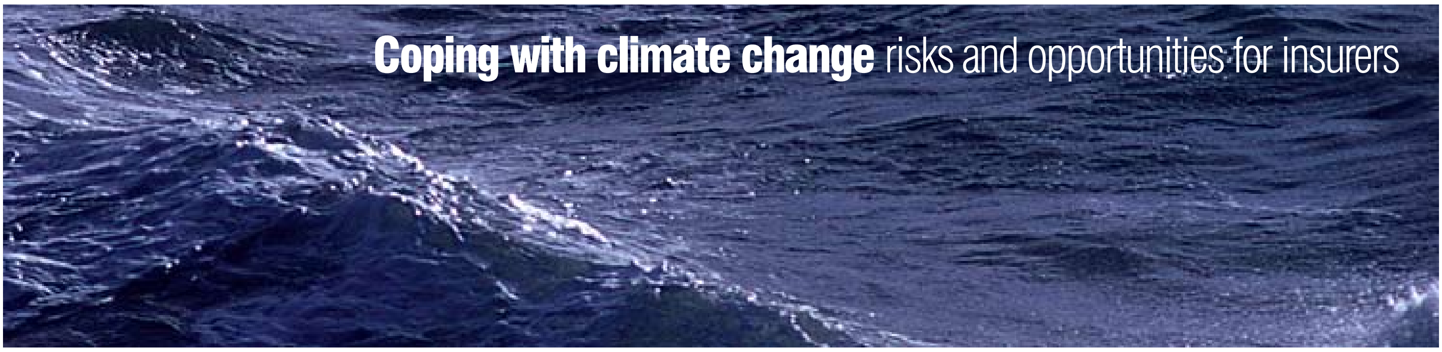

Chapter 3

The science of climate change – implications for risk management

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3.1 Introduction

This chapter focuses on the aspects of climate of greatest relevance to the insurance industry: observed and projected changes in climate extremes, including severe and tropical cyclones, floods, droughts and heat waves. Major changes in climate extremes have happened in the past 40 years, and major changes are expected in the future (Goodess, 2005). Expert judgement in the Fourth Assessment Report (AR4, referenced as: IPCC, 2007) has assessed the increasing trends in heavy precipitation events, area affected by drought, intense tropical cyclone activity and incidence of extreme high sea level to be more likely than not (Table 1) influenced by human activity. The observed trends towards fewer cold days and nights, and warmer and more frequent hot nights over land areas are considered to have a likely human contribution (IPCC, 2007 [TS[1]]).

Table 1: Standard terms used to define the likelihood of an event in the IPCC AR4.

Likelihood Terminology	Likelihood of the occurrence/outcome
Virtually certain	>99% probability
Extremely likely	>95% probability
Very likely	>90% probability
Likely	>66% probability
More likely than not	>50% probability
About as likely as not	>33 to 66% probability
Unlikely	>33% probability
Very unlikely	>10% probability
Extremely unlikely	>5% probability
Exceptionally unlikely	>1% probability

There have been significant advances in our scientific understanding of climate change in recent years. This progress has resulted from huge increases in available data, improvements in the methods of analysis, and significant developments in our understanding and modelling of the physical processes underpinning climate variability and change (IPCC, 2007 [TS]). These improvements have been collated and documented in the Report of Working Group I to the Fourth Assessment Report (AR4 WG1) of the IPCC (Intergovernmental Panel on Climate Change), 2007 [Box 1]. Evidence for the certainty of human-induced climate change continues to mount (Hegerl et al., 2007a, b), and scientific confidence in the assessment of a human contribution to recent climate change has grown considerably since the TAR (Third Assessment Report):

"Anthropogenic warming of the climate system is widespread and can be detected in temperature observations taken at the surface, in the free atmosphere and in the oceans" (IPCC, 2007 [TS]).

There is an urgent need for societal action to develop coherent mitigation and adaptation strategies. Projections of climate change indicate an increase in many types of extreme climate events in the coming decades. This chapter highlights some of the most serious challenges that lie ahead and emphasises the clear and pressing need for insurers to assess and effectively manage these risks.

BOX 1
The Intergovernmental Panel on Climate Change

The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme to assess the scientific, technical and, socioeconomic information relevant to understanding human-induced climate change. The IPCC process is one of synthesis and assessment conducted through three working groups. Working Group I (WGI) assesses the state of knowledge on the climate system and climate change; Working Groups II and III (WGII, WGIII) collectively assess the vulnerability of socioeconomic and environmental systems to climate change, and the mitigation options for reducing emissions of greenhouse gases. In addition, a Task Force is in charge of the IPCC National Greenhouse Gas Inventories Programme. The IPCC has played a crucial role in advising and supplying information to governmental and intergovernmental organisations and providing a legal and policy framework for managing the risks of climate change.

[1] TS refers to Technical Summary

3.2 Observed climate change

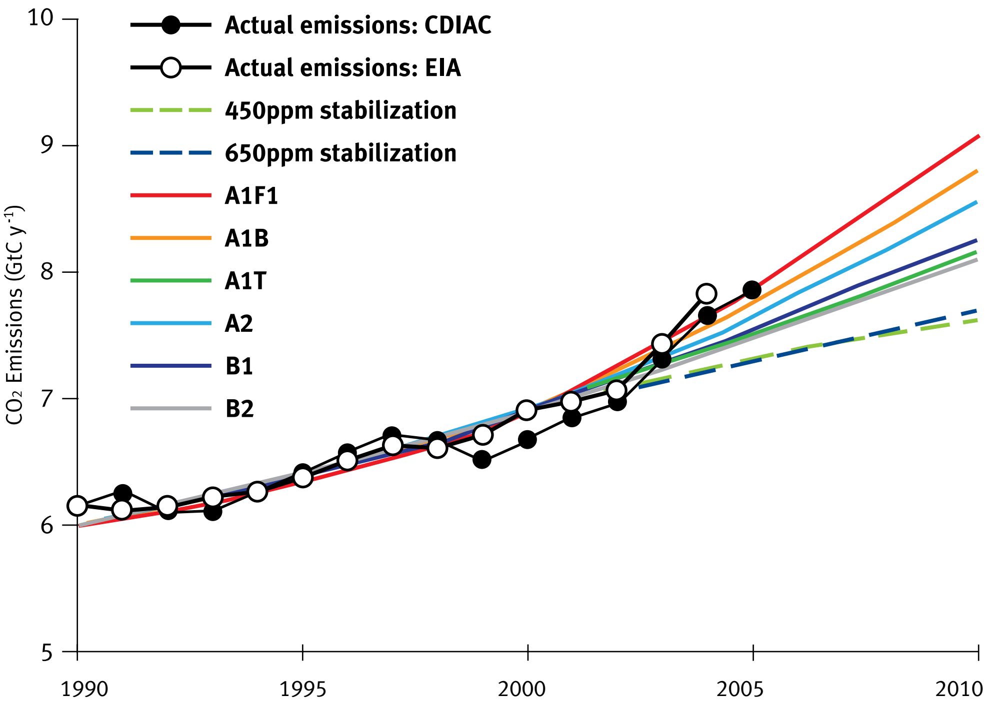
This section focuses on the detection of trends in climate extremes (storms, floods, drought, heat waves) for Europe. In recognition of the global relevance and industry-wide costs of some weather-related hazards, a discussion of tropical cyclones (Section Severe storms and tropical cyclones) and climate extremes in China (Box 3) are also included.

Emissions and global warming

Changes in emissions of greenhouse gases

Increases in atmospheric concentrations of greenhouse gases (GHG) since pre-industrial levels (1750) are largely due to human activities. The increase in the long-lived GHGs (carbon dioxide, methane and nitrous oxides) in the last four decades far exceeds that of any other time found in ice-core records which date back 650,000 years (IPCC, 2007 [TS]). Collectively, these gases produce a warming effect. Atmospheric carbon dioxide (CO_2) is the principal agent in global warming, and accounts for 63% of the effect of the long-lived GHGs. Since 1750, emissions of CO_2 have increased, due to increasing use of fossil fuel and land use changes such as deforestation, from 280 ppm to 384 ppm in 2007 (NOAA, 2008). Annual changes in global mean CO_2 emissions since 1990 are shown in Figure 1.

Figure 1: Observed CO_2 emissions (1990-2005), compared with six IPCC emissions scenarios and two stabilisation trajectories (from Raupach et al. 2007, p10289).



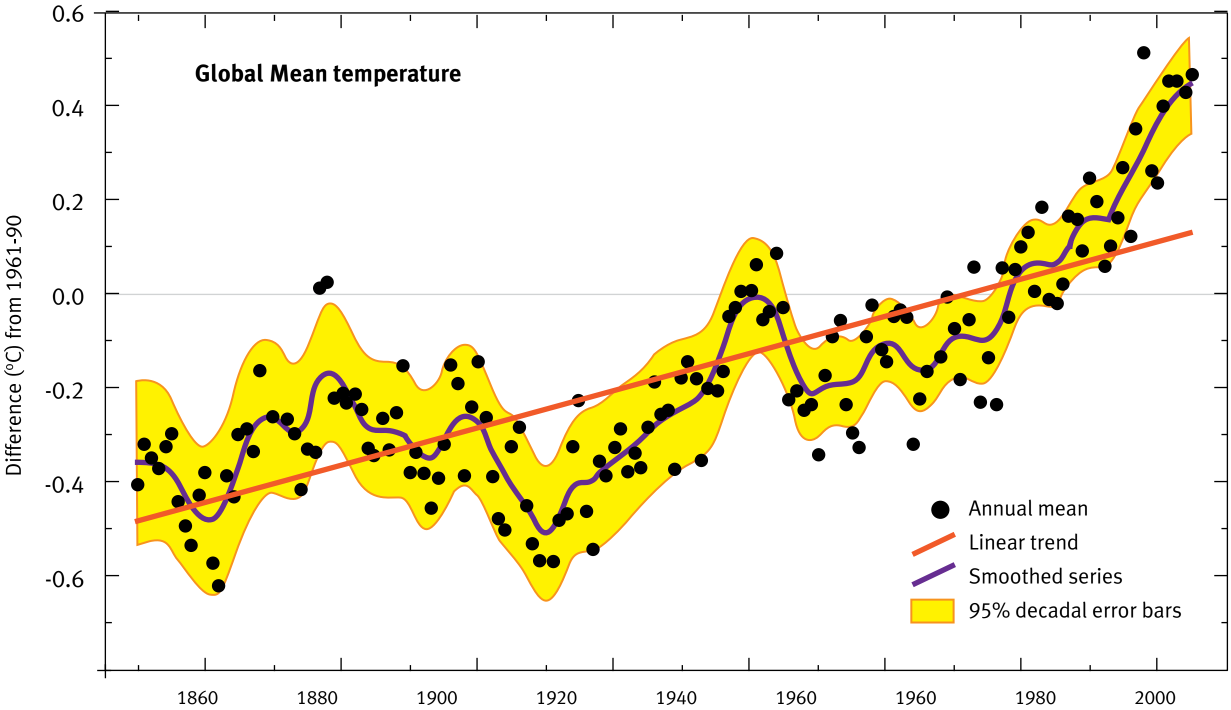
It is very likely that human emissions of GHG caused most of the observed increase in global surface temperatures since the mid 20th century. In the TAR, this statement was judged as likely, i.e., between the TAR and the AR4 there has been an increase from 66% to 90% in the confidence with which this statement can be made. Without a human influence, it is likely that natural factors (i.e., solar and volcanic effects) would have resulted in cooling instead of warming during this period (IPCC, 2007 [TS]).

Global temperature and sea level: Scientists confirm that 'warming of the climate system is unequivocal' (IPCC, 2007 [SPM[2]]). Twelve of the previous thirteen years (1995-2007) rank among the warmest in the global surface air temperature record since 1850 (see Figure 2). Recent research shows the effects of urbanisation and changes in land use to be negligible on the average temperature record at hemispheric and continental-scales (IPCC, 2007 [TS]). The TAR noted a discrepancy between the surface temperature record and radiosonde and satellite measurements of tropospheric (the lowest part of the atmosphere)

[2] SPM refers to the Summary for Policy Makers.

temperature. Revised analyses of the latter have removed this concern (IPCC, 2007 [TS]). Formal attribution assessments undertaken by the IPCC in AR4 suggest that it is very likely that human activity since the mid-20th century has caused much of the observed increase in global mean temperatures and contributed to sea level rise, that it is likely that human influence has contributed to ocean warming, and to reductions in the extent of Arctic sea ice and widespread glacial retreat.

Figure 2: Annual global mean observed temperatures (black dots, from the HadCRUT3 data set) along with simple fits to the data.

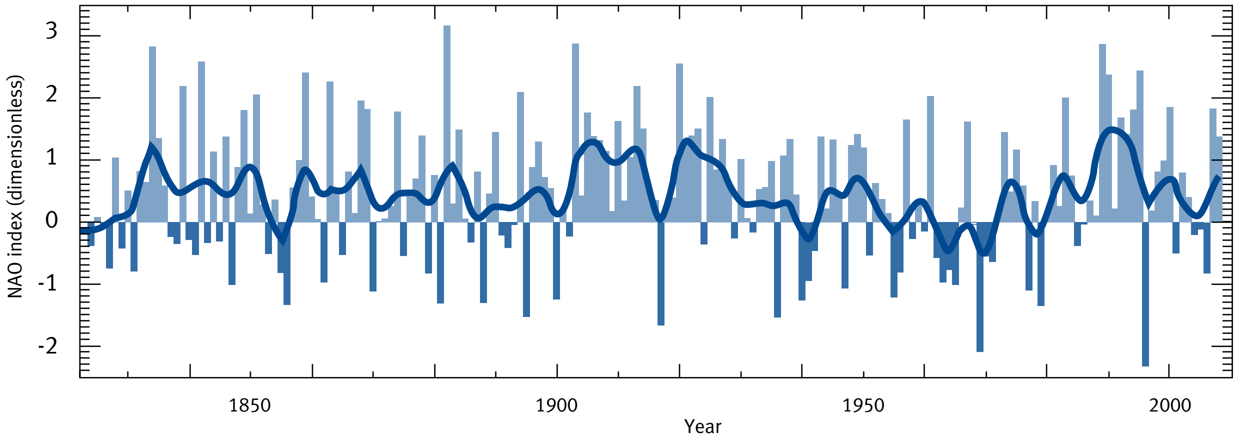


The left hand axis shows anomalies relative to the 1961 to 1990 average and the right hand axis shows the estimated actual temperature (°C). Linear trend fits to the last 25 (yellow), 50 (orange), 100 (purple) and 150 years (red) are shown, for shorter recent periods, the slope is greater, indicating accelerated warming. The blue curve is a smoothed depiction to capture the decadal variations. To give an idea of whether the fluctuations are meaningful, decadal 5% to 95% (light grey) error ranges about that line are given (accordingly, annual values do exceed those limits). Results from climate models driven by estimated radiative forcings for the 20th century (IPCC, 2007: Chapter 9) suggest that there was little change prior to about 1915, and that a substantial fraction of the early 20th-century change was contributed by naturally occurring influences including solar radiation changes, volcanism and natural variability. From about 1940 to 1970 the increasing industrialisation following World War II increased pollution in the Northern Hemisphere, contributing to cooling, and increases in carbon dioxide and other greenhouse gases dominate the observed warming after the mid-1970s [reproduced from Trenberth et al., 2007; IPCC WGI AR4 FAQ3.1].

Large-scale circulation patterns

Trends in large-scale atmospheric circulation patterns have also been observed during recent decades, such as a poleward shift and strengthening of the westerly winds in the mid-latitudes of both hemispheres. In the Northern Hemisphere these changes are evident in the increase in the winter North Atlantic Oscillation (NAO) index from the mid-1960s to the mid-1990s, which is a measure of these winds and their associated storm track in the Atlantic part of the hemisphere. The cause of this increase in westerly wind strength is currently uncertain. There is strong evidence that this increase was greater than might have been expected from natural internal variability of the atmosphere, and therefore that some climate forcing factor(s) might be driving these changes (Gillett et al., 2003). Climate model simulations of the response to increasing GHGs, while mostly pointing towards increased westerly circulation, greatly underestimate the magnitude of change compared with the observations (Osborn, 2004) and a similar outcome is found when other climate forcing factors (including natural changes) are incorporated (Miller et al., 2006). A further twist in the story is that the NAO index (Figure 3) and the strength of the westerlies have returned to values close to the long-term average during the last 10 years (Osborn, 2006).

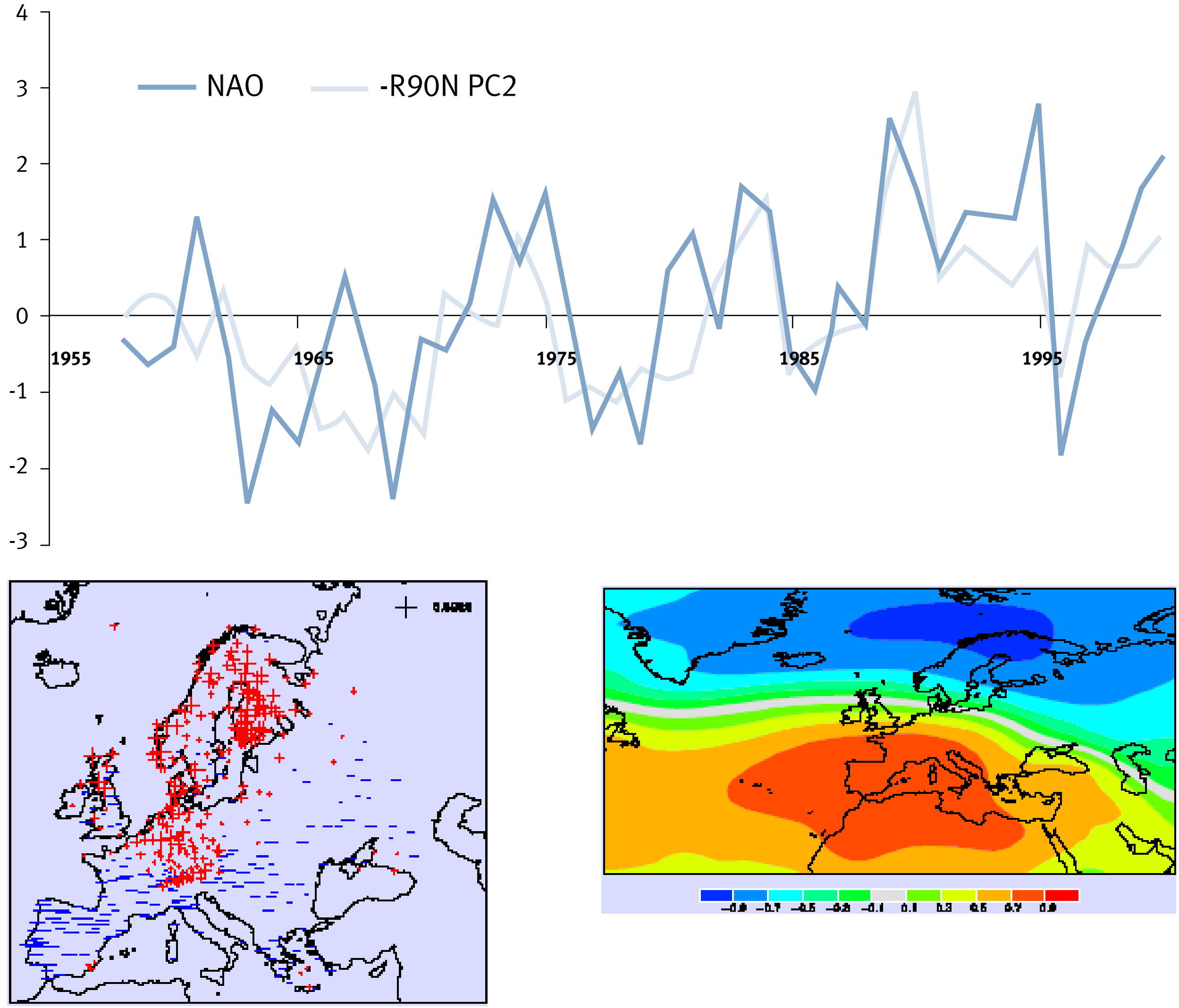
Figure 3: Winter NAO index updated to winter 2007/2008



Source: Tim Osborn, http://www.cru.uea.ac.uk~timo/datapages/naoi.htm

Changes in the NAO and other large-scale patterns of atmospheric circulation are important for explaining many regional features of the changing climate and its extremes, particularly in winter. The STARDEX EU-funded project found that changes in large-scale patterns of circulation could explain some of the observed changes in climate extremes (Haylock and Goodess, 2004). For example, the observed tendency towards positive values of the NAO index in the 1980s/1990s is associated with an increasing trend in heavy winter precipitation in northern Europe and a decreasing trend in heavy winter precipitation in southern Europe over the period 1958-2000 (Figure 4). The fluctuation in the NAO index (Figures 3, 4) is part of multi-decadal variability. The increase during the 1980s and 1990s was much stronger than expected based on model simulations and may have contributed to a stronger increase in winter precipitation intensity in northern Europe than would have otherwise occurred. Changes in the frequency, intensity and clustering of European windstorms are also partly related to changes in the NAO.

Figure 4: Correlation between the NAO and a statistically derived variable representing the number of winter heavy rainfall days for the period 1958-2000 (top).

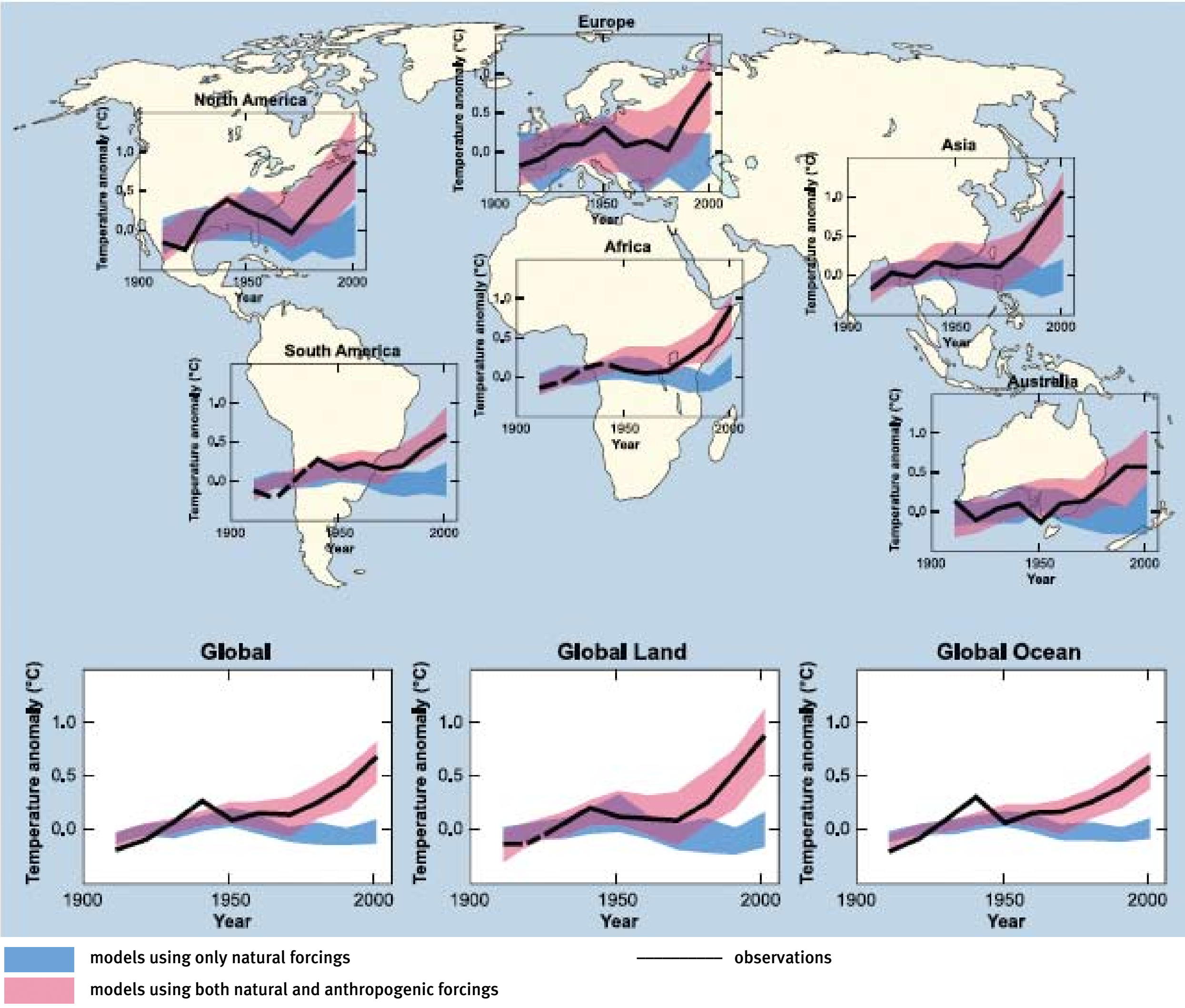


The pattern of winter heavy rainfall days (bottom left: red + indicates a positive trend/relationship, blue - a negative trend/relationship) and the associated sea level pressure patterns (bottom right). (Reproduced from the STARDEX final report Goodess, 2005; Haylock and Goodess, 2004)

Regional perspective

The human influence on warming is discernible at a continental scale (Figure 5) but there are difficulties in simulating and attributing temperature changes at smaller geographical scales (IPCC, 2007 [SPM]). Analysing a network of long-term records across Europe, Moberg et al. (2006) demonstrate a clear warming trend which is stronger in winter (1.0°C per century) than summer (0.8°C per century). In addition, they found the warming to be greater for extreme warm periods than extreme cold periods. Indicator-based regional assessments have been undertaken to identify the extent to which climate change and its consequences on natural and social systems is already occurring. The European Environment Agency (2004) assembled 22 indicators of climate change in Europe, including temperature and precipitation extremes, sea level rise, flooding and human health. For many of these indicators a clear trend exists and negative impacts are already being observed. In some cases there are benefits, e.g., a longer growing season. The most relevant points are noted in the appropriate sections below.

Figure 5: Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.



Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901 to 1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5% to 95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5% to 95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. [Source: IPCC 2007 WGI AR4, FAQ 9.2, Figure 1]

Severe storms and tropical cyclones

Severe European storms

There has been a net increase in the frequency and intensity of extreme extratropical storms over land surfaces in the Northern Hemisphere since about 1950 (IPCC WG1 Ch10; Alexander et al., 2005 [for the UK]). In addition, analysis of historical storm tracks has revealed a poleward shift and evidence of seriality, i.e., clustering of storms in time. This storm clustering poses a considerable cumulative hazard to reinsurance and insurer retentions; the damaging effect of subsequent storms in a clustering event is magnified by the earlier storms (Mailier et al. 2006, Stephenson, 2006). For example, a series of three severe storms (Anatol, Lothar, and Martin) swept across Europe in December 1999. The most expensive wind storm event was Lothar, which caused an estimated insured loss of $5.8bn (Swiss Re, 2000), largely within Germany, France and Switzerland, and a total economic loss of $11.5 bn, (Munich Re, 2001). Swiss Re (2000) estimate that insurance losses of the magnitude of Lothar have a return period of 8-10 years. The storms Lothar and Martin were separated by a time interval of just 36 hours. In the UK, windstorms since 1987 have cost almost €5 bn and caused more than 150 fatalities (ABI, 2003).

Variations in large-scale patterns and modes, such as the NAO, may modulate the location and rate of progression of storm tracks across Western Europe and may be implicated in the serial clustering of cyclones across Europe (Mailier et al., 2006). The STARDEX project has established links between specific large-scale atmospheric patterns and storms in Europe (Figure 4). For example, severe winter storms and river flooding in southwest Germany have been linked to a West cyclonic (Wz) zonal circulation pattern. This 'critical' pattern increased dramatically in frequency and maximum persistence over the period 1958-2001 (Goodess, 2005). The particular climate models examined within the STARDEX project did not, however, indicate any future increase in the frequency of this circulation pattern. As the ability of climate models to reproduce such circulation patterns improves, it should be possible to make more confident statements about likely future trends in their frequency of occurrence and persistence.

Tropical cyclones

The North Atlantic Hurricane region (which also encompasses the Caribbean) is the region where there is little dispute about the quality of the data – at least back to 1944, when aircraft surveillance began. For all other regions where tropical cyclones (the collective term as they are referred to as hurricanes in some areas and typhoons and cyclones in others) occur, data on numbers, tracks and intensity are only reliable since the start of the satellite era in 1979. In the North Atlantic region, the numbers of intense hurricanes (strength 4 or 5 on the Saffir-Simpson Intensity scale) have increased particularly since the early 1980s. In all regions, variations in tropical cyclone parameters (number, intensity and duration) are dominated by the El Niño/Southern Oscillation (ENSO) phenomenon and decadal variability, which result in a redistribution of tropical storm numbers and their tracks, so that increases in one basin are often compensated by decreases over other oceans. El Niño events for example, reduce the number of events in the North Atlantic region, but increase the number in the Northeastern Pacific region.

Until March 2004, when the first one occurred, there had been no recorded tropical cyclone in the South Atlantic. Here, it has always been believed that SSTs were too cool to initiate development.

Tornadoes, hail and thunderstorms

Small-scale severe weather phenomena such as tornadoes, hail and thunderstorms have very large spatial variability which has hampered their detection and consistent measurement and recording (IPCC WG1 Ch10). Evidence for changes in these extremes has been questioned. Discontinuities in tornado series have been reported (e.g., Trapp et al., 2005). It is likely that an increase in tornado reports in Europe is largely due to enhanced techniques of detection and improved efficiency in reporting (IPCC WG1 Ch10). Difficulties in detecting changes in severe thunderstorms due to the coarse network of observation stations have been highlighted. Research has attempted to overcome these difficulties by linking the occurrence of severe thunderstorms to larger-scale processes, and then considering changes in the distribution of these phenomena (Bissolli et al, 2007).

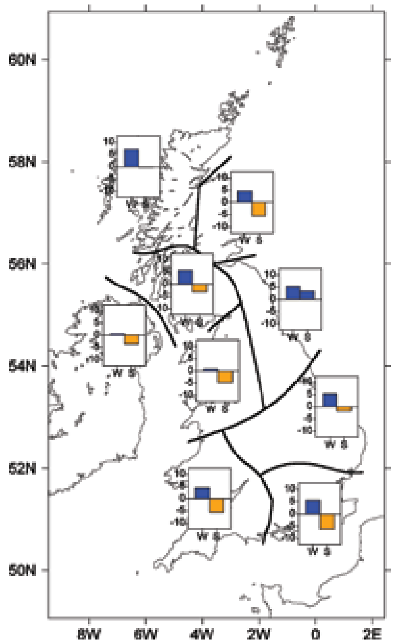
Coastal and inland floods

In the UK, nearly 2 million properties are at risk from flooding along the coast, rivers, and estuaries, and 80, 000 properties are at risk of flooding in urban areas due to storm drainage systems being overwhelmed (OST, 2004).

Heavy precipitation events

Since 1950, there have been substantial increases in the number of heavy precipitation events over many land areas around the globe (IPCC, 2007 [TS41]) and in Europe in winter (Moberg et al., 2006). This positive trend is consistent with the climate-change signal expected from increasing emissions of GHGs. For Europe in summer, there is a weak (but insignificant) trend towards fewer but more intense rainfall events (Moberg et al., 2006). For the period 1961-2000 in the UK, daily rainfall has followed the European winter pattern, by becoming more intense. However, summer rainfall events have become less intense (Osborn et al., 2000; Osborn and Hulme, 2002). These analyses have been extended to include daily precipitation observations up to 2006 (Maraun et al., 2008). Over the most densely observed period (1961-2006), most regions (Figure 6) show a trend towards increased importance of heavy rainfall events during winter (except for north-west England and Northern Ireland) and a trend towards decreased importance of heavy rainfall events during summer (except for north Scotland and north-east England). There are more complex changes than simple linear trends, however, and regional time series of precipitation intensity indicate, for example, that these trends may have levelled off in recent years. Nevertheless, in the context of the full analysis from 1900 -2006, UK precipitation over the last 20 years does appear to have been unusually extreme in winter, spring and autumn.

Figure 6: Regional trends



Regional trends over the period 1961-2006 in the contribution (%) made by heavy precipitation events to total winter (left-hand bars labelled "W") and summer (right-hand bars labelled "S") rainfall (Maraun et al., 2008). The heavy precipitation events are defined such that they contribute 10% of the seasonal totals during the 1961-1995 reference period (Osborn et al., 2000). A contribution trend of 5% (evident in most regions during winter) implies a change from a contribution of around 7.5% in the 1960s to a contribution of around 12.5% in the recent decade.

May to July 2007 was the wettest 'summer' period in England and Wales since the start of the monthly precipitation record in 1766 (UK Meteorological Office, http://www.metoffice.gov.uk/climate/uk/interesting/may_july2007/index.html). The total for this period was 415 mm, more than 60 mm more than the previous May-July record. In June and July, three storms were particularly significant (Marsh and Hannaford, 2007). In mid June a band of exceptionally heavy rainfall brought significant flooding across an area extending from the Midlands to the North East. In the last week of June, a slow-moving low pressure system generated record-breaking rainfall amounts from Worcestershire to the North York Moors. The final significant storm of the summer travelled northwards from France, stalling over central England, and resulting in exceptional rainfall totals and widespread flooding across the Cotswolds and the lower reaches of the Warwickshire Avon Basin. Although the summer floods of 2007 in the UK are out of step with the observational trends, they serve to demonstrate the dangers posed by flash flooding particularly in urban areas. The severity and extent of the flooding was extreme. Fourteen deaths have been linked to these events, over 55 thousand properties and six thousand businesses were flooded. Estimates of the total insured losses resulting from these floods are in the order of £2.25-£3.25 billion (Stuart-Menteth, 2007; ABI, 2007).

Extreme precipitation events have a huge impact on human lives and economic activities. The annual number of flood events in Europe increased between 1975 and 2001, and the number of people affected by floods has risen significantly (European Environment Agency, 2004). It is estimated that the Central and Eastern European floods of August 2002 caused over 100 deaths, and were responsible for huge economic losses of €21.1 billion and insured losses of €3.4 billion (Munich Re, 2002; see Box 2).

The aftermath of the floods of August 2002 led many to wonder if this event was indicative of the effects of human-induced climate change. Experiments using a range

BOX 2

Floods in Europe – August 2002

The Central European flood of August 2002 caused over 100 fatalities, and estimated insured losses of around $3.4 bn with total economic losses of around $16 bn (Munich Re, 2005; Munich Re, 2003). It was the most costly weather-related catastrophe in Europe in recent decades. Prolonged and heavy rainfall culminated in flooding along several major rivers in Europe, including the Elbe, Vltava (Moldau), Danube, Inn and Salzach. The flood affected a huge expanse of Central and Eastern Europe, including, Germany, Austria, the Czech Republic, Italy, Spain, Russia, Slovakia and Hungary (Caspary, 2004).

Originating from south of Greenland, a rain-bearing, low-pressure system (commonly classified as circulation type Vb by German meteorologists) tracked across Europe along the southern flank of the Alps passing over the Mediterranean Sea and picking up vast amounts of moisture. As the extremely warm and humid air system turned northwards on a track near to the eastern Alps, it encountered a cold front and the deluge began. Record-breaking rainfall amounts and intensities were recorded at several raingauges across Central Europe. The torrential rain fell on already saturated soils, and flowed to rivers already close to bank full. The extreme river flow rates in the Danube and Elbe subsequently led to major floods and the inundation of large urban areas (Rudolf and Rap, 2003; Ulbrich et al., 2003a, b).

of global climate models suggest that this event is consistent with a trend towards more intense summer rainfall events in parts of Europe (Ulbrich et al., 2003b). A recent EU-project STARDEX identified critical circulation patterns associated with extreme events such as the European storms and floods of August 2002 (see Section on Drought).

The flood of August 2002 is a stark demonstration of the vulnerability of society to extreme events, and provides an insight into the magnitude of the challenges to come.

Sea level rise and storm surges

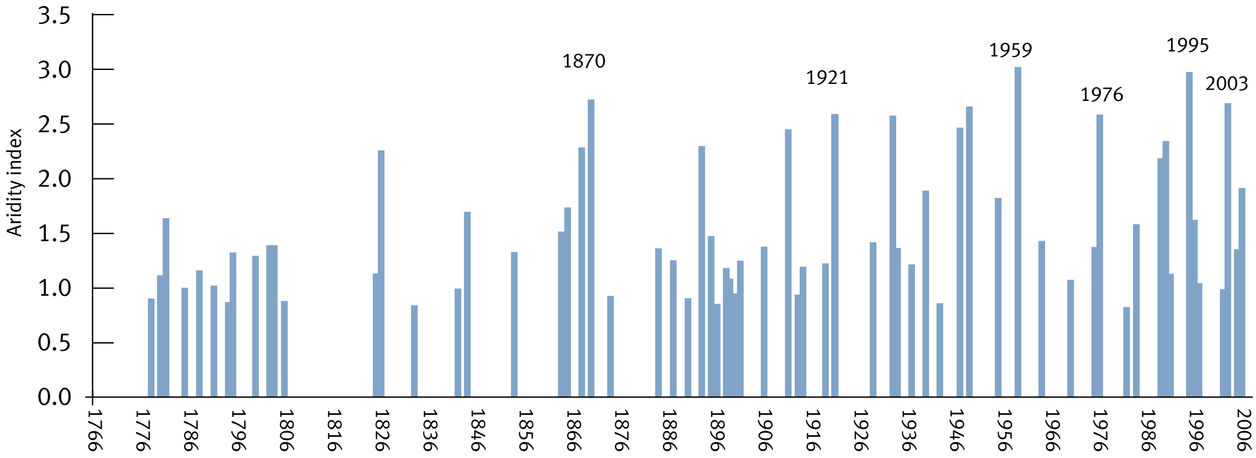
Thermal expansion of the oceans and the melting of glaciers and ice caps have contributed substantially to sea level rise over the last 40 years. Between the years 1961 and 2003, the global mean sea level rise is estimated (using tide gauge records) to be 1.8 mm per year (IPCC, 2007 [TS]). This figure masks considerable regional variability, with sea levels rising more in the Western Pacific and eastern Indian Oceans, and falling in the Eastern Pacific and Western Indian Oceans. The variability in sea level rise at regional and local scales is associated with ENSO, the NAO, variability in wind, variability in ocean temperature, salinity and, circulation, glacial isostatic adjustment (the continuing, though gradually slowing, long-term vertical movement of landmasses in response to de-glaciation following the last ice age, amounting to about 0.7 mm per year relative sea level rise in south-east England), earthquakes, abstraction of fluids (oil, gas, water) from deltas, and changes in rates of fluvial sedimentation and erosion. In the past century, sea level around Europe has risen by between 0.8 mm per year (Brest, France and Newlyn, Cornwall) and 3.0 mm per year (Narvik, Norway) (European Environment Agency, 2004).

Storm surges tend to accompany tropical or extra-tropical cyclone activity and generally culminate in serious coastal flooding particularly when combined with a high tide. Of the relatively few stations with long-records of sea level heights, the majority of sites show an increasing trend in extreme sea level height (Bindoff et al., 2007). In the European Union, one third of the population lives within 50 km of the coast. In the UK, it is estimated that one million properties are at risk from sea and tidal flooding (DEFRA, 2004). It is only the Thames Barrier and associated tidal defences that have made central London a viable place to live and work (McRobie et al., 2005).

Drought

Since the 1970s, droughts have become longer and more intense, particularly in the tropics and sub-tropics and are strongly influenced by the cycle of El Niño events (IPCC, 2007 [TS]). Recent extreme droughts have occurred in Central and Southwest Asia (1998-2003); Australia (2002-2003), and Western North America (1999-2004). In Europe, the most notable droughts of the past three decades occurred in 1975-76, 1989-91, 2003 and 2005-06. However, there is substantial regional variation. In southern Europe, the number of very wet days has significantly decreased in recent decades, and annual rainfall has decreased by up to 20% in the 20th century (European Environment Agency, 2004). In the UK, there have been a succession of dry summers in the last two decades: 1990, 1995, 2003, 2006. Long-term trends in the severity of summer droughts for England and Wales has been analysed for the period 1776-2005 (Marsh et al., 2007). A clear increase in summer drought severity is apparent in the 20th century relative to the 19th century (Figure 7). Winter rainfall has a relatively larger contribution to water resources than summer rainfall, particularly in the ground-water fed systems of the southeast of England. Long time series of rainfall deficits show no evidence of trend because winter rainfall has been increasing while summer rainfall is decreasing in England and Wales (Barker et al., 2004). The net result is a modest increase in runoff and groundwater recharge.

Figure 7: An aridity index for England and Wales, 1776-2006



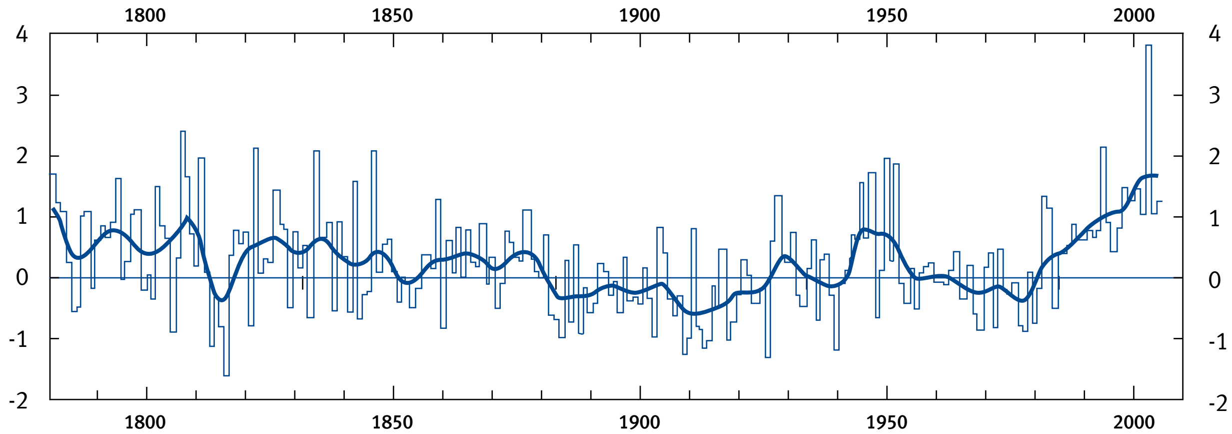
Source: date obtained from Terry Marsh 2008, after Marsh et al. 2007, weather 2007 62(4):92

Temperature extremes

Heat waves

Since the latter half of the 20th century, the duration of summer heat waves has increased globally (IPCC, 2007). The summer of 2003 in western and central Europe was the warmest since instrumental records commenced (IPCC WG1 Ch 10). For central Europe, the summer temperature was 3.8°C higher than the long-term average (Figure 8). Estimates vary, but the final death toll resulting from the summer European heat wave of 2003 could be in excess of 70,000 (Robine et al., 2008). Meteorological and human factors giving rise to the summer 2003 heat wave have been described in depth (e.g., Black et al., 2004; Fink et al., 2004; Stott et al., 2004). The IPCC AR4 concluded that “surface temperature extremes have likely been affected by anthropogenic forcing,” “and there is evidence that anthropogenic forcing may have substantially increased the risk of extremely warm summer conditions regionally, such as the 2003 European heat wave” (IPCC, 2007 [TS]; Hegerl et al., 2007b).

Figure 8: Central Europe summer temperature (anomalies from 1961-90)



Source: IPCC, 2007:Box 3.8.5

Cold extremes

A decreasing trend in the number of frost days has been identified for the period 1951-2003 for over 70% of the global land area (IPCC WG1 Ch 10), and most parts of Europe. The shift towards a positive phase of the NAO from the 1960s to the 1990s, and the associated strengthening of the westerly circulation, probably contributed to the observed trend towards milder European winters and a decrease in the number of cold and frost days (European Environment Agency, 2004). Beniston

(2005) links these NAO variations to a significant increase in extreme positive high-temperature anomalies in the Swiss Alps in winter (i.e., to an increase in cold season 'heat waves'). The STARDEX project examined 481 stations across Europe for trends in frost days for the period 1958-2000 and found a decreasing trend over most regions except some parts of the Greek mainland (Goodess, 2005). The largest decreases are up to 0.8 frost days per year (i.e., 8 fewer frost days per decade) with a mean of 0.17 frost days per year (1.7 fewer frost days per decade). Since the mid 1990s, the NAO has fallen back towards average conditions. Further study is needed to determine the extent to which these various measures of cold season extremes have also returned to earlier values and what proportion of the changes have remained because they are linked to an underlying climate change that may be driven more directly by greenhouse-gas-induced warming than by NAO variations.

Change in observed frequency of extreme events

A recent assessment (IPCC, 2007) of trends in climate extremes used expert opinion to indicate the likelihood of: observed recent trends, human influence on the observed trends, and projections of these trends for the later 20th century (Table 2, see Section 3.4). The available scientific evidence does not always support popular opinion/anecdotal evidence of increases in the frequency of extremes. In trend analyses of extremes, the greatest uncertainties tend to be found for wind storms and discrepancies are reported in the trends of overall numbers and intensity of cyclones. Leckebusch et al. (2007) report no significant trends in North Atlantic / European storm activity. Trends that have been identified are for specific types of cyclones, or for specific sub regions. For example, Trigo et al (2000) found a decline in the number of intense Mediterranean cyclones and an increase in 'non-intense' cyclones. In a 45-year record, Guijarro et al. (2006) show a significant decrease in the cyclonic circulation in the Western Mediterranean, and an increase in the Eastern Mediterranean.

In any one series, it becomes more difficult to detect a real trend as the event becomes rarer and the sampling noise increases (Frei and Schär, 2001; Frei et al., 2006; Moberg et al., 2006). For this reason, scientists tend not to focus on very extreme events but on moderately extreme but more frequent events or "deviations" to increase the likelihood of detecting a real trend. Although these extremes are not necessarily those most relevant to insurance, a balance is struck between reliability and robustness, and impacts relevance. New approaches have been developed to disentangle the confused signals of variability and trend. For example, as part of work on the CRANIUM (Climate change Risk Assessment: New Impact and Uncertainty Methods; http://www.cru.uea.ac.uk/cru/projects/cranium/) project, a new technique has been developed by Newcastle University for estimating extreme rainfall trends with given confidence limits (Goodess et al., 2007). It allows two important questions to be addressed: (1) for a fixed length of record, how large a trend is required to be detectable with certain levels of confidence, and (2) for a given trend, how long a record is required for detection? New statistical techniques such as this are also relevant to the difficulties in calculating and interpreting return periods in a non-stationary climate (Jones and Reid, 2001). For example, Fowler and Kilsby (2002) have questioned the validity of estimates of return periods for drought events in contemporary records for the UK. Nonetheless, return periods provide a useful means of quantifying risks. Dlugolecki (2008), for example, calculated return periods for 'hot' and 'cold' (defined by the highest and lowest 10% respectively) extreme months for the long record of central England temperatures (CET). Decadal counts of extremes, indicate an increase in 'hot' extremes from the 1960s to the 2000s (10 'hot' months in the 1960s; 33 hot months in the 2000s). There were five 'cold' months in the 1960s rising to eight 'cold' months in the 1980s, and zero 'cold' months in the 2000s to date. Extending this analysis to more extreme months, Dlugolecki (2008) found that the shifts were relatively much greater when the level of 'hot' was set at 5% and 1%. "What was historically a 10-year event now occurs every 2.7 years, the 20-year event occurs every 4.3 years, and the return period for a 100-year event is just 12.5 years."

Table 2: Recent trends, assessment of human influence on trends, and projections of extreme weather and climate events for which there is evidence of an observed late 20th-century trend

Phenomenon and direction of trend	Likelihood that trend occurred in late 20th century (typically post-1980)	Likelihood of a human contribution to observed trend	Likelihood of future trend based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	Very likely[a]	Likely	Virtually certain
Warmer and more frequent hot days and nights over land areas	Very likely[b]	Likely (nights)	Virtually certain[c]
Warm spells / heat waves: Frequency increases over most land areas	Likely	More likely than not	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increase over most areas	Likely	More likely than not	Very likely
Area affected by droughts increases	Likely in many regions since 1970s	More likely than not	Likely
Intense tropical cyclone activity increases	Likely in many regions since 1970s	More likely than not	Likely
Increased incidence of extreme high sea level (excludes tsunamis)[d]	Likely	More likely than not[e]	Likely[f]

Notes:

[a] Decreased frequency of cold days and nights (coldest 10%).

[b] Increased frequency of hot days and nights (hottest 10%).

[c] Warming of the most extreme days/nights each year.

[d] Extreme high sea level depends on average sea level and on regional weather systems. It is defined here as the highest 1% of hourly values of observed sea level at a station for a given reference period.

[e] Changes in observed extreme high sea level closely follow the changes in average sea level. It is very likely that anthropogenic activity contributed to a rise in average sea level.

[f] In all scenarios the projected global average sea level at 2100 is higher than in the reference period. The effect of changes in regional weather systems on sea level extremes has not been assessed.

BOX 3
Climate change in China

The observed warming trend is above the global mean trend in East Asia. Models project a median temperature increase of 3.3°C between 1980-1999 and 2080-2099. This warming is projected to be greater in winter, and in north-western regions (Christensen et al., 2007a; Xu et al., 2006b; Shi et al., 2007). Monsoons are a key feature of the climate of China. Model projections for the Asian region frequently show a weakening of the large-scale tropical circulation and monsoonal flows. However, it is likely that this weakening of the circulation pattern will be accompanied by a warming-enhanced advection of moisture, resulting in increased monsoonal precipitation in all seasons. The construction of climate scenarios for Asia are constrained by a lack of observational data in some areas, model shortcomings in simulating spatial variability in 20th century climate and a lack of regional-scale studies of climate change. Also, there is incomplete understanding of the factors that influence monsoon processes, and the ENSO.

Tropical cyclones:

Historically, typhoons have wrought considerable damage across China. Typhoons are tropical cyclones of the western North Pacific basin. The three most economically damaging typhoons since 1999 have averaged economic losses of $US 2.7 bn (Ketang, 2000). The Yangtze delta is particularly vulnerable to typhoons (tropical cyclones) and the storm surges generated by these typhoons have been as extreme as 5.2 m (Zhong and Chen, 1999). The genesis and tracking of typhoons have been linked to large scale circulation patterns such as ENSO (e.g., Saunders et al., 2000; Wu et al., 2004; Ho et al., 2004). Although there are no apparent trends in the annual number of typhoons over the period 1945-2003 for coastal provinces of China (Fogarty et al., 2006), extreme rainfall and winds accompanying tropical cyclones are likely to increase in East Asia (Christensen et al., 2007a). If the destructive power of typhoons intensify in the future, it seems likely that their economic costs will also increase.

Coastal flooding:

Much of China's rapid urbanisation (and economic development) has taken place in the eastern provinces on land which is particularly vulnerable to sea level rise and the risk of storm surge. Consequently, an increasing trend in casualties from storm surges has been reported (Ye, 2006). The potential risk of coastal inundation due to sea level rise has been examined for the Pearl River delta in southern China. This is an area of rapid economic development with a population of 12 million and a population density of 1230 people km-2. Sea levels have been rising exponentially in this area and are projected to be 29 cm higher by 2030, relative to 1990 values. In the previous four decades 190 flood events have been recorded across the deltaic plain and flood defences are inadequate even under current conditions. To increase the standards to meet a 30 cm rise in sea level by 2030 is estimated to cost approximately $US 263 million (Huang et al., 2004).

Inland flooding:

Vulnerability to floods has increased in China as population pressures have given rise to rapid urban development within flood plain zones. In 1998, a severe flood in the Yangtze River catchment (Eastern China) led to 3700 deaths, 223 million people were displaced, 25 million hectares of agricultural land was inundated, and the total cost was estimated as $30 bn (Jun, 2006). The flood of 1998 was associated with the East Asian summer monsoon which is the dominant driver of rainfall events in the Yangtze River basin (Jiang et al., 2005; Becker et al., 2006). However, in 1998 the monsoon came earlier than usual, and precipitation was more intense. Vulnerability to floods has also increased as pressure for agricultural land has resulted in the loss of dikes, storage reservoirs and natural wetlands; land reclamation schemes in flood plains; and deforestation of hill slopes. Many flood defence systems in China are only built to withstand floods with return periods of 1 in 10-20 years, a criteria much lower than for many more developed nations (Jun, 2006; Ye, 2006). Intense precipitation is very likely to increase in Asia (Christensen et al., 2007a) and more specifically China (Zhai et al., 2005). Climate simulations indicate an increase in the number of rain days in northwest China (Gao et al., 2002) and in the number of rainstorm days in East China (Su et al., 2006), and a decrease in rain days but an increase in days of heavy rain in south China (Gao et al., 2002; Kitoh et al., 2005; Ye, 2006).

Water resources/drought:

There are large regional differences in observed trends in precipitation extremes and in the aridity index in China (Wu et al., 2006). The northern provinces are suffering from a protracted drought which began in the 1980s (Ma and Fu, 2006). The increasing frequency of dry extremes and drought is particularly pronounced in the Yellow River valley (Qian and Lin, 2005). In southern China, although an increasing trend in summer precipitation is observed (Zhai and Wang, 2003; Ye, 2006), a late spring drought has been identified over South China in recent decades (Xin et al., 2006; Zhai et al., 2005). This spring drought is associated with the positive winter phase of the NAO (Xin et al., 2006). Single-model projections derived with the PRECIS RCM indicate that seasonal precipitation will decrease in South China (-36% in winter) by the end of the 21st century, with very much weaker decreases suggested for East China (-8% in autumn) and Northwest China (-2% in autumn) (Xu et al., 2006a).

Heat waves:

Notable heat waves have occurred in 1998 and 2003 in Shanghai, China. Mortality is strongly associated with the intensity and duration of the heat wave (Tan et al., 2007). Extreme maximum temperatures in China are projected to increase in the future (Xu et al., 2006a). It is very likely that summer heat waves in East Asia will be more frequent, more intense, and last longer (Christensen et al., 2007a).

Financial losses:

Direct economic losses due to all natural hazards have increased exponentially in China from the 1970s (Ye, 2006). Much of the accelerating increase in losses has resulted from the explosion of economic activity and development since the policy reforms of 1979 (Ye, 2006). Weather-related disasters account for over 70% of the total losses of all natural disasters in China, and 3%-5% of the GDP (Jun, 2006).

3.3 Climate models

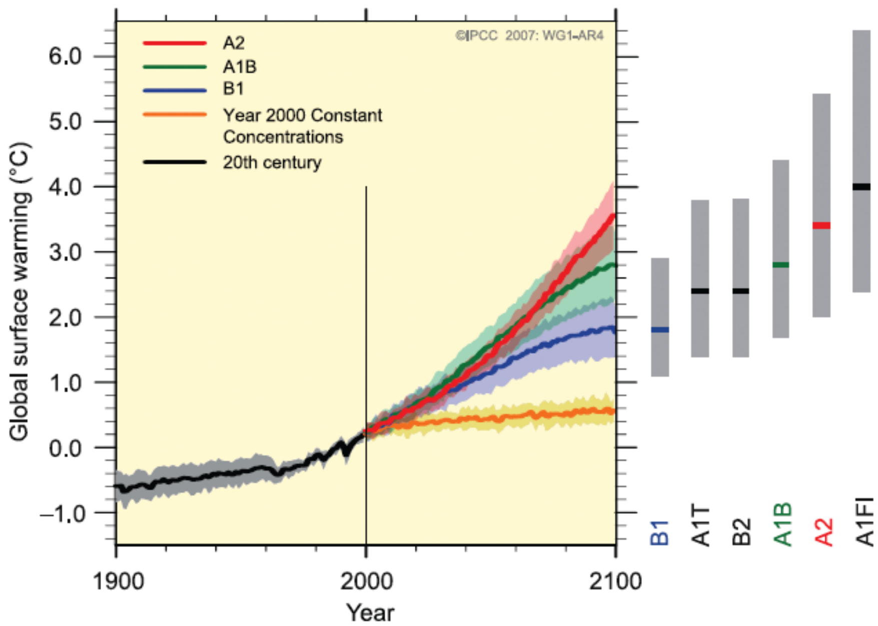
Atmosphere-Ocean General Circulation Models (AOGCMs)

Climate models are built on well-established physical laws and principles and can simulate many aspects of past and present climate. The most comprehensive climate models are atmosphere-ocean general circulation models (AOGCMs). These models include components representing atmospheric, oceanic, land surface, and ice-mass processes that evolve over time. There have been substantial advances in AOGCMs in recent years. The number of processes modelled has increased and there have been considerable improvements in computation methods and representations of sea ice, the atmospheric boundary layer and ocean mixing. As a result, the simulation of past and present climates continues to improve and strengthens confidence in future projections (Stone et al., 2007).

Limitations and uncertainties

Scientists strive to attain a complete understanding of the complexity of the climate system. The key sources of uncertainty involve cloud feedbacks (especially from low clouds), the cryosphere (feedbacks from snow, ice and frozen ground), ocean heat uptake and mixing, land use and, connections between climate and biological/geological chemical cycles (IPCC, 2007 [TC]). Parameterisations are used to represent unresolved small-scale physical processes. Projections of future climate vary for two reasons: first, due to uncertainty about the future concentrations of GHGs, and second, due to differences in the way the different AOGCMs treat parameterisations (IPCC, 2007 [TS]). Up to 2040, the course of global-scale temperature change is largely pre-determined. Figure 9 quantifies these uncertainties as time progresses.

Figure 9: Multi-model averages and assessed ranges for surface warming



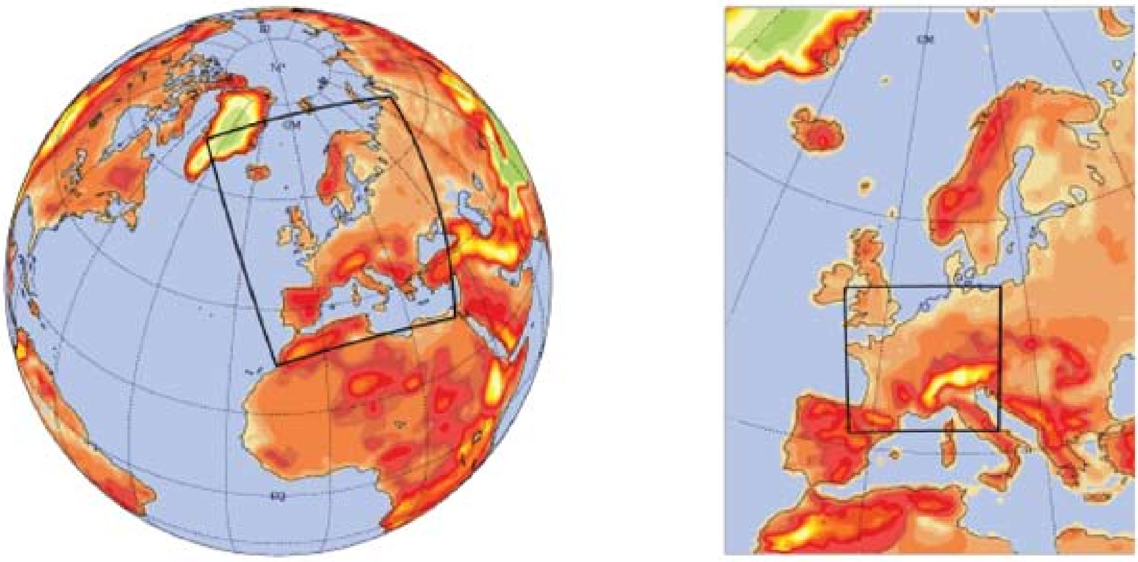
Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. [Source: IPCC WGI AR4, Figure SPM5]

Extreme events are, by nature, short-lived and of limited spatial extent in contrast to the coarse resolution of AOGCMs. While recent model developments have brought improvements in the simulation of some extreme events (e.g., related to temperature), there remains greater uncertainty in projections of extreme events associated with mid-latitude and tropical cyclones (see Table 2). The ability of models to reproduce present-day extremes is a factor in the confidence we might have of future trends. For example, the frequency and amount of precipitation falling during severe storms tends to be underestimated (Randall et al., 2007). Higher resolution climate models are better able to replicate the frequency and distribution of tropical storms, but their intensity is still not well represented (Oouchi et al., 2006).

Regional climate models and downscaling

Although the spatial resolution of AOGCMs has improved, it remains too coarse to resolve many regional and local features. Therefore, AOGCMs are used to drive regional climate models (RCMs) which can provide a satisfactory representation of some extreme events (Fowler et al., 2005). Recently, for example, direct RCM output has been combined with hydrological models to simulate riverflows (including high and low flow) in the UK (Fowler and Kilsby, 2007). Parallel to advances in regional models, 'downscaling' techniques have demonstrated improved skill in simulating local climate in present-day conditions (IPCC, 2007 [TS]). Downscaling relates to the technique of translating the gridded output from AOGCMs (with a typical resolution of 300 km across Europe) to the finer resolution required for impact studies (Figure 10). There are two main methods of downscaling: statistical (e.g., Goodess, 2005; Haylock et al., 2006; Schmidli et al., 2007) which can achieve any resolution down to point data, and dynamical (e.g., Christensen et al, 2007b) which nests an RCM within the coarser-scale global climate model and typically attains a resolution of 25-50km for a whole continent. Downscaling introduces another set of modelling uncertainties, e.g., projections of climate change at finer scales tend to be more uncertain where there is complex topography (IPCC, 2007 [TC]). It is recommended good practice to use a multi-model approach to downscaling, whether statistical or dynamical downscaling is used (Goodess, 2005). It is also important to use multiple AOGCMs prior to downscaling since this global uncertainty tends to dominate regional uncertainties). In the case of summer rainfall, however, the downscaling uncertainties can be of comparable magnitude to the forcing uncertainties (Déqué et al., 2007).

Figure 10: Dynamical downscaling: a RCM nested within a GCM.



GCM **RCM**

The larger window shows a typical European-wide 50km domain, and a smaller domain that has been run at a spatial resolution of 12km. The higher resolution of the RCM yields an improved representation of, for example, the underlying topography within the model domain, such as the Alps and Pyrenees.

Europe has led and is continuing to lead the way in downscaling and the use of downscaled outputs via three major EU-funded projects, PRUDENCE, STARDEX and, ENSEMBLES. PRUDENCE focused on dynamical downscaling and demonstrates the value of using several models to represent uncertainty, while the focus of STARDEX was on statistical downscaling. STARDEX also compared the two different approaches to downscaling. The spatial and time scales for downscaled outputs vary among projects. For the European domain, PRUDENCE used a spatial resolution of 50 km, while STARDEX produced point values, and the RCM resolution in ENSEMBLES will be 25 km. Projections for PRUDENCE (and STARDEX point values) were for the time slices 1961-1990 and 2071-2100, whereas ENSEMBLES focuses on nearer windows of time because these are more relevant to decision-making among stakeholders including the insurance industry.

Emissions scenarios

The IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000) are the most widely used scenarios in projections of climate change. An illustrative range of six SRES 'marker' scenarios or storylines, has been defined (Table 3). Previous research has tended to focus on the A2 and B2 marker scenarios, however, more recently there has been a greater focus on the A1B scenario (such as in the IPCC AR4, and in the EU-funded ENSEMBLES project).

Table 3: Brief description of the IPCC SRES

Scenario	Storyline Description	CO_2 concentration by 2050	CO_2 concentration by 2100
A1B:	World of very rapid economic growth. Balanced energy sources. A medium-high emissions scenario	532 ppm	717 ppm
A1FI:	World of very rapid economic growth. Fossil fuel intensive. A high emissions scenario	567 ppm	970 ppm
A1T:	World of very rapid economic growth. Predominantly non-fossil fuel. A low emissions scenario	501 ppm	582 ppm
B1:	Global solutions to economic, social and environmental sustainability, illustrating a convergent world. A low emissions scenario	488 ppm	549 ppm
B2:	A heterogeneous world with local emphasis and less rapid development. A medium-low emissions scenario	478 ppm	621 ppm
A2:	A very heterogeneous and regionally oriented world of rapid population and economic growth. A medium-high emissions scenario	532 ppm	856 ppm

There has been debate on the appropriateness of different metrics for assessing GDP (Gross Domestic Produce) in emission scenarios. PPP (Purchasing Power Parity) is the preferred metric for international comparisons of incomes for countries at varying stages of development, while the MER (Market Exchange Rate) is the preferred metric for analyses that include internationally traded products. It is claimed that the use of the MER has led to a positive bias in emissions scenarios and hence warming projections. Barker et al (2007) insist that the choice of GDP metric does not appreciably influence projections of emissions, when used consistently. Although the IPCC SRES have been widely adopted in studies of the potential impacts of climate change, other scenarios have been devised such as the Foresight scenarios (OST, 2004) used in flood risk management in the UK, and the 'Conventional Worlds', 'Barbarization', and 'Great Transitions' scenarios (IPCC, 2007).

3.4 Climate change projections

Future pattern of warming

There have been significant advances since the TAR, with the emergence of probabilistic projections of climate change (IPCC, 2007 [TS]). Even if GHG and emissions were held constant, warming would still continue for several decades due to the thermal inertia of the oceans and cryosphere. If future GHG emissions were within the range of the SRES marker scenarios a mean global increase of 0.2°C per decade would be expected (IPCC, 2007 [TS]) (Figure 9). Over continental areas, the projected warming is greater than the global average (IPCC, 2007 [TS]), and up to 2030 is insensitive to the choice of emissions scenario (Figure 9). By the end of the 21st century European temperatures are simulated to be between 2.2°C and 5.4°C warmer than the end of the 20th century. This warming is likely to be greater in northern Europe in the winter and greater in the Mediterranean area in the summer.

Extreme events

Society is particularly vulnerable to a shift in the intensity and frequency of extreme events, especially severe storms and tropical cyclones, flood, drought and heat waves. Even a small change (<10%) in the severity of an event can result in a huge increase in property damage and associated financial losses. Since the TAR, more climate models have been used in the simulation and projection of extremes. These provide more information about the probability distribution functions of extremes and other extreme statistics. There is some evidence that climate extremes are changing more rapidly than-average climate (Schär et al., 2004). Furthermore, scientists consider that there may be a non-linear association between a change in the mean of a distribution and behaviour at the extremes because other features of the distribution have also changed (Hanson et al., 2007). Research on the projection of climate extremes remains patchy, and for some regions only a few studies have been undertaken (IPCC, 2007 [TS]). For example, the analysis of some extremes, such as tropical cyclones is still limited by data inadequacies, scientific understanding and model resolution. There is greater confidence for other variables, such as projections of winter extremes (and in particular temperature extremes) in Europe (Goodess, 2005).

Severe storms in Europe

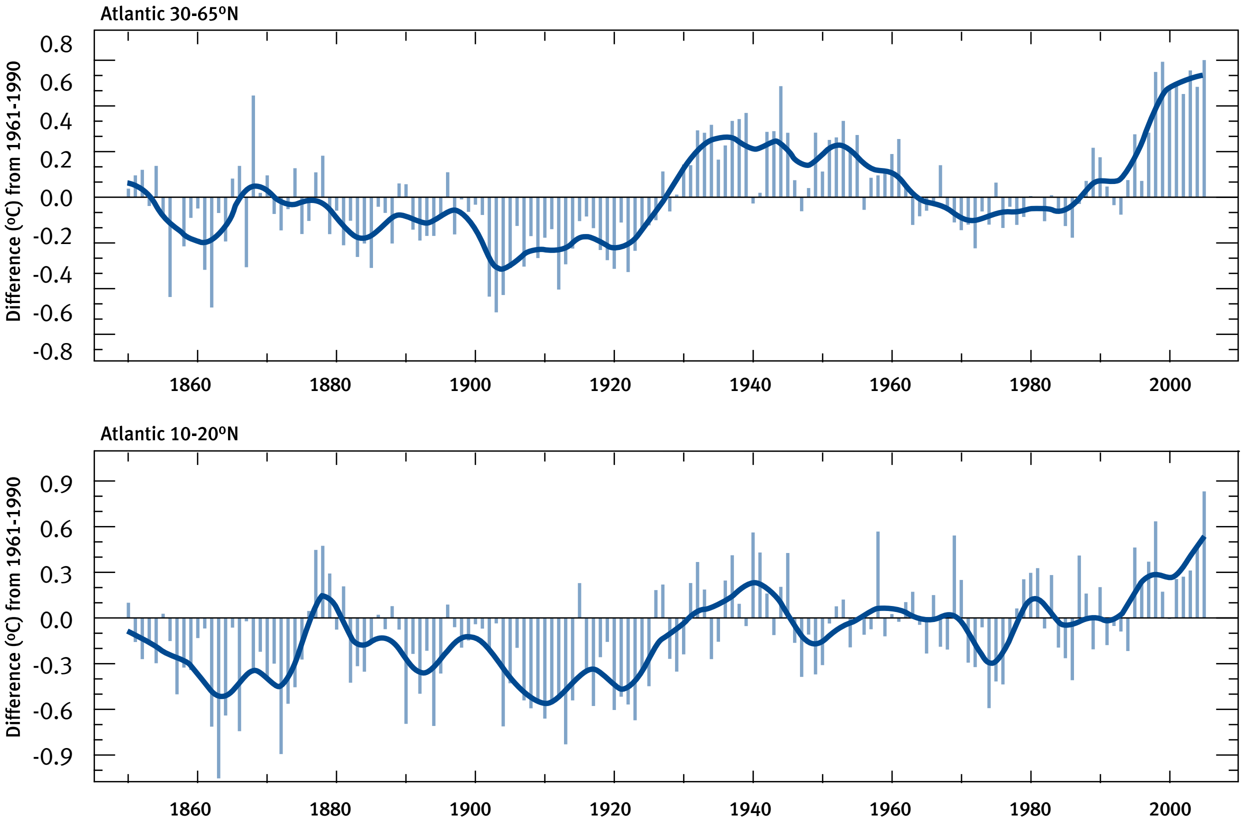
Storm tracks are projected to shift polewards, and some studies simulate a reduction in mid-latitude storms (IPCC, 2007 [TS]). An increase in low probability high impact storms or multiple successive severe storms could severely affect parts of the financial sector. In Europe, extreme wind speeds are generally associated with intense winter cyclones (e.g., Leckebusch and Ulbrich, 2004). Scientific opinion of the IPCC is that ‘it is more likely than not that there will be an increase in average and extreme wind speeds in northern Europe’ (Christensen al., 2007a). In the EU-project PRUDENCE, extreme wind speeds (i.e., in the top 10 per cent of daily winter wind speeds) were projected to increase by 3-25% in most mid-latitude areas by the latter half of the 21st century and were more pronounced for the North Sea, the United Kingdom, France, northern Switzerland, and Germany (Beniston et al., 2007). An increase in the 99th percentile of daily winter wind speeds was projected for the winter season only (Rockel and Woth, 2007). Several studies indicate a decrease in the total number of Mediterranean cyclones (e.g., Leckebusch et al., 2006; Pinto et al., 2006; Ulbrich et al., 2006), but it is uncertain whether the number of intense cyclones will increase or decrease (Lionello et al., 2002; Pinto et al., 2006; Anagnostopoulou et al., 2006). Rockel and Woth (2007) highlight the necessity of considering the output from a range of models when assessing future changes in extreme winds.

Mid-latitude winter storms play an important role in property loss across Europe. Using an ensemble of four climate models (with one integration each), it is estimated that storm-related losses could increase by up to 37% and 21% respectively for the UK and Germany, by the end of the 21st century (Leckebusch et al., 2007). A subsequent study ran an ensemble of three climate change simulations for a single AOGCM to estimate insured loss potentials for a wider area of Europe (Pinto et al., 2007). The projected storm loss potentials are greatest for Germany and France and least for Portugal and Spain. An important finding is an increase in the interannual variability of insured losses (indicative of a shortening of the return period for very extreme events) particularly for Germany, the United Kingdom, and France (Pinto et al., 2007). Swiss Re (2006) estimated an increase in annual insured losses of 16-68% over the period 1975-2085 in Europe. In agreement with Pinto et al (2006), Swiss Re (2006) project the greatest impact in Germany (three-fold the mean European value). Within the UK, the regions most vulnerable to future increase in storm activity are indicated to be Northern Ireland and Scotland (Leckebusch et al., 2006). However, due to a high concentration of buildings, urban conurbations in England are particularly vulnerable to storm damage. One earlier study suggests that the UK cities likely to sustain the greatest windstorm property damage are London, Birmingham and Swansea (ABI, 2003).

Tropical cyclones

There is a strong correlation between the number of intense hurricanes in the North Atlantic and SSTs in the main development region in the tropical Atlantic. While this is accepted by all scientists, the major discussion point is what has caused the increase in SSTs. Some (e.g., Trenberth et al., 2007; Emanuel, 2005; Webster et al., 2005, Emanuel et al., 2008) believe SSTs are increasing due to the gradual warming of the climate system (i.e. global warming), so will continue into the future, while others (Goldenberg et al., 2001; Landsea et al., 2006) believe that the increased SSTs are part of a ~60-yr cycle known as the Atlantic Multidecadal Oscillation (AMO, Figure 11). Whichever of these hypotheses is believed does not make that much difference to the next 5-10 years, as SSTs will remain high whoever is right. In the longer term, global warming will increase SSTs in most regions, so that the next trough (2020s/2030s) in the AMO will not reduce SSTs back to the levels experienced in the last trough during the 1960s and 1970s. Warmer SSTs in the development region are likely to increase the length of the hurricane season, as the period when SSTs are above 26.5°C will be extended with continued warming. SSTs are not the only factor affecting storm numbers, duration or intensity, but it is the one that is extremely likely to increase in the future.

Figure 11: Atlantic Multi-decadal Oscillation (AMO) index, 1850-2005.



The AMO index is represented by annual anomalies of SST in the extratropical North Atlantic (30–65°N; top), and in a more muted fashion in the tropical Atlantic (10°N –20°N) SST anomalies (bottom). Both series come from the HadSST2 dataset (Rayner et al., 2006) and are relative to the 1961 to 1990 mean (°C). The smooth blue curves show decadal variations). [Reproduced from IPCC, 2007: Chapter 3]

As stated above, for all other regions where tropical cyclones occur, the lengths of records are too short to estimate correlations with SSTs reliably. In the Northwestern Pacific region, where the strongest and most frequent tropical cyclones occur, there is likely no relationship whatsoever with SSTs, as the absolute values of SSTs in the main development region are already well above the required threshold for tropical cyclone initiation. This implies that further warming will be unlikely to have much effect except to potentially increase intensity and duration. With continued warming in the North Atlantic, it is likely that this region will also pass through this limit at some point late in the 21st century.

Drought

The risk of summer drought is expected to increase in Europe, particularly in Southern Europe (IPCC, 2007). By the latter half of the 21st century, droughts in the Mediterranean could start earlier in the season and have a longer duration. The regions most likely to be impacted are the southern Iberian Peninsula, the Alps, the eastern Adriatic seaboard, and southern Greece (Beniston et al., 2007). An ever increasing demand for water is likely to exacerbate problems of water shortage due to climate change. Consequently, action on water scarcity and drought is high on the EU policy agenda and a working group was formed in 2003 to combat these challenges: Water Scarcity Drafting Group: Water Scarcity Management in the Context of WFD (June 2006). The most recent report (EC: Water Scarcity and Droughts; Second Interim report, June 2007) provides an updated overview of the extent and severity of water scarcity events and droughts at the EU level and additional information at the national levels. A future objective of the working group is to establish a European Drought Observatory and early warning system (European Commission, 2007).

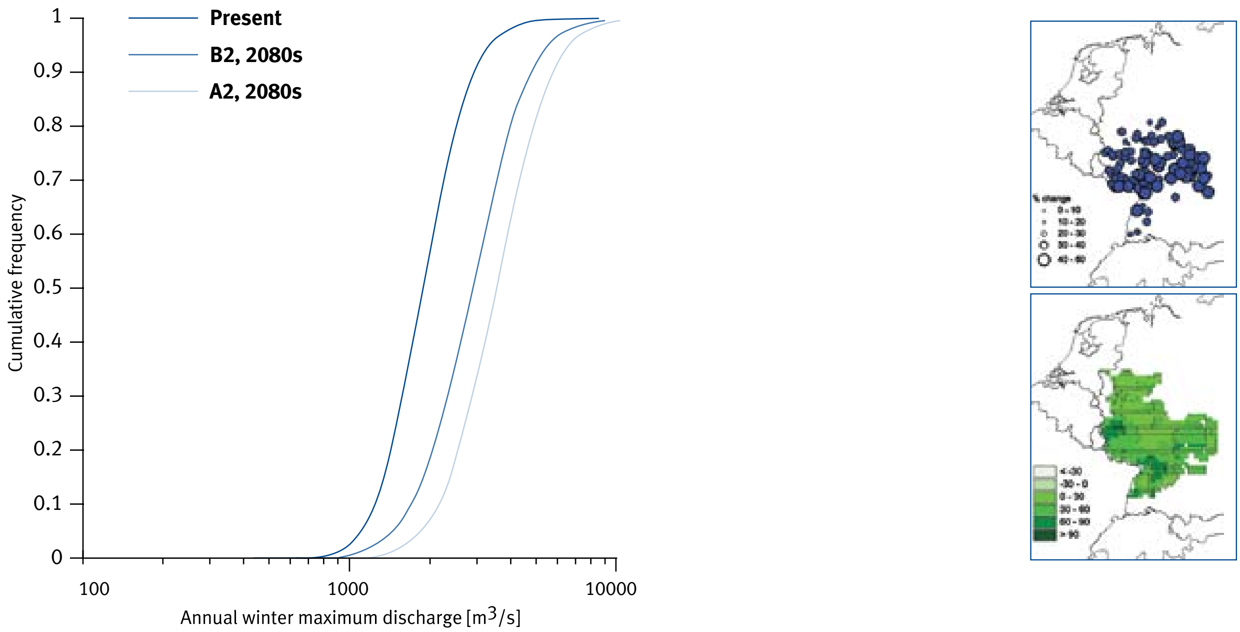
There is potentially high susceptibility to drought in the UK, and a generally good awareness of the potential challenges of climate change in the water supply industry, however, adaptive action plans are yet to be devised and implemented across all sectors and activities (European Environment Agency, 2007). There are two major aspects of drought that are of relevance to the financial sector. First, clay shrinkage due to soil moisture deficits following protracted droughts can induce building subsidence (CII, 2001). A second major implication is the negative effect of water scarcity in manufacturing processes and in energy production (for cooling and for hydroelectricity).

Soil moisture deficits are likely to increase in the future as summer rain decreases and potential evapo-transpiration increases. However, there is considerable uncertainty regarding future changes of drought for the UK. Projected changes in the drought severity index (DSI) were estimated for the UK using four AOGCMs and six RCMs (Blenkinsop and Fowler, 2007). The results indicated a greater likelihood of short-term summer droughts over southern and central England. Long-term droughts are projected to become shorter and less severe due to increases in winter precipitation. However, inter-model differences cast high uncertainty on these projected changes. Current research is working to produce probabilistic projections to deal with these modelling uncertainties (see Section 3.4, Assessing the risk of climate change through probabilistic projections). For example, Wilby and Harris (2006) demonstrated a probabilistic framework which addresses uncertainties in hydrological as well as climate modelling. The likelihood of a reduction in summer low flows in the River Thames by the 2080s was estimated using four AOGCMs, two emissions scenarios, two statistical downscaling techniques, two hydrological model structures and two sets of hydrological parameters. The choice of AOGCM and method of downscaling were found to be the greatest components of uncertainty. For example, a conditional experiment (with weights applied to each uncertainty component) yielded a likelihood of lower minimum summer flows for the 2080s which ranged from 47% to 100% depending on the choice of AOGCM.

Heavy rainfall events and fluvial floods

Modelling results indicate a global trend towards fewer rain days but heavier daily rainfall events in some regions (IPCC, 2007 [TS]). Extremes of daily rainfall are very likely to increase in northern Europe, south Asia, East Asia, Australia and New Zealand (in part these areas reflect the geographical coverage of research) (IPCC, 2007 [TS]). The EU-funded project, MICE (Hanson et al., 2007), found more days with intense precipitation in northern Europe, and fewer days with intense precipitation in southern Europe and particularly in Mediterranean countries. The STARDEX project examined future trends in extremes for six case-study regions in Europe (Goodess, 2005), and found that extreme winter rainfall is likely to increase by the end of the 21st century in four of the six case-study areas: SE and NW England; German Rhine; central continental Greece; and the Alps. Figure 12 shows the projected increase (typically 30-40%) in maximum 5-day winter precipitation on the Mosel catchment for the 2080s. This pattern of change is consistent with the observed changes for 1958-2001 which are also shown in the figure. Finally, the figure shows that the projected precipitation changes may lead to substantial increases in extreme discharges in this tributary of the River Rhine (i.e., the flow-duration curve shifts to the right, particularly for the higher A2 scenario). Expressed in more-readily understood terms, the results presented in Figure 12 indicate a 69% increase in the 100 year return period winter discharge for the B2 scenario, and a 104% increase for the A2 scenario.

Figure 12: Projected changes in flow duration winter maximum discharge for the Cochem gauge, Mosel – main figure.



Top right figure shows the % change in greatest 5-day winter rainfall for the A2 SRES scenario A2,in the 2080s. Bottom right figure shows the observed % change in greatest 5-day winter rainfall, 1958-2001 for 611 stations [Source: Andras Bardossy, USTUTT-IWS]

Frei et al (2006) estimate that in northern Europe, a 40- to 100- year return value of the present climate could correspond to a 20-year return value for the climate of 2070-2100. In parallel, the PRUDENCE project estimated increases in heavy winter precipitation in central and northern Europe and decreases in the south, by the latter half of the 21st century. Heavy summer precipitation is estimated to increase in north-eastern Europe and Scandinavia and decrease in southern Europe (Bensiton et al., 2007). Furthermore, the PRUDENCE results indicate an increase in the variability of precipitation in many parts of Europe even for the summer season (Christensen and Christensen, 2003).

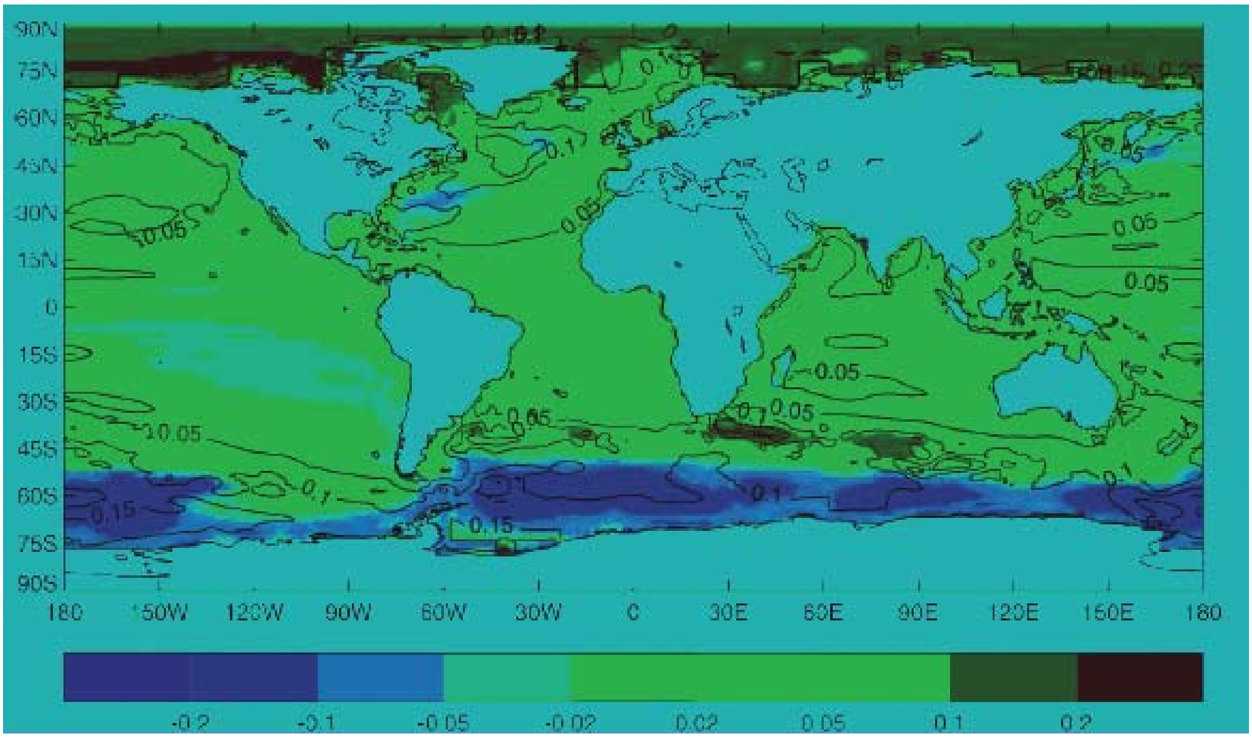
In the UK, for the northwest and southeast of England, winter rainfall is likely to increase by a factor of 1 to 1.25 by the end of the 21st century (Haylock et al., 2006). Several regional assessments of changes in extreme rainfall events have been undertaken for Britain using RCMs (e.g., Jones and Reid, 2001; Ekström et al., 2005). Jones and Reid (2001) used Hadley Centre RCM integrations to estimate changes in heavy precipitation events over Britain for the period 2080-2100. More days of high precipitation (upper 10% of precipitation for the control integration) were projected for all seasons. The greatest increase was projected for southern Britain where there could be up to 4.5 more days of heavy precipitation in the winter season. There could be up to 3 more days of heavy rainfall in western Britain for the other seasons. An analysis of return periods suggests that the greatest increases in the threshold values (relative to the control output) for particular events could be in the south/south-east of England, with a GHG/control ratio of up to 1.8 for the 50-year return period. This translates to an increase (for southern Britain) of up to 32, 22, 16 and 10 more events above the threshold values for 1 in 5-, 10-, 20- , and 50-year return periods (Jones and Reid, 2001). A subsequent study by Ekström et al. (2005), used an RCM and a medium-high emissions scenario SRES A2 for 2070-2100, and estimated that the magnitude of extreme short duration (1-2 days) precipitation events could increase by 10% across much of England and up to 30% in eastern Scotland (Ekström et al., 2005). For the longer-duration extremes (5-10 days) increases in event magnitude reach 20% in eastern Scotland, but decrease by up to 20% in central and eastern England. Apparent differences in the results of these two studies highlight the large uncertainty ranges associated with regional projections of climate change – the results are driven by different RCMs. In addition, the two studies use different definitions of extreme precipitation.

An increase in heavy rainfall events such as described above will have serious consequences for the environment and human activities, and may stress urban infrastructure beyond the limits of its initial design. Intense short duration rainfall events have implications for the design of urban storm drainage and sewer systems while the longer duration extremes have implications for flood defence schemes. Even a small increase in storm rainfall would require considerable adaptation of storm drainage systems to maintain service levels (UKWIR, 2004). In parts of Europe, such as the Rhine, the risk of fluvial flooding is expected to increase substantially in line with projected increases in peak river discharge in winter (Figure 12). Although the rate of increase in flood risk in the UK is sensitive to the chosen emissions scenario, there is more consistency in the spatial pattern which shows a concentration of maximum risk in the Lancashire/Humber corridor, the coastline of southeast England, and the major estuaries (OST, 2004).

Sea level rise

It is expected that sea level will continue to rise throughout this century due to the thermal expansion of oceans and melting of land ice. Regional values in sea level rise could be 50% or more higher than mean values (Figure 13). The regional variation in sea level rise is attributed to the spatial variation in: thermosteric (a change in density induced by a change in temperature) sea level changes that are in turn influenced by changes in indices such as ENSO and the NAO, salinity, ocean surface circulation, surface atmospheric pressure changes, and the response of the solid earth and oceans to previous and present day ice melt/loads. Between 2000 and 2020, the rate of thermal expansion is expected to be in the region of 1.3 ± 0.7 mm per year under the SRES A1B scenario (IPCC, 2007: TS).

Figure 13: Local variation in sea level (in metres) from the global 1961-90 mean by 2100



Source: IPCC AR4

(i.e., positive values indicate greater local than global sea level change).

Around the UK, the estimated rate of sea level rise is greatest for the coastline and estuaries of south-west England, south-east England, East Anglia, East Midlands, Yorkshire and Humberside where there is the compounding effect of gradual post-glacial subsidence. For these regions, sea levels could be 13-15 cm higher than the 1961-90 mean by the 2050s under a low emissions scenario, and 42-44 cm higher under a high emissions scenario (Shennan and Horton, 2002). It is anticipated that the risk of coastal flooding will increase more rapidly than river flooding (Hall et al., 2006). Assuming a sea level rise of 40 cm by the 2040s, insurance catastrophe models have estimated that there could be a 48% increase in the number of properties at risk of flooding in eastern England, and a single extreme coastal flooding event could accrue costs of £16 billion (ABI, 2006). For England and

Wales, it is estimated the annual economic damage from coastal flooding could increase from £0.5 billion to between £1.0 and £13.5 billion depending on climate and socio-economic scenarios (Hall et al., 2006).

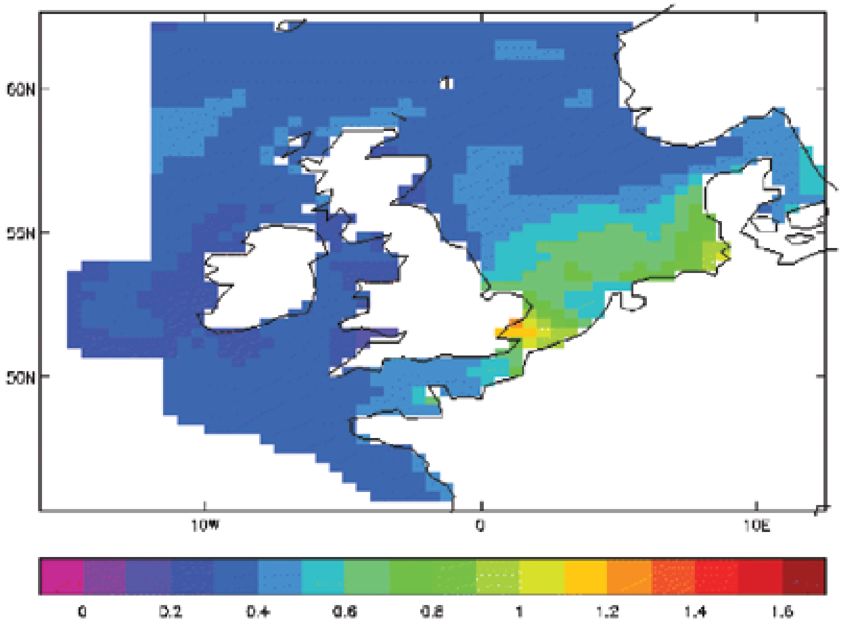
A quarter of the population of England and Wales live and work in the Thames catchment. The Thames Barrier (including a network of dikes on the Thames estuary) was developed in the 1970s to protect London and the surrounding area from a sea surge with a probability of 1 in 1000, by 2030 (Lavery and Donovan, 2005). However, acceleration in the rate of sea level rise and a changing frequency of storm surges, compounded by isostatic land settlement, has necessitated an upgrade of the Thames tidal defences. The Environment Agency's Thames Estuary 2100 project TE2100 is assessing future challenges and needs and the results will be available in 2008 (OST, 2004). A consultation document has been published by the Environment Agency, Managing Flood Risk: Thames Region Catchment Flood Management Plan (Environment Agency, 2007) setting out the strategic action plan for different types of flood plain within the Thames catchment. An extreme surge/flood event could result in damages in the order of £4-£5 billion due to the Gateway development (London Climate Change Partnership, 2005).

Storm surges

Rising sea levels and greater storm activity suggest that storm surge risk is likely to increase along many coasts, especially since the rate of increase in extreme sea level could be greater than the increase in mean values locally (Woodworth, 2006). The EU PRUDENCE project estimated changes in surge-related storminess and storm surge statistics around the North Sea coastline. In these simulations, westerly wind speed extremes intensify and there is an increase in the number of North Sea gales. A greater number of North Sea storms are projected by the latter half of the 21st century, leading to more storm surges along the North Sea coastline, especially in The Netherlands, Germany and Denmark (Beniston et al., 2007). The number of storm surge events could increase by 50-100% along the southern North Sea coast by the end of the 21st century (Woth et al., 2006). Meier (2006) demonstrated substantial variation in the projected change in storm surges from different RCM simulations for the Baltic Sea region, but a greater increase in extreme (100-year) events was nonetheless noted relative to the mean sea level.

Using a storm surge model combined with a RCM, Lowe and Gregory (2005) project increases in extreme sea level (storm surges with a 50-year return period) along the entire coastline of the UK (Figure 14). The largest increases in storm surge are along the coast of southeast England and amount to 1.2 m (assuming the medium-high A2 SRES scenario) by the end of the 21st century. Since only a limited range of climate models have been used, the range of uncertainties cannot be reliably quantified (Lowe and Gregory, 2005). A Bayesian framework has been adopted to assess the risk of extreme surges on the UK east coast (Coles and Tawn, 2005). The development of such models provides a starting point for estimating the coastal flood loss distributions that are frequently required by the insurance industry. Muir Wood et al (2005) developed a probabilistic catastrophe loss model of storm-surge flood risk for eastern England. For a storm surge of similar magnitude to that of 1953 (which affected 1600 km of the East Anglian coastline and resulted in 300 fatalities) the loss estimates were calculated as £5million for a surge arriving close to a neap tide, and more than £2 billion when the surge coincides with the highest astronomical spring tide. Losses were weighted by the respective rates of the individual scenarios in the probabilistic model to arrive at an 'expected loss' for property inundation (of 9500 properties) of £470million. Interruption to business and additional living expenses is estimated to add a further 20% to this value. ABI (2006) estimate that the financial costs of a flooding event equivalent to that of 1953 of around £2billion for the existing sea level could rise to around £7billion for a sea level rise of 0.4 m (excluding the costs of disruption, or the economic impact on essential public services). Assuming improvements to coastal defences, the estimated financial costs are reduced to around £1billion and £3.7billion respectively.

Figure 14: The change with respect to 1961-1990 in the 50-year return period storm-surge height(m) in the North Sea for the period 2071-2100 under the A2 scenario.



Source: Lowe and Gregory, 2005

Heat waves

The results from multi-model simulations suggest that it is very likely that heat waves will become more frequent over most land areas (IPCC, 2007 [SPM]). Heat waves will intensify, be more frequent and of longer duration (IPCC, 2007 [TS]). By the end of the 21st century in Europe, it has been projected that every summer in many regions of Europe will be hotter than the 10% hottest summers during the period 1961 to 1990 (Stott et al., 2004). Every second summer could be as hot, or hotter, than the summer of 2003, for high emissions scenarios by 2080 (Stott et al., 2004). In addition to changes to the mean temperature, Schar et al. (2004) suggest that the inter-annual variability of temperature could increase, and that the 2003 summer could be an early sign of this effect. Using nine different RCMs, Lenderink et al. (2007) confirm a projected increase in temperature variability, and suggest that it will be particularly large in central Europe and smaller in southern Europe. Central Europe could experience the same number of hot days as currently experienced in southern Europe (Beniston et al., 2007).

The effects of heat waves are accentuated in urban areas. In London, the number of hot days (i.e. at least 25°C) could double by the 2020s, and could be 3 to 5 times greater by the 2050s (London Climate Change Partnership, 2005). Very hot days, with temperatures greater than 30°C will also become more common, as will extreme temperatures such as those experienced during the heat wave of August 2003 (London Climate Change Partnership, 2005). In London, there could be a 40% increase in the number of nights with intense urban heat island (UHI) incidents (Wilby, 2008). The young, the elderly and the sick, are at risk particularly to the lack of nocturnal relief in temperatures. In addition, a greater incidence of warm daytime temperature extremes could lead to a higher incidence of heat stress in the work place. If temperatures far exceed the comfort zone, business activities may be interrupted. Business can also be interrupted or delayed through the damaging effects of extreme heat on transport infrastructure (rutting of road surfaces, deterioration of concrete, lower skid resistance, problems with expansion joints, and buckling of railway tracks).

Cold extremes

In Europe, cold winters (occurring every 10 years during the period 1961-90) are projected to disappear almost completely by 2080 (Luterbacher et al., 2004). In an analysis of frost days in the USA, Meehl et al. (2004) found that while the number of frost days decreased almost everywhere by the end of the 21st century the greatest decrease is in marginal areas closer to 0°C. Tebaldi et al. (2006) corroborated these findings for Europe: the greatest decrease in frost days was projected for Scandinavia and the smallest decrease for the Atlantic and Mediterranean coasts of Europe. Geographical variation in simulated changes in frost days is in part associated with regional changes in circulation (Meehl et al., 2004).

Limitations and sources of uncertainties in regional projections

There are five main sources of uncertainties that propagate from the initial source of climate change through to the regional/local economic and social impact (Goodess et al., 2007; Walsh et al., 2007). First, there are uncertainties in greenhouse gas emissions and the corresponding concentration scenarios. The second and third major sources relate to uncertainty in the climate models: inter-model variability (variability in the response of different climate models), and intra-model variability (different response of any single climate model to slightly different starting conditions). Natural variability of the climate system is a fourth source of uncertainty and is, in part, reflected in the inter-model variability. The fifth source of uncertainty is in the method used for downscaling from the coarse-scale output of climate models, to the finer resolution (temporal/spatial) of regional or local climate scenarios (Goodess et al., 2007; Christensen and Christensen, 2007). Impacts model uncertainties should also be considered (Wilby and Harris, 2006).

At the larger scale, the response to future climate change of some key modes of climate variability, such as ENSO, varies between climate models. These differences may be related to the different ways in which present-day conditions are simulated. Some of the main processes that drive ENSO, NAO and the distribution of tropical cyclones are not clearly understood (IPCC, 2007 [TS]). Future projection of the response of tropical cyclones to climate change is constrained by the resolution of most climate models (e.g., Yoshimura et al., 2006; Meehl et al., 2007). For other extremes there are seasonal variations in skill and uncertainty. In the STARDEX project, for example, uncertainties were found to be greater for summer rainfall extremes than for winter rainfall extremes (Goodess, 2005; Schmidli et al., 2007).

Although work on projections of extremes has expanded in recent years as the skill and resolution of models improves and as the importance of these events in terms of impacts assessments and decision making is increasingly recognised, the needs of stakeholders for appropriate information are still not fully met. In particular, very little, if any research has been published on joint probability events[3] or sequences of events. Yet, these kinds of events can be critical in terms of their impacts. Combined river and tidal flooding is a major concern for locations such as Lewes – a case study in the ASCCUE project (Walsh et al., 2007). Flooding due to intense rainfall combined with a storm surge coming up the Thames is also a potential risk. Wind-driven rain can have a major impact on building integrity and a wind storm will cause more damage due to up-rooted trees when the ground is already saturated from previous rainfall. Little or no information is available on some very high-spatial resolution extremes such as hail storms.

Assessing the risk of climate change through probabilistic projections

Recently, there has been a move towards more comprehensive treatment of assessing uncertainties in climate scenarios, paving the way for the development of probabilistic projections consistent with a risk-based approach to decision making (Goodess et al., 2007).

Probabilistic climate projections do not provide a single estimate of change but a range generally in the form of a probability density function estimated from a number of different climate model simulations (an ensemble). The use of ensembles provides a greater range of plausible future climates (e.g., Stainforth et al., 2004) than if using a single scenario. Research communities in Europe (e.g., ENSEMBLES; UK Environment Agency; UKCIP) and the US (e.g., http://www.assessment.ucar.edu/uncertainty_models) are actively involved in developing methods for the construction of probabilistic projections (see links to relevant projects at http://www.cru.uea.ac.uk/projects/ensembles/ScenariosPortal and in Goodess, 2007). The most common approach is to develop 'conditional' probabilistic projections, i.e., conditional on a single emissions scenario rather than also trying to incorporate emissions uncertainty.

'Super-ensembles' from global climate models have become available since the TAR, e.g., the Hadley Centre's QUMP (Quantifying Uncertainty in Model Predictions) (Harris et al., 2006) and the climateprediction.net experiment (Stainforth et al., 2005). Super-ensembles consist of a large number (e.g., currently over 100 in QUMP, and thousands in climateprediction.net) of runs, performed with global climate models. The output from these large ensembles is typically presented at a sub-continental scale. Estimates of climate change can be given as uncertainty ranges (e.g., median and confidence limits) for a particular window of time.

The new sub-continental probabilistic projections remain at too coarse a spatial resolution for many impact and adaptation studies. Thus downscaling is still required to provide relevant information, with the new challenge of constructing probabilistic projections. The CRANIUM (Climate change Risk Assessment: New Impact and Uncertainty Methods) project provides one of the first examples of such point-specific projections for the UK produced by combining PRUDENCE RCM output with a

[3] Joint probability refers to the possibility of two or more events happening simultaneously, such as a river flood and a storm surge.

daily weather generator in a probabilistic framework (Goodess, 2007). Appropriate methods for constructing probabilistic climate projections are currently being explored by a number of UK and European research teams. A number of these different approaches are combined in order to construct the next national UK climate projections – UKCIP08 (see Box 4) (UKCIPO8 has been deferred to 2009 due to unexpected technical difficulties).

BOX 4
UK 21st Century climate scenarios 2008 (UKCIP08)

The UK Climate Impacts Programme (UKCIP) is committed to presenting probabilistic information with its next generation of climate scenarios (UKCIP08) due to be published in November 2008 (http://www.ukcip08.org.uk/). This is an important and world-leading initiative and is especially relevant for risk-management decisions.

UKCIP02, the current set of climate change scenarios are constructed using the mean of three runs of the Hadley Centre regional climate model (RCM). It is a single measure of change for one emissions scenario that is subsequently scaled for each of the other emissions scenarios and time periods.

UKCIP08 will be based on a 'super ensemble' of the Hadley Centre climate models and other IPCC climate models. The new scenarios will not attach probabilities to the emissions scenarios but will be conditional on each of three SRES emission scenarios: B1, A1B and A1FI. The ensemble means are weighted according to the reliability of the climate model from which it comes. For each emissions scenarios a statistical distribution (probability distribution) will be provided that demonstrate a range of possible changes and an estimated likelihood of occurrence. The first results of this technique for constructing probabilistic scenarios were published in Nature in 2004 (Murphy et al., 2004)

The proposed format of the UKCIP08 climate scenarios:

- 25 km x 25 km spatial resolution; some administrative regions and river catchments.
- 30-year overlapping time slices with an increment of 10 years (i.e., 2011-2040, 2021-2050, …., 2071-2100.
- Slightly expanded range of climate variables (including some marine scenarios and river flows) for monthly, seasonal and annual changes, with some information about climate extremes. Daily (and sub-daily) time series (for precipitation, maximum and minimum temperature, vapour pressure, wind speed, sunshine and potential evapotranspiration) will be developed using a weather generator (for areas from 5 km by 5 km to 1000km^2) accessed from a dedicated web interface.
- Changes are relative to the baseline 1961-90.
- Delivered as a series of 'scientific' and 'summary' reports and guidance documents.
- The first of these scientific reports describes the climate of the United Kingdom and recent trends (Jenkins et al., 2007).

The use of a consistent probabilistic framework allows impact assessment studies to consider uncertainties due to the emissions scenario, the global climate model, and the method of downscaling. It is also possible to extend the consideration of uncertainty to the climate change impacts models. Uncertainties in impacts modelling have not been much addressed so far but Wilby and Harris (2006), for example, demonstrate that there are uncertainties arising from the choice of parameter values used in hydrological models and associated with the choice of hydrological model (see Section 3.4, Extreme events). Thus the move towards probabilistic projections is fully justified by scientific considerations and is also consistent with the wider move towards risk-based decision making. It does, however, raise many communication challenges (Goodess, 2007; Stainforth et al., 2007; Goodess et al., 2007).

Stakeholders, such as the insurance industry, need to consider how best these new probabilistic climate projections and impact implications can be applied in risk-management assessments to optimise adaptation decisions. If nothing else, these new scientific developments demonstrate that is it unwise to rely on scenarios and projections based on single models. Thus the IPCC confidence limits (Box 1), for example, are derived using evidence from a body of evidence (whether observations or models) – see http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf.

Attribution of climate change and liability

The AR4 estimates that there is a 90% probability that global warming can be attributed to human activity since the mid 20th century (IPCC, 2007). Although it is not possible to unequivocally attribute any single extreme climate event to emissions of GHGs, since there is always a chance that such an event will occur due to chance, there has been recent consideration of the possibility that future advances in science could enable the human influence to be disentangled from the natural variability of the climate system for some specific events using a risk-based perspective (Allen, 2003; Allen and Lord, 2004). This raises the question: 'Will it ever be possible to sue anyone for damaging the climate?' A number of climate-change related lawsuits have already been filed, although they are related to technical legal issues such as the adequate consideration of climate change in environmental risk assessment. In the future, could businesses be held responsible for climate change due to emissions of GHGs? Could building service engineers be found negligent for not taking adequate consideration of the consequences of climate change?

There have been some recent advances in the science of climate attribution for extreme events. As noted above, direct attribution is not possible for single events, but it may be possible to identify the increase in risk. For example, Stott et al. (2004) use risk and probability analysis – expressed as 'fraction of attributable risk' – to quantify the association between emissions of GHGs and the summer heat wave of 2003 in Europe. They conclude that human behaviour has increased the risk of a persistent anticyclone resulting in a heat wave of the magnitude of 2003 by a factor of about four. They also estimate with 90% confidence that human activity (primarily through GHG emissions) is responsible for more than 50% of the risk of such a heat wave.

Allen and Lord (2004) suggest that businesses will increasingly have to consider how their decisions affect liability for the damages of climate change. Lash and Wellington (2007) recommend that businesses consider climate-change related litigation alongside other carbon-related risks and opportunities, namely, mandatory emissions-reduction legislation, carbon-related costs being passed on through the supply chain, the competitive environment of 'climate-friendly' products and technology, and the environmental reputation of the business. Competitive advantage can be gained by (i) quantifying the carbon 'footprint' of the enterprise, (ii) assessing carbon-related risks and opportunities, (iii) developing and implementing adaptation strategies, and (iv) seizing new climate change related opportunities and mitigating risks ahead of rivals. In a perceived political vacuum, environmental lawyers are exploring litigation strategies to address the risks associated with global warming. The law suits, if successful, could necessitate regulatory changes which would subsequently create new climate-related risks for sectors with a large carbon 'footprint' (Grossman, 2007).

While a carbon-footprint-based approach may be a practical option, the natural variability of climate and limited availability of appropriate data make attribution of liability for specific extreme events at regional/local scale an unrealistic approach.

3.5 Abrupt or accelerated climate change

'The climate system tends to respond to changes in a gradual way until it crosses some threshold: thereafter any change that is defined as abrupt is one where the change in the response is much larger than the change in the forcing' (Randall et al. 2007).

Abrupt or dangerous climate change is of particular concern for impact studies related to the financial sector. Processes of abrupt climate change include the shutting down of a major component of the North Atlantic circulation, the collapse of the West Antarctic Ice Sheet and, accelerated climate change resulting from, e.g., major emissions of methane from permafrost melting of the ocean floor. These key vulnerabilities of the climate system were the focus of the International Symposium on Stabilisation of Greenhouse Gases: Avoiding Dangerous Climate Change (see Hadley Centre, 2005; Schellnhuber et al., 2006).

The Meridional Overturning Circulation

Much attention has focused on the response of the ocean, and in particular changes in Meridional Overturning Circulation (MOC). The MOC of the North Atlantic Ocean conveys a large amount of heat and salt from low to high latitudes where heat is released to the atmosphere, warming the North Atlantic and surrounding areas, while cooling the surface water, which sinks and flows southward. Water density (determined by temperature and salinity) and wind stress are important drivers of this circulation. Modelling experiments (e.g., Vellinga and Wood, 2002) and studies of past climate (e.g., Clark et al., 2002) indicate that a disruption (shut down) of the MOC could result in abrupt climate change in the North Atlantic region. It is important to note, however, that the impact of such an event is most unlikely to be as great as is sometimes popularly depicted (e.g., in the film 'The Day after Tomorrow'), because the heat transport by the MOC is not the only process that sustains mild winters in north-west Europe (Seager et al., 2002).

As concentrations of GHG increase, most climate models simulate a gradual weakening of the MOC as the surface water at high latitudes warms and, in some models, become less saline. Some models do indicate the existence of thresholds beyond which a rapid collapse of the MOC might occur (e.g., Challenor et al., 2006), but these models generally have a less complete representation of the climate system. There is a potential for the Greenland ice-sheet to dilute surface waters and accelerate the slowdown of the MOC but this seems unlikely, because current models simulate a gradual rather than a rapid melting of the ice-sheet. Working Group I of the AR4 (Meehl et al., 2007) concludes that it is very likely that the Atlantic Ocean MOC will weaken, but it is very unlikely that there will be a large abrupt change by the end of the 21st century.

[4] Also called the Gulf Stream, or THC thermohaline circulation.

The consequence of a gradual weakening of the MOC is a relative cooling of land areas adjoining the North Atlantic on decadal to centennial time scales (e.g., Stouffer et al., 2006). When superimposed on the GHG-induced warming, the result is reduced warming in this region rather than actual cooling. This effect of a gradually weakening Atlantic Ocean MOC is already present in the AOGCM/downscaled projections previously discussed, and, therefore, implicitly included in the impact or mitigation studies that use these projections. However, few impact or mitigation studies have considered the consequences of a much less likely, though still possible, abrupt shutdown of the MOC which could dominate over the GHG-induced warming to produce regional cooling in Europe (Vellinga and Wood, 2007). Some researchers claim that there would be large implications to ecosystems, health, migration, transportation, infrastructure, and water resources (e.g., Arnell et al., 2005). Others maintain that it is premature to argue that abrupt climate change "imposes unacceptable costs on society or the world economy, represents a catastrophic impact of climate change, or constitutes a dangerous change in climate that should therefore be avoided at all reasonable costs" (Hulme, 2003).

Rapid melting of the Greenland and the West Antarctic ice sheets

There has been speculation about the possible rapid melting of one or both of these ice sheets. Sea level was 4 to 6 m higher than today during the previous Interglacial period (~125,000 years ago), and raised beaches around the world show that rapid melting did occur then. The sea level community is divided as to whether this resulted from a melting of one or other of these two ice sheets or a combination from the two. The Greenland ice sheet is much more well studied and IPCC (2007) concluded that if global mean temperatures were sustained in excess of 1.9 to 4.6ºC above pre-industrial values for millennia, the virtual complete elimination of the ice sheet would eventually (after centuries) lead to a sea level rise of about 7m.

There are several mechanisms which may cause rapid melting and collapse of the West Antarctic ice sheet. The ice sheet is grounded below sea level, making it potentially unstable if melting occurred in neighbouring ice sheets. A second mechanism is the rapid acceleration of streams within the West Antarctic Ice Sheet. A collapse of the West Antarctic Ice Sheet would increase sea levels globally by approximately 5 m (at a rate not exceeding 1 m / century) (Leipprand et al., 2007). There is evidence of many ice streams speeding up their rate of flow, but measurement records are too short to determine whether this acceleration will continue or is only a temporary variation.

Without adaptation, major European coastal cities, including in Europe, London, Hamburg, Venice, Amsterdam and Rotterdam would be inundated if such a scenario were to occur. The rate of change is crucial, however, and studies indicate that the rate would likely be slow enough for adaptation to take place despite the massive costs that would be involved.

Accelerated climate change

Some feedbacks in the climate system are not well understood or represented in climate models. Some of these may be positive feedbacks that could increase temperatures more rapidly than simulated by current AOGCM models. For example, higher temperatures may lead to the release of methane from the ocean bed or wetlands (Ehhalt, 2001). More recently, it has been shown that higher temperatures would accelerate the rate of carbon release from soils (Knorr et al., 2005), and may already be limiting the ability of the oceans to take up some of the anthropogenic carbon dioxide (Le Quéré et al., 2007). Although some of the new projections presented in the IPCC AR4 do include some carbon cycle feedback, they do not include the uncertainty in strength of this feedback. The consequences for society of accelerated climate change include impacts on agriculture and food security, health and mortality, water availability, ecosystems and infrastructure (Arnell et al., 2005).

Larger changes in future climate cannot, therefore, be excluded. However, an inadequate knowledge of feedbacks and their strengths limits the ability to assess the probability of an upper limit to the projected change. Nevertheless, future climate change would only exceed the range of projections reported in the IPCC AR4 if these unknown feedbacks are real and the climate change without these additional feedbacks was already at or near the upper limit of the IPCC AR4 projections (requiring both a high emissions scenario and a high climate sensitivity).

3.6 Recommendations to insurers and other stakeholders

- Estimates of future risk should not incorporate climate as a stationary component. Climate change is already happening and major changes are anticipated in the future.
- Insurance market bodies should expand the time horizon for assessing impacts of climate change to clearly identify and understand the long-term risks and opportunities.
- Dialogue and collaboration between the insurance industry and scenario developers is required for guidance on relevant complex extremes such as sequences of events, or joint probability events. What are critical combinations of climate variables?
- Dialogue and collaboration is also required with respect to understanding and communication of uncertainties.
- Risk management should consider a wide range of climate projections from multiple climate models, and should not rely on single model output.
- Appropriate consideration is needed of the new generation of probabilistic projections of climate change in order to optimise adaptation decisions.
- There should be preparation for national and international policy shifts in response to climate change.
- Collaboration is needed with other economic sectors, NGOs and community groups to find sustainable solutions and provide risk management expertise to the challenge of climate change.

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Biography

Maureen Agnew

Maureen Agnew is a Senior Research Associate in the Climatic Research Unit, School of Environmental Sciences, University of East Anglia, and Honorary Visiting Fellow in the Department of Geography, Loughborough University. Maureen has worked in the School of Environmental Sciences since 1996 on a wide range of projects covering the construction of future climate change scenarios, the impacts of observed climate variability and climate extremes and, assessments of the potential impacts of, and adaptation to, future climate change. Her particular research interests are in the impacts of climate variability and change on social and environmental systems with a specific focus on human health, tourism, the insurance industry, retailing and other service sectors. Maureen was a Contributing Author of the chapter on Industry, Settlement and Society in the Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change She was co-author of the chapter, The climate system and its implications for the UK, in the 2001 Chartered Insurance Institute report Climate Change and Insurance. Maureen has been an author or co-author on 12 peer-reviewed journal papers, four books, and seven book chapters.

Dr Clare Goodess

Dr Clare Goodess is a Senior Researcher and Research Manager with over 25 years experience of contract research in the internationally-renowned Climatic Research Unit (CRU) at the University of East Anglia in Norwich. Her main current research interest is in the development of projections of regional climate change over the coming century and working with users and decision makers to ensure that these are used effectively in climate change impacts and adaptation studies. She has a particular interest in past and future changes in the occurrence of extreme weather events. Clare has co-ordinated and worked on many major UK and European climate change projects. Amongst many other UK activities, she has contributed to a recent assessment of the impacts of climate change on UK health (for the Department of Health). Her main UK research interests, however, lie in providing climate information and projections for use in impacts and adaptation studies on the built environment and infrastructure. Within the Building Knowledge for a Changing Climate programme, she co-ordinated the EPSRC BETWIXT project as well as the CRU contribution to the CRANIUM project – and is leading CRU involvement in a new EPSRC project that will use UKCIP08 results in the building design field. Clare is a member of the UKCIP08 steering group which is overseeing development of the new national climate change scenarios. At the European level, Clare is the coordinator of work on the production of probabilistic regional climate projections in the ENSEMBLES integrated project and co-ordinator of integrating case-studies within the CIRCE project on impacts of climate change in the Mediterranean. As well as a long-standing interest in Mediterranean climate, Clare is developing links with Indian scientists, particularly those interested in downscaling techniques and applications, through the UKIERI programme.

Biography

Phil Jones

Phil Jones has been Director of the Climatic Research Unit since 1998. He was Convening Lead Author of the Chapter on Atmospheric Observations in the Intergovernmental Panel on Climate Change (IPCC) 2007 Report. He is most well known for developing the global temperature record and has written extensively on the analysis of instrumental temperature, precipitation and pressure data. He has also been at the forefront of studies that have sought to place the 150-year record of instrumental temperatures into the longer context of the last thousand years using proxy climatic series and longer European instrumental temperature records. He was awarded the Hans Oeschger Medal of the European Geophysical Society (2002), the International Journal of Climatology prize of the Royal Meteorological Society (2002) and the editor's award for reviewing by Geophysical Research Letters (2006). He is recognised as one of the top 0.5% of highly-cited researchers in the Geosciences field by the ISI. He is an elected member of Academia Europaea. PDJ is a member of the Atmospheric Observation Panel of the Global Climate Observing System and the Expert Team on Climate Change Detection and Indices of the World Meteorological Organization.

Tim Osborn

Tim Osborn is an Academic Fellow in the Climatic Research Unit, part of the School of Environmental Sciences at the University of East Anglia, where he has worked since 1990. As an Academic Fellow, he carries out scientific research into various aspects of the global climate system, while also contributing to the teaching of undergraduate and masters students and supervising the research of postgraduate students. Tim Osborn's research interests cover the fields of natural climate variability, uncertainties in observational records, and the construction of scenarios of possible future climate change. Some specific foci of his research are climate variations over the last 1000 years, variability of heavy precipitation events and of droughts, the North Atlantic Oscillation, and the influence of changes in the thermohaline circulation of the ocean. His research is undertaken using a combination of climate model simulations and empirical analysis of climate records from instruments and climate proxies (particularly tree-rings). Tim Osborn has authored or co-authored over 70 papers that have appeared in peer-reviewed journals or books. Twenty-three of these papers have been cited at least 30 times, and ten of them at least 100 times. In 2004, he was awarded the Hugh Robert Mill Medal by the Royal Meteorological Society in recognition of his research into the variability of precipitation.