (Brown et al., 2008). The largest increasing trends were found in Europe, Asia and Canada, where daily maximum temperatures have warmed by between 1 and 3 ºC since 1950. This study has demonstrated that extreme temperatures have already changed outside of the range of natural variability (as simulated by the HadCM3 climate model) between 1950 and 2004. With continuing global warming, the magnitude of extreme temperatures is likely to continue to increase, although when future extremes will consistently be outside of the extremes for the current climate is difficult to predict.

Quantifying the impact of climate change on precipitation extremes is much more difficult than for temperature extremes. Kendon et al. (2008) showed that precipitation extremes over Europe are subject to large influences from annual and multi-decadal variability, which makes projections of future precipitation extremes in this area highly uncertain. Kharin et al. (2007) analysed precipitation extremes in the IPCC ensemble of global climate models, and showed that the relative changes in precipitation extremes were larger than relative changes in annual mean precipitation. As an example, for each 1ºC of global warming the intensity of a 1 in 20 year precipitation event would increase by 6%.

Fowler and Ekström (2009) analysed extreme precipitation events over different regions of the UK using projections from 13 different regional climate models for the period 2071-2100 under the SRES A2 scenario. The models were validated against present day extremes beforehand. These authors found that precipitation extremes in winter, spring and autumn increased, with winter extremes increasing by 5-30%, depending on the season and UK region. Short-duration extreme precipitation is projected to increase more than longer-duration extreme precipitation. The models had little skill in simulating present day summer precipitation extremes, and both increases and decreases in future summer extreme rainfall were projected. Model consensus in extreme precipitation change in winter reflects the dominance of a robust mechanism (namely increasing atmospheric moisture with warming). In summer, there are competing processes such that the sign of extreme precipitation change over the UK is uncertain, although an increase in the proportion of summer rainfall falling as extreme events is reliable (Kendon et al.2009).

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A3.5 Q5. How does ”climate variability” relate to climate change?

Adaptation to climate variability is challenging in many parts of the world, which means that any human-induced changes in modes of climate variability could have major impacts around the globe. This summary will focus on two major modes of climate variability, El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO).

IPCC AR4 summary – ENSO

The El Niño Southern-Oscillation (ENSO) refers to a pattern of warming and cooling of the eastern tropical Pacific Ocean which oscillates on a timescale between 2 and 7 years. The warm phase of the ENSO cycle is termed El Niño, and the cool phase La Niña. ENSO is associated with fluctuations of surface pressure in the tropics and subtropics and is a coupled atmosphere-ocean phenomenon. ENSO is the dominant mode of global-scale variability on interannual timescales and has a great impact on the patterns of wind, SST and precipitation in the tropical Pacific. ENSO is closely linked with variations in precipitation and temperature across many other areas of the globe, in particular the monsoon rainfall over India.

There is no consistent signal from the IPCC AR4 climate model projections for future changes in the amplitude or frequency of ENSO. Similarly, some models project greater variability of the ENSO cycle in response to global warming, others reduced variability, and others no change at all. The multi-model mean suggests a weak shift towards the warm phase of the cycle, with sea surface temperatures in the central and eastern tropical Pacific warming more than those in the west, and with an eastward shift in mean precipitation, associated with weaker tropical atmospheric circulations, such as Pacific trade winds.

ENSO is known to exhibit a relationship with the Asian monsoon. Analysis of observational data reveals a correlation between ENSO and tropical circulation, such that there is a tendency for less summer monsoon rainfall in El Niño years and more in La Niña years. However, this relationship appears to have weakened recently, the reason for this being a subject of current scientific debate. Climate model projections suggest that a future warmer climate could result in the weakening of the ENSO-monsoon relationship.

Recent (post-AR4) advances in understanding of ENSO

A review of climate modelling with respect to El Niño (Guilyardi et al., 2009) noted the recent improvement in the representation of the present-day ENSO cycle in climate models. Despite this improvement, there is no consistency in the response of the ENSO cycle to climate change. Guilyardi et al. (2009) suggested a number of ways that model deficiencies could be identified and improvements made, including using paleoclimate simulations to test models.

Turner et al. (2007a,b) carried out an investigation into the effect of model biases on the ENSO cycle and the Asian monsoon. They found that including flux adjustments (an extra flux of heat into the ocean to compensate for model errors) in the climate model magnified the response to climate change, suggesting that the true impact of greenhouse gas forcing may be masked by systematic model biases. It was suggested that the presence of interdecadal changes in the monsoon-ENSO system in flux-adjusted simulations made for greater uncertainty in projections of future climate.

Vecchi et al. (2008) found that different types of models projected different responses of ENSO to a warming climate. They compared the response of ENSO to climate change of three different types of climate model; a full atmospheric model coupled to a slab-ocean model (i.e. a simplified ocean), a fully-coupled climate model (with full representations of both oceanic and atmospheric processes), and another model with simplified atmospheric processes but a full representation of the ocean. The first two types of model projected future conditions that were more like the warm phase of the ENSO cycle, although the change was smaller in the fully-coupled simulations. In contrast, the climate model with a simplified atmospheric component projected conditions more like the cold phase (La Niña) of the ENSO cycle in response to global warming. Vecchi et al. (2008) also highlighted problems with observational data. Two data sets of sea surface temperatures were shown to have different historical trends in the tropical east Pacific which made model validation of these trends very difficult.

The Met Office with other research organisations has developed a higher resolution version of the HadGEM1 global climate model (HiGEM; Shaffrey et al., 2009). The HiGEM model produced a much more realistic ENSO cycle than the lower resolution HadGEM1 model, owing to its ability to simulate small-scale ocean-atmosphere interactions. HiGEM also produced more realistic precipitation patterns and teleconnections associated with ENSO.

Seasonal forecasting of the ENSO cycle by individual models has good skill up to several months ahead. Multi-model mean predictions from ensembles of models have greater skill than individual models (e.g. Palmer et al., 2004).

IPCC AR4 summary – NAO

The North Atlantic Oscillation (NAO) refers to variations in the pressure difference between regions near Iceland and regions near the Azores. This pressure difference in winter determines the strength of westerly winds across the Atlantic into Europe. For northern Europe a positive phase of the NAO means stronger westerly winds, mild winters and frequent rain, whereas the negative phase, when westerly winds are suppressed, results in more blocking, lower temperatures, more frosts and drier conditions. For southern Europe, the Mediterranean and parts of North Africa, these signals are reversed.

The pattern and year to year variations in the NAO are well reproduced by climate models. However, the observed trend towards positive values in the NAO over late decades in the 20th Century is not usually reproduced, even if the simulations are performed with observed 20th-century ocean and climate forcings. The only exception to date involves the Met Office HadAM3 model. Here, if the observed lower stratospheric winds are also provided to the simulations, the full observed trend in the NAO is modelled (Scaife et al, 2005). In the AR4 climate projections, there is a weak shift of the NAO towards positive values in response to global warming, associated with a poleward shift in atmospheric jet streams. A similar but stronger signal has been seen in the recent climate record, though this observed signal is less evident in the last decade. However, there are a few emerging studies which contradict this finding for the Atlantic, some of which again implicate the stratosphere.

Recent (post-AR4) advances in understanding of the NAO

A study by Huebener et al (2007) used one fully-coupled climate model with ocean, tropospheric and stratospheric components. This model projected a southward shift in Atlantic atmospheric jet and the northern hemisphere winter storm track. This study highlights the importance of proper representation of the stratosphere in climate change simulations, in particular for the variability of the NAO which is known to be influenced by the strength of circulation in the stratosphere.

To date, most research into the NAO has considered its behaviour in winter. Folland et al. (2009) provided a definitive analysis of a pattern which these authors call the summer NAO. This pattern is able to explain the principal variations of summer climate over northern Europe (mean temperatures, precipitation, and cloudiness). This phenomenon plays a leading role in the recent wet UK summers.

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A3.6 Q6. What do studies on climate change impacts indicate when there is limited scientific consensus or understanding?

We describe parts of the Earth system where there is limited evidence, understanding, or scientific consensus on key processes and future behaviour. Some of these elements have the potential to invalidate or significantly change projections of global climate change, should we learn unexpected things about them.

Abrupt or rapid climate change

There is considerable paleoclimate evidence that large, rapid and widespread changes in climate occurred in the past (Rahmstorf 2002, Alley *et al*., 2003). Many climate models allow the possibility of such change in the future (e.g. IPCC 2007 box 10.1), although many of the driving processes of abrupt change are highly uncertain. An expert review of potential policy relevant "tipping points" and abrupt changes in the Earth system (Lenton *et al*. 2008), and companion study (Kriegler *et al*., 2009) identify and rank the threats of such changes given global warming. They identify feedbacks due to Arctic sea ice melt; the collapse of the meridional overturning circulation (MOC) in the North Atlantic related to the Atlantic Multidecadal Oscillation; melting of the Greenland Ice Sheet (GIS); disintegration of the West Antarctic Ice Sheet (WAIS); dieback of the Amazon Rainforest; and persistent change in the El Nino regime, as having a large potential impact, combined with significant uncertainties. We briefly detail these below. The study also identifies a number of potential "tipping elements", such as the venting of marine methane hydrates or the onset of ocean anoxia, where the timescales of change were too large (>1000 years) to consider as "abrupt". Finally, the study considers tipping elements that might have an impact on smaller spatial scales, such as changes in the Indian summer monsoon, or the Sahel and West African monsoon.

Arctic sea ice

The summer loss of Arctic sea ice is a "tipping element" that is less uncertain. Melting sea ice exposes a darker ocean, which leads to increased local warming through absorption of radiation. There is a greater consensus that a threshold in the system leading to ice-free summers will be passed this century (Lenton *et al*., 2008), with half of the IPCC AR4 model simulations becoming ice free in September during this century (Holland *et al*., 2006). There is a greater uncertainty about the prospect of year-round ice loss.

The meridional overturning circulation (MOC)

The MOC in the North Atlantic transports large amounts of heat northwards across the equator, warming Northern Europe and the Eastern seaboard of the USA. Coupled atmosphere-ocean models were used to simulate the impacts of climate change on the MOC (see IPCC 2007 Ch.10), projecting a weakening of the MOC during the 21st century of up to 50%, but none simulate a sudden or complete shutdown. Weakening occurs at the same rate as global warming, and is sensitive to warming of the surface ocean waters, and freshwater input to the North Atlantic from precipitation cycle changes and Greenland ice sheet melt water. The IPCC regards the shutdown of the MOC as *very unlikely* (<10% probability). Current understanding of the relevant ocean and atmospheric processes is incomplete, and the possibility of a rapid reduction or shutdown of the MOC cannot be entirely ruled out. Vellinga and Wood (2008) used a climate model to simulate the impact of a complete shutdown of the MOC. Northern hemisphere temperatures were -1.7 C cooler, but global warming limited the recovery of Arctic sea ice. Sea levels on the Atlantic coasts were projected to be up to 25 cm higher.

Ice sheets

The West Antarctic ice sheet (WAIS) and Greenland ice sheet both have the potential to raise sea level by several metres. The WAIS is grounded below sea level, and therefore vulnerable to disintegration if ocean water undercuts the ice sheet and separates the ice from bedrock (Oppenheimer & Alley 2004). Recent observations have shown that both ice sheets are losing mass (IPCC 2007, Velicogna & Wahr, 2006), with ice sheet models unable to explain the speed of recent changes. However, there are large uncertainties in the interpretation of observations and models, and Lenton *et al*. (2008) give a 300 year timescale as a lower limit for significant changes in either ice sheet.

The Amazon rainforest

The Amazon rainforest is sensitive to changes in temperature and patterns of rainfall; a ”dieback” of the Amazon could lead to strong feedbacks on global temperature, as large amounts of carbon stored in the forest would be released to the atmosphere (Phillips *et al*., 2009). Some projections of future climate show dieback of the Amazon (Cox *et al*., 2000) where as others do not (White *et al*., 1999). A large source of uncertainty in the future of the Amazon is the amount of deforestation, human induced land-use change, and changes in fire frequency in the region (Golding & Betts 2008). These elements could interact strongly with potential changes in regional temperature and precipitation caused by changes in the El Nino Southern Oscillation (ENSO). Some AOGCMs project a greater frequency of El-Nino like conditions in the future, increasing the probability of Amazon dieback. However other models project reductions in ENSO frequency. The most realistic models project no clear change in frequency, but an increase in amplitude (Guilyardi 2006).

Tropospheric Ozone

Tropospheric ozone (O3) is known to be toxic to vegetation (Ashmore, 2005), and reducing plant productivity. Surface ozone levels are greater than 40 parts per billion over many regions of the globe. These levels of ozone may cause visible leaf injury and damage to plants, with a reduction in crop yields and economic costs of several billion dollars per annum in the US, Europe and East Asia (Wang & Mauzerall, 2004). Reduced plant productivity means that less CO2 is absorbed by plants and more remains in the atmosphere, increasing global warming. Sitch *et al*. (2007) estimated that the effective radiative forcing of tropospheric ozone would be doubled due to the extra CO_2 in the atmosphere. If emissions of ozone precursors continue to rise, further economic losses from ozone damage to vegetation could occur, together with an increased rate of global warming.

Volcanic eruptions

Collins (2004) used an ensemble of 20 hindcasts to assess the skill of the Hadley Centre's climate model HadCM3 in reproducing the observed impacts of the eruptions of El Chichòn (1982) and Mt Pinatubo (1991). Cooler summers were predicted in the northern hemisphere after each eruption, but the following winters were milder. Although the climate impact of each eruption could be seen in the results, it was obscured by natural climate variability in some regions. There was no clear impact on either the NAO or ENSO cycles. Although the NAO index was larger in the ensemble mean hindcast after each eruption, it was still well within the normal range of values. The eruptions did not modify the ENSO cycle, but there is the possibility that they could dampen or amplify an existing El Niño or La Niña. The author noted that the ensemble hindcasts could be improved by careful initialisation of the models with observed atmospheric and oceanic conditions.

Sea temperatures and ecosystem change

Rosenzweig et al. (2008) combined observations of changes in land ecosystems and surface temperature data, and performed a statistical analysis of the patterns of change at continental scales. They showed that changes in natural systems since at least 1970 occurred in regions of observed temperature increases, and that these temperature increases at continental scales could not be explained by natural climatic variations alone. The strongest agreements between the temperature changes and the observed system responses are in Asia and North America. The agreement is less strong for Europe owing to the smaller area with observed system responses and large natural climate variability in this region. For the other continents, the data coverage was too sparse for any confidence to be placed in the results.

Ocean Acidification

Progress has been made in understanding the impacts of increasing carbon dioxide levels on marine ecosystems. The oceans absorb about 30% of the CO_2 emitted from fossil fuel use and land use change, where it forms carbonic acid and increases the acidity of the oceans. This problem is caused directly by emissions of CO_2, as opposed to climate change in general. A decline in shell weights of several marine species has already been observed (Moy et al. 2009; De'ath et al., 2009). One recent modelling study concluded that "all coral reefs will cease to grow and start to dissolve" (Silverman et al. 2009), should atmospheric CO_2 levels reach 560 ppm. In addition, the food chains of many fisheries depend on corals and other shell-forming organisms; ocean acidification is thus a direct threat to fisheries, with many other wide-reaching impacts on biodiversity. Research work on the impacts of ocean acidification on marine ecosystems is still in its infancy, and how these impacts may propagate through to fisheries is still largely unknown.

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A3.7 Q7. How robust and dependable are climate data, globally and for the UK and China?

Observations of the weather and the earth system are the bedrock of climate science and also at the heart of the assessment of insurance risk. They are used to understand historical risks, develop both statistical and physical models and verify if events happened and if forecasts were accurate. As the need for resilience to weather and climate risk becomes increasingly important, so there is an increasing need for observations at ever higher levels of completeness and granularity – both in time and space. The longest available instrumental record of temperature in the world is the Central England Temperature (Parker et al, 1992) which is representative of a triangular area of the United Kingdom, enclosed by Bristol, Lancashire and London and started in 1659. Other “proxy” data go back further, being based on a relationship between some long term record, e.g. tree rings or oxygen isotope ratios in air bubbles trapped in ice, and climate variables.

Observations have errors associated with the actual observation accuracy which is rooted in the method of observation, and also what the observation represents, be it a very local phenomenon or a large region – a representivity error. An example of these would be a radiosonde balloon that has very detailed vertical resolution as it floats through the atmosphere, but very low horizontal spatial resolution being a single value, compared to a satellite sounding that sees the entire depth of the atmosphere as one observation but has very high horizontal granularity.

Raw observations are not easily utilised as the measurement methods tend to change and often need expert cleaning, calibration and quality control. They are often formed into gridded analyses, using various methods to fill in data voids. Examples of these include the multi-decadal global re-analysis projects of NCEP (Kalnay et al, 1996) and ECMWF (Uppala et al, 2005), which provide consistent global coverage of most meteorological variables using every available source of observation from surface sites to satellite. These analyses do have their own associated biases and errors (especially representivity), and use a physical weather forecasting model to do the data assimilation and interpolation (i.e. relating temperature to atmospheric pressure and therefore wind speeds). For climate timescales, the ACRE project (http://www.met-acre.org/) aims to reconstruct daily weather analysis as far back as 250 years ago, which will be of particular relevance to the insurance industry.

Climate change detection has also driven a different type of observational gridded analysis that has focused on reducing observation errors and detecting small changes in the climate system over long periods of time (e.g. for sea surface temperature see Rayner et al, 2006).

Availability of raw and processed weather and climate data is dependent on country of origin. Many data are available freely for academic research, whereas the commercial exploitation policy is country dependent. Some countries seek commercial revenue to recover the costs of expensive observing programmes, whilst others see data availability in itself as a stimulus to the wider market.

Examples of Global Data

A very high resolution climate dataset has been produced by Hijmans et al. (2005). These authors interpolated average monthly climate data for the period 1950 – 2000 from weather stations all over the globe onto a 30 arc-second resolution grid (referred to as "1 km^2" resolution). Variables included are monthly total precipitation, and monthly mean, minimum and maximum temperature. The data are available for global land areas except Antarctica.

Examples of UK data

UK Climate Projections 2009 (UKCP09) provides a climate analysis tool which features the most comprehensive set of probabilistic climate projections yet produced. As part of this project, gridded climate data at a resolution of 5 km have been made available from the Met Office web site, and are freely available for commercial exploitation within certain bounds. The gridded datasets are derived from observations for the period 1961 – 2006 from climatological and meteorological stations that comprise the extensive UK observational network. Regression and interpolation techniques have been used to generate the gridded values from the irregular station network, taking into account factors such as latitude and longitude, altitude and terrain shape, coastal influence and urban land use. The methods used to generate the monthly and annual grids are described in more detail by Perry and Hollis (2005).

Examples of Chinese data

A paper by Hong et al. (2005) describes the creation of a gridded climate database for China which has a resolution of 0.01º in both latitude and longitude. Observations of minimum and maximum temperatures and precipitation from weather stations for the period 1971-2000 were used.

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A3.8 Q8. What future changes and improvements can be expected in global & regional climate modelling?

Understanding of the greenhouse effect started as early as 1827, with a paper by the French mathematician and physicist Joseph Fourier. Faraday's successor at the Royal Institution, John Tyndall, also explored the topic in the 1860's and Arrhenius' paper from 1896 states 4 - 5.7 ºC of warming globally can be expected for a doubling of CO2-concentrations in the atmosphere, an estimate of similar order of magnitude to the IPCC AR4 climate sensitivity of a *likely* range of 2 - 4.5 ºC. As such, the overall message that changes in the composition of the atmosphere impact the climate have been remarkably consistent for over 100 years.

However, the details of what the global and regional impacts will be and when they will happen is still a developing science – not least because future emissions are uncertain. In making information available to those wishing to study impacts or make policy, scientists are now beginning to encompass methods to quantify the inherent uncertainty within projections. One method of doing this is to use data from a range of models, either variants of a single model (e.g. Murphy et al, 2004) or from different models (e.g. the CMIP3 database, Meehl et al, 2007) and provide a probabilistic prediction. An example that combines both of these approaches is the recently launched UK Climate Projections (UKCP09 – see Murphy et al 2009). The assumption here is that by adjusting the representation of processes within a model or by using models with different representations, the likely uncertainties are covered and one can give predictions that encompass the truth. In this case, future improvements to models would not invalidate current results but could significantly change the shape of the probability distribution functions, and therefore user-relevant decisions made from them.

There is also a likelihood that limitations in the resolution and/or the poor (or missing) representation of processes in ***all*** current models fundamentally constrains the projections away from the "truth". This would mean that as resolution and our understanding and ability to simulate key processes improve, future projections will invalidate some of the results of current models. This is addressed in **Question 7.**

Scientists focus on identifying those "robust" processes that we expect to be reproduced in future projections. This is done by looking for physical understanding of the mechanisms driving the changes and for reproducibility of results in different models. Unfortunately, changes in extremes such as floods and hurricanes are where the biggest uncertainties lie and projections from current global models are almost certainly limited by relatively low resolution. Downscaling using regional models captures aspects of regional detail such as orographic forcing, but cannot capture the remotely forced influence of processes that are unresolved or poorly represented in the coarse resolution global model.

Can better information be expected?

Advances in climate modelling are governed by three factors, all underpinned by improvements in basic physical science and mathematical techniques, and the limitations of computational resources available: (1) the resolution / granularity of models is important to capture some physical processes such as heat wave / cold winter blocking in the atmosphere (Matsueda 2009) or coupled ocean-atmospheric processes in El Nino (Roberts et al 2009). (2) Improvements in the representation of existing physical processes and/or the addition of currently missing processes in models. Examples include key processes such as clouds, the inclusion of new physical mechanisms by including a well resolved stratosphere in global models (Marshall et al 2009, Ineson et al, 2008), or the inclusion of whole new sub-system interactions (e.g. with the carbon cycle), and (3) The need for multiple experiments or "ensembles" of scenarios in a structured framework to assess errors and certainty as discussed above. Advances are being made incrementally in all three of these areas that will likely lead to improved regional climate projections within the next 5-10 years.

What prospects are there for near term climate model forecasts?

Ideas associated with "seamless prediction" and "climate services" are rapidly evolving as forecast information is becoming available on operational and strategically relevant business decision timescales (months to 20 years). Here weather forecasts and initialised climate forecasts on seasonal and longer timescales are being used to help develop, calibrate and verify longer range climate forecasts (Palmer et al. 2009, Scaife et al 2009). Data assimilation processes that are used in weather forecasts (the "nowcast"), are being used to initialise the deep ocean (Smith et al. 2007), ice and land surface to allow natural variations in the climate to be forecast that are critical on these timescales - including El Nino, monsoons, North Atlantic Oscillation, and the Atlantic Multi-decadal Oscillation to name but a few. These will complement and develop the wide range of statistical and analogue forecasts based on historical statistics already available.

An approach to this is the use of a single physical modelling framework for making forecasts from 1 day to multi century projections (e.g. the Unified Model as currently used at the Met Office following Cullen et al, 1990). This enables knowledge gained from 1.5km weather models (used in 5 day forecasts) on the importance of high resolution physical and dynamical processes to be used to improve seasonal and decadal forecasts and climate projections. An important aspect of this is that where forecasts are verifiable (see e.g. Vitart et al 2007, Smith et al 2007), this can add user-relevant confidence to the value of longer-range climate projections.

As part of these emerging climate forecasts, "decadal forecasts" that forecast inter-annual changes in climate are the newest technological development (e.g. Smith et al. 2007, Keenlyside et al. 2008). These include both natural and anthropogenic climate changes and will offer new possibilities of risk management on the annual contract timescale – both on global and regional scales.

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A4 DOWNSCALING TECHNIQUE

Adapted from "Hurricanes and global warming: Results from downscaling IPCC AR4 simulations", BAMS Volume 89, March, 2008 by Kerry Emanuel, et al.

From their figure 8. we obtain the following changes in intensity Δ(100*ln(A1B/CTR) (%)):

Model	**Delta (%)**
CCSM3	*11.4*
CNRM	*6.5*
CSIRO	*9.9*
ECHAM	*14.6*
GFDL	*2.1*
MIROC	*10.0*
MRI	*21.3*

The definitions of Emanuel's duration (D) and mean intensity (I) are:

$$D \equiv \frac{1}{N}\sum_{i=1}^{N}\frac{\int_0^{\tau_i} V_{\max}^{i}\,dt}{V_{s\max}^{i}}$$

where N is the sample size (frequency), V^i_max is the maximum wind of storm i at any given time, V^i_smax is the lifetime maximum wind of storm i, and tau_i is the lifetime of each storm.

$$I \equiv \frac{\sum_{i=1}^{N}\int_0^{\tau_i} V_{\max}^{3}\,dt}{ND}$$

This is the mean of the cube of the maximum wind speed accumulated over the lifetime of each storm, divided by the duration. We assume that all winds in all tropical cyclones are scaled by a factor k in the future. Rearranging and substituting for D gives:

$$\Delta = 100 \cdot \ln\left({}^{I_{A1B}}\!\big/\!{}_{I_{CTR}} \right)$$

$$\Delta' = {}^{I_{A1B}}\!\big/\!{}_{I_{CTR}}$$

$$\Delta' \cdot I_{CTR} = I_{A1B}$$

$$\Delta' \cdot \frac{\int_0^{\tau_i} V_{\max}^3 dt}{\int_0^{\tau_i} \left({}^{V_{\max}}\!\big/\!{}_{V_{s\max}} \right) dt} = \frac{\int_0^{\tau_i} k^3 V_{\max}^3 dt}{\int_0^{\tau_i} \left({}^{kV_{\max}}\!\big/\!{}_{kV_{s\max}} \right) dt}$$

$$\Delta' \cdot \frac{\int_0^{\tau_i} V_{\max}^3 dt}{\int_0^{\tau_i} \left({}^{V_{\max}}\!\big/\!{}_{V_{s\max}} \right) dt} = k^3 \frac{\int_0^{\tau_i} V_{\max}^3 dt}{\int_0^{\tau_i} \left({}^{V_{\max}}\!\big/\!{}_{V_{s\max}} \right) dt}$$

$$\Delta' = k^3$$

Given this approach of linear scaling of wind, k can be applied to the CDF of damaging winds with limited error. The mean and standard deviation of k from Emanuel's results are 1.037 and 0.02 respectively.

Limitations

1. These results are from only one study although it does use seven different GCMs.
2. The scaling of winds in this way will enhance the damaging winds of severe storms more than those of weaker storms given wind energy increases with the cube of wind speed.
3. All the assessed models show an increase in intensity. By taking the mean and providing a scenario range of the mean plus and minus twice the standard deviation produces a "low end" scenario of intensity reduction.
4. No information is provided in this approach on the changing structure of tropical cyclones with intensity, their lifetime characteristics or their track and landfall statistics.

A5 BASELINE AND CLIMATE CONDITIONED HAZARD DISTRIBUTIONS

The following section provides a brief overview of the baseline and the climate conditioned distributions that were used, and also includes a brief overview of the procedure that was applied to obtain these.

GB Flood

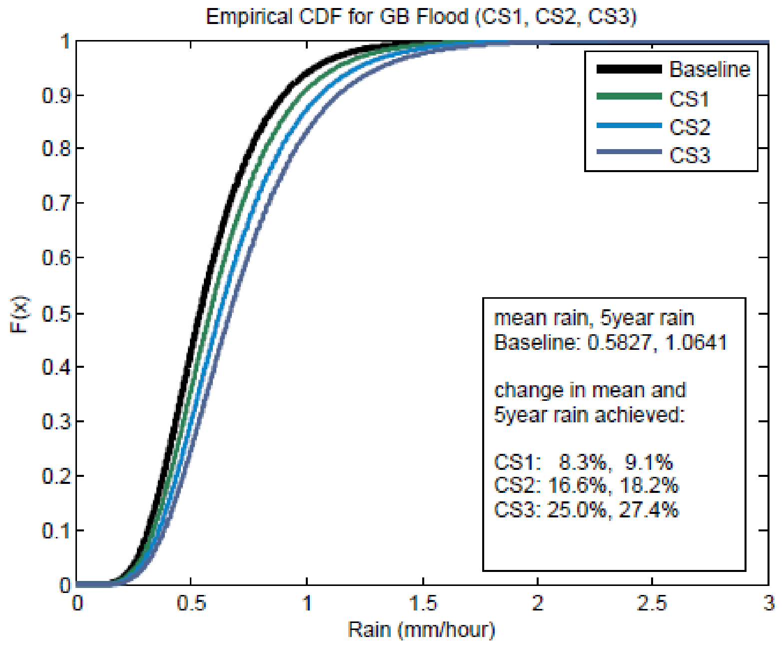


Figure A5.1: Empirical cumulative distribution function for Rainfall of the GB Flood model. Baseline rainfall distribution is shown in black. The climate adjusted distributions for climate scenarios 1 to 3 are shown in green, teal and dark blue respectively. See textbox in figure for mean rainfall and 5-year-rain for baseline and CS1 to CS3.

For this peril, both changes in the mean and the 5 year event intensities were prescribed. In order to accommodate these requirements we fitted the distribution of rainfall to the exponentiated Gumbel distribution (Nadarajah 2006). Using this fit, the target mean and the 5 year event rain were computed, after which a non-linear optimization procedure was applied to iteratively find the new, climate adjusted catalogue accordingly.

Reference

Nadarajah, S.: "The exponentiated Gumbel distribution with climate application." Environmetrics, V(17), 2006: 13–23.

UK Wind

Sampling Algorithm

The sampling algorithm for developing climate adjusted catalogues for UK Wind and China Typhoons is based on a multivariate heuristic "goal-seeking" method. The method achieves the adjustment goals without impacting event frequency, and is based on a series of random "swaps" – randomly removing one event from the original catalogue, and duplicating a different event. The algorithm heuristically performs only those swaps that lead towards the end climatological goal, ignoring swaps that lead away from the target measure(s). When the catalogue is within a small tolerance of the goal, it writes out the re-sampled catalogue, assigning a random year to any duplicated event. In addition to calibrating the tolerance, the user of the algorithm can also specify the number of times they are willing to allow any single event to be duplicated.

For the UK Wind model results, the following distributions were achieved (with an accuracy of 0.2°, i.e. the mean latitude of the climate adjusted catalogue met the target within 0.2° latitude). The red distribution represents the base and the blue distribution is that obtained after the mean latitude in the base has been adjusted.

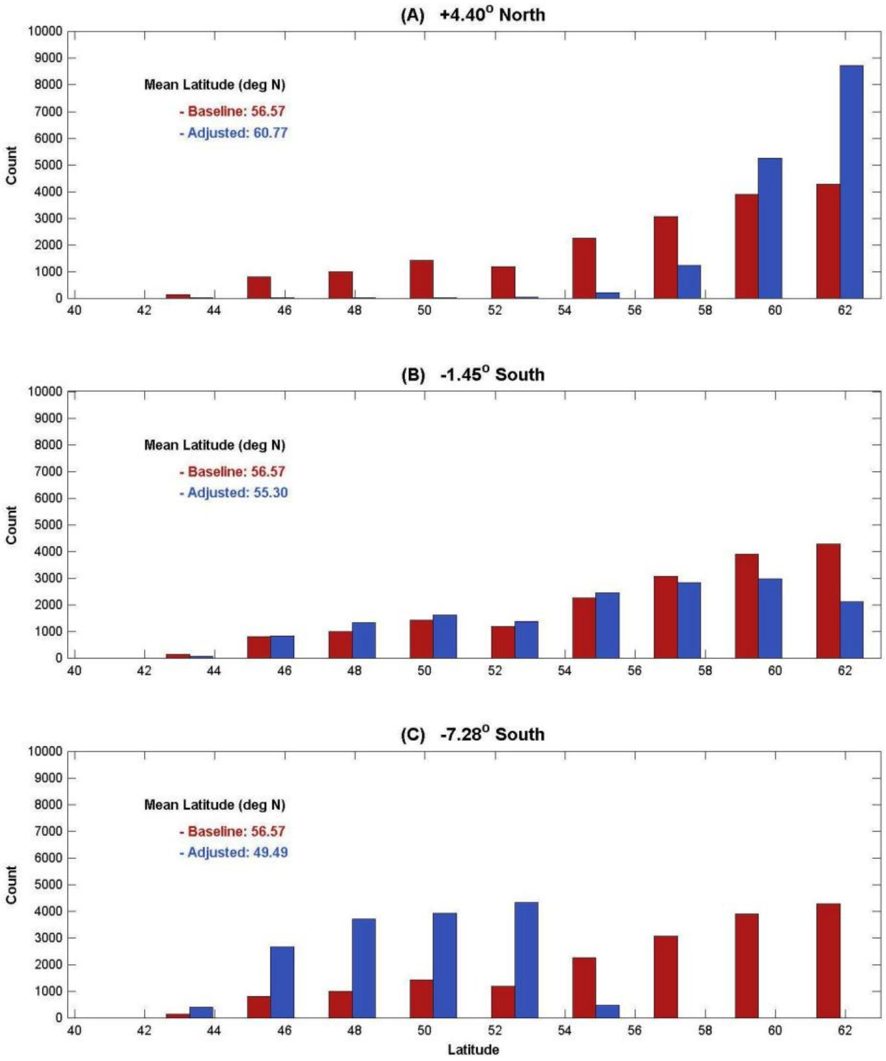
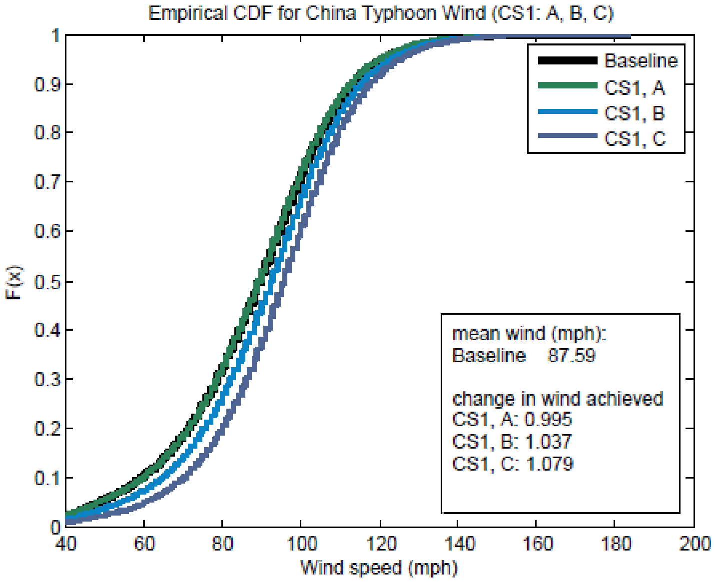


Figure A5.2: Comparison of distribution of mean latitude track for UK Wind for baseline (red) and climate adjusted (blue) catalogues. The histograms shows comparison of baseline and experiment A (top panel), experiment B (middle panel), and experiment C (bottom panel). Also indicated are the mean latitude track of the baseline and the climate scenarios.

China Typhoon

The baseline and required climate adjusted distribution for wind (including the sensitivity of experiments for the wind intensity) are shown in the figure below. The obtained, climate adjusted catalogues all met the required targets of increased wind as indicated in the figure (shown for CS1, CS2 and CS3, top to bottom).



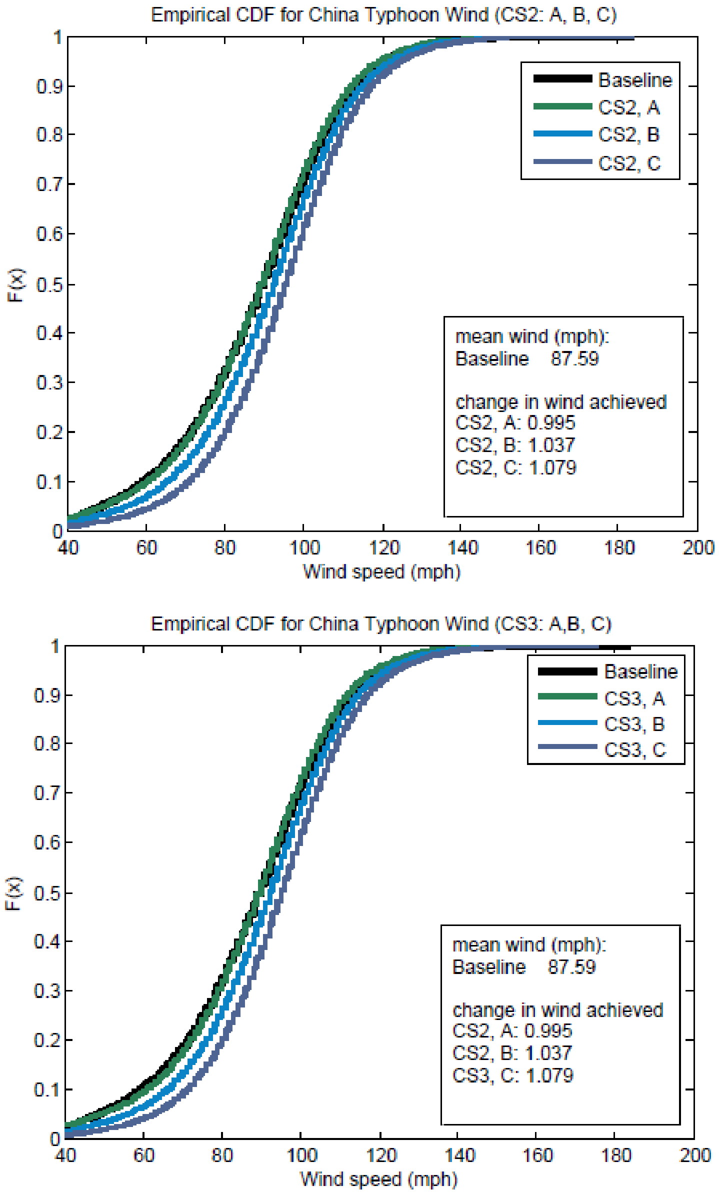
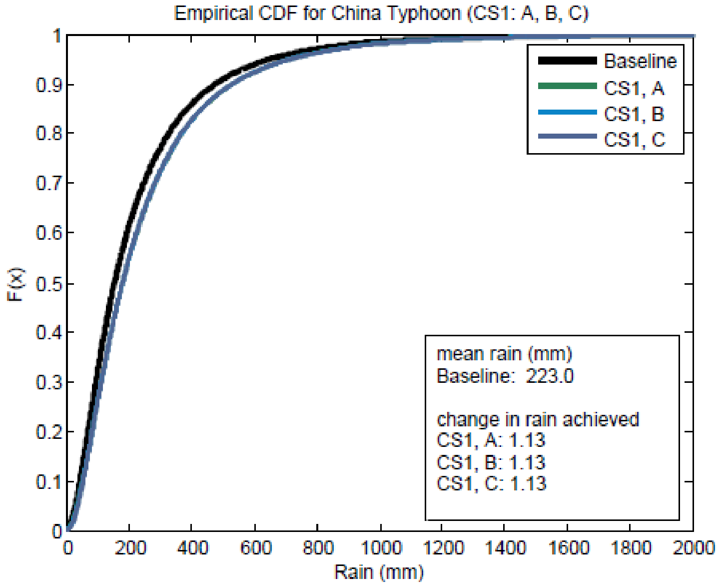
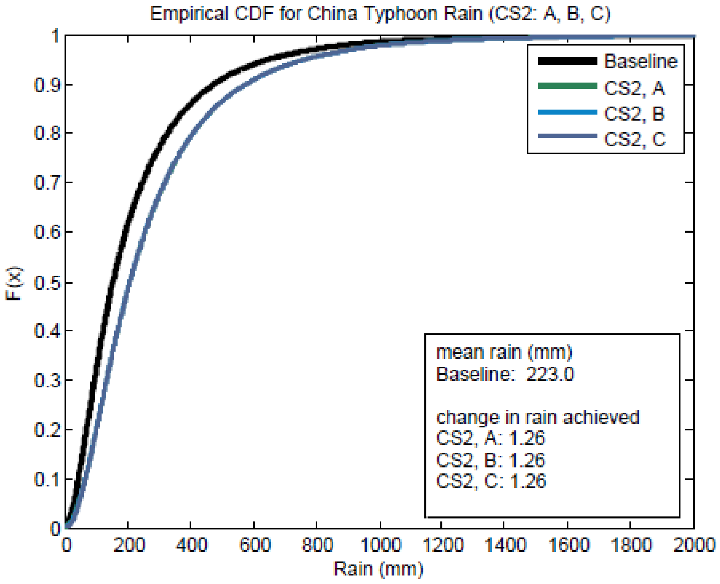


Figure A5.3: Same as figure A5.1, but showing the baseline and climate adjusted distributions for China Typhoon Wind for CS1 (top), CS2 (middle) and CS3 (bottom).

The rainfall distributions for the various climate adjusted experiments also achieved a perfect match with the target increase. Below are the rainfall distributions for CS1, CS2 and CS3 respectively.


Empirical CDF for China Typhoon (CS1: A, B, C)
F(x)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rain (mm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Baseline
CS1, A
CS1, B
CS1, C
mean rain (mm)
Baseline: 223.0
change in rain achieved
CS1, A: 1.13
CS1, B: 1.13
CS1, C: 1.13


Empirical CDF for China Typhoon Rain (CS2: A, B, C)
F(x)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rain (mm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Baseline
CS2, A
CS2, B
CS2, C
mean rain (mm)
Baseline: 223.0
change in rain achieved
CS2, A: 1.26
CS2, B: 1.26
CS2, C: 1.26

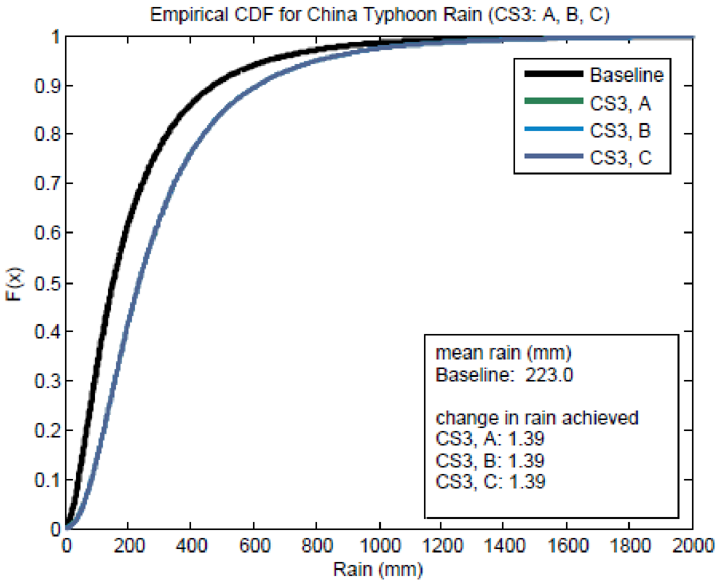


Figure A5.4: Same as figure A5.1, but showing the baseline and climate adjusted distributions for China Typhoon Rain for CS1 (top), CS2 (middle) and CS3 (bottom). See textbox in figure for mean wind and rainfall distributions for baseline and various climate scenarios.

A6 TECHNICAL APROACH TO MODELLING GB FLOOD RISK

Description

The AIR Inland Flood Model for Great Britain captures the effects of precipitation-induced on- and off-floodplain flooding on insured properties in England, Wales and Scotland. It is a fully stochastic, event-based inland (on- and off-floodplain) flood model, which captures all the complexities inherent in a flood generation process. These processes include the space-time patterns of rainfall input, the effect of highly variable climate, topography, soil type and other local factors that determine the amount of rainfall drained to the rivers. The generation of the stochastic, simulated events which populate the catalogue is accomplished by means of a space-time rainfall generator. The output of which is fed into a large-scale stochastic hydrologic model where rainfall is converted to runoff. The hydrologic model propagates the "flood wave" through the river network, and computes the discharge at each location along the river network at each instant in time.

Modelled Perils

On-floodplain inland flooding for river reaches with contributing area larger than 10 km^2 and off-floodplain (hill slope) flooding for locations with contributing area less than 10 km^2.

Rain and Runoff are calculated according to (units are mm/hr):

$$\mathrm{Rain} = \frac{\sum_{i=1}^{n}(\mathrm{Rain}_i * \mathrm{Area}_i)}{\sum_{i=1}^{n} \mathrm{Area}_i}$$

$$\mathrm{Runoff} = \frac{\sum_{i=1}^{n}(\mathrm{Runoff}_i * \mathrm{Area}_i)}{\sum_{i=1}^{n} \mathrm{Area}_i}$$

Model Domain: The model, which is run on a 8 km-by-8 km grid, includes a domain that covers the entire area of England, Wales, Scotland and most of the Scottish Islands where the elevation is above 9 meters. Note that the current release of the model does not include Northern Ireland. Figure A6.1 shows the model domain.

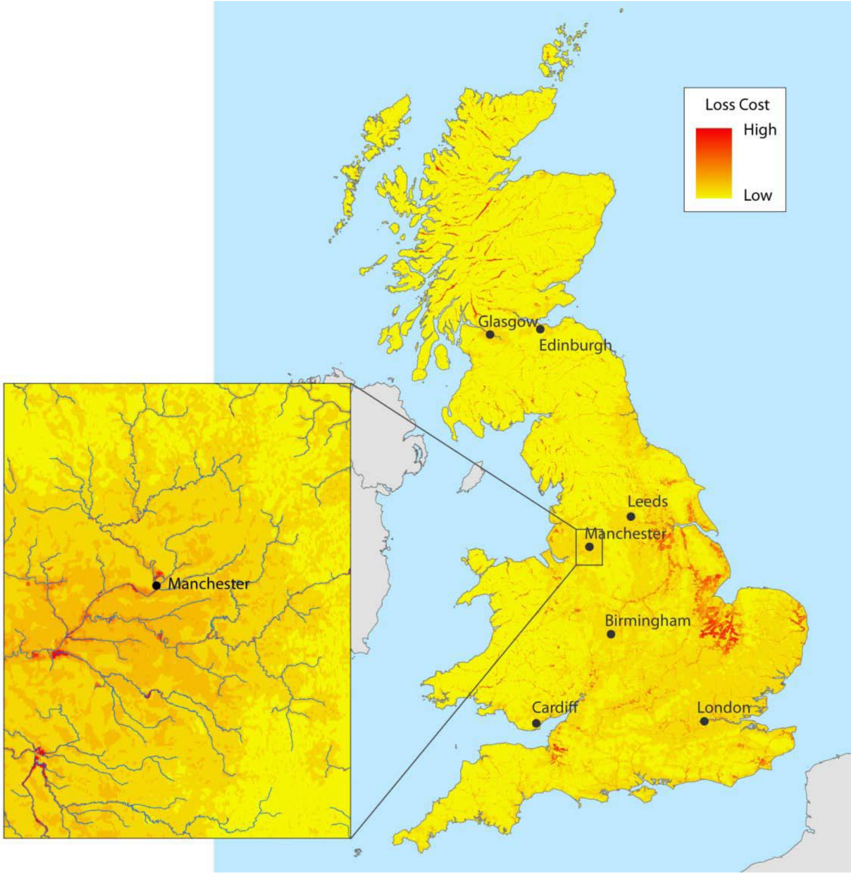
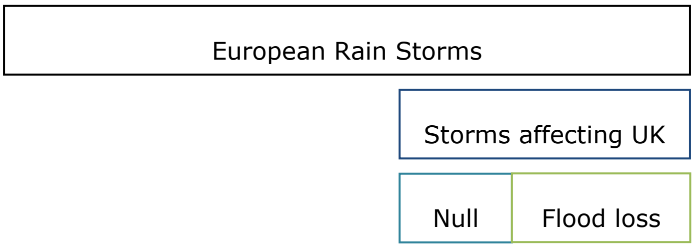


Figure A6.1: Model domain of the GB Flood model showing the combined on- and off-floodplain flood risk in Great Britain with zoom of Manchester

The intensity measure(s) for the flood model are the amount of rain (mm/hr) and runoff (mm/hr) accumulated per unit area due to the individual events and antecedent conditions of the soil (saturated soils lead to faster discharge).

Frequency Information



Overall Frequency:	7-9 historical data (7-9 events per year)
Storms affecting UK (regardless of losses):	8.0 stochastic catalogue
Null events:	2.7
UK Flood loss generating events:	5.3

Note: “Null events” are describing storms for which the rain and runoff were acting such that no flooding occurred over regions considered in this study.

Adapted from
AIR Worldwide Corporation, "AIR Inland Flood Model for Great Britain", 2008, 108 pp. (proprietary)

A7 TECHNICAL APPROACH TO MODELLING EUROPEAN WINDSTORM RISK

Description

The AIR Extratropical Cyclone Model for the European Region captures the effects of extratropical cyclone winds on insured properties in Europe. This event-based model is designed for portfolio risk management. Wind intensity computations are based on a storm's intensity, size, location, forward speed and direction, as well as the underlying terrain and land use in the region. In the local intensity component of the model, the effects of surface friction and the flux of surface heat, moisture, and momentum on wind intensity are considered in order to properly calculate property damage. The model is built to meet the wide spectrum of risk management needs of the insurance industry and accounts for the policy conditions specific to the European region.

Modelled Peril

The model explicitly incorporates the effects of surface friction, land use variation and the flux of surface heat, moisture and momentum in its simulation of each windstorm event.

The criterion used for selection is the occurrence of wind speeds of at least 20 meters per second (m/s) at the 10 meter level as resolved by the reanalysis data set. A wind speed of 20 m/s at 10 m is generally considered as the threshold for minimal property damage. Events that are of sufficient intensity to cause insured property damage comprise the AIR Europe Windstorm Model's final catalogue of over 27,000 loss-producing events. The stochastic data catalogue is based on simulated stochastic events, which in turn were derived from the historical reanalysis dataset (NCAR/NCEP) from 1958 to 2008/2009

Model Domain

The spatial resolution for the European wind model itself uses a domain consisting of two nested grids, as shown in Figure A7.1. The first, outer grid, which is at a 90-km resolution, allows for storms to develop offshore. The second, inner grid is a 30-km resolution. Note that the calculations of local intensity include topographical effects modelled at a 5-km resolution. In the vertical dimension, the model domain consists of multiple layers that extend from the surface to the tropopause (approximately 14 km).

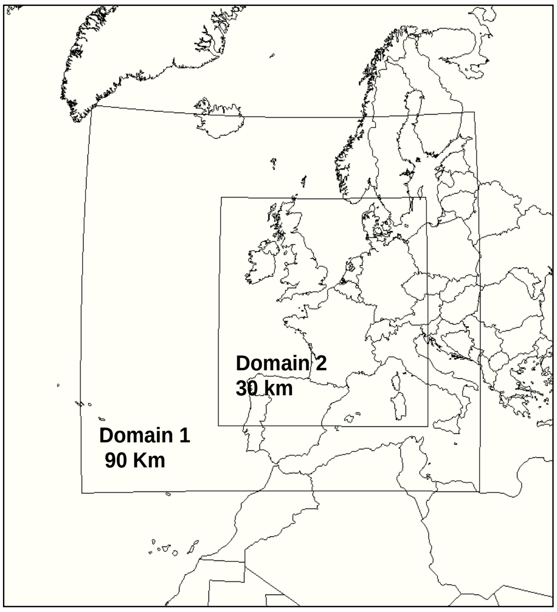
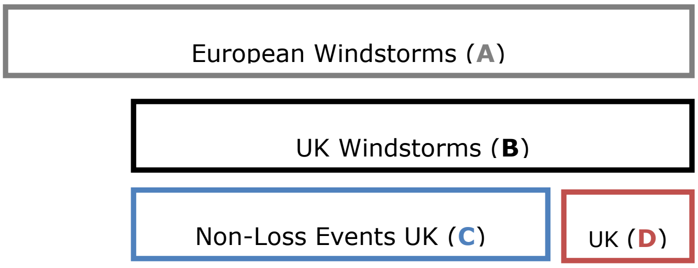


Figure A7.1: Model domain of the European Wind model that is used to assess the impact of windstorms in the UK.

Frequency Information:



Overall annual frequency of Europe ETC's (regardless of losses): ~24.0 from historical data

Overall annual frequency for Europe (regardless of losses): 23.97 from stochastic catalogue (**A**)
Wind storm events affecting UK (regardless of losses): 20.32 stochastic catalogue (B)
Null events for UK (not causing losses): 17.97 (**C**)
Wind storm events affecting Europe (generating losses): 2.78
Wind storm events affecting UK (generating losses): 2.35 (**D**)

Adapted from
AIR Worldwide Corporation, "AIR Extratropical Cyclone Model - European Region", 2006, pp. 28. (proprietary)

A8 TECHNICAL APPROACH TO MODELLING CHINA TYPHOON RISK

Description

The China Typhoon model calculates the losses /hazard risk due to wind and associated flooding from tropical cyclones. The data catalogue is based on the best-track data set, from which simulated stochastic events were derived.

Modelled Peril

Wind speeds of 40mph and above (at 10m, 1 min sustained wind) are generally required for potentially damaging conditions that generate losses.

Model Domain

The China Typhoon model includes the area enclosed in a box spanning from 100°E, 18°N to 136°E, 54°N and utilizes a 5km grid resolution, see Fig. A8.1.

Note, the stochastic catalogue does not include any events that originate in the Indian Ocean Basin; only tracks that originate in the Northwest Pacific ocean are considered.

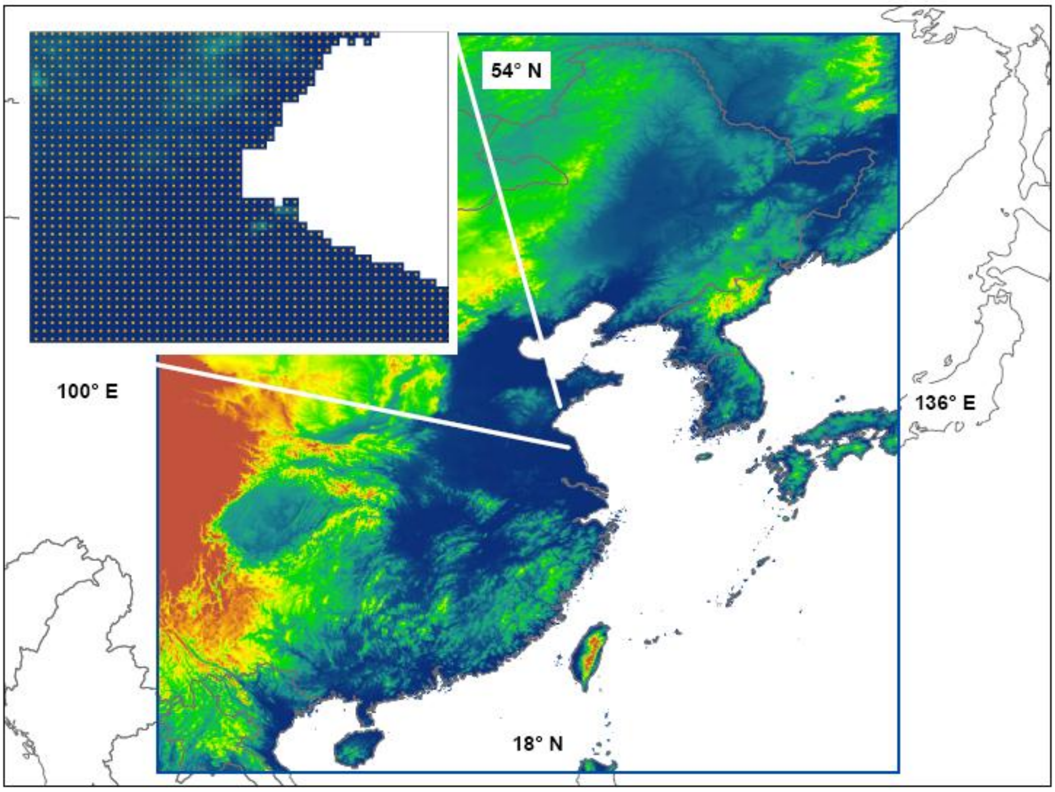
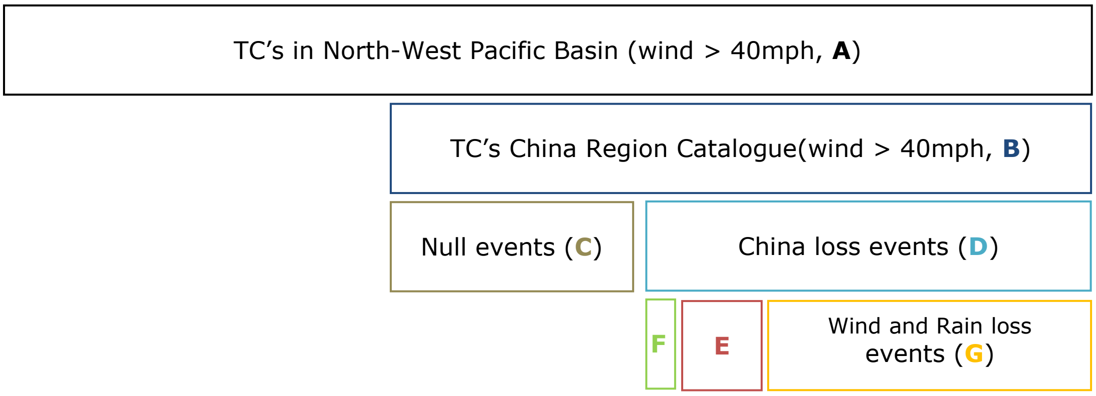


Figure A8.1: Model domain of the China Typhoon model. The model includes an area spanning from 100°E, 18°N to 136°E, 54°N. Inset shows 5km model grid-resolution. Note that countries adjacent to China are part of the model-domain; however, losses are only considered for China.

Frequency Information

The following schematic shows the conceptual structure of the content for the China Typhoon stochastic catalo.



Basinwide Annual Frequency:	29.47	from best track regardless of loss (>40 mph), **A**
Storms Affecting China Region:	18.72	from stochastic catalogue regardless of loss, **B**
	8.59	null events (causing losses outside of China), **C**
	10.13	China loss events, **D**
	1.95	wind loss only, **E**
	0.40	flood loss only, **F**
	7.78	wind and flood loss, **G**

(where: B = C + D, and D = E + F + G)

Adapted from

AIR Worldwide Corporation, "AIR China Typhoon Model", 2007, pp. 75. (proprietary)

A9 GLOSSARY

Italics indicate terms which are defined elsewhere in the glossary.

*Indicates definitions taken from, or based on those from, IPCC AR4.

Average annual loss (AAL) – Average annual loss, or AAL, refers to the aggregation of losses that can be expected to occur per year, *on average*, over a period of many years. Clearly, significant events will not happen every year; thus it is important to emphasise that AAL is a *long-term* average.

Altimetry - In the context of this report, a method of determining the local height of the ocean surface.

Anoxia - In the context of this report, depletion of the ocean of oxygen below the surface levels.

Atlantic Multidecadal Oscillation (AMO)* - A mode of climate variability in the North Atlantic with variation typically over 65-75 years, between cool and warm sea surface temperature phases.

Baseline catalogue - Catalogue that reflects the current climatology.

Blocking - In middle latitudes, interruption of the normal eastward movement of depressions and similar *synoptic* phenomena for at least a few days.

Clausius-Clapeyron relationship - A relationship describing the change of pressure with temperature in an equilibrium state between two phases (e.g. gas and liquid) of the same substance.

Climate conditioned catalogue - Adjusted or re-sampled catalogue to reflect conditions in a climate different than the current (climatology).

Climate scenario / climate change scenario - A plausible future description of the climate, typically based on climate model simulations and usually including additional information e.g. about the observed current climate or emissions scenario. Climate change scenario refers to the *difference* between a climate scenario and the current climate.

Climate sensitivity* - Equilibrium climate sensitivity refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. Transient climate response refers to the change in the global surface temperature, averaged over a 20-year period, centred at the time of atmospheric carbon dioxide doubling, that is, at year 70 in a 1%-per-year compound carbon dioxide increase experiment with a global coupled climate model. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing.

Coupled atmosphere-ocean phenomenon - A process (such as *ENSO*) which involves events in both the atmosphere and the ocean.

Coupled model - A climate model whose ocean and atmospheric components are coupled together with a formal description of interactions between ocean and atmosphere – cf. *uncoupled model.*

Cyclogenesis - The initiation or strengthening of cyclonic (anticlockwise) circulation around an existing cyclone/depression.

Deductible - Portion of covered loss that is not paid by the insurer.

Downscaling* - A method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

El Niño Southern Oscillation (ENSO)* - A pattern of warming and cooling of the eastern tropical Pacific Ocean which oscillates on a timescale between 2 and 7 years. The warm phase of the ENSO cycle is termed El Niño, and the cool phase La Niña. ENSO is associated with fluctuations of surface pressure in the tropics and subtropics and is a coupled atmosphere-ocean phenomenon. ENSO is the dominant mode of global-scale variability on interannual timescales and has a great impact on the patterns of wind, SST and precipitation in the tropical Pacific. ENSO is closely linked with variations in precipitation and temperature across many other areas of the globe, in particular the monsoon rainfall over India.

Emissions scenario* - A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.

Ensemble* - A group of parallel model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterise the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed-parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty than is possible with traditional multi-model ensembles.

Equilibrium climate simulation* - A climate model simulation run with a sudden change in concentrations of greenhouse gases (for a doubling of CO_2, this would be an "equilibrium *climate sensitivity*" experiment), and then allowed to reach equilibrium subject to the new forcing (cf. *transient climate simulation*).

Extratropical cyclone/storm - Cyclones/storms occurring in the middle latitudes of the Earth (i.e. outside the tropics – cf. *tropical cyclone/storm*).

Fluvial flooding - Flooding resulting from rivers bursting their banks due to increased flow (usually following prolonged rainfall, exceptionally heavy rainfall, or snowmelt).

Ground-up losses - Total insured losses, including deductibles, before application of any retention or reinsurance.

Hindcast - A retrospective forecast, simulating a past period and using observed information. Usually used in forecast/model validation studies, by testing the ability of the forecast/model to reproduce observed events.

Jet stream - Narrow, fast flowing, air currents found in the atmosphere at the tropopause (troposphere-stratosphere transition).

Loss Cost Pricing - Pricing of property insurance is often accomplished by calculating a loss cost, (also referred to as a pure loss premium), and then adjusting for expenses, both fixed and premium-variable, and profit in order to determine an adequate premium to be charged.

Meridional overturning circulation (MOC)* - A description of ocean circulation: specifically, north-south (meridional) overturning circulation in the ocean quantified by east-west (zonal) sums of mass transports in different layers of the ocean (where these layers are defined by different depths or densities). MOC is often quantified in order to assess the strength of the thermohaline circulation (THC), which cannot be measured directly.

North Atlantic Oscillation (NAO)* - A mode of climate variability characterised by opposing variations of barometric pressure near Iceland and near the Azores, therefore corresponding to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded cyclones with their associated frontal systems.

Orography - The variation over a specified area of the height of ground above sea level (including hills, mountains, etc).

Percentage change - Amount of change observed in an experiment with respect to the baseline.

Pluvial flooding - Flooding resulting from rainfall-generated runoff over the land surface, before such runoff enters any natural or man-made watercourse (rivers, lakes, sewers etc). It is usually associated with high-intensity rainfall, but can also occur in other circumstances, e.g. if the ground is frozen, or already saturated (e.g. following sustained periods of rain).

Portfolio - The book of business of an insurer or reinsurer, including all policies in force and open reserves.

Probability of Exceedance - The likelihood that a certain level of loss will be exceeded. For example, a 1% probability of exceedance implies there is a 1-in-100 chance of that loss being met or exceeded.

Retention - Assumption of risk of loss by means of noninsurance, self-insurance, or deductibles. In reinsurance, the net amount of risk the ceding company keeps for its own account.

Reinsurance - Transaction in which one party, the "reinsurer," in consideration of a premium paid to it, agrees to indemnify another party, the "reinsured," for part or all of the liability assumed by the reinsured under a policy of insurance that it has issued.

Required Minimum Capital - Increased amounts of capital that insurers might be required to hold. In this study we assume that the 200-year losses are representative of RMC.

Shock Losses – Extreme event losses that are extremely infrequent (say, with probability of 0.4% or less) and are significantly above the average annual expected amount of catastrophe losses, thereby causing a shock to the insurer’s financial condition and possibly create concern for continued operations.

Slab-ocean model* - In a climate model, a simplified representation of the ocean as a motionless layer of water with a depth of 50 to 100 m. Climate models with a slab ocean can only be used for estimating the equilibrium response of climate to a given forcing, not the transient evolution of climate.

Storm track* - Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalised to refer to the regions where the main tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems.

Sub-grid process - A process occurring on a scale too fine to be resolved by a climate model operating at a particular resolution (e.g. cloud formation in a *GCM*). Such processes are usually described in climate models in a parameterised way.

Supplemental capital – Reserved capital or other forms of investment which could be used as a financial strategy to supplement regulatory requirements which dictate how institutions handle their capital. Estimates of total required capital may be improved by accounting for potential future risks such as climate change, but the choice of whether supplemental capital is required would be dependent on an individual company’s appetite for risk amongst other risk mitigation strategies.

Surge event / storm surge event* - The temporary increase, at a particular place, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is quantified as the excess above the level expected from the tidal variation alone at that time and place.

Synoptic phenomenon - A meteorological phenomenon extending over a wide geographic area, such as a cyclone/depression or anticyclone (area of high pressure).

Tail Value at Risk (TVar) – Tail Value at Risk, or TVar, is the average of all simulated event losses beyond some specified probability.

Take-up Rate - The proportion of properties formally covered by insurance for a particular hazard (e.g. wind, flood).

Transient climate simulation* - A climate model simulation run with varying concentrations of greenhouse gases, e.g. according to an *emissions scenario*, representing a plausible evolution of climate change with time (cf. *equilibrium climate simulation*).

Tropical storm/cyclone - "Tropical cyclone" is a generic term for a low-pressure system over tropical or subtropical waters, with intense convective activity (e.g. thunderstorms) and winds circulating in a cyclonic (anticlockwise) direction in the northern hemisphere (clockwise, in the southern hemisphere). A "tropical storm" is a tropical cyclone with maximum sustained surface wind speeds of at least 39 miles per hour, and a "hurricane" is a very intense tropical cyclone with wind speeds of more than 73 miles per hour. Generally these storms can form in environments with (1) warm ocean waters (>26.5°C), (2) an unstable atmosphere, (3) a moist mid-troposphere, (4) sufficient distance from the equator, (5) near-surface spin and convergence of the air, and (6) low values of vertical wind shear (Shepherd and Knutson, 2007 – see reference list in Appendix A3, Question 3).

TVar 0.4% – The probability weighted average of all simulated event losses beyond the 0.4% exceedance probability (250-year loss).

Uncoupled model - A climate model whose ocean and atmospheric components are not coupled together – cf. *coupled model.* Typically, the ocean and atmosphere components of uncoupled models would be run independently.

Wind shear - Rate of change of the wind vector with distance, in a direction perpendicular to the wind direction. Wind shear is important in the development of *tropical cyclones*.

100-year loss - The 100-year loss is the loss that has a 1% probability of occurring or being exceeded in any year. Note that the 100-year loss is defined in the context of a given climate regime; that is, the 100-year loss in the *current* climate regime may be different from the 100-year loss in a future climate regime.

200-year loss - The 200-year loss is the loss that has a 0.5% probability of occurring or being exceeded in any year. Note that the 200-year loss is defined in the context of a given climate regime; that is, the 200-year loss in the *current* climate regime may be different from the 200-year loss in a future climate regime.

Abbreviations

AAL	Average Annual Loss

AMO	Atlantic Multidecadal Oscillation
AOGCM	atmosphere-ocean global climate model
AR4	Fourth Assessment Report (by the IPCC, 2007)
ChT	China Typhoon
CMIP3	Third Coupled Model Intercomparison Project
ECMWF	European Centre for Medium-range Weather Forecasting
ENSO	El Niño Southern Oscillation
GBF	Great Britain Flood
GCM	Global climate model
GIS	Greenland ice sheet
IPCC	Intergovernmental Panel on Climate Change
MOC	Meridional overturning circulation
NAO	North Atlantic Oscillation
NCEP	National Center for Environmental Prediction
QUMP	Quantifying Uncertainty in Model Predictions
RCM	Regional climate model
SRES	Special Report on Emissions Scenarios
SST	Sea surface temperature
TVar 0.4%	The average of all simulated event losses beyond the 0.4% exceedance probability (the 250-year loss).
UKCP09	United Kingdom Climate Projections 2009
UKW	United Kingdom Windstorm
WAIS	West Antarctic ice sheet

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