CATASTROPHE MODELLING AND CLIMATE CHANGE

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1 EXECUTIVE SUMMARY

SCIENTIFIC RESEARCH POINTS CONCLUSIVELY TO THE EXISTENCE OF CLIMATE CHANGE DRIVEN BY HUMAN ACTIVITY. Nevertheless, significant uncertainty remains on the nature and extent of the changes to our climate and the specific impacts this will generate. Many of the effects will become apparent over the coming decades and anticipating them will require forward projections, not solely historical data.

CHANGES IN THE CLIMATE AND WEATHER PATTERNS HAVE THE POTENTIAL TO AFFECT EXTREME WEATHER EVENTS. Insurers have a key interest in understanding the impact of climate change on the frequency of extreme weather events. The frequency of heat waves has increased in Europe, Asia and Australia and more regions show an increase in the number of heavy precipitation events than a decrease. It is virtually certain that since the 1970s there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic basin.

CATASTROPHE MODELLING TECHNOLOGY IS NOW USED EXTENSIVELY BY INSURERS, REINSURERS, GOVERNMENTS, CAPITAL MARKETS AND OTHER FINANCIAL ENTITIES. They are an integral part of any organisation that deals with natural catastrophe risk and are used most commonly to perform activities such as risk selection and underwriting, reserving and ratemaking, development of mitigation strategies, design of risk transfer mechanisms, exposure and aggregate management, portfolio optimisation, pricing, reinsurance decision-making and capital setting. The models help to quantify our understanding of the natural world.

CLIMATE CHANGE TRENDS MAY BE IMPLICITLY BUILT INTO CATASTROPHE MODELS, GIVEN THE HEAVY USE OF HISTORICAL DATA IN CONSTRUCTING THEM; HOWEVER THESE TRENDS ARE NOT NECESSARILY EXPLICITLY INCORPORATED INTO THE MODELLING OUTPUT. Uncertainties associated with the estimation of the extent and frequency of the most extreme events means that the climate change impact can be difficult to account for in risk models.

THE SENSITIVITY OF HURRICANE LOSSES IS INFLUENCED BY A NUMBER OF FACTORS RELATED TO CLIMATE CHANGE, SUCH AS SEA-LEVEL RISE AND SEA SURFACE TEMPERATURE. There is a relationship between sea surface temperatures and hurricane strength which suggests a gradual increasing trend. It is thus imperative that changes in these are modelled accurately.

THE APPROXIMATELY 20 CENTIMETRES OF SEA-LEVEL RISE AT THE SOUTHERN TIP OF MANHATTAN ISLAND INCREASED SUPERSTORM SANDY'S SURGE LOSSES BY 30% IN NEW YORK ALONE. Further increases in sea-level in this region may non-linearly increase the loss potential from similar storms. Catastrophe models that dynamically model surge based on current mean sea-level already factor this increased risk into their projections.

CLIMATE MODELS CONTINUE TO PROJECT IMPACTS ON EXTREME WEATHER IN THE COMING DECADES. EQECAT show how future climate scenarios could see increases in the frequency of intense storms in Europe, with a possible shift in storm track towards northern latitudes. JBA notes that climate change has already increased the probability of flood events in the UK such as those which occurred in 2000, and a 1 in 5 rainfall event could be 40% larger in future.

2 INTRODUCTION

The insurance industry has in recent years incurred major losses as a result of extreme weather. 2011 is regarded as a record year for natural catastrophe, with insured losses costing the industry more than $127 billion[i]. A series of catastrophes at the end of the 1980s and the beginning of the 1990s posed a major challenge to the insurance industry. The adoption of natural catastrophe models in the 1990s helped the industry to analyse and measure risk more accurately, and use of these tools has now become the norm. Given the prevalence of catastrophe models in insurance and the rising cost of extreme weather events, the accuracy of modelled outputs is a key interest for insurers. The potential for climate change to drive changes in the severity and likelihood of extreme weather events could have implications for the accuracy of natural catastrophe models, and this report examines whether and how catastrophe models account for climate change through a series of case studies provided by a range of academic and commercial model providers.

The Earth's global climate system is warming. This conclusion is supported by a large body of evidence which is presented in the scientific literature and most comprehensively in the five Assessment Reports published by the Intergovernmental Panel on Climate Change (IPCC)[1]. Increasing greenhouse gas concentrations in the atmosphere, largely due to human activity such as combustion of fossil fuels and land use change, result in an enhancement of the planet's natural greenhouse effect and in increased surface warming. The additionally captured energy is stored to the largest part in the oceans and, in combination with a warming of surface air temperatures, results in changes to the physical climate system. One example is the impact on the hydrological cycle in the form of changed rainfall, in changes to atmospheric circulation and weather patterns, in a reduction of global ice and snow coverage and in thermal expansion of the oceans and subsequent sea level rise. These trends challenge insurers to examine both the economic impact of climate change and the adequacy of the tools used to measure and price risks.

One of the primary concerns for insurers is the potential for these changes in climate and weather patterns to affect extreme weather events. The Fourth Assessment Report of the IPCC (IPCC, 2007) highlighted the importance of our understanding of extreme events, due to their disproportionate impact on society and ecosystems when compared with gradual changes in the average climate. In 2012 the IPCC published a Special Report focusing specifically on managing the risks of extreme climate events (IPCC, 2012, from now on referred to as SREX) and the recently released draft of the IPCC's Fifth Assessment Report (IPCC, 2013) includes an update of the understanding and observational evidence of changes in climate extremes.

This report has three main parts. The first section reviews the latest findings in climate change science and its effect on extreme weather events. The second outlines what catastrophe modelling is and how it came to be developed. The third section examines whether and how catastrophes models account for climate change through a series of case studies provided by a range of model providers, including AIR, RMS and EQECAT. The appendices provide detail on the terminology used to describe levels of confidence and likelihood (Appendix 1) and the limitations of climate models (Appendix 2).

[1] See Appendix 1 for further detail.

3 THE SCIENCE OF CLIMATE CHANGE

The Summary for Policymakers of the IPCC's Fifth Assessment Report (2013) reports an unequivocal warming of the climate system. Changes are observed in atmospheric and oceanic temperatures, the extent of ice and snow coverage, and the concentration of greenhouse gases in the atmosphere. Many of these changes have been unprecedented over time scales from decades to millennia. Global average air temperatures during the last three decades have been the warmest since 1850 and, in the northern hemisphere, the past 30 years were likely the warmest period for at least 1,400 years. These long term changes are generating widespread impacts, notably:

- Increasing accumulation of energy in the world's oceans: it is virtually certain[2] that the top 700 m of the oceans warmed over the last four decades.

- From 1901-2010 global mean sea levels rose by approximately 19 cm. The rate of sea level change since the middle of the 19th century is larger than the average rate of change over the past two millennia.

- There are changes in the mass losses in the Greenland and Antarctic ice sheets, a decrease in the size of glaciers all over the world and a shrinking extent of Arctic sea ice in the Northern Hemisphere.

- Atmospheric levels of the greenhouse gases carbon dioxide (CO_2), methane and nitrous oxide are higher than at any time during the last 800,000 years. The main causes for this are the combustion of fossil fuels and changes in land use. Since pre-industrial times atmospheric CO_2 concentrations have increased by 40% and the world's oceans have absorbed about 30% of the emitted carbon. This increased uptake by the oceans results in their increased acidification levels.

Increased greenhouse gas concentrations, observed warming trends and scientific understanding of the climate system point to a clear human influence on the climate system. Continued emissions of greenhouse gases will result in further warming and are likely lead to changes in many climate system components.

3.1 TEMPERATURE EXTREMES

The current understanding, which is based on a large body of evidence, indicates that most of the global land areas that were analysed have undergone a significant warming in both minimum and maximum temperature extremes since the early 20th century[ii]. An investigation of multiple data sets has shown with high confidence a stronger increase in minimum temperatures than in maximum temperatures on a global scale, and a global decrease in the number of cold nights and days with a simultaneous increase in warm days and nights is very likely. There is however only medium confidence in the reduction of the daily temperature range, and the overall impact on probability distributions remains an open question[iii].

In contrast to the observed large-scale warming, some regions exhibit changes that are indicative of episodes of local cooling. These regions include central North America, the eastern United States and parts of South America. The difference in the trend for these regions appears to be linked with maximum temperatures that are connected with changes in the water cycle and land-atmosphere interactions and long-term (multi-decadal) variability in the Atlantic and Pacific Oceans. There is only medium confidence that the length and frequency of warm spells or heat waves have globally increased since the 1950s, which is partly due to regionally insufficient data and remaining inconsistencies in the definition of extreme temperature events. Nevertheless, it is considered likely that during this time period the frequency of heat waves has increased in Europe, Asia and Australia[iv].

[2] See Appendix 1 for common phrases used in the IPCC reports.

3.2 PRECIPITATION AND DROUGHTS

A generally wetter climate is reflected consistently in changes to precipitation extremes. Recent findings continue to support the earlier assessments that more regions show a statistically significant increase in the number of heavy precipitation events than a decrease. However, the level of statistical significance is lower for precipitation extremes than for extreme temperatures. This is due to spatial patterns of change being less coherent when compared with temperature trends, as well as large areas showing opposite signs in their respective trend. There is strong regional and sub-regional variation in precipitation extremes since 1950. Additionally, it remains difficult to provide a universally valid definition for extreme precipitation events. Only North and Central America and Europe exhibit likely (or higher confidence) increases in either frequency or intensity of heavy precipitation. In Europe and the Mediterranean there remains significant seasonal and regional variability with a large part of the increase occurring during winter (see e.g. Table 2.13 in IPCC, 2013). In Asia and Oceania, regions showing increasing extreme precipitation outweigh those exhibiting a decrease, whereas for Africa a significant trend of extreme precipitation could not be established. In addition, the trends for small scale severe local weather phenomena (such as hail or thunderstorms) are uncertain due to inhomogeneous historical data and insufficient density of monitoring stations[v].

Assessment of changes in the magnitude or frequency of floods remains difficult. Working Group II of the IPCC's Fourth Assessment Report stated that no general trend existed in the incidence of floods. River management is an important factor influencing trends in flooding. The strongest indication for flood trends has so far been found in high latitudes of the Northern Hemisphere, although regional variability is such that no clear evidence is currently available. SREX reports an earlier onset of spring flow in regions dominated by snow, however both SREX and IPCC (2013) did not find global trends for flood occurrences, citing lack of evidence.

The occurrence of droughts, on the other hand, was comprehensively assessed in the SREX report. SREX concluded that distinction between different types of drought and complex issues with defining droughts have a significant impact on conclusions on global scale trends, and reported with medium confidence that since the mid-20th century some regions of the world had experienced more intensive and longer droughts (IPCC, 2012). Due to the scarcity of direct measurements of soil moisture and other variables related to drought often other related variables hydrological proxies are used for drought assessments. The severity of an assessed drought event is highly dependent on the choice of variable and the length of time scale considered. Agreement is however found for some regions. There is high confidence of increasing drought in the Mediterranean and West Africa and also high confidence is reported for a decrease in drought for central North America and north-west Australia.

3.3 TROPICAL AND EXTRA-TROPICAL STORMS

Tropical and extra-tropical storms account for the highest impact extreme events. There is limited evidence for a long-term trend in the number of tropical storms globally. In addition to frequency or storm count it is necessary to consider the associated changes in the intensity and duration of tropical cyclones. The quality of observations has changed significantly over the past century, for instance after the availability of satellite data. Measurements of storm intensity are very sensitive to observation technology and therefore long-term historical trends are influenced by changes therein. Regionally it is virtually certain that since the 1970s there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic basin[vi]. However over the last 100 years there have been other periods of high activity. The variability of trends makes a confident attribution to climate change challenging, although there are good physical reasons to expect hurricanes to be stronger on average.

There is limited evidence for a change in extra-tropical storms or extreme winds globally. Long-term wind measurements exist often for too short periods (particularly in the Southern Hemisphere) or are inconsistent due to changes in observation technology in order to derive long-term records. Therefore proxy data is commonly used such as in-situ surface pressure observations or pressure data from reanalyses to derive changes in the geostrophic wind field. In the latter case the findings are sensitive to the reanalysis product with newer generation products typically outperforming earlier reanalyses. Studies using reanalysis data suggest a northward and eastward shift of Atlantic cyclone activity, with intensification of cyclones during winter and at high latitudes[vii].

4 CATASTROPHE MODELLING

4.1 EVOLUTION AND ROLE OF CATASTROPHE MODELLING IN THE INSURANCE INDUSTRY

Catastrophe modelling is a comparatively young discipline, with its origins embedded within property insurance and the science of natural hazards. It aims to help companies anticipate the likelihood and severity of potential future catastrophes before they occur so that they can adequately prepare for their financial impact[viii].

Commercially available catastrophe models (often referred to as 'cat models') have only been in existence for the last 25 years. Prior to the birth of catastrophe models in the late 1980s, rudimentary methods were adopted for estimating catastrophe losses. Standard actuarial techniques were not appropriate to estimate future catastrophe losses. Historical loss data was, and still is, scarce, especially for low frequency high severity events with the potential to threaten insurer solvency. For risk acceptance, underwriters used spatial risk mapping and measuring of hazards, but these had traditionally been performed quite separately. For pricing, they relied either upon internally generated Probable Maximum Losses (PMLs) using rule-of-thumb formulae, or upon realistic estimations of potential loss using subjectively derived deterministic scenarios. There was a clear focus on the severity of potential events, but no reference to frequency. At this time the unfulfilled aspiration for simultaneous consideration of these elements was recognised by those responsible for founding three of the globally recognised catastrophe modelling software providers: AIR (1987), RMS (1988) and EQECAT (1994).

Despite the commercial availability of the first probabilistic catastrophe models in the late 1980s, their use was not widespread. Reinsurance cover was readily available and the market was somewhat benign. Meanwhile the software providers were generating large probabilistic US hurricane industry loss estimates of USD $20-30bn occurring with a reasonably significant probability[ix]. In 1989, the magnitude of loss caused by both Hurricane Hugo ($4bn[x]) and the Loma Prieta earthquake ($6bn[xi]) sparked initial interest in the use of catastrophe models amongst insurers and reinsurers. However, it was the unprecedented and unforeseen loss size from Hurricane Andrew in 1992 which really highlighted deficiencies in the purely actuarial approach to quantifying catastrophe risk losses. In real-time, AIR issued a fax to its clients estimating losses in excess of $13bn based upon the AIR hurricane model. Months later, the Property Claims Service (PCS) reported an industry loss of $15.5bn[xii]. Losses of this size hit the market hard, resulting in the insolvency of 11 insurers[xiii]. As a response, adoption of catastrophe models grew exponentially as they were viewed as a more sophisticated and reliable approach to catastrophe risk assessment.

Increasing population densities and property values in hazard prone areas has led to diversification in the use and coverage of catastrophe models. Catastrophe modelling technology is now used extensively by insurers, reinsurers, governments, capital markets and other financial entities. Catastrophe models are an integral part of any organisation that deals with natural catastrophe risk[xiv], and are used most commonly to perform activities such as risk selection and underwriting, reserving and ratemaking, development of mitigation strategies, design of risk transfer mechanisms, exposure and aggregate management, portfolio optimisation, pricing, reinsurance decision-making and capital setting.

Catastrophe models are developed by harnessing loss and hazard observations, building upon existing data, testing existing models and incorporating these lessons into future catastrophe modelling advances. Recent developments include explicit modelling of windstorm clustering, better understanding of inter-country demand surge relationships, potential for occurrence and impact of storm surge, response of business interruption losses, development and damage of hurricanes beyond coastal areas and appreciation of non-modelled components of catastrophe models. The events of 9/11 also drove the first development of models for man-made catastrophes, in the form of terrorism models.

By their nature, models represent an approximation of expected outcomes, and they are just one of many tools used to enhance the understanding and management of risk. Newly available loss data, increasing understanding of the science of natural hazards, and advancements in computing capability and technology all contribute to the evolution of catastrophe models and the dynamic discipline of catastrophe modelling.

4.2 HOW DOES A CATASTROPHE MODEL WORK?

Catastrophe modelling software contains a vendor-specific view of hazard risk, and vulnerability of insured property. This view is devised using observed data as a basis. The software then facilitates application of this view of risk to a specific client's book of business in order to quantify probability and size of potential loss.

This is achieved by reducing the complexity inherent in physical interaction between hazard and vulnerability, by parameterising characteristics to a limited set of measurable metrics. These metrics are applied systematically, consistently and repeatedly to a custom set of exposure data. The insurance related financial characteristics can then be overlaid to give a net loss bespoke to the client using the tool.

Most catastrophe models accomplish this by adopting a modular approach (Figure 1).

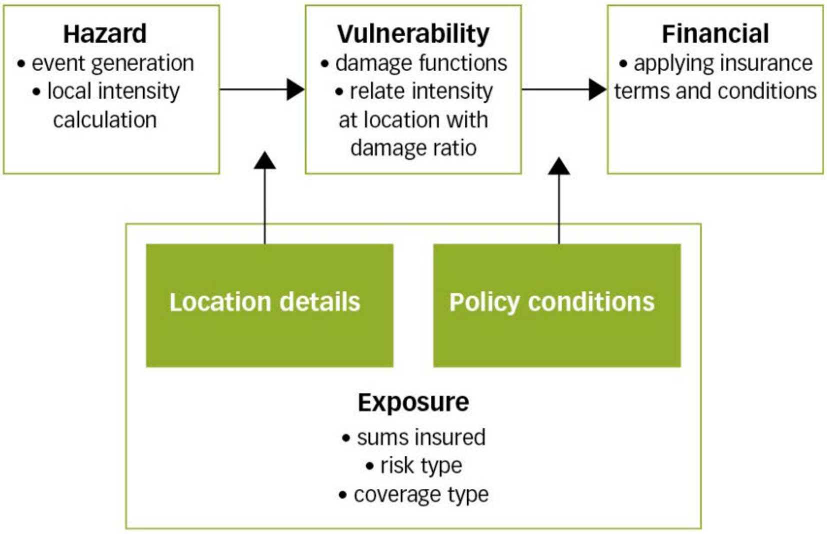


Figure 1: Adapted from Dlugolecki et al., 2009

Operating the software is however only a small part of what it takes to optimise the use of catastrophe modelling within a business. It is imperative that those responsible for running the model can also effectively understand, interpret and convey the output with consideration for the models' limitations.

Catastrophe models can provide a variety of financial outputs, the most common of which are the Annual Average Loss (AAL) and the Exceedance Probability (EP) Curve. The AAL is sometimes also referred to as the 'pure premium' or 'burning cost' and can be incorporated into pricing along with an allowance for expenses and recommended return on capital. The EP Curve is commonly depicted as a graphical representation of the probability that a certain level of loss will be exceeded. Reading off points on the curve will give different views on frequency and severity of losses for the book of business being modelled. These curves are valuable for insurers and reinsurers to determine the size and distribution of their portfolios' potential losses[xv].

Even though catastrophe models are sophisticated, they cannot capture the full spectrum of risks that exist in the real world. Each catastrophe modelling vendor will have a suite of models covering region/perils that are of interest to their clients. No model is currently capable of covering every peril in every region, leading gaps in model availability which can be termed 'model miss'..

Where a catastrophe model does quantify losses for a region/peril, the process is complex and depends on many assumptions which naturally result in a degree of uncertainty around that loss. This uncertainty increases for more extreme events where there is little empirical experience and instances where exposure data imported into the catastrophe model by the client is of poor quality. It is paramount that the limitations of the model and the uncertainty inherent in its outputs are conveyed effectively during the decision making process.

In order for catastrophe models to assist in the forecasting of risk exposure, they must incorporate observed trends. The next section provides a series of case studies to examine how the catastrophe modelling community is addressing the challenge of long term climate change trends.

5 CATASTROPHE MODELS AND CLIMATE CHANGE

Having reviewed the latest findings on climate change and outlined the workings behind catastrophe modelling, this section details a series of studies from catastrophe model providers across a range of natural hazards in order to assess the extent to which climate change influences the outputs of catastrophe models.

In the case study provided by EQECAT it is shown that a northward shift of European storm track and intensification of the strongest storms is projected by at least one global climate model. Madeleine-Sophie Déroche of the Climate – Knowledge Innovation Centre points out that the intensification is a consistent feature amongst the latest generation models, but systematic track changes are shown to vary depending on the model and region being analysed. UK flood modelling by JBA supports research by the UK Government which shows that climate change could almost double the number of properties at significant risk of flooding by 2035 unless there is additional action. It is argued by several case studies that any recent climate trends will implicitly be included in the data that is used to construct catastrophe models.

Three case studies address cyclone hazard. An attempt at medium–term (1-5 years) forecasting is shown by RMS which includes sea surface temperature trends as a predictor for anomalous Atlantic Hurricane activity. They find a small adjustment of the number of cyclones using this method. A more significant effect of climate change is found when considering that as much of 30% of the surge contribution to losses from Superstorm Sandy can be attributable to long-term changes in sea-level. AIR also found modest increases for cyclone losses in the South Pacific, but found no compelling evidence for a climate change signal in US thunderstorms. James Elsner from Climatek makes the case for increased losses of 5% per decade in the North Atlantic driven by trends in sea-surface temperature. He also points out that climate models underestimate the sensitivity of cyclones to temperature. The three independent tropical case studies and approaches show consistency in the direction and order of magnitude of the changes projected.

Note that the case studies reflect the views and opinions of the contributors – in any one case the views don't necessarily reflect the views of Lloyd's or the other contributors.

EUROPEAN WINDSTORM

By Iain Willis, Product Manager at EQECAT

ORIGINS

Every winter, deep low pressure systems originating in the mid and high latitudes of the Atlantic give rise to intense Extra Tropical Cyclones (ETC). Unlike Tropical Cyclones (such as Typhoons or Hurricanes), European windstorms usually begin along a polar front where a body of low pressure from the North encounters high pressure from the South. The movement of these opposing air masses creates a cyclonic shear, which, if given the right circumstances, can cause an anti-clockwise rotation of the air mass around a core of low pressure. Following this process of 'cyclogenesis' (Figure 2), the Extra Tropical Cyclone tracks eastwards, driven by the fast moving Northern Hemisphere jet streams (and at speeds ranging from between 30-70mph). Since Extra Tropical Cyclones are frontal systems, largely driven by the temperature and pressure contrasts of the mid-latitudes, European windstorm frequency and severity is typically greater during the winter months.

Figure 2: The development of an Extra-tropical Cyclone (ETC)

Studying the path of European windstorms using sources such as remote sensing data, historical wind speeds, and subsequent reanalysis (e.g. ERA-Interim), the data shows that the most common trend is for storms to track across the Northern latitudes of Europe, primarily impacting the UK, Ireland and Scandinavian countries. Such a trend might suggest that countries in the lower latitudes of Europe are not exposed to windstorms. This is not the case. European windstorms can deviate from this norm and often with devastating consequences. As seen in Figure 3, highlighting the storm tracks[xvi] of multiple industry loss events, windstorm Xynthia (February 2010) emanated from the lower latitudes of the Atlantic, before tracking North-Eastwards across Portugal, Spain and France, causing a total of 2.9bn[xvii] USD in insured loss.

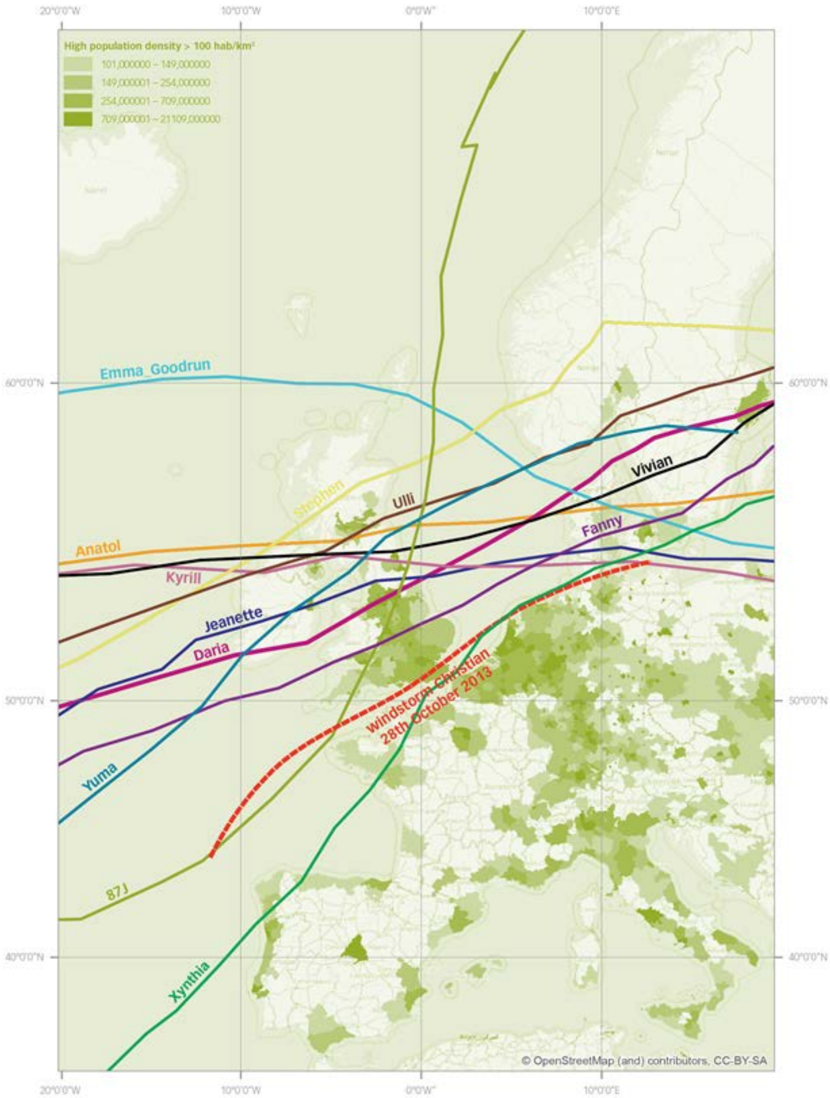


Figure 3: Storm tracks of major industry loss events and European population density (Source: EQECAT / Storm tracks based on the Extreme Wind Storms Catalogue (XWS), University of Reading, 2013)

Unlike Hurricanes, which tend to have a defined, central core of low pressure, European windstorms are often more disparate in structure. Similarly, a European windstorm's size and structure can greatly affect its damage potential and footprint. For example, windstorm Daria (January 1990) had a very large footprint of damage whereas windstorm Klaus (January 2009) rapidly intensified as it tracked across continental Europe, creating a small but very damaging radius of strong winds.

FREQUENCY AND INDUSTRY LOSS

Between 1959-2001 reanalysis data shows an average of about 19 windstorms a year over Europe. Of these events however, we would only expect around a third of these storms to result in an insured loss. The most severe and frequent occur primarily between the months of December and February although the impact of an early season event, such as Windstorm Christian (October 2013) or the Great Storm of '87 (October 1987), can be more damaging as most trees still retain their leaves at this time of year. Within the historical data there is considerable variability both in the number of storms and their relative severity. The winter of

1989/1990 had the highest windstorm frequency with 37 events recorded. It proved a notable year as several of the windstorms were significant from an insured loss perspective, such as windstorms Daria (25th January), Vivan (26th February) and Wiebke (28th February). Such seasonal intensity is not in isolation and also took place during the 1999 storm season as Anatol, Lothar and Martin caused a total loss of $13.9 billion[xviii]. Lothar and Martin occurred within 36hrs of each other, both impacting similar areas of central Europe. Such frequency is commonly referred to as 'temporal clustering'. Due to the magnitude and aggregation of insured losses in such years, the pattern and periodicity of temporal clustering is of considerable interest to the insurance market. As traditional excess of loss reinsurance contracts are often based around the 72 hours clause, the impact of having multiple meteorological events occurring within this period causes major concern as reinsurance trigger levels may be reached by the aggregation of these smaller events, rather than by a single, very large windstorm.

European windstorm severity is currently assessed by meteorologists using a Storm Severity Index (SSI). A single value is calculated for a storm event based on several physical characteristics of the event. This typically includes factors such as the maximum observed wind speed, a minimum wind speed threshold (e.g. 25 m/s), storm duration, and the physical extent of the storm over land areas. By using such metrics, meteorologists are able to assess the relative severity of these large complex cyclones. It is important to note that there remains no universal standard for calculating SSIs and they continue to be a moot point for meteorologists.

Studying the insured losses from single historic windstorms, the most significant events were recorded from Daria (1990) and Lothar (1999) with insured losses totalling $8.2 billion and $8 billion[xix] respectively However, the most recent large scale loss from a windstorm was in 2007 when Kyrill (18th January) impacted much of central Europe causing $6.7 billion insured loss[xx]. The common factor in the characteristic of the most damaging windstorms concerns their international impact, i.e. a single storm can impact multiple countries as it tracks across central Europe. Due to the very high wind speeds of these storms (typically found to the south of the storm vortex) and the large synoptic size (~1000km), destruction to property, contents, and business downtime is on a very large scale. As the storm track of Kyrill shows (Figure 3), it was able to cause considerable damage across multiple European countries including Austria, Belgium, France, Germany, Ireland, Netherlands, Poland, the Czech Republic and the United Kingdom.

CLIMATE MODELLING

In considering how climate change will affect the pattern of European windstorms, it is necessary to make use of Global Climate Models (GCM). These state-of-the-art numerical weather models have become an integral tool in meteorological research and help scientists simulate future climates in line with IPCC emission scenarios (SRES)[3].

EQECAT have worked closely with the Free University of Berlin in using the ECHAM5 coupled climate model as well as our European windstorm catastrophe model (Eurowind™) to study the meteorological and financial impacts that future climate conditions may bring. Comparing twenty-five different storm parameter statistics (including storm severity, wind speed, area, duration, and atmospheric pressure) of the entire 20th Century with the 2007 SRES emission scenarios (A2 and A1B) for the 21st Century, the use of a GCM has provided us with valuable insight into the possible impacts of climate change on European windstorm track density and severity. Results were calculated at five different meridional European transects spread evenly across the longitudes of 0°E to 20°E.

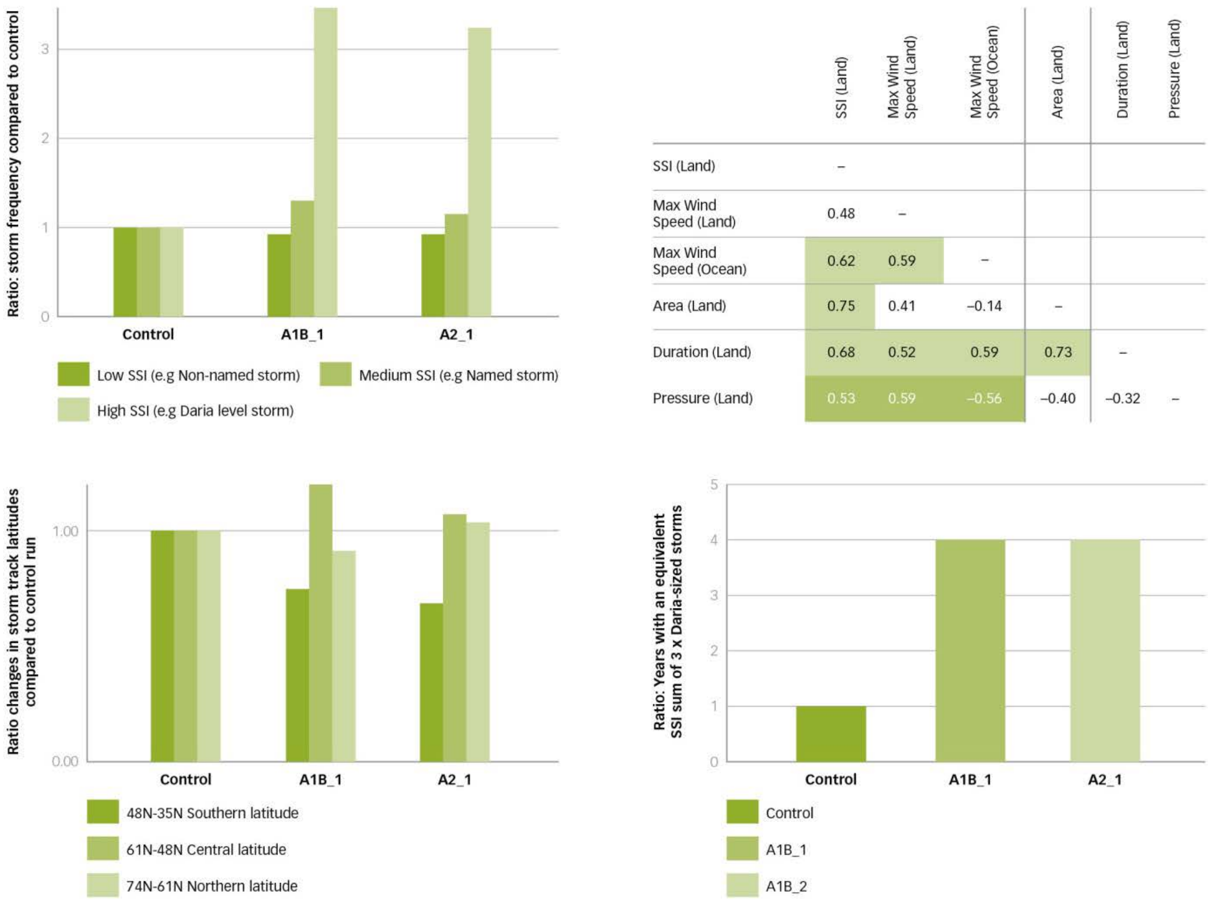
It is important to note that ECHAM5 is one several GCMs used by the IPCC community and therefore several scenario runs cannot capture the full spectrum of uncertainties associated with climate change simulations. ECHAM5 results have been shown to lie in the middle of all ENSEMBLES simulations, but the results presented here must still be seen as one of many possible climate change outcomes.

Despite the differences in various GCM research methodologies, model assumptions, resolution and the magnitude of storm behaviour, there has proved to be consensus between EQECAT's results and other published research in this field. Other climate change findings [xxi,xxii,xxiii,xxiv] have all noted that changes in near-surface temperature, baroclinicity (low level temperature contrast) and sea-ice will greatly affect the strength and location of mid-latitude cyclone activity. On a global perspective, such changes may result in a

[3] Control run was based on CO_2 emissions from 1900-2001.

gradual polar shift in storm track density. With regard to windstorm activity in the European mid-latitudes, EQECAT's research highlighted the following observations in future climate scenarios:

1. An increasing volatility - fewer smaller storms but an increase in the frequency of very large storms;
2. A shift in the latitude of European windstorms towards central Europe (between bands 48N-61N); and
3. A four-fold increase in the frequency of years with several severe storms (this is based on the normalised equivalent of an SSI sum of three times Daria sized storm events per year).



	SSI (Land)	Max Wind Speed (Land)	Max Wind Speed (Ocean)	Area (Land)	Duration (Land)	Pressure (Land)
SSI (Land)	–					
Max Wind Speed (Land)	0.48	–				
Max Wind Speed (Ocean)	0.62	0.59	–			
Area (Land)	0.75	0.41	−0.14	–		
Duration (Land)	0.68	0.52	0.59	0.73	–	
Pressure (Land)	0.53	0.59	−0.56	−0.40	−0.32	–

Figure 4: Possible climate change impacts on European windstorm (Clockwise from Top Left: a) Increasing severe storms b) Correlations between SSI and storm parameters c) Frequency of years with equivalent SSI of 3 x Daria-sized storms d) Location of storm activity)[4]

In considering the consequences of these changes to insured loss, the overall impact on European exposure from these results implies a 3-5% decrease in the total number of potentially damaging storms but a 10-20% increase in the number of larger storms[5]. Likewise, the progressive shift of storm tracks to the central latitudes in Europe could increase the severe storm losses seen in major European markets, disproportionately impacting France and Germany.

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[4] Findings are based on EQECAT whitepaper 'Activity of Catastrophic Windstorm Events in Europe in the 21st Century' (2011).

[5] Defined as having an SSI equal to or greater than windstorm Daria.

MODELLING

Various techniques are employed in modelling ETC. These range from solutions such as pressure field analysis, using historically recorded wind speed data, to the use of supercomputers and Numerical Weather Prediction (NWP). In recent years, and given the rapid advancement of IT, meteorologists and modellers are increasingly turning their attention to NWP and GCMs.

NWP can essentially be split into macro and meso-scale models. Although both are computationally very intensive and based on the same mathematical equations of thermo dynamics, the subsequent geographic scale, complexity and end-purpose of these models varies considerably. Meso-scale NWP modelling is generally at a very high resolution but is only run for short periods of time. For this reason it is typically used for short-term weather forecasting. A good example in the progression of this science was evidenced in October 2013 by the European forecasts that predicted with considerable accuracy the track and intensity of windstorm Christian (also referred to as the St Jude’s day storm in the UK) several days before it made landfall. Macro scale modelling concerns the use of GCM and Atmosphere-Ocean General Circulation Models (AOGCM). These models can be used to simulate weather on a global scale for thousands of years. Unlike meso-scale techniques, AOGCMs take into account the changing condition of global climate controls such as the extent of sea-ice, vegetation coverage, and the complex interaction between the oceans and the atmosphere. In doing so, they are extremely useful for studying longer-term processes such as natural and anthropogenic climate change, as well as key weather pattern signals (e.g. NAO, AMO, ENSO).

European windstorm modelling has evolved considerably in recent years. Given that historically observed wind speed data has only been recorded for the last 50 years, and with varying granularity, it provides only a small window into the past with which to understand the frequency of this complex peril. However, given the advances in GCMs, probabilistic analysis, the reanalysis of historic data, and the downscaling[6] techniques EQECAT is now able to employ, European windstorm modelling is rapidly evolving.

In creating *Eurowind*TM (a fully probabilistic risk model that quantifies prospective risk from windstorms in 24 countries across Europe), EQECAT makes use of these latest capabilities. We combine over 50 years of historically observed wind speed data (from thousands of meteorological stations across Europe) with a 1200-year climate simulation from using an AOGCM to inform on the key parameters of this peril. Historic storm seeds are used to develop a stochastic catalogue of synthetic storms. Using a perturbation approach, theoretical distributions are fitted to major parameters of historical storms (e.g. SSI, duration, track, severity) to probabilistically generate new storms. This historic and synthetic storm catalogue features ~20,000 events. Making use of a state-of-the-art AOGCM model, we are able to validate key metrics, such as storm frequency, clustering, and the spatial coverage of European windstorms. Likewise, in downscaling these large cyclonic events, we employ a combination of both deterministic and probabilistic modelling techniques. For example, the latest global land use information and digital elevation data (DEM) are combined to accurately modify wind behaviour, together with local gust parameterization to model the damaging surface winds of an Extra Tropical Cyclone.

EQECAT does not incorporate future climate change scenarios into its standard catastrophe models. It would be largely premature to do this given the enormous volatility in catastrophic event activity on annual and decadal timescales. However, given the use of historically recorded wind speed data over the last 50 years in constructing EQECAT’s European windstorm model, climate variability during this time could be considered to be implicitly built into the model. From an industry perspective, EQECAT’s paradigm is to remain focused on our clients' need to write business in today’s market and concentrate on quantifying the current risk via the best available science and data.

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[6] Downscaling methods are developed to obtain local-scale surface weather from regional-scale atmospheric variables that are provided by GCMs.

EUROPEAN WINDSTORMS

By Madeleine-Sophie Déroche, Junior Analyst at Climate-KIC / LMD / LSCE

EUROPEAN WINTER WINDSTORMS ASSOCIATED WITH EXTRA-TROPICAL CYCLONES

ETCs are one of the main atmospheric phenomena of the mid-latitude regions, where they are responsible for episodes of strong surface wind speeds and rainfall. In the northern hemisphere, the development of such systems is favoured during the autumn and winter seasons (October to March), when the temperature difference between the Equator and the Poles is the strongest. Intense ETCs associated with extreme surface wind speeds (also called windstorms), are generated over the North Atlantic region and sometimes reach Western and Central Europe. They can cause wind-related damage as well as flood events (Kyrill, 2007) and storm surges (Xynthia, 2010).

The dynamical processes at the origin of the development of extreme ETCs have been studied either by focusing on one specific windstorm that caused important damages[xxv,xxvi,xxvii] or by comparing the meteorological situation for a group of extreme ETCs[xxviii,xxix]. A key process that emerges is the interaction and mutual amplification of anomalies at the upper and lower levels of the troposphere through vertical motions. Extreme ETCs are more frequent and more intense during the positive phase of the North Atlantic Oscillation (i.e. main atmospheric pattern driving the weather over Europe in winter), and are more likely to reach Europe with a strong polar jet stream (i.e. eastward wind at 11 km height).

OBSERVED TRENDS IN EUROPEAN WINTER WINDSTORMS IN THE RECENT PAST

The assessment of windstorm trends depends on the type of data that are used. Studies that consider storminess over the North Atlantic region (either from wind speed or pressure measurements from meteorological stations) find significant variations at decadal and longer time scales, with a minimum of storminess around 1960 and a maximum around 1990. Values of storminess at the beginning of the 21st century are as high as those at the beginning of the 20th century[xxx,xxxi,xxxii]. However, when looking at trends in specific countries and for shorter time periods, one finds that local variations do not coincide with the ones from the more extended North Atlantic region[xxxiii,xxxiv]. This highlights the importance of the chosen geographical area and the length of available records when dealing with trends of atmospheric processes with a high natural variability. Reanalysis datasets, in other words assimilation of observations into climate model, are another type of meteorological data that are used to analyse the recent past. Studies focusing on storminess over Europe find an increase over different periods of time[xxxv,xxxvi].

Observed increasing trends in wind-related damage during the last decades seem to be mainly due to an increased vulnerability of the population and of natural environments. On the one hand, the increase in economic losses associated with windstorms can be explained by the growth of insured population in exposed areas[xxxvii,xxxviii]. On the other hand, a warming climate may impact natural environments, making them more vulnerable to windstorms. In Switzerland, warmer and wetter winters have been observed over the last decades impacting the quality of soils and favouring forest damages during windstorm events[xxxix].

GLOBAL CLIMATE MODELS

GCMs compute the three-dimensional time evolution of the atmosphere and the ocean, including the wind or current, temperature and moisture content. The models divide the atmosphere into “boxes”, where each meteorological variable is represented by one value. The equations of motion are then discretized over these boxes and solved; processes that occur at a scale smaller than the box size are represented implicitly. The performance of GCMs follows the technological evolution of supercomputers, leading in particular to more and smaller boxes.

An advantage of using GCMs for weather-related risks is the opportunity to analyse all the factors that contribute to or hinder the development of a specific phenomenon[xl]. The low resolution (large boxes) of previous generations of GCMs led to a poor simulation of ETCs, but many current GCM simulations now yield a sufficient resolution to investigate ETCs from both physical and impact perspectives. The comparison with reanalysis datasets for the current period indeed shows that ETCs are now well simulated[xli]. Storm tracks over the North Atlantic region are well represented even though there are still some biases affecting the number of ETCs reaching Europe and their intensity[xlii].

CLIMATE CHANGE MODELLING: FROM SRES TO RCPS

Since the 1990s, the IPCC has coordinated a worldwide assessment exercise consisting of a review of published scientific research papers. Synchronised with the IPCC reports, a number of model inter-comparison projects (MIP) use GCMs from major worldwide institutions to assess the impact on climate of both past and future emissions of greenhouse gases (GHG) and aerosols that change the energy balance of the Earth. The modelling of future climate change and its impacts is based on projected emission scenarios.

Since the first IPCC assessment report (FAR) in 1990, four sets of emissions scenarios have been released and the approach used to define them has evolved[xliii]. The three first sets were based on assumptions on the potential evolution of economic and population growth, energy supply and consumption patterns, development of clean technologies and undertaken climate policies. In 2000, the scenarios from the Special Report on Emission Scenarios (SRES) encompassed a wider range of uncertainties and took into account more social, political and economic factors than scenarios back in 1990[xliv,xlv,xlvi]. From these socio-economic storylines, time series of GHG emissions were derived and used to force GCMs. It took several years to complete this sequential process, leading to a high risk that the basic socio-economic assumptions would change, be verified or proven false.

Since 2008, a new approach to design emission scenarios has been chosen for the purpose of the last IPCC assessment report (AR5)[xlvii]. The new emission scenarios, named Representative Concentration Pathways (RCPs), are now based on the identification in the existing literature of possible levels of radiative forcing by 2100. Socio-economic assumptions do not underlie the RCPs and possible paths leading to these levels of forcing are thus no longer restricted to only one per emission scenario.

PROJECTED TRENDS FROM MODELS PARTICIPATING TO THE FIFTH COUPLED MODEL INTERCOMPARISON PROJECT (CMIP5)

The latest model inter-comparison project (CMIP5) a worldwide coordination between climate institutes running their GCMs in the purpose of the assessment of climate change impact. A study comparing the results from different ETC detection methodologies applied to one CMIP5 model finds an increase in the number of intense ETCs in the Northern Hemisphere[xlviii]. However looking at the response of the storm tracks to climate change, results differ from one model to the other. In order to explain these differences, it is possible to analyse in detail within each GCM the processes surrounding the occurrence of ETCs[xlix]. It has been shown that changes in the meridional (i.e. northward) and vertical gradients of the temperature have competing effects and it is difficult to assess what the overall impact would be. Another important factor is the increase in atmospheric moisture content that provides a latent heat reservoir increasing the potential intensification of individual ETCs, but also will have a general weakening effect on the development of ETCs by enhancing the energy transport from the Equator to the Pole and reducing the temperature difference.

UK FLOOD

By Professor Rob Lamb, Chief Scientist, Richard Wylde, Meteorologist, and Jessica Skeggs, Hazard Mapping Specialist at JBA Group

THE EVIDENCE FOR CHANGE IN THE UK

Although winter rainfall totals have changed little in the last 50 years and annual totals appear not to have changed significantly since records began in 1766, over the last half century an increasing proportion of the UK's winter rain has fallen during intense wet spells. Additionally, a report on historical trends[l] in the UK climate concluded in 2008 that sea levels have risen around the UK over the past century.

Past and present greenhouse gas emissions mean further climate change is inevitable in the next 20 to 30 years no matter how emissions change in the future. Current UK climate projections[li] are based on the analysis of outputs from multiple climate models and scenarios for future greenhouse gas emissions. However, predicting the influence of human-induced change is complicated by the internal variability in the climate system. Over the next few decades, this internal variability is a major source of uncertainty. It is estimated to account for nearly half of quantifiable uncertainty associated with regional winter precipitation changes for the period 2010-2019, compared with only a quarter of the prediction uncertainty by the 2080s[lii]. Even so, statistically significant changes in accumulations of winter rainfall (the type of weather pattern associated with some major recent floods such as in the winter of 2000) could be detectable by the 2020s[liii]. For the shorter intense storms that are associated with surface water flooding, there is more variability and so it will take longer to detect significant trends. Despite this, there are accepted physical mechanisms by which an increase in extreme rainfall should be expected and emerging observational evidence in support of this[liv].

Long term records of river flooding also paint a complex picture. River flows are affected by changes such as land use and drainage works as well as by the climate, and there is little statistical evidence for long-term trends in maximum river flows over the last 80 to 120 years despite many shorter-term fluctuations[lv]. This evidence does not rule out the possibility that climate change has affected river flooding, or that it will do so in future, although it does illustrate that long-term trends are difficult to identify when set against the variability of river flow records.

Recent studies[lvi] have used climate models to attribute specific flooding events, at least in part, to climate change. For the UK it has been suggested[lvii] that there was very likely to have been at least a 20% increase in the risk of occurrence of the winter of 2000 floods (which damaged almost 10,000 properties and led to insured losses worth an estimated £1.3 billion, or £1.85 billion at today's values) associated with human-induced climate change. These conclusions are dependent on a complex chain of models and assumptions, and may not necessarily reflect future changes. However, they do provide emerging evidence of an increasing risk of inland flooding in the UK and form part of a growing international evidence base on the attribution of extremes – despite individual weather events having not been previously[lviii] attributed to climate change.

FUTURE CLIMATE CHANGE

Over longer time horizons, the greenhouse gas emissions are expected to have an increasing influence on predicted climate in the UK. By the 2050s, there is clear divergence in the latest UK climate change projections between alternative future greenhouse gas scenarios. By the 2080s, UK projections shows that there could be around three times as many days in winter with heavy rainfall (defined as more than 25mm in a day) as in the recent past. It is plausible[lix] that the amount of rain in extreme rain storms (defined as storms with a 1 in 5 annual probability, or rarer) could increase locally by 40%.

The impact of climate change on river flooding is highly dependent on the geography of the river catchment. Research based on climate models that have been used in the UK projections shows a range of increases in peak river flows from 10% to 15% over the period between 2015 and 2039, rising to a range of 20% to 30% by the 2080s[lx]. Flood risk is, of course, also affected by property development and by investment in flood risk management measures.

Sea levels around the UK are projected to rise too. The predicted changes depend on what assumptions are made about future greenhouse gas emissions, and on the method used to characterize scientific uncertainty in the modelling. For the UK climate projections, central estimates of sea level rise for a medium emissions scenario (a world in which there is less, but still increasing reliance on fossil fuels) are in the range 24-36 cm by the 2080s, relative to 1990 levels[lxi]. However under a high emissions scenario (in which reliance on fossil fuels continues to increase rapidly) there is a chance that sea level could rise by approximately 70 cm. There are credible (though unlikely) extreme scenarios that would lead to even greater increases in sea level of up to 1.9m.

WHAT DOES THIS MEAN FOR FLOOD RISK?

The UK Government's Adaptation Sub Committee has reported that "current levels of investment in flood defences and in the uptake of protection measures for individual properties will not keep pace with the increasing risks of flooding. Climate change could almost double the number of properties at significant risk of flooding by 2035 unless there is additional action."[lxii] The Environment Agency estimates that investment needs to increase by £20 million above inflation every year merely to stand still and avoid increasing the risk associated with climate change and deterioration of flood defences. Increased investment to counter projected climate change could bring about a four-fold reduction in the risk of flooding compared with a scenario of no additional action.

DO FLOOD RISK MODELS ACCOUNT FOR CLIMATE CHANGE?

The UK climate projections are gradually being incorporated into flood risk models used for the purposes of local flood risk management and investment plans. Assessments of risk at national scale are also building in climate change to inform long-term investment strategy[lxiii]. The UKCP09 projections provided a step change in the available detail, and for the first time a probabilistic treatment of the scientific uncertainty in the climate models. There are case studies demonstrating the application of the probabilistic projections in assessing future flood risk[lxiv,lxv], but these require advanced modelling methods and are not yet routinely applied.

Box 1 demonstrates the sensitivity of flood risk to future climate change for a part of the River Thames basin, based on detailed flood risk mapping and scenarios derived from the latest UK climate projections.

In the insurance industry, probabilistic catastrophe models from companies such as AIR, EQECAT, JBA and RMS are available to assist insurance companies assess their likely losses due to flooding in the UK. Most catastrophe models are based on long term data which may have a signal of climate change from the recent past inherently present within them. However, uncertainties associated with the estimation of both the degree to which climate change is occurring and to the resulting change in local flood severities and frequencies means that the impact can be difficult to account for in risk models. The catastrophe models used today to consider UK flood risk (both river and sea surge) do not, therefore, explicitly model the impact of future climate change.

FORWARD LOOK

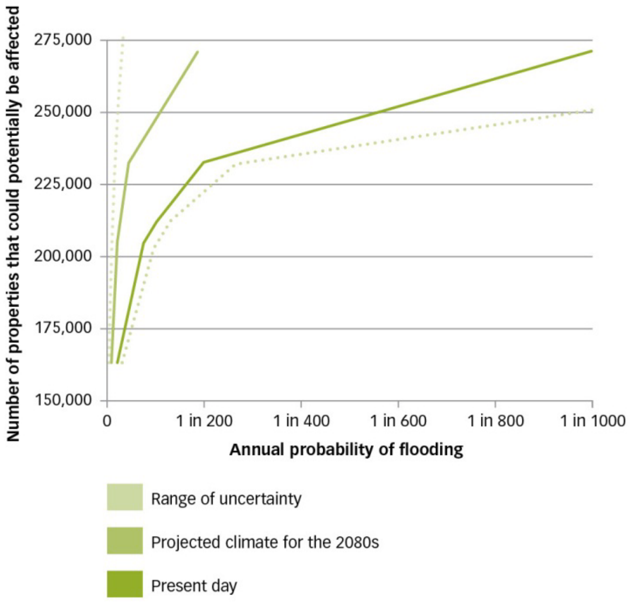
Future climate change is inherently uncertain because we cannot be sure about how greenhouse gas emissions may be changed by economic development, technology and government policies around the world. However climate models are driving towards greater spatial detail and better resolution of key physical processes. Over the next decade it is possible that weather forecasting and medium-term climate models may start to converge, giving better foresight of weather at the annual scale and more precise projections about how the climate will respond over the longer term to changes in the atmosphere caused by human activity. Allied to these changes, we can expect progress in the representation of internal variability, and a view of future climate that includes better knowledge of variability as well as of average conditions.

There should be more explicit accounting for uncertainties, especially in predictions made by hybrid models that integrate climate, weather and flood risk more closely than at present. Models used to predict flooding will become more efficient and able to provide better information at property level. Side-by-side with these developments, JBA can anticipate greater integration of projections of climate with other changes (such as land use change, flood mitigation investments and industry losses). Studies[lxvi,lxvii] have already stressed the need to quantify climate change in catastrophe modelling. It is anticipated that methods to do this will develop if, as expected, the effects of climate changes become more apparent over the coming decades. This process must be properly structured and make good use of the evolving climate science, and so communication between researchers, catastrophe modellers and insurers is expected to be important.

Box 1 Climate change sensitivity of river flooding in Thames region.

The graph below shows a projected range of climate change impacts on the number of properties at risk of river flooding with an annual probability of once in 1,000 years, or greater, in the Thames region of England, in and around London. The analysis is based on detailed flood maps produced by JBA Risk Management using its 2D hydrodynamic flood modelling software JFlow combined with high resolution (5m horizontal resolution or greater) digital terrain data (courtesy of Astrium) and Ordnance Survey AddressPoint data, which is used to identify the location of properties within the floodplain.

The implications of climate change are assessed using data derived from the UK 2009 Climate Projections (UKCP09) and converted into a plausible range of changes in flood flows estimated by the Environment Agency in England for adapting to climate change in flood risk management economic appraisal[lxviii]. The data here show the baseline situation ("present day", reflecting the climate of the recent past) and projections for climatic conditions that are projected for a period around the 2080s (assuming no other changes such as development or increased flood defences). The range of projections is wide because it includes uncertainties related to climate modelling and also assumptions made in the UK climate projections about future greenhouse gas emissions. Although the uncertainty analysis includes the possibility of no increase or even a small reduction in risk, the results suggest a far greater likelihood of a substantial increase in the number of properties that could be affected by river flooding.



Climate change sensitivity of river flooding in Thames region

NORTH ATLANTIC HURRICANES

By Paul Wilson, Senior Director, Model Development at RMS

Hurricanes pose the single greatest threat of catastrophic damage to the vast insurance and population concentrations along the US eastern seaboard, gulf coast and throughout the Caribbean. This case study explores two ways in which the sensitivity of modelled hurricane catastrophe losses are influenced by factors related to climate change. The study will outline the basic structure of hurricane 'cat' models, the development of medium-term rate sets and the influence of climate change on such forecasts. The final section will present a brief study of sea-level rise on modelled loss results for Superstorm Sandy.

The potential for climate change to affect the behaviour of tropical storms in general and Atlantic hurricanes in particular has been a topic of significant debate in the scientific community - the key challenge lies in determining if the observed signal exceeds the variability expected from natural causes. In 2010 Knutson et al. concluded that it is uncertain if past changes in tropical cyclone characteristics exceed the variability expected due to natural causes and that projections of future changes are of low confidence for individual basins[lxix]. Exceptions to this statement are important; the frequency of most intense storms are expected to increase in most basins and secondary loss characteristics like tropical cyclone rainfall have a much higher likelihood of increasing significantly for most storms. Understanding to what extent catastrophe loss models already factor in these changes is important in understanding how these models may evolve to capture any changes to the risk in the future.

Catastrophe models use complex statistical and physics-based models to extrapolate the observed data to produce physically consistent, event based, representations of all possible hurricanes. Traditionally hurricane models have relied on statistical track models coupled to parametric models of hurricane wind-fields to define the damage footprints of storms. Increasingly numerical models which capture the storm dynamics are being used to supplement statistical models and expand the input in data sparse regions. Similarly the complexity of models continues to evolve capturing more of the secondary characteristics which can impact the potential losses. The most sophisticated models now include explicit modelling of storm surge over the lifecycle of each event and in the future extreme rainfall and tropical cyclone induced flooding will become a standard contribution to the total modelled loss.

CLIMATE CHANGE AND MEDIUM TERM VIEWS OF NORTH ATLANTIC HURRICANE ACTIVITY

It is common practice for 'cat' models to be defined according to the long-term climatology. This is particularly true of frequency assumptions where a direct calibration to the long-term historical record is common. In fact in some regions of the US such conditions are a regulatory requirement. Atlantic hurricane risk is however known to be non-stationary; aside from the well-known seasonal modulations driven by climate modes like the El-Niño Southern Oscillation (ENSO) the observations, particularly in the basin, indicate that periods of higher and lower hurricane frequency can persist for decades. Debate still exists as to the driving mechanism behind such variability – i.e. are natural oscillations, such as the Atlantic Multi-decadal Oscillation (or Atlantic Meridional Mode), or human influences, such as aerosol pollution in the 1970s and 80s, the driving mechanism? Whatever the cause it is clear that when using catastrophe models to manage hurricane risk over the duration of multi-year insurance contracts it is important to consider how the models deal with the inherent variability in hurricane frequency. Using the average of all long-term historical activity will tend to overestimate the risk during periods of lower activity and underestimate the risk during periods of higher activity. To account for this, in 2006, RMS released the first version of its north Atlantic hurricane model to specifically recognise the current higher phase of activity by forecasting the expected activity over the next 1-5 years. At the time this 'medium-term rate' methodology relied on an expert elicitation process, where leading experts in hurricane climatology were tasked with defining the expected activity. Over the next 7 years this methodology evolved alongside the scientific research on hurricane activity into an objective statistical forecast derived from a suite of statistical models, weighted depending on each model ability to hind cast (retrospectively forecast) previous periods of history.

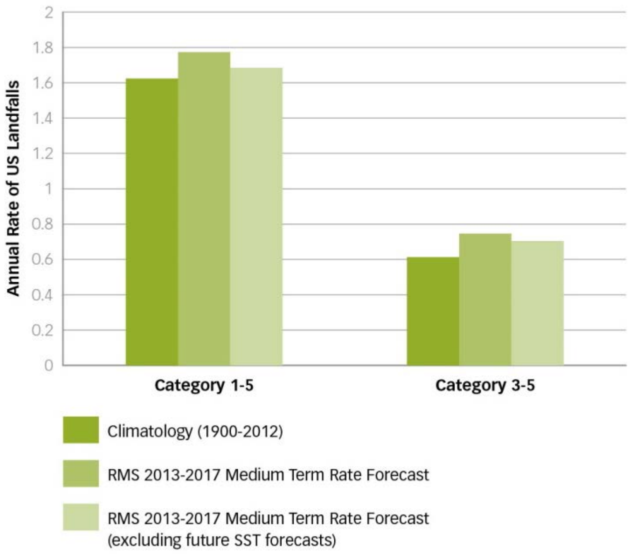


Figure 5: RMS's 2013-2017 US landfall rate forecast with and without the inclusion of SST based forecasts compared to the 1900-2012 climatology for both category 1-5 and category 3-5 landfalls

A key aspect of the methodology is the relationship between sea surface temperatures, particularly in the main hurricane development region of the Atlantic, and hurricane activity. Laepple et al. (2008) demonstrated that, using climate model output skilful forecasts of sea-surface temperatures could be made on these timeframes[lxx]. Based on this result RMS's medium-term rate forecast explicitly considers the trend in sea-surface temperatures represented in climate change projections as part of its construction. While the inclusion of such trends is important in accurately defining the risk, and accounting for all the potential theories of higher hurricane activity, the relative contribution to the current forecasts of activity can be shown to be small compared to the multi-decadal variability observed in the historical data. Figure 5 shows the current RMS medium-term hurricane landfall rate forecast for the US coastline both with and without the inclusion of such sea surface temperature forecasts. The percentage increase in category 1-5 and category 3-5 landfall forecasts over the 1900-2012 climatology decreases from 7 to 3% and 18 to 13% respectively when sea-surface temperature forecasts are excluded.

SEA LEVEL RISE AND STORM SURGE RISK

The final section of this case study will focus on storm surge. The importance of what had previously been considered, and modelled, as a secondary loss characteristic was highlighted dramatically by Katrina in 2005, Ike in 2008 and again by Sandy in 2012. Sandy caused an estimated $20-25 billion of insured losses mostly in New York and New Jersey largely arising from flooding due to the storm surge associated with what was a relatively low wind speed, albeit a large storm[lxxi]. Much has been made of the fact that Sandy made landfall near high tide and the anomalous, but by no means unexpected, path taken by the storm when it interacted with a second low pressure system- Hall and Sobel estimated a 700 year return period for Superstorm Sandy's track[lxxii]. The contribution of sea-level change has however only recently be highlighted.

Superstorm Sandy broke 16 historical tide records along the east coast[lxxiii] and Sweet et al. (2013) have estimated a one-to-two third decrease in the return period of a Sandy level event recurrence between 1950 and 2012 due to global sea-level rise (thermal expansion and ice melt), ocean circulation variation and subsidence. Previously Lin et al. (2012) had examined the potential implications of sea-level rise in New York, indicating a dramatic increase in the risk of storm surge with increases in sea-level[lxxiv] and Hoffman et al. (2008) had examined the potential increases in loss due to sea-level rise from the perspective of a catastrophe loss model for the entire United States[lxxv]. Following these studies Figure 6 shows the impact of sea-level change on RMS's storm surge model recreation of Superstorm Sandy. Figure 6a shows the monthly mean sea-level recorded at the Battery in New York from 1900 to 2012. Figure 6b shows the modelled full ground-up surge only losses for New York with between plus and minus 85 centimetres of sea-change. The approximately 20 centimetres of sea-level rise at the Battery since the 1950s, with all other factors remaining constant, increased Sandy's ground-up surge losses by 30% in New York alone. Further increases in sea-level in this region would non-linearly increase the loss potential from similar storms. Catastrophe models that dynamically model surge based on current mean sea-level already factor this increased risk into their projections.

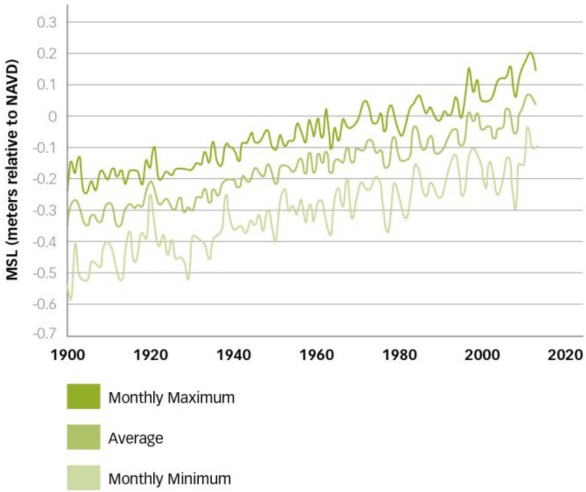


Figure 6a: Monthly mean and monthly range of mean sea level (in meters relative to the North American Vertical Datum) as recorded at the Battery (NYC).

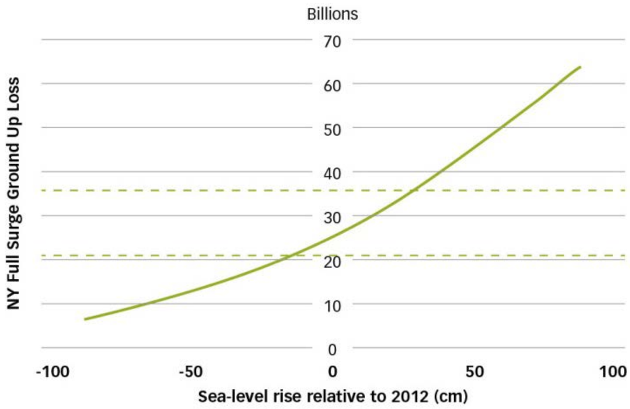


Figure 6b: Full Ground-up surge only loss based off the RMS Superstorm Sandy reconstruction with between +/-85cm of sea-level change (input as a boundary condition to the model analysis). Losses are based off the RMS industry exposure database. For additional context the blue dashed lines represent the 90% percentile range of loss from various tidal conditions using current mean-sea level.

CONCLUSIONS

This case study has briefly examined the extent to which climate change currently impacts the results of catastrophe loss models. The influence of trends in sea surface temperatures are shown to be a small contributor to frequency adjustments as represented in RMS medium-term forecast. This result mirrors statements made in studies of detection and attribution of climate change in tropical cyclone activity where natural variability is considered to dominate on the timeframes of interest (1-5 years). The impact of changes in sea-level are shown to be more significant, with changes in Superstorm Sandy's modelled surge losses due to sea-level rise at the Battery over the past 50-years equating to approximately a 30% increase in the ground-up surge losses from Sandy's in New York.

US SEVERE THUNDERSTORMS AND SOUTH PACIFIC TROPICAL CYCLONES

By Ioana Dima, Senior Research Scientist, and Shane Latchman, Manager of Research and Consulting and Client Services at AIR Worldwide

The table below provides the key features of the two models discussed in this article: U.S. Severe Thunderstorm and South Pacific Tropical Cyclone.

Model Characteristic	U.S. Severe Thunderstorm	South Pacific Tropical Cyclone
Number of Simulated Years	10,000	10,000
Number of Simulated Events	409,000	408,044
Region covered	48 Contiguous states in U.S.	15 South Pacific islands
Perils Modelled	Straight line winds, hail, tornado	Tropical cyclone, precipitation induced flood, storm surge
Climate Change incorporated	10,000	10,000
Number of Simulated Years	Only to the extent that a climate change signal is present in the historical data used in the model calibration	
Exposure considered	Buildings and contents	Buildings, infastructure and crops

SEVERE THUNDERSTORM RISK IN THE UNITED STATES: PAST TRENDS AND FUTURE PROJECTIONS

Thunderstorms represent an essential component of the climate system as they act to redistribute heat, moisture, and trace gases in the atmosphere, both horizontally and vertically. Thunderstorms can pose great danger to communities and can cause catastrophic social and economic damage through flash flooding, strong winds, damaging hail, and deadly tornadoes. But often such storms are also viewed as beneficial, providing much needed rainfall to agriculture and the freshwater supply.

Based on recent research studies using numerical weather models to evaluate the current activity in severe storms[lxxvi], no statistically significant trends have been identified in the data. This is consistent with an AIR study carried out in 2010, which analysed the recent historical record using data from NOAA's Storm Prediction Centre (SPC). Figure 7 shows the observed yearly counts in tornadoes, hail and damaging wind events from 1995 to 2010.

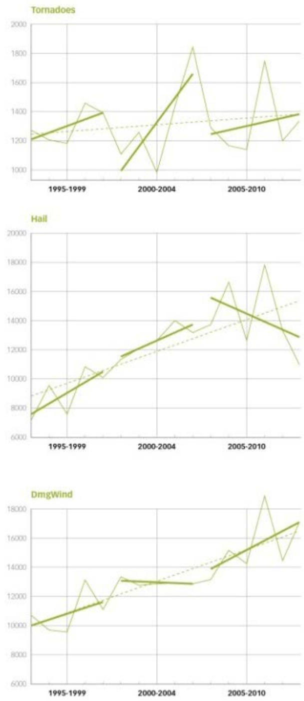


Figure 7: Yearly count for each peril (thin solid line) with 5-year trends (heavy solid lines) and the 15-year trend (thin dotted line) superimposed

For tornadoes (upper panel) there is no significant long term trend throughout the data, while for hail (middle panel) there is an upward trend when considering all 15 years analysed, but that is called into question by the last 6-year period that shows a clear downward trend. The damaging wind counts (bottom panel) show an upward trend but the trend value is much reduced when considering only the stronger wind classes.

The validity of any of those trends is uncertain given the large number of issues with the data.

A question that is often posed is whether there are any trends in the economic and insured losses. Trended losses from Property Claim Services® are shown in Figure 8. There is a lot of year to year variability in the observed storm losses, but there is no strong evidence to suggest the existence of a statistically significant trend.

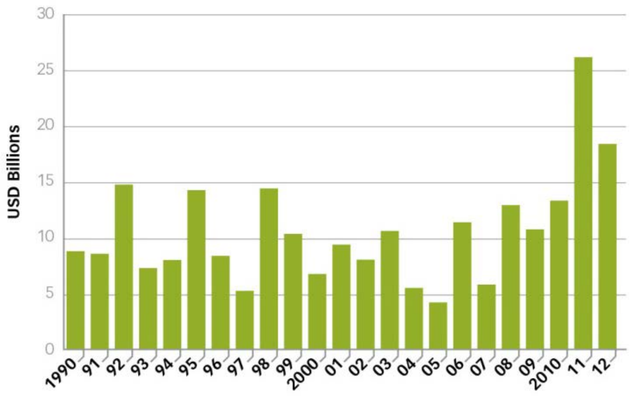


Figure 8: US severe thunderstorm losses (trended to 2012) as reported by PCS

In 2011, there was record-breaking damage from severe thunderstorms in the US, and indeed 2011 stands out in Figure 8 as an outlier when compared to previous years.

So what happened that year? Some of the climate conditions speculated to be correlated with higher severe thunderstorm activity were present in 2011. But more than that, 2011 was most likely a case of unlucky coincidence, with major outbreaks occurring in areas of high exposure.

And how does climate change influence severe thunderstorms? The observed warming of the planet generally results in two competing mechanisms that ultimately can alter the severe thunderstorm risk:

- A weaker lower level global temperature gradient between equator and poles which in turn causes a weakening of the vertical wind shear. Since wind shear is a crucial ingredient for severe thunderstorm formation and development, this would result in a reduced probability of severe thunderstorms occurring in the future.

- An increase in vertical instability and low-level moisture would result in an increased probability of severe thunderstorms in the future, since both these factors are important for the formation and development of thunderstorms.

Model results consistently show that, independent of other factors, the increased moisture in a future warmer world would result in increased intensity of precipitation events[lxxvii]. A recent study of severe weather sees a higher risk of thunderstorms by mid-century through projected increases in severe atmospheric environments[lxxviii]. Similarly, a paper by Sander et al. (2013) finds higher peaks and a greater variability in thunderstorm-related losses in the last two decades compare to the preceding two decades[lxxix]. However, extensive previous research into these processes[lxxx,lxxxi,lxxxii,lxxxiii,lxxxiv,lxxxv,lxxxvi] has not provided any definitive conclusions about a future change in the peril. Thus, whether we should expect more or fewer storms in the future, and whether they will be more or less intense, are still open questions.

There are several factors that need to be considered when evaluating severe thunderstorm data and especially the existence of any trends in this data:

- Thunderstorm reports are not produced by standard instrumentation but instead rely on human reporting – thus demographic considerations such as the proximity of population to events must be taken into account when working with such data

- Reporting of severe thunderstorms has changed over time due to factors such as weather RADAR and the proliferation of the internet. Also, dedicated storm spotters have impacted the data collection process, potentially increasing observed frequency.

Hence, an increase in severe thunderstorm losses cannot readily be attributed to climate change. Certainly no individual season, such as was seen in 2011, can be blamed on climate change. There are several other factors that can contribute to the increase in losses in any given year: multiple storms affecting more urban areas, the exposure value increasing in the urban and suburban areas, the population increasing in formerly rural areas, as well as changes in construction practices by the roofing industry.

In 2014, AIR is preparing to release an important update to its Severe Thunderstorm Model for the United States. This update aims to incorporate the latest research and scientific studies on the topic, as well as utilizing all available SPC data through 2011. In addition, AIR researchers are employing several new smoothing and data augmentation methods to supplement the SPC data, including the use of high-resolution radar data to better account for hail micro-events, statistical de-trending methods to account for population growth, and meteorological parameters that realistically capture atmospheric conditions favourable for severe thunderstorm formation.

Uncertainty remains surrounding definitive conclusions on the impact of climate change on severe thunderstorms. Hence, climate change is represented in the model only to the extent that a climate change signal is imbedded in historical severe thunderstorm data on which the model's stochastic catalogue of events is based.

TROPICAL CYCLONE RISK IN THE SOUTH PACIFIC REGION: MID- AND END-OF-CENTURY PROJECTIONS

AIR carried out a tropical cyclone risk assessment for 15 Pacific island countries (identified in Figure 9) through the World Bank's Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI). The study considered the effects of tropical cyclone wind, precipitation-induced flood, and storm surge. The South Pacific region is known for the frequent occurrence of tropical cyclones. In the last 60 years, the Pacific Region from Taiwan to New Zealand in latitude and from Indonesia to east of Hawaii in longitude has experienced 41 tropical cyclones per year, on average. Almost 16 per year formed south of the equator and 25 per year formed north of the equator.

Scientists have noted that even though the global annual frequency of all tropical cyclones has remained constant, notable changes have been observed regionally: a decrease in the total number of tropical cyclones was observed in the Northwestern Pacific and an increase was noted in the North Atlantic[lxxxvii]. Furthermore, an upward trend was found in the global proportion of category 4-5 hurricanes, offset by a similar decrease in the proportion of category 1-2 hurricanes - a relationship that is reproduced in each ocean basin.

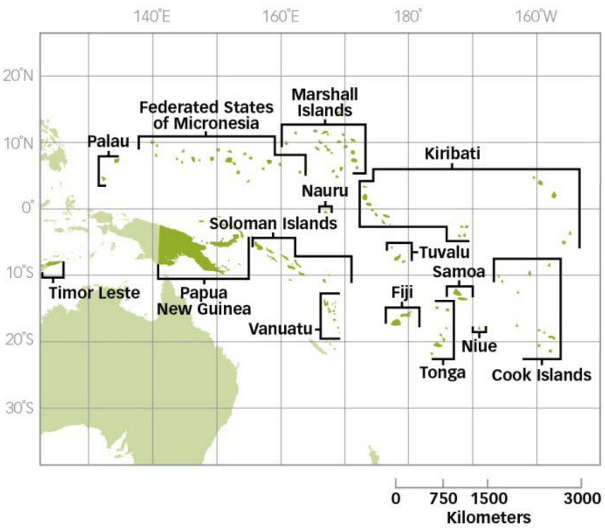


Figure 9: The South Pacific region and the location of the 15 countries considered in the model

It is uncertain whether these observed trends will continue into the future. The community consensus delivered via the latest IPCC report (SREX/IPCC, 2012) states that the global average tropical cyclone maximum wind speed is likely to increase in the future, although increases may not occur in all ocean basins. Also, the report states that it is likely that the global frequency of tropical cyclones will remain essentially unchanged.

For the study AIR carried out for the South Pacific, Geoscience Australia provided general circulation model output from a total of 11 different GCMs from two generations of GCM experiments, referred to as CMIP3 and CMIP5. The CMIP5 models are the next generation of GCMs and therefore represent the most up-to date understanding of the climate system. For both hemispheres, there is an expected future increase in the relative frequency of tropical depressions, tropical storms, and category 5 storms and a general decrease in the number of storms in other categories. Most notable is the increase in category 5 storms which may have a measurable impact on observed losses in the region.

Sea surface temperatures in most regions of tropical cyclone formation have increased by several tenths of a degree Celsius during recent decades. Most scientists believe that the increase in human-induced greenhouse gas have very likely contributed to this warming[lxxxviii]. The upper layer of the ocean represents the main source of energy for tropical cyclone formation and development. Ocean warming therefore has a direct impact on the intensity and life cycle of such storms by providing more energy to the storms and allowing for a possible increase in severity and frequency. Note that no future increases in precipitation and sea level were considered in the analysis.

Another direct consequence of a warmer ocean is the melting of glaciers and the thermal expansion of ocean water. Both these effects increase the volume of the ocean, raising its surface level. Further increases in sea level would consequently result in higher storm surge levels associated with tropical cyclones.

The small low-level islands in the South Pacific are directly experiencing the effects of sea level rise. A telling example is the case of the low-lying Pacific nation of Kiribati, which is currently negotiating to buy land in Fiji so it can relocate its islanders under threat from rising sea levels. Meanwhile, a Japanese company has proposed building a 'floating nation' for Kiribati, with the help of a set of circular, vast "lily-pads" on the surface of the ocean (Figure 10).

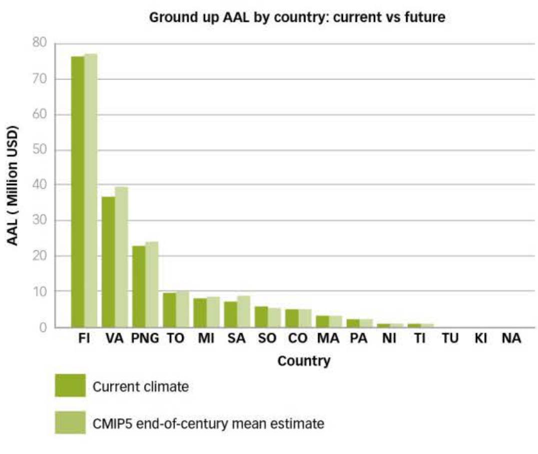
Figure 10: Concept design for an artificial Kiribati (Source: The Daily Telegraph)

There are several other factors that need to be considered when estimating current and future tropical cyclone risk. The size of the island (which affects storm degradation and surge), the island land cover (which impacts frictional effects on the storm), and topography (which impact storm surge and wind flow), are all key factors in evaluating the associated tropical cyclone hazard for each country. Equally important in determining the local and regional risk are the inevitable changes in coastal population and exposure and the migration of the population within each country and from one country to another. On the vulnerability side, one should also consider any building code improvements that have been or will be implemented over the years, specific changes in building construction materials as well as implementation and mitigation practices.

Updates to the current AIR model for the region are being considered as more historical data is gathered and as new scientific findings become generally accepted by the scientific community and therefore can be included within the modelling framework. The model and its associated stochastic catalogue of tropical cyclones is a reflection of the current state of the climate. Any natural or anthropogenic climate variability signals existing in the historical record are thus implicitly part of the current catalogue.

For the climate impact assessment, a climate conditioning process was developed and implemented in order to evaluate changes in losses for different climate change scenarios. The climate conditioning of the stochastic catalogue was done through a 'targeted sampling' method, where particular events are added or removed from the data set as informed by changes in the numerical model output from different GCMs, under different future climate change scenarios. Climate changes of particular interest for the project are those associated with changes in the relative frequencies of all category storms (from tropical depressions to category 5 tropical cyclones) and changes in the latitude of the mean tracks.

Figure 11 (left panel) illustrates changes in the current climate Average Annual Loss (AAL) under a future climate change scenario, for each country considered. Most countries (Micronesia, Cook Islands, Fiji, Papua, Samoa, Niue, Vanuatu, Timor-Leste, Tonga) observe increases in losses under the future climate. There are a few countries (Solomon Islands, Palau), however, where losses are projected to decrease on average, while other countries (Tuvalu, Marshall Islands, Kiribati, Nauru) observe minimal changes. Note that no adjustment to account for future economic or population growth was considered.



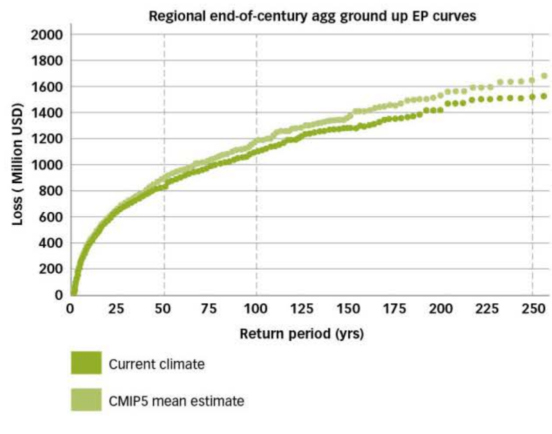


Figure 11: Left panel - end of century AAL future projections (blue bars) compared to the current climate (green bars) for the 15 countries considered. Right panel - regional (all countries) end of century EP-curve for the future climate (blue curve) compared to the current climate (green curve)

Comparing regional return period losses (‘regional’ refers to all countries in the study region), as shown in Figure 11 (right panel), reveals that the loss curve for the current climate consistently sits below the higher loss future climate curve. At the 250 year return period, the mean estimated loss for all islands increases by 8%, while the worst case scenario among the full range of individual models indicates a much more significant possible increase in loss of 25%. The current regional average annual loss is expected to increase by 1% by mid-century and by 4% by the end of the century.

CONCLUSIONS

A review of the available literature shows there is no common outlook on the impact of climate change on severe thunderstorm activity, and analyses carried out by AIR on storm data did not show a statistically significant trend across all different perils.

For tropical cyclones in the South Pacific, the analysis of global climate model output in combination with AIR’s catastrophe models results in a small general increase in losses across various return periods. This impact could be exacerbated by rising sea levels on storm surge loss which was not explicitly incorporated into the modelling output described here.

INCREASING HURRICANE INTENSITY WITH WARMING SEAS: IMPLICATIONS FOR RISK MODELLING

By Professor James B. Elsner, President of Climatek

OBSERVATIONS

We find that hurricanes are getting stronger worldwide but especially over the North Atlantic[lxxxix]. The upward trend in hurricane strength is physically and statistically related to the warming seas[xc]. We estimate that the increasing intensity of the strongest hurricanes amounts to about 10 m/s per degree Centigrade (Celsius) of warming.

The estimates are made in two ways, one by regressing the limiting hurricane intensity onto sea-surface temperature (SST) (see Figure 12) and the other by regressing the lifetime highest wind speed onto SST controlling for El Nino (see Figure 13)[xci].

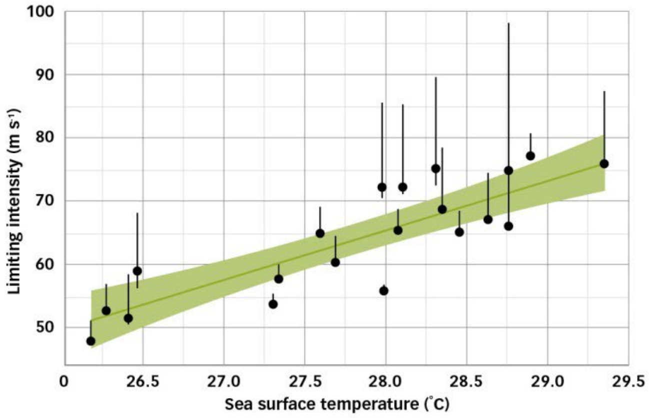
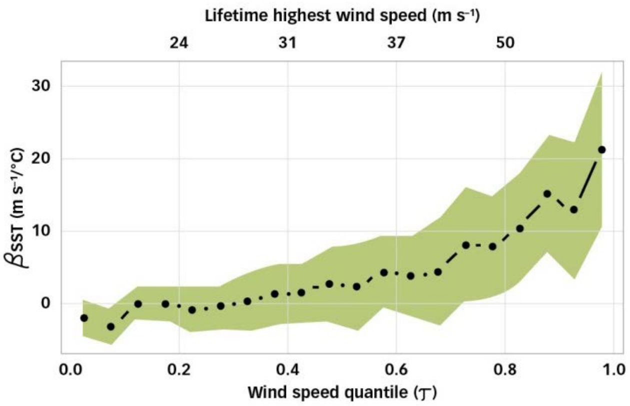


Figure 12: Sensitivity of limiting hurricane intensity to SST based on the U.S. National Hurricane Center's best-track hurricane data interpolated to one-hour values and the U.S. National Oceanic and Atmospheric Administration's SST data averaged over the months of August through October. The analysis is done using data from the years 1981-2010. The slope is 8 m/s per degree C. The 95% uncertainty interval is in grey[xcii].

Figure 13: Regression coefficient of the SST term from a regression of lifetime highest wind speed on SST and El Nino. The regression coefficient increases for stronger hurricanes and is significantly different from zero at hurricanes having lifetime maximum winds exceeding 50 m/s. The 95% uncertainty interval is in grey[xciii].



Over the long-term approximately one-third of all Atlantic hurricanes hit the United States. An objective and relevant measure of hurricane impact is the record of wind damage losses. We show that the relationship between wind speed and loss is exponential and that loss increases with wind speed at a rate of 5% per m/s (see Figure 14).

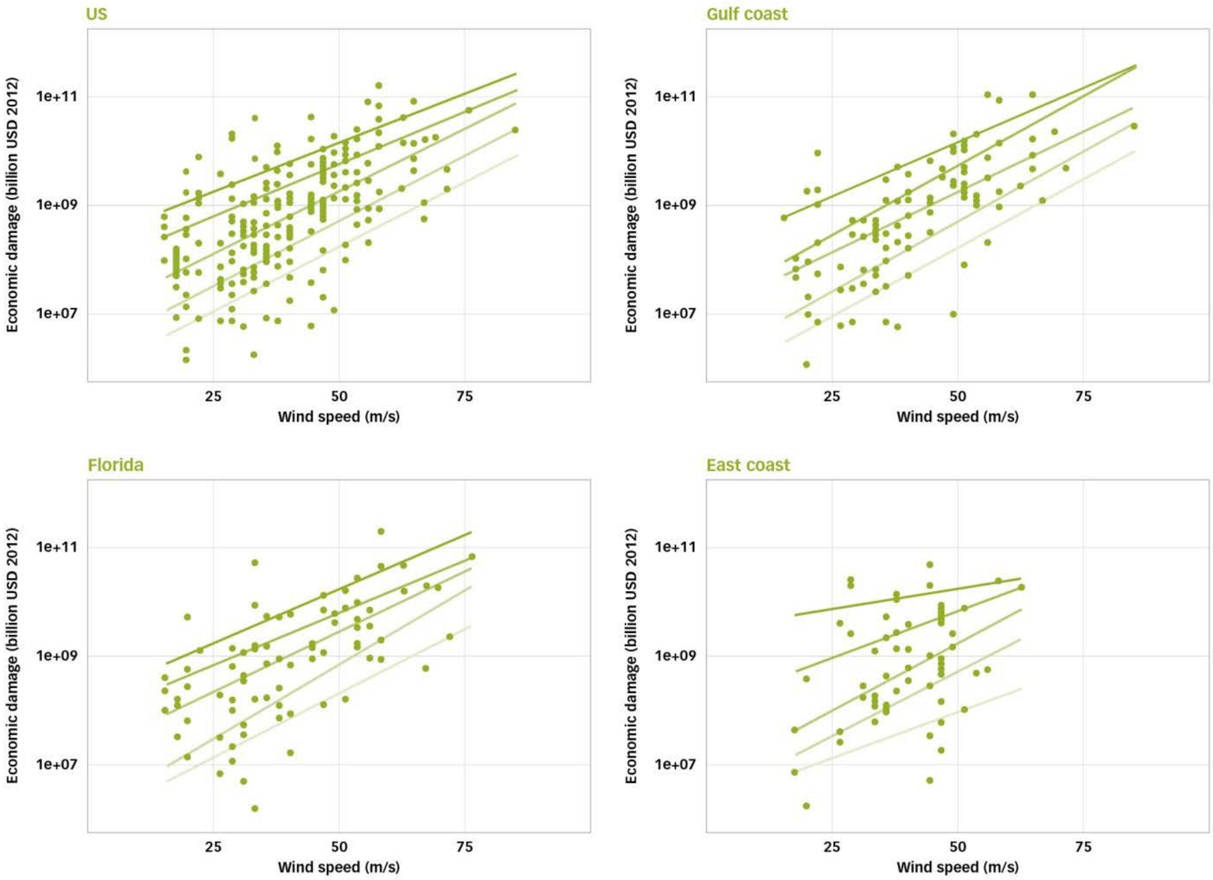


Figure 14: Quantile fits of damage as a function of wind speed. Lines are drawn at the 0.10, 0.25, 0.50, 0.75, and 0.90 centiles of damage. The slopes are close to 5% per m/sxciv.

The relationship is derived using quantile regression and a data set comprising wind speeds of hurricanes hitting the United States and normalized economic losses[7]. We suggest that the offsets for the different quantiles account for exposure-related factors such as population density, precipitation, and surface roughness, and that once these effects are accounted for, the increase in loss with wind speed is consistent across quantiles. Since the strongest storms are getting stronger at a rate of approximately 1 m/s per decade we can expect a 5% increase in loss in ten years independent of any change in exposure.

CLIMATE MODELS

Global climate models (GCMs) that bring together ocean and atmospheric processes now have sufficient resolution to generate tropical cyclones. The models are first tuned to simulate historical hurricanes and then used to generate scenarios of activity for the next 50 to 100 years.

We suggest that the reliability of a future hurricane scenario can be judged by how well the model in generating the scenario reproduces the sensitivity of limiting hurricane intensity to SST[xcv,xcvi]. We estimate the sensitivity from hurricane data generated by the model called "HiRAM" developed at the Geophysical Fluid Dynamics Laboratory in Princeton, NJ USA and by the FSU model developed at Florida State University in Tallahassee, FL USA. We also estimate the sensitivity from hurricane data generated by a 'downscaling' technique developed by Kerry Emanuel at the Massachusetts Institute of Technology in Boston, MA USA.

[7] Loss data are from ICAT Damage Estimator (http://www.icatdamageestimator.com).

Figure 15 shows a bar plot comparing the sensitivities estimated from observations and estimated from the three models. The GFDL HiRAM and FSU Model were run with three different initial conditions and only the largest of the three sensitivities is plotted.

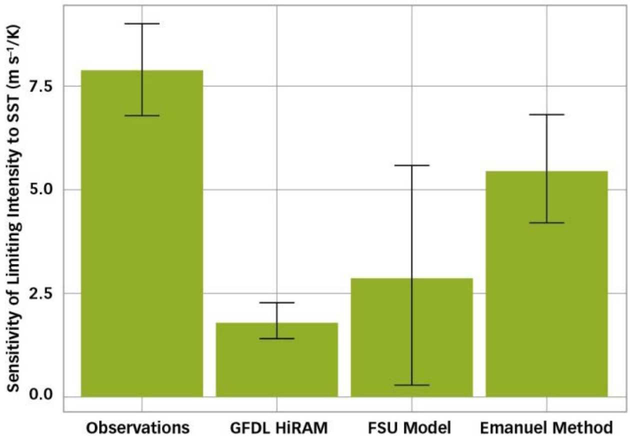


Figure 15: Sensitivity of limiting intensity to SST estimates from observations and models. The vertical bar is one standard error.

We speculate that the lower sensitivity is due to the inability of a GCM-derived tropical cyclone to operate as an idealized heat engine, where the maximum potential intensity is directly related to the underlying ocean heat. This is likely a consequence of the inability of the GCM to resolve the inner-core thermodynamics where heat is converted to work. We further speculate that GCM temperatures near the tropopause do not match those in the real atmosphere, which would likely influence the sensitivity estimates. Work on this topic is ongoing.

6 CONCLUSIONS AND RECOMMENDATIONS

The scientific consensus that the global climate is changing - and that this change will accelerate - continues to strengthen. However, as a number of authors have observed in this report, establishing current impact on risk levels is extremely challenging.

When interpreting the historical evidence and projections over the next decades, it is useful to consider any change as a combination of natural variability and an underlying tendency caused by anthropogenic emissions. In the broadest sense those perils with the longest and most robust data sets do show trends that are consistent with the physical understanding as presented by climate models. However, for many extreme perils the natural variability to date is larger than the underlying climate change tendency. Future projections show that in the coming decades the underlying tendency is expected to emerge more clearly.

The catastrophe model case studies illustrate a wide range of approaches used in the industry. The impact of climate change is mostly not explicitly reflected in the catastrophe models, but all contributors note that any climate changes to date will be implicitly included in the recent data they use to create their models.

Within a time horizon of much less than a decade an empirical recent data based approach appears sound, as natural variability is expected to dominate over the underlying trend. Nevertheless if longer time horizons are required then climate model projections will need to be more relied upon. These climate change projection based approaches are required for those making long-term commitments, for example, insuring or investing in infrastructure. The reduction of greenhouse gases remains an essential and urgent requirement to limit the risks and the inevitable cost of managing them.

7 APPENDICES

Appendix 1 – Note on climate extreme indices and levels of confidence and likelihood

In order to describe and quantify extreme climate events a list of indices has been recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI). An overview of the most common indices is also shown in Box 2.4 Table 1 in IPCC (2013) and in Table 1 in Donat *et al.* (2013).

The physical science findings presented here make use of the expressions for confidence and likelihood used in IPCC (2013) as defined and described therein in its Technical Summary chapter. Important findings in the Fifth Assessment Report (AR5) are assigned a qualitative expression for *confidence* in the validity of the finding (*very low*, *low*, *medium*, *high*, and *very high*), as well as an expression for *likelihood* indicating probabilistically quantified uncertainties (*Virtually certain* (99–100% probability), *Very likely* (90–100% probability), *Likely* (66–100% probability), *About as likely as not* (33–66% probability), *Unlikely* (0–33% probability), *Very unlikely* (0–10% probability), *Exceptionally unlikely* (0–1% probability)). The use of both expressions in IPCC (2013) follows guidelines for authors and is based on the author's team's evaluation of the associated evidence and agreement with respect to the finding. Table 1 below (taken from IPCC, 2013) shows the relationship between summary statements for evidence and agreement and the level of confidence.

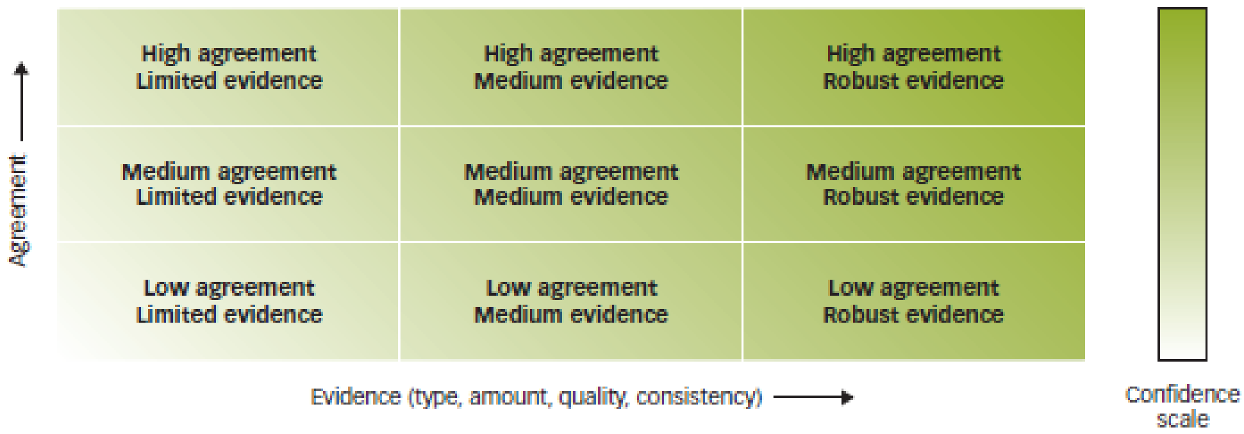


Table 1: Summary statements on agreement and evidence and their relationship to the level of confidence (taken from the Technical Summary of AR5, Box TS.1, Figure 1).

Appendix 2 – Limitations of climate models

The following section outlines the key challenges and limitations of climate models. These lead to significant limitations in predicting the effects of climate change. They do not, however, undermine the key findings of climate change. Our understanding of the laws of physics and our observation of past climates are enough to cause deep concern. The models may not be reliably assessed as when and where droughts, for example, occur, but they all show increases. This additional doubt should not cause comfort; quite the opposite.

1 TEMPORAL SCALE

The modes of natural variability within the climate system, such as the North Atlantic Oscillation or El Nino Southern Oscillation, work overtime periods from months to decades. Climate change within the context of human impacts on the natural climate system operates over a period from decades to centuries. The climate parameters of an individual year are usually compared with a reference period of 30 years. Models used to simulate the climate system aim typically to project changes in climate over the 21st century. These timescales are in sharp contrast with the duration of individual extreme events (from days to months) and may not be resolved sufficiently by climate models.

2 SPATIAL SCALE

The horizontal resolution of global climate models is of the order of 100s of kilometres. One of the main reasons for this is constraints in the performance of present-day supercomputers. Another issue is also the handling, processing and storage of the large amounts of data produced by the models. In recent years this has been addressed by the increasing development and use of Regional Climate Models which allow finer spatial resolution for a limited regional domain. Nevertheless, producing climate projections for a specific geolocation remains challenging. Parameters that exhibit strong regional variability, such as rainfall, are often difficult to reproduce accurately in climate models.

3 QUALITY OF OBSERVATIONS

The availability of observational data, its quality and consistency are important factors which affect the statistical evaluation of extreme events. It is essential to be able to put a specific extreme event into the correct historical context. Changes in measurement practices over time can affect some variables more strongly than others. Satellite data provides a relatively consistent record with global coverage since the 1970s. This time period may however be too short to provide reliable long-term trends in extremes. Many parameters that are of importance in the context of climate extremes cannot be derived from satellite or are not available at the necessary spatial and temporal resolution. Particularly in Africa and in South America surface observational data often have reduced coverage in space or time compared with corresponding data records from North America or Europe. Severe local weather events, such as hail or thunderstorms, are not captured sufficiently due to the density of observational meteorological stations being too coarse to capture all these events.

4 UNCERTAINTY AND CLIMATE VARIABILITY

Climate projections are associated with a level of uncertainty. Contributing factors are the natural variability of the climate system masking the changes resulting from anthropogenic influences, the accuracy of the assumptions made about the future in the form of scenarios, and the climate model's limited ability to accurately reproduce the climate system. The latter may be an artefact of computational or numerical modelling constraints, but also a reflection of insufficient understanding of the relevant climate processes

On the time scale of years to decades natural modes of the climate system result in natural variability in the regional climate. Examples for such modes are El Niño Southern Oscillation, the Northern or Southern Annular Mode, the North Atlantic Oscillation or the Pacific Decadal Oscillation. Gradual or sudden changes in these climatic modes can affect weather patterns potentially at great distance through teleconnections and affect the frequency or intensity of extreme events[xcvii]. Particularly within a short time from the present the signal of such natural variability in the climate system will likely exceed the changes to the climate system from gradual increases in atmospheric greenhouse gas concentrations. To what extent climate oscillations are affected by anthropogenic climate change is an active area of research. Climate models receive inputs (boundary conditions) from future scenarios in order to project climatic changes over the 21st century and beyond. In these scenarios assumptions are made regarding demographic developments in the world population, demand and supply of energy, technological and socio-economic developments over many decades into the future[xcviii, xcix]. As a wide range of potential future developments are conceivable, climate model projections are typically integrated using boundary conditions from a range of future scenarios. Therefore climate models provide not one specific deterministic value but rather a range of results. Not only are the model results dependent on the quality of data available for initial and boundary conditions; different models also use different numerical methods and parameterisations to simulate climate relevant processes. As a consequence multi-model ensembles are carried out for the purpose of climate projections whenever possible[c].

Key challenges in modelling the climate are small scale processes, such as clouds and convection, which cannot be resolved by most climate models. Hawkins and Sutton (2009) have investigated the contributing factors to uncertainty for regional climate predictions[ci] and Table 2 shows the relative importance of three key factors over time into the future from a starting point in the year 2000: choice of scenario, choice of climate model, and impact of natural climate variability. In the short term climate variability is the dominant factor. Further into the future variability and inter-model differences become less important and the dominant factor at this point is the choice of scenario. In the IPCC (2013) specific expressions are used to narrow down qualitatively and quantitatively the level of uncertainty associated with the changes to the climate system and to extreme climate. Table 2 presents an overview of uncertainties observed and projected trends of extreme events.

Phenomenon and direction of trend	Assessment that changes occurred (since 1950 unless otherwise indicated)	Likelihood of further changes during early 21st century
Increases in intense tropical cyclone activity	Low confidence in long term (centennial) changes. Virtually certain in North Atlantic since 1970.	Low confidence
Increase in the frequency, intensity, and/or amount of heavy precipitation events	Likely more land areas with increases than decreases	Likely over many land areas
Increases in intensity and/or duration of drought	Low confidence on a global scale. Likely changes in some regions.	Low confidence
Increased incidence and/or magnitude of extreme high sea level	Likely (since 1970)	Likely
Warmer and/or fewer cold days and nights over most land areas	Very likely	Likely
Warmer and/or more frequent hot days and nights over most land areas	Very likely	Likely
Warm spells/heat waves. Frequency and/or duration increases over most land areas	Medium confidence on a global scale. Likely in large parts of Europe, Asia and Australia.	Not formally assessed

Table 2: Modified after IPCC (2013), Summary for Policymakers

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