

360

RISK PROJECT

3

CATASTROPHE TRENDS
RAPID CLIMATE CHANGE

FACT:
**WE MUST EITHER
INVEST MORE IN
SUSTAINABLE
APPROACHES TO
FLOOD AND COASTAL
MANAGEMENT OR
LEARN TO LIVE WITH
INCREASED FLOODING.**

Sir David King, Chief Scientist to the UK Government



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RAPID CLIMATE CHANGE

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FOREWORD

Since our first report on climate change, 'Adapt or Bust', we have seen the most conclusive evidence yet that the climate's current warming trend is directly linked to human activity. The Intergovernmental Panel on Climate Change has effectively closed the debate, and the latest science suggests that change will take place faster than previously thought. At the same time, we have seen certain media coverage and messaging around climate change questioned by some of the scientific community as irresponsible "Hollywoodisation" of the facts. How rapidly can we expect climate change to take place? What does it mean for our lifetime?

It is vital that the insurance community has an accurate and balanced understanding which reflects the latest thinking on climate change but which avoids sensationalism. The impact of climate change is far from certain and not completely understood. However, the experts writing in this report suggest that there is sufficient probability of change occurring within our lifetime to demand our attention now. Take UK flood risk for example: the Association of British Insurers calculates that an additional 50% of homes in eastern England will be at risk by 2040, while the cost of damage could be reduced by 40% if action is taken to develop the appropriate defences.

Building upon our previous work, this report therefore explores what climate change could mean in four areas of particular relevance to the insurance industry: sea level rise, melting icecaps, flood and drought. We aren't suggesting these are the only areas that could experience change in our lifetime, but they each have significant implications for the insurance industry and so we think it's a good place to start.

Global models of our climate do not yet agree on regional impacts and the extreme effects of climate change. But they still contain much useful information and we urge scientists to share this with the business community, rather than wait until their models agree. Not having all the answers must not stop business preparing for a range of possible outcomes and planning for a variety of contingencies, even if some of them seem implausible. More uncertainty means more risk, and calls for a fresh and flexible approach to management of climate related risk, in our view. Insurance strategists should also consider how their traditional markets will change in the future and where new insurance markets will open up.

This report draws on the expertise of four leading UK scientists and we have reproduced their scientific papers as written. It is important that we begin to share a common language

with the scientific world, and we have also added a short glossary at the back and a comprehensive executive summary. Science can only point towards the measures we need to take but it seems clear that the insurance industry should start to prepare now for more severe and more frequent losses as a result of climate change by the middle of the century.

For our part, Lloyd's will continue to review and analyse the latest science as it becomes available, and to invest in new research where needed. One means by which we will do this is through our membership of the Lighthill Risk Network. This network is run as a not-for-profit organisation and has been formed in partnership with the reinsurance brokers Benfield and Guy Carpenter, underwriting business Catlin, and modelling company Risk Management Solutions and seeks to link up the academic community with those in the business world. It is open to all in the insurance industry for a small annual subscription and offers various services that will grow over time, including expert panel discussions (for example on climate change and catastrophe modeling), a data catalogue and of course access to a network of academics.

Finally, we would like to express our sincere thanks to each of the four scientists who have contributed to this report. We hope that the report will prove useful both to insurers as they begin to think about the possible impacts and outcomes of climate change in our lifetime, and to all businesses as they prepare to mitigate against it.



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EXECUTIVE SUMMARY

Until now, we have tended to think of climate change as a gradual phenomenon which will take place slowly over a long period of hundreds – or perhaps thousands – of years. In turn, this thinking is likely to influence how we forecast and prepare for climate related loss, with the impact expected to be felt evenly over time, and any increase in loss taking place incrementally. In fact, the latest science presented in this report suggests that climate change is likely to bring increasingly dramatic, and possibly rapid, effects at a local level, which differ in their intensity and even in their outcome. In addition, a growing number of potential feedback mechanisms within the climate have the capacity to cause tipping points in the system and speed change further. While we cannot yet determine what the exact impact of climate change will be, the evidence is increasing to suggest we will see tangible change within our lifetime, and insurers and business should begin to consider and prepare for the range of outcomes now.

1 THE INSURANCE INDUSTRY SHOULD START PLANNING AND MODELLING NOW FOR A HIGHER LEVEL OF LOSSES ACROSS THE WORLD BY THE MIDDLE OF THE CENTURY AS BOTH THE SEVERITY AND FREQUENCY OF WEATHER EVENTS INCREASE.

The alternative - waiting until definitive scientific pronouncements on impact at a regional level or likelihood of catastrophic change are available – seems like an increasingly risky strategy.

- With a wealth of new research becoming available recently, the global insurance sector and the wider business community should factor the latest science into its business planning.
- Global warming is not only changing the average climate, but will also make it more erratic which should be of particular concern to the insurance industry.
- As climate change takes hold, insurers and businesses should therefore keep a close watch on future developments, and be prepared to revise their longer term strategies regularly.
- While not all of the increased risks may result in huge losses which significantly damage the capital of the insurance industry, increased unexpected attritional losses could certainly impact financial performance on a regular basis.

2 SEA LEVELS WILL RISE FASTER THIS CENTURY THAN LAST CENTURY, AND THE PROSPECT OF A RAPID RISE IN SEA LEVEL WITHIN OUR LIFETIME IS INCREASING.

Over coming decades we can expect to see global sea levels rise up to ten times faster than a century ago, putting coastal communities - including key urban conurbations in the developed world - at increased risk. In particular:

- If global warming modifies Gulf Stream currents, Northern European coastal sea levels could rise by up to a metre over a few decades.
- Increased storminess, with a greater frequency of storm surges, could pose a threat to coastal communities throughout the world within the short to medium term.
- A further concern is that higher sea levels could increase the impact of tsunamis in the Asia-Pacific in particular, and combine with crustal movements to encourage dramatic shifts in sea level along plate lines.

3 EVIDENCE IS BUILDING TO SUGGEST THAT LARGE PORTIONS OF ICE SHEETS WILL MELT IN THIS CENTURY, SPEEDING SEA LEVEL RISE FURTHER AND INCREASING UNCERTAINTY FOR COASTAL COMMUNITIES ABOUT THE SPEED AND IMPACT OF CLIMATE CHANGE.

There are a range of scientific views on the stability of the ice sheets, but although meaningful predictions are impossible, an increase in instability is a credible risk. In particular:

- Greenland's ice sheet, previously thought to be stable, is now showing signs of rapid melt, and commentators are beginning to speculate that the resulting injections of cold freshwater into the North Atlantic could impact upon the climate of Europe.
- At the other pole, the Western Antarctic Ice Sheet is more prone to rapid collapse, is losing mass, and its outlet glaciers are speeding up, and its stability is regarded as a key issue in the debate concerning the nature and occurrence of 'dangerous climate change'.

4 FLOODS CURRENTLY ACCOUNT FOR HALF OF ALL DEATHS CAUSED BY NATURAL DISASTERS, BUT THE FREQUENCY AND MAGNITUDE OF FLOODING IS SET TO INCREASE WITHIN OUR LIFETIME.

Under some scenarios, which are looking increasingly plausible, studies suggest annual flood damage in England and Wales could reach 10 times today's level. Society needs to improve its flood management ability, and the insurance industry should factor the upward trends into its modelling. In particular:

- Fuelled by higher winter precipitation in temperate areas and changes to freezing patterns, lowland areas will experience greater flooding while in mountainous areas, flood risk will increase in winter but reduce in spring.
- Despite an overall trend towards drier summers, we are likely to see more thunderstorms and a greater frequency of destructive flash floods, and current computer models of climate may understate this risk.
- There is considerable though disputed evidence that tropical cyclones are becoming more intensive in line with higher sea temperatures, increasing coastal flooding risk.
- The impact of coastal flooding will grow due to increasing coastal populations and greater storm surge.

5 DROUGHT PATTERNS ARE ALREADY CHANGING IN A WAY THAT IS CONSISTENT WITH A WARMING WORLD, AND THIS IS EXPECTED TO CONTINUE DURING OUR LIFETIME.

Droughts result from long lasting large scale climate features, and can often be traced to recognised patterns of climate variability, however these are shifting compared to the observed historical record.

- Regions susceptible to drought during El Nino such as Southern Africa will become more vulnerable to drought by the middle of the century.
- Some climate models predict an almost permanent El Nino within our lifetime (though not all agree), with such an event leading to the drying of the Amazon and release of significant amounts of extra carbon dioxide into the atmosphere, leading to further warming.
- Near permanent drought conditions could evolve in some areas due to changes in global circulation patterns and, conversely, some other drought prone regions will become less at risk.
- The changes to local regions can be far more dramatic than changes in global averages.



RAPID SEA LEVEL RISE
BY PROFESSOR
DAVID SMITH

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INTRODUCTION

The level of the global sea surface has probably been rising continuously for at least two hundred years. However, the rise is spatially variable and in addition, the relative rise in the level of the sea against the coast varies according to the behaviour of the earth's crust. It follows that assessment of the impact of sea level rise in a given area will depend upon a number of factors which will vary from place to place. Even so, there is growing evidence that rates of sea level rise may be increasing in many areas and that over a timescale of just decades, the rising sea level will pose a serious threat to coastal communities in low-lying areas.

discussed, after which land movements and relative sea level changes at the coast are examined. The account will conclude with a discussion of the prospects for rapid sea level rise in the near future.

CHANGES IN THE GLOBAL SEA SURFACE

The shape of the sea surface

The global sea surface is by no means spheroidal in shape, but is marked by raised areas and depressions, as satellite observations confirm. In terms of a mathematically defined ellipsoid, the sea surface varies through at least 170 metres, with the lowest area off South-West India and the highest off

“200 MILLION PEOPLE MAY BE DIRECTLY AFFECTED BY SEA LEVEL RISE, WITH SEVERAL MAJOR COASTAL CITIES, INCLUDING LONDON [...] PARTICULARLY SERIOUSLY AFFECTED.”

The recently published Stern Review on the economics of climate change remarks that under presently envisaged global climate change, 200 million people may be directly affected by sea level rise, with several major coastal cities, including London, Tokyo, Shanghai, Hong Kong, Mumbai, Cairo, Kolkata, Karachi, Buenos Aires, St Petersburg and New York particularly seriously affected, not to mention vulnerable ocean islands and low-lying coasts in SE Asia (Stern Review, 2006). In this account, changes in the level of the global sea surface are

the North coast of Papua New Guinea. Local studies have confirmed striking changes in the ocean surface altitude over even tens of kilometres, notably off Greece (Smith et al, 2000). Such variations primarily reflect geophysical factors, but an additional factor is the presence of ocean currents, which raise the sea surface along their lengths and along the coasts they reach: thus, the Gulf Stream causes the sea surface to lie a few centimetres at a higher altitude on western coasts of the UK than on eastern coasts. It is also believed that warming

could cause a change to take place in the global ocean current system, in which the Gulf Stream could be modified by changes in the input of warmer water in the North Atlantic, paradoxically resulting in a temporary cooling in the climate of North-West Europe during an otherwise warming world. One effect of this would be an increase in the sea surface of up to one metre around North-West European coasts over a very short period, perhaps a few decades (Levermann et al, 2005).

The effect of storminess changes

Changing storminess may also affect the global sea surface in particular areas. Wind moving across the ocean surface will increase its altitude locally and affect wave height, while atmospheric pressure will also affect the water surface altitude, as demonstrated in the classic study of the 1953 storm surge in the North Sea by Rossiter (1954). Storminess in the North Atlantic has been the subject of many studies (Smith et al, 2000). A number of studies have sought to relate storminess in this area to the North Atlantic Oscillation (the NAO), a variation in the air pressure gradient between the Azores and Iceland, which appears to fluctuate on a decadal

Gehrels et al (2005) estimate a sea surface rise during the 19th century of 1.6 millimetres per year, but since about 1900 of 3.2 millimetres per year. In the United Kingdom, the Liverpool tide gauge, which has provided a record since 1768, shows a mean rise from 1768 to 1880 of 0.39 ± 0.17 millimetres per year, increasing to 1.22 ± 0.25 millimetres per year in the 20th century (Woodworth, 1999). Thus available evidence points to an increasing rate of rise, this change of rate having begun probably during the 20th century. IPCC maintain that the rate of sea surface rise from anthropogenic climate change during the 20th century was between 0.3 and 0.8 millimetres per year, tacitly accepting that some element of the rise is due to natural factors. Recent work (Rahmstorf 2007) suggests that sea level by the middle of the century could be significantly higher and in 2100 will be between 0.5 to 1.4 metres above the 1990 level.

Rapid changes in the global sea surface

Almost all authorities agree that the global sea surface is rising, and that the rate of rise is probably increasing. Forecast rates of at least five millimetres, and possibly 10 millimetres per year are up to 10 times those which were obtained only a century

“A FURTHER CONCERN IS THAT TSUNAMI IMPACT WILL BE GREATER WITH A HIGHER SEA SURFACE LEVEL.”

timescale, perhaps related to the Pacific Southern Oscillation (El Nino/La Nina). Some studies have indicated a relationship between wave height and the NAO. Combined with a rising sea surface, increasing storminess with a greater frequency of storm surges poses a threat to coastal communities.

Previous estimates of sea level rise showed that the global sea surface during the 20th century rose by between one and two millimetres per year, primarily as a result of the thermal expansion of the oceans but also as a result of land ice melting resulting from global warming. In addition, it is estimated that the rate of rise in the 21st century will exceed that noted for the 20th century. The graphs produced imply an accelerating rise.

More recent research supports the notion of an increase in the global sea surface over the period given, and in particular provides support for an increasing rate. Thus in the Mediterranean, Flemming and Webb (1986) note that during the last century sea level has risen much faster than in the previous 2000 years; in Maine, after correction for crustal movements,

ago, and in this context constitute “rapid” rises over century, and possibly decadal timescales. Such rises will be exacerbated for coastal populations by the likely increases in storminess and the impact of storm surges (Smith et al, 2000). A further concern is that tsunami impact will be greater with a higher sea surface level, and although the frequency of these phenomena cannot be determined at present, it is noted that over the last 12 years four major tsunami have hit the island chain of Indonesia-Papua New Guinea. Studies of past tsunami have grown greatly in recent years (eg Smith et al, 2004), offering the possibility of improved knowledge of their magnitude and frequency.

SEA LEVEL RISE AT THE COAST

The concept of relative sea level

It is emphasised that quoted rates of global sea surface rise do not necessarily apply at specific coastal locations, where land movement is an important factor. In order to emphasise this, the term relative sea level, referring to the observed changes in sea level at the coast is now routinely used.

Areas of pronounced isostasy

Many areas of the globe, including Scandinavia, the British Isles, Canada and the northern United States, and northern Russia, were once occupied by large glaciers and ice sheets, and are thus affected by glacio-isostasy. In these areas, the mass of ice on the earth's crust caused the land first to

(Chen et al, 2006, Monaghan et al, 2006) indicate a marked increase in the ablation (melting) rate of the Greenland ice sheet, while the West Antarctic ice sheet accumulation rate is not now believed to exceed its ablation rate and since the base of this ice sheet is largely below sea level it is thought inherently unstable and susceptible to rapid retreat. The Greenland ice sheet, if

“THE RATE OF RISE IN THE 21ST CENTURY WILL EXCEED THAT NOTED FOR THE 20TH CENTURY.”

become depressed, then when the ice melted to rise again to its original height, while along the periphery of the loaded area land movement was in the opposite sense (eg Smith, 2005). These areas today are still rising, with rates of up to 10 millimetres per year in some areas of the world. Thus in the UK the area occupied by the thickest ice, central Scotland, is still rising whilst in South-East England the land surface is being depressed. The sum total of this is that assuming a sea surface rise of two millimetres per year, relative sea level is falling around the Forth and Clyde estuaries by around 0.5 millimetres per year, but rising by up to four millimetres per year around the Thames estuary (eg Shennan, 1989). In Ireland, relative sea level at Belfast is stable, but to the south is rising by around two millimetres per year (Pugh, 1987).

Beyond areas affected by glacio-isostasy, other forms of isostasy occur, notably in deltaic areas and in island volcanic areas. These areas experience the same process in terms of crustal movement, generally less pronounced than in formerly glaciated areas, though in some cases at least matching glacio-isostasy.

Areas of neotectonics

Along plate margins of the world, crustal movements may be rapid, resulting in rapid movements in relative sea level, whether positive or negative, at the coast. Some of the more spectacular of these movements have occurred in Indonesia and Papua New Guinea, New Zealand, and the Mediterranean. In the latter area, both positive and negative movements at the coast of up to 10m are recorded over periods of a few hundred years (eg Pirazzoli, 1991). In North-West Europe, such movements are not recorded, but crustal movements along pre-existing fault lines amounting to one metre over several hundred years have been identified in Scotland (Sissons, 1972; Firth and Stewart, 2000).

The prospect of rapid sea level changes in the future

Present estimates of changes in the global sea surface take no account of the implications of the recently observed changes in the Greenland and West Antarctic ice sheets. Recent studies

melted, would raise the global sea surface by around seven metres and the West Antarctic ice sheet by around five metres.

CONCLUSIONS

Over coming decades we can expect to see global sea levels undergo a rapid rise, up to ten times faster than a century ago. This will very likely be much greater if the changes feared for both the Greenland and Antarctic ice sheets take place. Taken with known crustal movements, the prospects for some coastal communities are a legitimate concern for the global insurance sector and the wider business community, and these trends should be factored into business planning going forward.

REFERENCES

- Chen, J.L., Wilson, C.R. and Tapley, B.D.** 2006. Satellite gravity measurements confirm accelerated melting of the Greenland ice sheet. *Science* DOI: 10.1126/science. 1129007.
- Firth, C.R. and Stewart, I.S.** 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews* 19, 1469-1493.
- Fleming, N.C. and Webb, C.O.** 1986. Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. *Zeitschrift für Geomorphologie Supplement* 62, 1-29.
- Gehrels, W.R., Kirby, J.R., Prokoph, A., Newnham, R.M., Achterberg, E.P., Evans, H., Black, S. and Scott, D.B.** 2005. Onset of recent rapid sea-level rise in the western Atlantic ocean. *Quaternary Science Reviews* 24, 2083-2100.
- HM Treasury and the Cabinet Office.** 2006. The Stern Review on the Economics of Climate Change. 576+xxvii pp. London.
- Levermann, A., Griesel, A., Hoffmann, M., Montoya, M. and Rahmstorf, S.** 2005. Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics* 24, 347.
- Monaghan, A.J., Bromwich, D.H., Fogt, R.L., Wang, S-H., Mayewski, P.A., Dixon, D.A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, I., Kaspari, S.D., Morgan, V.I., Oerter, H., Van Ommen, T.D., Van der Veen, C.J. and Wen, J.** 2006. Insignificant change in Antarctic snowfall since the International Geophysical Year. *Science* 313 (5788), 827-831.
- Pirazzoli, P.A.** 1991. World atlas of Holocene sea-level changes. Elsevier, Amsterdam. 300pp.
- Pugh, D.T.** 1987. *Tides, surges and mean sea level*. Wiley, New York.
- Rahmstorf, S.** 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, 315, 368-370.
- Rositer, J.R.** 1954. The North Sea storm surge of 31 January and 1 February 1953. *Philosophical Transactions of the Royal Society of London A246*, 371-400.
- Shennan, I.** 1989. Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science* 4, 77-89.
- Sissons, J.B.** 1972. Dislocation and non-uniform uplift of raised shorelines in the western part of the Forth valley. *Transactions of the Institute of British Geographers* 55, 145-159.
- Smith, D.E., Raper, S.B., Zerbini, S. and Sanchez-Arcilla, A. (eds.)** 2000. Sea level change and coastal processes: implications for Europe. European Commission, Brussels, 247pp.
- Smith, D.E.** 2005. Evidence for Secular Sea Surface level changes in the Holocene Raised Shorelines of Scotland, UK. *Journal of Coastal Research* 42, 26-42.
- Smith, D.E., Shi, S., Brooks, C.L., Cullingford, R.A., Dawson, A.G., Dawson, S., Firth, C.R., Foster, I.D.L., Fretwell, P.T., Haggart, B.A., Holloway, L.K. and Long, D.** 2004. The Holocene Storegga Slide tsunami in the United Kingdom. *Quaternary Science Reviews* 23/24, 2295-2325.
- Woodworth, P.L.** 1999. High waters at Liverpool since 1768: the UK's longest sea level record. *Geophysical Research Letters* 26, 1589-1592.



**DESTABILISATION
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Dr Stephan Harrison is Associate Professor in Quaternary Science at Exeter; Senior Research Associate, Oxford University Centre for the Environment; and Director of Climate Change Risk Management. He has a PhD in Quaternary Science and over 20 years research experience in climate change and mountain palaeoglaciology and geomorphology. Stephan Harrison has worked for 10 field seasons on the glaciers of Patagonia studying their fluctuation histories over the last 15,000 years and the geomorphological impact of recent glacier retreat on valley-side slopes. He spent five years working on an EU-funded project which examined glacier retreat, climate change and hydrological responses in the northern Tian Shan mountains of Kazakhstan. In such arid regions of central Asia, much of the water used for economic development comes from summer melting of glaciers and permafrost, and these supplies are replenished during winter snowfalls. With global warming, such supplies are under threat and this will have profound political, economic and social repercussions. Stephan Harrison has also worked in the mountains of Iceland, Norway, the European Alps and the Himalayas.

INTRODUCTION

One of the major concerns about the effects of anthropogenic global warming (AGW) is the impact this might have on the stability of two large ice sheets on earth, Greenland and the West Antarctic Ice Sheet (WAIS). Rapid melting from these has the potential to increase sea levels significantly and create the conditions for the reorganisation of the oceans, with subsequent severe climatic impacts. Ice sheets have become unstable in the past; in the late Pleistocene, deglaciation of ice sheets lead to large-scale calving events, with consequent rapid increases in sea level. Of concern to the insurance industry is the potential of these ice masses to become destabilised under conditions of present and future warming and this section will outline the major recent scientific findings in this field to help inform business responses to such risks.

(see Alley et al 2005). Three problems exist: empirical data are sparse in space and time; the physics in the models is not complete; and our understanding of the processes involved at the grounding line (the junction between land-based ice and where it starts to float) are partial (Vielí and Payne 2005). As a result, we have to assess ice sheet stability largely on the basis of current observations and assessments of their behaviour in the past.

Projections of the stability of the ice sheets suggest that large portions of them will melt during this century. Hansen (2005) suggests that melting will occur with a rise in the global mean surface temperature of more than 1°C; Oppenheimer and Alley (2005) suggests melting at 2°C and Overpeck et al (2006) with polar warming of less than 5°C. Gregory et al (2004) suggests that the Greenland ice sheet would be eliminated over the next

“RAPID MELTING [...] HAS THE POTENTIAL TO INCREASE SEA LEVELS SIGNIFICANTLY AND CREATE THE CONDITIONS FOR THE REORGANISATION OF THE OCEANS, WITH SUBSEQUENT SEVERE CLIMATIC IMPACTS.”

Perhaps the major problem in assessing the likely impact of AGW on the stability of the ice sheets is that the current level of sophistication of numerical ice sheet models does not allow us to understand ice sheet behaviour under AGW with much credibility

1,000 years with a rise in temperature of 3°C in the region. All of these figures are within the range of projected warming during this century as set out by the Intergovernmental Panel on Climate Change in its latest report (IPCC AR4).

However, what is the likelihood of significant ice sheet collapse over shorter time scales? One major unknown is the nature of the conditions at the base of the ice sheet (rheology, debris concentrations over large spatial scales etc) and the temperature gradient in the basal ice (which affects basal shear stress, basal sliding, water availability and the likelihood of rapid sediment deformation). Evidence from palaeoglaciology shows us that land-based ice sheets (such as the major portions of the Laurentide and Fenno-Scandian ice sheet) were largely stable and melted slowly. Conversely, ice sheets with significant marine couplings (such as that coupled to the Hudson Strait) broke up rapidly resulting in rapid discharge of icebergs and significant sea level rise from displacement.

GREENLAND ICE SHEET

Most of the Greenland Ice Sheet is not marine based and is therefore not likely to be in imminent danger of collapse. However, several of the large outlet glaciers draining the ice

recession. Calving of the 15 kilometres long floating ice tongue has reduced its length by about four kilometres and increased the production of icebergs (Mayer and Herzfeld 2005). Theoretical considerations suggest that downwasting and acceleration of the glacier are linked and self-sustaining and these characteristics have been termed the "Jakobshavns Effect". This is caused by positive feedback mechanisms triggering rapid ice discharge, deep crevassing and basal uncoupling to produce high calving fluxes (see Zwally et al).

The latest research (Chen et al 2006) on Greenland melting rates between April 2002 and November 2005 shows melting from South-East Greenland taking place five times greater over the last two years of the study compared to the first 18 months. They estimated total ice melting rate over Greenland as -239 ± 23 cubic kilometres per year, mostly (69% and 164 cubic kilometres per year) from East Greenland. They suggest that this increased melting adds on its own over 0.5 millimetres

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sheet have increased their velocities and ice discharge rates in recent years and these have the potential to draw down significant areas of inland ice.

Two fast-flowing tidewater glaciers in South-East Greenland have been studied recently. Helheim and Kangerdlugssuaq Glaciers drain around 10% of the Greenland Ice Sheet and both underwent significant recession and acceleration between 2001 and 2005 and have receded three to five kilometres since July 2003 (de Lange et al 2005; Sterns and Hamilton, 2005). Helheim Glacier increased its velocity by 40% between 1995 and 2005, while Kangerdlugssuaq Glacier tripled its velocity from the period 1988 to 2005 when it flowed at around 14 kilometres a year. Both glaciers have also downwasted by about 100 metres over the last decade or so.

Along with Glaciar San Rafael, Jakobshavn Isbrae is generally regarded as the fastest moving glacier in the world sustaining velocities around 20 metres a day. Both of these glaciers are tidewater where the significant contribution to ablation is derived from calving. Dietrich et al (2005) showed that Jakobshavn Isbrae has recently undergone a significant increase in velocity (up to 40 metres a day) and terminus

per year of global sea level rise. They also speculate that such injections of cold freshwater into the North Atlantic may impact upon the Norwegian current and affect the climate of Europe.

One of the authors, (B.D.Tapley) said "This melting process may be approaching a point where it won't be centuries before Greenland's ice melts, but a much shorter time-frame," but also noted that it is not possible to suggest a timetable for this.

WESTERN ANTARCTIC ICE SHEET

Recent climate change appears to have had variable impacts upon Antarctica. It is not at present clear whether the centre of the continent is undergoing warming or not as few long-term records are available. Some models suggested that the interior of the continent would experience increased snowfall. However, recent research by Monaghan et al (2006) suggests that there has been no statistically significant change in snowfall since the 1950s, further indicating that Antarctic precipitation is not mitigating global sea level rise as expected, despite recent winter warming of the overlying atmosphere. The Antarctic Peninsula is, however, experiencing significant warming (Turner et al 2005).

In contrast to the Greenland Ice Sheet, much of the WAIS lies at, or below, sea level and hence has the potential to collapse rapidly. Its stability is regarded as a key issue in the debate concerning the nature and occurrence of 'dangerous climate change' (Oppenheimer and Alley 2004). Overall, the WAIS is losing mass. Recent studies (Velicogna and Wahr, 2006) use information from satellites on the globe's gravity field to assess the amount of ice loss of the continent during the period 2002-2005. Their work showed that the Antarctic ice sheet decreased its mass at a rate of 152 ± 80 cubic kilometres a year of ice (equivalent to 0.4 ± 0.2 millimetres a year of global sea level rise) and most of this ice loss came from the WAIS. Uncertainties in the amount of isostatic readjustment to past ice loss produce the cited errors.

The Larsen B ice shelf collapsed in 2002 and this is probably the first time that this ice shelf has collapsed during the Holocene (Domack et al 2005). With subsequent removal of horizontal compressive forces, glaciers draining the Antarctic Peninsula increased their velocities by factors of two to eight with downwasting rates in the order of 10 metres a year (Scambos et al 2004). Overall ice loss is greater than 27 cubic kilometres a year (Rignot et al 2004). The future behaviour of these outlet glaciers is sensitively dependent upon the configuration of the subglacial bedrock and it appears that the glaciers flow into ice shelves several hundreds of metres thicker than was previously believed (Thomas et al 2004). These conduits thus provide routes for ice discharge from the central parts of the WAIS if ice sheet collapse is initiated.

“MUCH OF THE WEST ANTARCTIC ICE SHEET LIES AT, OR BELOW, SEA LEVEL AND HENCE HAS THE POTENTIAL TO COLLAPSE RAPIDLY.”

Other recent work has concentrated on the ice shelves buttressing the ice sheet and on the behaviour of its outlet glaciers. Two glaciers (Thwaites and Pine Island Glaciers) have shown recent changes in behaviour and suggest that the region is more sensitive to climate change than was previously thought (Shepherd et al 2004). These large glaciers drain the WAIS into the Amundsen Sea and their behaviour is closely linked with the overall stability of the WAIS. Work by Rignot (2001) on Thwaites Glacier showed that the grounding line had retreated 1.4 kilometres between 1992 and 1996 with a downwasting of the lower part of the glacier at 1.4 metres a year. Rignot et al (2002) reported that Pine Island Glacier increased its velocity over 150 kilometres of the glacier by 18% between 1992 and 2000, downwasted at 1.6 metres a year and seen a five kilometre retreat in grounding line between 1992 and 1996.

Payne et al (2004) believe that the changing behaviour of Pine Island Glacier may have significant implications for the long-term stability of the WAIS suggesting that there is a strong coupling between the interior of the ice sheet and the surrounding ocean.

Such changes in behaviour are likely to have been initiated by collapse of buttressing ice shelves rather than changes in basal shear stresses caused by increased meltwater production (see De Angelis and Skvarca 2003) although with regional warming and increased ice velocity the future contribution of changing subglacial conditions may be significant.

A recent study has raised the intriguing possibility that jökulhlaups periodically occur from the sub-glacial lakes of Antarctica. The research (Erlingsson 2006) suggests that Lake Vostok forms part of a system described by the 'Captured Ice Shelf Theory' whereby an ice shelf develops a hydrostatic seal over a sub-ice water body. Such water bodies are hypothesized to lead to the development of catastrophic lake outburst floods.

Lake Vostok is a sub-glacial lake under the East Antarctic ice at almost 3500m above sea level in East Antarctica. The lake is 260 kilometres long, 81 kilometres wide and with an area of about 14,000 square kilometres. It has a volume of 5400 ± 1600 cubic kilometres. Erlingsson (2006) suggests that "Lake Vostok is now almost full, and a jökulhlaup of several thousand cubic kilometers appears possible at any time" and argues that the volume of the lake varies with climate, increasing during interglacials. Any lake drainage would be through the Byrd Glacier to the Ross Ice Shelf and might create an ice stream which would rapidly drain large parts of the East Antarctic.

CONCLUSIONS

In conclusion, there are a range of views on the stability of the ice sheets, from Huybrechts et al (2004) who suggest that their net contribution to sea level change over the 21st century is not significantly different from zero to those (outlined in this report) who argue that the ice sheets are displaying signs of instability.

It is our view that there are clear and worrying trends in the behaviour of component parts of the Greenland and Antarctic Ice Sheet, with the WAIS in particular showing anomalous behaviour. Meaningful predictions of the likelihood of rapid, catastrophic ice discharge, ice sheet collapse or lake outbursts in the near future are impossible. However, an increase in instability, with a resultant impact on sea level within our lifetime, is a credible risk. Insurers and other commercial institutions sensitive to these risks should keep a close watch on future developments and be prepared to revise their strategies regularly.

REFERENCES

- Alley, R.B., Clark, P.U., Huybrechts, P. and Joughlin, I.** 2005. Ice-sheet and sea-level changes. *Science*, 310, 456-460.
- Chen, J.L., Wilson, C.R. and Tapley, B.D.** 2006. Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet. *Science* DOI: 10.1126/science.1129007.
- de Lange R., Murray, T., Luckman, A., Hanna, E.,** 2005. Dramatic Changes in the Flow Velocity of Helheim Glacier, SE Greenland: a Result of Climate Forcing? AGU, Session: The Dynamics of Glacier System Response: Tidewater Glaciers and the Ice Streams and Outlet Glaciers of Greenland and Antarctica, San Francisco, 5-9 December 2005.
- De Angelis, H. and Skvarca, P.** 2003. Glacier surge after ice shelf collapse. *Science*, 299, 1560-1562.
- Dietrich, R., Maas, H., Baessler, M., Ruelke, A., Schwalbe, E.,** 2005. Recent Flow Velocities at the Front of Jakobshavn Isbrae/ Greenland from 2004 Field Observations American Geophysical Union, Fall Meeting 2005, abstract #C41A-05.
- Domack, E., Duran, D., Leventer, A., Ishman, S., Doane, S., McCallum, S., Amblas, S., Ring, J., Gilbert, R., & Prentice, M.** 2005. Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. *Nature*, Vol. 436.
- Erlingsson, U.,** 2006: Lake Vostok behaves like a 'captured lake' and may be near to creating an Antarctic jökulhlaup. *Geografiska Annaler*, 88 A (1): 1-7.
- Gregory, J.M., Huybrechts, P. and Raper, S.B.** 2004. Threatened loss of the Greenland ice-sheet. *Nature*, 428, 616.
- Hansen, J.** 2005. A slippery slope. How much global warming constitutes "dangerous anthropogenic interference"? *Climatic Change*, 68, 269-279, 2005.
- Huybrechts, P., Gregory, J., Janssens, I., Wild, M.** 2004. Modelling Antarctic and Greenland volume changes during the 20th and 21st centuries forced by GCM time slice integrations. *Global and Planetary Change*, 42(1-4), 83-105.
- Monaghan, A.J., Bromwich, D.H., Fogt, R.L., Wang, S-H., Mayewski, P.A., Dixon, D.A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S.D., Morgan, V.I., Oerter, H., Van Ommen, T.D., Van der Veen, C.J., Wen, J.** 2006. Insignificant Change in Antarctic Snowfall Since the International Geophysical Year. *Science* 11 August 2006: Vol. 313. no. 5788, pp. 827 - 831.
- Oppenheimer, M., and Alley, R.B.** 2004. The West Antarctic Ice Sheet and Long Term Climate Policy. *Climatic Change*, 64(1-2), 1-10.
- Oppenheimer, M. and Alley, R.B.,** Ice sheets, global warming and Article 2 of the UNFCCC. *Climatic Change*, 68, 257-267, 2005.
- M. Oppenheimer.** 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature*, 393, 325-332.
- Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B. and Kiehl, J.T.** 2006. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* 311: 1747-1750.
- Payne, A.J., Vieli, A., Shephard, A., Wingham, D.J., and Rignot, E.** 2004. Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophysical Research Letters*, 31, L23401.
- Rignot, E.** 2001 Evidence for rapid retreat and mass loss of Thwaites Glacier, West Antarctica *Journal of Glaciology*, Volume 47, Number 157, March 2001, pp. 213-222(10).
- Rignot, E. Vaughan, D.G., Schmelz, M., Dupont, T. MacAyeal, D.** 2002 Acceleration of Pine Island and Thwaites Glaciers, West Antarctica *Annals of Glaciology*, Vol. 34, Number 1, 189-196.
- Rignot, E. G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas.** 2004. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters*, 31(18), L18401, doi:10.1029/2004GL020697.
- Scambos, T. A., J. A. Bohlander, C.A. Shuman, and P. Skvarca.** 2004. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophysical Research Letters*, 31(18), L18402, doi:10.1029/2004GL02067.
- Shepherd, A., Wingham, D., and Rignot, E.** 2004. Warm ocean is eroding West Antarctic Ice Sheet. *Geophysical Research Letters*, 31(23), L23402, doi:10.1029/2004GL021106.
- Sterns, L.A. and Hamilton, G.S.** 2005. Rapid Changes in Outlet Glacier Dynamics in Greenland: Implications for Ice Sheet Mass Balance and Sea Level Rise Scenarios American Geophysical Union, Fall Meeting 2005, abstract #C23A-1159.
- Thomas, R., E. Rignot, G. Casassa, P. Kanagaratnam, C. Acuña, T. Akins, H. Brecher, E. Frederick.** 2004. Accelerated Sea-Level Rise from West Antarctica. *Science*, 306(5694), 255-258.
- Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. and Lgovkina, S.** 2005. Antarctic climate change during the last 50 years. *International Journal of Climatology* 25: 279-294.
- Velicogna, I. and Wahr, J.** 2006 Measurements of Time-Variable Gravity Show Mass Loss in Antarctica science *Science*. Vol. 311. no. 5768, pp. 1754 - 1756.
- Vieli, A., and A.J. Payne** (2005) Modelling the grounding line migration of marine ice sheets, *Journal of Geophysical Research* 110, F01003.
- Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J. and Steffen, K.** 2002. Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, 297, 218-222.

An aerial photograph showing a vast agricultural landscape completely inundated with brown floodwater. A network of roads, including a prominent multi-lane highway on the left and several smaller roads, winds through the flooded fields. The water level is high, reaching the tops of trees and structures. The scene illustrates the impact of severe flooding on infrastructure and agriculture.

INCREASED FREQUENCY AND INTENSITY OF FLOODS BY DR MATT WILSON

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Dr Matt Wilson is a lecturer at Exeter University. Dr Wilson has both a BSc and a PhD from Southampton University, the latter in computational flood modelling. He is particularly interested in the assessment of uncertainty in predictions of flood inundation and the assimilation of remotely sensed data into models. His past research has included the geostatistical assessment of the effect of topographic uncertainty on the prediction of flood inundation. Dr Wilson's recent work includes the modelling of large rivers, including the Amazon (Brazil) and Ohio (United States) rivers. Matt Wilson's projects include a "virtual mission" to develop specifications for a surface water remote sensing satellite (WatER).

INTRODUCTION

Flooding is an international problem that is set to increase under climate change over the next 50 to 100 years. Globally, it currently accounts for 40% of all natural hazards and half of all deaths caused by natural disasters, with most flood events occurring in developing, tropical regions (Ohl & Tapsell 2000). Worldwide, major flood events are already very frequent (Alcántara-Ayala 2002), yet are predicted to become more so: although there is considerable uncertainty in the predictions, changes in the frequencies of extreme events such as floods may be one of the most significant consequences of climate change (Katz and Brown 1992, Karl et al 1993, Frei et al 1998, Jones 1999). Both observations and computer models suggest that the atmospheric hydrological cycle is accelerating and intensifying, which results in increasing river discharge and flood risk (Voss et al 2002; Stocker and Raible 2005, Huntington 2006).

1. Lowland river flooding in larger river channels: primarily caused by long-duration rainfall from one or more frontal systems, or by springtime snowmelt.
2. Flash flooding of small river channels or along drainage pathways: primarily caused by short-duration, intensive rainfall from convective thunderstorm events.
3. Coastal flooding: primarily caused by localised sea-level rise induced by storm surges including those from tropical cyclones.

Flooding may be caused by a combination of these and other factors – the frequency of each type of flooding depends on the frequency of the causal weather event, combined with non-climate factors such as the location of a susceptible population. However, it is likely that events with an intensity

“[FLOODING] CURRENTLY ACCOUNTS FOR 40% OF ALL NATURAL HAZARDS AND HALF OF ALL DEATHS CAUSED BY NATURAL DISASTERS.”

There are two main strands to the flooding problem: (i) anthropogenic factors such as societal vulnerability to flooding, including levels of flood protection and (ii) climate driven factors such as weather events. Importantly, flooding only becomes a major hazard to life and property when people live or work in flood prone areas (O’Keefe et al 1976, Burton et al 1993). However, the size of these areas will increase if, as predicted, flooding becomes more severe under climate change.

There are several types of flooding that are likely to be affected strongly by climate change. Principally these are:

of today’s 100-year floods may recur every 10 to 50 years by the 2070s (Lehner et al 2006), and the future 100 year flood event will be more severe. The reason is that climate change is expected to alter average temperature and precipitation values, which are key factors for flood risk. Climate change will affect the weather events that cause flooding, both in terms of frequency of event and intensity. The likely changes in the principal flood types and the weather types causing them are summarised here.

LOWLAND RIVER FLOODING

In a warmer climate, the atmosphere will contain more water, and with intensification of low-pressure systems will make more water available for precipitation (Frei et al 1998). Climate model integrations suggest increases in both the frequency and intensity of heavy rainfall in high latitudes of the northern hemisphere (Palmer and Räisänen 2002, Ekström et al 2005). These trends could take hold by the middle of the century, and it is expected that discharge from Eurasian rivers may increase by 18-70% by the end of the century. There is already evidence to suggest that the frequency of major flooding is increasing: Milly et al (2002) found that the incidence of great floods (floods that exceed 100-year levels in basins larger than 200,000 square kilometres) increased substantially in the 20th century. There is a statistically significant positive trend in the risk of great floods, which they found to be consistent with results from climate models.

Increases in average precipitation and its variability are expected for northern European regions, suggesting higher flood risks (Arnell et al 2000). UKCIP02 predicts that UK winter

to occur every 40 years, and the 100 year event will be around 10% more severe.

In a similar study, Hall et al (2005) conducted an assessment of current and future flood risk in England and Wales, and estimated the current expected annual economic flood damage to residential and commercial property to be \$550m (uncertainty range: \$330m to \$1.15bn). Their study indicated that, under high emission and relatively loose regulation scenarios, this figure may be expected to rise to \$8bn by 2050 and \$11.3bn by 2080. Even under a global sustainability scenario, future annual economic damage is predicted at \$2.7bn by 2080, nearly five times today's levels.

Many extreme floods are caused by intense precipitation in mountainous areas, or a combination of precipitation and snowmelt (Kaczmarek 2003). In the western United States, increased winter precipitation, together with an increase in the rainfall-portion of precipitation (at the expense of snowfall), is expected to lead to large increases in high-runoff events in river basins already prone to winter flooding (Kim 2005). One

“CLIMATE MODEL INTEGRATIONS SUGGEST INCREASED IN BOTH THE FREQUENCY AND INTENSITY OF HEAVY RAINFALL IN HIGH LATITUDES OF THE NORTHERN HEMISPHERE.”

rainfall will increase (Hulme et al 2002). Palmer and Räisänen (2002) estimate that, in the UK alone, the probability of the total winter precipitation will significantly increase by 2050 and the probability of it exceeding two standard deviations above normal levels will increase by a factor of five over the next 100 years. Similar increases were found for the Asian monsoon season, with implications for flooding in Bangladesh.

Lehner et al (2006) used a global integrated water model (WaterGAP), driven by climate change projections (temperature and precipitation) from General Circulation Models (GCMs), and by a set of scenario assumptions for changes in human water use. The scenarios investigated represent the “business as usual approach” for economic growth and activity and imply an average annual increase of CO₂ emissions of 1% per year. The study finds that, as early as 2020, across large parts of the northern Europe, the north of the UK and the Iberian peninsular floods with a return period of 100 years today can be expected

primary reason for this is higher average temperatures: the resulting higher freezing levels leads to a change in the normal type of precipitation from snow to rainfall, and an increase in winter snowmelt (Kim 2005). Similarly, in Poland, Kaczmarek (2003) found that the risk of snowmelt induced flooding is linked to the North Atlantic Oscillation (NAO): trends to positive NAO leads to an increase in surface air temperature and a temporal redistribution of winter and spring runoff. Thus, winter runoff increases leading to an increase in flood risk; conversely spring snowmelt decreases, reducing flood risk.

FLASH FLOODING

Intense rainfall from convective thunderstorms may only last a few hours, but can result in serious flooding in catchments that are small, steep or highly urbanised (Dale 2005). In the UK, the Boscastle flash flooding of August 2004 was caused by such an event. While the UKCIP02 study in the UK predicts that summer rainfall will dramatically decrease (Hulme et al 2002),

thunderstorms are likely to become more frequent and produce heavier and more intense rainfall (Dale 2005), thus increasing the likelihood of summer flash flooding (such as the Boscastle event). Similarly, Christensen & Christensen (2003) have found that climate warming is likely to lead to a shift towards heavier intensive summertime precipitation for large parts of Europe. Thus, despite a general trend to drier summer conditions in Europe, episodes of severe flooding may become more frequent due to short (1-5 days) episodes of heavy precipitation.

Due to the small spatial and temporal scales in which thunderstorm events occur, they are extremely difficult to predict, both for an individual event and as part of climate scenarios. The scale at which climate change predictions are provided is the main problem – these are very coarse relative to the events, both spatially and temporally (Dale 2005). Hence in order to use such predictions to assess likely changes in flood risk, GCM outputs must be downscaled to the level of the hydrological model, which is recognised to be difficult (Prudhomme et al 2002). Therefore, models that use climate change predictions to quantify the likely change in flood risk and its economic impact (for example, the European study by Lehner et al 2006 or the UK study by Hall et al 2005) may underestimate the risk of flooding from small spatial scale and short duration events such as those from flash flooding and subsequently may underestimate the likely future economic damage.

COASTAL FLOODING

The risk from coastal flooding is significant. Nicholls (2005) shows that the number of people likely to be affected by coastal flooding will increase over the next century due to both increasing coastal populations and an increase in storm

One of the most potentially serious causes of coastal flooding are from storm surges induced by tropical cyclones. Cyclone activity occurs generally in regions where sea surface temperature exceeds 26°C. Sea surface temperatures (SSTs) vary widely on interannual and multidecadal timescales, but there is a non-linear upward trend in SSTs over the 20th century, most pronounced over the last 35 years (Trenberth 2005) and particularly since 1995 (Goldenberg et al 2001). Higher SSTs are associated with increased water vapour in the lower troposphere that tend to increase the energy available for atmospheric convection, such as thunderstorms, and for the development of tropical cyclones (Holland, 1997).

There is considerable scientific uncertainty concerning the attribution of changes in tropical cyclone frequency and intensity. However, while the frequency of tropical cyclones has not been found to be increasing, theory and modelling predict that with increasing global mean temperatures, the intensity will increase (Emanuel 1987, Knutson and Tuleya 2004), which has been confirmed by statistical analysis of past cyclone activity (Trenberth 2005, Webster et al 2005). Recent work by Emanuel (2005) has shown a strong correlation between net cyclone power dissipation and tropical sea surface temperature, and suggests an upward trend in tropical cyclone destructive potential, especially when taking into account an increasing coastal population, and particularly in low-lying cities such as New Orleans. Warnings of the vulnerability of New Orleans to a large (category 5) cyclone were given years prior to the Katrina cyclone in August 2005 (see Nature, 431, p.388, 2004), yet the city's levee system was not designed for storms stronger than category-3 (see Nature 437, p.174-176, 2005), and vulnerability

“FUTURE ANNUAL ECONOMIC [UK FLOOD] DAMAGE IS PREDICTED AT \$2.7BN BY 2080, NEARLY FIVE TIMES THE LEVELS OF TODAY.”

surges. The UK study by Hall et al (2005) assesses coastal flooding as forming 26% of all UK flood risk in 2002, but predicts that this is likely to rise to 46% by 2080, primarily due to increasing probability of overtopping of the Thames Barrier that protects central London. Global-mean sea-level is projected to rise between 22 and 34 centimetres by the 2080s (relative to 1990 levels) (Johns et al 2003), both exacerbating storm surges and causing increased coastal erosion leading to a loss of coastal wetlands (Nicholls 2002).

has increased due to the loss of Mississippi wetlands that act as a buffer. As cyclones become more intensive generally, the frequency of category-5 cyclones will likely increase.

SOME ISSUES OF FLOOD HAZARD MANAGEMENT

Climate and climate change is only part of the flooding problem: how the surface water and the flood hazard are managed is as important. White and Howe (2004) show that poor surface water management can exacerbate the severity of flooding and its

impact. For example, urban drainage systems combined with a large area of impermeable surfaces tend to move water rapidly to the watercourse, leading to reduced lag time between a precipitation event and the stream discharge peak. In turn, this causes higher streamflow, leading to a greater risk of flooding downstream. In addition, urban drainage may be overloaded by the high volume of water, leading to sewer surcharge (Aronica and Lanza, 2005). Increased urbanisation, combined with an

CONCLUSIONS

For all types of climate-driven flood event, the frequency and magnitude of flooding is likely to increase by the middle of the century under climate change. This fact should be built into risk modelling and business planning scenarios, with the following trends particularly highlighted:

- In many temperate areas winter precipitation is likely to increase, raising the risk of lowland flooding.

“CLIMATE AND CLIMATE CHANGE IS ONLY PART OF THE FLOODING PROBLEM: HOW THE SURFACE WATER AND THE FLOOD HAZARD ARE MANAGED IS AS IMPORTANT.”

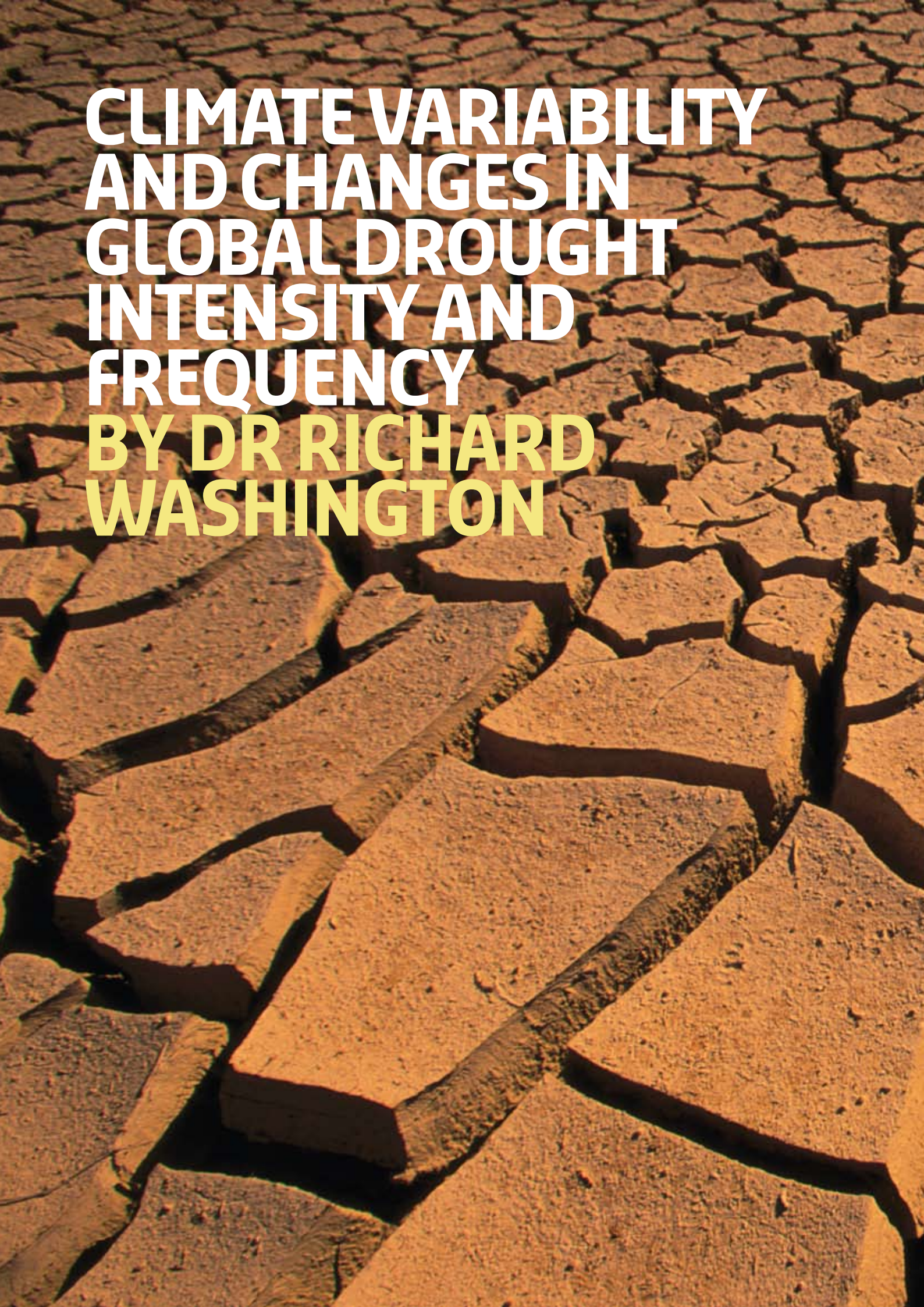
increase in the frequency and intensity of storm rainfall events, will increase the risk of flooding (Holman et al 2005).

For flood protection, the current 100-year event (that is, the event magnitude with a 1% probability of being exceeded in any year, based on past observations) is often used in many engineering approaches, from reservoir design to designated flooding zones and embankments (Lehner et al 2006). However, as discussed, under climate change, events of this magnitude are likely to occur more frequently. Thus, current levels of flood protection are likely to be insufficient to protect people and property.

- In mountainous areas, higher temperatures will increase the freezing level and change the runoff regime, raising flood risk in winter but reducing it in spring.
- As temperature increases, the likelihood of convective thunderstorms increases, raising the risk of flash flooding.
- Sea-level rise will exacerbate storm-surges and increase the risk of coastal flooding.
- There is considerable (and disputed) evidence that tropical cyclones are becoming more intensive as sea surface temperature increases, raising the risk of coastal flooding.

REFERENCES

- Alcántara-Ayala, I.** (2002), Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries, *Geomorphology* 47, 107–124.
- Arnell, NW, Grabs, W, Mimikou, M, Schumann, A, Reynard, NS, Kaczmarek, Z, Oancea, V, Buchtele, J, Kasperek, L, Blazoka, S, Starosolszky, O, Kuzin, A** (2000) Effect of Climate Change on Hydrological Regimes and Water Resources in Europe, Summary of report of projects EV5V-CT93-0293 and EV5V-CT94-0114, University of Southampton, UK.
- Aronica, GT and Lanza, LG** (2005), Drainage efficiency in urban areas: a case study, *Hydrological Processes*, 19, 1105–1119.
- Burton, I, Kates, R, White, G.** (1993), *The Environment as Hazard*, Guildford, New York.
- Christensen, JH, Christensen, OB** (2003), Severe summertime flooding in Europe, *Nature*, 421, 805–806.
- Dale, M** (2005), Impact of climate change on UK flooding and future predictions, *Proceedings of the Institute of Civil Engineers: Water Management*, 158, 135–140.
- Ekström, M, Fowler, HJ, Kilsby, CG, Jones, PD** (2005) New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies, *Journal of Hydrology*, 300, 234–251.
- Emanuel, KA** (1987), The dependence of hurricane intensity on climate, *Nature*, 326, 483–485.
- Emanuel, KA** (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, 436, 686–688.
- Frei, C, Schar, C, Luthi, D, Davies, HC** (1998), Heavy precipitation processes in a warmer climate, *Geophysical Research Letters*, 25(9), 1431–1434.
- Goldenberg, SB, Landsea, CW, Mestas-Nuñez, AM, Gray, WM** (2001) The Recent Increase in Atlantic Hurricane Activity: Causes and Implications, *Science*, 293, 474–479.
- Hall, JW, Sayers, PB, Dawson, RJ (2005), National-scale assessment of current and future flood risk in England and Wales, *Natural Hazards*, 36, 147–164.
- Holland GJ** (1997) The maximum potential intensity of tropical cyclones, *Journal of the Atmospheric Sciences*, 54, 2519–2540.
- Holman, IP, Nicholls, RJ, Berry, PM, Harrison, PA, Audsley E, Shackley, S and Rounsevell, MDA** (2005), A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: Part II: results, *Climatic Change*, 71, 43–73.
- Hulme, M, Jenkins, GJ, Lu, X, Turnpenny, JR, Mitchell, TD, Jones, RG, Lowe, J, Murphy, JM, Hassell, D, Boorman, P, McDonald, R, Hill, S** (2002) *Climate change scenarios for the United Kingdom*. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UKCIP02 Scientific Report.
- Huntington, TG** (2006) Evidence for intensification of the global water cycle: Review and synthesis, *Journal of Hydrology* 319 (2006) 83–95.
- Johns, TC, Gregory, JM, Ingram, WJ, Johnson, CE, Jones, A, Lowe, JA, Mitchell, JFB, Roberts, DL, Sexton, DMH, Stevenson, DS, Tett, SFB, Woodage, MJ** (2003) Anthropogenic climate change from 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, *Climate Dynamics* 20, 583–612.
- Kaczmarek, Z** (2003) The impact of climate variability on flood risk in Poland, *Risk Analysis*, 23, 559–566.
- Karl, T, Quayle, RG, Groisman, PI** (1993), Detecting climate variations and change: New challenges for observing data management systems, *Journal of Climate*, 6, 1481–1494.
- Katz, WR, Brown, G** (1992) Extreme events in changing climate: Variability is more important than averages, *Climatic Change*, 21, 289–302.
- Kim, J** (2005) A projection of the effects of the climatic change induced by increased CO₂ on extreme hydrologic event in the western US, *Climatic Change*, 68, 153–168.
- Knutson, TR, Tuleya, RE** (2004) Impact of CO₂-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization, *Journal of Climate*, 17, 3477–3495.
- Lehner, B, Döll, P, Alcamo, J, Henrichs, T, Kaspar, F** (2006), Estimating the impact of global change on flood and drought risks in Europe: a continental integrated analysis, *Climatic Change*, 75, 273–299.
- Milly, PCD, Wetherald, RT, Dunne, KA, Delworth, TL** (2002), Increasing risk of great floods in a changing climate, *Nature*, 415, 514–517.
- Nicholls, RJ** (2002) Analysis of global impacts of sea-level rise: a case study of flooding, *Physics and Chemistry of the Earth* 27, 1455–1466.
- Nicholls, RJ** (2005) Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios, *Global Environmental Change*, 14, 69–86.
- Ohi, C, Tapsell, S** (2000), Flooding and human health: the dangers posed are not always obvious, *British Medical Journal*, 321, 1167–1168.
- O’Keefe, P, Westgate, K, Wisner, B** (1976), Taking the naturalness out of natural disasters, *Nature*, 260, 56–57.
- Palmer and Räisänen** (2002) Quantifying the risk of extreme seasonal precipitation events in a changing climate, *Nature*, 415, 512–514.
- Peterson, BJ, Holmes, RM, McClelland, JW, Vörösmarty, CJ, Lammers, RB, Shiklomanov, AI, Shiklomanov IA, Rahmstorf, S** (2002) Increasing River Discharge to the Arctic Ocean, *Science*, 298, 2171–2173.
- Prudhomme, C, Reynard, N, Crooks, S** (2002), Downscaling of global climate models for flood frequency analysis: where are we now?, *Hydrological Processes*, 16, 1137–1150.
- Stocker, TF & Raible, CC** (2005) Water cycle shifts gear, *Nature*, 434, 830–833.
- Trenberth, K** (2005) Uncertainty in Hurricanes and Global Warming, *Science*, 308, 1753–1754.
- Voss, R, May, W, Roeckner, E** (2002) Enhanced resolution modeling study on anthropogenic climate change: Changes in extremes of the hydrological cycle, *International Journal of Climatology*, 22, 755–777.
- Webster, PJ, Holland, GJ, Curry, JA and Chang, H-R** (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, 309, 1844–1846.
- White, I, Howe, J** (2004), The mismanagement of surface water, *Applied Geography*, 24, 261–280.



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Dr Richard Washington is a lecturer in Climate Science at Oxford University Centre for the Environment and a Fellow of Keble College, Oxford. His expertise is in climate variability and climate prediction. Extremes associated with climate change are likely to come about from climate variability superimposed on the changing climate system. Understanding variability is therefore crucial and Richard Washington has a strong regional perspective on climate, especially the tropical and subtropical climates of the world. In particular, he has many years of experience in evaluating how well climate models perform in key regions of the world.

INTRODUCTION

Regional climate extremes occur when climate variability imposes large anomalies on the average state of the climate system. The anomalies tend to be large compared with long-term century long trends although the anomalies are not usually maintained for longer than a few months. Nevertheless it is the anomalies arising from variability that tend to pose the key problems for power generation, agricultural output, human health etc.

AGW is already imposing a change on the mean state of climate and this is expected to accelerate later in the 21st century. Future climate variability will therefore occur on a different background mean state of climate. In the case of heat waves, for example, temperature anomalies resulting from climate variability will be larger as a result of the increased mean temperature alone. But the patterns of variability themselves are also predicted to

many cases droughts can be traced to recognised patterns of climate variability, such as El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). ENSO is related to widespread droughts and floods across the globe. The pattern of variability has two opposite extremes, La Niña (cooling in the central tropical Pacific near-surface ocean) and El Niño (warming in the central tropical Pacific near surface-ocean). La Niña is associated with drought conditions in the central Pacific and East Africa and El Niño with drought conditions over the western tropical Pacific (including Indonesia), Eastern Australia, southern Africa, the Sahel and parts of north east Brazil. Taken over the last 50 years, these regions experience a probability of above average rainfall of 0-20% during El Niño events (Mason and Goddard, 2001).

Outside the summer months, the NAO is associated with roughly 50% of the climate variability of North Africa, the North Atlantic,

“NEAR PERMANENT DROUGHT CONDITIONS COULD EVOLVE IN SOME AREAS DUE TO CHANGES IN GLOBAL CIRCULATION PATTERNS.”

change as a function of AGW so that extremes relating to climate variability will come about because of two recognisable sources (change in mean state and change in variability).

DROUGHTS AND PATTERNS OF VARIABILITY

Unlike floods, which can result from small scale features such as individual thunderstorm systems (eg the Boscastle Floods of August 2004), droughts result from persistent, large scale and organised features of weather and climate which act to suppress rain producing systems (eg thunderstorms) that may be expected to occur in a particular season and region. In

Europe and the east coast of the USA. This pattern of variability has two extremes. In the negative phase in which North West Europe is dry and cold (eg winter 2005/6) and North Africa is wet, the midlatitude storm track steers anomalously south through the Mediterranean. In the positive phase, North Africa is dry and North West Europe wet and mild with the storm track passing through Northwest Europe.

OBSERVED CHANGES TO PATTERNS OF VARIABILITY

The last few decades have seen an increase in both the

frequency and intensity of El Niño events. Accordingly, drought conditions in the regions which El Niño has influence have been extreme. In southern Africa for example, an extreme drought with widespread loss of livelihoods occurred in the southern summer of 1982/3 in association with the largest El Niño yet observed. Estimates of the return period for such a strong El Niño are in the range of a few thousand years. An even stronger El Niño occurred in 1997/8. Similarly, the early 1990s saw the most long lived El Niño event in the observational record with devastating droughts and loss of livelihoods across Southern Africa.

El Niño years are globally warm years. The last few decades have been unusually warm. Intense El Niño events have been more frequent. ENSO and AGW are therefore closely bound up (Vecchi et al, 2006).

Similarly, the last three decades have witnessed the most unusually strong and persistent positive phase of the NAO. Droughts across the Mediterranean countries and North

changing patterns of drought in association with this change. We argue that the latter route is the safer approach. In the former approach, drought conditions in climate models could come about through a variety of causes, some real but not yet understood, some simply because of model systematic bias. Since the connection between large scale patterns of variability and drought is strong, the latter approach provides a firm basis for identifying droughts associated with established causes (see also Douville et al, 2006).

Yu and Boer (2002) have analysed the resultant ENSO structure in a number of climate models forced with Greenhouse gases. The majority of models tend to produce a semi-permanent El Niño like response after several decades of warming. The effect of this is to drive semi-permanent drought conditions in the drought prone El Niño regions of the globe. In the UK Met Office Model HadCM3, for example, this response is associated with the drying of the Amazon and the loss of that crucial carbon sink starting to take place by the middle of the century. Others however, analysing a single climate model, report ENSO

“GLOBAL WARMING IS CHANGING THE AVERAGE CLIMATE; BUT IT IS ALSO MAKING IT MORE ERRATIC WHICH IS OF PARTICULAR CONCERN TO THE INSURANCE INDUSTRY.”

Africa associated with this pattern have led to alarming water resource conditions in some countries. Positive NAO years are globally warm years. The last few decades have been unusually warm. The last few decades have been striking in the number of positive NAO years. The NAO and AGW are therefore closely linked (Gillett et al, 2003).

PREDICTED CHANGES TO PATTERNS OF VARIABILITY

It is clear from the observed record that the basic characteristics of patterns of variability associated with widespread drought conditions are changing and that these changes are consistent with the warming which is being experienced.

Assessing changes to future drought conditions can only be done with climate model simulations. There are two broad approaches. One is to assess region for region how drought metrics (eg frequency, intensity, longevity) change. The other is to consider how the patterns of variability change and consider the

behaviour to remain largely unchanged in the presence of increase greenhouse forcing (Zelle et al, 2005). More work is needed to evaluate the model physics which generates the ENSO events and the sustained patterns in these models. In the meantime, by 2050, the indications are that regions which currently suffer from El Niño related droughts (such as Southern Africa) will become more vulnerable while those associated with La Niña related droughts (such as East Africa) are likely to be less drought prone.

CHANGE TO GLOBAL RAINFALL

So far we have discussed drought conditions associated with patterns of climate variability. Long term drying and near permanent drought conditions could evolve for certain regions because of changes to the large scale (general) circulation. Regions currently experiencing a brief season of winter rains from mid-latitude storms could become much drier by 2050 if the storm track shifts its average position in future decades. In general, climate models point to an intensification of the tropical

convection in future decades. As a consequence, subsidence in the subtropical latitudes (the location of the world's major deserts) intensifies as well, leading to generally drier conditions for such regions. Careful studies of available climate model data for key regions are necessary in order to assess the probability of such change.

CONCLUSIONS

Droughts result from long-lasting, large-scale climate features and are linked to ENSO and also the NAO, both of which are in turn linked to man-made climate change. Compared to the observed historical record, drought patterns are changing in a way that is consistent with a warming world. Global warming is not only changing the average climate; but it is also making it more erratic which should be of particular concern to the insurance industry. Some climate models predict an almost permanent El Nino (though not all agree with this) and such an event could lead to the drying of the Amazon and eventual release of significant amounts of extra Carbon Dioxide into the atmosphere, leading to further warming. As a result, the possibility of near permanent drought conditions evolving by the middle of the century in some areas due changes in global circulation patterns is a credible risk.

REFERENCES

- Douville H, Salas-Melia D, Tyteca S.** 2006. On the tropical origin of uncertainties in the global land precipitation response to global warming, *Climate Dynamics* 26 (4): 367-385.
- Mason, S. J., and L. Goddard,** 2001: Probabilistic precipitation anomalies associated with ENSO *Bulletin of the American Meteorological Society*, 82, 619-638.
- Gillett, N., F. W. Zwiers, A. J. Weaver, P. A. Stott.** 2003. Detection of human influence on sea level pressure, *Nature*, 422, 292-294.
- Vecchi, G.A. et al,** 2006. Weakening of the Tropical Pacific Atmospheric Circulation due to anthropogenic forcing, *Nature*, vol 441, 73-76.
- Yu B, Boer GJ.** 2002. The roles of radiation and dynamical processes in the El Nino like response to global warming, *Climate Dynamics* 19 (5-6): 539-553.
- Zelle H, Van Oldenborgh GJ, Burgers G.** 2005. El Nino and Greenhouse warming, results from ensemble simulations with the NCAR CCSM, *Journal of Climate* 18 (22): 4669-4683.

GLOSSARY

Anthropogenic Global Warming (AGW) Warming of global average temperatures caused by the actions of mankind.

Ablation The removal of ice or snow from the surface of a mass of ice.

Anomalies Differences from the average level.

atmospheric convection Currents of air caused by the sun heating the earth's surface and the hot air rising, cooling and then falling again.

basal shear stresses Forces developed at the base of a glacier controlled by factors such as basal friction, bed permeability, amount of water and ice thickness.

calving The process where icebergs break off from the ice sheet to which they were previously attached.

deglaciation Melting of a glacier to uncover land beneath it.

downwasting the thinning of a glacier or other ice mass from the surface, as compared to "recession" which is the lateral retreat of an ice mass.

El Nino Major fluctuations in the temperature of sea surface waters in the Eastern Pacific Ocean. El Nino is a physical appearance of a wider Ocean/Atmosphere phenomenon called ENSO (the "El Nino Southern Oscillation"). Results in unusually hot temperatures in the equatorial pacific.

frontal systems A "front" is the transition zone between two air masses of different pressure.

GCM Global climate model (also known as General Circulation Model). Computer models of the climate based on scientific equations and a simplified segmentation of the earth's atmosphere and oceans.

HadCM3 A GCM created by the UK Met Office (Hadley Centre), the model on which many of the latest UK scientific predictions are made.

Holocene A period of time starting around 11,400 years ago up to the present day. The Holocene started roughly at the end of the last ice age and includes the complete development of human civilisation. It was preceded by the Pleistocene period.

Hydrostatic seal An area of still water.

IPCC Intergovernmental Panel on Climate Change, established in 1988 by the United Nations.

IPCC TAR IPCC Third Assessment Report, published in 2001.

IPCC AR4 IPCC Fourth Assessment Report, an executive summary was published in February 2007; the full report is due to be published later in the year.

Isostatic Readjustment The tectonic plates are believed to float on lower layers of the earth's interior once a gravitational equilibrium (or "isostasy") is reached. When the ice sheets melt the weight on the plates is reduced and a new equilibrium ("readjustment") is found.

Jökulhlaups Large sudden outbursts of water from pressurised lakes trapped underneath glaciers or ice sheets.

La Nina A physical appearance of a wider Ocean/Atmosphere phenomenon called ENSO (the "El Nino Southern Oscillation"). Results in unusually cold sea surface temperatures in the equatorial pacific.

marine couplings Region where the glacier joins the sea.

neotectonics Movements in the earth's crust that happened recently or are still happening.

North Atlantic Oscillation (NAO) Fluctuations in air pressure as measured in the Azores and Iceland. Controls the strength and direction of storm tracks across Northern Europe.

Palaeoglaciology A science which reconstructs the nature and form of former glaciers from geological and glaciological evidence and theory.

Pleistocene A period of time lasting for around 1.8 million years and finishing at the end of the last ice age around 12,000 years ago. Followed by the Holocene period.

Recession The ways in which glaciers become less extensive through time, usually because of melting of ice.

storm surges Temporary increases in sea level caused by low pressure systems reducing atmospheric pressure and allowing the water level to rise; this small effect is then significantly amplified by high winds which cause the water

to pile up. These are expected to become significantly worse under climate change scenarios.

terminus The downslope margin of a glacier.

tropical cyclones A storm system with a low pressure centre with rotation. The storms rotate in different directions in each hemisphere.

troposphere The lowest portion of earth's atmosphere containing the majority of its water vapour. In the Troposphere the temperature decreases with altitude.

variability Some outcomes are known in advance and some have an element of doubt. The average outcome may be known (such as the amount of rainfall during May) but the actual outcome may be different. This difference is known as the variability of the outcome. Under climate change the average level may change; but (possibly more worrying for insurers) the level of variability may increase as well.

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