Financial Risks of Climate Change

Technical Annexes

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Climate Risk Management Limited

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http://www.abi.org.uk/climatechange

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CONTENTS

1.0 Introduction

This report comprises a series of technical annexes prepared to assist with a project commissioned by the Association of British Insurers (ABI). The project has been undertaken to inform the debate on climate change and extreme events in relation to the insurance industry. The project seeks to quantify the financial costs of extreme weather events over the coming decades under various climate scenarios (with and without policy responses on mitigation and adaptation), and assess the implications for the insurance industry, their policyholders and capital markets.

1.1 Project scope

The ABI and the Project Board in defining the scope agreed that the study should focus on the most costly aspects of weather today and that a quantitative analysis be undertaken for:

- Tropical cyclones
    - North Atlantic
    - North Pacific Basin
- Extra tropical cyclones
    - Europe

The project concentrated on the major property insurance markets in Europe, North America and Japan – to the extent that resources and the availability of data from the insurance industry permitted.

A separate analysis of the following extreme events relative to the United Kingdom has also been included within the project.

- Flooding
- Subsidence

In addition to the above a qualitative review based on existing published sources would explore current views on the impacts arising from:

- Heat waves
- Health
- Agriculture
- European flooding

The analyses contained in this report do not include the increase in exposure to climate risks arising from changes in socio-economic factors.

1.2 Project Objectives

The project had three main objectives:

- to add to current estimates of the global financial costs of climate change by providing estimates of the future costs of extreme weather based on current scientific evidence
- to examine the secondary effect of climate change on extreme weather events on global insurance markets. Increases in the volatility of extreme

weather could also result in changes in the amount of capital that the insurance industry needs to hold for claims

- to quantify the impact of taking action today to limit the causes and consequences of climate change on extreme weather events, including steps to reduce carbon emissions and adaptation measures.

1.3 Climate change and extreme weather

The Earth's climate is changing and will continue to change over this century. The 1990s were the warmest decade globally since records began, with the four warmest years all occurring since 1998. In 2003, Europe experienced its hottest summer for at least 500 years, with temperatures more than 2°C warmer than the average. In the UK, temperatures reached a record-breaking 38°C. Temperatures could increase by a further 6 °C by the end of the century if there is no action to tackle climate change.

Whilst extreme events cannot be used to prove climate change, a trend towards more extreme and intense weather events is consistent with the developments that scientists expect in a warmer climate. Research by the Intergovernmental Panel on Climate Change (IPCC) suggests that the increase in the surface temperature for the Northern hemisphere during the 20th Century was probably greater than that of any other century in the last thousand years. IPCC projections put the increase in average global surface temperature in the range of 1.4 to 5.8°C over the period 1990 to 2100.[1]

Its is accepted by the majority of the world's scientists that man-made emissions of greenhouse gases are changing our climate, bringing higher temperatures, changing rainfall, rising sea levels and possibly more storms. Although some uncertainty still exists with regard to the extent of the impact of climate change on extreme weather, it is clear that this is becoming a major challenge for the insurance industry

A review of the existing climate science has been undertaken which is presented in Section 3 'Impacts of climate change on costs of extreme weather'.

1.4 Main issues

One of the main threats of increased extreme events is a risk of increased property losses. The Intergovernmental Panel on Climate Change (IPCC) has confirmed that the combined effects of increasingly severe climatic events and underlying socio-economic trends (such as population growth and unplanned urbanization) have the potential to undermine the value of business assets, diminish investment viability and stress insurers, reinsurers, and banks to the point of impaired profitability and insolvency. As UNEPFI have stated that even in the extreme case, whole regions may become unviable for commercial financial services. [2]

The major issue for insurers is that the climate is inherently unpredictable to the extent that the existing probability of 'normal' extreme events is difficult to estimate. As the climate continues to change the usual method of using historical information

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[1] Intergovernmental panel on climate change. www.ippc.ch

[2] Climate change and the Financial Services Industry. Module 1 Threats and Opportunities. UNEP FI Climate change working group.

to predict forward becomes unfeasible for pricing. The climate will continue to change as greenhouse gases continue to increase.

Global warming could increase the frequency and severity of extreme weather events in some regions around the world, such as floods, storms and very dry summers. These types of events are exactly those which insurance provides some financial protection for. If the financial impacts of climate change are not understood it will mean that insurers will have greater uncertainty. This will lead to greater risk aversion e.g. higher premium rates, withdrawal from the market on the part of the insurer. To remain competitive and ultimately to provide the best service to the customer the impacts of climate change need to be fully costed.

1.5 Insurance as a measure of financial costs

Insurance is a good indicator of financial costs as it allows a price to be put on events, in particular to assess the amount of damage each event causes. In a previous study the ABI points out that insurance offers important economic benefits where activities are seen as risky and a risk control or transfer mechanism is needed.[3] It allows companies and individuals to continue to undertake risky activities, which otherwise they would not undertake. Insurance plays an important role by providing a risk transfer mechanism which otherwise would fall to the state. Any impact on the insurance industry has wider implications for other stakeholders.

The insurance industry is well placed to lead the way in the debate on the costs of climate change. Insured and non insured losses can be used to indicate financial costs of extreme events. The costs can be used to look at the potential consequences of not taking any action as losses increase.

Initial estimates on cost of climate change were undertaken by the United Nations Environmental Programme Finance Initiative (UNEP FI) who put the cost to the global economy of climate change-driven natural disasters at $150 billion per year within the next decade, based on current trends.[4]

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[3] The Economic Value of General Insurance. ABI December 2004

[4] UNEP FI CEO briefing: Climate risk to global economy. UNEP FI www.unepfi.net

2.0 Paying for natural catastrophes – who bears the costs?

2.1 Insurance coverage

The industry opinion on climate change varies according to location. Insurers in Europe and Asia are giving significant consideration to climate change and the implications that this will have on their business.

Not only are there widely dispersed agreements on the effects of climate change and the impact on the insurance industry, but also the extent to which private insurance arrangements cover property damage varies substantially between countries. In some cases, the private market covers much of the risk, while in others, the government is more closely involved.

There are a wide variety of approaches used by governments to address catastrophic risk. Some governments require insurers to provide natural catastrophe insurance and provide financial assistance to the insurers in the wake of catastrophic events, while others generally rely on the private market. A summary is provided in Table 2.1.

Within Europe coverage varies from country to country. Natural catastrophe coverage is mandatory in France and Spain and the national governments are explicitly committed to providing financial support to insurers through state-backed entities and state guarantees. Other governments, such as Germany, neither require natural catastrophe insurance nor provide explicit financial commitments.[5]

In the UK, commercial and residential property policies mainly cover the full array of natural perils. Flooding has become an issue within the UK with insurers who warned government in 2000 that they would not cover business in flood prone areas unless flood defences were improved and buildings protected more efficiently. A two-year plan was agreed but it still remains an issue. [6]

In the Caribbean property policies cover fire and allied perils such as windstorms and earthquake. Each island is subject to local regulations and customs and so different coverage is available on different islands. For example on Puerto Rico flooding is generally excluded in residential and commercial but it is included on other islands.

The system in the USA is unique and has not been copied by other countries. The USA property policies usually cover wind, including tornadoes and hurricanes as well as fire and explosion. Flood and earthquake hazards are normally excluded. In most states earthquake cover is available as separate cover. A special program, underwritten by the federal government covers the flood peril up to $250,000 in insured value for residential exposures and up to $500,000 for non-residential exposures.[7] Special programs have also been set up which are state funded. These include the Florida Windstorm Underwriting Association (FWUA).

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[5] Catastrophe risk. US and European approaches to insure natural catastrophe and terrorism risks. GAO United States Government Accountability Office.

[6] World Catastrophe markets 2004. Guy Carpenter. www.guycarp.com

[7] Climate Change and the Insurance Industry. The Changing Risk Landscape:Implications for Insurance Risk Management 1999. Andrew Dlugolecki

The costs of natural catastrophes fall on different parts of society depending on the arrangements.

- Where private insurance covers weather risks, the costs of climate change will be shared between the insured portions of society. With risk-based pricing, those at greatest risk pay most for this risk-sharing, while those who avoid risk pay least. This distributes the costs of weather equitably amongst policyholders.
- Where government carries the risk directly or as “insurer of last resort”, the costs of weather events are borne by the taxpayer, contributing according to the tax-regime of the country. There is no reward for avoiding risks, and no personal penalty for accepting them.
- Where there is no insurance or state-backed compensation for weather risks, the costs of natural catastrophes fall on the individual. In many cases, these costs could be a substantial portion of an individual’s wealth, leading to devastating personal and business liabilities. The individual can only prevent potentially bankrupting costs by avoiding or carefully managing risk.

For insurance markets that have historically had limited capacity, a pooled or government-backed compensation system may be the only way to deal with the costs of natural catastrophes. Nevertheless, even some quite developed insurance markets are faced with single-event losses of such proportions that even this capacity is exceeded. Will this become more common with climate change despite growth of the global economy?

Climate change could alter the viability of these different arrangements by increasing the costs borne through each mechanism, and the relationships between those funding and receiving compensation.

Table 2.1: Country Catastrophe Coverage

Country	Programme	Start Year	Catastrophe's covered	Primary/ Reinsurance	Adaptation requirements	Limits	Government Funding	Triggers	Second event coverage
France	Catastrophes Naturelles (CATNAT)	1982	Personal and commercial property as a result of floods, subsidence, mud slides, earthquakes, tidal waves and avalanches		Yes	unlimited	Yes	State decides if an event falls within the scope of the programme	Yes
Iceland	Icelandic Catastrophic Fund	1975	Earthquakes, volcanic eruptions, snow avalanches, landslides and floods (automatic cover available to properties and contents insured against fire)	Primary	No	Prorata if capacity exceeded	No	Covered event	Yes
Norway	Norsk Naturskadepool	1980	Personal and commercial property affected by floods, storms, earthquakes, avalanches, volcanic eruptions and tidal waves	Reinsurance	No	Limit per disaster of NOK10.0 billion	No	Covered event	Yes
Spain	Consorcio de Compensacion de Seguros	1954	Business interruption and damage to personal and commercial property as a result of earthquakes, tidal waves, floods, volcanic erruptions, storms	Primary	Building codes	Limits on claims	No	Covered event (event must be abnormal in terms of victims and geographical area)	Yes
Netherlands	WTS	1998	Compensation for loss or damage which is not insured	Primary	Yes		Yes		
Switzerland	Elementarschadenpool	1939	Fooding, storm, hail, avalanche, rockfall, earthslip	Primary	No	Yes	No	Covered event	Yes
Turkey	Turkey Catastrophe Insurance Pool	2000	Earthquake	Primary	Yes	Limits on claims	No	Covered event	Yes

Country	Programme	Start Year	Catastrophe's covered	Primary/ Reinsurance	Adaptation requirements	Limits	Government Funding	Triggers	Second event coverage
USA	National Flood Insurance Programme	1968	Flooding (including subsidence)	Primary	Yes – risk assessments required and risk control measures implemented	Maximum cover limits for residential and commercial property	Yes	Covered event	Yes
USA	Florida Hurricane Catastrophe Fund	1993	Residential property as a result of windstorm during hurricane	Reinsurance	Limited funding available for adaptation studies	No	No	Hurricane declared by NHC	Yes
USA	Citizens Property Insurance Corporation	2002	Residential property as a result of hurricane	Primary			No		
USA	Fair Access to Insurance Requirements (FAIR) plans (31 states have coverage)		Each state has different coverage	Primary			No		
USA	Market Assistance Plans (MAPs) (3 states have plans)		Coastal properties	Primary			No		
USA	California Earthquake Authority	1996	Residential property (limitations)	Primary	No	Prorata if capacity exceeded	No	Covered event	Yes
Japan	Japanese Earthquake Reinsurance Company	1966	Residential property as a result of earthquake, tsunami, volcanic eruption	Reinsurance	No	Prorata if capacity exceeded	Japanese Government underwrites	Covered event	Yes
New Zealand	Earthquake Commission	1994	Personal property as a result of earthquake, tsunami, landslide, volcani eruption and geothermal activity	Primary	Building code enforcement	Limits on claims	No	Covered event	Yes
Taiwan	Taiwan Residential Earthquake Insurance Pool	2002	Earthquake	Primary	No	Limits on claims	Yes		Yes

Sources: *US and European approaches to insure natural catastrophe and terrorism risks, US Government Accountability Office, February 2005; The world reinsurance market 2004, Guy Carpenter, September 2004; Comité Europeen Des Assurances, March 2004*

2.2 The insurance industry in practice

The insurance market is cyclical. “Soft” market conditions, when premium rates decrease (usually due to over capacity) are followed by generally shorter and sharper periods of “hard” market conditions. In recent years, increasing frequency and size of loss events, coupled with falls in investment income within the insurance industry has meant a return to “hard” conditions (with the reduction / withdrawal of cover and an increase in premiums).

The cyclical nature of the industry is further enhanced as these extreme events happen sporadically. The lessons learned diminish over time, and as new extreme events occur the market tends to react quickly to cover itself.

In principle, insurance premiums look to cover expected claims (for the corresponding policies), operating and administrative costs and a return on investment for the capital providers: this is known as the fair premium. In strong equity markets, any underwriting losses are usually covered by strong investment income making up the shortfall. In addition, providing losses are not catastrophic, the annual cycle of premium renewal means that the effects of one year’s loss could be reduced the following year by increasing premiums.[8]

2.3 Reinsurance arrangements

To cover the most extreme events, insurers rely on reinsurance – either through the private market or from the state. The reinsurer assumes responsibility for covering a portion of the risk, especially for rare but extreme event losses. This enables insurers to access greater capital in a cost-effective way, and assists in managing liquidity following a large claim event. In most markets, regulation by the state setting out capital requirements ensures solvency for all but the most unusual events.

Extreme weather events place significant demands on the financial capacity of the insurance industry. The loss potential from these types of events can be enormous, with severe financial consequences. After Hurricane Andrew hit Miami Dade Florida in 1992 causing $16 bn of insured damage, 11 reinsurers went into receivership. The size of the global reinsurance market for property in 2004 is around $55 bn.[10]

2.4 Alternative risk transfer

Conventional reinsurance arrangements will be tested if extreme events increase in frequency and/or severity. There may be insufficient capital in insurance markets to cover these losses. Insurers are looking to other alternative risk transfer mechanisms to help diversify their capital and manage liquidity problems following a series of large claims. These mechanisms will become increasingly valuable as climate risk increases.

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[8] Earth Observation responses to geo-information market drivers. Aon Insurance sector summary report. www.aon.com

[9] Catastrophe risk. US and European approaches to insure natural catastrophe and terrorism risks. GAO United States government accountability office.

[10] The management of losses arising from extreme events. GIRO 2002.

Insurers could limit risk exposure by transferring natural catastrophe risk into the capital markets. Due to their size, financial markets offer enormous potential for insurers to diversify risks: the value of global financial markets currently stands at close to $120,000 bn[11]. But transaction costs can be considerable, and the unfamiliarity of investors with insurance risks means that they currently demand a relatively large risk premium.

Alternative risk transfer markets are considered one mechanism by which the risk exposure can be transferred. These are seen to be expanding, particularly in the USA, as customers seek cost effective ways to deal with their increasing weather exposures. Alternative Risk Transfer (ART) is the term given to unconventional insurance arrangements.

Insurers and large corporations are already experimenting with catastrophe bonds as an ART mechanism. A catastrophe bond or CAT bond is a high-yield debt instrument that raises money in case of a catastrophe such as a hurricane or earthquake. These pay out, not on proof of loss, but on fulfilment of a trigger condition, for example a Category 4 hurricane striking mainland USA. Investors provide the capital and in return receive a superior interest rate. However they run the risk of losing their return and even the capital in some contracts.

It has been stated that some insurers and re-insurers benefit from catastrophe bonds because the bonds diversify their funding base for catastrophic risk. However, these bonds currently occupy a small niche in the global catastrophe reinsurance market and many insurers view the costs associated with issuing them as significantly exceeding traditional reinsurance.[12]

The advantages of CAT bonds are that they are not closely linked with the stock market or economic conditions and offer significant attractions to investors. For example, for the same level of risk, investors can usually obtain a higher yield with CAT bonds relative to alternative investments. Another benefit is that the insurance risk securities of CATs show no correlation with equities or corporate bonds, meaning they'd provide a good diversification of risks.

Guy Carpenter[13] states that the catastrophe bond market witnessed yet another record year in 2003, with total issuance of $1.73 billion, an impressive 42 percent year-on-year increase from 2002’s record of $1.22 billion. During the year, a total of eight transactions were completed, with three originating from first-time issuers. Since 1997, when the market began in earnest, 54 catastrophe bond issues have been completed with total risk limits of almost $8bn. The sustainability of CAT bonds has yet to be tested by a trigger event, requiring payment to the bondholders. The current enthusiastic investor interest in CAT bonds may change.

Weather derivatives are another financial instrument used by companies to hedge against the risk of weather-related losses. The investor who sells a weather derivative accepts the risk by charging the buyer a premium. If nothing happens, then the investor makes a profit. They pay out on a specified trigger, for example, temperature over a specified period, not on proof of loss. This is different from insurance, which is for low probability events such as hurricanes and tornados. These are more established in the USA than Europe, although the market for them is beginning to pick up.

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[11] Taking Stock of the World’s Capital Markets, McKinsey & Company, February 2005, http://www.mckinsey.com/mgi/publications

[12] Catastrophe risk. US and European approaches to insure natural catastrophe and terrorism risks. GAO United States government accountability office.

[13] Market Update: The Catastrophe Bond Market at Year-End 2003. April 2004 Guy Carpenter

An overview of the key issues for weather derivatives and CAT bonds is provided in Table 2.2. Further information on alternative mechanisms and sources of capital is provided in Section 6 Appendix A.

Table 2.2 Alterative Risk Transfer Mechanisms

ART	Description	Seller / Buyers	Advantages	Disadvantages	Comment
CAT bonds	Financial contracts which pay out on fulfilment of a trigger condition. They are usually event based and triggered by a loss from a particular pre-defined catastrophe	Sellers are mostly insurance companies. Buyers are major investors such as mutual and pension funds. The investors provide the capital in return for superior interest rates.	▪ Simple to administer once set up ▪ Yield is high ▪ Risk is uncorrelated with other asset classes	▪ Expensive to set up as a Special Purpose Vehicle is required ▪ Risk of loss of return on capital	▪ They diversify funding base for catastrophic risk by accessing capital not normally available to insurance ▪ It is thought not a single cat bond has paid out so considered good returns at little risk ▪ Help to increase capacity in the market
Weather Derivatives	Pay out on a specific trigger but usually cover a period of time	Sellers are usually energy companies. Buyers are pension, mutual funds and insurance companies.	▪ Difficult to insure risks can be covered ▪ Cedant loss history is irrelevant as payout determined by index of objective measurements. ▪ Catastrophe software modelling error eliminated.	▪ Accurate prediction of information is required ▪ Expensive to set up ▪ Damage incurred may exceed the indemnity covered	▪ They are used to hedge risk. Access investor capital not normally available to insurance. ▪ Used to hedge or diversify risk

2.5 Catastrophe models

The growth trends in climate related losses have been increasing over the last few decades. The forecasting and timing of these events is difficult and is made even the more so under climate change. Historic records cannot be used to project the future impact of these extreme weather events under climate change.

The modelling companies and re-insurers use probabilistic models to determine the relationship between loss frequency and intensity. In the past, losses were assessed primarily by way of scenarios of selected large events, which were generally based on historic storms. The drawback of this approach is that it does not supply any information about the expected return period and does not have any input of future climate change. By contrast, probabilistic models are able to do so because their analyses are based on a vast number of events of differing severity within a clearly defined observation period. This allows an explicit calculation of the frequency (or return period) or each possible loss level. This approach ultimately generates an integrated view of the size and frequency of all possible events, represented by the loss frequency curve. [14] However, these models are based on historic records.

One of the ways in which extreme hazards have come to be addressed is through the use of catastrophe models. Catastrophe models were developed in response to a previous need by insurers to try and understand extreme events. Although the existing catastrophe models are also based on historic occurrence, they also have built in possible scenarios. The models simulate all the possible events that could unfold, and then weight them by chance of occurrence to produce a picture of average and extreme costs from these events (see Table 2.3).

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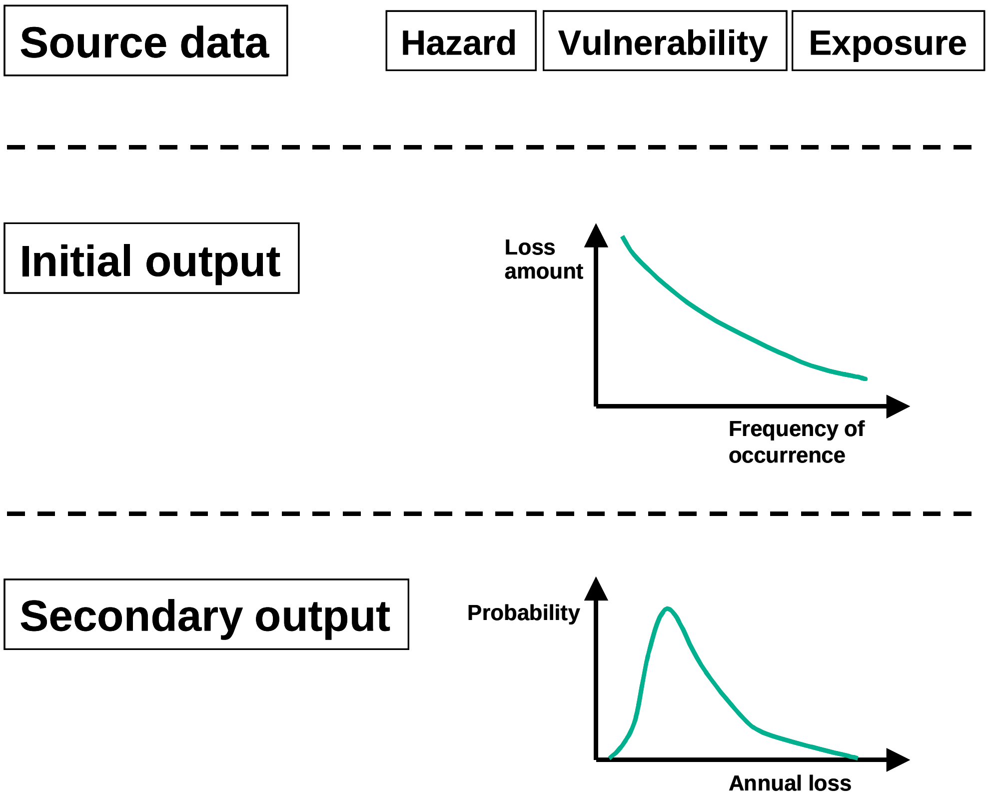
[14] Storm over Europe An underestimated risk. Swiss Re 2000. www.swissre.com

Table 2.3 Basic structure of an insurance model for natural catastrophes.



Source: *Natural catastrophes and reinsurance, Swiss Re, August 2003*

The models typically comprise three basic building blocks:[15]

- Hazard – Where, how often and with what intensity do events occur? This is usually the initial input to the model, represented as a frequency distribution of different event intensities
- Vulnerability – What is the extent of damage for a given event intensity?
- Exposure – What is the value at risk, and what proportion of the loss is insured?

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[15] *Natural catastrophes and reinsurance*, Swiss Re, August 2003, http://www.swissre.com/INTERNET/pwswpspr.nsf/alldocbyidkeylu/ESTR-5LUA2R?OpenDocument

3.0 Impacts of climate change on extreme weather around the world

3.1 Introduction

The North Atlantic hurricane season in 2004 was one of the most active and destructive in history. By the end of the season there had been a total of 14 tropical storms and 8 hurricanes, of which 7 were "major" (with wind speeds of at least 50 ms^{-1}). Moreover, three of these "intense" hurricanes and one lesser hurricane made landfall in the U.S, resulting in insured losses of just over US$ 17 billion[16]. At the same time, the 2004 typhoon season in the Western North Pacific was also highly unusual, seeing a total of 21 typhoons. The number is not unusual in itself, but the intensity of the most severe typhoons and the frequency that they crossed land was. Japan, for example, generally averages 2.6 typhoon strikes annually, but was struck by 10 typhoons in 2004, surpassing the 6 strikes it experienced during its previous worst season. More strikingly, 9 of these 10 typhoons were “severe” by virtue of their high wind speeds. Insured losses are estimated at about US$ 6 billion[17]. Globally, insured losses from windstorms in 2004 totalled US$ 38. To put 2004 in context, in 1992, the previous most expensive year for windstorms, insured losses amounted to US$ 30 billion, of which US$ 22 billion resulted from a single storm, Hurricane Andrew[18].

The events of 2004 have lead to much speculation about the relationship between anthropogenic climate change and the frequency and intensity of these extreme weather events. Was 2004 a sign of things to come with global warming? Global temperatures are rising as a result of an accumulation of greenhouse gases in the atmosphere, with 1998, 2002, 2003 and 2004 being among the warmest years on record. Surface sea temperatures are also rising, which increases moisture evaporation, making the atmosphere more humid. All this is fuel for tropical storms. This has lead to the following hypothesis: since global warming provides more energy to fuel tropical storms, should we not expect to see an intensification of storm activity in a warming world. Although the mechanism that generates windstorms that affect Europe is different to that of tropical cyclones, they still derive energy from the atmosphere. So, as the amount of energy in the climate system increases with global warming, should we not also expect to see an increase in windstorm activity over Europe.

In this section, we consider what the climate science says about this hypothesis, and estimate the financial costs and insured losses if storms were to be affected as some of the climate science suggests. We focus on the big three extreme weather events – hurricanes, typhoons and European windstorms, given the potential of these events to cause catastrophic socio-economic impacts. Future climate change can be avoided if projected global greenhouse emissions are reduced significantly in the near future. However, we are already “locked-in” to some amount of climate change as the effects of historic emissions are still working their way through the climate system. The impacts of unavoidable climate variability and change can only be managed through adaptation. In this section, we therefore also examine the impact on financial costs and insured losses of moving to lower emissions scenarios, as well ways in which we can reduce our vulnerability to extreme storms, should they intensify with climate change.

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[16] Sigma Database, Swiss Re.

[17] Sigma Database, Swiss Re.

[18] Swiss Re, Sigma, No 1, 2005.

3.2 What is a tropical cyclone?

Hurricanes and typhoons are familiar to most of us from satellite images, as gigantic columns of clouds (up to 16 km high) that spiral around a distinct centre – the so-called "eye". The spiral of clouds generally has a diameter of between 200 and 600 km, but can be as large as 1,000 km in diameter. The scientific community refers to such storms as tropical cyclones (see Box 1).

Box 1: What is a Tropical Cyclone?

Tropical cyclones refer to non-frontal synoptic scale low-pressure systems with organised convection (i.e. thunderstorm activity) and well-defined cyclonic surface wind circulation. They form in tropical waters to the north and south of the equator when warm air creates rising air current, producing large cumulonimbus clouds, which are often characteristic of thunderstorms.

Tropical cyclones with maximum sustained wind speeds[19] not exceeding 18 ms^{-1} are known as **tropical depressions**. Once the wind speed near the centre of the depression reaches 18 ms^{-1}, the cyclone is called a **tropical storm** and given a name. If wind speeds reach 33 ms^{-1} then the storm is called a **hurricane** in the Atlantic Ocean and east of the International Date Line in the Pacific, and a **typhoon** west of the International Date Line in the Northwest Pacific.

The bulk of major hurricanes that develop in the Northwest Atlantic Basin originate from mid-tropospheric easterly low pressure disturbances that move off West Africa. If meteorological conditions are favourable, these disturbances intensify and grow into hurricanes that move west and north-westward. About 60 easterly low pressure disturbances form off West Africa each season, but only a small number of these typically develop into hurricanes when they reach the Central Atlantic.

Tropical cyclones generated in the Pacific form in four distinct Basins: Northeast, Central, Northwest and South Pacific Ocean. The Northwest Pacific Basin covers the Pacific Ocean north of the equator and west of the International Date Line, and storms occur in this basin throughout the year, although the main season extends from July to November, with a peak in late August-early September. This basin is the most active in the world, accounting for approximately one third of global cyclone activity. On average, this basin will see 23 storms in a normal season.

Sources: Holland (1993), Henderson-Sellers, A. et al (1998), CSU (2004) and NOAA National Hurricane Centre

Tropical cyclones pack a huge amount of energy that gives them particularly destructive powers, with extremely strong winds, heavy rainfall and storm surges[20]. The most powerful storms can have sustained wind speeds in excess of 70 ms^{-1} and produce storm surges 6 metres or more above normal. Simulated cyclones can produce between 15 and 20 trillion litres of rain per day.

The intensity of tropical cyclones is typically measured with respect to the Saffir-Simpson Hurricane Scale (see Table 3.1). The scale is applicable to storms with sustained wind speeds in excess of 33 ms^{-1}. As noted above, storms with wind speeds below this threshold are simply called tropical storms. A tropical cyclone is classified as "intense" or "major" if sustained wind speeds exceed 50 ms^{-1} (that is, Category 3, 4 or 5 storms on the Saffir-Simpson scale).

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[19] That is, the top speed sustained for one minute at 10 metres above the surface. Peak wind speeds would typically be 20-25 per cent higher (www.noaa.gov).

[20] The NOAA define a storm surge as the onshore rush of sea caused by both the high winds associated with a landfalling storm and the low pressure of the storm. The strongest winds around the centre of a tropical cyclone force masses of water into surges. Moreover, the low pressure in the centre causes the sea level to rise. While a storm surge is distinct from a tidal surge (which is independent of the prevailing weather), it is during high tide that storm surges are most destructive.

Table 3.1: The Saffir-Simpson Hurricane Scale

Category	Winds	Pressure	Storm Surge	Relative Potential Destruction	Example
	(miles h^{-1})	(mbar)	(ft above normal)		
	(m s^{-1})		(m above normal)		
One	74-95	> 980	4-5	1	Danny (1997)
	33-44		1.0-1.7		Allison (1995)
Two	96-110	965-979	6-8	10	Bonnie (1998)
	43-49		1.8-2.6		Georges (1998)
Three	111-130	945-964	9-12	50	Fran (1996)
	50-58		2.7-3.8		Roxanne (1995)
Four	131-155	920-944	13-18	100	Felix (1995)
	59-69		3.9-5.6		Opal (1995)
Five	> 155	< 920	> 18	250	Mitch (1998)
	> 69		> 5.6		Gilbert (1988)

3.3 Analysis of historical activity

What does the recent past tell us about the potential impact of climate change on the character of hurricanes? Meteorologists working at the National Oceanic and Atmospheric Administration (NOAA) and Colorado State University[21] have shown that the number and intensities of tropical cyclones in the North Atlantic Basin exhibit substantial inter-decadal variability (see Figure 3.1 and Figure 3.2)[22]. This inter-decadal variability also extends to landfall locations.

As the figures show, the number of hurricanes and their intensity vary greatly across time. During the last half century the annual number of hurricanes forming in the Atlantic Basin has been as low as 2 and as high as 12. The number of hurricanes making landfall per year in the U.S. ranges from a low of zero to a high of 6 (indeed, in 1985, 6 out of 7 hurricanes made landfall). On closer inspection it is evident that hurricane activity is related to the periodically recurring warm and cold cycle in the Atlantic. This cycle, called the Atlantic Multi-decadal Oscillation (AMO), is controlled by gradual changes in the North Atlantic Ocean currents. When seawater in high latitudes is warm and salty, the weight of the extra salt allows it to sink easily and the thermohaline circulation, which moves warm water northward in the Atlantic Ocean, runs quickly and warm water moves northward freely. When seawater in high latitudes is relatively fresh, it has to be colder in order to sink, and the circulation runs more leisurely.

A faster circulation during a warm phase causes the mid-latitude westerlies to stay north of the tropical Atlantic. As a result, tropical Trade Winds, which blow steadily from the east, produce conditions that are favourable for hurricane genesis. When the thermohaline circulation is weaker, as during a cold phase, the westerlies bend farther southward above the Trade Winds, which causes increased wind-shear that suppresses hurricane activity. That was the AMO phase we were in during the relatively inactive 1970s through early 1990s period. As shown in figures 3.3 and 3.4, during this period, the

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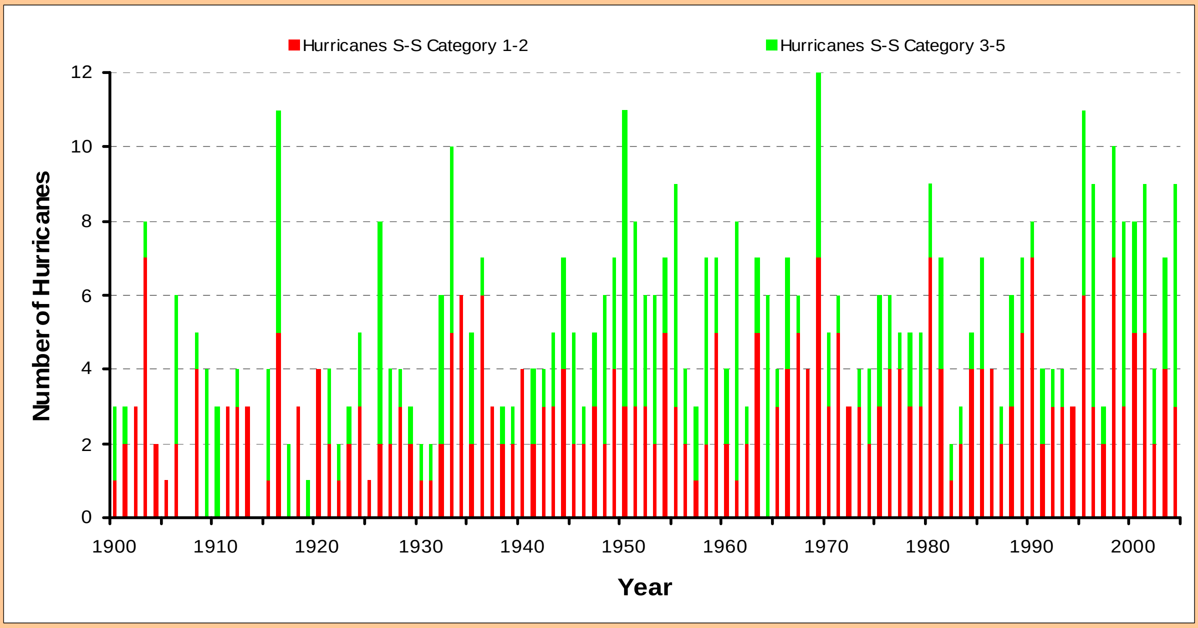
[21] Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez and W.M. Gray (2001) "The Recent Increase in Atlantic Hurricane Activity: Causes and Implications", Science, 293: 474-479.

[22] The natural variability of hurricanes and tropical cyclones generally has been subject to much research (see also, for example, Chan and Shi 1996, Chang 1996, Landsea et al 1999, Chu and Clark 1999, Meehl et al 2000, Elsner et al 2001, Chia and Ropelewski 2002 and Tsutsui et al 2004).

Atlantic Basin averaged 8.6 tropical storms, 5 hurricanes and 1.5 "major" hurricanes per season. Prior to 1970 there was an active (warm) phase that started in the mid 1920s. Over this period the average number of "major" hurricanes per season was 2.7.

The AMO is currently in another active (warm) phase that began after 1995. With the exception of 1997 and 2002, which were El Nino years[23], the years since 1995 have been the most active on record in terms of number and intensity of hurricanes (see Figures 3.3 and 3.4). Between 1995 and 2003 the Atlantic Basin has averaged 13 tropical storms, 7.7 hurricanes and 3.6 "major" hurricanes per season.

Figure 3.1: Variability in Hurricane Genesis in North Atlantic Basin



Source: Derived from HURDAT "best track" data (NOAA National Hurricane Centre)

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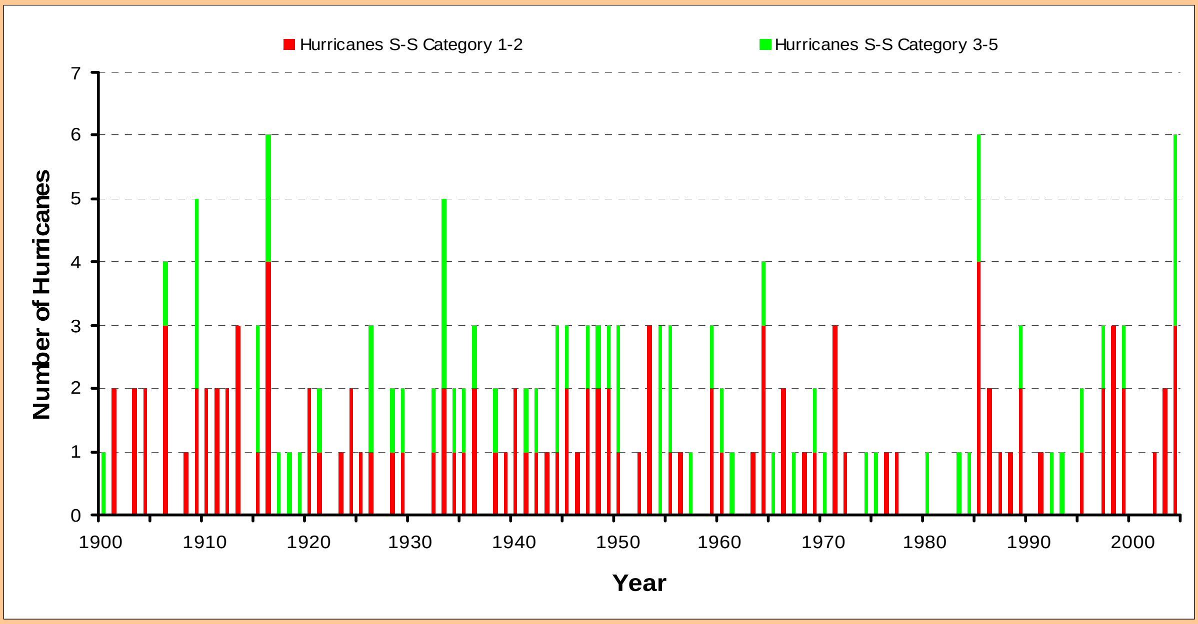
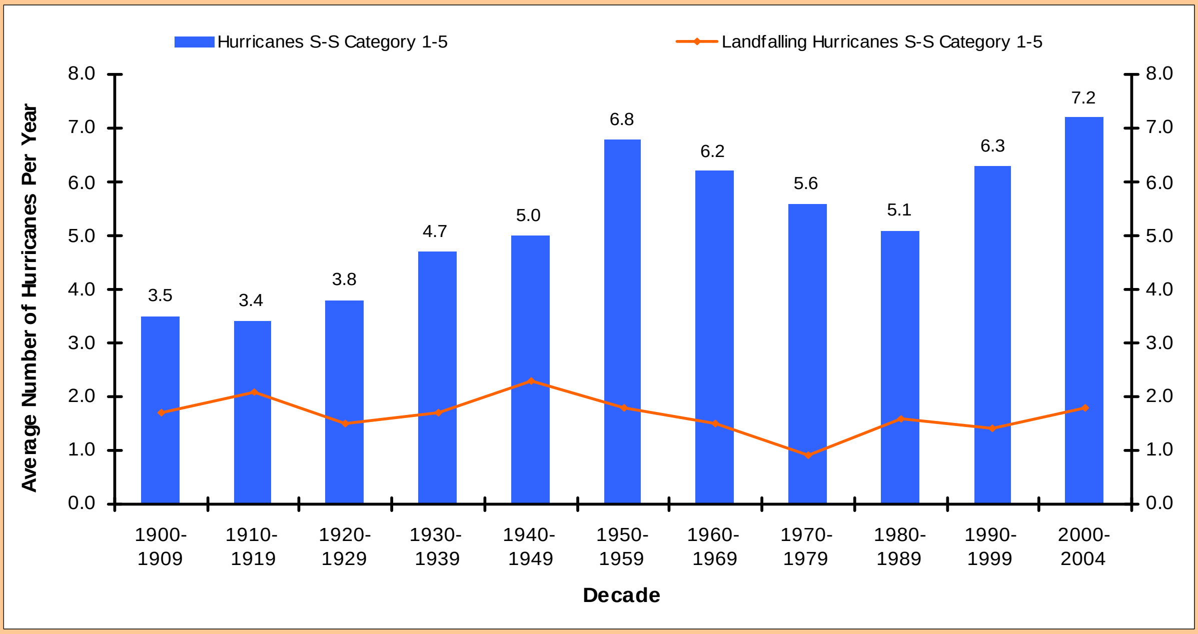
[23] The El Nino Southern Oscillation (ENSO) (El Nino and La Nina patterns in the pacific) have a significant influence over tropical cyclone activity. A warm-phase ENSO (El Nino) tends to increase tropical cyclone activity in the Pacific, but tends to inhibit activity in the Atlantic. The converse holds for a cold-phase ENSO (La Nina).

Figure 3.2: Variability in North Atlantic Basin Hurricanes Making Landfall in the U.S.



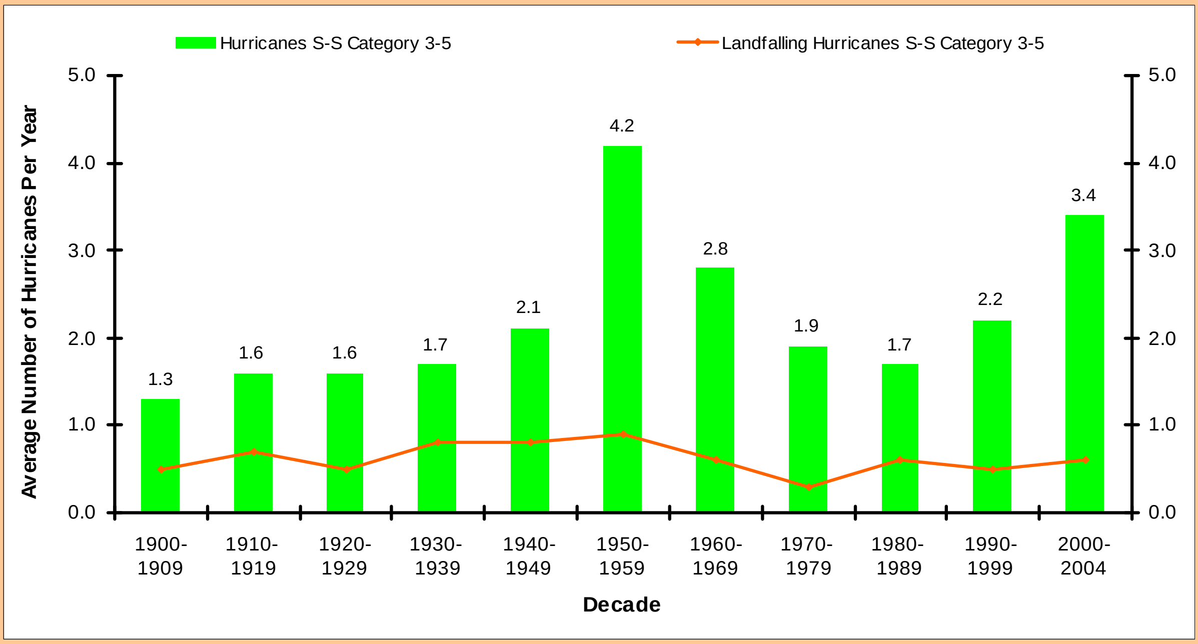
Source: Derived from HURDAT “best track” data (NOAA National Hurricane Centre)

Figure 3.3: Inter-decadal Variability in Hurricane Genesis in the North Atlantic Basin and Those Making Landfall in the U.S.



Source: Derived from HURDAT “best track” data (NOAA National Hurricane Centre)

Figure 3.4: Inter-decadal Variability in "Major" Hurricane Genesis in the North Atlantic Basin and Those Making Landfall in the U.S.



Source: Derived from HURDAT "best track" data (NOAA National Hurricane Centre)

A similar inter-decadal tropical cyclone phenomenon may be taking place in the Western North Pacific Basin, although this cycle is much less documented[24]; historical records also do not extend as far back as in the Atlantic Basin. Chan and Shi[25] found that both the frequency and the total number of tropical storms and typhoons have been increasing since about 1980, and this increase was preceded by decrease over the 1970s. This variability is illustrated by the polynomial trend line in Figure 3.5; note also that an upward trend in activity is also exhibited in the time series. Unlike the inter-decadal variability in the Atlantic Basin, the cause of the decadal-scale variations in the Western North Pacific Basin is unknown.

Over the period 1950-2003 the average number of tropical cyclones making landfall in Japan was 2.7 per year, which is about 9.5 per cent of the tropical cyclones forming annually in the basin, on average, over the same period.

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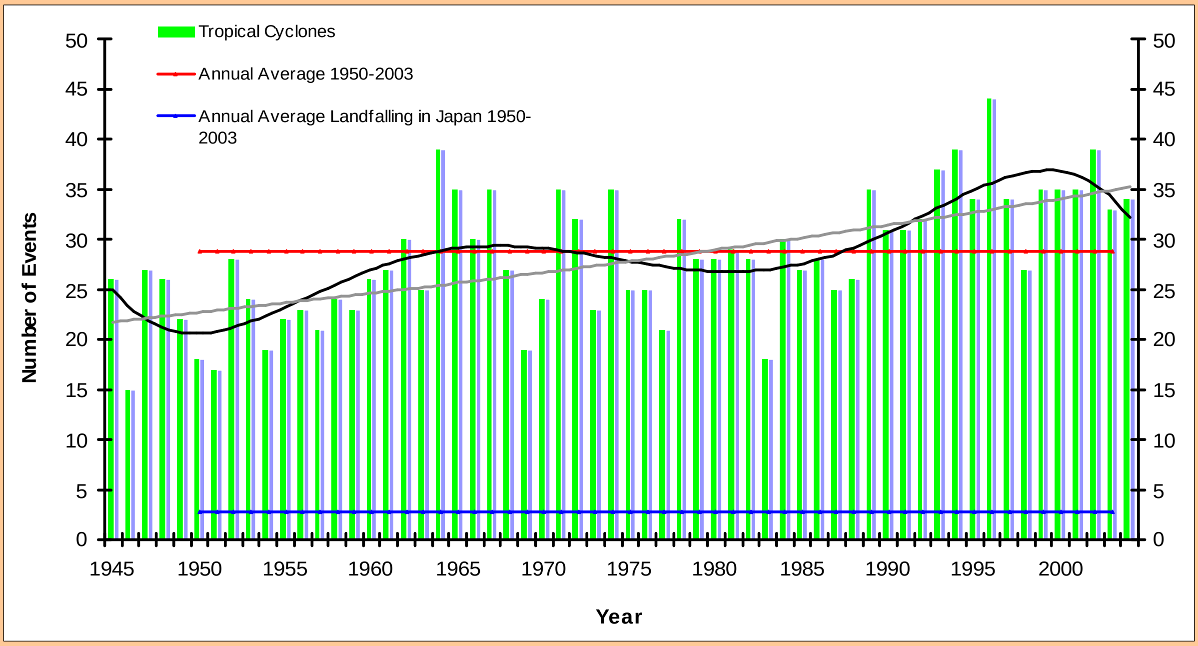
[24] "Are we getting stronger and more frequent hurricanes, typhoons and tropical cyclones in the last few years?", NOAA Research Division (www.noaa.gov/hrd/).

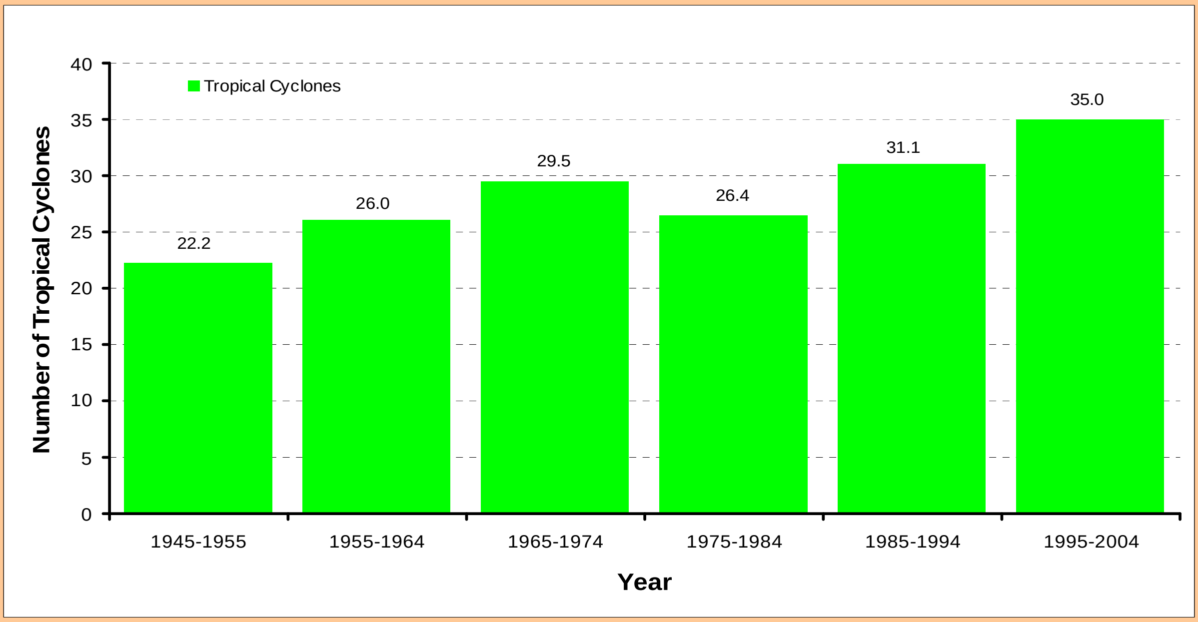
[25] Chan, J.C.L. and J. Shi (1996) "Long-term Trends and Inter-annual Variability in Tropical Cyclone Activity over the Western North Pacific", *Geophysical Research Letters*, 23: 2765-2767.

Figure 3.5: Variability and Trend in Tropical Cyclone Genesis in Western North Pacific Basin



Source: Derived from "best track" data (Joint Typhoon Warning Centre).

Figure 3.6: Inter-decadal Variability in Tropical Cyclone Genesis in Western North Pacific Basin

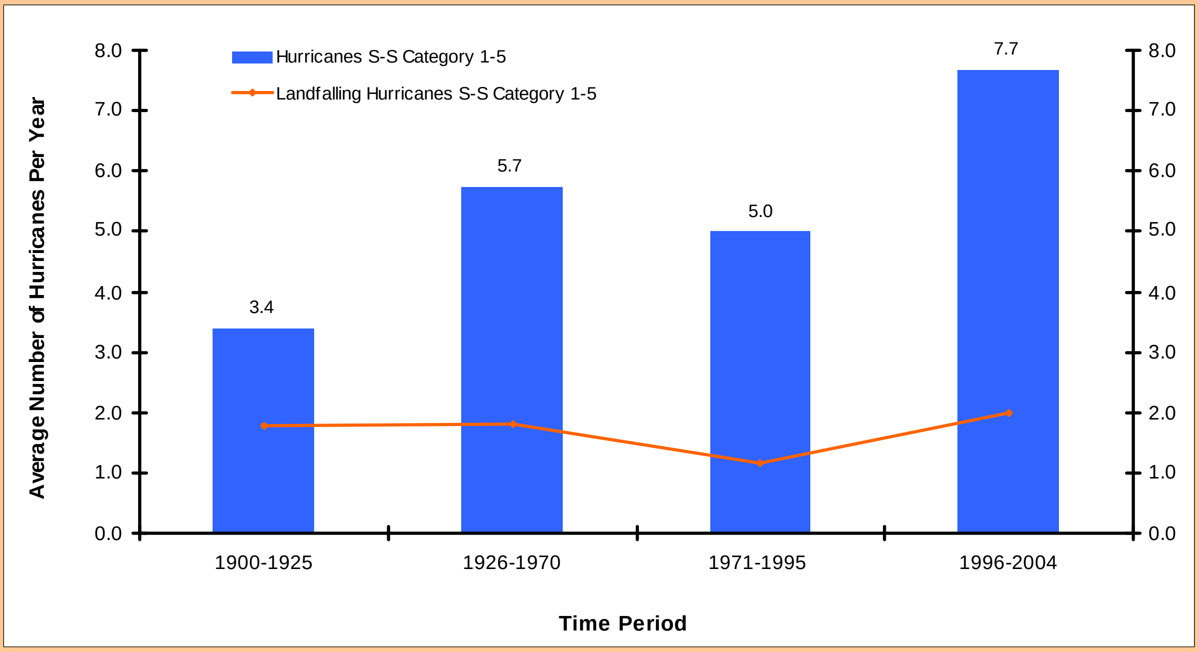


Source: Derived from "best track" data (Joint Typhoon Warning Centre). NB there are some doubts about the quality of the track data prior to 1972.

3.4 Tropical cyclones and climate change

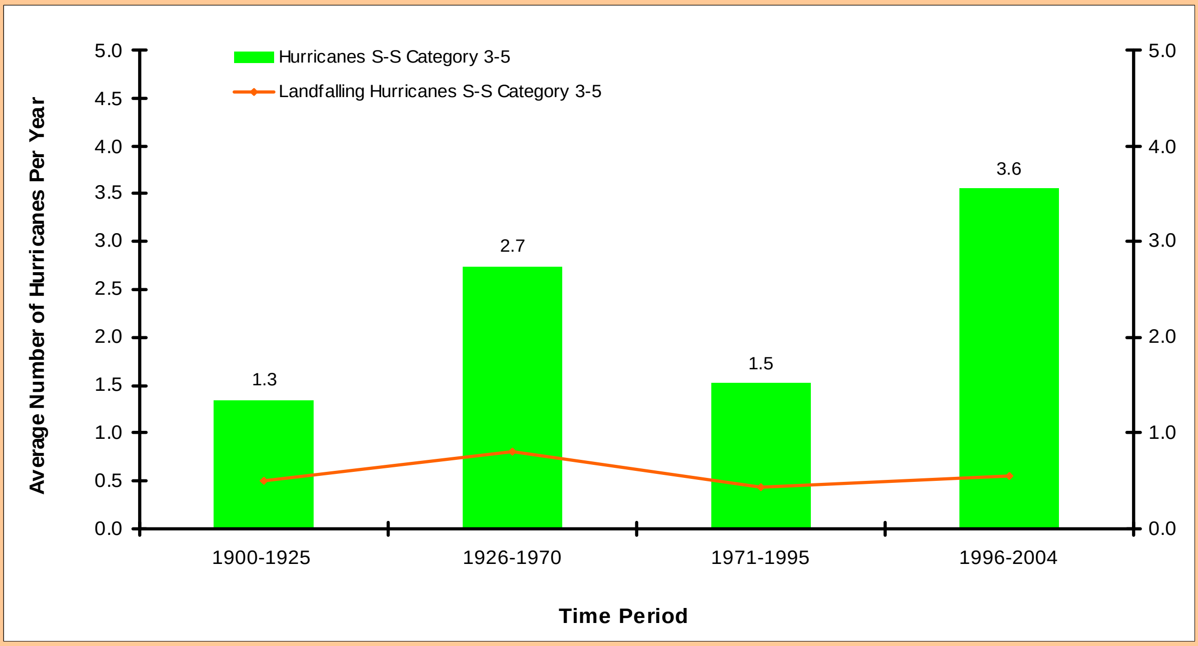
Over the last 100 years the tropical North Atlantic has experienced a gradual warming trend (with sea surface temperatures increasing by about 0.3°C). However, hurricane activity in the basin has not exhibited a distinct trend, but rather discrete inter-decadal variability. Moreover, this variability is much greater than one might anticipate from such a gradual warming trend. This raises questions about whether the increased activity currently being experienced in the North Atlantic results from anthropogenic global warming. Nonetheless, the average number of hurricanes and “major” hurricanes during the current AMO (warm) phase is higher than during the previous AMO (as demonstrated in Figures 3.7 and 3.8). In fact, the average number of hurricanes during the preceding AMO cold phase was also higher than during the last AMO cold phase. One could reasonably ask whether the observed inter-decadal variability in hurricane activity, in accordance with the AMO (warm and cold phase) cycle, is actually masking an upward trend in hurricane activity as a result of global warming. Figure 3.9, which plots the five-year moving average of hurricane activity in the Atlantic Basin, does suggest a slight upward trend in activity.

Figure 3.7: Hurricane Genesis in the North Atlantic Basin and Those Making Landfall in the U.S. During Atlantic Warm and Cold Phases



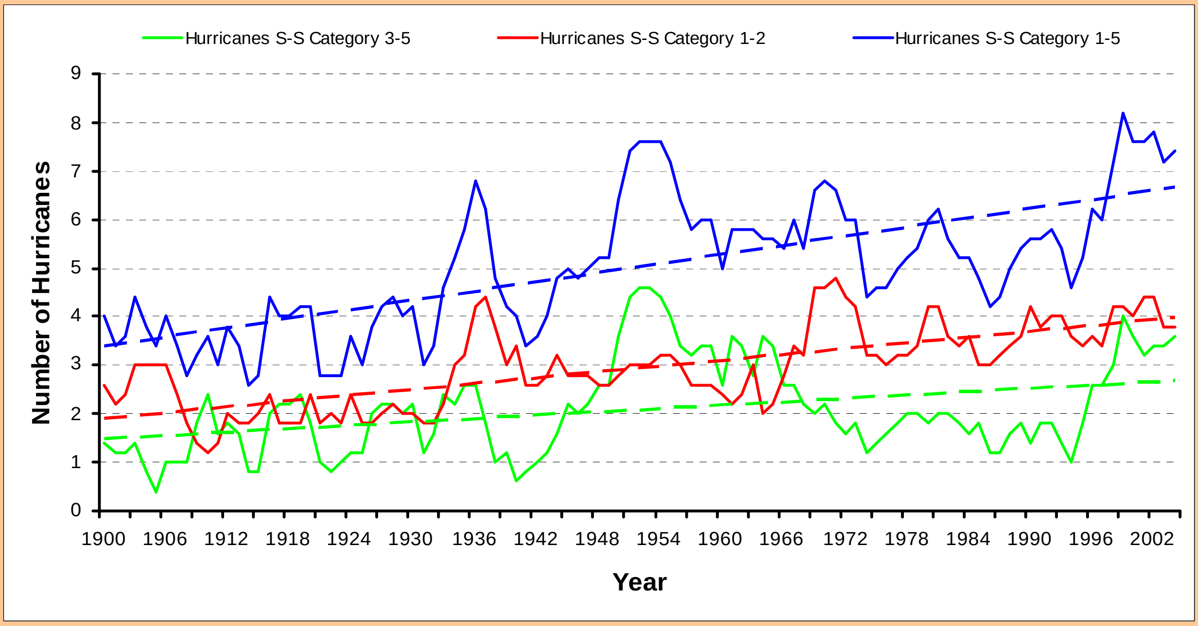
Source: Derived from HURDAT “best track” data (NOAA National Hurricane Centre)

Figure 3.8: "Major" Hurricane Genesis in the North Atlantic Basin and Those Making Landfall in the U.S. During Atlantic Warm and Cold Phases



Source: Derived from HURDAT "best track" data (NOAA National Hurricane Centre)

Figure 3.9: Trends in Hurricane Genesis in the North Atlantic Basin (5-year moving average)



Source: Derived from HURDAT "best track" data (NOAA National Hurricane Centre)

3.5 European windstorms

Windstorms are the main cause of insured losses due to natural events in Europe; since 1970 there have been 55 significant windstorms in Europe, resulting in total insured losses of about US$ 44.4 billion. The scientific community refers to European windstorms as extra-tropical cyclones. Also, as they typically occur between October and March they are often referred to as winter storms.

The majority of windstorms affecting Europe originate in the North East Atlantic (along the 45^o of latitude or the “polar front”) and then move east, pushed along by the Jet Stream. As they move forward, at speeds of up to 40 ms^{-1}, the wind field becomes elongated. The highest wind speeds are observed to the right-hand side of the storm track directly behind the advancing cold front (sometimes up to several hundred kilometres from the track). The heaviest precipitation is found along the warm front. The storms themselves can have diameters of 1,000 to 2,000 kilometres.

While several hundred storms form annually, most of them dissipate before they reach Europe; around 180 low pressure systems cross the Atlantic per annum, which typically result in three major windstorms. Whether the storms cross Europe depends on the state of the Icelandic low and the Azores high pressure systems. In general, when the Icelandic low is well developed, more low pressure systems (and thus windstorms) will advance across Europe, as opposed to drifting northeast between Iceland and the top of the UK (see Box 2).

Box 2: The North Atlantic Oscillation

The North Atlantic Oscillation (NAO) characterises natural variability in air pressure over the North Atlantic. It also has a significant influence on the development and path of extra-tropical cyclones. The NAO is described as an index that measures the pressure differential between the Icelandic low and the Azores high. When the Icelandic low is well developed there is a marked difference in air pressure with the Azores high, and the NAO index is positive. High positive index values are associated with strong westerly air flows, which carry warm humid air, as well as more storms, well into Europe. During positive phases of the NAO index, Europe therefore experiences relatively mild and windy winters.

In contrast, when the NAO index is negative, the westerly air flows are weaker and the above conditions are reversed. That is, during a negative phase of the NAO index Europe will tend to experience relatively dry, cool and less windy winters.

Fluctuations in the NAO index are irregular; it switches between negative and positive phases every 5 to 25 years.

While the influence of the NAO on winter storms reaching into Europe is not in doubt, the real question in the context of climate change is whether anthropogenic GHG emissions are influencing the phases of the index. (We return to this below.)

In contrast to tropical cyclones, which are fuelled by condensation over warm waters, European windstorms are fuelled by the temperature differential between cold (arctic) and warm (tropical) air. As a result, European windstorms do not necessarily reduce in intensity when making landfall in the same way that hurricanes do. The larger the temperature differential between the cold air mass and the warm air mass, the larger the windstorm. Moreover, since the temperature differential is larger in winter (October to March), European windstorms tend to be stronger during this period.

As mentioned above, since 1970 there have been 55 windstorm events in Europe generating sufficient losses to be recorded by Swiss Re's Sigma series[26]. In total, these events have resulted in total insured losses of US$ 44.4 billion. Seven events account for US$ 28.4 billion: windstorm 87J (US$ 5.0 billion), windstorm Daria (US$ 6.6 billion), windstorm Herta (US$ 1.2 billion), windstorm Vivian (US$ 4.6 billion), windstorm Anatol (US$ 1.7 billion), windstorm Lothar (US$ 6.6 billion) and windstorm Martin (US$ 2.7 billion). That is, 64 per cent of total insured losses resulted from 13 per cent of windstorms.

In looking at Figure 3.10 there is no real discernible year-on-year trend over the period 1970-2004, in either the number of events or insured losses; any pattern in insured losses over such a relatively short time period is very unlikely given the scale of losses resulting from the big 7 storms. There is, however, an upward trend in the number of windstorm events when we consider inter-decadal trends; the average number of events between 1970 and 1979 was 0.4 per annum, rising to 2.8 per annum between 1990 and 1999 (see Figure 3.11).

One should be cautious in drawing any conclusions regarding the role of climate change when looking at trends in insured events however. To date, trends in insured losses have been driven predominantly by socio-economic factors, including population growth, concentrations of population in urban areas, and rising quantities of increasingly valuable assets in risk prone areas. There have also been improvements in monitoring, so that more events are identified and recorded annually.

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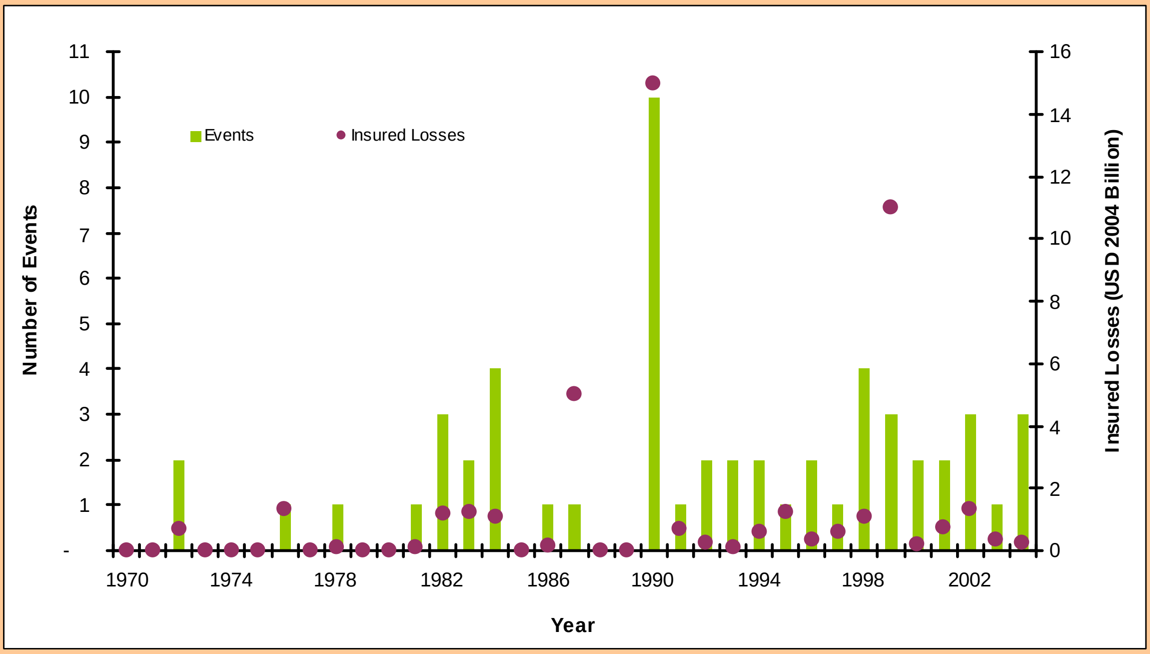
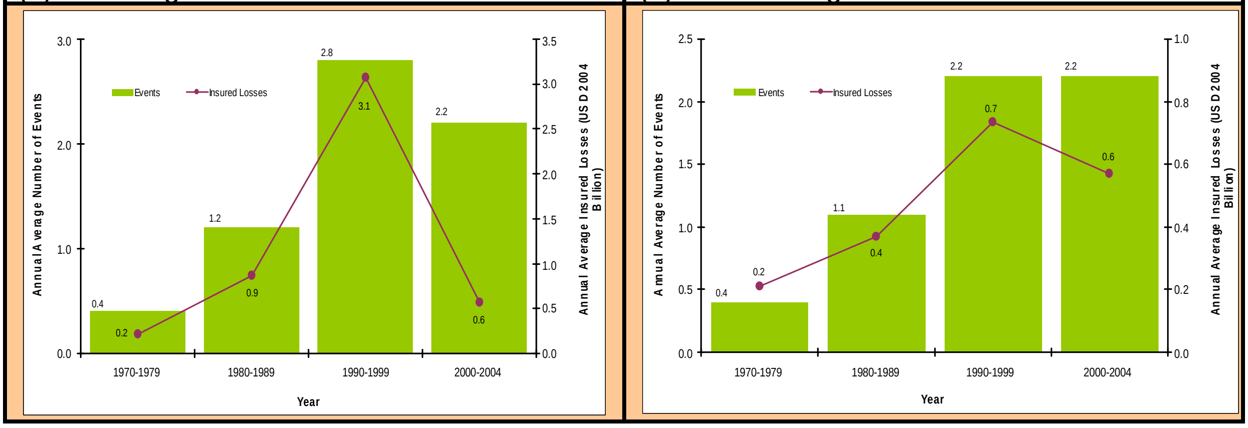
[26] For example, for the 2004 reporting year, Swiss Re, Sigma only records events with insured losses greater than US$ 37.5 million, total losses greater than US$ 74.9 million or 20 or more fatalities.

Figure 3.10: Number of Severe Windstorm Events and Associated Insured Losses in Europe 1970-2004



Source: Sigma Database, Swiss Re

Figure 3.11: Annual Average Number of Severe Windstorm Events and Annual Average Insured Losses By Decade in Europe (1970-2004)



(a) With “Big” Seven

(a) Without “Big” Seven

Source: Sigma Database, Swiss Re

3.6 Summary of climate science

Broadly, concern over the possible future changes in cyclone activity as a result of climate change relates to changes in[27]:

- the frequency and area of occurrence;
- the mean intensity;
- the maximum intensity; and
- the rain and wind structure.

Several approaches have been used to assess the potential impact of climate change on these aspects of cyclone activity, including: using global climate models to directly simulate cyclone activity, empirical downscaling, estimates based on theoretical maximum potential, and nested high resolution simulation experiments (see Box 3).

Box 3: Approaches to Assess the Impact of Climate Change on Cyclone Activity

- Coupled Ocean-Atmosphere General Circulation Models (OAGCM) and Atmospheric General Circulation Models (AGCM) linked to Mixed-Layer Ocean (MLO) sub-models or employing sea surface temperature predictions from OAGCM. These models have been used to directly simulate cyclone activity. However, published studies –particularly earlier studies, as shown below – do not exhibit much consistency. Some studies show frequency increasing, while others find a decrease in frequency, depending on the model used. These inconsistent results have brought into question the capacity of these (coarse) models to realistically simulate cyclogenesis.
- An alternative to using global climate models to directly simulate cyclone activity is to infer cyclogenesis from the climatic output of these models using meteorological-based empirical methods, such as Gray's genesis parameters. One such study (reference) finds that a doubling of CO2 concentrations results in an increase of cyclone frequency of between 4 and 7 per cent. However, these meteorological-based empirical methods were developed for the present climate and need to be modified for application to future climates. There is thus some uncertainty over the reliability of these modified empirical methods.
- 'Up-scaling' thermodynamic models, such as those of Emanuel (1986) and Holland (1997). The maximum intensity that a tropical cyclone can achieve in any given atmospheric (thermodynamic) environment is called the maximum potential intensity (MPI). The basic Carnot model of MPI, as developed by Emanuel (1986 and 1995), predicts that the maximum tropical cyclone wind speed will increase with global warming. The MPI essentially places an upper ('speed') limit on the magnitude of the change in wind speed. However, these models are known not to capture all the relevant processes.
- Meso-scale models driven off-line from the output of OAGCM or AGCM have greater resolution and are better at capturing cyclone climatology than the coarser models.

Sources: Henderson-Sellers, A. et al[12] and Knutson[28]

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[27] Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster and K. McGuffie (1998) "Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment, *Bulletin of the American Meteorological Society*, 79(1): 19-38.

[28] Knutson, T.R. (2002) "Modelling the Impact of Future Warming on Tropical Cyclone Activity", IPCC Workshop on Extreme Weather and Climate Events, Workshop Report, Beijing, China, 11-13 June, 2002.

3.6.1 Tropical cyclones

Up to 2001, the results of research into the possible impact of climate change on the frequency and character of tropical cyclones is best captured in the conclusions of the IPCC (First, Second and Third) Assessment Reports. A selection of key studies underlying the IPCC Reports are summarised in Box A1 in Appendix A.

The First Assessment Report (FAR) from the IPCC[29] (IPCC, 1990) stated that: "…*climate models give no consistent indication whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades*".

The Intergovernmental Panel on Climate Change published its Second Assessment Report (SAR) in 1996. The "Science of Climate Change" report stated that (Houghton et al, 1996, p. 334):
"…*the-state-of-the-science* [tropical cyclone simulations in enhanced greenhouse conditions] *remains poor because*: (i) *tropical cyclones cannot be adequately simulated in present GCMs* [General Circulation Model or Global Climate Model]; (ii) *some aspects of ENSO* [El Niño Southern Oscillation] *are not well simulated in GCMs*; (iii) *other large-scale changes in the atmospheric general circulation which could affect tropical cyclones cannot yet be discounted*; *and* (iv) *natural variability of tropical storms is very large, so small trends are likely to be lost in the noise*."

It went on to say:
"*In conclusion, it is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of tropical cyclones will change*".

In the Technical Summary the IPCC state: "*Although some models now represent tropical storms with some realism for present day climate, the state of the science does not allow assessment of future changes*" (IPCC, 1996, p. 44).

However, by the time of the IPCC Third Assessment Report (TAR) in 2001 - the "Science of Climate Change" concluded that: "…*there is some evidence that regional frequencies of tropical cyclones may change, but none that their locations will change. There is also evidence that the peak intensity may increase by 5% to 10% and precipitation rates may increase by 20% to 30%*" (IPCC, 2001, Box 10.2). The IPCC went on to say, however, that "*There is a need for much more work in this area to provide more robust results*."

Indeed, more research into the possible links between climate change and future tropical cyclone activity has been undertaken. A selection of key post IPCC TAR studies are summarised in Box A2 at Appendix A. However, these studies do not change the main conclusions of the TAR. Specifically, the literature (and expert opinion) remains inconclusive on changes to the frequency of tropical cyclones under global warming; the range of estimates and uncertainties is still very large. Hence, in this study we do not consider simulating changes to the frequency of tropical cyclones.

Further evidence is emerging to support the TAR conclusions on tropical cyclone intensity, that both wind speeds and precipitation rates are likely to increase in an atmosphere with higher levels of CO_2 concentrations. One such recent study, by Knutson and Tuleya (2004), found that in moving from a control (base) case to a "high-CO_2" (roughly 2.2 x CO_2 concentrations) case:

- The minimum central pressure of tropical storms (averaged over hours 97-120) drops by an average of 10 mb, from 934 mb to 924 mb.

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[29] www.ipcc.ch Intergovernmental Panel on Climate change

- The pressure fall (i.e. the difference between the minimum central pressure and the environmental surface pressure) is 14 per cent greater (range is 13 to 15 per cent greater).
- "Intense" (Category 3-5) tropical cyclones increase, on average, by half a Saffir-Simpson Category.
- Maximum surface wind speeds increase by an average of 3.4 ms^{-1}, from 59.3 ms^{-1} to 62.7 ms^{-1}. Equivalent to an increase of 6 per cent (range is +5 to +7 per cent).
- The mean instantaneous precipitation rate (averaged over all grid points within a 100 km of the storm centre at hour 120) increases from 80 to 95 cmd^{-1}. Equivalent to an increase of 18 per cent (range is +12 to +26 per cent).
- The maximum precipitation rate anywhere in the storm domain increases from, on average, 706 to 875 cmd^{-1}. Equivalent to an increase of 24 per cent (range is +17 to +33 per cent).

Regarding the tracking of tropical cyclones there is little evidence of any change in the North Atlantic, although one recent study suggests that sea surface warming may inhibit the landfall of hurricanes over Southeast Florida. Likewise, there is little evidence of significantly different storm tracks in the Western North Pacific, although the storms track slightly more pole ward.

3.6.2 Extra-tropical cyclones

There are a growing number of studies addressing possible changes in extra-tropical cyclone activity - a selection of these are summarised in Box A3 at Appendix A. However, there are still large uncertainties in model predictions, despite a growing body of work since the IPCC TAR. For example, simulations of the north Atlantic storm track in present day climate simulations differ considerably from observed data. This means that predictions of future changes in the location of the track have to be treated with some caution. The results of different models are also inconsistent, with some models (e.g. HadAM3P) showing a southward shift in the north Atlantic storm track, while other models (e.g. HadCM2) show a shortening of the north Atlantic track. The former tends to increase the number of storms over the UK, whereas the latter would lead to fewer storms over the UK. There is also uncertainty with respect to the mechanisms governing the climate signals.

Nonetheless, some consensus is emerging (although still incomplete) between models that points towards an increase in the frequency of "deep" winter storms (with central pressure less than 970 mb) over the north Atlantic. Moreover, we may see these "deep" storms tracking further south over the UK and further into western and central Europe, with the North Atlantic Oscillation (NAO) possibly intensifying as CO_2 concentrations increase in the future[30]. One study, by Leckebusch and Ulbrich (2004), simulated CO_2-induced changes to the activity of extreme storms and found that[31]:

- There is a 20 per cent increase in storms in the 95th percentile (sea level pressure) that track across southern England, France, Germany, northern Switzerland, and the Benelux countries.
- 95th percentile maximum wind speeds in storms that track across southern England, France, Germany, northern Switzerland, and the Benelux countries increase by 10 per cent.

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[30] See, for example, Kuzmina et al (2005).

[31] Although the study did not attempt to quantify the impact on less intense storms (i.e. windstorms in the lower percentiles of the distribution of possible events), it implied that these may also be affected.

These climate change signals in storm activity were observed under IPCC SRES emission scenario A2 (see below) towards the end of the century.

3.7 Financial impacts of changes in the character of storms

As evident from the above discussion, considerable uncertainty remains over the influence of projected climate change on tropical and extra-tropical cyclone activity. While it is premature to treat any (emerging) link between climate change and storm activity / character as definitive, it is at least worth evaluating the potential impacts, if some of the more recent estimates of climate-induced changes in the character of storms were indeed to be realised.

To this end, we simulate three simple climate-stress tests using insurance industry natural catastrophe models, based on the Knutson and Tuleya (2004) and Leckebusch and Ulbrich (2004) findings[32]:

- The maximum surface wind speeds in hurricanes in the Atlantic Basin have been increased by 6 per cent.
- The maximum surface wind speeds in typhoons in the Western North Pacific Basin have also been increased by 6 per cent.
- There is a 20 per cent increase in the top 5 per cent (in terms of sea level pressure) of windstorms affecting Western Europe. This does not imply an increase in the total number of storms, but rather a shift in the existing distribution towards more intense storms, with higher winds.

Wind speed is not the only hazard associated with these storms. As noted above, damage from tropical cyclones and European windstorms is also caused by storm surges and intense precipitation, in combination with the high winds. Furthermore, there is increasing evidence that both the storm surge and rainfall generated by these storms may increase as a result of climate change. In order to generate a more complete picture of the potential financial costs of stronger storms, the predicted changes in these other two hazards should be simulated simultaneously. The results presented below will therefore tend to underestimate the true financial cost and insured losses of the storm events simulated. (There are other reasons why the results will tend to understate the true damages; these are discussed below).

The studies from which the proposed stress tests for hurricanes and typhoons are based relate solely to a future world in which CO_2 concentrations essentially double. However, in this study we are also interested in the implications of moving from higher emission scenarios to lower ones, and therefore must be able to scale the results of the simulations to alternative CO_2 concentrations. To facilitate this we also undertook a couple of sensitivity tests, involving: (a) increasing the 6 per cent change in wind speed by 50 per cent, and (b) decreasing the 6 per cent change in wind speed by 30 per cent. Adjustments of this order are representative of the changes in CO_2 concentrations (and corresponding radiative forcing) required to move from roughly a doubling of concentrations to specific emission scenarios.

The simulations were undertaken by the natural catastrophe modelling team at AIR-worldwide[33]. Using their natural catastrophe models for hurricanes, typhoons and

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[32] Converium Re performed a similar exercise for a particular portfolio of typhoon events in the Northwest Pacific Basin. Converium estimated that expected annual losses in a warmer climate (in which sea surface temperatures increase by about 2.2°C, inducing tropical cyclones to increase in intensity by between 5-12 per cent) could be between 40-50 per cent higher by the end of the century, ceteris paribus (Converium, 2004).

European windstorms, AIR estimated the incremental impact on property (including residential, commercial and industrial facilities, and automobiles) of moving from a baseline (or current) storm event set, to one in which the above climate-stress tests are included.

3.8 Tropical cyclones

The results of the simulated climate-stress tests for hurricanes and typhoons are presented in Table 3.2. Since the natural catastrophe models used were essentially built to service the insurance industry, the output is in terms of insured losses. That is, the losses represent damages to insured properties after the application of insurance policy conditions, such as deductibles, coverage limits, loss triggers, coinsurance, and risk or policy specific reinsurance terms. Also, since the models are fully probabilistic, the loss estimates are annual expected (or average) losses, derived from probability loss distributions.

Table 3.2: Increment in Average Annual Insured Losses

Climate Stress-test	**Hurricanes Affecting U.S.** (US$ 2004 Billion)	**Typhoons Affecting Japan** (US$ 2004 Billion)
Central case: Wind speeds increase by 6%	3.9	1.6
Sensitivity: Wind speeds increase by 4%	2.6	1.0
Sensitivity: Wind speeds increase by 9%	6.5	2.6

Source: AIR-worldwide

Insurers and reinsurers are hugely interested in the insured losses associated with extreme possibilities; typically measured as the losses arising once every 100 years (or losses with a 1 per cent exceedance probability) or losses arising once every 250 years (or losses with a 0.4 per cent exceedance probability). Table 3.3 and Table 3.4 present the results for both these extreme possibilities, respectively. Looking at Table 3.3, for example, a 6 per cent increase in maximum surface wind speeds is estimated to increase 1-in-250 year insured losses from hurricanes by US$ 61.8 billion. If wind speeds were to increase by 9 per cent (which is within the range cited in the scientific literature) 1-in-250 year insured losses from hurricanes are estimated to increase by US$ 97.5 billion.

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[33] While AIR-Worldwide Corporation kindly simulated the climate-stress tests using their models, the scenarios simulated should in no way be interpreted as being representative of AIR-Worldwide Corporation's view on the effects of climate change on hurricanes, typhoons or European windstorms.

Table 3.3: Increment in Insured Losses with a 1 Per Cent Exceedance Probability

Climate Stress-test	**Hurricanes Affecting U.S.** (US$ 2004 Billion)	**Typhoons Affecting Japan** (US$ 2004 Billion)
Central case: Wind speeds increase by 6%	40.8	10.1
Sensitivity: Wind speeds increase by 4%	26.6	6.6
Sensitivity: Wind speeds increase by 9%	68.3	17.3

Source: AIR-worldwide

Table 3.4: Increment in Insured Losses with a 0.4 Per Cent Exceedance Probability

Climate Stress-test	**Hurricanes Affecting U.S.** (US$ 2004 Billion)	**Typhoons Affecting Japan** (US$ 2004 Billion)
Central case: Wind speeds increase by 6%	61.8	14.4
Sensitivity: Wind speeds increase by 4%	41.9	9.0
Sensitivity: Wind speeds increase by 9%	97.5	24.9

Source: AIR-worldwide

In order to approximate the costs of changes in wind speed different to those directly simulated, we have fitted curves to the data points and extrapolated them forward and backward to encompass increases in wind speed ranging from zero to 10 per cent (with a power function offering the best fit in all cases); noting that this is a rather crude approximation. The resulting loss functions are provided at Appendix B.

3.9 Investigating the impacts of mitigation

The 6 per cent increase in maximum surface wind speed is the average increase observed across 3 tropical cyclone basins (including the Western North Pacific and North Atlantic) in an experiment in which CO_2 concentrations increase over an 80-year period at a compound rate of 1 per cent per annum. This results in CO_2 concentrations that are higher by a factor of 2.22 by year 80; concentrations double at year 70. Unfortunately, the experiment is not based on a specific starting concentration, and therefore the 6 per cent increase wind speed cannot be related directly to a specific IPCC SRES emission scenario (or specific future year) on the basis of CO_2 concentrations (see Box 4). However, by year 80 in the experiment radiative forcing[34] is approximately 4.2 Wm^{-2}, and

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[34] The IPCC (IPCC, 1996) use the following definition: "The radiative forcing of the surface-troposphere system due to the perturbation in, or the introduction of, an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropopause after allowing for

each of the SRES emission scenarios has a specific profile of radiative forcing. This provides us with the basis of a link between (a) estimated changes in wind speed, (b) radiative forcing, (c) CO_2 concentrations and (d) the SRES emissions scenarios; with changes in wind speed linked to expected insured losses through the loss curves found at Appendix B.

Box 4: Summary of the IPCC SRES Emission Scenarios

In 2000 the IPCC published a set of greenhouse gas emission scenarios. The scenarios are based around four different storylines, which describe consistently the relationships between the determinants of emissions and their evolution over time, and to provide context for quantification of the scenarios.

A1

The A1 storyline describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B)

A2

The A2 storyline describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than other storylines.

B1

The B1 storyline describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Sources: p. 63 IPCC Technical Summary of the Working Group I Report.

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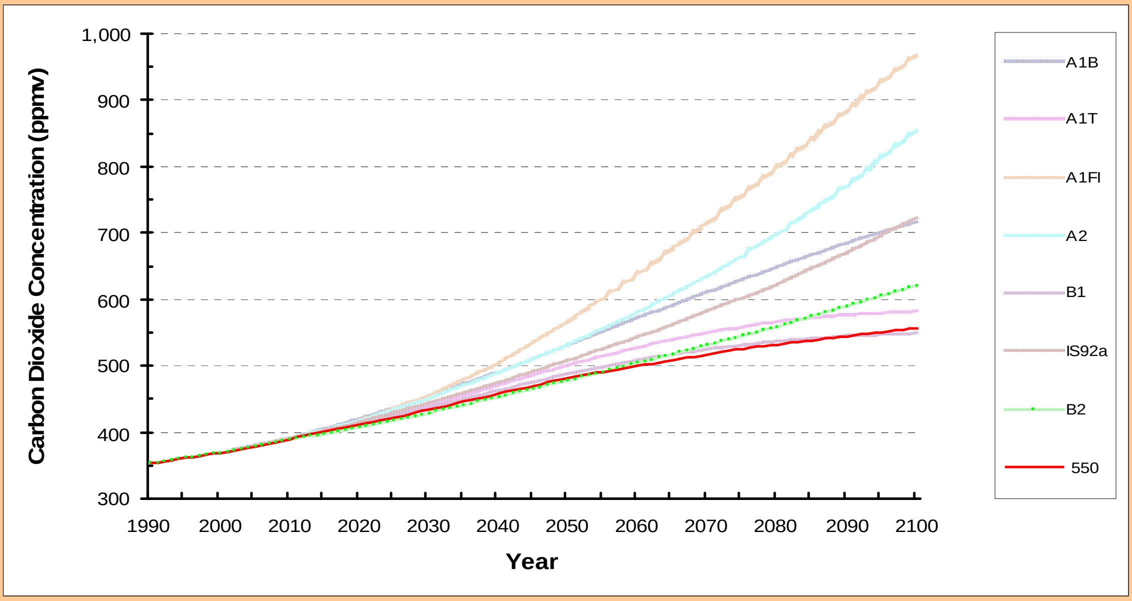
stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values."

Figure 3.12 contains the projected CO_2 concentrations for the six illustrative SRES scenarios, based on the ISAM model. The figure also shows the concentration profiles corresponding to an emission path designed to move the A1 SRES emissions scenarios towards stabilisation of CO_2 concentrations at 550 ppm by 2200. We have computed the associated radiative forcing using the following simplified expression from Table 6.2 in IPCC Technical Summary of Working Group I:

$$\Delta F = \alpha \ln (C / Co)$$

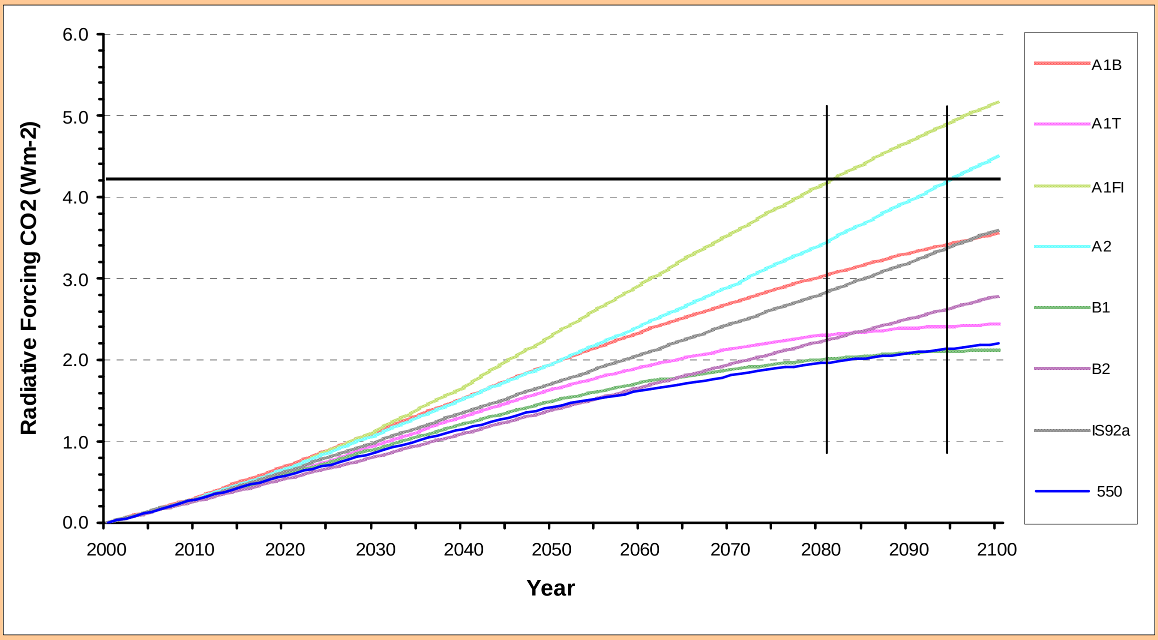
Where ΔF is the change in radiative forcing (in Wm^{-2}), α is a constant equal to 5.35, C is the concentration of CO_2 in ppm, and the subscript zero denotes the unperturbed concentration. Starting in 2000 the estimated radiative forcing for the six illustrative SRES emissions scenarios shown in Figure 3.12 is displayed in Figure 3.13. Of note, radiative forcing (of 4.2 Wm^{-2}) that gives rise to the 6 per cent increase in wind speeds is only reached under A1F1 and A2, and not until after 2080.

Figure 3.12: Atmospheric Concentrations of CO_2 for the Six Illustrative IPCC SRES Emissions Scenarios, the IS92a Scenario and 550 Stabilisation Scenario



Source: ISAM Model (reference case)

Figure 3.13: Estimated Radiative Forcing for the Six Illustrative IPCC SRES Emissions Scenarios, the IS92a Scenario and Two 550 Stabilisation Scenarios



In order to extrapolate changes in wind speed to different magnitudes of radiative forcing it is necessary to make the simplifying assumption that a 1 per cent decrease (increase) in radiative forcing results in a 1 per cent decrease (increase) in the change in wind speed. This assumption allows us to map changes in wind speed (from zero per cent to 10 per cent) to the full range of radiative forcing displayed in Figure 3.13; the lower the radiative forcing relative to 4.2 Wm^{-2}, the lower the change in the maximum surface wind speeds for hurricanes and typhoons. It is then a matter of using the loss functions at Appendix B to calculate the increment in annual average insured losses (or the increment in 1-in-100 or 1-250 year insured losses) for the full range of wind speed changes associated with each emissions scenario.

The above procedure is probably best illustrated though an example: Under the A1F1 emission scenario CO_2 concentrations in 2070 are estimated to be about 716 ppm. The corresponding level of radiative forcing relative to 2000 is about 3.5 Wm^{-2}. This level of radiative forcing is estimated to increase maximum surface wind speeds by roughly 5 per cent. According to the relevant loss function, a 5 per cent increase in hurricane wind speeds, in turn, is simulated to increase average annual losses by about US$ 3.2 billion. This procedure had been undertaken for all the emissions scenarios shown in Figure 3.12. The results for various future time slices are found at Appendix C.

The figures at Appendix C show the three measures of incremental insured losses for each emission scenario averaged over 20 year time slices. As expected, the emission scenario with the highest radiative forcing, A1F1, also results in the highest increment in average losses. As Table 3.5 shows, under A1F1, annual average insured losses from increased wind speeds in hurricanes are estimated to increase by US$ 4.3 billion per annum, on average, over the period 2080-2099. However, if emission were to reduce in accordance with the 550 stabilisation emission profile, annual average insured losses from increased wind speeds in hurricanes would increase by only US$ 0.8 billion per annum, on average, over the same period. The corresponding increments in annual average insured losses for typhoons are US$ 1.7 billion (A1F1) and 0.3 billion (A1 550) per annum.

To put these insured loss estimates into context, based on industry experience, insured losses from Atlantic hurricanes since 1995 averaged US$ 5.5 billion per year. Japanese typhoons produce average insured losses of US$ 2.5 billion per year over the same period. By the end of the century, annual average insured losses from typhoons, for example, would therefore increase by nearly 70 per cent under emission scenario A1F1, ceteris paribus, if climate change were to induce wind speeds to increase by 6 per cent per 4.2 Wm^{-2} of radiative forcing. Under a medium emission scenario like IS92a, annual average insured losses from typhoons would increase by 40 per cent.

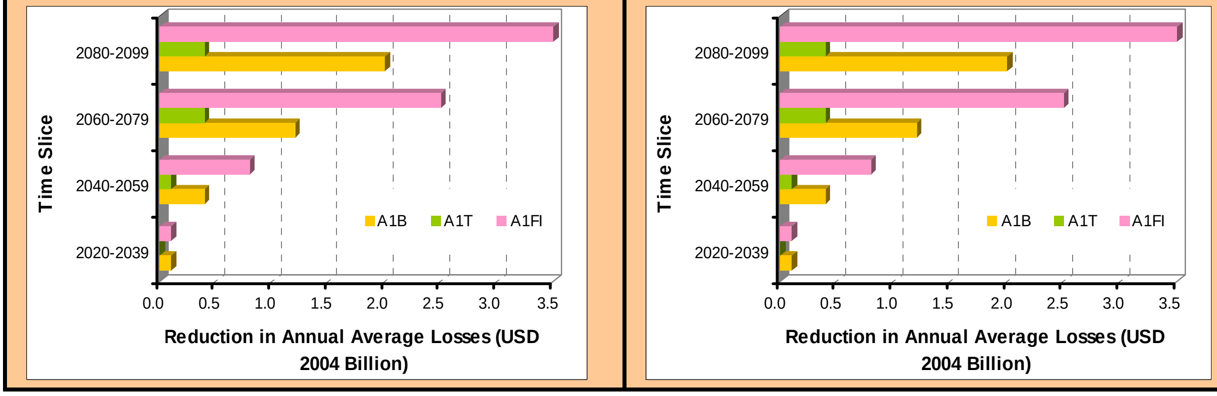
Table 3.5: Increment in Average Annual Insured Losses over the Time Slice 2080-2099

Emission Scenario	**Hurricanes** (US$ 2004 Billion Per Year)	**Typhoons** (US$ 2004 Billion Per Year)
A1B	2.8	1.1
A1T	1.2	0.5
A1F1	4.3	1.7
A2	3.5	1.4
B1	0.8	0.3
B2	1.4	0.5
550	0.8	0.3
IS92a	2.6	1.0

Figure 3.14 and Figure 3.15 show the change in incremental annual average losses in moving from the A1 scenario group to a specific 550 stabilisation emissions profile for both (a) hurricanes and (b) typhoons. For example, if in the absence of action global emissions were to evolve along the A1B emission path, but international action was introduced to reduce carbon emissions sufficiently to put us on the specified 550 stabilisation path, then the increment in annual average insured losses from hurricanes over the period 2080-2099 would be reduced by just under US$ 2.0 billion. That is, instead of annual average insured losses increasing by US$ 2.8 billion per year, they would only increase by US$ 0.8 billion per year.

The change in incremental probable maximum losses in moving from the A1 scenario group to the 550 stabilisation emissions profile, for both hurricanes and typhoons, is provided at Appendix D.

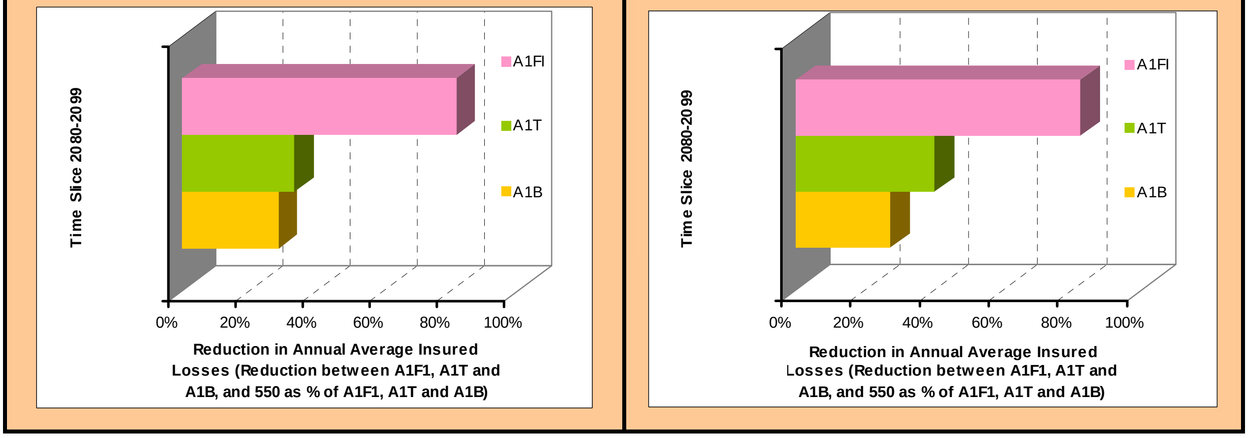
Figure 3.14: Illustration of the Benefits of Moving to a Lower Emission Path For Various Future Time Slices: Change in Annual Average Insured Losses



(a) Hurricanes

(b) Typhoons

Figure 3.15: Illustration of the Benefits of Moving to a Lower Emission Path For 2080-2099 Time Slice: Percentage Reduction in Annual Average Insured Losses



(a) Hurricanes

(b) Typhoons

3.10 Extra-tropical cyclones

The results of the simulated climate-stress test for European windstorms are presented in Table 3.6. If climate change were to induce a 20 per cent increase in the top 5 per of windstorms (by central pressure) annual average insured losses are simulated to increase by just under US$ 0.4 billion. The insured losses airing from a 1-in-100 and 1-in-250 year insured loss are estimated to increase by about US$ 2.0 and 2.3 billion, respectively.

To put these losses in context, the average annual insured losses from windstorms affecting Europe over the period 1970-2004 was roughly US$ 1.5 billion, including the "big" seven events. Removing the "big" seven events, average annual insured losses drop to just under US$ 0.5 billion per year.

Table 3.6: Increment in Insured Losses for Climate-Stress Tests: Extra-tropical Cyclones Affecting Western Europe

Measure of Insurance Loss	**Insured Losses** (US$ 2004 Billion)
Annual average losses	0.4
1 per cent exceedence probability (1-in-100 year storm)	2.0
0.4 per cent exceedence probability (1-in-250 year storm)	2.3

Source: AIR-worldwide

It was not possible to conduct the same sensitivity tests for European windstorms that were performed for hurricanes and typhoons. As a consequence, we are unable to quantify the increment in insured losses for each of the different emissions scenarios, or from moving from a relatively high emission scenario to a relatively low (stabilisation) scenario. The increase in extreme European windstorms simulated in this study was observed under the A2 emissions scenario, but the same climate signal was much less pronounced under the B2 scenario. This implies that reducing emissions, in moving from the relatively high A2 scenario to the lower B2 scenario, will reduce annual average insured losses; we just do not know by how much.

Recall, that the stress-tests on tropical cyclones were applied to the entire distribution of all possible hurricanes and typhoons, whereas the stress-test on European windstorms was restricted to the extreme upper tail of the distribution of all possible storms. The impacts of climate change on less intense European windstorms were not modelled, due to a lack of quantitative information about the possible impacts. In comparing Table 3.6 with Tables 3.2- 3.4, for example, one should not conclude that the climate signal concerning European windstorms is weak relative to the signal for tropical cyclones.

3.11 Total financial versus insured losses

Above we focused on insured losses, which are only a fraction of total financial costs. Specifically, insured losses comprise the proportion of total financial losses covered by an insurance contract. Financial losses, as measured by insurers, refer to total damages arising from impacts on financial assets or activities, such as property, infrastructure, business interruption, etc. Insured losses as a percentage of total financial losses from windstorms affecting each of Japan, the U.S and Europe, based on current industry experience, are roughly 60-65 per cent, 55-60 per cent and 50-55 per cent, respectively. Put another way, total financial losses in, for example, Europe, are about twice as much as the insured loss estimates presented above.

We have used these ratios to re-scale the estimated increments to annual average insured losses in order to approximate the increment to annual average total financial losses for the various climate-stress tests. The results are presented below. It is important to note, however, that these loss estimates do not fully reflect the total “economic” (as measured by economists) losses associated with hurricanes, typhoons and European windstorms. First, we have only explicitly simulated increases to one hazard (i.e. wind), ignoring precipitation and storm surge. Second, we have only considered the damage caused by this one hazard on one receptor (i.e. property), thus ignoring impacts on, for example, human health and ecosystems. And third, we are valuing all losses on the basis of market prices (e.g. replacement cost), which may not accurately reflect the full welfare losses associated with property damage; as measured by society's maximum willingness-to-pay to avoid damage from windstorms, or the minimum compensation that society is willing-to-accept in order to tolerate damage from windstorms. The loss estimates presented below are therefore likely to considerably understate the true welfare costs, if we were to see windstorms intensify as a result of climate change.

The estimated increment in financial losses for the simulated climate-stress tests for hurricanes and typhoons are presented in Table 3.7. If climate change were to increase maximum surface wind speeds by 6 per cent, annual average financial losses are estimated to increase be about US$ 6.8 billion and US$ 1.6 billion for hurricanes and typhoons, respectively.

If climate change were to induce a 20 per cent increase in the top 5 per of European windstorms (by central pressure) annual average financial losses are simulated to increase by just under US$ 0.8 billion.

Table 3.7: Increment in Average Annual Financial Losses

Climate Stress-test	**Hurricanes Affecting U.S.** (US$ 2004 Billion)	**Typhoons Affecting Japan** (US$ 2004 Billion)
Central case: Wind speeds increase by 6%	6.8	2.5
Sensitivity: Wind speeds increase by 4%	4.4	1.6
Sensitivity: Wind speeds increase by 9%	11.3	4.1

Figure 3.16 and Figure 3.17 show the incremental total financial losses for each of the various emissions scenarios considered, averaged over 20 year time slices, for hurricanes and typhoons, respectively. As with insured losses, the emissions scenario with the highest radiative forcing, A1F1, also results in the highest increment in average annual financial losses.

Figure 3.18 and Figure 3.19 show the change in incremental annual average financial losses in moving from the A1 scenario group to a specific 550 stabilisation emissions profile for both (a) hurricanes and (b) typhoons. If, under business-as-usual, global emissions were to evolve along the A1B emission path, and international action was introduced to reduce carbon emissions sufficiently to put us on the specified 550 stabilisation path, then the increment in annual average financial losses from hurricanes over the period 2080-2099 would be reduced by about US$ 3.3 billion, on average, per year. That is, instead of annual average financial losses increasing by US$ 4.8 billion per year, they would only increase by US$ 1.5 billion per year. Moving from A1B to the 550 stabilisation path, reduces the increment in annual average financial losses from typhoons over the period 2080-2099 by about US$ 1.2 billion, on average, per year.

Figure 3.16: Hurricanes: Average Annual Increment in Average Annual Financial Losses

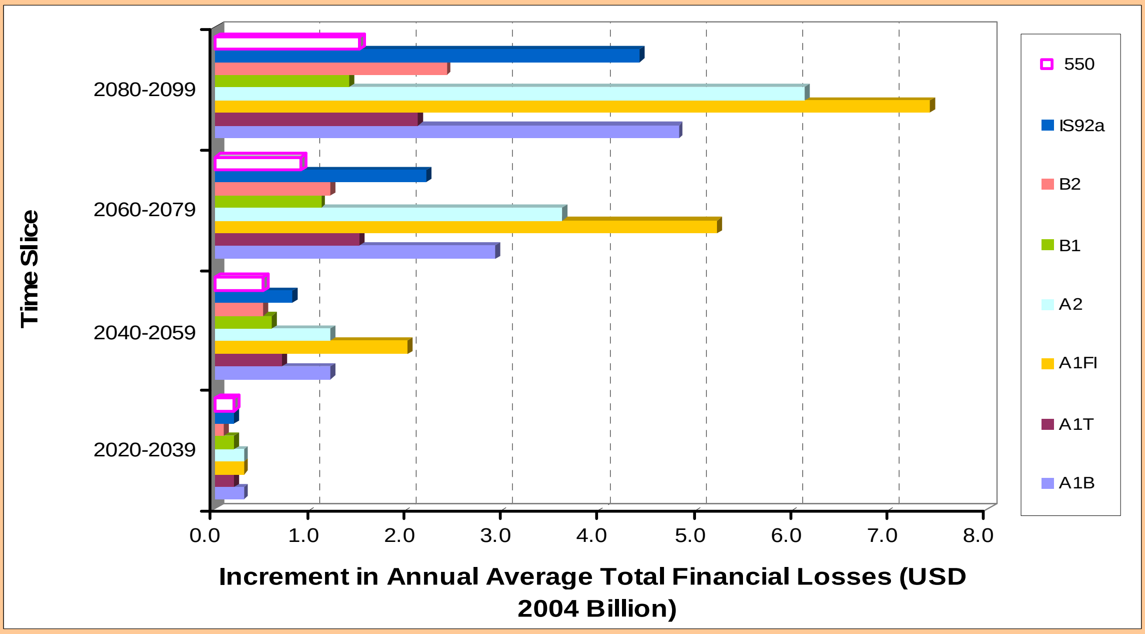


Figure 3.17: Typhoons: Average Annual Increment in Average Annual Financial Losses

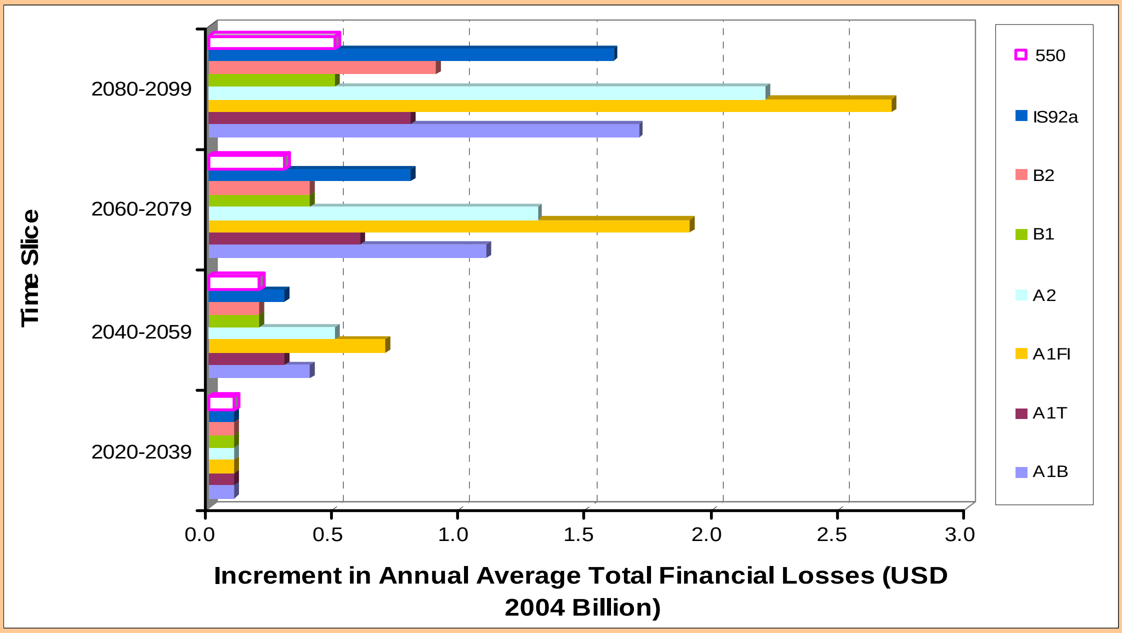


Figure 3.18: Illustration of the Benefits of Moving to a Lower Emission Path For Various Future Time Slices: Change in Annual Average Financial Losses

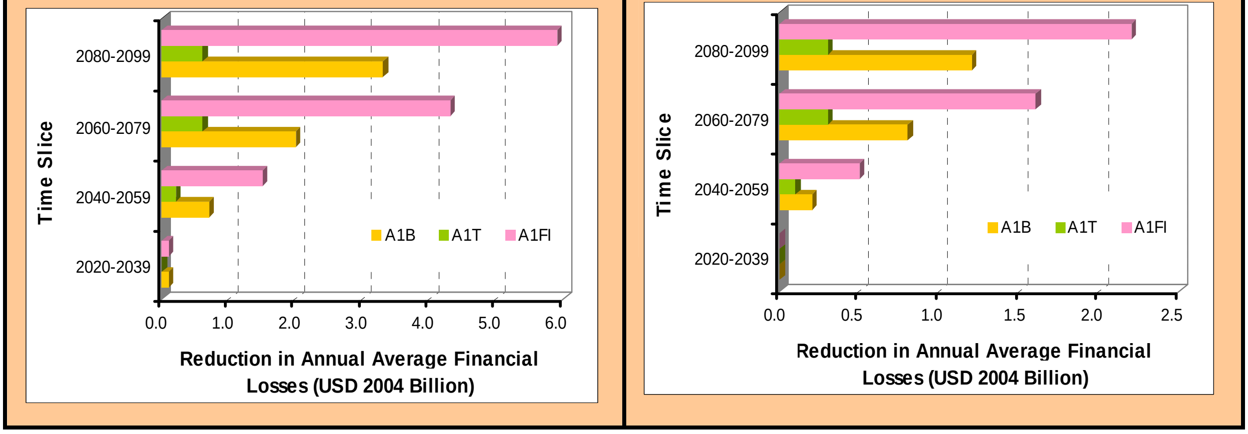
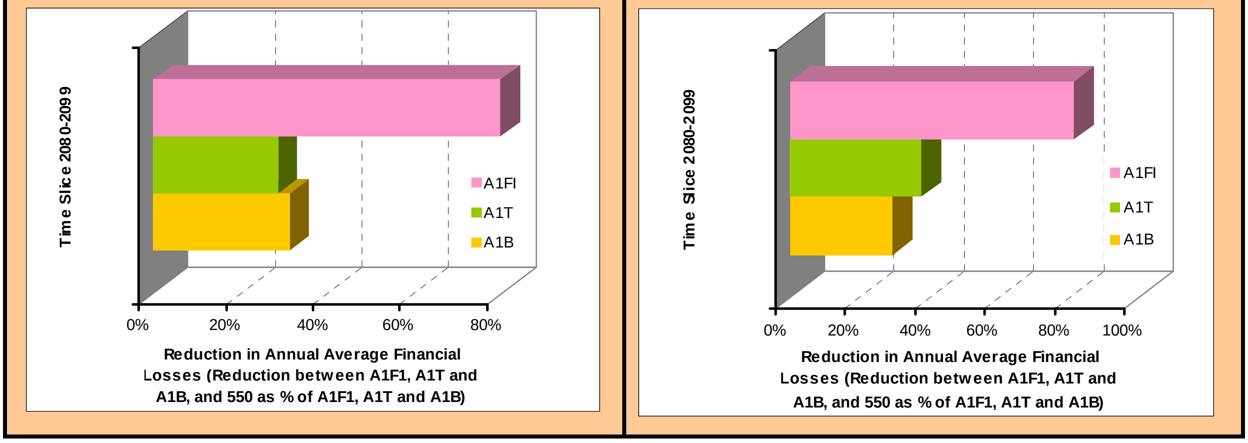

(a) Hurricanes (b) Typhoons

Figure 3.19: Illustration of the Benefits of Moving to a Lower Emission Path For 2080-2099 Future Time Slice: Percentage Reduction in Annual Average Financial Losses


(a) Hurricanes (b) Typhoons

3.12 Socio-economic developments

In viewing the trend data for windstorms outlined above it would be easy to conclude that windstorms have become more severe over time. However, reported insured and economic losses fail to account for socio-economic developments that may actually be increasing society's vulnerability to windstorms. The following factors will make the losses resulting from the same storm, hitting the same area, higher today than 20 years ago:

- First, population patterns within a defined area change with time. And more people are locating in vulnerable coastal areas. For example, the NOAA estimates that from 1980 to 2003 the coastal population in the U.S. grew by 33 million, and the coastal population is projected to increase by a further 12 million by 2015. Household sizes are also decreasing. This means that the stock-at-risk to the windstorm hazard is increasing with time.
- Second, one dollar will buy you less land, residential and commercial property, building materials, etc. today than it did 20 years ago, as a result of increases in the general price level. In other words, the nominal (and possibly, real) value of the (increasing) stock-at-risk to windstorms will tend to (also) increase with time.

- Third, real incomes are also increasing with time. That is, people are simply wealthier, and therefore tend to have more (physical) assets. Houses, for example, are becoming bigger and more elaborate. People therefore have more to lose.

Failure to account for these factors over time will lead one to misread the historic record. In the context of the present study, failure to account for the same factors will understate the simulated losses, which is indeed the case, since the climate-stress tests are applied to a static exposure data set. That is, the stock-at-risk and the value of that stock are assumed to remain constant, despite the fact that we are looking at time periods nearly 100 years into the future.

To gain some insight as to the extent to which the losses are underestimated consider Table 3.8, which contains one set of projections for per capita incomes (in Purchasing Power Parity 1995 US$), which is an indicator of real income, for Western Europe, Japan and the U.S. Table 9 contains population projections for the EU15 and Poland, Japan and south and southeast U.S. coastal states.

Table 3.8: Index: Projected Per Capita Incomes 2000-2100 (2004 = 100) (PPP 1995 US$)

Year	Western Europe	Japan	U.S.
2000	89	91	94
2025	159	146	134
2050	220	202	176
2075	271	238	219
2100	323	280	262

Source: IMAGE 2.2 (www.rivm.nl)

Table 3.9: Index: Estimated Projected Populations 2000-2100 (2004 = 100)

Year	EU15 and Poland [a]	Japan [b]	S & SE U.S. States [c]
2000	100	100	96
2025	104	95	124
2050	99	79	160
2075	99	62	207
2100	99	50	267

Source: (a) Projections from Eurostat to 2050; extrapolation to 2100 based on annualised growth rate 2000-2050. (b) Medium variant projection 2000-2100 made by the National Institute of Population and Security Research (www.ipss.go.jp). (c) Medium variant projection 2000-2050 made by US Census Bureau (www.census.gov); extrapolation to 2100 based on annualised growth rate 2000-2050.

Looking at Europe, for example, population (as an indicator of the size of the stock-at-risk) is projected to remain virtually constant till the end of the century. However, per capita incomes (as an indicator of individuals' wealth or a proxy for the value stock-at-risk) are projected to more than triple. Although this does not necessarily mean that the insured and financial loss estimates presented above for European windstorms would necessarily be three times higher, it does provide an indication of the extent to which they could be underestimated.

The potential for the losses given in Tables 3.2- 3.4 and Table 3.7 to be underestimated appears to be an even greater issue for the U.S. Both the population in states vulnerable to hurricanes and their wealth are forecast to nearly triple by 2100, relative to 2004.

We have not used the indices in Table 3.8 and Table 3.9 to adjust the incremental insured and financial loss estimates reported above for two reasons:

- Each emissions scenario has a specific underlying socio-economic scenario, which would include, for example, scenario specific forecasts of per capita income. To use indices of socio-economic variables that were not specific to an emissions scenario would introduce inconsistencies to the analysis.
- Both the "quantity" and "price" component of the loss estimates should be projected separately though time, and at a level of resolution that is consistent with the catastrophe model. To apply an "aggregate" index of price and quantity at a coarse resolution would fail to (a) reflect the appropriate weighting of "quantity" and "price" in the total loss estimates, and (b) account for spatial variations in the vulnerable of specific "quantity" and "price" combinations.

Future work in this area should strive to accurately accommodate the evolution of socio-economic variables over time.

3.13 Investigating the impacts of adaptation

Just as failing to account for the above socio-economic factors will lead us to underestimate the future incremental economic and insured losses of changing storm activity, failing to allow for adaptation will lead us to overestimate the incremental losses. The impact of windstorms depends on the frequency, intensity and duration of landfalling systems, and on the degree of preparedness and types of mitigation measures available to, and employed by, different groups within the population at risk (Diaz and Pulwarty, 1997). The latter set of measures will reduce the vulnerability of the affected population to windstorm damage, thereby reducing the impact of the climate signal on future storm activity.

When discussing adaptation to windstorms it is useful to distinguish between what insurers can do to mitigate (insured) losses, and what individuals can do to prevent damages from storms and reduce costs following a storm. The former is discussed more in the Section 6, although some of the measures that insurers can employ to mitigate losses can also be designed so as to provide households with economic incentives to implement preventative measures; essentially rewarding clients who do so. We highlight the role of insurers in providing the right incentives.

Table 3.10: Selection of Loss Mitigation Measures Adopted in Florida

Type of Measure	Examples
Financial	Discounts available through special windstorm underwriters. For example, Florida Windstorm Underwriting Association (FWUA) offers discounts to policyholders based on specific mitigation devices designed to protect their homes. Discounts range between 3 per cent and 18 per cent. Mandatory windstorm deductibles, typically 2 per cent of any loss (as opposed to traditional, fixed dollar deductible).
Informational	Continuous direct education of policyholders. Countless educational efforts aimed at teaching homeowners how to protect their property against windstorm damage by retrofitting existing or building new properties. Funding of educational initiatives through third parties. Use of industry trade associations to promote awareness and mitigation (e.g. IBHS, III) Federal initiatives (e.g. Federal Emergency Management Agency's Project Impact)
Building Codes	Florida's building code adopted new, higher standards for homes, including the 116 mph wind standard. Codes strengthened increasing wind resistance for roofs. More building and roofing inspectors were hired to increase compliance with building standards in some counties (e.g. Dade County). New regulations require review of building plans by a structural engineer. Supporting/funding research into wind-resistant designs. Federal initiatives (e.g. FEMA's Project Impact)
Public/Fiscal	Florida legislature established and funded a trust to provide support for recovery and mitigation efforts not covered by federal grants. Dade County passed a special sales tax to generate revenue for local recovery and mitigation efforts. Dade County created a hazard mitigation plan in order to receive federal disaster assistance under FEMA's 404 Hazard Mitigation Grant Program.
Partnerships	Insurers assist government and relief organisations with mitigation programs. Activate network of communication with many organisations in the event a hurricane appears imminent (e.g. relief and weather organizations add web link to insurer organization web sites with mitigation information).

Source: Insurance Information Institute

3.13.1 Building codes

When windstorms make landfall some property damage is inevitable. However, different building materials and construction techniques - wooden frame and masonry - are more vulnerable to wind damage than others. Other factors, such as building height, the reinforcement of walls and the strength of steel frames, also affect the vulnerability of structures to wind damage. High winds that enter a property through an opening in the building's envelope (e.g. window or door) raise the internal air pressure, which can cause the building to blow apart. Construction practices that take account of these factors, along with the addition of protective devices, such as approved storm shutters, can thus help buildings become more resistant to winds.

According to a study commissioned by the Institute for Business and Home Safety, if all properties in south Florida meet the strong building code requirements for Miami-Dade and Broward counties, damages from a repeat of Hurricane Andrew (taking the same track in 2002 as it did in 1992) would drop by nearly 50 per cent for residential property and about 40 per cent for commercial property[35]. Overall, damages would drop by just over 45 per cent if all residences and businesses were retro-fitted or built to meet the more stringent code.

It is estimated that, in Florida, to construct a home that better withstands hurricanes would cost from 4 to 9 per cent more than a conventional home. At the same time, surveys show that, on average, individuals are prepared to pay up to 6 per cent more for a "fortified" dwelling.

Storm shutters and other protective devices for doors, windows, skylights and vents have also proved effective in reducing damage from high winds, by preventing them from penetrating the building's envelope and stopping rain from damaging the building's interior and contents. In recognition of this, insurers offer credits to clients who install such devices, which reduces their premiums. To qualify for credits, homeowners in Florida must install devices that are able to resist specified wind pressures. Additional credits can be gained by installing further measures that are able to withstand impacts from wind-blown debris.

3.13.2 Building code enforcement

In 1983 hurricane Alicia made landfall over Texas, causing US$ (current prices) 675 million in insured losses By contrast, Hurricane Diana, which hit North Carolina 1984, caused insured losses of US$ 36 (current prices) million. Given that the storms were roughly equal in size and intensity, why were the losses so different? A later study found that the level of building code enforcement was a key factor explaining the difference in claim costs. In North Carolina, building codes were found to be effectively enforced, and a as result only 3 percent of homes in suffered major structural damage from the hurricane. This was not the case with the area affected by hurricane Alicia, where close to 70 per cent of insured losses was attributed to poor code enforcement.

These findings promoted the former National Committee on Property Insurance (now the Institute for Business and Home Safety) to investigate the level of building code enforcement in Southern states. They found that officials and inspectors in about half of the counties surveyed were not enforcing the building code wind-resistance standards. It was estimated that between 25 and 40 percent of the losses from Hurricane Andrew could have been avoided with proper enforcement of building codes: Indeed, a Dade

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[35] See IBHS News Release, 25.08.2002 (www.ibhs.org).

County, Florida Grand Jury report issued in December 1992 confirmed that much of the damage was due to lax code enforcement.

As a result, the insurance industry began to develop a building code compliance rating system - the Building Code Effectiveness Grading Schedule (BCEGS). Under this scheme the building codes in an area are assessed, as well as how the code is enforced. An areas is then assigned a score out of ten, with 1 = robust enforcement of a strong code, and 10 = no recognisable code. Credits are they allocated on the basis of the score; with a score of 10 not qualifying for credits. The underlying principle is simple: buildings in areas with strong codes that are effectively enforced should incur lower losses on average, and therefore should be rewarded with lower premiums. Thus, communities are given an economic incentive (in the form of lower premiums and lower losses) to introduce, and enforce, strong building codes.

Preliminary indications from the 2004 hurricane season highlight the value of stronger codes, with most of the severely damaged structures (and sources of loss) being built prior to Hurricane Andrew, after which the BCEGS was initiated. Comparing homes built between 1994 and 2002, with those built after 2002, showed that those built after 2002 suffered about 40 percent less damage.

3.13.3 Planning

The NOAA found that in 2003, 53 per cent of the population in the U.S. lived in coastal counties, which collectively account for 17 per cent of the country's land mass. Twenty-three of the 25 most densely populated areas in the U.S. are on the coast. As mentioned above, between 1980 and 2003, the population of coastal counties grew by 33 million people, or 28 per cent. The population of Florida grew by 75 percent and Texas by 52 percent; two states that are at high risk to hurricanes. Furthermore, growth is expected to continue. Between 2003 and 2008 the coastal population in those states most vulnerable to windstorms is expected to grow by 1.1 million, or 8 percent, with the highest growth expected in the southern Florida. Coastal counties in the Carolinas and Georgia are also expected to see considerable population increases. Large Increases are forecast for the Houston, Texas area and Florida's central Gulf Coast. Globally, the U.N. estimates that nearly 40 per cent of the world's population live within 100 km of the coast, and that this proportion is increasing.

The growth and concentration of buildings (and wealth) in windstorm-prone areas raises questions about public policy regarding coastal development / planning. Also, allowing such development to continue potential gives rise to hidden subsidies within insurance transactions[36].

Insurers can make people who live in high risk (coastal) areas pay their fair share of the cost of windstorms by introducing higher deductibles for storm damage. These deductibles, which exist in regions prone to hail as well as hurricane damage, are generally equal to a percentage of the structure's insured value. Seventeen states and the District of Columbia have hurricane deductibles. In Florida rates for windstorm coverage are now based on the structure's ability to withstand damage by high winds, calculated using computer models, instead of the likelihood of fire damage.

Insurers in catastrophe-vulnerable states now require percentage deductibles on homeowners' insurance policies for wind damage losses, as opposed to a dollar deductible, to limit their exposure to catastrophic losses from natural disasters.

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[36] For instance, hidden subsidies would arise if rates for property insurance are no longer commensurate with risk because, for example, regulators prevented insurers from raising rates to actuarially justified levels.

Percentage deductibles, which are now mandatory in some coastal areas, vary from 1 per cent of a home's insured value to 15 per cent, depending on many factors, including the "trigger" - i.e. the event to which the deductible applies. In some states, homeowners have a "buy back" option, which allows them to pay a higher premium in return for a fixed rather than percentage deductible.

Although these deductibles are primarily designed to mitigate insurers' losses, they still provide an economic incentive to individuals when deciding where to locate and how much wealth to invest in a high-risk area.

3.15 Appendices

Appendix A

Summary of Selected Studies into the Possible Impact of Climate Change on Cyclone Activity

Box A1: Some Key Studies into the Impact of Climate Change on the Frequency and Character of Tropical Cyclones

Pre IPCC FAR

In 1986, Kerry Emanuel, a hurricane scientist at MIT, published a paper in the Journal of the Atmospheric Sciences (Emanuel 1986), which showed that if the sea-surface temperature falls below approximately 26.5ºC intense hurricanes become a theoretical impossibility. Cooler sea-surface temperatures limit the growth of convective clouds in the hurricane system, which is necessary to fuel the tropical cyclone heat engine. Emanuel further showed that a hurricane has a well-defined Maximum Potential Intensity (MPI) that is governed by the thermodynamic environment – specifically, the degree of disequilibrium between the atmosphere and the underlying ocean. In short, a warmer sea-surface could theoretically increase the MPI of a storm. However, most hurricanes, most of the time, will not reach this upper limit either because of storm-caused cooling of the sea or because of wind shear.

The following year, Emanuel showed that an increase in greenhouse gases increases the thermodynamic disequilibrium between the atmosphere and the underlying ocean, which in turn increases the theoretical MPI of storms. For example, for a 3ºC increase in sea-surface temperatures, the potential destructive power of storms that approach their MPI could increase by 40-50 per cent (Emanuel, 1987).

More recently, Emanuel stated that the critical, physical factor in hurricane intensity is sea surface temperature. Sea surface temperature "sets a speed limit for storms, in that the maximum surface temperature of the water resource governs the maximum possible wind speed" (Boulder, Colorado, Sept. 13 2004, UPI). He went on to say that "If you increase the sea surface temperature limit 10 per cent, the maximum wind speed achieved by a hurricane will increase by 10 per cent". Furthermore, "If we know the climate we can calculate the speed limit". As an example, if a doubling of atmospheric concentrations of CO2 doubled and sea surface temperatures increased by about 2oC in the tropics, "That would give hurricanes a roughly 10 per cent higher wind speed".

In 1990, another hurricane scientist, William Gray, published an article in Science dealing with the landfall of intense hurricanes in the United States. Atlantic hurricane activity from 1970 to 1987 was less than half of the activity observed from 1947 to 1969 (Gray, 1990). Over this period however, the greenhouse gas concentration went up exponentially and, yet, there was a decrease in number of intense hurricanes.

Also in 1990, a group of researchers at Arizona State University challenged the prediction of increasing numbers and intensities of hurricanes due to an enhanced greenhouse effect. Idso et al (1990, p. 261) found that "…there is basically no trend of any sort in the number of hurricanes experienced in any of the four regions [the central Atlantic, the east coast of the U.S., the Gulf of Mexico, and the Caribbean Sea for the period from 1947 to 1987] with respect to variations in temperature". Indeed, they found that warmer years produced the lowest numbers of hurricane days, whereas, cooler years produced more than the average number of hurricane days. Idso et al (1990, p. 262) also examined trends within different intensity classes and concluded that: "For global warming on the order of ½ to 1oC, our analyses suggest that there would be no change in the frequency of occurrence of Atlantic/Caribbean hurricanes, but that there would be a significant decrease in the intensities of such storms".

More research raised further doubts about the relationship between the enhanced greenhouse effect and hurricane activity. Broccoli and Manabe (1990) found that, when they allowed certain cloud-related feedbacks to be included in their modelling experiments, they found a 15 per cent reduction in the number of hurricane days in a 2 x CO2 environment. However, their results were highly dependent upon how cloud processes were represented within the modelling, which has subsequently been questioned.

IPCC FAR – IPCC SAR

Ryan et al (1992) proposed that areas conducive to cyclogenesis could expand in a warmer world. In addition, O'Brien et al (1992) suggested that tropical sea surface temperatures would increase from 1ºC to 4ºC in a 2 x CO2 environment. This, in turn, would double the number of hurricanes, increase their strength by 40-60 per cent, and extend the hurricane season. Using an 11-layered, GCM coupled with an ocean model, Haarsma et al (1993) found that in a 2 x CO2 environment, the frequency of hurricanes would increase by 50 per cent and the mean intensity (the maximum simulated wind speed) of the storms by 20 per cent. The number of intense hurricanes developing would also increase.

However, contrasting conclusions arose from the work of Lighthill et al (1994), who examined both a list of conditions that permit the formation and development of hurricanes , and outturn data on hurricane activity since 1944 in the Atlantic and since 1970 in the Pacific. Both analyses led to the conclusion that "…even though the possibility of some minor effects of global warming on tropical cyclone frequency and intensity cannot be excluded, they must effectively be 'swamped' by large natural variability" (Lighthill et al, 1994, p. 214). Both Emanuel (1995) and Broccoli et al (1995) questioned the underlying evaluation, with the former arguing that both the basic physics and outturn data on hurricane activity actually suggests that warming in the tropical oceans would lead to an increase in the MPI of hurricanes.

Bengtsson et al (1995 and 1996) used high-resolution (T106) simulations with a coupled ocean-atmosphere model to demonstrate that the enhanced greenhouse effect would strengthen the upper-level westerlies in the vicinity of hurricane development, which would inhibit hurricane activity. In a 2 x CO2 environment they found no change in the current global distribution and seasonality of hurricanes. However, the number of hurricanes in the northern hemisphere fell by 25 per cent per annum in the 2 x CO2 environment, while in the southern hemisphere, the number of hurricanes dropped by 57 per cent per annum. Regarding storm intensity, there seems to be no reduction in their overall strength. The difference in the hemispheric responses has raised questions about the ability of the model used to properly represent tropical cyclones. Landsea (1997) also raised methodological concerns about the experimental design.

An article by Landsea et al (1996) examined hurricanes in the North Atlantic Basin since 1944 and found that "…a long-term (five decade) downward trend continues to be evident primarily in the frequency of intense hurricanes. In addition, the mean maximum intensity (i.e. averaged over all cyclones in a season), has decreased" (Landsea et al, 1996, p. 1700). This re-confirmed his previous findings (Landsea, 1993) that hurricane frequency and intensity in this basin have not increased over the past five decades.

Li (1996) applied the Emanuel (1986) and Holland (1997) thermodynamic models of MPI within a CGM and found increased maximum potential cyclone intensities in both cases, although the increases in MPI found in the analysis are within the uncertainty range derived from individual model predictions.

Karl et al (1995 and 1996) examined outturn data on the number and intensity of hurricanes that made landfall on the U.S over the past century. They also found that the number decreased over the period 1940s-1980s. However, prior to the 1940s the records showed an increase in the number of storms. Similar conclusions were also reached by Elsner et al (1996).

Using the NCAR Climate System Model, a coupled atmosphere-ocean GCM, Tsutsui and Kasahara (1996) performed a +1 per cent CO2 per annum transient experiment to compare tropical cyclone intensity and frequency under the present and a 2 x CO2 climate. Globally, the difference in total days of cyclone occurrences per annum (524 in the present vs. 538 with global warming) is not statistically significant. The North Atlantic Basin experiences a decrease (from 98 to 86 days per annum) while the Western North Pacific Basin experiences an increase (from 176 to 196 days per annum). However, there is a statistically significant increase in intense cyclones and decrease in weak cyclones. Thus, global warming appears to increase the mean intensity of tropical cyclones.

IPCC SAR – IPCC TAR

Saunders and Harris (1997) reviewed the literature on environmental factors likely to affect the number of tropical cyclones in the North Atlantic Basin. They identified the following key factors: tropospheric wind shear, ENSO, the stratospheric quasi-biennial oscillation, monsoon rainfall in the western Sahel, Caribbean sea-level pressure anomalies, and sea-surface temperatures in the tropical latitudes where cyclogenesis occurs. Using regression techniques, they evaluated the relationship between these factors and the number of tropical cyclones in the records, and found that sea-surface temperature played a significant role. This led Saunders and Harris to conclude that unusually warm sea-surface temperatures in 1995 were largely to blame for the large number of tropical storms and hurricanes observed in the North Atlantic in that year. By implication, warming of the sea surface with climate change could result in a larger number of tropical cyclones in the future. However, in the same year a paper by Karl et al (1997) concluded that “Overall, it seems unlikely that tropical cyclones will increase significantly on a global scale. In some regions, activity may escalate; in others, it will lessen” (Karl et al, 1997, p. 83).

Henderson-Sellers et al (1998), members of the steering committee of the WMO Commission for Atmospheric Sciences (CAS), prepared a paper that synthesised post IPCC SAR research on the potential for changes in tropical cyclone activity in a warming climate. They concluded that progress has been made towards advancing our understanding of the possible impacts of the enhanced greenhouse effect on tropical cyclone activity. Since the publication of the IPCC SAR, the state of knowledge has advanced enough to permit the following conclusions (Henderson-Sellers et al, 1998):

- There are no apparent global trends in tropical cyclone frequency, intensity or location from analyses of historical records.
- There is no evidence to suggest any major changes in the area or global location of tropical cyclone genesis in an enhanced greenhouse environment.
- Thermodynamic ‘up-scaling’ models seem to have some skill in predicting maximum potential intensity (MPI) and these models predict an increase in MPI of 10-20 per cent for a 2 x CO2 environment. However, the known omissions from these models act to reduce these increases.

Knutson et al (1998) and Knutson and Tuleya (1999) examined how the character of hurricanes could change in response to global warming. Specifically, they used a regional, high-resolution, hurricane prediction model nested within a GCM to investigate the impact of warming on hurricane intensities in the Western North Pacific Basin. For a sea surface temperature increase of about 2.2oC on average (induced by a +1 per cent CO2 per annum transient experiment using the Geophysical Fluid Dynamics Laboratory R30 coupled ocean-atmosphere climate model) a selection of simulated case study hurricanes were more intense than a set of control storms by 3 to 7 ms-1 (equivalent to 5 to 11 per cent) for the maximum wind speed and 7 to 24 hPa for central surface pressure.

The latter study also noted that near-storm (i.e. along the storm track) precipitation was 28 per cent higher in the high-CO2 sample of hurricanes relative to the control sample, and the mean radius of the hurricane force winds was also 2-3 per cent wider. Knutson and Tuleya (1999) also concluded that the results for the Western North Pacific Basin are “qualitatively applicable to other tropical storm basins”.

The above studies neglect the possible feedback of sea surface cooling induced by the cyclone, which would be expected to reduce the intensity of tropical storms. However, Knutson et al (2001), using a hurricane model with ocean coupling, found that even though ocean-coupling reduced the intensity of simulated tropical cyclones, the net impact on the simulated CO2 warming-induced intensification of tropical cyclones is relatively minor. For both coupled and uncoupled simulations, maximum surface wind speeds are on average about 5-6 per cent higher in the high-CO2 sample of cyclones over the six basins, and are 3-10 per cent higher across the different basins. Both the coupled and uncoupled simulations also show significant increases in near-storm precipitation in the high-CO2 sample of cyclones relative to the control sample. In other words, the CO2 warming-induced intensification of cyclones would still occur even when the sea surface cooling feedback is included.

Royer et al (1998) examined cyclogenesis bounded by large-scale atmospheric and oceanic conditions and found that only small changes in tropical cyclone frequencies would occur for a 2 x CO2 environment: up to a 10 per cent increase in the Northern Hemisphere (primarily in the Western North Pacific Basin) and up to a 5 per cent decrease in the Southern Hemisphere.

Sources: Various in box

Box A2: Some Key Studies into the Impact of Climate Change on the Frequency and Character of Tropical Cyclones Post IPCC TAR

Jun Yoshimura, a senior researcher at the Meteorological Research Institute in Tsukuba, Japan, simulated the impact of global warming on tropical cyclones using the NEC Earth Simulator. The results that are available in English show that in CO2 enhanced climate (the change in CO2 concentrations is unknown), in which sea surface temperatures rise by an average of 1.7oC, the annual average number of cyclones (defined by the researchers as having wind speeds in excess of 61.2 kph) will drop by 20 per cent by the end of the century (from 83.6 to 66.5) (IHT / Asashi, 2004). The reduction in cyclones is due to a smaller temperature differential between the sea surface temperature and the air above. There will, however, be an increase in intense storms with maximum wind speeds exceeding 144 kph. Storms will be stronger because there will be more water vapour in the air.

At the recent 2nd International Workshop on the Kyosei Project, 24-26th February 2005, two papers were presented on the impact of global warming on tropical cyclone activity. Again using the NEC Earth Simulator, in which tropical cyclone climatology was simulated within a 20-km grid cell GCM, Yoshimura et al (2005) concluded that, by the end of the century, tropical cyclone formation globally will decrease by approximately 30 per cent. But the frequency of intense tropical cyclones (e.g. with wind speeds greater than 45 ms-1) will increase significantly, with the maximum wind speed increasing by 8.8 ms-1 on average.

The second paper by Hasegawa (2005) used the CCSR/NIES/FRCGC T106L56 AGCM to simulate tropical cyclone activity in a high CO2 environment. CO2 concentrations in the control experiment were 345 ppmv and 690 ppmv under a 2 x CO2 climate. Both simulations covered the 20 year period 1979-1998 and were limited to the Western North Pacific Basin. The simulation found that the number of days per annum with typhoons greater than 1000 hPa was unchanged, but typhoons with pressures less than 1000 hPa declined by about 26 per cent. Overall, total typhoon days per annum fell by 8 per cent under a 2 x CO2 climate. The simulation also found that mean and peak precipitation increased in the 2 x CO2 sample. Typhoons of the same intensity (minimum pressure) bring heavier precipitation (with mean precipitation increasing by 3.43 mm per day or +14 per cent) due to increased moisture holding capacity. Thus, despite the fall in typhoon numbers per annum, the mean precipitation actually increases by about 8 per cent.

A recent study by Knutson and Tuleya (2004) explores the sensitivity of their earlier work to the choice of climate model used to define the CO2 warmed climate (previously only one GCM was used), as well as to the choice of convective parameterisation used in the nested regional model that simulates the hurricanes. The authors simulated just under 1300 five-day duration tropical cyclones using a high-resolution version of the GFDL hurricane prediction system (with grid spacing as fine as 9 km and with 42 levels). All simulated storms were embedded in a uniform 5 ms-11 easterly flow. The large-scale thermodynamic boundary conditions for the simulations were derived from nine different GCMs. The CO2-induced changes in sea surface temperature from all nine GCMs, based on 80-yr linear trends from +1 per cent CO2 per annum transient experiments, range from about +0.8oC to +2.4oC in the three tropical storm basins studied (Western North Pacific, North East Pacific and North Atlantic) . Four different moist convection parameterisations are tested in the hurricane prediction model. Nearly all combinations of climate model boundary conditions and hurricane model convection schemes show a CO2-induced increase in both storm intensity and near-storm precipitation rates. The aggregate results, averaged across all experiments, indicate a 14 per cent (a range of 13-15 per cent) increase in central pressure fall (the mean for the high-CO2 storms is 10.4 mb lower than the mean for the control storms) , a 6 per cent (a range of 5-7 per cent) increase in the maximum surface wind speed , and an 18 per cent increase in the instantaneous precipitation rate averaged over 100 km of the storm centre at hour 120 . The percentage change in precipitation is more sensitive to the choice of convective parameterisation than is the percentage change of intensity (with a range of 12 per cent to 26 per cent). In all cases, the shift in the high CO2 distributions is statistically significant.

The intensification of major storms under the high-CO2 case is roughly equivalent to half a category upward shift on the Saffir-Simpson hurricane intensity scale (Knutson and Tuleya, 2004). In other words, if the frequency of tropical cyclones remains the same over time, the authors suggest that global warming may result in a gradual increase in the risk of seeing more category 4 and 5 storms. Examples of what to expect then are Ivan and Isabel of 2003.

Elsner and Jagger (2004) suggested that warming sea surface temperatures lead to an atmosphere with less humidity, and in turn less large-scale ascent and deep convection, which leads to drying-aloft and circulation anomalies, both of which inhibit cyclogenesis and encourage cyclones to miss Southeast Florida. The authors tested this hypothesis by establishing a significant relationship between sea surface temperatures (in the Greater Antilles) and annual counts of hurricanes over Southeast Florida. They found that during the 27 years in which temperature was below the long-term trend, there were 8 hurricanes over this region (4 of which were "major") By contrast, during the 28 years when temperatures were above the long-term trend there was only 1 hurricane, which was not and "major". The authors therefore concluded that "surface warming [as a result of global warming] over the Greater Antilles is statistically linked to fewer hurricanes over [Southeast] Florida".

Sources: Various in box

Box A3: Some Recent Studies into the Impact of Climate Change on the Frequency and Character of Extra-tropical Cyclones

North Atlantic extra-tropical cyclones can lead to high surface wind speeds in western and central Europe, especially over the seas or in coastal and mountainous regions.

Hanson et al (2004) investigated the potential changes in windstorm occurrence over the North Atlantic and Europe as a result of greenhouse gas induced climate change. This study looked specifically at cyclones or depressions.

Reanalysis data from the National Centres for Environmental Prediction (NCEP) was used as a proxy for the observed data and this was used to validate the Hadley Centre HadAM3H global atmosphere model for the baseline period 1961-90. Climate models were then used to construct climatologies of cyclones over this baseline period and for the end of the century (2070-2099). Simulations run for the future period were based on scenarios A2 and B2 from the IPCC SRES.

The study area extended from 80ºN-20ºN and 80º-30ºE and the project looked at the extended winter period October to March. Two measures of intensity were used to examine changes in the character of cyclones. The minimum central pressure (hPa) achieved at any time during the life span of a cyclone and the maximum deepening rate of each cyclone (hPa per 12 hr period). Validation of the model indicated that HadAM3H underestimates the number of cyclones per year by up to 30 per cent, but replicates the general distribution of cyclones well.

For the A2 scenario there was a statistically significant increase in the number of cyclones and extreme cyclones found over the Labrador Sea, Iceland and to the north and west of the UK, and also over south-eastern England for cyclones achieving at least 1,000 hPa. Significant decreases were found to the north of Newfoundland and over Greenland. Similar changes were found for the B2 scenario, although there was no significant change in the frequency of cyclones with central pressures less than or equal to 1,000 hPa over the southeast of England. Overall cyclones were predicted to become weaker in the future under both scenarios.

Percentage Changes in Future Monthly Cyclone Frequency Across the North Atlantic (A2 future minus A2 present and B2 future minus B2 present)

Scenario	Cyclone Intensity	Oct	Nov	Dec	Jan	Feb	Mar
A2	less than 1000hPa	-11%	-5%	0	-12%	-4%	-4%
B2	less than 1000hPa	-4%	-5%	+2%	0	-3%	-3%
A2	less than 970hPa	-30%	+11%	-20%	-18%	-7%	+23%
B2	less than 970hPa	-7%	+11%	+4%	-5%	-15%	-5%

Source: Hanson et al (2004)

A general reduction in cyclone frequency was predicted for both scenarios throughout the extended winter period. But significant decreases (i.e. those beyond the range of natural variability) were found only in October (under A2) and November and March (under both A2 and B2) for cyclones with central pressures less than or equal to 1,000 hPa and in February (under B2) for cyclones with central pressures less than or equal to 970 hPa. Otherwise all changes lie within the present day range of natural variability.

Hanson at el (2004) also looked at the UK in more detail, comparing the results from HadAM3H with the results from a regional model (HadRM3H). They found no evidence from either model to support a conclusion that cyclones over the UK will become more intense in the future. However, they state the robustness of this result is questionable in light of the fact that both climate models underestimate the current levels of cyclone activity across the study area.

HadRM3H predicts that in the future, during the winter (December to February), cyclones with central pressures less than or equal to 1,000 hPa will increase on average from 7 per year to around 9 under the A2 scenario and to 8 under B2. Results from HadAM3H are less conclusive, where 4.5 events occur on average at the moment, this may increase to 5 per year under A2 and may fall to 4 per year under B2. During the autumn (September to November) HadRM3H shows a decrease from 4.5 to 3.5 (under A2) and 3 (under B2) and HadAM3H also predicts a decrease. However, there was some evidence from HadRM3H to support a seasonal shift in extreme cyclones, with this model predicting an increase in extreme cyclones in the autumn and a decrease in the winter. HadAM3H produces different results suggesting the overall number of cyclones will increase in the future in the UK, but the proportion of weak and intense cyclones will remain the same indicating an increase in intense cyclones. The two scenarios showed no consistent change in future monthly activity, however, they did show that any changes in the B2 scenario in the future tended to be smaller than those for the A2 scenario.

There were conflicting results from the two models for the potential changes in cyclone frequency across the UK under the A2 scenario. HadAM3H indicates that the frequency of cyclones with central pressures less than or equal to 1,000 hPa will increase in the northern and eastern areas of the UK, whilst the central and southern areas will experience a decrease. HadRM3H showed an increase in frequency across most of the regions with the largest increase in the central region (Scotland, Northern and South-western England). For B2, the results were a little more consistent. HadAM3H indicated an increase in frequency across the entire region, apart from the far north and over Southern Wales and south-western England. HadRM3H shows an increase across the entire region in the future with the greatest concentration over western England, Wales and Scotland. For extreme cyclones (with central pressures less than or equal to 970 hPa), both models show a general decrease in activity over eastern UK and an increase over the north for A2. Similar results are also seen for B2, apart from in the southern region, where HadRM3H indicates an increase in cyclone activity and HadAM3H indicates no change in activity.

HadRM3 was also used to estimate changes in wind speeds under A2 and B2. They concluded that for the UK overall there is likely to be little noticeable effect of global warming on extreme wind speeds. However, from Southern Ireland, through Wales and central England, to East Anglia, the high emission A2 scenario is associated with reduced frequency and reduced intensity of extreme wind events. Under lower emissions with the B2 scenario, this mitigation of high wind speeds is diminished and there is some evidence of increased wind speeds.

Overall, Hanson et al (2004) concluded that the Hadley Centre Regional Climate Model indicates that there will be no significant change in storm activity or intensity towards the end of the century (2070-2099), and therefore current climatology could be used by the insurance industry to assess potential damage in the future.

Leckebusch and Ulbrich (2000) studied the relationship between cyclones and extreme wind events over the winter period (October to March) in Europe under a control period (1960-1989) and a future period (2070 to 2099), again based on the IPCC SRES A2 and B2 emission scenarios. Cyclone systems over the Northeast Atlantic and Europe were identified from the Hadley Centre HadCM3 model using a cyclone identification algorithm developed by Murray and Simmonds (1991), which is based on the search of the maxima of the Laplacian of the mean sea level pressure (MSLP). Extreme cyclone systems were defined as exceedance of the 95th percentile. Extreme wind speeds were also analysed, these were defined as values above the 95th percentile of the daily maximum wind speed at the lowest level, and related to the core pressure of the nearest cyclone system.

As with Hanson et al (2004) the findings were validated against the track density climatology of the NCEP re-analysis data. Although HadCM3 underestimates the number of tracks, realistic patterns of track density over the investigation area are simulated. An analysis of all cyclones under an A2 scenario identified a 6.9 per cent reduction of tracks compared to the present day climate and a similar trend under was found in the B2 scenario. However, the study then concentrated on extreme events related to mid-latitude cyclone development and this work showed that extreme cyclones were particularly affected under increased greenhouse gas conditions. Extreme or highly extreme depressions that surpassed the 95th or 99th percentile value once in their lifetime were investigated. The results showed changes for extreme cyclone systems under the A2 emissions scenario, while for the B2 the changes are less pronounced.

The results indicated an increase in track density under A2, notably above western parts of Central Europe and the Northeast Atlantic, where the maximum was reached with an approximate increase of 20 per cent. Indicating the pathways of extreme cyclones will shift to the south, resulting in an increasing amount of strong depressions, which in particular affect western parts of central Europe. These changes were less pronounced in the B2 scenario, especially over western Central Europe, the British Isles, and the Northeast Atlantic. Tests of statistical significance showed that relevant changes over England between A2 and B2 scenarios, whereas the positive A2 climate signal with respect to the control period is of statistical significance only for small areas.

For highly extreme cyclones (99th percentile value) more explicit results were attained. The number of highly extreme cyclones in the control climate is small with a maximum of about 1.5 cyclones per winter, situated over Iceland and the Norwegian Sea. For the A2 scenario there was an increase in highly extreme cyclone above the Northeast Atlantic south of 60ºN, with the maximum increase south of Iceland, with increased values of up to nearly 50 per cent. These positive changes of highly extreme cyclone system occurrence extend eastward to western Central Europe. Tests of statistical significance showed significant changes over Western Central Europe in the A2 scenario compared with control climate and with B2.

To summarise, climate change conditions according to the A2 scenario reveal a clear signal towards more extreme cyclone systems affecting Western and Central Europe. The results show that changes occur in particular for the A2 scenario for extreme cyclone systems, while for the B2 scenario the changes are less pronounced. Over western parts of Central Europe the track density of extreme cyclones increases for A2, accompanied towards a tendency towards more intense systems. With respect to A2, the tendency towards more extreme wind events caused by deepening cyclones is identified for several regions of Western Europe such as Spain, France, UK or Germany.

Leckebusch and Ulbrich (2000) found that their results were in general agreement with the results of former studies about North Atlantic and Europe storm climatic variability. Carnell and Senior (1998) used a previous version of the global model (HadCM2), under a similar climate change scenario, and found a shortening of the climatological tracks at their north eastern ends when all systems were considered. Additionally they found a tendency towards deeper low centres, although the amount of storms in the model reduced. In contrast, Knippertz et al. (2000) revealed increased cyclone frequency above Northern Europe, corresponding to an enlargement of the upper tropospheric storm track to the northeast Atlantic from a greenhouse gas simulation of the ECHAM4/OPYC3 model. Schubert et al (1998) identified a shift of the cyclone track density northward in a climate change scenario run by ECHAM3 atmospheric global circulation model.

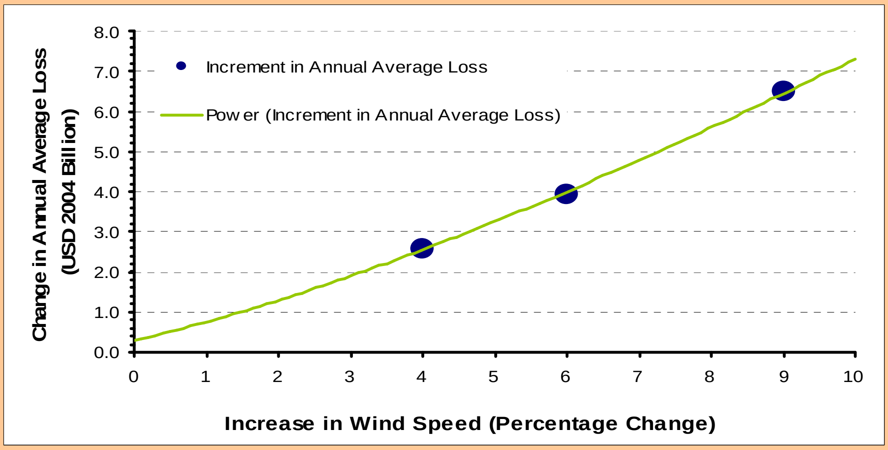
MICE (Modelling the Impact of Climate Extremes) is a EU funded project, which uses information from climate models to explore future changes in extreme events across Europe in response to global warming. Under MICE, two GIS based storm damage models have been developed, building upon the work done by Hanson et al (2004) and Leckebusch and Ulbrich (2000). GIS-based storm model 1, based on the approach of Klawa and Ulbrich (2003), will be used to estimate storm related property damages over different regions of Central Europe. The University of East Anglia have constructed GIS-based storm model 2 – a high resolution storm damage model for Great Britain, based on the work done in Hanson et al. (2004) and Hanson (2001).

Sources: Various in box

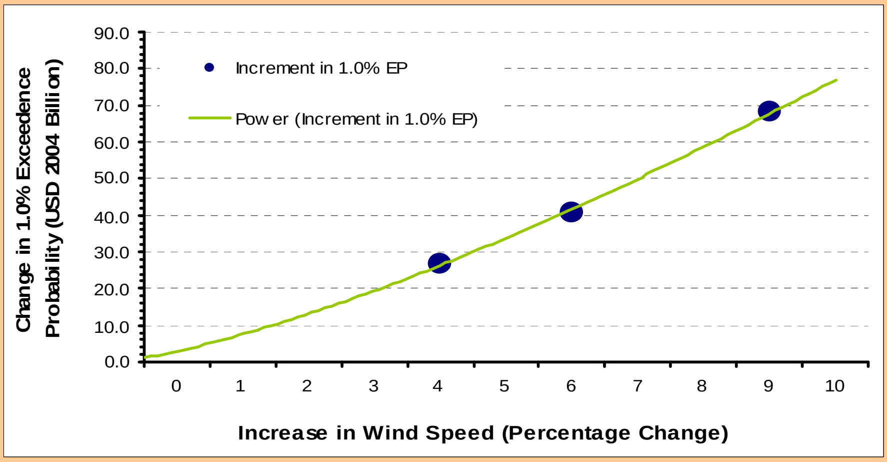
Appendix B

Approximated Loss Curves for Changes in Wind Speed

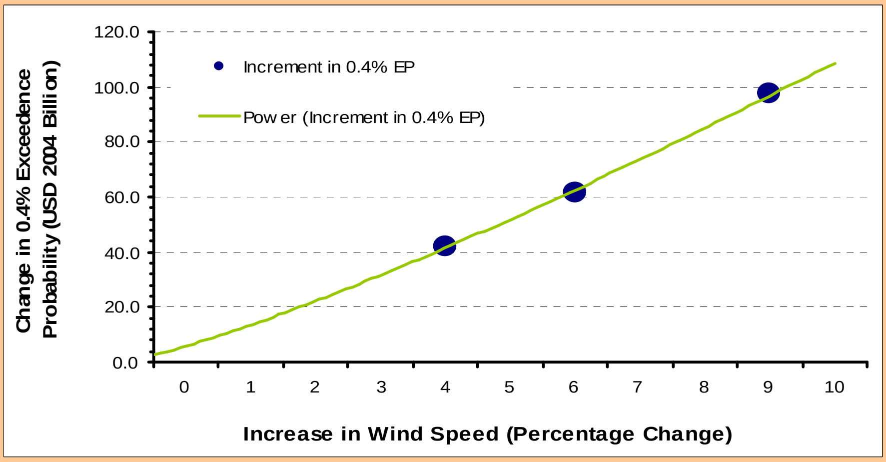
Hurricanes: Increment in Average Annual (Insured) Loss for Climate-Stress Tests



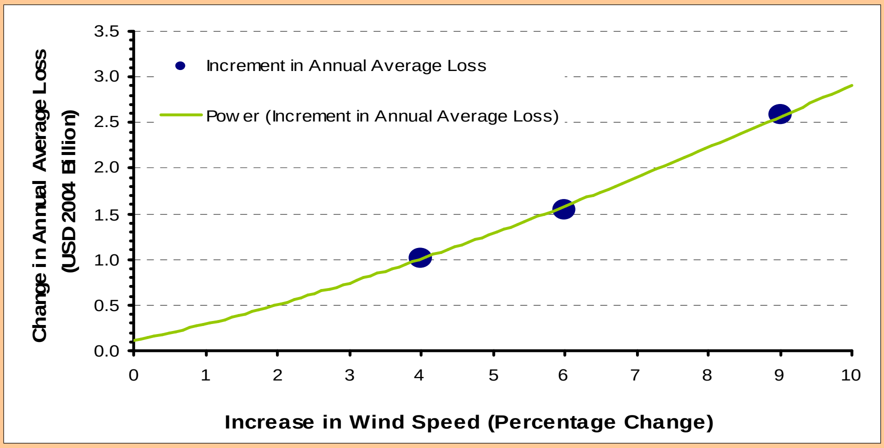
Hurricanes: Increment in 1 Per Cent Exceedance Probability for Climate-Stress Tests



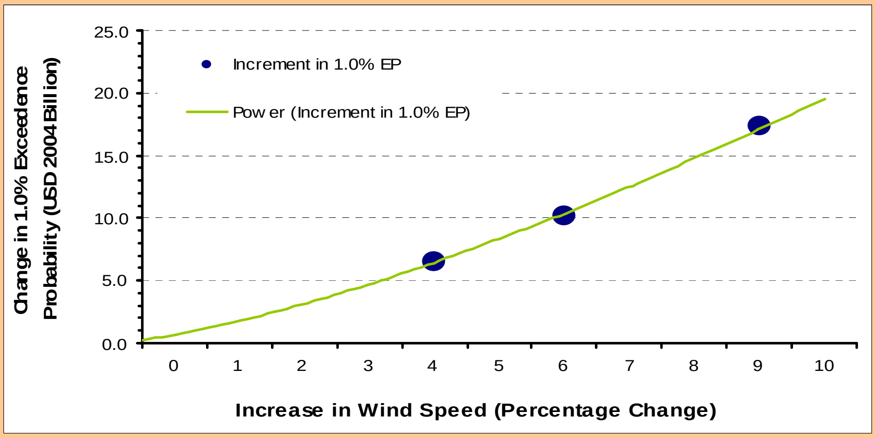
Hurricanes: Increment in 0.4 Per Cent Exceedance Probability for Climate-Stress Tests



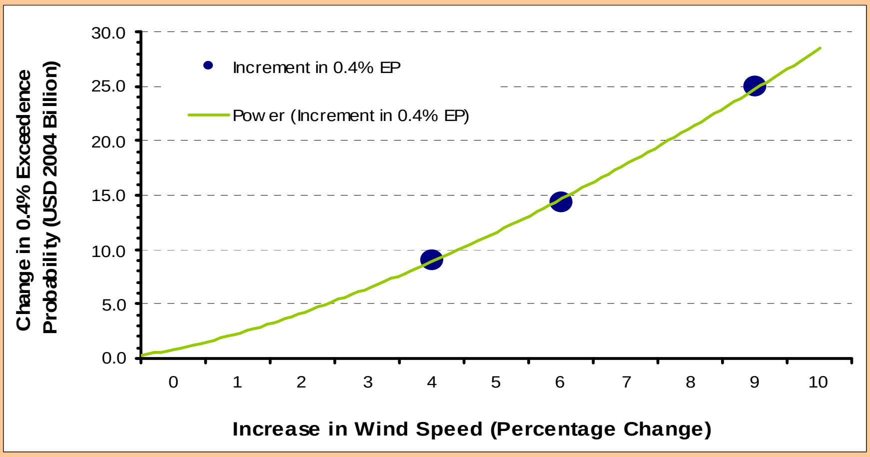
Typhoons: Increment in Average Annual (Insured) Loss for Climate-Stress Tests



Typhoons: Increment in 1 Per Cent Exceedance Probability for Climate-Stress Tests



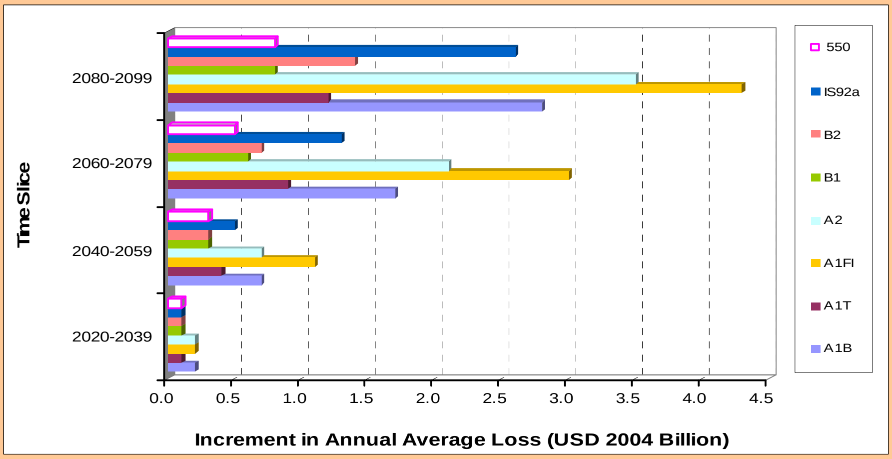
Typhoons: Increment in 0.4 Per Cent Exceedance Probability for Climate-Stress Tests



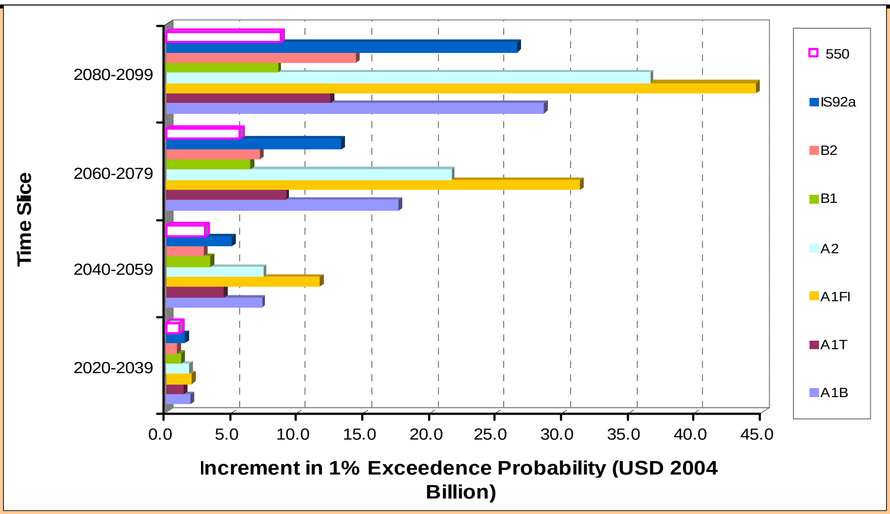
Appendix C

Estimated Insured Losses for Changes in Tropical Cyclone Wind Speed Under Various CO_2 Emission Scenarios

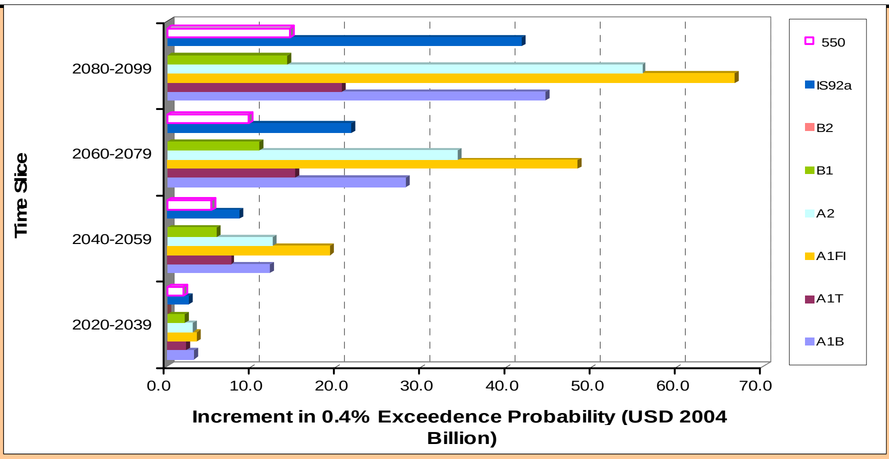
Hurricanes: Average Annual Increment in Average Annual (Insured) Loss



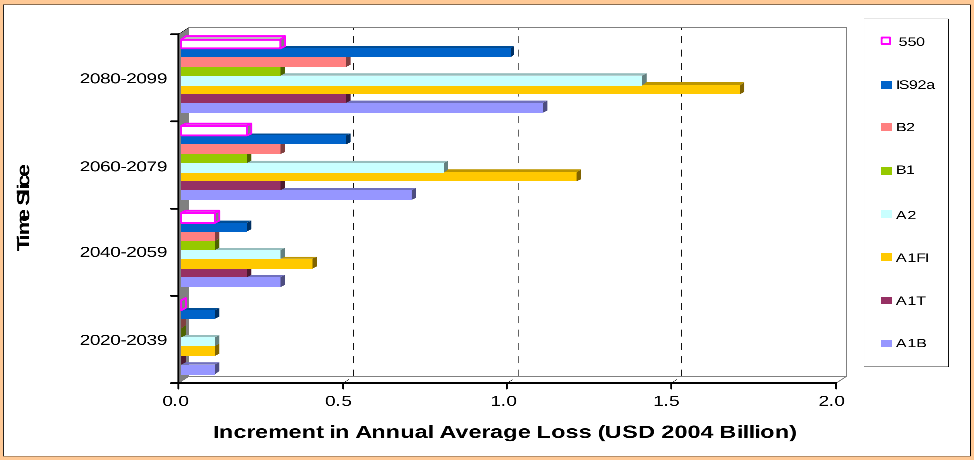
Hurricanes: Average Annual Increment in 1 Per Cent Exceedance Probability



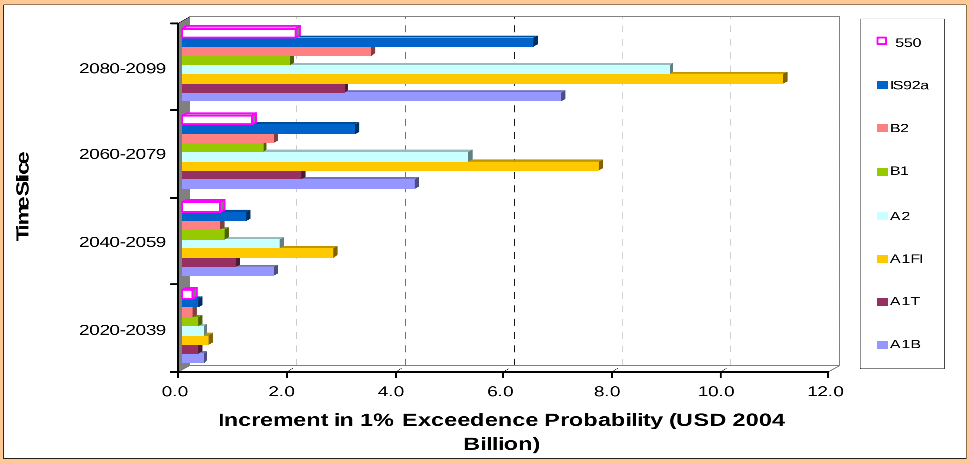
Hurricanes: Average Annual Increment in 0.4 Per Cent Exceedance Probability



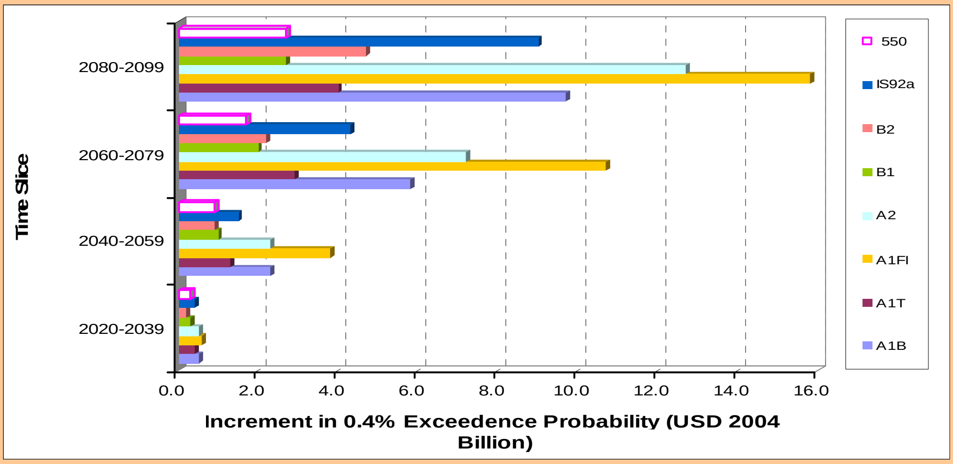
Typhoons: Average Annual Increment in Average Annual (Insured) Loss



Typhoons: Average Annual Increment in 1 Per Cent Exceedance Probability



Typhoons: Average Annual Increment in 0.4 Per Cent Exceedance Probability



Appendix D

Reduction in Probable Maximum (Insured) Losses in Moving from IPCC SRES A1 Family Group to 550 Stabilisation Scenario: Hurricanes and Typhoons

Illustration of the Benefits of Moving to a Lower Emission Path For Various Future Time Slices: Change in 1% Exceedence Probability

(a) Hurricanes (b) Typhoons

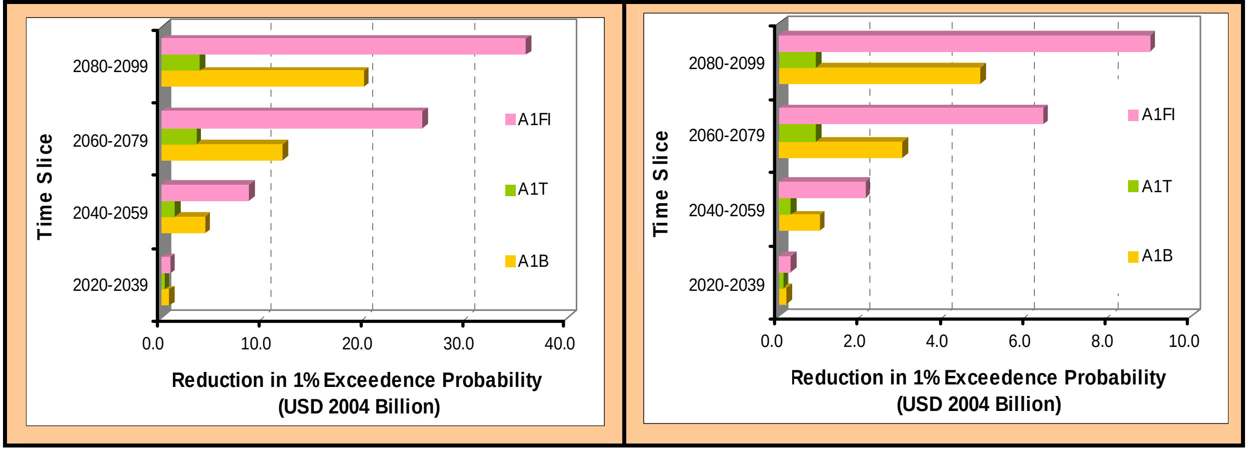
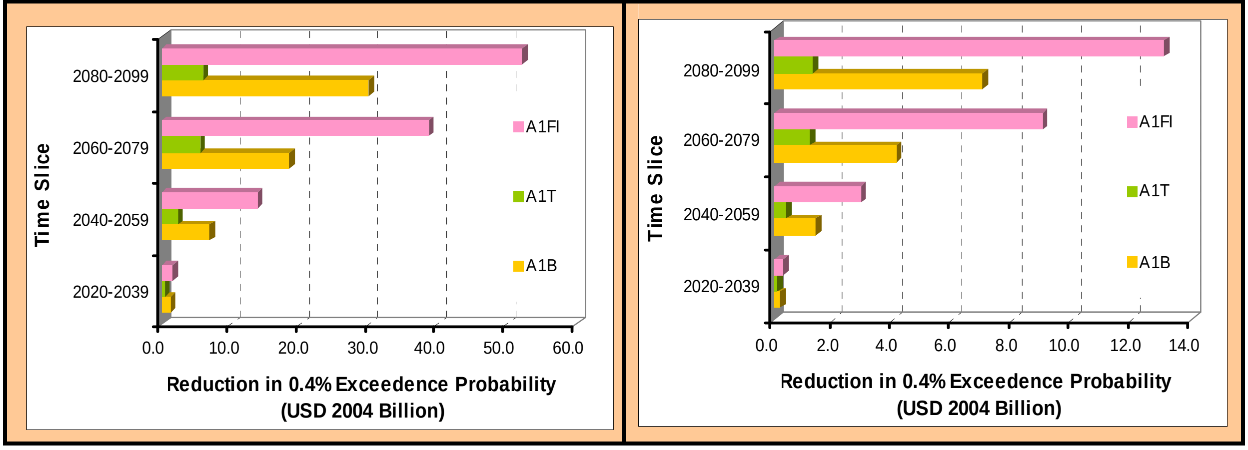


Illustration of the Benefits of Moving to a Lower Emission Path For Various Future Time Slices: Change in 0.4% Exceedence Probability

(a) Hurricanes (b) Typhoons



3.16 References

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylha, K., Koffi, B., Palutiokof, J., Scholl, R., Semmler, T. and Woth, K. (2004) Future Extreme Evnets in European Climate: An Exploration of Regional Climate Model Projections. Joint Paper PRUDENCE WP5.

Broccoli, A.J. and S. Manabe (1990) “Can Existing Climate Models be Used to Study Anthropogenic Changes in Tropical Cyclone Intensity?”, *Geophysical Research Letters*, 17: 1917-20.

Broccoli, A.J., S. Manabe, J.F.B. Mitchell and L. Bengtsson (1995) Comments on “Global: Climate Change and Tropical Cyclones: Part II”, *Bulletin of the American Meteorological Society*, 76:2243-45.

Carnell, R. E. and C.A. Senior (1998) "Changes in Mid-latitude Variability due to Increasing Greenhouse Gases and Sulphate Aerosols", *Climate Dynamics*, 14: 369-383.

Chan, J.C.L. (1985) “Tropical Cyclone Activity in the Northwest Pacific in Relation to the El Niño/Southern Oscillation Phenomenon”, Monthly Weather Review, 113: 599-606.

Chan, J.C.L. and J. Shi (1996) “Long-term Trends and Inter-annual Variability in Tropical Cyclone Activity over the Western North Pacific”, *Geophysical Research Letters*, 23: 2765-2767.

Chang, J-C. (1996) “An Exploratory Study of the Relationship Between Annual Frequency of Invaded Typhoons in Taiwan and El Niño/Southern Oscillation”, *Terrestrial, Atmospheric and Oceanic Sciences*, 7: 83-105.

Chia, H.H. and C.F. Ropelewski (2002) "The Inter-annual Variability in the Genesis Location of Tropical Cyclone sin the Northwest Pacific", *Journal of Climate*, 15: 2934-2944.

Chu, P.-S. and J.D. Clark (1999) “Decadal Variations of Tropical Cyclone Activity over the Central North Pacific”, *Bulletin of American Meteorological Society*, 80(9): 2717-1881.

Coles, S. (2001) *An Introduction to Statistical Modelling of Extreme Values*, Springer: London Berlin Heidelberg.

Converium (2004) “Climate Change and Its Impact on Tropical Cyclones”, Global Natural Hazards, Converium Re, Zurich, Switzerland.

CSU (2004) “Forecast of Atlantic Hurricane Activity from October 2004 and Seasonal Update through September”, Department of Atmospheric Science, Colorado State University.

Diaz, H. F. and R.S. Pulwarty (editors) (1997) *Hurricanes: Climate and Socio-economic Impacts*, New York: Springer-Verlag: 292.

Elsner, J.B. and T.H. Jagger (2004) "Florida Hurricane Decline Linked to Surface Warming", 26th Conference on Hurricanes and Tropical Meteorology, 2-7 May 2004, Miami, FL.

Elsner, J.B., B.H. Bossak and X. Niu (2001) "Secular Changes to the ENSO-US Hurricane Relationship", *Geophysical Research Letters*, 28: 4123-4126.

Elsner, J.B., G.S. Lehmiller and T.B. Kimberlain (1996) “Objective Classification of Atlantic Hurricanes”, *Journal of Climate*, 9: 2880-88.

Emanuel, K.A. (1986) “An Air-sea Interaction Theory for Tropical Cyclones. Part I: Steady-state maintenance”, *Journal of the Atmospheric Sciences*, 43: 585-604.

Emanuel, K.A. (1995) Comments on “Global Climate Change and Tropical Cyclones: Part II”, *Bulletin of the American Meteorological Society*, 76: 2241-43.

Flather, R. and J. Smith (1998) "First Estimates of Changes in Extreme Storm Surge Elevation due to Doubling CO_2", *Global Atmos. Ocean Systems*, 6:193-208.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez and W.M. Gray (2001) "The Recent Increase in Atlantic Hurricane Activity: Causes and Implications", Science, 293: 474-479.

Gray, W.M. (1968) “Global View of the Origin of Tropical Disturbances and Storms”, *Monthly Weather Review*, 96: 669-700.

Gray, W.M. (1979) “Hurricanes: Their Formation, Structure and Likely Role in the General Circulation”, *Meteorology Over the Tropical Oceans*, D.B. Shaw (Editor), Royal Meteorological Society, Berks: 155-218.

Gray, W.M. (1990) “Strong Association Between West African Rainfall and U.S. Landfall of Intense Hurricanes”, *Science*, 249: 1251-56.

Haarsma, R.J., J.F.B. Mitchell and C.A. Senior (1993) “Tropical Disturbances in a GCM”, *Climate Dynamics*, 8: 247-57.

Hanson, C. E. (2001) "A Cyclone Climatology of the North Atlantic and its Implications for the Insurance Market", PhD Thesis, University of East Anglia, UK.

Hanson, C. E., T. Holt and J.P. Palutikof (2004) "An Integrated Assessment of the Potential for Change in Storm Activity over Europe: Implications for Insurance and Forestry in the UK", Tyndall Centre for Climate Change Research, UK.

Hasegawa, A. (2005) “Tropical Cyclone and Heavy Precipitation Over the Western North Pacific in Present and Doubled CO_2 Climate Simulations”, 2nd International Workshop on the Kyosei Project, 24-26th February 2005, Hawaii.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster and K. McGuffie (1998) “Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment, *Bulletin of the American Meteorological Society*, 79(1): 19-38.

Holland, G.J. (1997) “The Maximum Potential Intensity of Tropical Cyclones”, *Journal of Atmospheric Science*, 54: 2519-2541.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (1996) *Climate Change 1995: The Science of Climate Change*, Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 572.

Idso, S.B., R.C. Balling Jr. and R.S. Cerveny (1990) “Carbon Dioxide and Hurricanes: Implications of Northern Hemispheric Warming for Atlantic/Caribbean Storms”, *Meteorology and Atmospheric Physics*, 42: 259-63.

IHT / Asahi (2004) “Typhoons: Fewer But Stronger?”, The Asahi Shibum, September 28th 2004 (www.asahi.com/english/).

Karl, T.R., N. Nicholls and J. Gregory (1997) “The Coming Climate”, *Scientific American*, 276: 79-83.

Karl, T.R., R.W. Knight, D.R. Easterling and R.G. Quayle (1995) “Trends in U.S. Climate During the Twentieth Century”, *Consequences*, 1: 3-12.

Karl, T.R., R.W. Knight, D.R. Easterling and R.G. Quayle (1996) “Indices of Climate Change for the United States”, *Bulletin of the American Meteorological Society*, 77: 279-291.

Klawa, M. and U. Ulbrich (2003) "A Model for the Estimation of Storm Losses and the Identification of Severe Storms in Germany", *Natural Hazards and Earth System Sciences*, 3: 725-732.

Knippertz, P., U. Ulbrich and P. Speth (2000) "Changing Cyclones and Surface Wind Speeds over North Atlantic and Europe in a Transient GHG Experiment", *Climate Research*, 15(2): 109-122.

Knutson, T.R. (2002) “Modelling the Impact of Future Warming on Tropical Cyclone Activity”, IPCC Workshop on Extreme Weather and Climate Events, Workshop Report, Beijing, China, 11-13 June, 2002.

Knutson, T.R. and R.E. Tuleya (1999) “Increased Hurricane Intensities with CO_2-induced Warming as Simulated Using the GFDL Hurricane Prediction System”, *Climate Dynamics* 15: 503-519.

Knutson, T.R. and R.E. Tuleya (2004) “Impact of CO_2 Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterisation”, *Journal of Climate*, 17(18): 34**77**–3495.

Knutson, T.R., R.E. Tuleya and Y. Kurihara (1999) “Simulated Increase of Hurricane Intensities in a CO2-warmed Climate”, *Science*, 279: 1018-1020.

Knutson, T.R., R.E. Tuleya, W. Shen and I. Ginis (2001) “Impact of CO_2 Induced Warming on Hurricane Intensities as Simulated in a Hurricane Model with Ocean Coupling”, *Journal of Climate*, 14: 2458–2468.

Kuzmina, S., L. Bengtsson, O. Johannessen, H. Drange, L. Bobylev and M. Miles (2005) ”The North Atlantic Oscillation and Greenhouse Gas Forcing”, submitted to Geophysical Research Letter.

Lambert, S. J. (1996) "Intense Extra-tropical Northern Hemisphere Winter Cyclone Events: 1899-1991", *Journal Geophysical Research*, 101(16): 21319-21325.

Landsea, C.W. (1993) “A Climatology of Intense (or Major) Atlantic Hurricanes”, *Monthly Weather Review*, 121: 1703-13.

Landsea, C.W., N. Nicholls, W.M. Gray and L.A. Avila (1996) “Downward Trends in the Frequency of Intense Atlantic Hurricanes During the Past Five Decades”, *Geophysical Research Letters*, 23: 1697-700.

Landsea, C.W., R.A. Pielke Jr., A.M. Mestas Nunez and J.A. Knaff (1999) “Atlantic Basin Hurricanes: Indices of Climate Changes”, *Climatic Change*, 42: 89-129.

Langenberg, H., A. Pfizenmayer, H. Von Storch, and J. Sundermann, (1999) "Storm Related Sea Level Variations Along the North Sea Coast: Natural Variability and Anthropogenic Change", *Cont. Shelf Research*, 19: 821-842.

Leckebusch, G. C. and U. Ulbrich (2004) "On the Relationship Between Cyclones and Extreme Wind Storms over Europe Under Climate Change", submitted to Global and Planetary Change.

Li, S. (1996) “Estimating Tropical Cyclone Intensity from Climate Models”, M.Sc. (Honours) Thesis, Climatic Impacts Centre, Macquarie University, Sydney, Australia, pp. 136.

Lighthill, J., G. Holland, W. Gray, C. Landsea, G. Craig, J. Evans, Y. Kurihara and C. Guard (1994) “Global Climate Change and Tropical Cyclones”, *Bulletin of the American Meteorological Society*, 75: 2147-57.

Lowe, J. A., J.M. Gregory and R.A. Flather (2001) Changes in the Occurrence of Storm Surges in the United Kingdom under a Future Climate Scenario using a Dynamic Storm Surge Model Driven by the Hadley Centre Climate Models", *Climate Dynamics*, 18: 197-188.

Malmquist, D. L. (editor) (1999) *European Windstorms and the North Atlantic Oscillation: Impacts, Characteristics, and Predictability*, Risk Prediction Initiative, Bermuda Biological Station for Research, Inc, RPI Series No. 2, pp. 21.

Meehl, G.A., F. Zwiers, J. Evans, T. Knutson, L. Mearns and P. Whetton (2000) “Trends in Extreme Weather and Climate Events: Issues Related to Modelling Extremes in Projections of Future Climate Change”, *Bulletin of the American Meteorological Society*, 81(3): 427-436.

Murray, R. J. and I. Simmonds (1991) "A Numerical Scheme for Tracking Cyclone Centres from Digital Data. Part I: Development and Operation of the Scheme", *Aust. Met. Mag*., 39: 155-166.

Neumann, C.J. (1993) Global Guide to Tropical Cyclone Forecasting, WMO/TC-No. 560, Report No., TCP-31, World Meteorological Organisation, Geneva.

O'Brien, S.T., B.P. Hayden and H.H. Shugart (1992) “Global Climatic Change, Hurricanes, and a Tropical Forest”, *Climatic Change*, 22: 175-90.

Rauthe, M., A. Hense and H. Paethe (2004) "A Model Inter-comparison Study of Climate Change Signals in Extra-tropical Circulation", International Journal of Climatology, 24: 643-662.

Ryan, B.F., I.G. Watterson and J.L. Evans (1992) “Tropical Cyclone Frequencies Inferred from Gray's Yearly Genesis Parameter: Validation of GCM Tropical Climates”, *Geophysical Research Letters*, 19: 1831-34.

Saunders, M.A. and A.R. Harris (1997) “Statistical Evidence Links Exceptional 1995 Atlantic Hurricane Season to Record Sea Warming”, *Geophysical Research Letters*, 24: 1255-58.

Schinke, H. (1993) "On the Occurrence of Deep Cyclones over Europe and the North Atlantic for the Period 1930-1991", *Beitr. Phys. Atmosph*, 66: 223-237.

Schubert, M., R. Perlwitz, R. Blender, K. Fraedrich and F. Lunkeit (1998) "North Atlantic Cyclones in CO_2-induced Warm Climate Simulations: Frequency, Intensity and Tracks", Climate Dynamics, 14: 827-837.

Senior, C. (2002) “Modelling Changes in Extreme Events”, IPCC Workshop on Extreme Weather and Climate Events, Workshop Report, Beijing, China, 11-13 June, 2002.

STOWASUS-Group (2001) "Regional Storm, Wave and Surge Scenarios for the 2100 Century", Stowasus-Final Report, DMI, EU commission.

Tsutsui, J. and A. Kasahara (1996) “Simulated Tropical Cyclones Using the National Centre for Atmospheric Research Community Climate Model”, *Journal Geophysical Research*, 101(10): 15013-15-032.

Tsutsui, J., H. Hatsushika and H. Kitabata (2004) "Inter-annual Variability or Tropical Cyclone Frequencies Implied from an Ensemble Climate Simulation with the NCAR Community Atmosphere Model", 26th Conference on Hurricanes and Tropical Meteorology, 2-7 May 2004, Miami, FL.

UKCIP (2002) *Climate Change Scenarios for the United Kingdom*, The UKCIP02 Scientific Report, the UK Climate Impacts Programmes, Oxford.

Walsh, K.J.E., K.C. Nguyen and J.L. McGregor (2004) "Climate Change, Tropical Cyclones and ENSO", 26th Conference on Hurricanes and Tropical Meteorology, 2-7 May 2004, Miami, FL.

WASA-Group (1998) "Changing Waves and Storms in the Northern Atlantic?", *Bulletin of the American Meteorological Society*, 79: 741-760.

Yoshimura, J., Oouchi, K., Yoshimura, H., Mizuta, R., Kusunoki, S. and A. Noda (2005) “Influences of Global Warming on the Tropical Cyclone Climatology as Simulated in a 20-km-mesh Global Atmosphere Model”, 2nd International Workshop on the Kyosei Project, 24-26th February 2005, Hawaii.

4.0 Impacts of climate change on costs of UK extreme weather

The consequences of climate change may have significant economic effects at the national scale. This section considers the flooding and subsidence impacts on property caused by climate change and estimates the costs of this for the UK.

4.1 Flooding

In this section we present cost estimates of the climate change-induced future impacts of flooding on property in the UK. These estimates are derived principally from the outputs of the DTI-sponsored Foresight Study entitled the Flood and Coastal Defence project[37]. Four specific sources of damage to property are considered: coastal flooding; intra-urban flooding and fluvial flooding. We assume that all property is insured and insurable.

Method

Step 1. Physical impact assessment

Estimation of the physical flood damage within the Foresight project was made based on a bottom-up process that primarily made use of the Risk Assessment for flood and coastal defence systems for Strategic Planning (RASP) system previously developed for Defra. Essentially, the RASP system allows climate and socio-economic changes to be imposed on geographically mapped physical receptors on a national (English) scale, thereby generating estimates of the number of physical units impacted by flooding. A similar although much more approximate attempt was made in the project to assess the risks of urban flooding, where simple urban drainage models were up-scaled to generate national estimates of the risks of urban flooding. Risks due to coastal erosion, using the outputs of the Future Coast project, another Defra research project[38]. The data necessary to apply these risk analysis methods were not universally available in Scotland and Northern Ireland, and where this was the case more approximate analyses were conducted.

The principal determinants – or drivers - of the size of impacts of flood risk identified in the Foresight study included:

- Climate change (precipitation and temperature)
- Catchment run-off
- Fluvial systems and processes
- Flood management
- Human behaviour
- Socio-economics
- Coastal processes (including coastal climate change factors)

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[37] *Future flooding*, Office of Science and Technology Foresight Programme, April 2004, http://www.foresight.gov.uk/previous_projects/flood_and_coastal_defence

[38] www.defra.gov.uk /environ/fcd/futurecoast.htm

The UKCIP02 climate scenarios[39] have been employed. These scenarios are based on four emissions scenarios corresponding to the SRES scenarios – as identified below. The Foresight Futures socio-economic scenarios developed by researchers at the Science and Technology Policy Research, University of Sussex (SPRU) for the Office of Science and Technology (OST, 2002) were employed. These scenarios are broadly consistent with the UKCIP socio-economic scenarios, and can also be mapped on to the climate scenarios – as shown in Table 4.1.

Table 4.1: **Correspondence between SRES, UKCIP02 scenarios and Foresight Futures**

SRES	**UKCIP02**	**Foresight Futures 2020**	**Commentary**
B1	Low emissions	Global sustainability	Medium-high growth, but low primary energy consumption. High emphasis on international action for environmental goals (*e.g.* greenhouse gas emissions control). Innovation of new and renewable energy sources.
B2	Medium-low emissions	Local stewardship	Low growth. Low consumption. However, less effective international action. Low innovation.
A2	Medium-high emissions	National enterprise	Medium-low growth, but with no action to limit emissions. Increasing and unregulated emissions from newly industrialised countries.
A1F1	High emissions	World markets	Highest national and global growth. No action to limit emissions. Price of fossil fuels may drive development of alternatives in the long term.

The Foresight project focussed on two of the three time slices used in the UKCIP02 scenarios, corresponding to the 2050s and 2080s. In the section below, we provide an extrapolation of the cost estimates for these time-slices back to the 2020s to give a first indication of the possible scale of costs in this time period.

In order to quantify the effect of climate change induced flooding on property – both residential and business - we need to be able to isolate it from non-climate change-induced flooding. The non-climate change baseline was therefore estimated by identifying i) the present day property impacts associated with a given weather event, and ii) the frequency of such an event in a non-climate change context (i.e. historical frequency). In the Foresight study, the baseline assumption on the future course of flood management was that current flood and coastal management policy was kept the same across all scenarios, including the current pattern of expenditure and technical approach. This present day flood and coastal management policy is referred to as the baseline flood management policy. Analysis of changing climate and socio-economic scenarios were superimposed on this fixed flood management policy, in order to assess the capacity of the current policy to cope with long-term changes.

Once the number of properties subject to flooding as a consequence of given present day weather events are estimated, the Foresight method estimates the frequency of the weather event under climate change scenarios in future time periods, enabling comparison of total physical property impacts under non-climate change and climate change frequencies of the weather events. The difference between the two totals

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[39] Climate change scenarios for the United Kingdom, UK Climate Impacts Programme. Hulme et al. April 2002. www.ukcip.org.uk

provides an estimate of the net number of possible property claims associated with weather events of different frequencies that can be attributable to climate change.

Step 2. Monetary impact assessment

Analysis of future flood risk involves consideration of both changes to the probability of flooding and the consequences of flooding. The physical impact assessment outlined above allows estimation of the changes in probability of flooding under climate scenarios, and when combined with the socio-economic scenarios produces estimates of the consequences, or impacts, of flooding in terms of the expected annual number of properties flooded, and to what depth. This physical impact data is converted into monetary terms by applying unit flood damage costs derived from the FHRC FLAIR cost database[40]. Multiplying these unit costs by the expected annual physical flood damages to property gives the expected annual economic impact of flooding to the nation, which is often referred to as annual average damage (AAD). For the four types of flooding/coastal erosion addressed in the Foresight study, estimates of AAD are calculated, and are presented below. The results taken directly from the Foresight study are presented for the four impact types for England and Wales, for the 2050s and 2080s. We then present the UK-wide results extrapolated from these results to cover the 2020s time-slice.

4.2 Results: fluvial and coastal flooding

As the results from the Foresight study presented in Table 4.2 show, the increases in economic damage under the two more consumerist (A1F1 and B1) scenarios show similar patterns of high or medium increases over much of England and Wales. The Thames valley and estuary is a hotspot, as is the Lancashire-Humber corridor and areas bordering the Bristol Channel, as well as the south east coastal strip. The pattern of economic damages is similar under Global Sustainability, though with markedly lower levels of increase. A general decrease is shown for Local Stewardship, reflecting both lower increases in probability of flood events and lower GDP growth, and therefore asset values at risk.

Table 4.2*: AAD for residential and commercial properties for UK from river & coastal flooding ($ million)*

Region	***Foresight Future***					
	Present day	***A1F1 2050s***	***A1F1 2080s***	***A2 2080s***	***B2 2080s***	***B1 2080s***
South-east	181	6230	6960	7330	680	2380
South-west	95	1580	3110	2200	180	640
Thames	476	4030	6040	3850	420	1150
East-Anglia	385	4400	5310	3850	390	1280
Midlands	126	1370	2560	1410	140	440
North-east	256	5310	7140	5130	510	1660
North-west	220	1830	4580	2380	270	680
Wales	167	1830	2750	2320	270	710
Scotland & N.I.	88	9160	12820	7330	730	4030
Total	1,995	35,740	51,270	35,800	3,320	12,970

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[40] www.fhrc.mdx.ac.uk Flood Hazard Research Centre

Using a process of linear extrapolation from the time slice centred on the 2080s to those centred on the 2020s and 2050s we derive estimates of the total AADs for river and coastal flooding in the UK, as presented in table 4.3

Table 4.3: AAD estimates for fluvial and coastal flooding under the low (B1) and high (A1F1) climate emission scenarios in UK ($m).

	B1	A1F1
2020s	6,000	22,000
2050s	9,000	37,000
2080s	13,000	50,000

4.3 Intra-urban flood risk

Table 4.4 below shows estimated changes in the AAD in the UK from intra-urban flooding. It should be noted that this does not include the cost of household or local flooding as a result of direct pluvial effects or of flood waves from sources external to the urban area.

Table 4.4: AAD in the UK due to Intra-urban Flooding ($ million)

	Pres.	**A1F1**		**A2**		**B2**		**B1**	
		2050s	**2080s**	**2050s**	**2080s**	**2050s**	**2080s**	**2050s**	**2080s**
UK	900	9,700	27,500	9,700	18,300	1,600	2,400	2,900	6,400

Using a process of linear extrapolation from the time slice centred on the 2080s to those centred on the 2020s and 2050s we derive estimates of the total AADs for intra-urban flooding in the UK, as presented in Table 4.5.

Table 4.5: AAD estimates for intra-urban flooding under the low (B1) and high (A1F1) climate emission scenarios in UK ($m).

	B1	A1F1
2020s	1,800	5,000
2050s	2,900	9,700
2080s	6,400	27,500

4.4 Mitigation and adaptation of flood impacts

The future costs associated with the three impact types discussed above are presented together over the three time-slices. The two climate scenarios featured are representative of high (A1F1) and low (B1) emission (and their corresponding socio-economic) scenarios, and therefore give an idea of the range of uncertainty surrounding the estimates of future flood and erosion costs. One may want to take the difference between two scenarios as being a representation of the benefits of a mitigation policy that allowed emissions to move from a high to a low emissions scenario. The problem with this approach is that the A and B socio-economic story-lines which underlie these emission scenarios are inconsistent with each other so that emission reductions between the two are nonsensical. We therefore include them simply to illustrate the range of costs associated with high and low emission scenarios.

On the basis of the evidence in the Foresight study (specifically, Chart 2.10 in the Executive Summary) of the relative importance of different climate and socio-economic drivers in determining the size of flood risks we make a crude assumption that a maximum of 50% of the total costs are specifically related to climate change. We make an adjustment on this basis in Table 4.6.

Table 4.6: Total AADs for time-dependent flood impacts in the UK under high and low emission scenarios

	B1	A1F1
2020s		
river & coast flooding	3,600	11,900
intra-urban flooding	640	2,200
2050s		
river & coast flooding	5,500	17,400
intra-urban flooding	1,190	4,600
2080s		
river & coast flooding	7,300	26,600
intra-urban flooding	2,900	13,500

The Foresight study also compares the baseline – i.e. no change from present flood management strategies - impact costs for riverine and coastal flooding presented above with the residual impact costs that would result from the imposition of an integrated portfolio of responses that includes elements of catchment-wide storage, land-use planning and realignment of coastal defences. This comparison between the impact costs in the baseline and from an integrated adaptation response to river and coastal flooding is presented for the 2080s time-slice in table 4.7.

Table 4.7: AADs for net climate flooding in baseline and adapted 2080s futures ($m)

	A1F1	B1
Baseline - river	26,600	7,300
-intra-urban	13,500	2,900
Integrated response -river	1,800	3,300
-intra-urban	5,500	550

Table 4.7 indicates the extent to which river, coastal and intra-urban flood impacts may be reduced by appropriate measures. However, it should be borne in mind that the cost reduction does not include any costs associated with the introduction of the adaptation measures themselves. Engineering costs of flood management additional to those under present regimes were estimated within the Foresight study to be between $18 million (£10 million) and $54 million (£30 million) per year over the period to 2100, suggesting – dependent on the cost of non-engineering responses – that an integrated adaptation response of the type investigated by Foresight is economically efficient.

4.5 Subsidence

In this sub-section we present estimates of the economic costs associated with the subsidence impacts on households in the UK under future climate change scenarios. This note is based on the findings of a recently completed case study undertaken for ABI and UKCIP[41]. Economic costs are split into two elements: insured and non-insured. Subsidence impacts to domestic property[42] are likely to arise from the combination of reduced rainfall and above-average temperatures predicted to become more frequent in the UKCIP02 climate change scenarios[43]. As the basis of such estimates we initially take the unusually dry and warm conditions that existed in the UK in summer 2003 as an historical analogue.

Method

Step 1. Physical impact assessment

In order to quantify the effect of climate change on subsidence we need to be able to isolate it from non-climate change-induced subsidence. We therefore estimate the non-climate change baseline by identifying i) the subsidence incidence associated with a given weather event as an historical analogue, and ii) the frequency of such an event in a non-climate change context (i.e. historical frequency).

i) We assume that the summer 2003 warm weather event is representative of a type of weather event that results in an increased incidence of subsidence in the UK. Thus, if we are able to identify the claims additional to those expected in a year of average temperatures we can estimate the excess number of claims that can be attributed to such a weather event of a given non-climate change frequency. To identify these additional claims we use the historical aggregate claim series data compiled by the ABI. We derive an estimate of 22,000 excess claims, which represents an increase of 69% on the average annual number of claims.

In order to estimate the total physical impact in future time periods under climate and non-climate change scenarios we consider the possible effects of socio-economic change on the number of properties that might be vulnerable to subsidence. We use the UKCIP (2001) socio-economic scenarios (SESs) developed for climate impact assessment as a starting point. The resulting estimates are driven solely by the information given in these scenarios relating to population and household size. Estimates for future time periods and scenarios range from approximately 15,000 to 35,000 cases of subsidence for a summer 2003 warm weather event.

ii) Once the number of properties subject to subsidence as a consequence of a given weather event - Summer 2003 is characterised as a 1 in 100 year event - has been derived, we estimate the frequency of the weather event under climate change scenarios in future time periods. We can then compare total expected annual subsidence incidence, (i.e. number of subsidence claims associated with a given event severity * frequency of the given event), under non-climate change and climate change frequencies of the weather event, aggregated over the time period to 2100. The difference between these two totals provides an estimate of the net number of claims associated with a weather event of this severity that can be attributable to

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[41] Metroeconomica (forthcoming). Property & Insurance Case Study. UKCIP

[42] Graves and Phillipson (2000) report that it is primarily the domestic building stock that is affected by subsidence since commercial and industrial buildings tend to have deeper foundations and be more heavily loaded, thereby eliminating the potential for subsidence.

[43] Climate change scenarios for the United Kingdom, UK Climate Impacts Programme. Hulme et al. April 2002. www.ukcip.org.uk

climate change. The output of this calculation is an input into the monetary impact assessment.

Step 2. Monetary impact assessment

The second step is to identify and estimate the expenditure incurred to replace (or restore) the asset damaged as a result of climate change, in unit cost terms. In the building subsidence context, domestic householders spread the risk of the cost by making annual payments (premiums) to insurance companies in return for coverage of the repair cost in the event of subsidence[44]. Aggregate historical data on subsidence claims supplied by the ABI for Great Britain are used to derive unit values in a range between $12,800 (£7000) and $22,000 (£12,000). These figures compare with a unit value of £10,000 adopted by Graves & Phillipson[45] (2000) and Driscoll & Crilly[46] (2000) in their analyses of climate change impacts on subsidence incidence for the Building Research Establishment, themselves derived from the typical costs of undertaking specific remedial work in the event of property subsidence. We assume $18,000 (£10,000) as a central value.

Note that the ABI aggregate data does not include all the cost of the subsidence damage. It is currently standard practice in the arrangements for buildings insurance coverage in the UK to require the policy holder (the householder) to contribute an initial increment of the cost of subsidence damage that is being claimed against the policy. Typical increment payments average about $1,800 (£1000) per property. Thus, the $18,000 (£10,000) total replacement cost per case of subsidence may reasonably be disaggregated into two components: $1,800 (£1000) borne by the household; $16,200 (£9000) borne by the insurance company in order to reflect the relative cost burdens.

Step 3. Aggregation

At this point, the aggregate number of properties estimated to be subject to subsidence under alternative non-climate and climate scenarios are multiplied by the unit cost of $18,000 (£10,000) per property and the probability of the weather event in the respective climate scenario to give an annual expected subsidence damage cost. i.e.

No. of properties X probability of weather event X unit cost of subsidence

We estimate the annual expected subsidence damage cost for the non-climate change reference scenario (under alternative socio-economic scenarios) and climate change scenarios corresponding to the IPCC SRES scenarios – as labelled. We then subtract the non-climate change costs from the costs attributed to the climate scenarios to produce the net climate change cost. The un-discounted annual totals that result are presented in table 4.8.

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[44] Note that in practice premiums are calculated as an aggregate sum to provide financial protection for the risk of suffering from other forms of property damage or loss in addition to subsidence. Thus, it is not possible to calculate the costs of subsidence from estimates of the premiums paid, but rather to look at the value of the claims made by households following subsidence to repair damage.

[45] Graves H.M. and M.C. Phillipson (2000) Potential implications of climate change in the built environment. FBE Report 2. December 2000.

[46] Driscoll & Crilly (2000) Subsidence damage to domestic buildings: lessons learned and questions remaining. BRE & FBE. September 2000.

Table 4.8: Undiscounted net climate change induced subsidence costs in UK ($m)

Year[47]	2020s		2050s		2080s	
	B1	A1F1	B1	A1F1	B1	A1F1
LS	45	55	75	120	90	175
GS	55	65	110	175	155	320
NE	55	65	90	145	120	240
WM	65	75	130	210	220	430

Socio-economic scenarios: LS = Local Stewardship; GS = Global Sustainability; NE = National Enterprise; WM = World Markets

On the basis of the annual costs given in table 4.8, we calculate that the total undiscounted cost of climate change induced subsidence for the entire period 2010-2100 – with no adaptive measures beyond straight repair of the damage - range from $6.3 (£3.45) billion to $21.4 (£11.7 billion)[48] (constant 2004 prices), depending on the socio-economic/climate scenario combination.

It is important to note that these annual and time-aggregated cost totals are derived by considering only the costs associated with a 1 in 100-year weather event. The climate -induced costs associated with weather events of different frequencies are not included. Thus, the costs presented above are likely to be only a portion of the total climate change -induced costs. An appreciation of this limitation can be had by comparing the annual expected costs of a future non-climate change 1 in 100 year event – which is $3.7m (£2m) – $6.4 (£3.5m), depending on the socio-economic scenario and future period considered – with the current annual average claim total due to subsidence of about $640 million (£350 million). One might assume in any case that increases in mean temperature over time would lead to increases in subsidence.

Therefore, in order to derive a total climate change induced costs it would be necessary to estimate the subsidence damage costs associated with all event frequencies. However, the time-series data does not exist to create this event frequency-cost profile. We are therefore forced to make an approximation of the total costs using an alternative method. We may, for example, assume an event frequency-cost profile based on expert judgment, or scale up current total subsidence costs on the basis of the difference in costs identified above for the Summer 2003-type event for non- and climate change scenarios. In imposing a subjectively-generated event frequency-cost profile we would need to know how the frequency of these events changes. However, this information is not available in the UKCIP (2002) climate scenarios publication. Similarly, regarding the scaling-up method, it is not clear on what basis any scaling-up should be made (e.g. additive or multiplicative).

Given these data and methodological limitations the problem of generating the climate change-induced aggregate costs that we require remains. One solution is to assume that the costs derived above from considering the Summer 2003-type event provide a lower-bound estimate of the total climate change-induced subsidence costs. A second solution is to use the results of other existing studies. Two studies are available: Dugolecki[49] and Graves and Phillipson[50].

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[47] The years presented here in fact only represent the three time-slices. These years are the mid-points within the time-slices.

[48] These totals are calculated for the two scenarios by multiplying the average annual cost identified for the three time periods by the 30 years within each period.

[49] Dugolecki, 2004 A changing climate for insurance.June 2004 ABI

Dugolecki[13] refers to research – unspecified – wherein a relationship between meteorological conditions and historical claims costs, based on insurance company data, was derived. When applied to climate scenario futures, this relationship generated climate change induced subsidence costs of $550million (£300 million) per year by the 2080s. Similarly, Graves and Phillipson estimate an increase in costs over today's average annual total of between $360 million (£200 million) and $730 million (£400 million) per year by the 2080s. These results compare with the range of costs of $165 million (£90 million) – $440 million (£240 million) per year we derive for the Summer 2003-type event from the low emissions-global sustainability and high emissions-world markets scenarios respectively, for the time-slice centred on the 2080s, and therefore appear to be broadly consistent. In the absence of other evidence that would allow us to extend our method to other event frequencies we therefore suggest to use the range provided by Graves and Phillipson of $360 million (£200 million) - $720 million (£400 million) per year, an effective up-scaling by broadly a factor of 2. We adopt this scalar in Table 4.9 below.

Table 4.9: Total AADs for time-dependent subsidence impacts in the UK and potential mitigation benefits

Time slice	B1	A1F1
2020s	130	160
2050s	220	440
2080s	330	880

4.6 Adaptation

As mentioned above, the cost estimates we present are based on the assumption that no adaptive measures beyond straight repair of the subsidence damage are implemented. However, this assumption may be unrealistic since a greater awareness and understanding of climate change is likely to lead to consideration of cost-effective adaptation. Indeed, it should be noted that the UK Government have recently recognized the threat of increased subsidence from climate change by introducing a new building regulation, (Building Regulation 2000 (2004 up-date) Structure A), requiring new building on clay soils to have foundations to a depth of 0.75m, revised from 0.5m previously. This is part-way to the foundation depth of 1 metre suggested by Driscoll & Crilly[51] as being sufficient to eliminate subsidence risk to 2100.

Recent work by Metroeconomica[52] provides some initial estimates of the costs and benefits of adaptation measures in response to a summer as dry and hot as 2003, where there was an increase in subsidence claims (Table 4.10).

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[50] Graves H.M. and M.C. Phillipson (2000) Potential implications of climate change in the built environment. FBE Report 2. December 2000.

[51] Driscoll & Crilly (2000) Subsidence damage to domestic buildings: lessons learned and questions remaining. BRE & FBE. September 2000.

[52] Metroeconomica (forthcoming). Property & Insurance Case Study. UKCIP

Table 4.10. Aggregate Benefits & Costs (and their distribution) of alternative adaptation options to property subsidence. (2004 prices)

Adaptation Measure	**Benefit**	**Cost**	**Bearer of Cost Burden**
Higher insurance premiums to cover higher remediation costs	Insurer covers costs of increased number of claims	$6.6 – $22.2bn Increased household insurance costs	House-owner bears increased costs
Withdrawal of insurance cover for properties vulnerable to subsidence	Insurer avoids increased exposure	$6.6 – $22.2bn Loss of property value	House-owner bears full remediation costs and loss of property value Possible exclusion for low income groups
Underpinning and structural measures	$6.6 – $22.2bn Maximum avoided loss.	$28 - $69bn Total cost of measures for all properties at risk	Benefit borne by insurer and house-owner Cost borne by house-builder or owner
Building regulations for: - deeper foundations of 1 metre - building materials	$2.7 – $10.3bn Not known	$3.7 – $6.4bn Not known	Benefit borne by insurer and house-owner Cost borne by house-builder or owner
Spatial planning policy	$2.7 – $10.3bn Maximum avoided loss	Loss of land values and possible social costs of higher density housing	Benefit borne by insurer and house-owner Cost borne by house and land-owners
Clearance of nearby vegetation or restrictions on future planting	$6.6 – $22.2bn Maximum avoided loss	Not known	Cost borne by house and land owners
Regular water sprinkling of vegetation	$6.6 – $22.2bn Max avoided loss	Not known	Cost borne by house and land owners

Note: ranges reflect cost and benefit estimates made under low and high emission scenarios associated with a 1 in 100 year event only

These results suggest that an option of requiring deeper foundations for new-build properties such as the newly introduced Building Regulation is – on balance – likely to produce a net benefit. However, spatial planning options and vegetation management options need to be studied further before an economically efficient adaptation strategy can be developed. Options of withdrawal of insurance coverage or increasing premiums to reflect the higher expected costs are not attractive options on either economic or social criteria.

4.7 Conclusions: climate-induced flooding, erosion and subsidence impacts in the UK.

The preceding sub-sections have summarised the findings of recent research on the costs of climate change of three impact types on property in the UK likely to be important to the operations of the insurance industry: flooding, coastal erosion and subsidence. The aggregate annual average damage estimates are presented in for the three 30-year time-slices to 2100. Note that the results for flooding and subsidence are not readily comparable with each other since the flooding estimates account for assumed increases in the value of the assets at risk over time whilst the subsidence estimates do not.

In the case of adaptation, evidence from the Foresight study suggests that – depending on the size of non-engineering costs involved – an integrated portfolio approach to flood prevention may be cost-efficient. Similarly for subsidence, deeper foundations may have a positive net benefit, though non-engineering approaches such as spatial planning policy may also have a role in future adaptation strategies.

5.0 Wider economic impacts of climate change

Sectoral impacts

The project scope has been confined to areas and issues for which a quantitative analysis could be undertaken, such as specific geographical areas, the property market and extreme events. Climate change will, however, have direct effects on all areas of insurance where the underwriting of risks is important e.g. general insurance (motor, travel, construction, corporate liability, business disruption), marine, health, and life and pensions. To give an indication, this section provides a brief qualitative review of some of the climate change impacts on, as examples, health, heat wave, agriculture and flooding. This section is intended to be illustrative of the range and scale of impacts and does not provide a comprehensive position statement.

5.1 Health

The net effect on health insurance is uncertain. The impacts of climate change vary dependent upon, for example, the characteristics and vulnerabilities of the population group, geographical region, national GDP, prosperity, and availability of medical services.. Some factors affecting the health of a population may be beneficial, others potentially damaging.

There is a growing scientific literature on health impacts, which explores the effects of a changing climate on disease, illness and vectors. The complexity of this literature and the specific impacts relevant to geographical regions require a more detailed assessment. Although the research work on disease impacts etc., is extensive, in comparison there have been relatively few attempts to understand how climate change will affect the provision of health care services.

Initial findings show that globally there is an increase in health risks with an increase in temperature. Smith and Hitz[53] review some of the main impacts on human health. Headline findings are:

- Globally – increase in health risks with increase in temperature;
- Spread of malaria seems linear and increasing with temperature[6]
- Increase in waterborne disease may be significant source of health risk – with increased water stress and reduced water quality in some areas leading to increased incidence of waterborne diseases.
- Rising temperatures may lead to decrease in cold-related mortality and increase in heat related mortality, with reduction in cold-related mortality greater than increase in heat-related deaths in first instance. Mortality estimates peak by 2050, with marginal changes from then on being positive[55]

Tol[56] presents estimates based on empirical linkages between climate and health. These estimates are shown in Table 5.1 below. These show that reductions in cold related mortality will outstrip heat related mortality in North America and the OECD Pacific nations. In other regions the same will be true in Latin America and Eastern

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[53] Smith, J. and S. Hitz (2003) *Background Paper: Estimating Global Impacts from Climate Change*. OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers. OECD, Paris.

Europe. Mortality will increase overall in Europe and all other regions of the world, with South and South East Asia and Africa being the worst affected.[54]

Table 5.1: Number of additional deaths (1000s) per 1^{o}C increase in global mean temperature

	Malaria	Schisto	Dengue	Heat related cardiovascular mortality	Cold related cardiovascular mortality	Heat related respiratory mortality	Total
OECD-A	0	0	0	11.4	-64.4	3	-50
OECD-E	0	0	0	11.7	-9.8	-2.8	-0.9
OECD-P	0	0	0	3.5	-13.1	1	-8.6
CEE and FSU	0	0	0	10.7	-87.5	4.5	-72.3
ME	0.2	-0.1	0	2.5	-8.9	9.9	3.6
LA	1.1	-0.1	0	8.1	-20	11.1	0.2
S&SEA	8.2	-0.1	6.7	17.5	-63.8	141.2	109.7
CPA	0	-0.1	0.4	24.3	-103.4	62.8	-16
AFR	56.5	-0.5	0.3	4.7	-18.2	24.8	68.3

Source: Tol (2002a)[54]

In a dynamic model, Tol[55] presents the impacts of climate change on health over time. For vector borne disease, the costs initially increase but then decrease as health care is assumed to improve with GDP. This is shown in Figure 5.1.

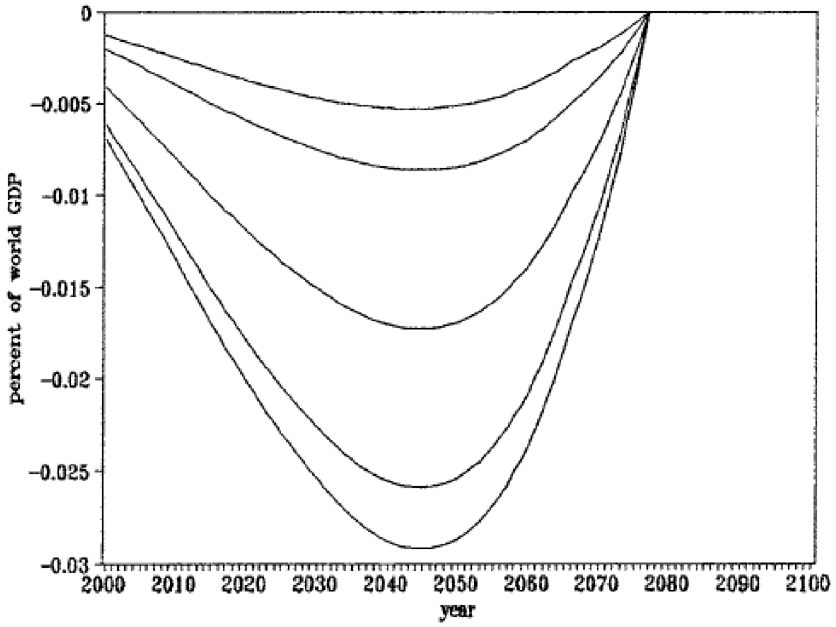

Figure 5.1 A sensivity analysis around the costs of increased vector-borne mortality. The central line depicts the case in which all parameters assume their central estimate. In the inner interval, the value of a statistical life is varied between its central estimate plus or minus its standard deviation. In the outer interval, the sensitivity of vector-borne mortality is varied between its central estimate plus or minus its standard deviation.

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[54] Tol, R. S. J. (2002a) “Estimates of the Damage Costs of Climate Change: Part I: Benchmark Estimates” *Environmental and Resource Economics* 21:47-73.

[55] Tol, R. S. J. (2002b) “Estimates of the Damage Costs of Climate Change: Part II Dynamic Estimates” *Environmental and Resource Economics* 21:135-160.

For heat and cold stress, the impacts over time are shown in Figure 5.2 below. In the central case, climate change reduces mortality. In 2200, climate change may have a net impact of a reduction of 1.5 million premature deaths[56].

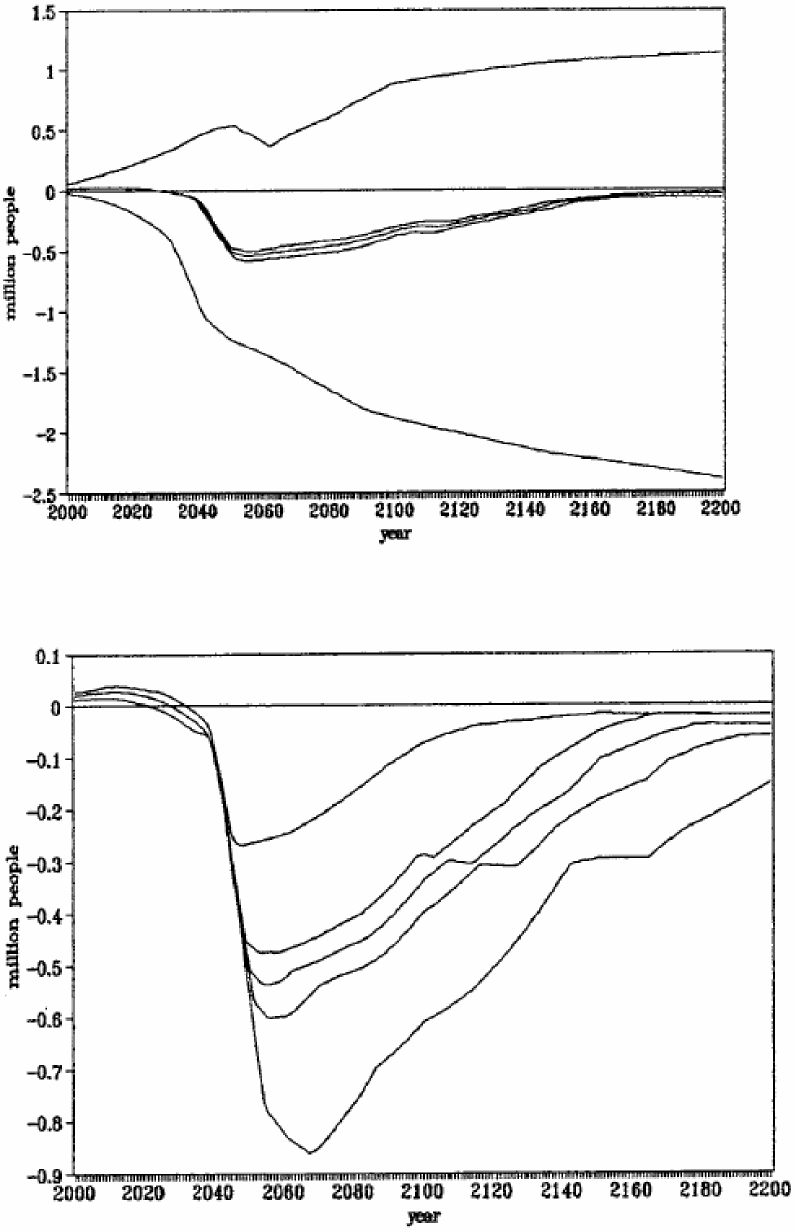

Fig 5.2 . A sensivity analysis around the change in cardiovascular and respiratory mortality due to climate change. In both panels, the central line depicts the case with all parameters set to their central estimate. In the upper panel, in the inner interval, the reaction of the age composition to changes in per capita income is varied bewteen its central estimate plus or minus its standard deviation. In the lower panel, in the inner interval, the reaction of baseline mortality to changes in age composition is varied between its central estimate plus or minus its standard deviation. In the outer interval, the maximum allowed change in mortality is varied between its central estimate plus or minus its standard deviation.

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[56] Tol, R. S. J. (2002b) "Estimates of the Damage Costs of Climate Change: Part II Dynamic Estimates" *Environmental and Resource Economics* 21:135-160

The provision and funding of state health care is already a major political, social and economic issue. The effect of climate change may be to add further dynamics into the relationship between state and private health care providers and the future role of, and requirements placed upon, government to provide adequate funding. There is a role for the insurance industry to play in working with governments to develop public policy responses to the emerging climate change driven risks.

Insurers will need to review their risk models to gain a better understanding of how the risks are changing. Modelling based on historic trends is no longer appropriate, if underwriting is to reflect risk characteristics. Assessments at regional level and over time are required to build a better risk profile of the market. These assessments need to be integrated with other economic and social factors.

5.2 Heat waves

The heat wave in Europe in 2003 served as a clear reminder of the perils of consistently high temperatures over an extended period and the impacts on health, utility services, transport, agriculture and the economy. The impacts on the insurance industry arising from a prolonged heat wave in developed countries are not well defined. The 2003 heat wave lasted three months and resulted in over 22,000 fatalities. Property damage was in the region of $13 billion. Other consequences included severe wildfires across Portugal, Spain and France, and economic losses were estimated at around US$15 billion.[57]

Some of the main impacts from 2003 listed below demonstrate how widespread the effects can be:

- The heat wave lasted three months resulting in over 20,000 fatalities
- $13bn property damage
- Disruption to inland shipping
- Impact on tourism – cancellations
- Disruption to manufacturing processes
- Power plants shut down through lack of cooling water
- Hydroelectric generating capacity affected
- Interruptions in energy supplies
- Low river flows
- Agricultural outputs reduced
- Reduction in worker efficiency

Climate change has already doubled the chance of a very-hot summer in Europe (e.g. 2003), and by the 2040s, more than half of all European summers will be warmer than that of 2003.[58] Table 5.2 gives examples of recent heat waves in Europe and some of their impacts.

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[57] Climate change 2004. Technical paper 02. Benfield Hazard Research Centre

[58] *Uncertainty, risk and dangerous climate change*, Hadley Centre, Met Office, December 2004, http://www.metoffice.com/research/hadleycentre/pubs/brochures/B2004/global.pdf

Table 5.2 Impact of heat-stress on premature deaths in Europe

Heatwave	**Attributable mortality**	**Reference**
Birmingham, UK 1976	Number of deaths increased by 10%: excess seen primarily in men and women aged 70-79 years	Ellis and others (1980)
London, UK 1976	9.7% increase in England and Wales and 15.4% in Greater London. Almost two-fold increase in mortality rate among elderly hospital inpatients (but not other inpatients).	Lye and Kamal (1977)
Portugal, 1981	1906 excess deaths (all causes, all ages) in Portugal, 406 in Lisbon in July including 63 heat deaths.	Garcia and others (1999)
Rome, Italy 1983	65 heat stroke deaths during heat-wave in the Latio region. 35% increase in deaths in July 1983 compared with July 1982 among those 65 years or older in Rome.	Todisco (1983)
Athens, Greece 1987	2690 heat-related hospital admissions and 926 heat-related deaths, estimated excess mortality >2000.	Katsouyanni and others (1988)
London, UK 1995	619 excess deaths: 8.9% increase in all-cause mortality and 15.4% in Greater London compared with moving average of 31 days for that period in all age groups.	Rooney and others (1998)
Europe 2003	Over 22,000 premature deaths in UK, France, Portugal, and Italy; Death rates doubled in Paris during 11-12 August when night-time temperatures reached 25.5 °C.	Kovats and others (2004)

Source: Kovats and Koppe (forthcoming)

The risk of severe heat waves in Europe will increase significantly bringing with it new challenges for those insurers providing health, property, business interruption, and fire cover. The limited availability of information indicates that further research and a greater understanding of the costs in this area is required.

National catastrophe programmes do not yet include heat wave as a relevant event. Is there a need for new programmes to be developed or for existing programmes to be extended? The complex inter relationships between social, economic and natural resource systems together with the market needs of consumers make it extremely difficult for a full risk assessment to be undertaken. Quantification of risk, which is the key to risk based pricing will remain difficult, unless adequate integrated assessment models can be developed. If the insurance industry feels unable to quantify the risks it may well see heat wave catastrophes as an event where governments need to take the leading role in providing insurance.

5.3 Agriculture

Climate change is likely to have important implications for world agriculture. Impacts have been predicted through a number of different pathways, some of which have been positive (e.g. increased CO_2 leading to increased yields) but most of which have been negative (e.g. reductions in water available for irrigation).

The possible effect of climate change on agricultural prices will be of importance to the insurance industry, given that agricultural products are significant inputs into a wide range of products and risks of crop failure or price changes may be offset through use of hedging.

Examples of the effects of extreme weather include:

- In the UK in 1995 the grain harvest was exceptionally good in some areas, whereas in others there were substantial crop failures. Particularly hard hit were cattle breeding and trout farming. Overall, British farmers sustained losses of GBP 180 million due to this climatic anomaly.[59]
- The heat wave across Europe in 2003 led to severe wildfires across Portugal, Spain and France that affected forestry and property. This resulted in economic losses of around US$15 bn.[60]
- The unusually warm summer of 1992 in northern Germany caused crop failures generating losses of approximately DEM 4 billion (US$ 3.1bn) at the then prevailing price levels.

5.4 Impact estimation techniques

A number of techniques have been applied in estimating the impacts of agriculture. Crop-climate experiments have been applied - using controlled conditions to estimate the impacts of different ambient levels of CO_2, different levels of temperature and different levels of irrigation on crop yield. The conditions examined in crop-climate experiments are commonly based on general circulation models (GCMs), which are models of the atmosphere and oceans that are used to forecast impacts of increased emissions or concentrations of greenhouse gases on climate.

Integrated assessment models (IAMs) have also been applied in the agricultural context, drawing on computer modeling, scenario analysis and qualitative assessments to yield estimates of the impacts of climate change on different sectors in the economy. Spatial analogues have also been used to assess the impacts of climate change on agriculture. This technique assumes that the geographical distribution of crops is primarily a function of temperature and precipitation conditions. By matching current crop production patterns with current climate conditions, one can project how current production patterns will change under alternative temperature and precipitation conditions. Clearly, there are advantages and disadvantages to the use of these different modeling techniques, and care should be taken in their application.

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[59] Opportunities and Risks of Climate Change, Swiss Re.2002

[60] Climate change 2004. Benfield Hazard Research Centre 2004

5.5 Impacts

The principal impacts of climate change on agriculture that have been identified derive from the following factors:

- increased CO_2 concentrations affecting yields
- increased likelihood of extreme weather events
- increased temperature
- soil degradation
- water availability
- spread of pests
- direct impacts on livestock

Studies have focused on the interactions between different elements of climate change - as there are important inter-linkages between the effects on crop growth of CO_2 elevation, temperature increase and water shortages. There are considerable uncertainties over the impact of climate change on crop yield, particularly with an increase in ambient temperature. The IPCC suggest that temperature may increase by between 1.4 to 5.8C by 2100[61]. Such a temperature increase may interact with different crops to impact the yields, as shown in Table 5.3. Horie et al[62] found that a moderate temperature increase, with a doubling of CO_2, would lead to a 30 percent increase in the rice yield. However, as temperature increase over 26C then yield falls. The impact is variable dependent on crop as well, for soybean Vu et. al.[63] found a 95% increase in net photosynthesis, whilst for wheat the predicted increase from a doubling of CO_2 concentrations ranged from 15 to 29% depending on the underlying conditions.

Climate change and elevated CO_2 levels may have important implications for the quality of crops. A number of impacts have been suggested in the literature, both positive and negative impacts have been predicted. However, in terms of nutrition the evidence presented in the IPCC[61] suggests an overall negative impact on crop quality, with decreased protein, iron and zinc levels resulting from increased levels of ambient $CO_{2.}$

The direct impact of water availability on crop productivity has to be considered alongside the impacts of increases in the level of ambient CO_2 as some complex interactions may be identified. With some crops, like cotton and spring wheat, the impact of CO_2 increases, have been shown to be small. However, in the case of rice, the impact is variable dependent on the temperature. For maize, some studies have shown that a reduction in water use per plant results from increased CO_2 levels[64]. These interactions are complex, and under drought conditions relative enhancement of growth due to increased CO_2 levels may be greater, as increased CO_2 levels mitigate against the impact of the closure of stomata on photosynthesis.

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[61] IPCC(2001a) Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge.

[62] Horie, T., J.T. Baker, H. Nakagawa, and T. Matsui (2000) "Crop ecosystem responses to climate change: rice" in K.R. Reddy and H.F. Hodges (eds.) *Climate Change and Global Crop Productivity*, CAB International, Wallingford, UK.

[63] Vu, J.C.V. , Allen, L.H. Jr, K. J. Boote and G. Bowes (1997) "Effects of elevated CO_2 and temperature on photosynthesis and Rubisco in rice and soybean" *Plant, Cell and Environment*, 20:1 pp68-76.

[64] Samarakoon, A. and R. M. Gifford (1996) "Elevated CO2 effects on water use and growth of maize in wet and drying soil" *Australian Journal of Plant Physiology* Volume 23 pp 53-62

Table 5.3: Impact of CO_2 increase on crop yield

Crop	**Study**	**Assumed CO2 increase**	**Interaction**	**Impact**
Rice	Horie et al (2000)	2xCO2	Moderate temperature increase	30% increase in rice yield but 10% reduction for every degree above 26C
		2xCO2	Extreme temperature increase (above 36.5C)	Negative impact on rice yield
	Vu et al (1997)	2xCO2	Temperature increase over 6C range	55-65% increase in net photosynthesis
Soybean	Vu et al, 1997	2xCO2	Temperature increase 28C to 40C	95% increase in net photosynthesis (linear relationship)
Wheat	Mckee et al, 1997	2xCO2	None	29% increase in grain mass
		2xCO2	Increased O3	Less than 5% increase in grain mass
	Mitchell et al, 1993	2xCO2	Nitrogen variation	15% increase in yield at ambient temperature with high N
		None	Temperature increase by 4C over ambient	19% decrease in yield at high N

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Rosenweig et al[65] examined the issue of how warmer temperatures and an increase in extreme weather events may affect agriculture. They found that extreme weather events have led to significant crop damage in the US. Soil degradation is likely to result from climate change, as changes in windspeeds and rainfall lead to increased erosion. This is likely to have an overall negative impact on agriculture, and will aggravate losses caused by increased temperature in drought-prone areas. Pests and diseases are likely to spread as a result of climate change. These will reduce yields.

Climate change is likely to have a significant impact on water resources through changes in precipitation, evaporation, the level of groundwater resources, changes in river flow and frequency and changes in water quality. Precipitation is very important for agriculture, and climate models predict a number of impacts, varying by region. Carter et al[66] predict an increase in annual precipitation in high and mid latitudes and in most equatorial regions. A general decrease in rainfall is expected in the tropics. However, climate change-induced changes are likely to be small compared with natural variability. Scenarios for the UK suggest an increase in the relative variability of seasonal and annual rainfall totals as a result of climate change. The incidence of heavy rainfall is also likely to increase.

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[65] Rosenweig, C., A. Iglesias, X.B. Yang, P. Epstein and E. Chivian (2000) *Climate Change and US Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases and Pests*, Centre for Health and the Global Environment, Boston.

[66] Carter, T.R., M. Hulme, J.F. Crossley, S. Malyshev, M.G. New, M.E. Schlesinger and H. Tuomenvirta (2000) *Climate Change in the 21st Century - Interim Characterizations based on the New IPCC Emissions Scenarios.* The Finnish Environment 433, Finnish Environment Institute, Helsinki.

5.5.1 Global impacts

Climate change is likely to have impacts on the global yield. Parry et al[67] investigated this using two climate scenarios - HadCM2 and HadCM3. Under HadCM2 scenarios the effects on climate change on crop yields appear to be broadly beneficial whilst HadCM3 scenarios show a general decline in yields. Globally, Parry et al predict a change in cereal production of between -4 and +2 percent and project price increases in cereals of between 13 and 45 percent. However, aggregated regional results hide other, distinct, patterns. For instance, if temperature increases are for more than a few days, it is expected that even high, mid-latitudes will witness adverse effects of climate change on agriculture.

Moreover, the more favourable effects on yield in temperate regions depend to a large extent on full realisation of the potentially beneficial direct effects of CO_2 on crop growth. These regional differences are likely to grow stronger over time, leading to a significant polarisation of effects, with beneficial effects on yields occurring in the developed world and negative effects in the developing world (excluding China). Decreases in potential crop yields are likely to be caused largely by shortening of the crop growing period, and decreases in water availability due to higher rates of evaporation.

The key uncertainties identified in Parry et al[67] that affect the results are:

- Climate change at the regional level
- Effects of future technological change on agricultural productivity
- Potential realisation of any benefits from the CO_2 fertilisation effect
- Water availability for irrigation in future
- Trends in demand and the wide array of possible adaptations.

Rosenweig and Iglesias[68] investigated the global impact on rice, wheat, maize and soybean. They found that as temperature increases become larger, the beneficial effects on yields - caused by elevated CO_2 - are outweighed by negative effects - brought about by higher evaporation rates and water deficiencies). It is also clear that if the modelling allows transient adjustment to a changing climate, the yield decreases are not as great as under a 2 X CO_2 stabilization scenario. The best performing crop was soybean, with yield changes of between -4 and +23 percent depending on the scenario considered.

Darwin[69] investigates the impact of climate change scenarios on GDP when cropland expansions are and are not allowed. When cropland expansion is allowed, world GDP increase or decreases depending on the scenario. The size of the impacts are relatively small, ranging from about -0.1 to +0.1 percent of 1990 GDP. World economic welfare appears to increase at relatively low levels of climate change and to decrease at higher levels.

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[67] Parry, M., C. Rosenzweig, A. Iglesias, G. Fischer and M. Livermore (1999) Climate Change and world food security: a new assessment. Global Environmental Change 9, 51-67

[68] Rosenzweig, C. and A. Iglesias (1998) The use of crop models for international climate change impct assessment. In: Understading Options for Agricultural Production, Tsuji, G.Y., G.Hoogrnboom, and P.K. Thorton (eds.) J.Kluwer Academic Publishers, Dortrecht, The Netherlands, 267-292.

[69] Darwin, R. (1999) "A farmer's view of the Ricardian approach to measuring agricultural effects of climatic change" *Climatic Change* 41:371-411.

The impact of climate change on yields in different regions and the resultant price shock was investigated by Winters et al[70]. The results are shown in Table 5.4 below. As can be seen from the table, significant impacts on both crop yield and price are predicted, with yield impacts for major crops decreasing in all cases bar three - cocoa in Africa and soybean in Africa and Latin America. Impacts on price vary from -42 percent for tobacco to +24.7 percent for tea. These indicate significant impacts on commodity markets as a result of climate change, and Winters et al suggest that these may have a negative impact on GDP per capita in these areas of between -1.6 percent and -6.5 percent when both impacts on prices and yields are taken into account.

Table 5.4: Yield and Price changes as a result of climate change

Crop type	Scenario: GISS			
	Crop yield change (%)			World Price shock (%)
Food crops	Africa	Latin America	Asia	
Maize	-23	-19.9	-33.8	1.3
Rice	0	-15.5	-12.2	24.2
Wheat	-15	-28.7	-18.5	-21.8
Coarse grains	-25	-21.4	-34.1	-6.7
Soybeans	8	11.6	-8.9	-20.3
Cash crops				
Cotton	-3	-11.6	-16.8	-22.2
Tobacco	0	-10.9	-10.5	-42
Sugar	-12	-17.4	-17.8	14.5
Oilseeds	-1	-10.1	-7.8	-22.8
Coffee	-5	-6	-9	16.7
Cocoa	7	0	0	-12
Tea	-5	-5.7	-9	24.7
Bananas	-3	-7.3	-8.6	16.1

Source: Winters et al (1999)

5.5.2 Regional impacts

As shown above, climate change is likely to have a varying impact on agriculture depending on the region being considered. For Europe the main impacts shown in the literature include impacts of increased CO_2 on crops, which were investigated by the EC CLAIRE project. Their findings were that for the four crops considered the yields were likely to increase: grapevine (+23%), onion (+24%), sugar beet (+34%) and wheat (+25%). Quality impacts appear to be crop-specific. For instance, the quality of grapes is found to be positively affected by increased CO_2 concentration in the middle of the ripening season by 8 - 10%, though at maturity stage the quality effect almost completely disappears. Other factors such as temperature increase, water availability and pests may also impact on the yields of crops.

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[70] Winters, P., R. Murgai, A. de Janvry, E. Sadoulet, and G. Frisvold (1999) "Climate change and agriculture: effects on developing countries" in Frisvold and Kuhn (eds) *Global Environmental Change and Agriculture*, Edward Elgar, Cheltenham.

A summary of the main regional impacts is provided below:

Northern Europe

- The growth of spring cereals is likely to be enhanced
- Cultivation of high-yielding autumn sown crops can be expected to increase, and a longer growing season may enable cultivation of higher yielding cultivars.
- The zones of suitability for crop species will expand northwards, including zones of crops not currently grown.
- Existing pests, diseases and weeds are likely to become more abundant and currently exotic species may appear.
- The need for plant protection will grow and the use of pesticides and fungicides may increase.
- The breakdown of soil organic matter will accelerate, increasing problems of maintaining good soil structure.
- On balance, the overall impact on crop yields in the northern countries is likely to be beneficial.

Southern Europe

- The combined increase in temperature and the decrease in precipitation during summer may enhance the problem of water shortage
- Increases in climatic inter annual variability and extreme events may affect crop production
- No area may become unsuitable for agricultural production though a reduction of suitable areas is predicted. These constraints may be overcome by the introduction of new crops.

North America

For North America the main predictions are as follows:

- Food production is projected to benefit from a warmer climate, but there will probably be strong regional effects.
- There is potential for increased drought in the U.S. Great Plains/Canadian Prairies and opportunities for a limited northward shift in production areas in Canada.
- The negative effects of climate change on agriculture in North America are probably over-estimated where behavioural, economic and institutional adjustments are not considered.
- Fischer et al[71] estimate +6 to +9% increases in cereal production in North America as a consequence of climate change.
- Including the direct physiological effects of CO_2 has a significant effect on the net impact estimated from climate change.

Asia

For Asia the main predictions are as follows:

- In Japan enhanced CO_2 in a warmer atmosphere will substantially increase rice yields and yield stability in northern and north-west Japan. In south central and south-western Japan, however, rice yields are expected to decline by at least 30% because of spikelet sterility and shorter rice growing duration[72]

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[71] Fischer, G., M. Shah and H. van Velthuizen (2002) *Climate Change and Agricultural Vulnerability*. Vienna: IAASA.

[72] Matsui T. and T. Horie, (1992) Effects of elevated and high temperature on growth and yield of rice part 2: sensitive period and pollen germination rate in high temperature steriliy of rice spikelets at flowering. Japan Journal of Crop Science, 61, 148-149.

- Wheat yield should increase in north-east China though because of an increase in respiration in a warmer atmosphere demanding water available, rice yield is likely to decline in China as a whole.
- In central and northern China, high temperatures during teaseling and drawing stages and lower soil moisture could result in reduced wheat yield.
- In tropical Asia, although wheat crops are likely to be sensitive to an increase in maximum temperature, rice crops would be vulnerable to an increase in minimum temperatures.
- In India, the adverse impacts of likely water shortage on wheat productivity may be minimised as a result of CO_2 elevation, the adverse effect of water shortage will be maintained for rice, resulting in a net decline in rice yields.
- The growth, reproduction, and spread of disease bacteria depend on air humidity; some diseases will become more widespread in temperate and tropical regions of Asia if the climate becomes warmer and wetter.
- Damage from diseases may be more serious because heat-stress conditions will weaken the disease resistance of host plants and provide pathogenic bacteria with more favourable growing conditions.

Africa

- Studies for Africa for instance show there may be significant impacts on crop yields as a result of climate change. Table 5.5 below shows that the impacts vary by crop - and adaptation may reduce the impacts. However, the impact on crops is generally negative, and Winters et al[73], as already mentioned above, suggest that agricultural prices may increase dramatically as a result of climate induced changes in supply.

Table 5.5: Impact of Climate Change on Crops in Africa

Study	Region	Crop	Climate Scenario	Yield impact no adaptation	Yield impact with adaptation	Socioeconomic impact
Winters et ak (1999)	Africa	Maize	GISS, GFDL, UKMO	na	-29 to -23%	Total agricultural production -13 to -9%, GDP per capita -10 to -7%, agricultural prices -9 to +56%
		Rice		na	0%	
		Wheat		na	-20 to -15%	
		Coarse grains		na	-30 to -25%	
		Soy bean		na	-2 to +10%	
		Cash crops		na	-10 to -4%	
Yates and Strzepek (1998)	Egypt	Wheat	GFDL and UKMO 2*CO2 equilibrium scenarios, GISS-A transient scenario at 2*CO2	-51 to -5%	-25 to -3%	Change in trade balance: -15 to +36%
		Rice		-27 to -5%	-13 to -3%	
		Maize		-30 to -17%	-15 to -8%	
		Soy bean		-21 to -1%	-10 to 0%	
		Fruit		-21 to -3%	-10 to-2%	
Smith et al (1996a)	The Gambia	Maize	CCC, GFDL, GISS	-26 to -15%	na	
		Millet-early		-44 to-29%	na	
		Millet-late		-21 to -14%	na	
		Groundnuts		+40 to +52%	na	
	Zimbabwe	Maize	CCC, GFDL	-14 to -12%	na	

Source: Based on IPCC (2001a)

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[73] Winters, P., R. Murgai, A. de Janvry, E. Sadoulet, and G. Frisvold (1999) "Climate change and agriculture: effects on developing countries" in Frisvold and Kuhn (eds) *Global Environmental Change and Agriculture*, Edward Elgar, Cheltenham.

Impacts on livestock in Africa may have cultural and economic costs. The following impacts on livestock can be predicted:

- As water supply reduces there will be directly proportional impacts in the livestock population
- As soil nutrient level increases due to increased CO_2 concentration then animal numbers may increase, offsetting negative impacts of water supply - Scholes et al[74] show a balancing of these two effects in Southern Africa
- Animal productivity is limited by protein (nitrogen) content of fodder. Increased CO_2 concentrations will decrease the carbon-to-nitrogen ratio of forage, though this may not impact on the palatability of the fodder as this represents increased starch content.
- In high altitude and latitude regions of Africa, death of livestock is caused by low temperatures. Thus as the frequency of cold periods fall, so livestock productivity will increase.
- Vector borne diseases such as trypanosomiasis may extend their distribution. For example the tsetse fly is predicted to extend its distribution within Africa.

Latin America

- Impacts in Latin America are similar to those shown in other continents. Crop yield is predicted to change as a result of climate change, though this varies depending on the location and the crop in question. Studies to date have shown that yields of wheat are expected to decrease, with a range of -50 to -5 percent depending on location. For maize the impact is likely to be positive in some regions (e.g. Chile) but negative in others (Argentina, Brazil), the forecast range is from -61 to +2 percent of yield. For soybean the range of impact varies from -22 to + 40 percent depending on region, with Brazil more likely to gain than Argentina.
- In terms of livestock, climate change is likely to have an impact on both the quantity and quality of produce - and both are predicted by country and by regions within countries. In Argentina, for example, alfalfa is used as feed alongside other forage crops. A temperature increase of $1^{o}C$ on this crop is anticipated to vary by region, with the crop yield in the area north of 36^{o} degrees South decreasing by 16 to 25 percent and that in the south increasing by 50 to 100 percent. The average impact will be between 4 to 8%. This will clearly have differential impacts on livestock production[75].

Australia and New Zealand

- For Australia various impacts have been identified in the literature. Howden et. al[76] estimated the increase in wheat yield resulting from a doubling of actual atmospheric CO_2 at 24%. Impacts are also predicted on grain quality, with protein content expected to fall by between 4 to 14 percent without additional nitrogen-based fertilisers. This is predicted to lead to an increase in gross margins

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[74] Scholes, R.J., G. Midgeley, and S. Wand (2000) "The impacts of climate change on South African rangelands" in *South African Country Studies on Climate Change*. Department of Environmental Affairs and Tourism, Pretoria

[75] Magrin, G. et al (1997b) *Proyecto de Estudio sobre el Cambio Climatico en Argentina*. Secretaria de Ciencia y Tecnologia, Buones Aires.

[76] Howden, S., P. Reyenga, H. Meinke and G. M. Mckeon (1999) "Integrated Global Change Impact Assessment on Australian Terrestrial Ecosystems: Overview Report" Working Paper 99/14 CSIRO, Canberra.

(assuming constant prices- a questionable assumption) of between 28 percent and 95 percent. Livestock in Australia is also likely to be impacted as increases in CO_2 concentrations, coupled with warmer conditions, are predicted to lengthen the growing season of pasture - thus having a potential to increase the weight of livestock. However, forage quality is predicted to decrease and increased heat stress of livestock is forecast. These two factors may mitigate against gains resulting from increased growth of pasture[76].

- For New Zealand, it is predicted that drier conditions will have an important impact on cereals, particularly in the Canterbury region. For maize production, rising temperatures may reduce the risk of growing this crop in the south, though water shortages in Canterbury[77].

5.6 Summary

This section reviews the principal factors that are thought to influence the effect of climate change on agriculture. These factors include:

- photosynthetic effects of elevated CO_2 on crops, which tend to raise crop yield
- temperature effects on crop growth which appear to raise yield, and then decrease yield beyond a certain temperature increase
- changes in rainfall patterns affecting water availability for crops and livestock, with less rainfall tending to lead to falls in yield, and
- climate variability.

In addition, weeds, pests and diseases may be affected by changes in climate though in this case the evidence of net effect on yields is unclear. The human response to these factors (e.g. by changing crops) may then determine the extent of these various effects. Clearly, the greater are the possibilities for adaptation, the higher are likely to be the net benefits, and the lower are the net negative effects.

The range of impacts identified is very wide and it has led IPCC[78] to draw a single conclusion: that, with very low confidence in its robustness, a global temperature rise of greater than 2.5°C is likely to exceed the capacity of the global food production system to adapt without price increases. However, results are judged to be too mixed to support a defensible conclusion regarding the vulnerability of the global balance of agricultural supply and demand to smaller amounts of warming than 2.5°C

Different crops are expected to face different impacts. For certain crops, e.g. rice and wheat, the predicted impact ranges from a strongly negative impact in some regions of the world to a positive impact in other regions, depending on the conditions under consideration. For soybeans, the projected impact ranges from negative in some parts of the world to positive in others - and the overall impact may be expected to be positive.

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[77] IPCC(2001a) *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge

[78] IPCC(2001a) *Climate Change 2001: Impacts, Adaptation and Vulnerability.* Cambridge University Press, Cambridge

The impact on prices of climate change has been estimated in two studies. Winters et al[79] predicted increases in price are projected for tea(24.7%), rice(24.2%), coffee(16.7%), bananas(16.1%), sugar(14.5%) and maize(1.3%). The same study suggested there would be decreases in price are projected for tobacco(-42%), oilseeds(-22.8%), cotton(-22.2%), wheat(-21.8%), soybeans(-20.3%), cocoa(-12%) and coarse grains(-6.7%). Parry et al[80] predict an increase in the price of cereals of between 13 and 45 percent. There are considerable uncertainties in these estimates, particularly when non-climate related factors are taken into account.

It is clear, when looking at these results, that they are highly sensitive to alternative climate model inputs, reflecting the wide range of yield impacts that have been estimated from crop models. In addition the limited sensitivity analyses that have been performed suggest that uncertainties in economic models alone are large and further imply that the economic impacts of climate change on agriculture are given low confidence. Further sensitivity analyses need to be taken to determine key assumptions and parameters and focus quantitative uncertainty analysis on those dimensions of the models before this confidence rating in the model results can be improved.

Improvements in the modelling of adaptive responses to climate change may also lead to better estimates of the impacts of climate change on agriculture. Strategies that could impact on the outcome include:

- Research and development into crops that will have better yields under changed climatic conditions;
- Sowing crops earlier in the year to maximise yield gain;
- Changing fertilising strategy to adapt to changing ambient CO_2 levels; and
- Investment in irrigation infrastructure to ensure water supply for crops, amongst others.

The use of agriculture as a source of sinks under the Bonn Agreement may also have important short term implications for agriculture in the developing world, notably in terms of changing incentives for cropland management, grazing land management and re-vegetation.

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[79] Winters, P., R. Murgai, A. de Janvry, E. Sadoulet, and G. Frisvold (1999) "Climate change and agriculture: effects on developing countries" in Frisvold and Kuhn (eds) *Global Environmental Change and Agriculture*, Edward Elgar, Cheltenham.

[80] Parry, M., C. Rosenzweig, A. Iglesias, G. Fischer and M. Livermore (1999) Climate Change and world food security: a new assessment. Global Environmental Change 9, 51-67.

5.7 Flooding

Flooding in the UK has been considered in this report in the previous section. This section reviews information on the impact of climate change of flooding in Europe.

Flood events can take many forms, including slow-onset riverine floods, rapid-onset flash floods, accumulation of rainwater in poorly-drained environments, and coastal floods caused by tidal and wave extremes, sometimes referred to as storm surges. Rising temperatures brought about by climate change have a direct impact on rising sea levels causing coastal flooding. The current thinking also indicates that climate change will cause an increase in rainfall intensity and changes in precipitation patterns that will lead to greater risk of floods. Although there is still uncertainty as to the extent of the impacts there are, however, a number of findings that have concluded that events such as major river floods could indeed become more frequent. This is summarized in table 5.6.

Table 5.6

A collection of views showing current thinking as regards changes in climate patterns on floods	
A general increase in mean precipitation between 30oN and 70oN has been observed. Mean precipitation has increased over northern Europe and decreased over southern Europe. Rainstorm intensity has increased over the past decades.	P. Vellinga and W. J. van Verseveld, Climate Change and extreme Weather events, WWF, September 2000) and (Groisman et al., 1999).
Changes in mean precipitation are associated with disproportionately large changes in the extremes. The increase in the probability of heavy precipitation is four times the increase in mean precipitation.	Groisman at al., Changes in the Probability of Heavy Precipitation: Important Indicators of Climate Change, Climatic Change, 42, 1999) and (Chris Folland et al. 2002)
There is a significant trend in the temperature difference between the lower and upper troposphere, globally and over North America, Europe and Australia. There is a 60%– 90% chance that the frequency of heavy precipitation events has increased by 2 to 4% over the past 50 years.	Folland et al., Observed climate variability and change, Weather, Royal Met Society, 2002
The above points led the IPCC work group II to release following statements: It is very likely (90%– 99% chance) that there will be an increase in flood and flood runoff, landslide and avalanche. There is a medium to high confidence that river flood hazard will increase across much of Europe.	Summary for Policymakers, Climate Change 2001: Impacts, Adaption and Vulnerability, Working Group II, IPCC
There has been an increase in the number and duration of westerly cyclonic circulation types over the past 100 years. This circulation type is most likely to cause heavy precipitation events.	G. Tetzlaff, Institute of Meteorology, PIK report no. 17, University Leipzig
Total summer time precipitation amounts will be substantially reduced over major parts of Southern and central Europe. However, intensive rain events - like those leading to the flooding in the Moldova, Danube, Elbe and Rhone in 2002 - will become more frequent and even more intensive.	Prudence: Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects

Source: Partner Re. 2002. Floods – Causes, Effects and Risk assessment and Prudence work.http://prudence.dmi.dk/

Climate change studies typically study the likely change in global temperatures over the coming decades, whereas river flood hazard is related to exceptional levels of rainfall in the catchment of one or more river basins. The exact link between rising temperature and enhanced levels of rainfall is difficult to quantify, and even more complex is to determine any increase in likelihood of extreme rainfall events (as opposed to annual mean values). In addition, generalisations are difficult, especially since the characteristics and response to rainfall of a river system vary per river basin according to factors such as topography, land use, types of precipitation, geology, local climate etc.

However it is clear from recent work and reported studies that we are seeing an increase in the costs of these types of events. Swiss Re estimated economic losses caused by floods amounted to $61 billion for the period from 1995 to 2004 (all losses inflated to 2005 prices). Since only the larger events are monitored in the Sigma database, and during this period there were no losses attributable to storm surge, the total amount is certainly higher.

The European 2002 floods caused an economic loss of €15 billion for Germany alone[81]. Approximately 20% of this was insured, two-thirds of which was then reinsured internationally. The economic loss in the Czech Republic has been estimated at up to 90 billion Crowns (€3 billion), approximately 30% higher than in 1997. The insurance loss is believed to be in the region of €800 million. In Austria, economic loss estimates stand in excess of €5 billion (€3 billion private; €2 billion commercial)[81].

Large river basin floods develop over huge areas following weeks of unusually high rainfall. In July and August 1997, flooding in central Europe caused 54 fatalities in Poland and required the evacuation of 162,000 people. The value of the economic losses throughout central Europe amounted to approximately US$5 billion, with insured losses of US$940 million.[82]

In France the 2003 summer heat wave was followed by severe flash floods in December, causing total losses of around US$1.5 billion (including insured loss of US$ 0.9 billion)[83].

Socio economic factors such as increased wealth, building alongside rivers, in flood plains and increased urbanisation also play a large part in contributing to the costs of flooding. Growing human vulnerability to flood events, combined with the uncertainties of climate change, should give cause for concern.

Catastrophic floods can create huge losses, which could potential exceed the insurance industry's ability to pay. Partner Re in 2002 showed that predicted potential insured losses from European floods to be as high as US$ 20 billion.[84] Pressures on capital requirements are more likely to arise through increases in the costs of flooding. This is discussed further in the following section.

There has been limited academic work that has been carried out to attempt to quantify the potential impact of climate change on river flood hazard in Europe. One such study has been carried out for the Rhine River as part of the Dutch funded

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[81] Partner Re. 2002. Floods – Causes, Effects and Risk assessment

[82] Insurance and other Financial Services. Pier Vellinga and Evan Mills

[83] Natural Catastrophes and man made disasters in 2003. Swiss Re Sigma Report no. 1/2004

[84] Partner re, 2002. Floods – Causes, Effects and Risk assessment

project ADAPT. Although specific to the Rhine, the conclusions of this report may apply more generally across Europe.

5.8 Case study: River Rhine

As part of the Dutch funded project ADAPT, the River Rhine has been analysed as a case study. One of the main objectives was to compare historic weather data with SRES climate change projections for the periods 2010-2039 and 2070-2099 and adjust, if necessary, SRES projections. A summary of the key findings from this work is outlined below.[85]

The Climate change scenarios that were run indicated that there would be a decrease in summer discharge and an increase in winter discharge. Figure 5.3 shows the change in precipitation patterns up to 2099. There is a projected increase in the frequency of extreme events in the variability bands around the mean run off in the projected periods.

The results of the simulations show a clear increase in both frequency and magnitude of the high water situations. Overall, an increased frequency of more severe droughts and flood events is to be expected as a result of the climate change scenarios. The study stated that the results are in accordance with earlier results obtained with the RHINEFLOW models for slightly different scenarios.[85]

In general the annual discharge regime of the River Rhine is expected to alter as a result of climate change. During wintertime, discharges are likely to increase and in summer time a decrease in river flows is expected. An increase in rainfall during periods when soils are saturated (i.e. winter and spring), along with earlier snowmelt, could increase the frequency and severity of floods. An increase in large-scale precipitation might lead to increased flood risks in winter. The increased temperatures expected in summer could lead to higher local precipitation extremes and associated flood risks in small catchment areas.

Currently, the estimated cost of at risk stock is estimated to be at €1,500 billion within the flood risk prone areas. If winter discharges increase significant adaptation actions will be needed. The impacts and effects of extreme peak flows can be enormous. Inundations with subsequent damages and losses will occur along river stretches where design criteria for flood protection are exceeded. Further research is required into the actual costs that will be associated with these flooding events.

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[85] Water, climate, food and environment in the Rhine Basin, contribution to ADAPT Project, Han Klein, Klaas Jan Douben, Willem van Deursen, Erik de Ruyter van Steveninck as part of Netherlands Climate Change Studies Assistance Programme (NCCSAP). Delft Hydraulics March 2005 http://www.falw.vu.nl/Onderzoeksinstituten/index.cfm?home_file.cfm?fileid=0F213F3D-AA60-4C81-A755BAC7895E046E&subsectionid=602C4835-C246-41FA-8DD706E7084B0D06

Figure 5.3 Change in precipitation patterns up to 2099 Source: Adapts project

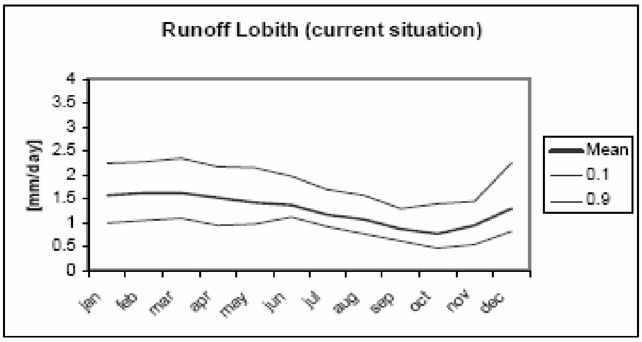

Figure 28 Mean runoff at Lobith (current situation)

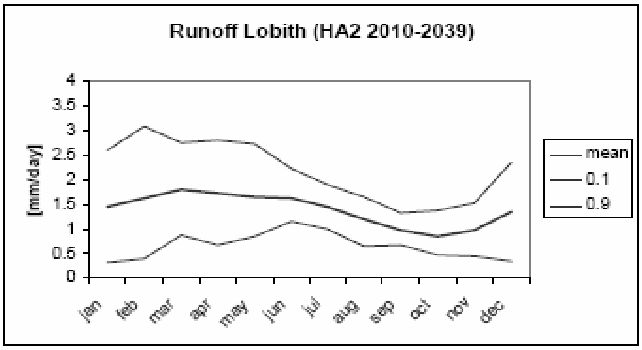

Figure 29 Scenario runoff at Lobith (SRES HA-2 scenario, 2010-2039)

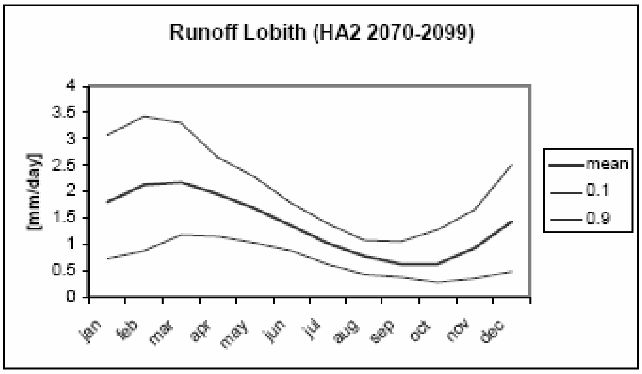

Figure 30 Scenario runoff at Lobith (SRES HA-2 scenario, 2070-2099)

5.9 Summary

Aside from the debate as to whether climate change can or cannot cause enhanced flood severities and frequencies, from a monetary damage perspective, several other factors must be considered.

Firstly, the damage caused by a flood relates to the area inundated. For flood events, not only does this relate to the severity of the event, but also to the extent to which human intervention can mitigate the effects of a flood. Hence even if it can be established that climate change is causing an increasing tendency for extreme discharges in river systems, the resultant effect on damage/loss may be reduced if adequate flood defence measures are put in place.

Recent events do prove, however, that flood losses have increased during recent years. There are many potential reasons for this. Monetary loss resulting from flooding depends on the values of the properties affected, and property prices are steadily increasing across Europe. In addition, in many countries, there is increasing pressure on governments to build in flood plain areas due to lack of building space elsewhere. Growing human vulnerability to flood events, combined with the uncertainties of climate change, should give cause for concern.

Flood events are currently, the second most costly weather related catastrophes after storms. Further research is needed on the science and also to quantify the cost of climate change on these events. This will enable further modeling to assist insurers to understand the financial costs of these events.

5.10 Sea level rise

One area that has been researched in recent years is that of the impacts of sea level rise.

Nicholls[86] presents an overview of the likely impacts due to sea level rise. Table 5.6 below presents a summary of the aggregated results from various country studies, showing the capital values and protection costs. The estimated total loss amounts to US$1,146,310 million – with the worst impacted being Japan ($849,000 million). In terms of impact relative to GNP, Guyana fairs worst with 11 times its annual GNP in estimated capital losses.

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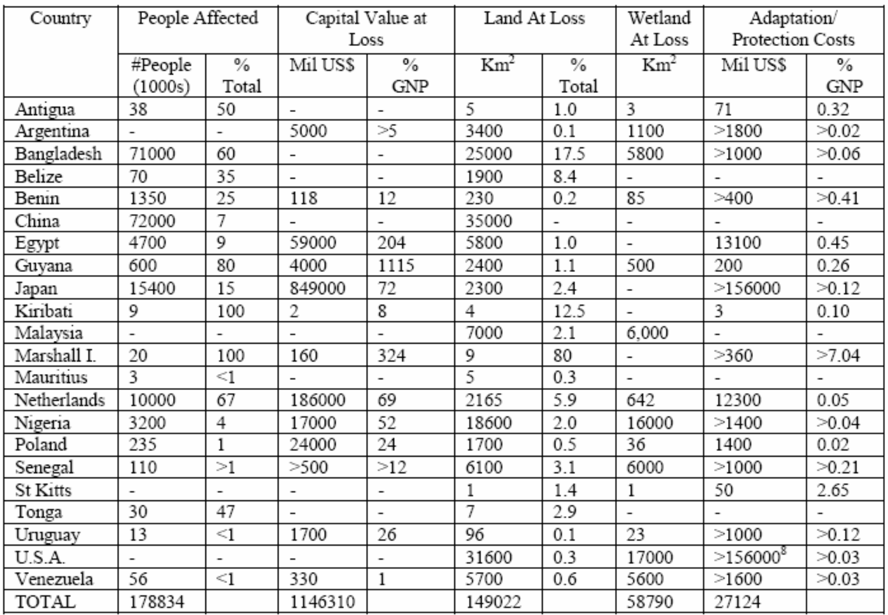
[86] Nicholls, R. (2003) "Case study on sea-level rise impacts", OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers, ENV/EPOC/GSP(2003)9/FINAL, OECD: Paris.

Table 5.6 **Aggregated results of country studies**



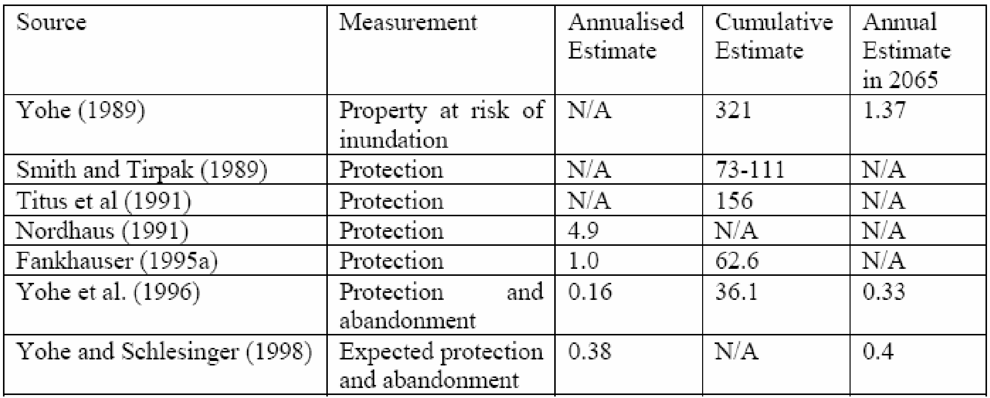
Country	People Affected		Capital Value at Loss		Land At Loss		Wetland At Loss	Adaptation/ Protection Costs	
	#People (1000s)	% Total	Mil US$	% GNP	Km^2	% Total	Km^2	Mil US$	% GNP
Antigua	38	50	-	-	5	1.0	3	71	0.32
Argentina	-	-	5000	>5	3400	0.1	1100	>1800	>0.02
Bangladesh	71000	60	-	-	25000	17.5	5800	>1000	>0.06
Belize	70	35	-	-	1900	8.4	-	-	-
Benin	1350	25	118	12	230	0.2	85	>400	>0.41
China	72000	7	-	-	35000	-	-	-	-
Egypt	4700	9	59000	204	5800	1.0	-	13100	0.45
Guyana	600	80	4000	1115	2400	1.1	500	200	0.26
Japan	15400	15	849000	72	2300	2.4	-	>156000	>0.12
Kiribati	9	100	2	8	4	12.5	-	3	0.10
Malaysia	-	-	-	-	7000	2.1	6,000	-	-
Marshall I.	20	100	160	324	9	80	-	>360	>7.04
Mauritius	3	<1	-	-	5	0.3	-	-	-
Netherlands	10000	67	186000	69	2165	5.9	642	12300	0.05
Nigeria	3200	4	17000	52	18600	2.0	16000	>1400	>0.04
Poland	235	1	24000	24	1700	0.5	36	1400	0.02
Senegal	110	>1	>500	>12	6100	3.1	6000	>1000	>0.21
St Kitts	-	-	-	-	1	1.4	1	50	2.65
Tonga	30	47	-	-	7	2.9	-	-	-
Uruguay	13	<1	1700	26	96	0.1	23	>1000	>0.12
U.S.A.	-	-	-	-	31600	0.3	17000	>156000[8]	>0.03
Venezuela	56	<1	330	1	5700	0.6	5600	>1600	>0.03
TOTAL	178834		1146310		149022		58790	27124	

Notes: Assuming Existing Development and a 1-m Rise in Sea level. All impacts assumed no adaptation, while adaptation assumes protection, except in areas of low population density. Costs are 1990 US$

Source: Bijlsma et al. (1996)

For the case of the United States of America, Table 5.7 presents an overview of recent studies[44]. Estimates of annual damages in 2065 range from $0.33bn to $1.37bn, with more recent estimates being at the conservative end of the scale.

Table 5.7 **Potential cost of sea-level rise along the developed coastline of the United States (billions of 1990 dollars)**



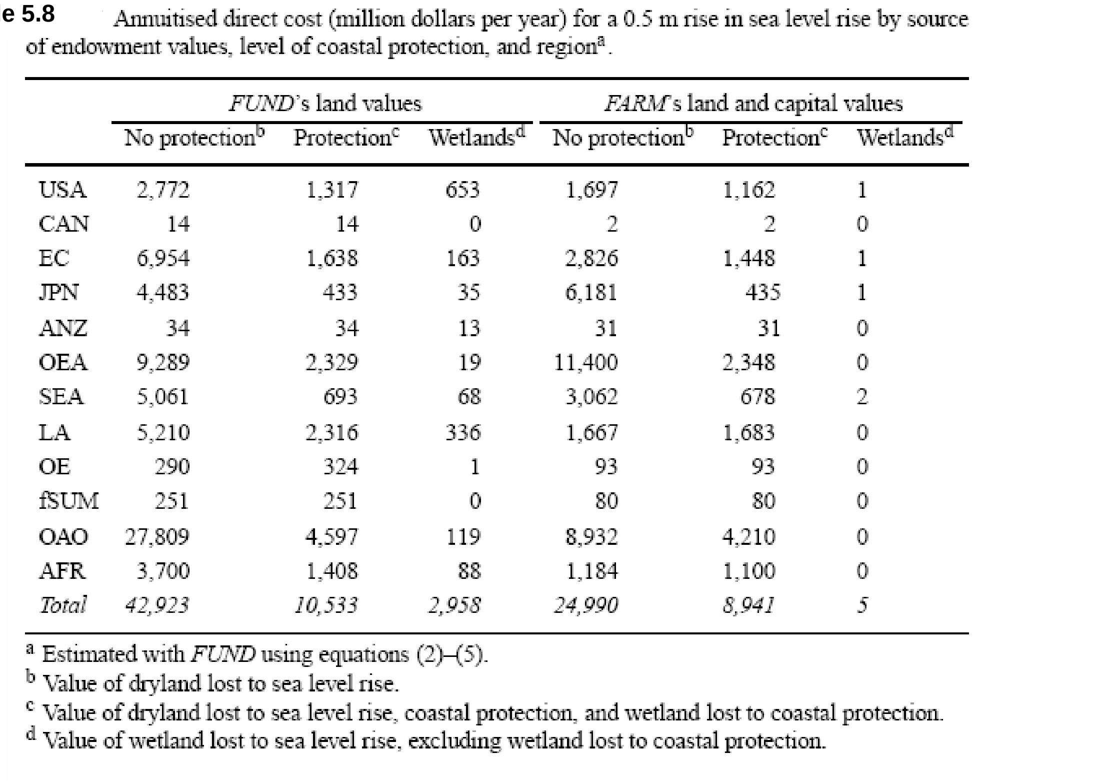
Source	Measurement	Annualised Estimate	Cumulative Estimate	Annual Estimate in 2065
Yohe (1989)	Property at risk of inundation	N/A	321	1.37
Smith and Tirpak (1989)	Protection	N/A	73-111	N/A
Titus et al (1991)	Protection	N/A	156	N/A
Nordhaus (1991)	Protection	4.9	N/A	N/A
Fankhauser (1995a)	Protection	1.0	62.6	N/A
Yohe et al. (1996)	Protection and abandonment	0.16	36.1	0.33
Yohe and Schlesinger (1998)	Expected protection and abandonment	0.38	N/A	0.4

Notes: For a 1-m Global Sea-Level Rise

Source: Adapted from Neumann et al. (2001)

Costs for the impacts of sea level rise have been estimated by Darwin and Tol[87]. The results are presented below in table 5.8 for various regions. It can be seen that the results depend on the values used for land and capital. Total damages range between $24bn to $42bn annually, where there is no protection assumed. The role of adaptation is shown by the impact of introducing protection, which lowers these impact estimates to $8bn and $10bn respectively.

Table 5.8



Annuitised direct cost (million dollars per year) for a 0.5 m rise in sea level rise by source of endowment values, level of coastal protection, and region[a].

	FUND's land values			*FARM*'s land and capital values		
	No protection[b]	Protection[c]	Wetlands[d]	No protection[b]	Protection[c]	Wetlands[d]
USA	2,772	1,317	653	1,697	1,162	1
CAN	14	14	0	2	2	0
EC	6,954	1,638	163	2,826	1,448	1
JPN	4,483	433	35	6,181	435	1
ANZ	34	34	13	31	31	0
OEA	9,289	2,329	19	11,400	2,348	0
SEA	5,061	693	68	3,062	678	2
LA	5,210	2,316	336	1,667	1,683	0
OE	290	324	1	93	93	0
fSUM	251	251	0	80	80	0
OAO	27,809	4,597	119	8,932	4,210	0
AFR	3,700	1,408	88	1,184	1,100	0
Total	*42,923*	*10,533*	*2,958*	*24,990*	*8,941*	*5*

[a] Estimated with *FUND* using equations (2)–(5).
[b] Value of dryland lost to sea level rise.
[c] Value of dryland lost to sea level rise, coastal protection, and wetland lost to coastal protection.
[d] Value of wetland lost to sea level rise, excluding wetland lost to coastal protection.

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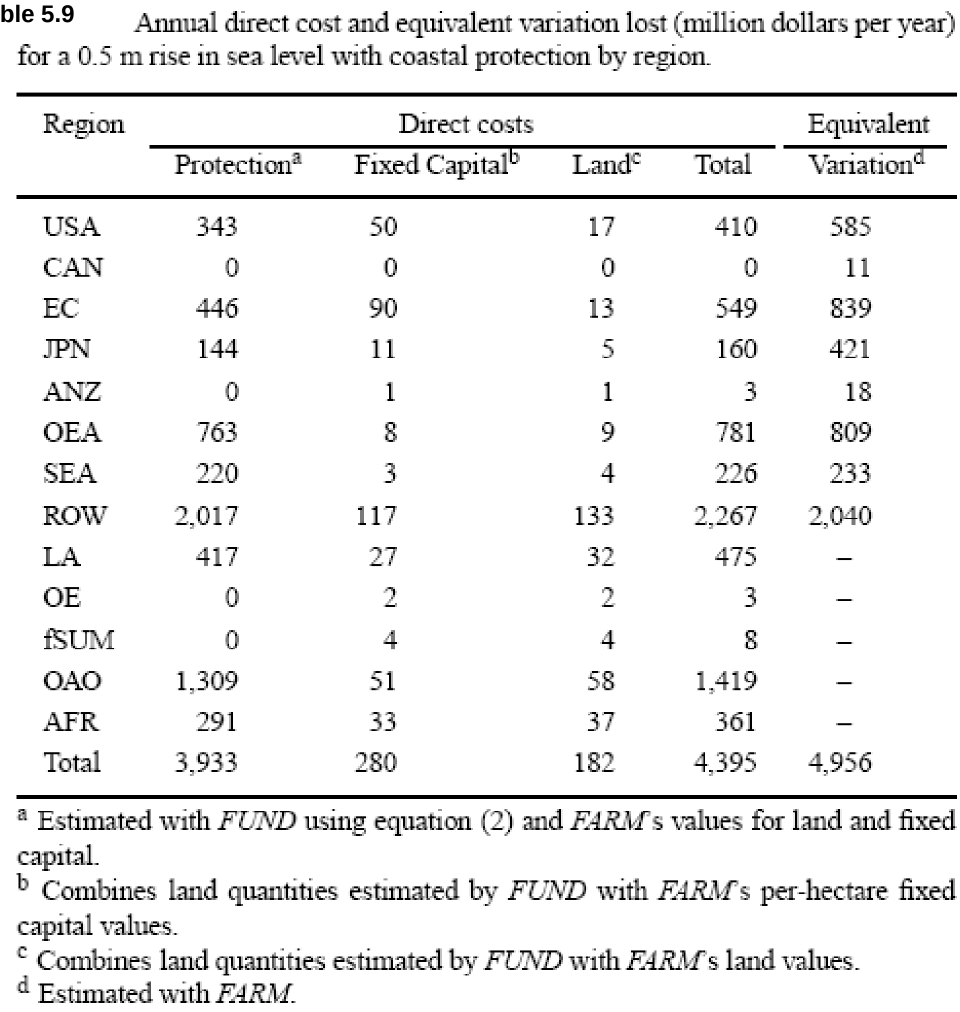
[87] Darwin, R. and R. Tol (2001), 'Estimates of the Economic Effects of Sea Level Rise', Environmental and Resource Economics, 19 (2), 113-129.

The breakdown of the welfare cost is reflected in Table 5.9. The direct cost may be around $4bn and the equivalent variation lost around $5bn. The largest OECD impacts are in the EU, where $1.4bn are lost annually.

Table 5.9



Annual direct cost and equivalent variation lost (million dollars per year) for a 0.5 m rise in sea level with coastal protection by region.

Region	Direct costs				Equivalent
	Protection[a]	Fixed Capital[b]	Land[c]	Total	Variation[d]
USA	343	50	17	410	585
CAN	0	0	0	0	11
EC	446	90	13	549	839
JPN	144	11	5	160	421
ANZ	0	1	1	3	18
OEA	763	8	9	781	809
SEA	220	3	4	226	233
ROW	2,017	117	133	2,267	2,040
LA	417	27	32	475	–
OE	0	2	2	3	–
fSUM	0	4	4	8	–
OAO	1,309	51	58	1,419	–
AFR	291	33	37	361	–
Total	3,933	280	182	4,395	4,956

[a] Estimated with *FUND* using equation (2) and *FARM*'s values for land and fixed capital.
[b] Combines land quantities estimated by *FUND* with *FARM*'s per-hectare fixed capital values.
[c] Combines land quantities estimated by *FUND* with *FARM*'s land values.
[d] Estimated with *FARM*.

5.11 Storm surge

Storm surge is another area, which will be effected by climate change. Windstorms generate storm surges that result in coastal flooding and tidal waves. Nicholls[88] summarises storm surges as follows:

"Surges are changes in sea level (either positive or negative) resulting from variations in atmospheric pressure and associated winds. They are additional to normal tides and when added to high tides they can cause extreme water levels and flooding: flooding would be most severe when a surge coincided with spring tides. Surges are most commonly produced by the passage of atmospheric tropical or extra-tropical depressions… Surges can reach 2 to 3 m as they did in the storm surge of 31 January/1 February 1953 when over 300 people lost their lives in the United Kingdom [add web site] and nearly 2,000 people were killed in the Netherlands (Smith and Ward, 1998)"

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[88] Nicholls, R. (2003) "Case study on sea-level rise impacts", OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers, ENV/EPOC/GSP(2003)9/FINAL, OECD: Paris.

Vulnerability to storm surges is a fact of life for over 200 million people globally, with the bulk living in South, East and South East Asia. Nicholls[88] estimates that 60% of those vulnerable are in these areas and that approximately 90% of those affected by flooding are from these areas.

Dawson et al[89] presents an estimate of £150 billion for a global mean sea level rise of 5-6m combined with a 1 in 1000 year storm surge event for the impact on properties protected by the Thames Barrier.

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[89] Dawson, R., J. Hall, P. Bates and R. Nicholls (undated) "Quantified Analysis of the Probability of Flooding in the Thames Estuary under imaginable worst-case sea-level rise scenarios".
Available online at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/annex5.pdf.

6.0 Financial implications of climate change

6.1 Introduction

Insurance is one of the main mechanisms used by individuals and business to manage risks, including the threat posed by natural hazards such as windstorms and floods. Insurance markets work by pooling risks across a large and diverse population. Each individual or business protects themselves against an uncertain loss by paying a "price" (an annual premium) for a pro rata share of the pool's expected losses. The premiums are held by the insurer in a fund, which is used, along with investment income and capital, to compensate those individuals or businesses that actually do experience losses.

Traditional insurance risk management is based on statistically measurable and predictable distributions of events and losses, which allows insurers to finance losses of randomly occurring events of relatively modest size through policy premiums. However, natural catastrophes, occur infrequently, but have very large loss potential. The diversification of very large losses, even across the global insurance pool, is difficult where such events have the potential to absorb huge quantities of capital. So what can we expect if climate change increases average and extreme losses from extreme weather events?

In this section we attempt to provide some answers to this question. First, we look at the characteristics of natural catastrophe insurance. This provides a framework for evaluating the impacts of intensifying windstorms on insurance pricing and capital capacity, as well as exploring how insurers manage catastrophe risks. We then assess how capital capacity and premiums could change subject to the climate-stress tests simulated in Section 3. The section concludes by briefly considering the wider economic effects of changes in the demand and supply of insurance.

6.2 Characteristics of natural catastrophe insurance

Insurance is unique. In contrast to other sectors in the economy, prices must be set and coverage sold before costs (claims) are known. Future costs must therefore be accurately estimated ex ante. In most cases insurers can use historical data to generate useful statistics, such as average annual loss per policy, that allow it set premiums that cover these expected losses plus administrative expense, and provide an adequate rate of return on capital. To this end two conditions are desirable: (a) the frequency of claims over time should be predictable and (b) losses experienced by one policy should be independent of losses experienced by another.

Natural catastrophes do not, however, comply with these two conditions. For a start, natural catastrophes are infrequent events, resulting in large losses in a few years and no losses in most years. Losses are therefore not predictable over time. Natural catastrophes are also sufficiently large in scale to affect many policies at once. Hence, losses across policies are highly correlated; a violation of the second condition.

In addition, natural catastrophes, while infrequent, typically result in very large losses, which can present a significant financial risk to insurers, including – in rare cases – insolvency.

Insurers that offer to cover natural catastrophes have therefore developed specialist tools to assess, and strategies to manage, such risks.

6.3 Managing Natural Catastrophe Risk

Strategies used by insurers to manage natural catastrophe risk generally encompass the following elements: first, defining "risk appetite" for natural catastrophe exposure; second, measuring and pricing the exposure; and third, managing the exposure.

Defining risk appetite

Each insurer will decide, for a specified period of time, how much loss it is willing (or able) to absorb without putting the business at unacceptable financial risk. This level of risk – in insurance jargon - defines the insurer's "risk appetite", which is frequently expressed in terms of the maximum acceptable reduction in capital per year from a specific hazard (e.g. a European windstorm) or set of hazards. Risk appetite can also be described in term of the maximum loss that is acceptable over a determined period of time (e.g. US$ 1 billion of loss only to be exceeded once in 100 years).

Many factors determine an insurers' risk appetite, including: the availability and cost of reinsurance, rate and solvency regulations, rating agency assessments, market conditions, the capital base and how it is allocated across business lines, and the cost of capital. For instance, some rating agencies may require insurers to set aside enough capital to pay for at least a 1-in-100, or even a 1-in-250, year insured loss[90].

As well as ensuring that insurance is affordable, regulators also want to make sure that insurers can cover their promises, even if a significant (e.g. 1-in-100 year loss) natural catastrophe occurs. One approach is to require insurers that write natural catastrophes to hold additional capital or reserves. Of course, holding more capital raises capital costs, which in turn raises cost of the catastrophe coverage. An appropriate balance must therefore be struck between imposing excessive safety margins, which can inflict deadweight losses on the economy, and assuring that the promises of insurers will be kept. Hence, insurers are not required to hold an amount of capital sufficient to cover all potential losses.

Measuring and pricing exposure

Once an insurer has defined its natural catastrophe risk appetite, but before it enters into a contract with the insured to compensate them for specified losses in return for paying an annual premium, the insurer must determine the likelihood that losses of assorted sizes will occur, in order to set premiums that are actuarially sound. That is, premiums that allow the insurer to meet its financial obligations in the event of a loss. To set such premiums insurers must be in a position to assess risk across the full distribution of future hazards that could occur, including those arising from events, which have a very small chance of occurring, but have significant consequences if they do take place.

A hypothetical example of this process is provided in Box 1. In reality, the process is much more complex. The purpose of the example is solely to illustrate, in general terms, the role of the loss distribution in the pricing process and in determining an insurer's capital requirements. This will provide a framework for looking at the results

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[90] For example, A. M. Best, a rating agency that assesses the financial strength of insurers, applies a stress test as part of the assessment process. This test involves reducing an insurer's surplus by the net after-tax catastrophe loss incurred once every 100 years to see its effect.

of the simulated climate-stress tests. The loss distribution itself is typically generated by natural catastrophe models, such as those discussed in Section 3.

As the example in Box 1 shows, when assessing the relationship between loss potential and the likelihood of a loss event occurring, insurers consider:

- **Average** (or Expected) **Annual Losses**: The insurer needs to know the amount they can expect to payout, on average, per annum for an insured item (e.g. building) or portfolio of items. The expected loss is a key component of the premium calculation.
- **Extreme** (or Maximum Probable) **Losses**: The insurer needs to know how much it would need to payout should a significant catastrophe occur. Information on extreme losses is used by insurers to define their capital base[91], including reinsurance cover, and is also factored into the premium calculation.

Regarding the latter point, as insured losses from natural catastrophes are highly variable, insurers need to hold sufficient capital to pay claims in the event that aggregate losses during a year are significantly worse than average. The determinants of an insurer's risk appetite will influence exactly how much capital is held.

While the price of insurance will vary according to market location (depending on the regulatory regime and competitive nature of the local market), premiums will, in general, comprise:

- The cost of annual average losses.
- The administrative expenses of policy writing and settling claims.
- Payments for capital that would be at risk if annual losses exceeded premium and investment income.
- All relevant taxes.

An insurer may also opt to transfer the risk of larger losses to reinsurers, in exchange for paying a premium[92]. The net cost of reinsurance[93] to the insurer will also be recouped from the insured, as part of the latter's premiums.

Therefore, other things being equal, increases in the mean or variance of the loss distribution, as anticipated with climate change, will tend to increase insurance premiums.

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[91] As mentioned above, a unique feature of natural catastrophes is that they tend to impose losses on a large number of individuals, in close proximity in time and space, or put another way, the risks are correlated with one another. The more correlated the risks, the larger the variability of an insurer's losses, and the more capital that must be held in reserve. Thus, covering natural catastrophes, with uncertain and volatile losses, places significant capital demands on insurers.

[92] The reinsurers' premium will have a similar structure to the primary insurers' premium, albeit, based on different loss functions.

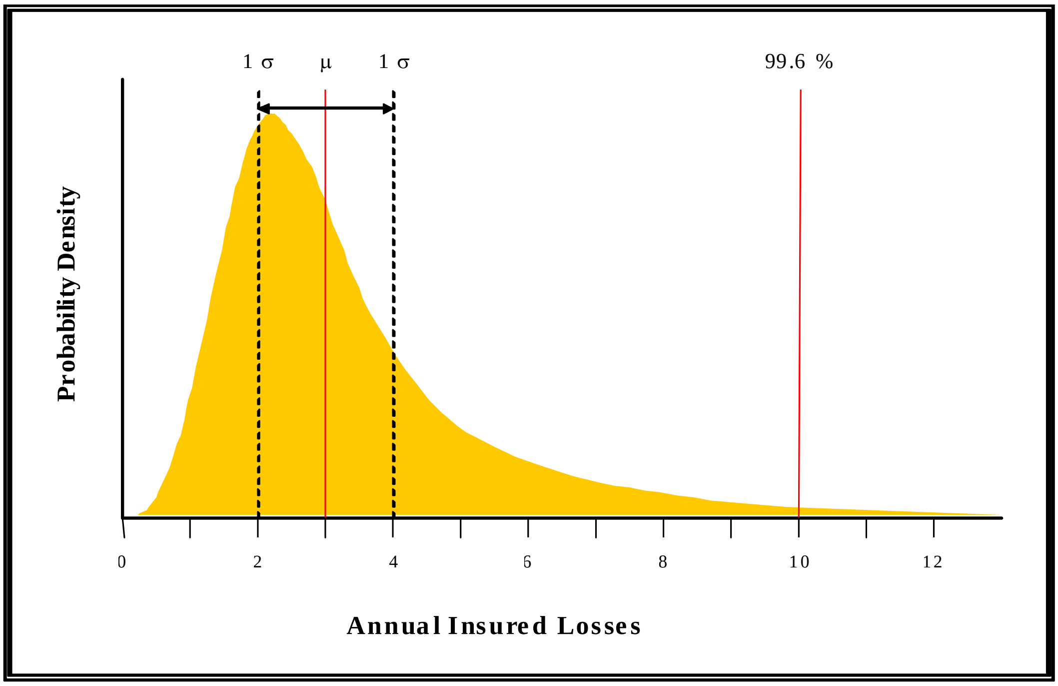
[93] That is, the premium paid to the reinsurer to accept the natural catastrophe exposure, less the expected loss transferred to the reinsurer.

Box 1: An Example of How Insurers Assess Risk For Natural Hazards

The Role of the Loss Distribution

A range of uncertain insurance claims, each with their own probability of occurrence, can be characterised as one distribution. An example of such a distribution is shown in the figure below.

Example Loss Distribution



For the purpose of writing an insurance policy, it is useful to consider the distribution as two distinct parts[94]:

- The central portion of the distribution, which deals with normal insured losses (claims).
- The tail end of the distribution, which deals with infrequent events with large insured losses, such as "intense" landfalling hurricanes or other natural catastrophes.

Insurers, reinsurers and regulators are most interested in the latter, since such extreme outcomes can adversely affect profitability and, in acute cases, solvency. Typical extreme outcomes of interest to the industry are 1-in100 and 1-in-250 year losses, with annual probabilities of 1.0 per cent and 0.4 per cent, respectively. Such events represent an "unexpected" loss, in that the corresponding claim far exceeds the expected or average insured loss. **Unexpected losses are a risk to the insurer**.

In the example distribution shown in the above figure the annual expected insured loss is 3.0 and the standard deviation of 1.0[95]. Clearly, in this example, the standard deviation provides an inappropriate measure of risk, since it only amounts to 1/10th of the insured losses that could be realised once in 250 years (where losses equal to 10.0).

If an insurer wants to be sure that it can pay claims in 99.6 per cent of all cases (i.e. that is, losses incurred once every 250 years), it needs access to sufficient resources to pay 10.0, as opposed to 3.0. The risk, in this case, is 7.0, which is the difference between the unexpected insured loss (10.0) and expected insured loss (3.0).

The insurer could seek 10.0 from prospective policyholders. However, they are unlikely to buy a policy in which the premiums vastly exceed their expected losses. As a result, the insurer will need to provide itself with sufficient capital to cover unexpected insured losses up to chosen threshold (i.e. the 1-in-250 year loss). In the example the insurer will need to allocate 7.0 to this line of business. The role of the capital is essentially to ensure that the insurer can pay its liabilities, even following a catastrophe.

But capital is not free; investors will want a competitive return on their investment and for the risk they are taking, otherwise they will invest their money elsewhere. The return required by the investor is the cost of the capital to the insurer. Exactly how high the rate of return is a matter of considerable debate, and it will vary from insurer to insurer. If the cost of capital is 10 per cent, then the cost of setting 7.0 aside to cover 99.6 per cent of annual claims is 0.7. The cost of capital must also be recovered within the price of insurance policies. The resulting risk-based premium, assuming expenses are roughly 10 per cent of expected claims, for the loss distribution shown above is thus 4.0. (This calculation is shown in the figure below.)

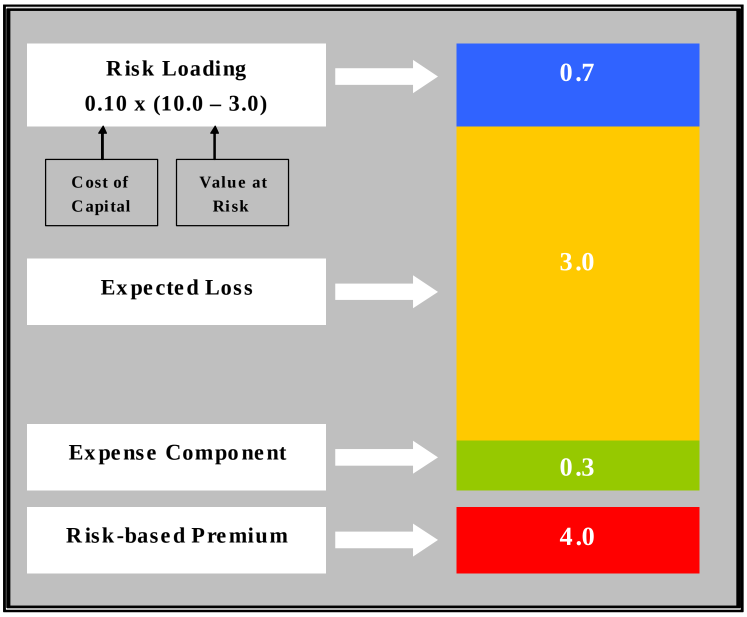
The Economic Value of Insurance

In the above example, investors are rewarded for providing capital to ensure that claims are paid even if insured losses are significantly worse than expected. (The investor provides 7.0 and receives 0.7 as the price for the risk assumed.) Moreover, the rate of return will tend to be relatively high, reflecting the risk premium required on investments in the insurance industry. At the same time, insurers have covered their costs and generated value for their shareholders.

The insured has also managed to transfer the risk of losses in excess of the premium (4.0) to the insurer; i.e. regardless of the size of the loss, the insured only pays the premium. As a result, individuals and businesses do not need to set aside capital to cover losses that could occur; although it is very unlikely that they would occur. The insured can thus allocate accessible capital to other (productive) uses.

In short, if the risk is appropriately priced, investors, insurers and the insured all stand to benefit.

Example of Components of Risk-based Premium



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[94] Saunders, D.E.A. (2005) "The Modelling of Extreme Events", presented to the Institute of Actuaries, 4th Aril 2005.

[95] The shape of a distribution is characterised by a variety of descriptive statistics, including the mean and standard deviation, which measures the dispersion of claims around the mean.

6.4 Managing catastrophic exposures

Once an insurer has assessed its exposure to natural catastrophe losses and set appropriate premium rates, it may need to reduce exposure, subject to its risk appetite. Ranges of options are available to insurers to control their exposure to natural catastrophe risk where capital capacity has been exceeded, including:

- Managing location and geographic concentration.
- Changing policy forms and coverage.
- Transferring exposure to reinsurers or capital markets.

6.4.1 Location and geographical concentration

Natural catastrophes, like hurricanes, are infrequent events that may or may not strike a particulate area during a year. An insurer with many exposures written over a large geographical area has a high likelihood of experiencing losses in any given year. A hurricane making landfall is likely to damage some of the properties covered by this insurer. However, in any one year, only a fraction of the properties over a widely distributed set of exposures will be affected. Thus, the chance of that insurer suffering substantial losses across its entire book of business is relatively low. In contrast, if an insurer has a concentration of properties in one location, it may not experience losses in a given year, but could face significant losses if that particular location is hit by a hurricane. Basically, the latter insurer will have less overall capacity than the former insurer. Thus, one way to increase capacity is to manage the geographic concentration and location of exposure.

6.4.2 Policy forms and coverage

Insurers can control losses from natural catastrophes, while making affordable coverage available, by changing policy conditions. Following Hurricane Andrew, for example, insurers changed the structure of deductibles and limits (see Section 6). From the point of view of the insurer these changes have two effects: first, they limit the amount the insurer is obliged to pay in the event of a loss; and second, they help reduce administrative expenses by limiting the number of small claims received. Natural catastrophes, such as severe European windstorms, result in numerous small claims. In these cases, the administrative effort to settle these claims can be disproportionate relative to the actual size of the loss incurred (e.g. the average claim after the European windstorm Lothar was only US$ 1,500).

Traditional deductibles are based on relatively low fixed amount; averaging US$ 100 in many markets exposed to European windstorms (Swiss Re, 2000)[96]. In Florida, after Hurricane Andrew, many insurers switched to mandatory windstorm deductibles, typically 2 per cent of any loss (as opposed to traditional, fixed dollar deductibles). While higher deductibles reduce insurers' exposure, by keeping costs down they also keep premiums down, which means that limited, affordable insurance can still be offered in risk-prone areas, where it might not otherwise be available.

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[96] Swiss Re (2000) "Storm over Europe: An underestimated risk", Swiss Reinsurance Company, Zurich

In addition, reducing the number of claims received speeds up processing times, which also benefits the insured. In short, insurers' resources are freed-up to assist those individuals and businesses suffering relatively large losses. In addition, suitably designed deductibles simultaneously provide policyholders with incentives to prevent or mitigate losses; reducing costs (and premiums) further.

Another option is to review coverage limits (i.e. the maximum amount payable, as either a fixed amount or percentage of the insured sum) in a policy, to mitigate the potential for adverse coverage determinations after a natural catastrophe; especially given the potential for significant catastrophes to induce "demand surge" for inputs to the repair and replacement of damaged properties.

Insurers could also reduce future exposure by participating in programmes to reduce or prevent property damage from natural catastrophes. A good example of such programmes is building codes and their enforcement. Insurers can provide the necessary economic incentives to private agents to ensure that these programmes, which are often developed jointly with public agencies, are successfully implemented. These loss mitigation or adaptation programmes were discussed in Section 3.

In response to increasing flood risks, attempts have been made to control development in some risk-prone areas. While no attempts have yet been made to control exposures to other perils by imposing legal restrictions on development within areas prone to, for example, hurricanes, the mitigation of losses in the long-run may be most effectively accomplished by limiting the accumulation of exposure in risk-prone areas. This option to mitigate losses takes on added significance given the potential socio-economic developments highlighted in Section 3.

6.4.3 Transferring risk to third parties

The traditional method for insurers to reduce exposure or transfer risk to a third party is to purchase reinsurance (see Box 2). In doing so insurers protect their capital base against large deviations in expected losses. Furthermore, insurers can write more business for the same amount of capital, since they no longer need to allocate capital to the risks that have been transferred to the reinsurer. However, the capacity of the global reinsurance market is finite, so there is a limit to the amount of risk that insurers can transfer to reinsurers; the price of reinsurance may also be prohibitive at higher layers of cover.

Box 2: Types of Reinsurance

There are basically two forms of reinsurance for natural catastrophes: treaty and facultative. With treaty reinsurance, the insurer cedes (transfers) all risks that meet certain criteria within a portfolio. In contrast, with facultative reinsurance insurers negotiate reinsurance on a policy-by-policy basis, with each policy being priced individually by the reinsurer. Coverage is also generally split between "proportional" and "non-proportional" cover. Under proportional (or pro-rata) cover, both premiums and losses are shared by reinsurer and insurer according to a contractually defined percentage for each policy written. With treaty insurance proportional cover is still reasonably common. Non-proportional cover is typically written on a per risk, per event, or per aggregate excess basis. Excess-of-loss reinsurance is a form of non-proportional cover that has been specifically designed for natural catastrophes. With a Cat XL treaty – as they are known - the reinsurer agrees to pay the insurer – per event – for that proportion of total losses that exceeds a specified minimum loss (i.e. the retention), but fall below a specified ceiling (i.e. upper limit of cover). Cat XL reinsurance typically involves very large sums of money. As a result, the cover tends to be divided into a number of distinct layers, which can be shared among several reinsurers.

The size of the global reinsurance market in 2004 (based on a survey of 43 significant reinsurance groups), as measured by gross written premiums, has been put at around US$ 150 billion[97], of which US$ 118 billion relates to non-life business lines (IAIS, 2004)[98]. Of the non-life amount, property accounts for about US$ 53 billion. Proportional cover in property reinsurance showed gross written premiums of close to US$ 36 billion, whereas gross written premiums for non-proportional cover totalled around US$ 17 billion. The total capital available to cover unanticipated losses held by the same group of reinsurers is about US$ 244 billion.

With the global P & C insurance sector expecting, on average, US$ 20 billion in natural catastrophe losses per annum, this would represent nearly 40 per cent of property gross written reinsurance premiums, and fewer than 10 per cent of the total capital available to reinsurers to cover losses across all lines of business. Industry wide measures of reinsurers' ability to cover losses is misleading, however, since it is individual firms that pay claims and not the industry as a whole; claims from a natural catastrophe could be concentrated in a few firms.

Insurers can also limit risk exposure to an acceptable level by transferring natural catastrophe risk into the capital markets, using innovative financial instruments, such as catastrophe bonds, contingent surplus notes, exchange-traded options and catastrophe equity puts. The process of "packaging" natural catastrophe risk as securities to sell in the capital markets is, rather appropriately, referred to as "securitisation".

These innovative risk transfer instruments are discussed at Appendix A. Due to their size financial markets offer enormous potential for insurers to diversify risks: the value of global financial markets currently stands at about US$ 118 trillion[99]. A US$ 100 billion loss event therefore does not even represent one-tenth of one per cent of the total value of global financial markets. Nonetheless, by the middle of 2004 only about US$ 8 billion in catastrophe bonds had been issued since 1997. Nearly half of the bonds (by dollar value) cover earthquakes, with about a third covering hurricanes. Two-thirds of the bonds (by dollar value) cover perils in the U.S.

Each instrument has its unique advantages and disadvantages, in terms of, for example, transaction costs, basis risk, moral hazard and adverse selection. Transaction costs can be considerable, and it is not likely that investors will know as much about an insurer's portfolio of risks as the insurer itself. Thus, there is always the potential for adverse selection in which the insurer offloads only unfavourable risks, keeping favourable risks on its books. The unfamiliarity of investors with insurance risks means that they currently demand a relatively large risk premium. This acts to hinder market development.

In general, whether securitising natural catastrophe risk proves successful will depend on: whether insurers find that securitisation provides a cost-effective mechanisms for transferring risk and increasing capacity, and whether investors find that securitising natural catastrophe risk improves the performance of their portfolios.

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[97] It has also been estimated as high as USD 175.5 billion (USD 146.0 billion in non-life gross written premiums).

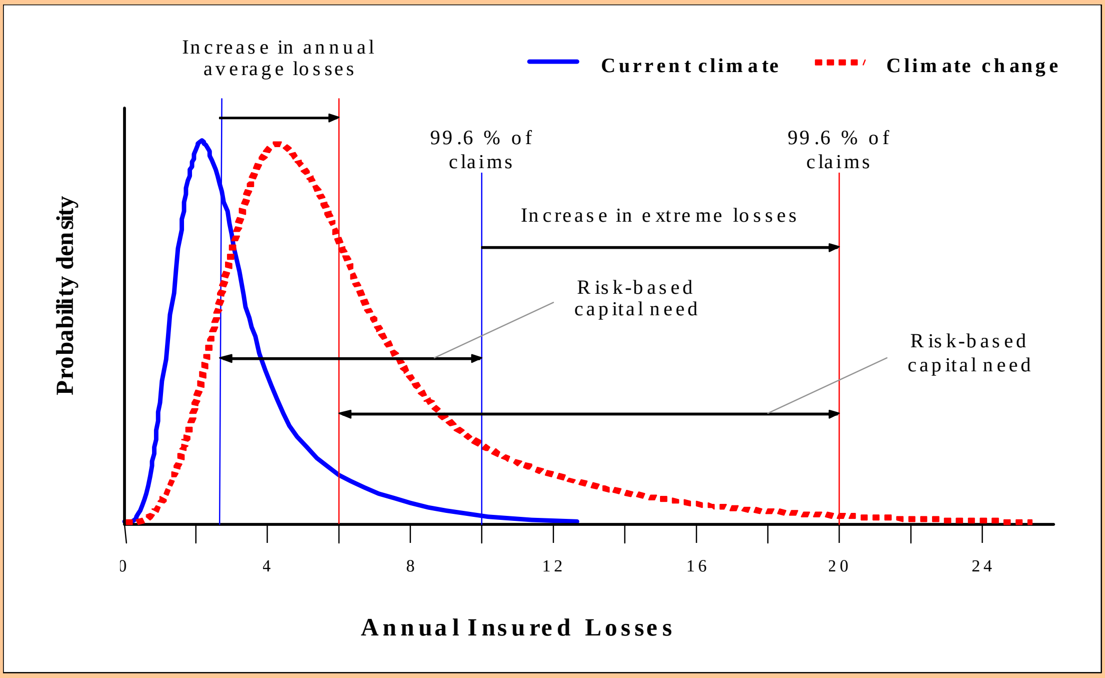
[98] IAIS (2004) "Global Reinsurance Market Report 2003", International Association of Insurance Supervisors, December 2004.

[99] McKinsey & Company, "Taking Stock of the World's Capital Markets", February 2005 (www.mckinsey.com/mgi/publications).

6.5 Implications of climate-stress tests

Using the framework described above we can now consider the implications of the estimated increments in average and extreme losses, as outlined in Section 3, resulting from our climate-stress tests. Starting with the loss distribution displayed in Box 1, increases in the average annual insured loss and extreme losses will, as predicted under our climate-stress tests for hurricanes, typhoons and European windstorms, shift (or elongate) the loss distribution to the right – as shown in Figure 6.1. In the figure we assume the insurer wants to be sure that it can pay claims in 99.6 per cent of all cases (i.e. including those arising from a 1-in-250 year loss should it occur). The point to note is that increases in average insured losses and extreme insured losses, as a result of climate change, will tend to increase the amount of risk-capital needed to satisfy the insurer's risk appetite, at whatever level it is defined.

Figure 6.1: Illustration of Impact of Climate Change on the Loss Distribution for Windstorms



6.6 Capital requirements

Before considering the impact of climate change on the capital requirements of insurers of Atlantic hurricanes, Japanese typhoons and European windstorms, we first need information on the baseline average annual losses and extreme losses. Table 6.1 presents baseline losses for these three storm perils, based on current industry experience.

Table 6.1: Current Loss Experience for Atlantic Hurricanes, Japanese Typhoons and European Windstorms

	Annual Average Total Financial Loss	Annual Average Insured Loss	Insured Loss with a Chance of Once Every 100 Years (1% EP)	Insured Loss with a Chance of Once Every 250 Years (0.4% EP)
	(US$ 2004 billion)	(US$ 2004 billion)	(US$ 2004 billion)	(US$ 2004 billion)
Atlantic hurricanes	9.4	5.4	60	85
Japanese typhoons	4.2	2.3	15	20
European windstorms	3.1	1.7	30	35

The simulated climate-induced increments in annual average and extreme insured losses for each of the tropical cyclone perils, under a high-emissions scenario (AIF1) and a low-emissions scenario (550) are shown in Table 6.2. Note that the radiative forcing under a 550 stabilisation emissions scenario and under the IPCC SRES B1 scenario are roughly equivalent over the time period 2080-2099. Consequently, the results presented below for the low-emissions scenario are very similar to those that would have been obtained under B1.

Table 6.2: Impact of Climate-stress Tests on Insured Losses from Atlantic Hurricanes and Japanese Typhoons under a High- and Low-emissions Scenario (2080-2099)

	Annual Average Insured Loss	Insured Loss with a Chance of Once Every 100 Years (1% EP)	Insured Loss with a Chance of Once Every 250 Years (0.4% EP)
	(US$ 2004 billion)	(US$ 2004 billion)	(US$ 2004 billion)
Atlantic hurricanes			
High-emissions scenario	4.3	44.5	66.7
Low-emissions scenario	0.8	8.6	14.5
Japanese typhoons			
High-emissions scenario	1.7	11.1	15.8
Low-emissions scenario	0.3	2.1	2.7

Looking at Atlantic hurricanes, Figure 6.2 and Figure 6.3 illustrate graphically the impact of combining the loss data listed in Table 6.1 and Table 6.2. As Figure 6.2 shows, under the A1F1 scenario, the maximum insured loss with a 1 per cent and 0.4 per cent chance of being exceeded annually is simulated to increase to US$ 105 billion and US$ 152 billion, respectively. Under a 550 stabilisation scenario however (shown in Figure 3), insured losses for the 1 per cent and 0.4 per cent exceedence probabilities are only estimated to increase to US$ 69 billion and US$ 100 billion. The simulated 1-250 year insured losses for hurricanes by the end of the century, for example, are nearly 35 per cent less under a 550 stabilisation path than under A1F1.

Figure 6.2: Simulated Change in "Right-hand Tail" of Exceedence Probability Curve for Atlantic Basin Hurricanes Affecting U.S. Under IPCC SRES A1F1 By End of Century (2080-2099)

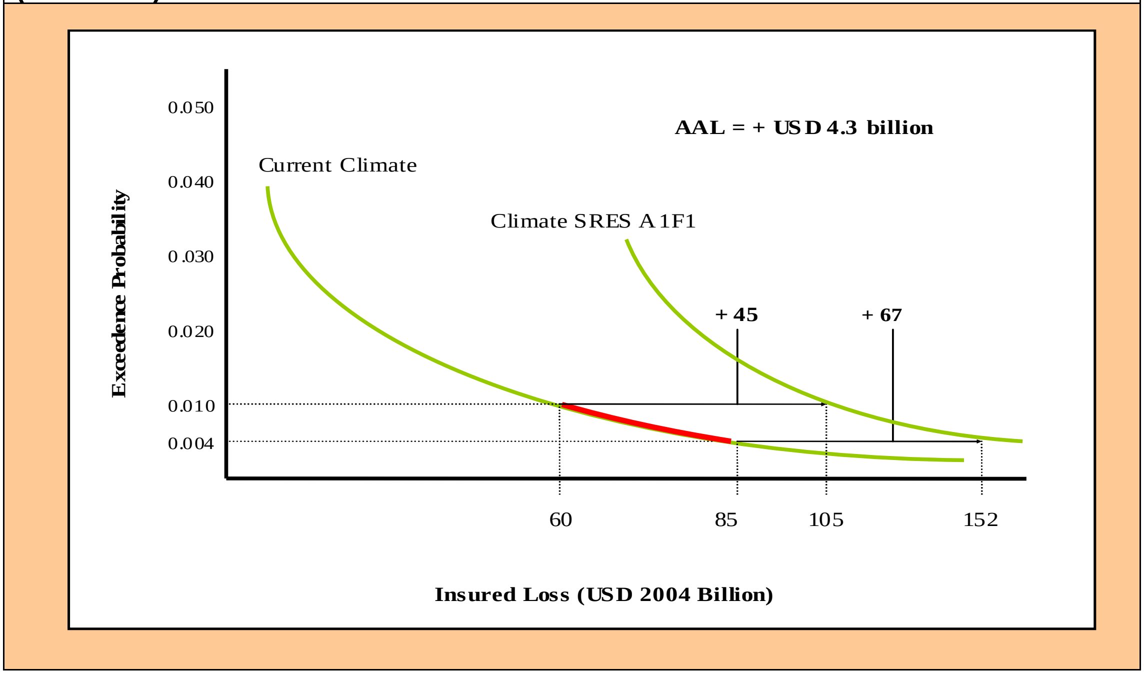
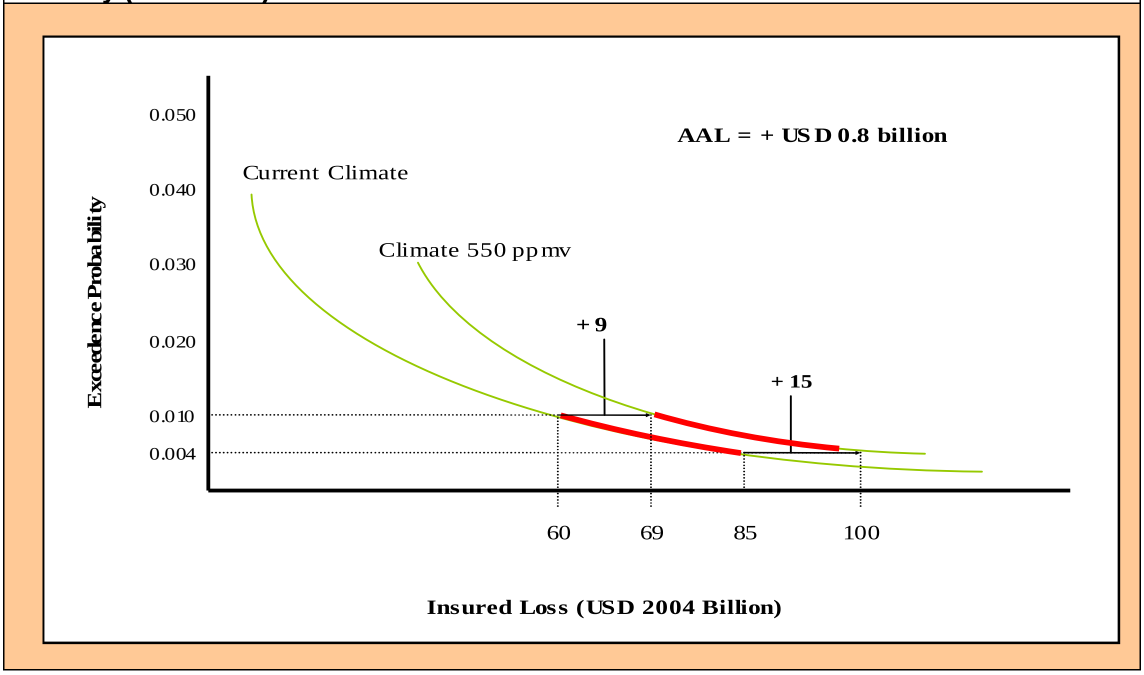


Figure 6.3: Simulated Change in "Right-hand Tail" of Exceedence Probability Curve for Atlantic Basin Hurricanes Affecting U.S. Under 550 Stabilisation Scenario By End of Century (2080-2099)



What about capital requirements? Based on the simple framework outlined in Box 1 above, for hurricane insurance markets at the end of the century, the additional risk-capital (RC) required under the A1F1 emission scenario for an industry risk appetite defined by a 1 per cent and 0.4 per cent exceedence probability is shown in the table below (rounded to the nearest billion US$):

1 per cent EP (hurricanes)			0.4 per cent EP (hurricanes)		
Current Climate:			Current Climate:		
EP = 60	AAL = 5	RC = 55 (= 60 – 5)	EP = 85	AAL = 5	RC = 80 (= 85 – 5)
Climate Change Signal:			Climate Change Signal:		
EP = 105 (= 60 + 45)	AAL = 9 (= 5 + 4)	RC = 96 (= 105 – 9)	EP = 152 (= 85 + 67)	AAL = 9 (= 5 + 4)	RC = 143 (= 152 – 9)
Incremental Effect:			Incremental Effect:		
EP = 45 (= 105 – 60)	AAL = 4 = (9 – 5)	RC = 41 = (96 – 55)	EP = 67 (= 152 – 85)	AAL = 4 = (9 – 5)	RC = 63 = (143 – 80)

Based on this simple framework, an additional US$ 41 billion in capital would need to be made available if the insurance industry desired to cover hurricane losses in 99 per cent of cases. To put this number in context, surplus (a key measure of capacity) in the U.S. P & C industry at the end of 2002 was just under US$ 300 billion. A similar analysis is presented below for the 550 stabilisation emissions scenario:

1 per cent EP (hurricanes)			0.4 per cent EP (hurricanes)		
Current Climate:			Current Climate:		
EP = 60	AAL = 5	RC = 55 (= 60 – 5)	EP = 85	AAL = 5	RC = 80 (= 85 – 5)
Climate Change Signal:			Climate Change Signal:		
EP = 69 (= 60 + 9)	AAL = 6 (= 5 + 1)	RC = 63 (= 69 – 6)	EP = 100 (= 85 + 15)	AAL = 6 (= 5 + 1)	RC = 94 (= 100 – 6)
Incremental Effect:			Incremental Effect:		
EP = 9 (= 69 – 60)	AAL = 1 = (6 – 5)	RC = 8 = (63 – 55)	EP = 15 (= 100 – 85)	AAL = 1 = (6 – 5)	RC = 14 = (94 – 80)

Under the 550 stabilisation emissions scenario, only an additional US$ 8 billion in capital is needed to if the insurance industry wants to cover hurricane losses in 99 per cent of cases. Hence, in moving from a relatively high emission scenario to stabilisation at 550 ppmv, the amount of risk-capital needed at the end of the century by the insurance industry to pay hurricanes claims in 99 per cent of all cases is reduced by 80 per cent (or US$ 33 billion).

Now, looking at Japanese typhoons, Figure 6.4 and Figure 6.5 illustrate graphically the impact of combining the loss data listed in Table 6.1 and Table 6.2. As Figure 6.4 shows, under the A1F1 scenario, the maximum insured loss with a 1 per cent and 0.4 per cent chance of being exceeded annually is simulated to increase to US$ 26 billion and US$ 36 billion, respectively. Under a 550 stabilisation scenario however (shown in Figure 6.3), insured losses for the 1 per cent and 0.4 per cent exceedence probabilities are only estimated to increase to US$ 17 billion and US$ 23 billion.

Figure 6.4: Simulated Change in “Right-hand Tail” of Exceedence Probability Curve for Japanese Typhoons Affecting U.S. Under IPCC SRES A1F1 By End of Century (2080-2099)

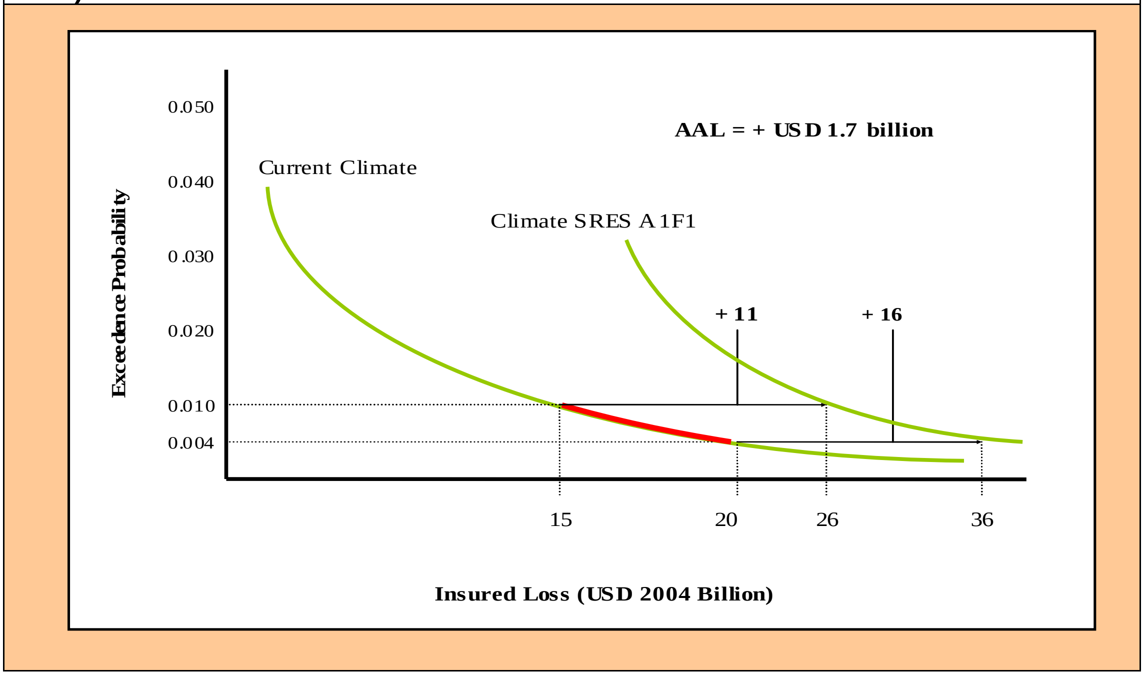
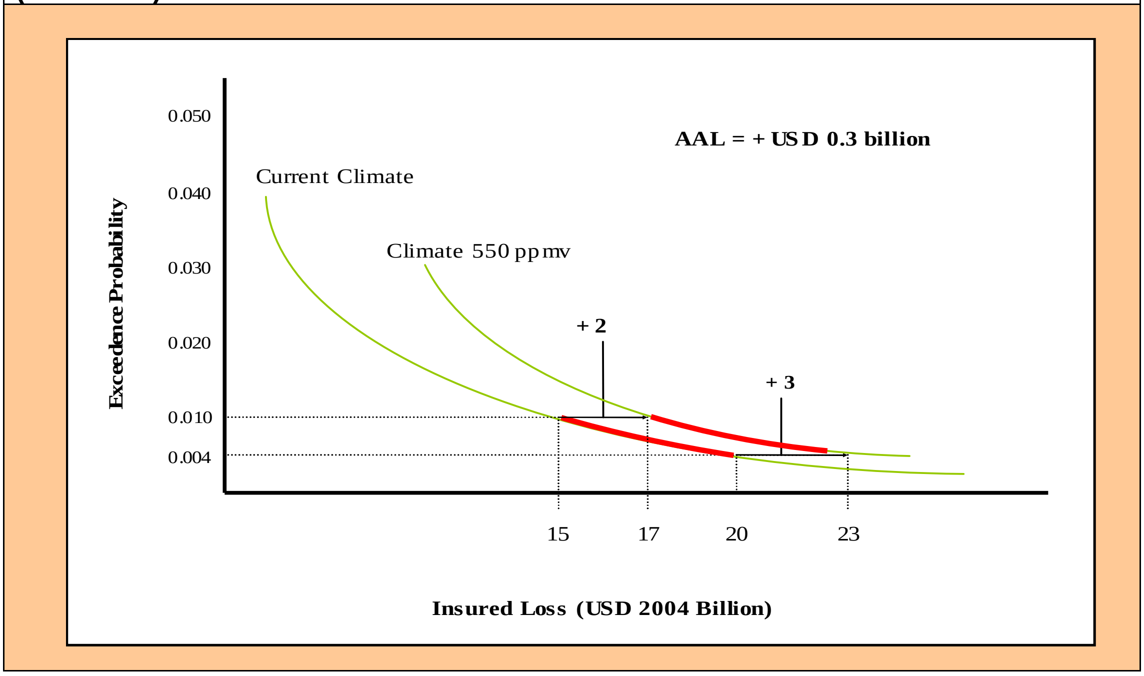


Figure 6.5: Simulated Change in “Right-hand Tail” of Exceedence Probability Curve for Japanese Typhoons Affecting U.S. Under 550 Stabilisation Scenario By End of Century (2080-2099)



Again, based on the simple framework outlined in Box 1 above, for typhoon insurance markets at the end of the century, the additional risk-capital (RC) required under the A1F1 emission scenario for an industry risk appetite defined by a 1 per cent and 0.4 per cent exceedence probability is shown in the table below (rounded to the nearest billion US$):

1 per cent EP (typhoons)			**0.4 per cent EP (typhoons)**		
Current Climate:			Current Climate:		
EP = 15	AAL = 2	RC = 13 (= 15 – 3)	EP = 20	AAL = 2	RC = 18 (= 20 – 2)
Climate Change Signal:			Climate Change Signal:		
EP = 26 (= 15 + 11)	AAL = 4 (= 2 + 2)	RC = 22 (= 26 – 4)	EP = 36 (= 20 + 16)	AAL = 4 (= 2 + 2)	RC = 32 (= 36 – 4)
Incremental Effect:			Incremental Effect:		
EP = 11 (= 26 – 15)	AAL = 2 = (4 – 2)	RC = 9 = (22 – 13)	EP = 16 (= 36 – 20)	AAL = 2 = (4 – 2)	RC = 14 = (32 – 18)

An additional US$ 9 billion in capital would need to be made available if the insurance industry desired to cover typhoon insured losses in 99 per cent of cases under this scenario; an additional US$ 14 billion in capital would need to be made available to cover insured losses in 99.6 per cent of cases. A similar analysis is presented below for the 550 stabilisation emissions scenario:

1 per cent EP (typhoons)			**0.4 per cent EP (typhoons)**		
Current Climate:			Current Climate:		
EP = 15	AAL = 2	RC = 13 (= 15 – 3)	EP = 20	AAL = 2	RC = 18 (= 20 – 2)
Climate Change Signal:			Climate Change Signal:		
EP = 17 (= 15 + 2)	AAL = 3 (= 2 +1)	RC = 14 (= 17 – 3)	EP = 23 (= 20 + 3)	AAL = 3 (= 2 + 1)	RC = 20 (= 23 – 3)
Incremental Effect:			Incremental Effect:		
EP = 2 (= 17 – 15)	AAL = 1 = (3 – 2)	RC = 1 = (14 – 13)	EP = 3 (= 23 – 20)	AAL = 1 = (3 – 2)	RC = 2 = (20 – 18)

Under the 550 stabilisation emissions scenario, only an additional US$ 1 billion in capital is needed to if the insurance industry wants to cover hurricane losses in 99 per cent of cases. Hence, in moving from a relatively high emission scenario to stabilisation at 550 ppmv, the amount of risk-capital needed at the end of the century by the insurance industry to pay typhoon claims in 99 per cent of all cases is reduced by close to 90 per cent (or US$ 8 billion).

To get a feel for the combined impact of the climate-stress test on hurricanes and typhoons, consider Figure 6.6, although it is acknowledged that the two EP curves are not strictly additive[100]. Under the SRES A1F1 emission scenario, by the end of the century, the aggregate maximum 1-in-100 year insured loss for hurricanes-typhoons is about US$ 131 billion by the end of the century. For a 1-in-250 year loss the figure is US$ 188 billion. If emissions were reduced to put us on a 550 stabilisation path, the aggregate maximum 1-in-100 year insured loss would reduce by US$ 45 billion (or by about 35 per cent), to US$ 86 billion.

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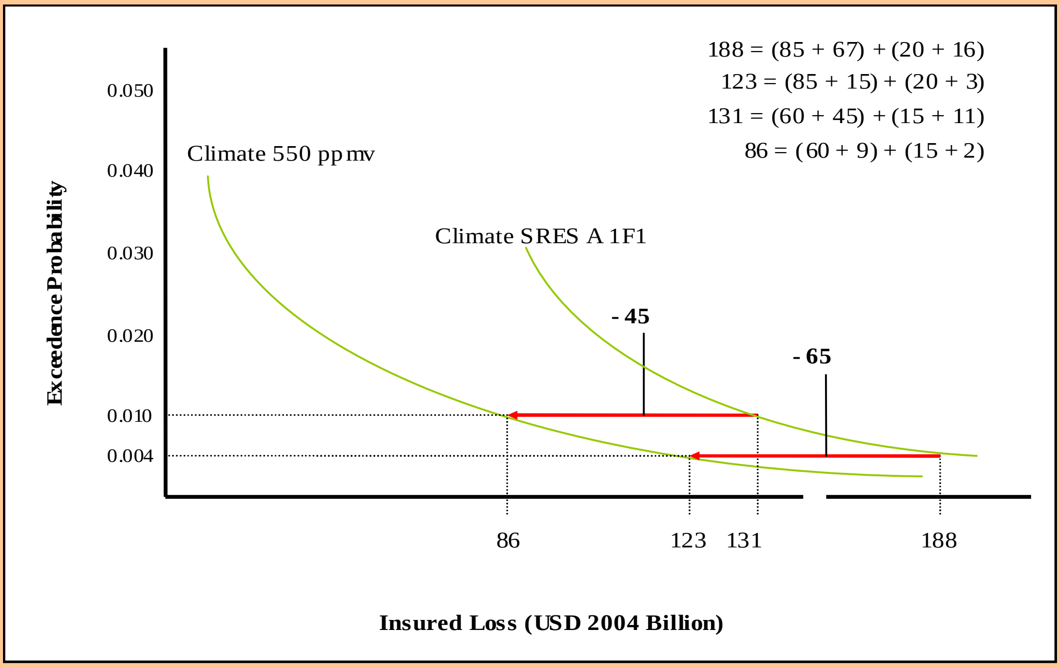
[100] As a result of the "portfolio effect", the losses at various EPs in a combined (aggregate) portfolio of peril regions will be (considerably) lower than the sum of the corresponding loss EPs in the individual regions.

Figure 6.6: Simulated Change in "Right-hand Tail" of Approximate Aggregate Exceedence Probability Curve for Hurricanes and Typhoons Under IPCC SRES A1F1 and 550 By End of Century (2080-2099)



The amount of risk-capital all insurers writing hurricane and typhoon cover need to have available at the end of the century if they want to pay claims in 99.6 per cent of all cases, under the high and low emission scenarios, is shown in the table below:

A1F1: 0.4 per cent EP (hurricanes and typhoons)			550: 0.4 per cent EP (hurricanes and typhoons)		
Current Climate:			Current Climate:		
EP = 105	AAL = 8	RC = 97 (= 105 – 8)	EP = 105	AAL = 8	RC = 97 (= 105 – 8)
Climate Change Signal:			Climate Change Signal:		
EP = 188 (= 105 + 83)	AAL = 14 (= 8 + 6)	RC = 174 (= 188 – 14)	EP = 123 (= 105 + 18)	AAL = 9 (= 8 + 1)	RC = 114 (= 123 – 9)
Incremental Effect:			Incremental Effect:		
EP = 83 (= 188 – 105)	AAL = 6 = (14 – 8)	RC = 77 = (174 – 97)	EP = 18 (= 123 – 105)	AAL = 1 = (9 – 8)	RC = 17 = (114 – 97)

Under the A1F1 emission scenario, by the end of the century, the insurance industry would need to make an additional US$ 77 billion in risk-capital available if it wanted to cover hurricane and typhoon losses in 99.6 per cent of all cases. In contrast, under the 550 stabilisation scenario, only an additional US$ 17 billion in capital is required. In moving from the high A1F1 emission scenario to stabilisation at 550 ppmv, the amount of risk-capital needed for these two insurance markets is thus reduced by over 75 per cent (or by US$ 60 billion).

The simulated climate-induced (under IPCC SRES A2) increment in the 1 per cent and 0.4 per cent exceedence probabilities for European windstorms is US$ 2.0 billion and US$ 2.3 billion, respectively, which roughly represents a 5 per cent increase on current exceedence probabilities. This may seem small, but the climate-stress test simulated was limited to the extreme "upper tail" of the full distribution of all feasible windstorm events. Potential impacts of climate change on less intense windstorms were not modelled (see Section 3). Changes in capital requirements for European windstorm insurance markets based on the climate-stress tests modelled in this study will therefore severely understate the full possible impacts. Bearing this limitation in mind, the additional risk-capital (RC) required under the A2 emission scenario for an industry risk appetite defined by a 1 per cent and 0.4 per cent exceedence probability is shown in the table below (rounded to the nearest billion US$):

1 per cent EP (Euro windstorms)			**0.4 per cent EP (Euro windstorms)**		
Current Climate:			Current Climate:		
EP = 30	AAL = 2	RC = 28 (= 30 – 2)	EP = 35	AAL = 2	RC = 33 (= 35 – 2)
Climate Change Signal:			Climate Change Signal:		
EP = 32 (= 30 + 2)	AAL = 2 (= 2 + small)	RC = 30 (= 32 – 2)	EP = 37 (= 35 + 2)	AAL = 2 (= 2 + small)	RC = 35 (= 37 – 2)
Incremental Effect:			Incremental Effect:		
EP = 2 (= 32– 30)	AAL = small = (2 – 2)	RC = 2 = (30 – 28)	EP = 2 (= 37 – 35)	AAL = small = (2 – 2)	RC = 2 = (35 – 33)

As noted in Box 1, in return for placing additional capital at risk, investors will seek a target (i.e. expected) rate of return at least as high as other investment opportunities of comparable risk[101]. The rate of return expected by investors is, in effect, a cost to insurers – the cost of using the investors' capital. Other things being equal, investors will demand higher rates of return for placing greater amounts of capital at risk. If climate change increases the risk-capital requirements for insurers of weather-related catastrophes – as suggested in this study – then insurers' costs of financing this capital will also rise. In principle, this will put upward pressure on premiums.

The potential impact of climate change on an insurer's risk-capital requirements will thus impact on policyholders through two channels: (1) by putting upward pressure on premiums (as insurers have to pay for additional risk-capital), and (2) by increasing the cost of capital generally within the economy. The latter however is only a theoretical possibility. If capital is finite, an increase in demand (by insurers) will raise its price. This could adversely affect other capital-intensive sectors in the economy. Whether the demands of insurers would actually lead to a notable increase in the "price" of capital is questionable, given the shear size of global capital markets (US$ 118 trillion) relative to the additional risk-capital requirements estimated above.

6.7 Premium prices

To get a feel for the relative size of the possible increases in premium rates for property insurance against hurricane and typhoon wind damage, we have used the simple framework outlined in Box 1 above. The process is illustrated in Figure below for U.S. hurricanes, assuming a 15 per cent cost of capital. We have repeated this calculation for costs of capital between 8 and 18 per cent, and also for the A1F1 and 550 stabilisation emissions scenario (for hurricanes and typhoons), and for the A2 emissions scenario (for European windstorms). For added ease, it is assumed that expenses do not change.

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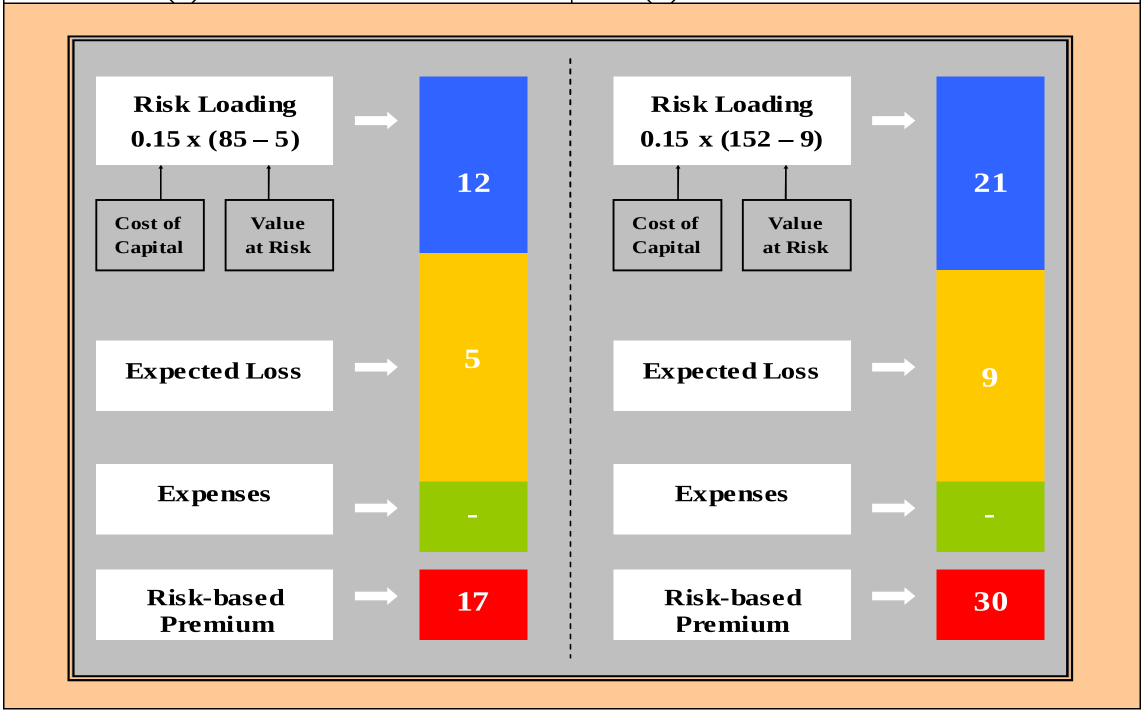
[101] Specifically, an insurer's cost of capital is the return that investors could otherwise achieve by investing their money directly themselves in a leveraged fund, plus additional compensation for various frictional costs, which are specific to insurers. Insurers operate in a highly regulated environment and are subject to an unfavourable taxation regime. As a result of these inefficiencies, which raise costs, investors will demand an additional rate of return on their risk capital.

Assuming that insurers want to meet claims in 99.6 per cent of all cases, this simplified analysis shows, other things being equal:

- **Hurricanes**: The simulated climate-stress tests under the A1F1 emissions scenario could increase aggregate market premiums by 2080-2099 relative to levels without the climate change signal by between US$ 9 and US$ 16 billion, depending on the cost of capital (the higher the cost of capital, the larger the increase in premiums).
- **Hurricanes**: The same climate-stress tests under the lower 550 stabilisation emissions scenario could increase premiums relative to levels without the climate change signal by between US$ 1 and US$ 2 billion, depending on the cost of capital.
- **Typhoons**: The simulated climate-stress tests under the A1F1 emissions scenario could increase aggregate market premiums by 2080-2099 relative to levels without the climate change signal by between US$ 3 and US$ 4 billion, depending on the cost of capital.
- **Typhoons**: The same climate-stress tests under the lower 550 stabilisation emissions scenario could increase premiums relative to levels without the climate change signal by between US$ 0.5 and US$ 0.7 billion, depending on the cost of capital.
- **European Windstorms**: The simulated climate-stress tests under the A2 emissions scenario could increase aggregate market premiums by 2080-2099 relative to levels without the climate change signal by between US$ 0.6 and US$ 0.8 billion, depending on the cost of capital.

It must be stressed, however, that prices are unlikely to change in the proportions suggested in this simplified analysis. Market dynamics – where the interaction of supply and demand can lead to marked price cycles – mean that actual premium rates often diverge from “technical premium”. This commonly observed price cycle for natural catastrophe insurance is discussed below.

Figure 6.7: Simplified Illustration of the Relative Impact on Aggregate Premiums for Hurricane Insurance Markets Under IPCC SRES A1F1 By End of Century (2080-2099) Assuming Insurers Want to Meet Claims in 99.6 Per Cent of All Cases



(a) Current climate

(b) Simulated climate-stress tests

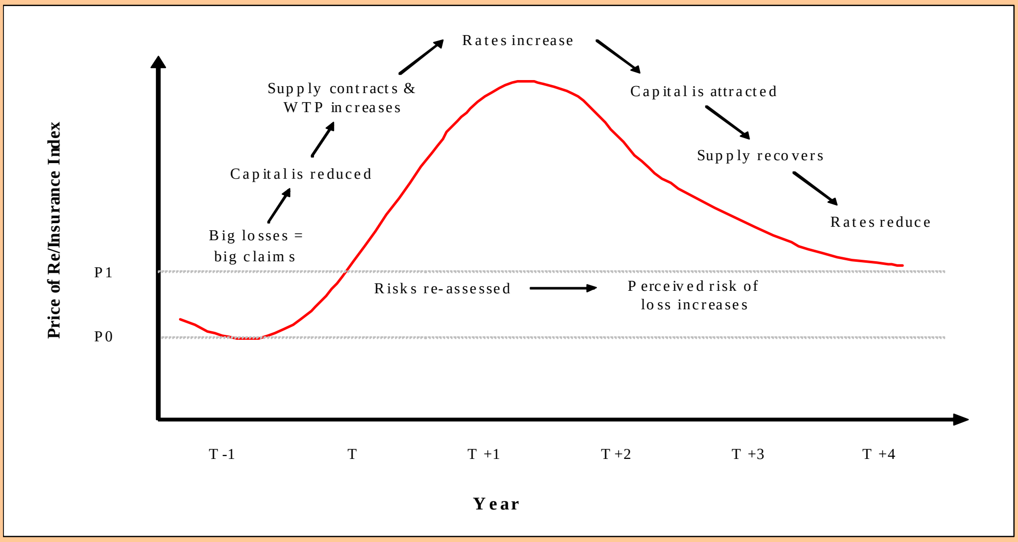
6.8 Short-run versus long-run impacts

The previous discussion essentially described the long-run response of insurance markets to the possible impacts of climate change on capital requirements and premiums. But the short-run response is more volatile. Broadly, in the short-run, following large unanticipated losses from an extreme weather event, insurers' capital is reduced, as the catastrophe leads to big claim payments, which are unlikely to be met through premium and investment income. As a consequence, insurers are not as willing, or as able, to offer the same level of coverage at current premium rates. The supply of insurance thus decreases. At the same time, having recently suffered from the impacts of the catastrophe, the insured's demand for cover is likely to increase. Falling supply and increasing demand act to push up premium rates. In time, the higher premium rates attract additional capital in search of improved returns. As a result, supply begins to recover, and premium rates begin to decline.

The big unanticipated losses heighten insurers' uncertainty about future losses. This prompts insurers to re-assess the risk of similar events occurring again, and this typically raises insurers' perceived risk of expected and extreme losses. So, even though prices begin to decline in the long-run following a catastrophe, they will not necessarily return to pre-catastrophe levels. This predictable sequence of events in response to an unanticipated extreme weather catastrophe is summarised in Figure 8, and illustrated with the example of hurricane Andrew in Box 3.

Therefore, not only might climate change put upward pressure on insurance premiums over time, it could also lead to increased volatility in insurance markets in the short-run, in the wake of increasingly severe, and variable weather. Especially, if the potential impacts of climate change on loss potential and variability are not anticipated properly (and priced) by insurers and reinsurers alike.

Figure 6.8: Stylised Illustration of Insurance Market Response to Catastrophic Event



Box 3: Unanticipated Losses: Case Example of Hurricane Andrew

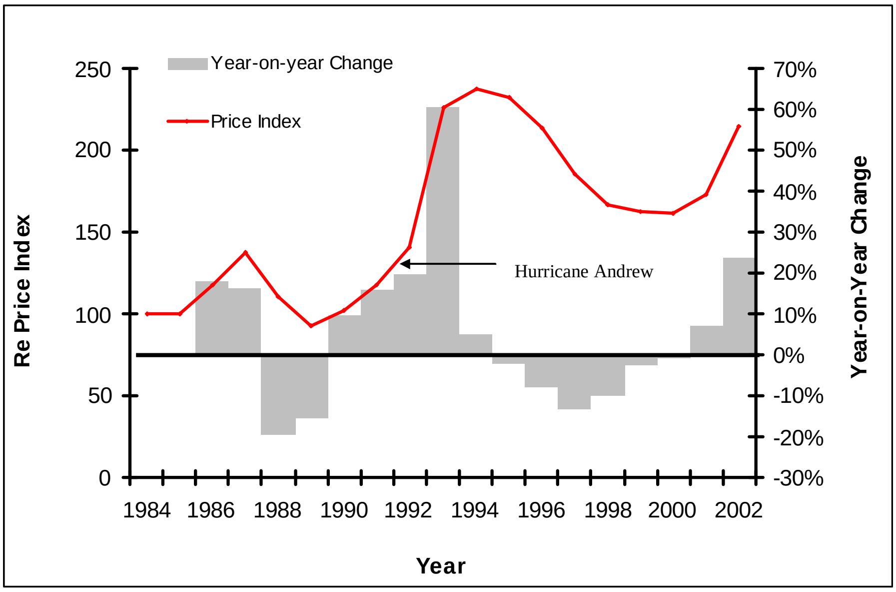
The destruction of Hurricane Andrew set a record for insured losses at the time. Property damage totalled US$ 35.6 billion, of which US$ 21.5 billion was insured. Almost two-thirds of claims were paid to holders of homeowner policies. Prior to Andrew the largest insured loss from a tropical cyclone resulted from Hurricane Hugo in 1989; this caused US$ 6.4 billion in insured losses. Following Hugo, insurers estimated that future hurricane losses would not exceed US$ 8 billion. Thus, the insured losses from Andrew were totally unexpected.

Year-on-year net underwriting losses for U.S. property and casualty insurers nearly doubled in 1992 (US$ 36.3 billion versus US$ 20.5 billion in 1991 and US$ 18.1 billion in 1993), and the insurance industry recorded its first operating loss in a decade. Three insurers paid claims in excess of US$ 1 billion, and 11 insurance companies became insolvent.

Unanticipated losses of the scale of Andrew reduce insurers' net worth and increase uncertainty about future losses. Both these factors tend to reduce insurance supply, which raises prices in the short-run as insurers try to lessen their exposure to catastrophic risk. Following Andrew 39 insurers attempted to cancel, or refused to renew close to 850,000 homeowner policies in Florida. Reinsurers also reduce their exposure by raising retentions and coinsurance amounts, and by reducing coverage. For example, the retention of one insurer went from US$ 30 million to US$ 100 million. As the supply of insurance shrinks, the price of reinsurance rises. As the figure below shows, reinsurance prices nearly doubled following Andrew, and continued to climb for about two years. Prices fell by 30 per cent between 1995 and 1998, but rose sharply again after the World Trade Centre bombings.

After the initial "supply shock" following a disaster, the industry enters a period of adjustment. The higher premium prices attract additional capital, as investors are attracted by the prospect of high rates of return. The inflow of capital restores and expands capacity. Between hurricane Andrew and the World Trade Centre bombings capital holdings climbed from US$ 163 billion to over US$ 300 billion. At the same time as capital flows into the industry, risks are re-evaluated and better understood. As a result, premium prices begin to reduce, although not to pre-catastrophe levels, since insurers' perceived risks of future expected losses will have increased.

"Paragon" Catastrophic Reinsurance Price Index (1984 = 100)[102]



6.9 Economic value of insurance

The example in Box 1 also illustrated the economic value of insurance. Insurance, in general, is capable of generating significant beneficial impacts within the economy, which are not necessarily captured by simply measuring the added value of the sector[103]. Broadly, these benefits are: risk transfer and indemnification, risk-based pricing and financial intermediation.

Risk transfer

By offering risk transfer and indemnification insurance allows risk-averse individuals or businesses to purchase large expensive items, such as houses or commercial premises. It allows them to make such purchases without needing to withhold large liquid contingency funds in order to pay for unexpected damages. Instead these funds can be used to make further purchases or productive investments. Insurance also facilitates innovation with the economy by underwriting new – relatively risky – research and technology. Basically, insurance allows individuals and businesses to undertake activities that they might not have otherwise engaged. Moreover, because insurance provides security against loss, less pressure might be placed on the state welfare system to the same end.

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[102] Paragon Reinsurance Risk Management Services, Inc. ("Paragon"). The Catastrophe Price Index is a relative measure of composite domestic U.S. property catastrophe prices. It compares the average market price at each renewal date with the average market price of one year prior. The January 2002 Catastrophe Price Index is based on a sample of over 150 companies representing almost 550 treaties, and approximately 40% of estimated industry subject premium. A standardized industry distribution reflecting variation in region, company size, limits, and retentions is used to compare the price of reinsurance over time. The index reflects overall market prices separate from shifts in actual reinsurance purchased. Weights used to compute the index are adjusted periodically and will reflect changes in the distribution of market purchases over an extended period of time.

[103] For example, according to a recent ABI study by the Centre for Risk and Insurance Studies at the University of Nottingham, the UK insurance industry contributes only about 0.3 per cent of UK GDP.

Risk-based pricing

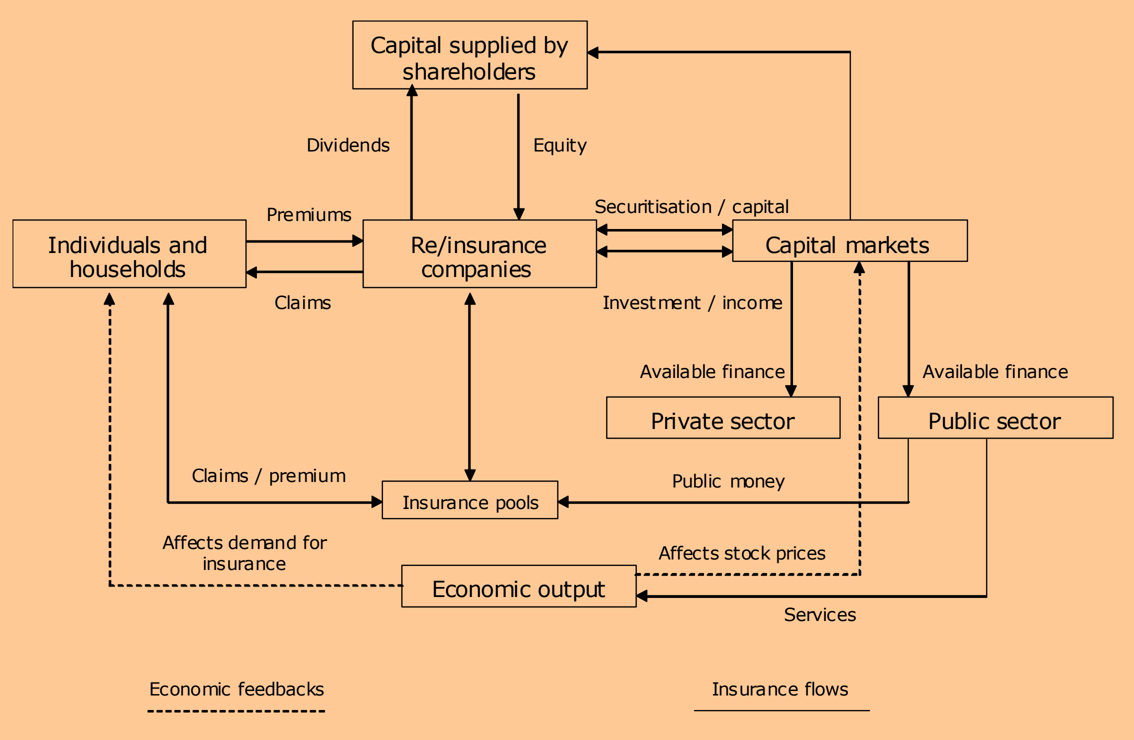
Insurance has the potential to reduce risk within the economy, since the premium reflects the risk associated with an insured individual or business. The more risk an individual poses to the accumulated human or physical capital stock, the higher the cost of insurance. But as the price of insurance rises, so does the incentive for individuals to modify their behaviour. Thus, insurance provides an incentive to reduce risk in order to reduce premiums.

Financial intermediation

Insurers invest the premiums they receive to generate income that can be used to supplement premiums when settling claims. Because insurers accrue income from their investments they are able to charge lower premium rates than they otherwise would. As institutional investors, insures are a key source of capital for the private sector and government. Furthermore, as financial intermediaries insurers help improve the efficiency of capital accumulation in the economy by reducing the transactions costs of bringing buyers and sellers together. Insurers aid the efficient accumulation of productive capital within the economy.

The links between the insurance industry and the wider economy, through which these benefits flow, are summarised in Figure 6.9. The question that now must be considered is how will the impacts of the climate-stress tests on the insurance industry, as discussed above, manifest themselves through insurance flows to the wider economy. One possible storyline is presented below, although it is very difficult to generalise across jurisdictions, since regulatory regimes and insurance markets will vary across countries, often considerably[104].

Figure 6.9: Links Between the Insurance Industry and the Wider Economy



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[104] See, for example, Ward and Zurbruegg (2000), which analysed the role of the insurance industry in contributing to economic growth, and found that the relationships are country specific. In some cases, the insurance industry promoted economic growth, whereas in other cases, the reverse was observed.

The prospect of potentially much larger damages from more intense windstorms could lead to an expansion in demand for insurance. The increase in demand will have direct and indirect economic impacts that manifest themselves through:

- Increased intermediary demand by the insurance industry.
    - In order to provide for additional cover and the associated extreme contingencies more financial capital will be required, which in turn will raise the real price of capital to both the private and public sector. Sectors in the economy that are relatively capital-intensive will thus have to offer higher rates of return, increasing their costs, in turn potentially leading to a decrease in output.
    - The higher rates of return will lead to an expansion in life insurance, and other products, depending on how they are linked in demand with property insurance (i.e. whether they are substitutes or complements to the goods whose price increases).
    - Those sectors that supply inputs to insurance (e.g. “business services” and “construction”) will experience an increase in output.
- Increases in insurance prices.
    - As a result, the quantity of insurance demanded by existing policyholders is reduced. That is, the higher prices “crowd” some policyholders out of the market. In these cases, expenditure will be switched to other products, benefiting the sectors that produce those products.
    - Sectors that are intensive purchasers of insurance will also experience an increase in costs, which could lead to a reduction in output. These sectors may have to reduce consumption of other inputs (including imports) in order to continue purchasing the more costly insurance. This would reduce both intermediary demand and the employment of labour. Reductions in the employment of labour will reduce the real wage rate.
- The overall net impact on price levels, output, and employment will depend on the structure of the economy. In the case of the UK, a 10 per cent expansion in demand for property insurance, raised the cost of capital by 0.03 per cent, reduced the wage rate by 0.02 per cent and increased GDP by 0.01 per cent. Insurance industry output increased by US$ 1,750 million; regarding other sectors, the biggest winner was “business services” where output increased by US$ 30 million, while the biggest loser was “finance”, where output fell by US$ 155 million.

6.10 Appendix A

Alternative Sources of Capital: Financial Markets

After Hurricane Andrew reduced the supply of traditional reinsurance, insurers were forced to look for new sources of capital capacity that could not be borne by insurers and reinsurers. Financial markets were the natural place to look for such capacity because of their sheer size. For example, a US$ 100 billion loss would amount to close to 30 per cent of the equity capital in the U.S. insurance market and about 40 per cent of the total capital of the global reinsurance market. However, such as loss would be less than ½ of 1 per cent of the U.S. stock and bond markets, and an even smaller fraction of the value of global securities market. Thus, the U.S. equity and debt markets alone far exceed the combined capacity of the global insurance industry.

Moreover, daily fluctuations in financial markets exceed the largest insured losses from natural catastrophes to date. Financial markets should therefore be able to absorb losses from extreme weather events without causing any significant disruption.

In addition, re/insurance markets are also subject to price and availability cycles, often resulting in price increases and supply restrictions following catastrophes, as discussed above. From the point of view of the economy, price volatility is, in general, undesirable. Additional capital would serve to dampen price volatility (Froot, 1999)[105].

Raising additional equity capital in the re/insurance industry to finance catastrophic losses, however, is costly and not necessarily efficient (Jaffee and Russell, 1997)[106]. For example, tax and accounting rules often penalise insurers for holding capital to cover infrequent events. Capital held by insurers is also subject to regulatory costs. Capital markets represent a more efficient source of additional capacity; for a start, they are more efficient at reducing informational asymmetries and facilitating price discovery (Cummins et al, 2002)[107].

Securities linked to natural catastrophes also offer investors a major advantage-portfolio diversification, since losses from natural disasters are largely uncorrelated with changes in the stock and bond markets (Canter et al, 1997).

The new products developed by financial markets to spread catastrophic risk among investors can be grouped into three categories: insurance linked bonds and notes, exchange-traded products and other structured products.

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[105] Kenneth A. Froot, *The Evolving Market for Catastrophic Event Risk*, Working Paper No. 7287 (Cambridge, Mass.: National Bureau of Economic Research, August 1999)

[106] Dwight M. Jaffee and Thomas Russell, "Catastrophe Insurance, Capital Markets, and Uninsurable Risks," *Journal of Risk and Insurance*, vol. 64, no. 2 (June 1997), pp. 205-230

[107] Cummins, J.D., D. Lalonde and R.D. Phillips (2002) "Managing Risk Using Indexed-Linked Catastrophic Loss Securities", Department of Risk Management and Insurance, Georgia State University.

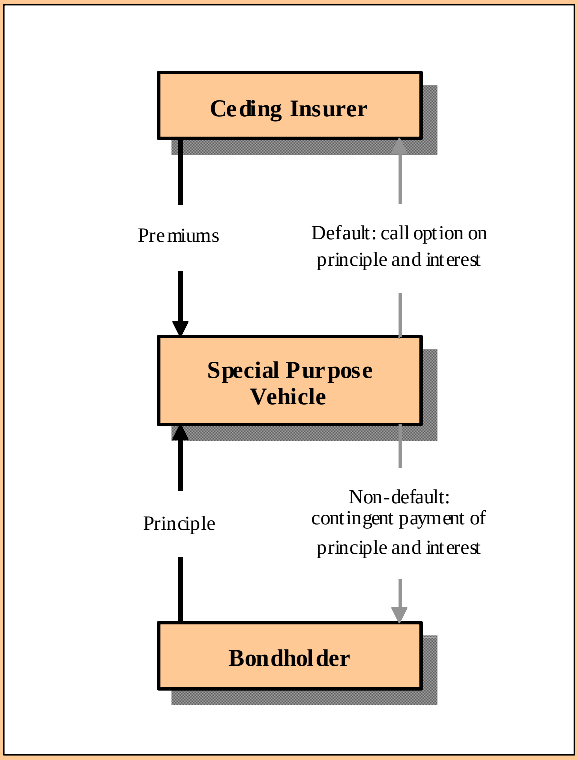
Catastrophe Bonds and Notes

Catastrophe bonds are subject to default on interest and principal, in part or in full, in the event of specified catastrophe during the life of the bond. Following an event covered by a bond, the default provisions enable the issuer – a special purpose vehicle - to use the money that would have otherwise been paid to bondholders to instead pay loss claims. For the issuer, such bonds not only provide additional reinsurance capacity, they also provide protection against the risk of counterparty (reinsurer) default. Bondholders are compensated for the default provision (which have low probabilities) by receiving high rates of return before the event occurs.

One disadvantage of catastrophe bonds is that they are susceptible to moral hazard: they give an insurer the incentive to relax underwriting and claims settlement standards, which can lead to higher than anticipated losses.

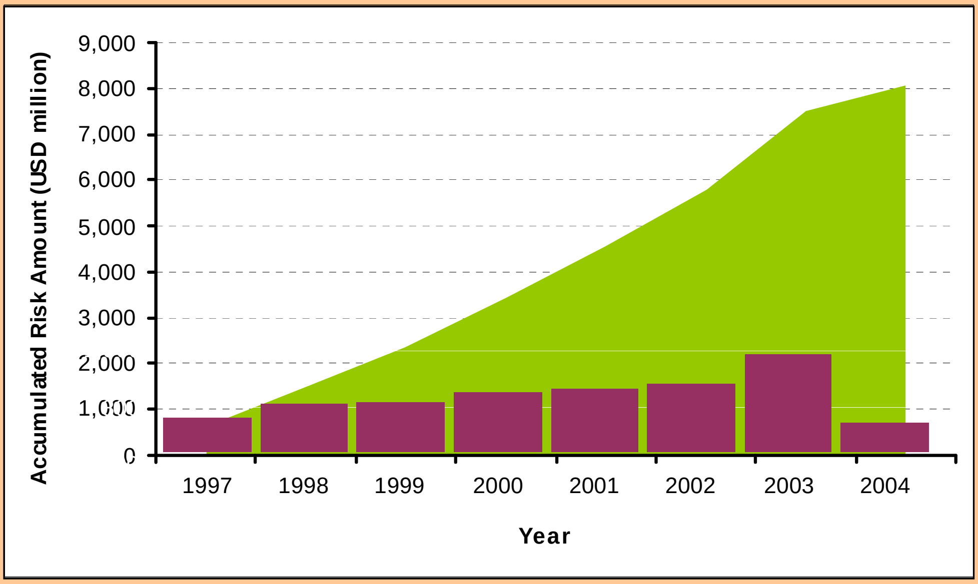
The general approach in the capital markets has been to create a reinsurance contract between the ceding insurer and a special purpose vehicle, which then effectively securitises the contract on the market (see Figure A1). This structure allows primary insurers to treat the bonds as reinsurance rather than debt for tax and accounting purposes. However, it also increases the transaction costs.

Figure A1: Structure of Basic Catastrophe Bond



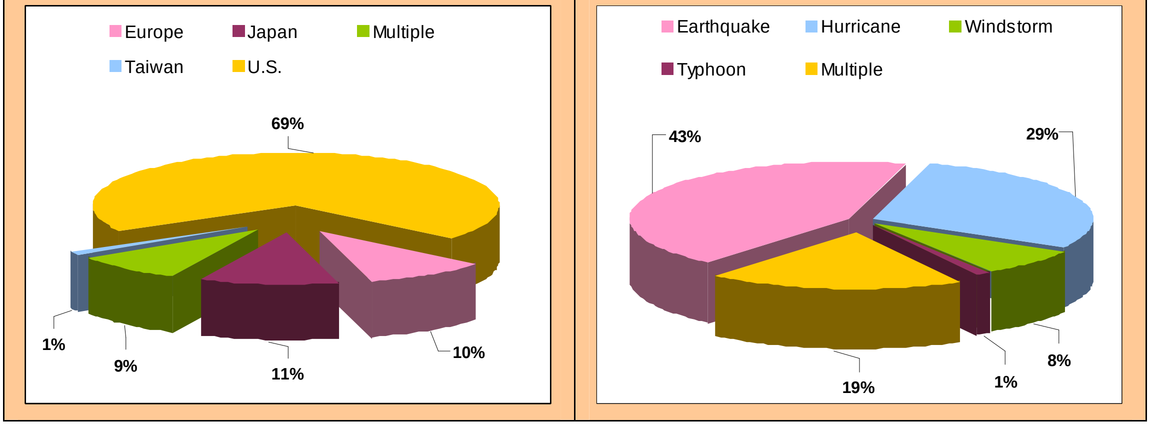
Between 1997 and early 2004, a total of US$ 8 billion in catastrophe bonds were issued (see Figure A2). Most of the issues were for losses with 1-in100 year return periods. To date, the default provisions have not been triggered on any bonds.

Figure A2: Summary of Catastrophe Bond Transactions (as at middle of 2004)



Source: Guy Carpenter

Figure A3: Summary of Catastrophe Bond Transactions (as at middle of 2004)



(a) Distribution of Accumulated Risk Amount By Risk Location

(b) Distribution of Risk Accumulated Amount By Peril

Source: Guy Carpenter

Catastrophe Options

Catastrophe options give the holder a right to demand payment under an options contract, if a catastrophe-related claims index exceeds some pre-specified threshold (i.e. the strike price). In this way, they differ from traditional reinsurance in their use of a loss index to trigger payouts, rather than losses for a particular insurer.

Use of an industry-wide loss index significantly reduces moral hazard and adverse selection because settlement is not based on the losses of a specific insurer. However, it does create basis risk, which arises because the options are not designed to match the losses of any individual portfolio, and, as a result, insurers could be exposed to a mismatch between their losses and the option's payout.

Catastrophe options have further disadvantages compared with other financial instruments used by insurers. For insurers, the cost of the options cannot be deducted from income until the options are exercised or expire. In contrast, reinsurance premiums can be deducted immediately. Some regulators may also not treat the options as reinsurance, which means that they may not necessarily be able to increase the level of coverage they have issued after purchasing options. In addition, for potential investors, the cost of informing oneself about catastrophe risks may be prohibitive. This is, nonetheless, a drawback with most capital market products for catastrophe risks.

In principle, catastrophe options can be traded at short notice and at relatively low cost. The options that were traded on the Chicago Board of Trade protected insurers from total insured losses of up to US$ 50 billion. However, trading activity ceased after December 2000 due to low trading volumes; the same happened to another trading venue, the Bermuda Commodities Exchange.

<u>Other Structured Products</u>

Contingent Surplus Note

Debt financing can also help insurers avoid financial distress following a catastrophe. Contingent surplus notes are essentially "put" rights, where insurers agree to sell, and purchasers agree to purchase, a debt note at a price agreed in advance. If the event does not occur, no debt note is issued. The debt note is thus a mechanism for risk financing, as opposed to risk transfer. The issuance of debt notes can be in exchange for cash or liquid assets, which are kept in a trust account. In the event of a catastrophe these liquid assets are exchanged, typically through a financial intermediary, for the debt note issued by the insurer, who in turn uses the funds to finance loss claims.

To induce investors to commit funds and compensate them for the risk of only partial repayment, they receive a high rate of return, or an up-front fee.

Contingent Equity Puts

Equity puts are another form of "option", in which investors, for a fee, agree to purchase equity shares at the request of an insurer in the wake of a catastrophe[108]. Insurers use the funds received from the sale of those shares to pay loss claims. The fee is designed to compensate the investor for the risk that the agreed price at which they agreed to buy the shares would actually be higher than the share's market price at the time the option was exercised.

As with surplus notes, equity puts are a form of risk financing (i.e. providing immediate liquidity), and do not perform the traditional reinsurance role of risk transfer.

Contingent equity put have a significant drawback for investors, in that it exposes them to the general business risk of the insurer. A catastrophe could occur after a period in which the insurer's shares have performed relatively poorly for reasons completely independent of the catastrophe, such as poor management.

Catastrophe Swaps

Swaps are another way of paying premiums for catastrophe reinsurance. In a swap arrangement, insurers essentially trade exposures and in doing so, diversify their holdings, thus reducing the risk that they could become insolvent after a disaster. For example, a UK based insurer might swap a portion of its flood exposure for some windstorm risk from a German-based insurer. Thus, swaps do not change an insurer's cash flows.

Most large swaps are negotiated directly between companies, but they must have a good understanding of counterparty risk. Swiss Re and Tokio Marine & Fire Insurance, for example, recently agreed to a US$ 450 million swap, which involved three exchanges of US$ 150 million each to cover losses from the following catastrophes: a Japanese earthquake for a California earthquake; a Japanese typhoon for a Florida hurricane; and a Japanese typhoon for a French storm[109].

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[109] Swiss Re, "Swiss Re and Tokio Marine Arrange Unique USD 450 Million Cat Risk Swap" (press release, Zurich, July 12, 2001)

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