Hazard & Risk Science Review 2009

A unique digest for the insurance industry of the latest natural hazard and risk science research

AON BENFIELD UCL Hazard Research Centre

UCL

Atmospheric

Geological

Hydrological

Climate Change

Sponsored by:

AON BENFIELD

PartnerRe

Hazard & Risk Science Review 2009

Foreword

Aon Benfield and PartnerRe are proud to present the Hazard & Risk Science Review 2009, the sixth edition of this unique publication.

In a year that has seen destruction caused by the L'Aquila earthquake in Italy and the deadliest wildfires in Australia's history, with insured losses reaching as high as AUD1.5bn, it is clear that there continues to be a strong requirement for in-depth research into natural hazards.

The Hazard & Risk Science Review once again assists in bridging the gap between re/insurance and academia by providing a synopsis of key research papers deemed most relevant to the industry. The 2009 Review continues to focus on the four main areas of hazard: atmospheric, geological, hydrological and climate change-related, and summaries of more than 70 scientific papers published during the past 12 months are featured in the publication. Academics from the Aon Benfield UCL Hazard Research Centre worked with natural catastrophe experts from both Aon Benfield and PartnerRe to source the papers that would provide most assistance in developing appropriate insurance and reinsurance solutions.

Our organisations both have a long-standing commitment to research, and we believe that the Review continues to assist the industry in developing its understanding of emerging risk science by providing the most up-to-date information in this area.

We hope that you find this year's publication a useful reference point.

Andrew Appel
Chief Executive Officer
Aon Benfield

Patrick Thiele
President and Chief Executive Officer
PartnerRe

Authors' note

While the last 12 months have not seen a catastrophe on the scale of the previous year's Cyclone Nargis or Sichuan earthquake, devastating wildfires in Australia and the Abruzzo earthquake in Italy have served to remind us that western developed nations are far from immune to natural disasters. As the world's population grows and becomes increasingly concentrated into ever-larger urban centres, so exposure and vulnerability to natural hazards will inevitably grow – in developing and developed nations alike. Climate change adds to the uncertainty and may increase the frequency and/or severity of major storm and flood events. In this year's Review, we present a digest of peer-reviewed papers that address critical issues, including hazard characterisation, forecasting and modelling that, together, seek to reduce vulnerability and exposure and diminish disaster risk. Our aim continues to be to improve industry awareness and understanding of natural catastrophes and the processes that drive them, to limit the number of shocks and surprises arising from hazardous events, and to help drive more informed business decisions on a day-to-day basis.

Professor Bill McGuire
Dr. Steve Edwards
Dr. Simon Day
Dr. Harvey Rodda
Mr. David Smart
Aon Benfield UCL Hazard Research Centre

Aon Benfield
55 Bishopsgate
London
EC2N 3BD
T: +44 (0)20 7088 0044
www.aonbenfield.com

PartnerRe
Wellesley House
90 Pitts Bay Road
Pembroke HM08
Bermuda
T: (1441) 292 0888
F: (1441) 292 7010
www.partnerre.com

AON BENFIELD UCL
Hazard
Research
Centre

Contents

1. EXECUTIVE SUMMARY

Pertinent findings and conclusions arising from scientific papers and reports addressed herein are individually highlighted below. The superscripted numbers following individual headlines take the reader directly to the relevant paper(s) in Sources and Further Reading at the end of each section

Geological hazards

- Potential and challenges of earthquake early-warning systems in Italy, Turkey and California. [2, 3, 27, 28]

- New studies shed light on attenuation of seismic waves in the Marmara Sea (Turkey) region and northern Italy, and examine implications for seismic intensity distributions. [17, 23]

- Borehole data suggest lower seismic wave attenuation rates for larger earthquakes, relative to smaller ones. [8]

- Model of ground motions produced by large to giant Cascadia Subduction Zone earthquakes, calibrated for cities of Seattle, Vancouver and Victoria. [4]

- New earthquake simulations highlight potential for stronger shaking in southern California and the Seattle area. [9, 11, 20]

- New earthquake hazard map for the Central Apennines region of Italy flags high level of near-future seismic hazard in L'Aquila area – within days of the April 2009 earthquake. [1]

- Slow subduction zones fingered as potential sources of major tsunamigenic earthquakes, as well as their faster-converging relatives. [12]

- Future tsunami threat from volcanic landslides in the Canary Islands and Alaska highlighted. [7, 15, 25]

- Tsunami hazard evaluated for the Caribbean, Oregon coast and Portugal. [5, 21, 26]

- New studies address building vulnerability in relation to future eruptions at Vesuvius (Italy) and Teide (Tenerife, Canary Islands). [16, 29]

Hydrological hazards

- UK extreme rainfall events back to 1866 analysed and complied to form digital archive. [36]

- Future flood hazard in Rome and Venice evaluated. [32, 37]

- Analysis of flood trends reveals an increase in flood hazard in Germany in the last half century, particularly in relation to flood frequency. [34]

- Role of uncertainties highlighted in creation of flood inundation maps. [31]

- Problem of characterising and predicting urban flood damage addressed in studies of flood events in the Netherlands and Germany. [30, 39]

- Innovative modelling technique used to evaluate flood hazard at river confluences. [40]

Atmospheric hazards

- North Atlantic hurricane activity linked to sea-surface temperature patterns in the Pacific. [50, 53]
- A study including an estimate of "missed" tropical cyclones in the pre-satellite era suggests a significant increase in North Atlantic hurricane numbers reported for the period 1900 to 2006. [58]
- Atlantic sea-surface temperatures and other parameters linked to frequency and location of US land-falling hurricanes. [46, 51]
- New study reveals an apparent decline in the annual numbers of Southern Hemisphere tropical cyclones since 1970, although not for the most powerful storms. [54]
- No significant change observed in tropical cyclone activity across East Asia. [44, 60]
- Problem of the paucity of historic data in evaluating hurricane landfall probability overcome by creation of synthetic dataset of North Atlantic storm tracks. [56]
- Multi-season forecast of Atlantic hurricane activity claimed possible out to five years. [48]
- Influences on storminess across the British Isles from 1920 to 2004 suggested. [41, 42]
- Return periods of Europe's most prominent windstorms estimated. [47]

Climate change

- Critical role of sea-surface temperatures examined in relation to tropical cyclone activity in a warmer world. [61, 71, 75, 77]
- Significant, general reduction in tropical cyclone frequency projected as the concentration of atmospheric carbon dioxide is doubled and quadrupled, particularly for the North Atlantic and tropical western North Pacific. [72]
- The Atlantic hurricane season appears to be getting longer, but the trend cannot be used to predict future changes to the season. [73]
- Satellite wind-speed data confirm a significant overall upward trend for wind-speeds in the most powerful tropical cyclones, across the tropics. [68]
- A fall in winter cyclone numbers is projected in the Northern Hemisphere, although a rise in the number of intense cyclones is forecast across the NE Atlantic, the British Isles and the North Pacific. [76]
- A warmer world is likely to bring a higher incidence of damaging wind events across Europe. [65]
- Jury out on a climate change signal in US tornado activity. [66]
- Climate change projected to drive an increase in the frequency and magnitude of extreme discharge levels in many European rivers. [64]

2. INTRODUCTION

In any single year, thousands of scientific papers addressing natural hazards, the processes and mechanisms that drive them, and their impacts and ramifications, are published in hundreds of journals and e-journals. Many of these papers contain information that is of direct relevance and considerable importance to the insurance market, but which can take several years to filter down from academia to the business world. The *Hazard and Risk Science Review* is designed to accelerate this process by drawing attention to new and pertinent research results. We present a summary of key publications from 2008 - 2009 with the aim of introducing the reader to current themes in a number of research domains. The summary text is intended to provide an introduction to the original work and its authors, by setting the science in a broader context and showing, where appropriate, its potential relevance to our business. Inevitably the new research addressed in the 2009 issue is only a tiny sample of the enormous amount of relevant material published over the last 12 months, and we do not claim that it is entirely representative of published research over the period. It does, however, highlight studies recommended by researchers and consultants of the Aon Benfield UCL Hazard Research Centre and natural catastrophe experts at Aon Benfield and PartnerRe that are considered to be particularly relevant to the interests of those involved in catastrophe insurance and reinsurance. The success of the review, launched in September 2004 at the Monte Carlo Reinsurance Rendez-Vous, is reflected in the fifteen thousand copies of the first five issues distributed throughout the market. We confidently expect this sixth *Hazard and Risk Science Review* to achieve an even wider circulation and further augment its function as an invaluable resource to the market, through providing a conduit from the arena of academic research to the business world. The Hazard and Risk Science Review is published annually in September, and incorporates research published during the twelve months to the preceding June.

This year's Review continues to adopt the straightforward fourfold structure developed in the launch issue in 2004, centring on geological, hydrological and atmospheric hazards, and on climate change and its hazard implications. With the L'Aquila earthquake disaster in Italy highlighting the fact that western Europe is far from immune to destructive geological phenomena, we lead this year with a summary of new research in geological hazard and risk. In particular, we address earthquake ground-motion studies in Italy, Europe and elsewhere, and examine the issue of earthquake early-warning. A common theme is that current event, and so insurance loss, models may understate inherent event uncertainties. In a change from previous issues of the Review, the papers and articles cited herein are now listed at the end of each section, providing a resource for the reader who wishes to pursue follow-up investigations. For ease of use, key themes covered within the Review are highlighted in the Executive Summary, with numbered links to the relevant publications in the bibliographies at the end of each section.

3. GEOLOGICAL HAZARDS

While the resulting loss of life and level of destruction was far from on a par with the 2008 Sichuan (China) earthquake, the Moment Magnitude 6.3 event that struck the Abruzzo region of Central Italy in April **(Figure 1)** provided a reminder that western Europe is also periodically affected by lethal earthquakes. The quake, the largest in Italy, since 1980, killed close to 300 people and damaged or destroyed up to 11,000 buildings, mainly in the town of L'Aquila and surrounding villages. Reconstruction costs are estimated at around USD16 bn, with total economic losses far higher. Without doubt, the L'Aquila event has served to keep the risks from earthquakes in urban areas at the forefront of catastrophe science.

Figure 1

Debris-blocked streets in the town of L'Aquila following the magnitude 6.3 earthquake in April 2009. The quake, the largest in Italy, since 1980, killed close to 300 people and damaged or destroyed up to 11,000 buildings, mainly in L'Aquila and surrounding villages. Reconstruction costs are estimated at around USD16 billion.

Courtesy: Wikipedia.

Earthquake warning and rapid response systems

Whilst a number of research groups have continued to pursue the elusive goal of specific prediction of earthquakes, days or even months in advance, another and perhaps more profitable area of research and development, has focussed on the seconds to tens of seconds that elapse between initial detection of an earthquake rupture on seismometers near the source and the peak intensity of shaking in nearby urban areas. The concept behind these studies is that of providing near-instantaneous automatic alarms to critical or hazardous facilities that can then be shut down in order to minimise damage from the earthquake. Papers published in *Geophysical Research Letters* by **A. Zollo**[28] (University of Naples, Italy) and colleagues; **H. Alcik**[2] (KOERI, Bogazici University, Istanbul, Turkey) and co-authors; and **R.M. Allen**[3] and others (University of California, Berkeley, USA), describe the implementation of such systems in, respectively, the Campania district of Southern Italy; the greater Istanbul area; and northern California.

All three papers focus on the problems of the automated data networks required to efficiently distribute the warnings and the algorithms needed to reliably analyse the warning signals (the amplitudes and wave-forms of the initial P-wave vibrations that travel ahead of the more damaging seismic waves) to provide near-instantaneous estimates of the strength, duration and frequency spectra of the damaging ground shaking that will follow. Such automatic systems need to be very carefully implemented, in particular to avoid false alarms: in their study Allen and colleagues emphasise the need to use records from multiple seismic stations, which implies dense seismic networks in the area covered by the system in order to ensure that the alarm is triggered in time to be useful. Similarly, Alcik and co-authors describe how multiple exceedances of threshold accelerations within ten-second intervals, as recorded at seismic stations within a network specifically designed to monitor the sections of the North Anatolian Fault just south of Istanbul, are to be used as a basis for alarms to critical facilities in the Istanbul area.

A similar concept to these seismometer-based warning systems, but on a global scale and on a longer timescale, can provide initial quantitative estimates of damage within an hour of an earthquake occurring. Writing in *Natural Hazards*, **M. Wyss**[27] World Agency of

Planetary Monitoring and Earthquake Risk Reduction (WAPMERR), Geneva, Switzerland and **M. Zibzibadze** (Georgia Seismic Monitoring Center, Tiblisi) show how global data from different information centres such as the National Earthquake Information Center (NEIC), USA, provide earthquake alerts and geophysicist-reviewed magnitude estimates that are used by WAPMERR to provide initial loss estimates for earthquakes exceeding different threshold magnitudes in different parts of the world, with a median delay of only 41 minutes after the start of the earthquakes concerned; as they note, a similar service aimed at providing initial impact assessments for disaster relief agencies is provided through the United States Geological Survey (USGS) PAGER webpage **(Figure 2)**. Such initial assessments are, however, only as good as the magnitude estimates provided by the global seismic networks and the key problem of providing timely identification of the very largest earthquakes (as emphasised by the gradual upgrading of the magnitude of the 2004 Sumatra earthquake over a period of days) still remains.

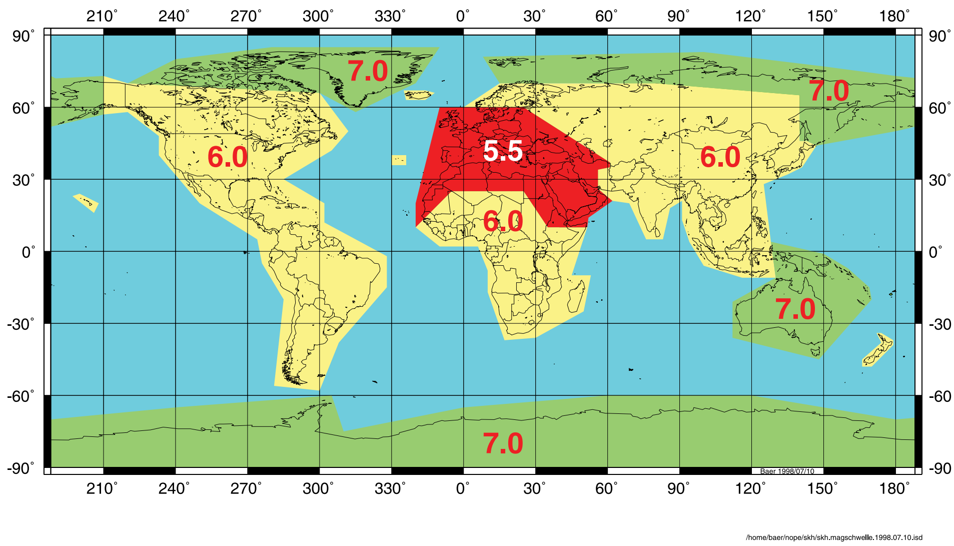


Figure 2

Zones of defined minimum earthquake magnitude for which World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) conducts a Seismic Data Review (SDR) and generates initial loss estimates (Wyss and Zibzibadze 2009). In the blue zone, WAPMERR only generates loss estimates for earthquakes with magnitude over 8.0.

Courtesy: Max Wyss.

Earthquake ground motion estimates and models

The models relating different parts of the earthquake wave-form that are built into the automated warning system algorithms are just one of many applications of studies that relate earthquake ground motions to earthquake sources. Central to these studies is the problem of attenuation of seismic waves with distance from the source fault rupture as they travel through the Earth. Attenuation varies between different regions of the Earth but also with the amplitudes and frequencies of seismic waves: the complexities of attenuation relationships therefore require both model and detailed empirical studies. In the past year, detailed empirical studies of particular regions include work published in *Bulletin of the Seismological Society of America (BSSA)* on the Marmara Sea area of Turkey by **M.B. Sørensen**[23] and co-workers at GFZ – Potsdam, Germany, who show that inclusion of an estimate of the finite fault rupture length in the attenuation equation increases the accuracy of the estimate of felt seismic intensity distributions in this key region; and a study of attenuation relations in Northern Italy by **M. Massa**[17] (INGV-Milano, Italy) and colleagues, also published in *BSSA*. The latter considers a whole range of intensity parameters including acceleration spectra over the ranges of damaging frequencies, and shows that many of the key measures of seismic intensity attenuate more rapidly for larger earthquakes in that region than was previously thought to be the case. Their work implies that such earthquakes may produce smaller losses, over smaller areas, than was previously thought, but also that accurate assessments of earthquake risk may be more dependent upon knowledge of the specific characteristics of faults closest to concentrations of population and risk exposure.

Attenuation relationships on wider scales are the subject of studies, both published in *BSSA*, by **D. Stromeyer**[24] and **G. Grünthal** (both at GFZ-Potsdam, Germany) and **F. Cotton**[8] (Universite Joseph Fourier, Grenoble, France) and colleagues. Stromeyer and Grunthal improve on the fit of their empirical attenuation equation to a large number of intensity data from European earthquakes by describing the data in terms of normal distributions (with a standard deviation of 0.7 magnitude units) about the mean attenuation relationship. In contrast to the results of Massa and colleagues for northern Italy, Cotton and co-workers use data from borehole accelerometers in Japan and elsewhere to indicate lower attenuation rates for larger earthquakes than smaller ones, but also a decrease in the sensitivity of attenuation rate to magnitude for larger earthquakes; again underlining the difficulty of extrapolating attenuation models from small, frequent earthquakes to the larger earthquakes that are of most interest for the understanding of earthquake risk.

Ground motion models and attenuation relationships appropriate to earthquakes in a different tectonic setting, that of the subduction zones where the largest earthquakes occur, are the subject of a study (also published in *BSSA*) by **G.M. Atkinson**[4] and **M. Macias** of the University of Western Ontario, Canada. They use strong-motion seismic records from the 2003 M8.1 Tokachi-Oki earthquake and its aftershocks in Japan to calibrate a model of ground motions in the cities of Vancouver, Victoria and Seattle produced by large to giant (moment magnitude M7.5 to M9.0) earthquakes on the Cascadia subduction zone. They emphasise the need to use magnitude-dependent attenuation relations specific to particular types of subduction zone and even specific regions, rather than attempting to produce a globally – applicable set of attenuation relationships in subduction zones. Overall, then, the picture to be gained from recent research into attenuation relationships is that significant levels of uncertainty exist even in the best-studied regions, and that in reducing these uncertainties the models become ever more region-specific. Accordingly, there is more interest in simulation of individual earthquakes in a scenario type approach.

Earthquake simulations

The advantages of the earthquake simulation approach is that it allows investigation of directivity of earthquake shaking due to ruptures on particular faults (typically with more intense shaking in the direction of rupture propagation), and the dependence of shaking patterns on rupture histories (including rupture propagation rates and displacement histories).

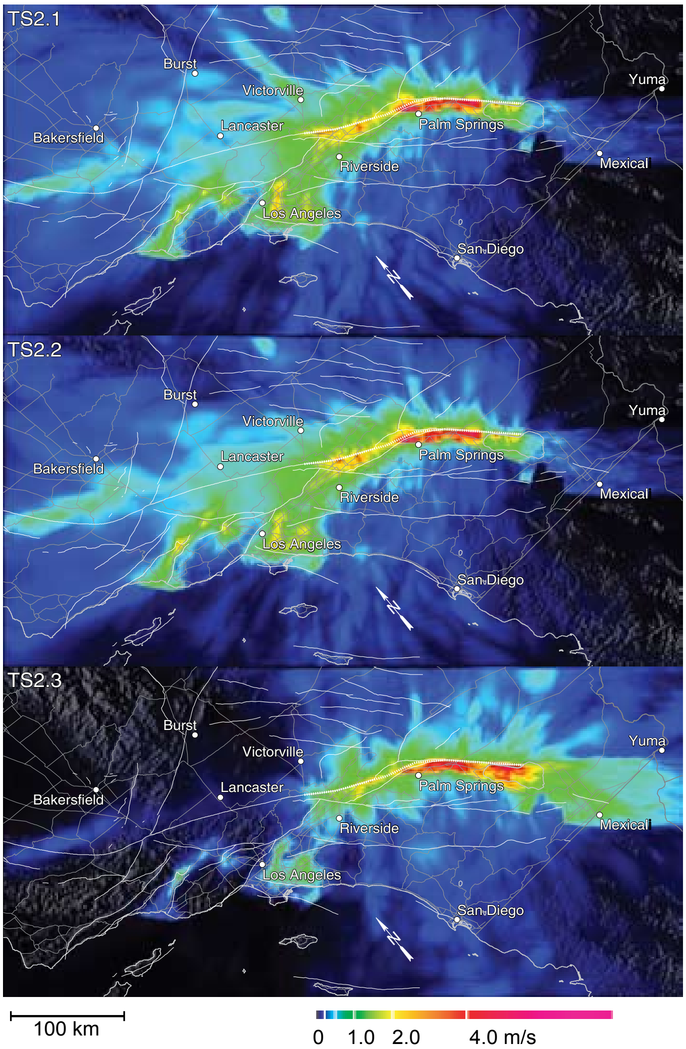
These aspects are particularly important in assessing earthquake risk where exposures are concentrated in small parts of the area of shaking. **K.B. Olsen**[20] (San Diego State University, California) and co-workers use the simulation approach in a paper published in *BSSA* to study a northward-propagating rupture on the southern San Andreas Fault, extending from near the Mexican border to an area just east of Los Angeles **(Figure 3)**.

Shaking from their model earthquake of moment magnitude Mw=7.7 is particularly intense in parts of the densely populated Los Angeles basin, greatly exceeding the intensities predicted by empirical models that do not include rupture direction effects. They also show, however, that the size of the discrepancy depends on the choice of rupture history and displacement heterogeneity in the source earthquake, as the directivity effect in this study is lower than in a previous study by the same authors which assumed a more continuous (or less “jerky”) fault rupture history and more uniform displacement on the fault in the earthquake. A similar conclusion is reached by **R.W. Graves**[11] from URS Corporation and co-workers in a study published in *Geophysical Research Letters*, who simulate a Mw=7.8 Southern San Andreas Fault earthquake and show that the patterns of ground accelerations are strongly dependent upon the fault rupture velocity.

Figure 3

Three simulation models of peak ground acceleration from a Mw=7.7 earthquake generated by a northward-propagating rupture on the southern San Andreas Fault zone (Olsen et al. 2008). Note the zones of high acceleration in the Los Angeles basin in all three simulations.

Courtesy: Kim Olsen.



Another application of the simulation approach is provided by a study of the effects of amplification of seismic waves in the Seattle Basin by **A. Frankel**[9] and colleagues at USGS Denver, Colorado. They simulate a series of earthquakes of sizes up to the Mw=6.8 Nisqually earthquake, including deep earthquakes within the subducted slab that produce shaking frequencies in the resonance range of many building types, and show a directional effect with earthquake ruptures to the southwest producing stronger shaking in the Seattle area than earthquakes to the north and the northwest, because of the curvature of the basin margin which causes focussing of seismic waves within the basin. Their study shows that detailed crustal structure models need to be included in accurate earthquake risk assessments both at regional level and for site-specific risk assessments.

Although earthquake simulations have, as yet, only been carried out in a small number of areas and for a small number of earthquake sources, they underline the limitations of more generalised earthquake damage models – particularly global earthquake risk models, used for example in reinsurance applications – and the need to recognise and allow for the significant uncertainties contained in these more general models.

Investigations of earthquake sources

The increased emphasis upon scenario models, indicated by the studies described in the previous section, renews the need for detailed understanding of the earthquake sources themselves. Key problems in this area of research include the size – frequency distribution of earthquakes; the controls on the maximum size of earthquake that can be expected in a given region; and the underlying question of whether conventional measures such as moment magnitude are fully satisfactory as quantifications of earthquake source size. Studies published in the past year have addressed all of these problems.

In a short research note published in *BSSA*, **T. Parsons**[22] and **E. Geist** of the USGS (Menlo Park, California) question the assumption made in many regional and local earthquake risk models, that the earthquake hazard produced on individual faults can be described in terms of repetitions of characteristic earthquakes specific to the fault concerned. Instead, they show that the earthquake histories of particular faults can be equally well described by the Gutenberg-Richter distribution of earthquake sizes used to analyse regional or global earthquake catalogues containing earthquakes on many faults, with earthquake frequency decreasing with magnitude according to a logarithmic relationship. Their study lends new weight to the long-standing idea that all faults (as defined at large map scale) are really fault zones containing large numbers of linked smaller faults of a wide spread of sizes, that may rupture together in different combinations or independently.

In such a situation, the upper limit on earthquake magnitude in a given region is governed by the thickness of the seismogenic zone, which is bounded by the Earth's surface (or by a near-surface zone of continuous fault creep) above, and the increase of temperature in the deeper crust, that ultimately leads to the onset of ductile rock deformation or flow at 350 to 450 degrees centigrade. This implies that regional-scale variation in maximum earthquake size should correlate with the geothermal temperature gradient, which can be independently measured. This concept has long been applied to explain why subduction zone thrust earthquakes, in regions of exceptionally low thermal gradient resulting from the subduction of cool oceanic lithosphere, are so very large. **T. Kudo**[13] (Chubu University, Japan) and colleagues, in another study published in *BSSA*, extend the concept to intra-crustal or upper plate earthquakes in Japan. They show that variation in maximum earthquake size across Japan correlates with geothermal gradient measurements. Such measurements may therefore be usefully incorporated in earthquake hazard and risk models, especially in regions with short earthquake catalogues that are likely to be unrepresentative of the long-term earthquake hazard from large earthquakes.

A third paper dealing with Japanese earthquakes has however highlighted the question of whether the standard measure of earthquake size, the moment magnitude Mw (a measure of the seismic moment or torque or the earthquake), is a fully valid measure of the seismic energy of the earthquake, which relates more closely to the ground accelerations (and hence, damage) that it produces. Writing in *BSSA*, **G.L. Choy**[6] and **J. Boatwright** (USGS, respectively at Menlo Park and Denver) compare the 1996 Kyushu and 2000 Tottori earthquakes, events with similar moment magnitudes (Mw=6.7). Using far-field seismic records, they show that the energy magnitudes of the two events were very different (1996 Kyushu Me=6.6; 2000 Tottori Me=7.4) and interpret this in terms of differing fault geology, with the Kyushu earthquake occurring in weak fault rocks within a mature subduction zone whilst the Tottori earthquake occurred in stronger, immature fault rocks in the crust of Japan.

Earthquake hazard mapping

The various studies on earthquake sources, simulations and ground motions described above all raise questions regarding the validity of assumptions built into many existing methods of constructing earthquake hazard maps. Despite this, hazard maps are key to current methods of seismic risk assessment, and the past year has seen one striking, if coincidental, success in hazard mapping. **A. Akinci**[1] Instituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy and colleagues prepared a time-dependent earthquake hazard map and assessment for crustal faults in the central Apennines region of Italy, published in *BSSA* in April 2009 **(Figure 4)**. Their study, which assumed characteristic earthquakes on the faults, used different levels of aperiodicity (departures from constant recurrence intervals of earthquakes) to study the extent to which hazard levels on individual faults vary with the times since the last major earthquakes on these faults. They showed that

AON BENFIELD UCL
Hazard
Research
Centre

hazard levels in the region were principally controlled by the local faults; and that especially if aperiodicity was low, the near-future probabilistic seismic hazard was locally much higher than would be the case if earthquake recurrence was random or aperiodic. One area that they identified as having particularly high levels of near-future seismic hazard was the city of L'Aquila, which by coincidence was severely damaged in an earthquake within days of publication of the paper.

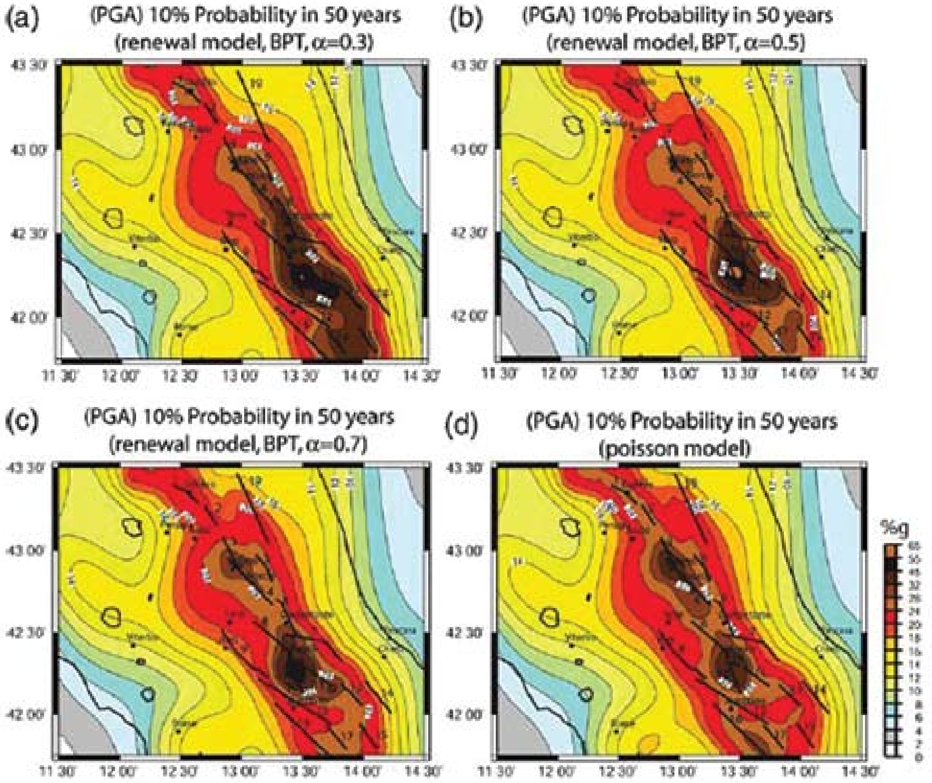


Figure 4

Predicted probabilistic peak ground acceleration (PGA) maps for the central Apennines constructed using different values of aperiodicity coefficient α (low α corresponds to more periodic earthquakes; α=1 is a random or Poissonian distribution) by Akinci et al. (2009). Note: L'Aquila is located in the central high PGA probability zone.

Courtesy: Aybige Akinci.

Great earthquakes and tsunami generation

There is wide acceptance of the hypothesis that the greatest earthquakes are generated in subduction zones where the rate of plate convergence is high (≥60 mm/year) and the age of the down-going oceanic lithosphere is young (usually >10 million years), which is a relationship supported by the huge Chile-Valdivia earthquake of 1960. This simple velocity-age relationship is, however, being challenged by evidence emerging from the seismic record and by several recent great earthquakes, such as the 2004 Boxing Day Sumatra-Andaman event, which was generated in a slow (≤40 mm/year) subduction environment. In a chapter in the book *Subduction Zone Geodynamics*, **M.-A. Gutscher**[12], Université de Brest (France), and **G. Westbrook**, University of Birmingham (UK), consider these environments, because their potential to generate great earthquakes and associated tsunami is now recognised, e.g., Nankai, Cascadia, Gibraltar (southwest Iberia) and Sumatra **(Figure 5)**, but poorly understood. Giant earthquakes generated in slow subduction zones recur at a lower rate (of the order of several hundred to a few thousand years) relative to rapidly converging margins. This low recurrence poses a significant problem for earthquake and tsunami risk assessment because it is difficult to properly assess the long-term seismic hazard presented by these slow zones. Comparison of the physical characteristics of slow and fast subduction systems clearly shows that the former have thicker and wider wedges of accreted sediment and a wider and shallower seismogenic zone. Because the wedge has low rigidity, an earthquake of a given seismic moment will produce more coseismic slip, and for a longer duration, than a deeper earthquake in more consolidated material. Consequently, shallow earthquakes in the wedge are highly efficient at generating strong tsunami.

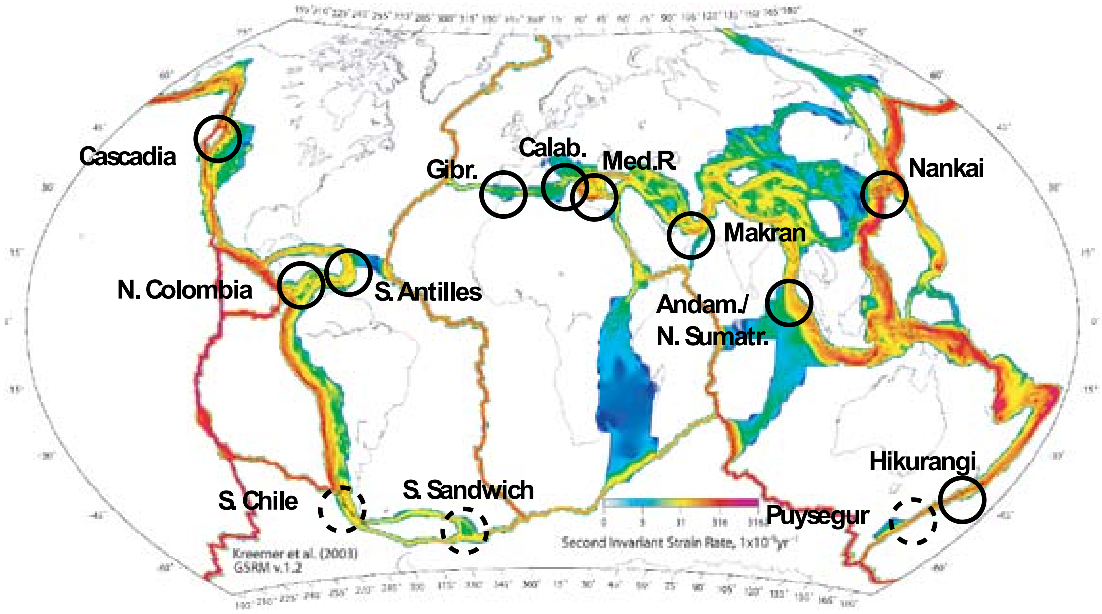


Figure 5

Global distribution of known slow subduction zones, superimposed on a strain map (from Gutscher and Westbrook 2009). Of the 13 slow zones marked, ten contain very broad accretionary wedges (solid circles) and three do not (dashed circles).

Courtesy: Marc-Andre Gutscher.

In stark contrast to slow subduction systems, **K. Furlong**[10] of the Pennsylvania State University, and co-researchers, examine the 1 April 2007 great tsunamigenic earthquake (moment magnitude 8.1) that ruptured the Solomon Islands subduction zone at the triple junction where the Pacific plate is underthrust independently by both the Solomon Sea–Woodlark Basin (135 mm/year) and Australian (97 mm/year) plates. Their paper in the journal *Science* demonstrates that in addition to the rupture traversing major geological boundaries, the earthquake was significant in other ways: first, it contravened speculation that subducting extremely young hot oceanic lithosphere will not produce great earthquakes; and second, it demonstrated that coseismic displacement was concentrated in the overriding plate, leading to significant surface uplift. The latter is particularly important because it increases the potential of an earthquake to both generate and amplify tsunami.

Mass movement and tsunami generation

Only recently are tools being developed that model the source, propagation and inundation components of a tsunami event. In terms of sources, earthquakes are the most obvious, but tsunami may also be generated by mass movement (volcano collapse, landslides into the sea and huge submarine landslides) and by volcanic eruptions. There is a great deal of interest in tsunami generated by instabilities on volcanic islands, for which the Canary Islands present excellent examples. It is now well known that a large-scale failure of the flank of the Cumbre Vieja volcano on La Palma has the potential to generate large amplitude waves that could have huge impact on the coastlines of the North Atlantic. Evidence is now emerging that the same coasts could be affected by a giant landslide originating in the Icod valley on Tenerife, which is the focus of the paper in *Earth and Planetary Science Letters* by **P. Coppo**[7] and co-researchers of Switzerland's University of Neuchâtel. In modelling the potential tsunami hazard, it is essential to quantify the volume of material that is likely to move, and the mechanism and speed of mass failure and transport. The paper considers the first parameter and reports on a geophysical survey to constrain the sliding surface. It estimates the potential volume to be at least 100 km^3, which may become displaced during the next strong felsic eruption of the Teide-Pico Viejo volcanic complex. The authors stress that more studies are urgently required to understand the structure and behaviour of volcanic islands prone to potential flank collapse, and that this information needs to be incorporated into models that feed into the production of a global map of tsunami hazard.

AON BENFIELD UCL Hazard Research Centre

The potential failure volume in the Icod valley correlates well with the typical estimates of 50–200 km^3 from Canary Island flank failures, but it is a failure of the Cumbre Vieja volcano in La Palma that is most likely, as this volcano is growing more rapidly than any other volcano in the Canary Islands. Previous studies of this potential failure and its consequences have been newsworthy, particularly the most extreme event involving simultaneous failure of up to 500 km^3. Some scientists have argued that such an event is unlikely, but in their paper in the *Journal of Geophysical Research*, **F. Løvholt**[15] of the Norwegian Geotechnical Institute, and colleagues, have re-modelled the consequences of a Cumbre Vieja collapse. By combining a multimaterial model for the wave generation with Boussinesq models for the far-field propagation, they generate an initial wave of several hundred metres height that is directed southwestwards, which would have catastrophic consequences for the coastal regions of the Canary Islands. The oceanic propagation of the tsunami would affect the whole of the central Atlantic, but the largest waves are smaller than the most pessimistic previously published estimates; for example, surface elevations are 2–3 times smaller than the worst estimates of 25 m along the coastline of Florida. However, these differences largely reflect uncertainties in the landslide source, as the rates of attenuation of the waves during their transoceanic propagation are very similar to the results of the previous studies.

Continuing with the theme of mass movement and tsunami generation, **C. Waythomas**[25] of the USGS Alaska Volcano Observatory, and co-researchers, consider the hazard originating in the Aleutian volcanic island arc, which forms the northern rim of the Pacific Ocean basin. Writing in *Quaternary Science Reviews*, they numerically simulate previously unrecognised tsunami hazards generated from three sources: submarine mass flows originating in submarine canyons, mass flows that evolve from submarine landslides on the trench slope, and failures of the flanks of volcanoes. All simulations produce run-ups of 10–20 m above sea level along coastlines nearest to the tsunami source. They also produce transoceanic tsunami, with the largest generated by submarine flows. Some of these tsunami produce waves that are several metres in elevation at far-field locations, such as Japan, Hawaii, and along the North and South American coastlines, where they may present a significant hazard.

Tsunami hazard assessment: probability and exposure

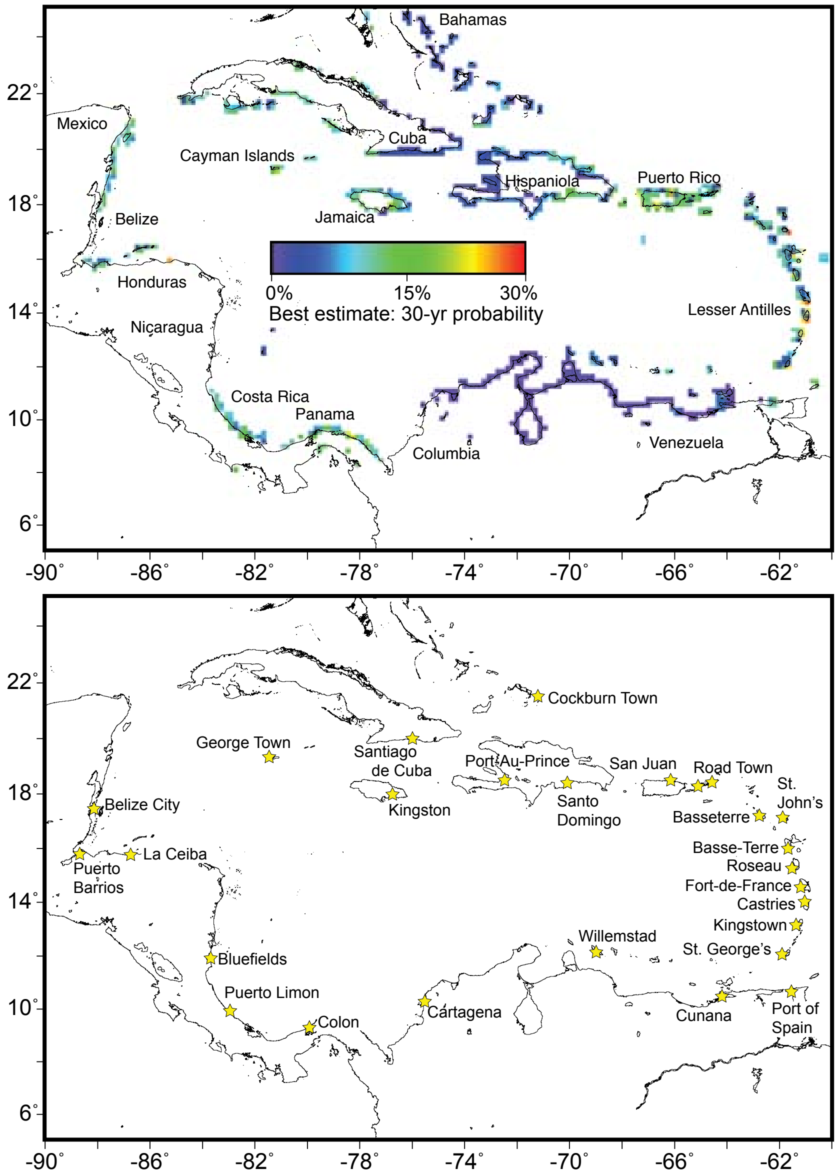
We begin this section in the Caribbean by referring to the paper in *Pure and Applied Geophysics* by **T. Parsons**[21] and **E. Geist** of the USGS at Menlo Park, who have calculated tsunami run-up (>0.5 m) probabilities at coastal sites in the region. They constructed an empirical tsunami probability map from the exceptional written records of events, which date back to 1498, and tested this against a second map they generated from numerically calculated run-up rates. Interestingly, this comparison demonstrated that the empirical model may under-represent tsunamis sourced by plate boundary earthquakes (reflecting, perhaps, the large interval between such events even compared to the ~500 year long historical earthquake catalogue for the Caribbean, as noted by Gutscher & Westbrook). In contrast, the synthetic catalogue derived from the numerical model lacks sources linked to landslides and back-arc faulting. In order to overcome these respective shortfalls, a third probability map was produced using a Bayesian method, which combined tsunami probabilities calculated from the synthetic catalogue with results of the empirical model.

The best-estimate results from this last method are portrayed in (**Figure 6)**, which shows that the highest probabilities (typically 10–20% in 30 years for run-up ≥0.5 m) are for the eastern Lesser Antilles, including the islands of Antigua, Barbuda, Dominica, Guadeloupe, Martinique, Grenada, St. Kitts, Nevis, St. Lucia, St. Vincent and the Grenadines. There is, however, a need to test the validity of these alternative probability maps with independent data, for example from palaeoseismic studies and investigation of prehistoric tsunami deposits.

Figure 6

Thirty-year probability of tsunami run-up (≥0.5 m) in 20 x 20 km cells at coastal sites in the Caribbean region (from Parsons and Geist 2008). The probability is derived from combined rate estimates from empirical and numerical models. Many of the important cities in the region are identified for reference.

Courtesy: Tom Parsons, United States Geological Survey.



Having identified, modelled and mapped regions likely to be affected by a tsunami, it is necessary to combine this information with the type of land use within defined tsunami-hazard zones. To this end, **N. Wood**[26] of the USGS in Washington State estimates tsunami exposure along the Oregon coast, linked to a tsunamigenic earthquake along the Cascadia subduction zone. The method is presented in *Applied Geography* and uses mid-resolution (30 m) Landsat Thematic Mapper land-cover data overlain on tsunami hazard zone data. This provides a simple first step for visualising and estimating potential exposure and it may also be adapted to allow for broad-scale assessments of critical infrastructure and economic impacts.

Superimposition of a past tsunami event on present-day land-use and economic conditions is another way of gleaning important information for hazard assessment. In this context, writing in the journal *Geography*, **D. Chester**[5] of the University of Liverpool revisits the 1755 Lisbon earthquake and tsunami. Together these cost Portugal around 32-48% of its gross domestic product, which probably makes the 1755 event the greatest natural disaster in financial terms to have impacted western Europe. If a similar event were to occur today (the worst-case scenario has a minimum estimated recurrence interval of 614±105 years), it would still have catastrophic consequences, as the Algarve region is essential to the Portuguese economy, particularly as it represents one of Europe's main tourist destinations. The resident population of this region is over 400,000, but the influx of tourists during the summer months more than doubles this number. The potential hazard is clear, when one considers that the

1755 tsunami took about 16–30 minutes to reach different parts of the Algarve coast, and it is estimated to have penetrated up to 2.5 km inland and had run-up heights reaching 20, perhaps even 30, metres. Chester concludes by calling for more hazard assessment and mapping in the Algarve, which is already underway in many areas. It must not be forgotten that strict building codes, which have been applied across the whole country and periodically updated, were pioneered in Portugal following the 1755 event.

Risk from explosive volcanic eruptions in Europe

Despite the passing of another twelve months without a major volcanic disaster, research on the impacts of volcanic eruptions continues to grow. Of particular note is a special volume of the *Journal of Volcanology and Geothermal Research* dedicated to Explosive eruption risk and decision support for European Union populations threatened by volcanoes (EXPLORIS). This innovative multi-disciplinary project was funded by the European Union and ran from 2002 to 2006, and during this time it developed an analytical approach to volcanic risk management that specifies and quantifies all the processes and effects of volcanic hazards that influence risk. Of the 16 papers published, relating to Vesuvius (Italy), Teide (Tenerife, Canary Islands), La Soufrière (Guadeloupe, French Antilles) and Sete Cidades (San Miguel, Azores), three are highlighted here.

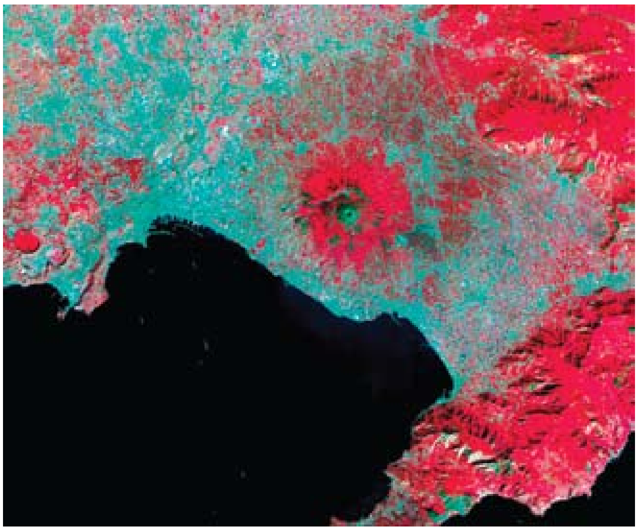


Figure 7

Image of Mt. Vesuvius (central Italy), acquired on 26 September 2000 by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The false-colour image covers an area of 36 x 45 km, with most of the developed land in Naples and the surrounding area showing up green.

Courtesy: NASA/GSFC/MITI/ERSDAC/JAROS and U.S./Japan ASTER Science Team.

We begin with Vesuvius, as a future explosive eruption here, which affects the huge urban population and infrastructure around the Bay of Naples **(Figure 7)**, should be considered amongst the most serious potential natural disasters in Europe. **A. Neri**[19] of the Italian INGV, and colleagues, have formulated an Event Tree that provides a logical pathway connecting generic probabilistic hazard assessment to quantitative risk evaluation at the volcano. The Event Tree was created to provide a formal structure in which diverse strands of information could be unified and linked together by using expert knowledge. The end product depicts the various eruption categories, with their likely probability of occurrence and associated uncertainty, as well as the generic hazards and timeline evolution associated with them. The paper highlights the importance of expert elicitation and presents a first example of how this can be used to integrate numerical simulations and field evidence to generate probabilistic maps of the hazard posed by pyroclastic flows. The Event Tree is organised to enable easy updating as new information becomes available, and this will be particularly important for enabling regular updating of risk assessments of buildings and infrastructure at different locations around the volcano.

With reference to this last point, **G. Zuccaro**[29] of the University of Naples, and colleagues, present a first attempt to develop a probabilistic dynamic model that allows detailed analysis of the vulnerability of built structures around Vesuvius, which is made possible and meaningful because of the comprehensive inventory of field data on buildings in the area.

The model considers three hazardous events, namely volcanogenic earthquakes, tephra falls and pyroclastic flows, and allows for consideration of single events or any sequence of these events. In the case of the latter, a timeline has been constructed to show the change in building vulnerability that occurs at each phase of a reference eruption, starting with volcanogenic earthquakes and loading of roofs with tephra prior to a pyroclastic flow. Results of the model are presented as maps showing either the extent of building damage or the number of casualties.

The theme of building vulnerability is also the subject of the paper by **J. Martí**[16] of Spain's Institute of Earth Sciences Jaume Almera, Consejo Superior de Investigaciones Científicas in Barcelona, and colleagues. These authors focus on the Icod valley of Tenerife, already considered earlier for its potential to generate tsunami, which is one of the areas most at risk in any future explosive event from the huge Teide-Pico Viejo complex. The study considers the same three hazards investigated by Zuccaro and colleagues, but emphasises the importance of surveying building stock and modelling humanitarian losses. Marti and colleagues point out that their work could easily be adapted to modelling economic losses under various hazard scenarios, simply by additional consideration of building quality and use in the survey. By assigning a construction cost per square metre it would be easy to estimate a replacement value per building. The studies of both Martí and Zuccaro, and their colleagues, could be extended to estimate economic losses associated with business interruption brought about by building and infrastructure damage.

EXPLORIS highlights the importance of constraining the past and future potential behaviour of volcanoes, but this still presents a huge challenge for volcanic hazard and risk estimation. In an effort to improve this situation, **A. Mendoza-Rosas**[18] and **S. De la Cruz-Reyna** of the Universidad Nacional Autónoma de México have published a statistical method in the *Journal of Volcanology and Geothermal Research*, which links geological and historical eruption time series in order to calculate probabilities of future explosive eruptions. Their first step in the method is to characterise eruptions by their magnitudes (volcanic explosivity index) and then to test the eruptive time series for independence between successive events and for the time dependence or stationarity of the process. Weibull analysis is then used to study the distribution of repose periods between successive eruptions, and a non-homogeneous generalised Pareto–Poisson process is used to obtain volcanic hazard estimations. When tested on Mexican volcanoes, this method produces higher exceedance probabilities for larger magnitude eruptions when compared to Poisson and Binomial distribution-based hazard estimates.

Towards an integration of sensor information

This section of the Review ends by considering how risk managers and geohazard analysts access sensor information, such as high-resolution airborne or space imagery, hyper-spectral data, borehole data, seismometer data, global positioning system networks, and other geophysical in-situ and space instrumentation. This is the subject of the paper by **G. Le Cozannet**[14] of the French Bureau de Recherches Géologiques et Minières (BRGM), and colleagues, which is published in *Sensors*. They argue that information about sensor networks is difficult to obtain and is available in too many formats to facilitate effective access. In order to promote decision-making based on greater access to information, interoperable catalogues are being developed as part of the Group on Earth Observations workplan. One example is GeoHazData, which is a prototype homogeneous inventory of hazard maps and their underlying data for a specific region. Currently this tool is open to critical review and time will tell if the approach is appropriate. Regardless, it does begin to address the need for homogeneous and systemic approaches to the presentation of data needed for hazard and risk analysis.

Sources and further reading

1. Akinci, A. F. et al. 2009 Effect of Time Dependence on Probabilistic Seismic-Hazard Maps and Deaggregation for the Central Apennines, Italy. *Bulletin of the Seismological Society of America* **99**, 585–610. doi: 10.1785/0120080053.

2. Alcik, H. et al. 2009. A study on warning algorithms for Istanbul earthquake early warning system. *Geophysical Research Letters* **36**. doi:10.1029/2008GL036659.

3. Allen, R. M. et al. 2009. Real-time earthquake detection and hazard assessment by ElarmS across California. *Geophysical Research Letters* **36**. doi:10.1029/2008GL036766.

4. Atkinson, G. M. & Macias, M. 2009 Predicted Ground Motions for Great Interface Earthquakes in the Cascadia Subduction Zone. *Bulletin of the Seismological Society of America* **99**, 1552–1578. doi: 10.1785/0120080147.

5. Chester, D. K. 2008 The effects of the 1755 Lisbon earthquake and tsunami on the Algarve region, southern Portugal. *Geography* **93**, 78-90.

6. Choy, G. L. & Boatwright, J. 2009 Differential Energy Radiation from Two Earthquakes in Japan with Identical Mw: The Kyushu 1996 and Tottori 2000 Earthquakes. *Bulletin of the Seismological Society of America* **99**, 1815–1826. doi: 10.1785/0120080078.

7. Coppo, N. P. et al. 2009 A deep scar in the flank of Tenerife (Canary Islands): geophysical contribution to tsunami hazard assessment. *Earth and Planetary Science Letters* **282**, 65-68. doi:10.1016/j.epsl.2009.03.017.

8. Cotton, F. et al. 2008 On the Discrepancy of Recent European Ground-Motion Observations and Predictions from Empirical Models: Analysis of KiK-net Accelerometric Data and Point-Sources Stochastic Simulations. *Bulletin of the Seismological Society of America* **98**, 2244–2261. doi: 10.1785/0120060084.

9. Frankel, A., Stephenson, W. and Carver, D. 2009 Sedimentary Basin Effects in Seattle, Washington: Ground-Motion Observations and 3D Simulations. *Bulletin of the Seismological Society of America* **99**, 1579–1611. doi: 10.1785/0120080203.

10. Furlong, K. P. et al. 2009 A great earthquake rupture across a rapidly evolving three-plate boundary. *Science* **324**, 226-229. doi: 10.1126/science.1167476.

11. Graves, R. W. et al. 2008 Broadband simulations for Mw 7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed. *Geophysical Research Letters* **35**. doi:10.1029/2008GL035750.

12. Gutscher, M. -A. and Westbrook, G. K. 2009 Great earthquakes in slow-subduction, low-taper margins. In: Lallemand S. and Funiciello F. (eds) *Subduction Zone Geodynamics*, Springer-Verlag p119-133. doi: 10.1007/978-3-540-87974-9.

13. Kudo, T., Tanaka, T. and Furumoto, M. 2009 Estimation of the Maximum Earthquake Magnitude from the Geothermal Gradient, *Bulletin of the Seismological Society of America* **99**, 396–399. doi: 10.1785/0120080946.

14. Le Cozannet, G. et al. 2008 Connecting hazard analysts and risk managers to sensor information. *Sensors* **8**, 3932-3937. doi: 10.3390/s8063932.

15. Løvholt, F. et al. 2008 Oceanic propagation of a potential tsunami from the La Palma Island. *Journal of Geophysical Research* **113**, C09026, doi:10.1029/2007JC004603.

16. Marti, J. et al. 2008 Estimating building exposure and impact to volcanic hazards in Icod de los Vinos, Tenerife (Canary Islands). *Journal of Volcanology and Geothermal Research* **178**, 553-561. doi:10.1016/j.jvolgeores.2008.07.010.

17. Massa, P. et al. 2008 Empirical Ground-Motion Prediction Equations for Northern Italy Using Weak- and Strong-Motion Amplitudes, Frequency Content, and Duration Parameters. *Bulletin of the Seismological Society of America* **98**,1319–1342. doi: 10.1785/0120070164.

18. Mendoza-Rosas, A. T. and De la Cruz-Reyna, S. 2008 A statistical method linking geological and historical eruption time series for volcanic hazard estimations: applications to active polygenetic volcanoes. *Journal of Volcanology and Geothermal Research* **176**, 277-290. doi:10.1016/j.jvolgeores.2008.04.005.

19. Neri, A. et al. 2008 Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius. *Journal of Volcanology and Geothermal Research* **178**, 397-415. doi:10.1016/j.jvolgeores.2008.05.014.

20. Olsen, K. B. et al. 2008 TeraShake2: Spontaneous Rupture Simulations of Mw 7:7 Earthquakes on the Southern San Andreas Fault, *Bulletin of the Seismological Society of America* **98**, 1162–1185. doi: 10.1785/0120070148.

21. Parsons, T. and Geist, E. L. 2008 Tsunami probability in the Caribbean region. *Pure and Applied Geophysics* **165**, 2089-2116. doi: 10.1007/s00024-008-0416-7.

22. Parsons, T. and Geist, E. L. 2009 Is There a Basis for Preferring Characteristic Earthquakes over a Gutenberg–Richter Distribution in Probabilistic Earthquake Forecasting? *Bulletin of the Seismological Society of America* **99**, 2012–2019. doi: 10.1785/0120080069.

23. Sørensen, M. B. et al. 2009 Attenuation of Macroseismic Intensity: A New Relation for the Marmara Sea Region, Northwest Turkey, *Bulletin of the Seismological Society of America* **99**, 538–553. doi: 10.1785/0120080299.

24. Stromeyer, D. & Grünthal, G. 2009 Attenuation Relationship of Macroseismic Intensities in Central Europe, Bulletin of the *Seismological Society of America* **99**, 554–565. doi: 10.1785/0120080011.

25. Waythomas, C. F. et al. 2009 Pacific Basin tsunami hazards associated with mass flows in the Aleutian arc of Alaska. *Quaternary Science Reviews* **28**, 1006-1019. doi:10.1016/j.quascirev.2009.02.019.

26. Wood, N. 2009 Tsunami exposure estimation with land-cover data: Oregon and the Cascadia subduction zone. *Applied Geography* **29**, 158-170. doi:10.1016/j.apgeog.2008.08.009.

27. Wyss, M. and Zibzibadze, M. 2009 Delay times of worldwide global earthquake alerts. *Natural Hazards*. **50**, 379-387, DOI - 10.1007/s11069-009-9344-9.

28. Zollo, A., et al. 2009 Earthquake early warning system in southern Italy: Methodologies and performance evaluation. *Geophysical Research Letters* **36**. doi:10.1029/2008GL036689.

29. Zuccaro, G. et al. 2008 Impact of explosive eruption scenarios at Vesuvius. *Journal of Volcanology and Geothermal Research* **178**, 416-453. doi:10.1016/j.jvolgeores.2008.01.005.

4. HYDROLOGICAL HAZARDS

Hydrological hazards over the past year have included severe snow-melt floods in the mid-western USA and Canada in March and April 2009, flash flooding in the Czech Republic and Poland in June, flooding in central and southern China in July and earlier in the year (January), floods in Queensland and the Northern Territory following tropical storm Dominic. One of the worst natural disasters this year was also a result of the hydrological conditions when bush fires in southern Australia ensued during the continuation of a severe drought.

UK precipitation and flood impacts

Following the 2007 summer floods, there has been a general concern about surface water management in the United Kingdom. Governmental bodies such as the Environment Agency and the Meteorological Office have been working together to provide a surface flood warning from extreme rainfall. A paper in *Weather* by Aon Benfield UCL Hazard Research Centre associate **H. Rodda**[36] together with researchers at Hydro-GIS Ltd and Oxford University, investigated extreme rainfall observations in the British Isles over the period 1866-1968. Data for this study was taken from the annual publication *British Rainfall*, which included listings of all daily rainfalls over a specific depth threshold together with detailed descriptions of the events from observers, rainfall maps and photographs **(Figure 8).**

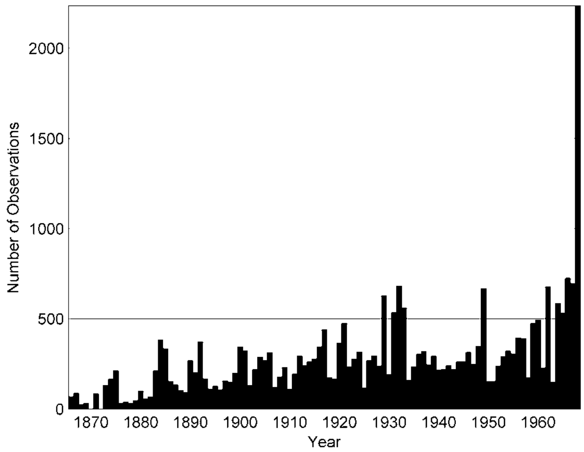


Figure 8

Numbers of extreme 24-hour rainfall observations per year from British Rainfall 1866-1968.

Courtesy: Harvey Rodda.

The research showed that extreme rainfalls of 100 mm or more in 24 hours are not uncommon. In fact over the study period there were only 3 years (1866, 1870 and 1873) where an annual maximum of over 100mm was not recorded and this was largely due to the sparse network of gauges at this time. Another particularly useful aspect of the study was that all the data was compiled into a digital archive with over 28,000 records. This archive, even as far back as the year 1900, includes records from over 4,000 gauges. This figure far exceeds the digital archives held by the Met Office where only a few hundred rain gauges have archived data going back over 100 years. This archive is now available to use for further research by interested parties.

Another aspect of the UK 2007 floods which was not widely reported in the media was the impact on agriculture in England. This topic is covered in a paper by **H. Posthumus**[35] and researchers from Cranfield University, UK, in the *Journal of Flood Risk Management*. Approximately 42,000 ha of agricultural land was flooded mostly in north-eastern and central southern England. This particular study looked at the damage experienced by farmers in three areas namely Yorkshire and Humberside, Worcester and Gloucestershire, and Oxfordshire. The flood impacts were assessed at the farm and land unit scale and financial losses calculated based on the physical damage and the unit price for crops although the damage was often indirect. The average loss per farm was calculated as nearly £90,000 (£1207/ha) with the highest losses in the horticultural sector of nearly £7,000/ha. The estimated total agricultural loss, given the area of farmland flooded was over £50 million and the study estimated a 40% decrease in the yield of cereals in flood affected areas.

European flooding: past and future

Going back a little further, the Central European floods of 2002 are still the subject of research in the field of flood management. In a paper also published in the *Journal of Flood Risk Management*, **M. Socher**[38] and **G. Böhme-Korn**, from the Saxon State Ministry for Environment and Agriculture, report on the lessons learned in the German state of Saxony in the years following these floods. About two-thirds of the state was affected in August 2002, with 21 deaths, 25,000 buildings damaged and a total economic loss estimated at EUR6.2 bn. The state government's review of the floods in 2003 initiated a revised flood protection strategy including a detailed assessment of the hydrology and flooding potential of the rivers in the region, proposing more than 1600 flood protection measures, and the production of flood maps for the communities at risk. The main thrust of the strategy was the rebuilding of flood defences and other hydraulic structures as these were damaged in a total of 18,000 locations. Rebuilding was prioritised on a points-based scoring system using both cost-benefit and more qualitative values. Highest priority was given to the construction of new flood detention reservoirs, dyke improvements, protection of settlements and infrastructure with a high qualitative value and measures with international and national cross border relevance.

The use of historical records to provide better estimates of design floods is explored in a paper in the *Journal of Hydrology* by **G. Calenda**[32] and researchers from the Universita Degli Studi Roma. The study on the Rome's River Tiber makes use of river-level records going back to the 15th Century, primarily to improve estimates of 200-500 year floods, which are commonly based on less than 100 years of systematic flow monitoring data. They advocate making use of "non-systematic" information whereby floods are described in historical accounts or recorded as physical marks on buildings and bridges etc. By combining historical observations of water level with information on the physical properties of the river including dates of construction of hydraulic structures and even channel surveys, historical flow-level rating curves were derived to calculate the flow associated with observed historical levels. This provided a much longer flow time series (1422-1989) from which the design flows could be calculated.

Also focusing on Italy, a paper entitled: *Sea level rise, hydrologic runoff and the flooding of Venice* was published in *Water Resources Research* by **A. Rinaldo**[37] and a team of researchers from Italy, Switzerland and the USA. The study was a response to proposed hydraulic engineering works designed to allow the temporary closure of the lagoon surrounding the city of Venice during storm-surge events in the Adriatic. The theme of the research was to consider what changes in the lagoon water levels may occur when it is closed to the open sea, largely from the input of freshwater from the surrounding terrestrial drainage and also from small scale meteorological effects on the lagoon water itself. To achieve this, detailed hydrological and hydrodynamic models were set up to predict the water levels from the contributing 2000 km^2 drainage basin with 27 channels flowing into the lagoon. This input was coupled with a finite element (i.e. triangular interpolation network) tidal model of the Venice Lagoon. The combined model was simulated using tidal and meteorological information from 2000-2007 and assuming climate change projections of a 30 cm and 50 cm rise in sea level. Concerns that under the barrier closure Venice may flood from the river input into the lagoon were proven to be false, even under the 50cm sea level rise scenario.

Heading north to Germany, a study of flood trends in the country was undertaken by **T. Petrow**[34] and **M. Merz** from the Geoforschungszentrum, Potsdam. Their paper in the *Journal of Hydrology* used data from 145 gauging stations over the period 1951-2002 to assess whether there are any significant trends in flooding in Germany. Nine previous studies either worldwide or for specific countries have found wide ranging trends in the frequency and magnitude of flooding over time. Such changes are not just the result of climate change – other environmental factors such as land use change and river engineering have significant effects on flooding. Eight different flood indicators were used based on the annual and seasonal (summer and winter) maxima and a statistical test (the Mann-Kendall test) was applied to the time series of each of these indicators. Overall, they found that the flood hazard in Germany increased over the study period, particularly in relation to flood frequency. However, clear differences were found when looking at the spatial patterns and the different flood indicators. Upward trends were evident in the rivers of southern and western Germany whereas almost no upward trends were found in eastern German rivers. Western rivers (the Rhine and Weser) were dominated by an increase in winter floods whereas the rivers of the Danube basin in the south were dominated by an increase in summer floods. There was no significant difference in the trends for different catchment areas. The seasonal and spatial coherence of the trends suggests that the changes are climate driven. Changes based on river engineering would show evidence in larger rivers but not for small rivers where few structures have been implemented.

Mapping flood risk and impacts

Following the programmes of flood risk mapping that are now established in many countries, a number of studies have been made which investigate the accuracy of the methods used for flood risk mapping. **J. D. Bales**[31] and **C. R. Wagner** from the USGS in North Carolina published a paper on the sources of uncertainty in flood inundation maps in the *Journal of Flood Risk Management*. Their study considered the widespread river flooding experienced in North Carolina following extreme rainfall associated with Hurricane Floyd in 1999 **(Figure 9)**. In particular they considered the sources of uncertainty associated with producing maps from a Light Detection and Ranging (LiDAR) derived Digital Terrain Model (DTM) and a 1-dimensional hydrodynamic model. Generating maps using such techniques gives a good representation of the maximum flood extent although the study identified that a change of elevation of 15cm from the DTM can give up to a 150m change in the horizontal position of the maximum flood extent. Another weakness of the 1-d hydrodynamic modelling is that the maximum flood extent is associated with the peak flow in the river but due to the time lag of the flow onto and back from the flood plain and local storage effects it was shown that different water levels can be associated with similar flows according to whether they occur on the rising and falling limbs of the flood hydrograph. In conclusion the authors warn that the creators and users of flood inundation maps need to be mindful of the uncertainties and sources of uncertainties associated with these maps.

Figure 9

Inland flooding in North Carolina associated with the 1999 landfall of Hurricane Floyd. Inland flooding is responsible for more than half the deaths associated with tropical cyclones striking the United States.

Courtesy: U.S. Army Corps of Engineers, J. Jordan.

In a paper published in the *Journal of Flood Risk Management*, **W. Veerbeek**[39] and **C. Zevenbergen**, from Dura Vermeer Business Development in the Netherlands, consider the issue of urban flood damage. In flood models, damage is often not given the same level of attention as the calculation of the depth and extent of water, and in this paper the authors consider the distribution of flood damage in the Netherlands city of Dordrecht. The city is at risk of flooding both from the sea and a series of rivers and canals, but is defended by dykes designed to withstand events up to the 1 in 4000 year flood. Perhaps unsurprisingly, estimates of damage show a large increase when this design flood level is exceeded. Potential damage following a 1 in 4000 year flood is considered in terms of its spatial distribution, the age of buildings affected, the actual components of the damage, and the effect of climate change. The results show damage is characterised by clusters of high damage mostly in post-war neighbourhoods but also with the city's historical building stock being affected. The largest damage component is to household interiors and for a scenario associated with the year 2100 flood damage could increase by a factor of 4.

The results of a similar study by **H. Apel**[30] and others from the Geoforschungszentrum, Potsdam (Germany) were reported in *Natural Hazards*. Titled *Flood risk analysis - how detailed do we need to be?* This study considered the different levels of complexity in flood risk modelling from estimates of flooded areas through to different methods of damage calculations using information from the August 2002 flood on the River Mulde in the city of Eilenburg in Saxony. The prediction of the flooded area was made using a linear interpolation of observed flood levels, a more complex 1-d/2-d hydrodynamic model, and in the most detail using a fully 2-d hydrodynamic model. Likewise the estimation of damage was over three levels of complexity: a simple damage function through to a meso-scale damage model and at the most detailed a micro-scale damage model where the individual buildings are taken into account. The performance of the different combinations of hazard and vulnerability predictions was measured against the actual flood extent and damage from the 2002 flood where water extents were available from satellite images and flood depth and the cost of damage were available for 380 buildings. Despite the varying levels of complexity for the flooded area, each technique produced almost identical flood outlines although some errors were apparent for the calculation of flood depths at an individual building level. The damage estimates ranged from just below EUR10 million to over EUR100 million with the full combination of techniques compared to the official cost of EUR77 million. The closest estimate was through a combination of the meso-scale damage model with the 1d/2d hydrodynamic model, although a much greater variation was evident with the choice of damage model as opposed to using different hazard models.

Another study, published in the *International Journal of River Basin Management*, also addressed the level of detail required for evaluating flood risk. **Y. Huang**[33], of the Water Resources Ministry in China, considered the use of different methods to predict flooded areas and damage following a dyke breach on the River Elbe, Germany. The rationale for the study was to find more rapid ways of assessing potential damage during a flood event. Flood forecasting methods traditionally predict a flow and associated water levels, but estimating the area flooded and the depth of flood water is not usually practical during the short (2-3 hour) lead times available to the forecasters. This is because the complex 1- and 2-d hydrodynamic models can take in the order of many hours to run and require a large amount of preparatory work. Instead the author describes a more rapid GIS based approach to estimate the maximum depth and extent of flooding following a dyke breach based largely on the DTM and grid cell based hydrological functions available in Arc GIS. These results are compared to those generated by the SOBEK1D2D model. Estimates of damage are also made using CORINE land use data. Both models predict very similar flood extents with a slightly greater water depth apparent from the SOBEK1D2D estimates. This greater depths means the damage estimates are also greater with the SOBEK1D2D model. Despite this the GIS method is able to provide an initial rapid assessment (within minutes) of the flooded area which can aid the authorities in terms of emergency management such as evacuations and strengthening flood defences.

Advances in flood modelling

A recent development in the field of flood modelling is the use of the so-called Copula Method to identify relationships between measured flows or water levels for river gauging stations covering a wide area. **C. Wang**[40] and researchers at the University of Central Florida have undertaken a study on Copula-based flood frequency analysis which was published in *Hydrological Processes*. They consider the flood hazard at the confluences of rivers where building or structures in the vicinity can be at risk of flooding from each river individually or both rivers together. If flows are high in one river the water levels in the adjoining river can also be affected through backwater effects. The joint probability of such flooding is reported in this paper through using the copula method. The study used three river basins (the Des Moines in Iowa; the Suwannee in Florida and the Calcasieu in Louisianna), each with two or more upstream tributary gauges and a further gauge downstream of the confluence. The paper reports the theory behind the Copula method in detail and tests four different types of the method against standard extreme value methods for deriving the design flood magnitudes. The authors advocate using the method for estimating floods at river basin confluences. Given that the methods do require a specialist understanding of complex mathematics, however, their application may be limited.

Sources and further reading

30. Apel, H. et al. 2009 Flood risk analyses—how detailed do we need to be? *Natural Hazards* **49**, 79–98.

31. Bales, J.D. & Wagner, C.R. 2009 Sources of uncertainty in flood inundation maps *Journal of Flood Risk Management* **2**, 139–147.

32. Calenda, G., Mancini, C.P. and Volpi, E. 2009 Selection of the probabilistic model of extreme floods: The case of the River Tiber in Rome *Journal of Hydrology* **371**, 1-11.

33. Huang, Y. 2009 Rapid flood risk assessment using GIS technology. *Journal of River Basin Management* **7**, 1, 3-14.

34. Petrow, T. & Merz, M. 2009 Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. *Journal of Hydrology* **371**, 129-141.

35. Posthumus, H. et al. 2009 Impacts of the summer 2007 Floods on agriculture in England. *Journal of Flood Risk Management* **2**, 1–8.

36. Rodda, H.J.E. et al. 2009 A digital archive of extreme rainfalls in the British Isles from 1866 to 1968 based on British Rainfall. *Weather* **64**, 3, 71-75.

37. Rinaldo, A. et al. 2008 Sea level rise, hydrologic runoff, and the flooding of Venice. *Water Resources Research* **44**. doi:10.1029/2008WR007195.

38. Socher, M. & Bohme-Korn, G. 2008 Central European Floods 2002: lessons learned in Saxony. *Journal of Flood Risk Management* **1**, 123–129.

39. Veerbeek, W. & Zevenbergen, C. 2009 Deconstructing urban flood damages: increasing the expressiveness of flood damage models combining a high level of detail with a broad attribute set. *Journal of Flood Risk Management* **2**, 45–57.

40. Wang, C., Chang, N. B. and Yeh, G.T. 2009 Copula-based flood frequency (COFF) analysis at the confluences of river systems. *Hydrological Processes* **23**, 1471 – 1486.

5. ATMOSPHERIC HAZARDS

At the time of writing (late July, 2009) tropical cyclone activity across the world's ocean basins remains quiet (see the Seasonal Tropical Cyclone Activity Update page at: http://www.coaps.fsu.edu/~maue/tropical/). This continues a downward trend in measures of integrated cyclone energy which is reaching historic low-levels of tropical cyclone activity on a global scale for the past 30 years. Despite North Atlantic hurricane activity being above normal in the 2008 season, producing the long lived Tropical Storm Bertha and record four-times landfalling Tropical Storm Fay, the Pacific basin season produced far fewer and far weaker storms than normal. This level of tropical cyclone activity is consistent with cooler sea surface temperatures (SSTs) in the Pacific for the past few years, associated with La Niña conditions, and relatively favourable atmospheric conditions (weak vertical wind shear) aloft for hurricane formation in the Atlantic basin. However, currently, a return to a positive ENSO (El Niño-Southern Oscillation) index and warmer conditions in the Pacific seems likely.

Tropical cyclone variability

In a paper published in *Geophysical Research Letters*, **R. Maue**[53], of the Center for Ocean-Atmospheric Prediction Studies at Florida State University, draws attention to this remarkable low-level of tropical cyclone activity in the Northern Hemisphere (NH) in recent years and the large observed variability of the past three decades, as measured by the Accumulated Cyclone Energy (ACE) index **(Figure 10)**.

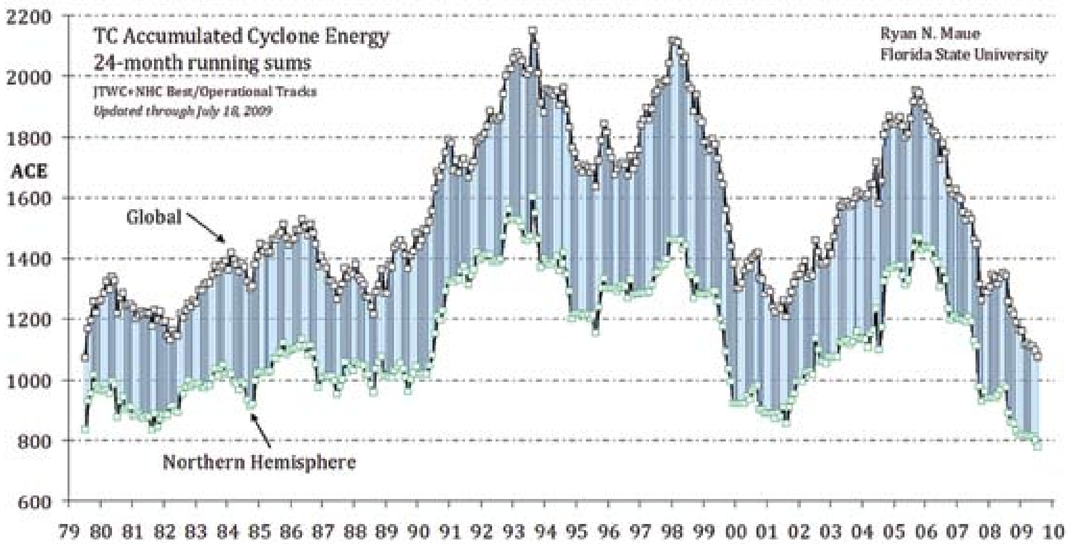


Figure 10

24-month running sum of tropical cyclone Accumulated Cyclone Energy, as defined by Maue (2009), for the entire globe (top black squares/time series) and the Northern Hemisphere only (bottom green squares/time series). The difference between the two time series is the Southern Hemisphere (SH) total. Data are shown from January 1979 to July 19, 2009 mainly because intensity estimates of SH cyclones are often missing in the Joint Typhoon Warning Centre best-tracks prior to 1980.

Courtesy: Ryan Maue, Florida State University.

Here he uses ACE as a metric of the combined total activity of each ocean basin during a calendar year, integrating frequency, duration and intensity from historical datasets. He finds the strong inter-annual variability of ACE is highly correlated with Pacific SST structure and variability, and that North Pacific boreal spring SST patterns may have considerable predictive value for subsequent NH tropical cyclone activity. Such a finding underlines how strongly tropical cyclone activity is modulated by the large scale modes of global climate variability, but the relevance to the controversy over the influence of Anthropogenic Global Warming (AGW) may be contested: the issue centers on his definition of ACE as an estimate of the actual kinetic energy of tropical storms.

On the subject of ENSO influence on NH tropical cyclone activity **H-M. Kim**[50] and colleagues, of the Georgia Institute of Technology, in a landmark paper published in *Science*, identify two distinct structures, hitherto unrecognised, in tropical Pacific Ocean warming and their different impacts on NH tropical cyclone activity **(Figure 11)**. Episodes of Eastern Pacific Warming (EPW) are identical to El Niño warming, whereas Central Pacific Warming (CPW) is centred mid-basin, on the international dateline, and associated with increased potential for landfall of storms along the Gulf of Mexico and Central America. The authors show that modulation of the vertical wind shear forced by differential Pacific teleconnections is responsible and the CPW mode is more predictable than EPW thus producing increased predictability of cyclones earlier in the season. An increase in the prevalence of CPW events in recent decades is also detected (within the limitations of the available datasets), but the reason for this increase is unclear.

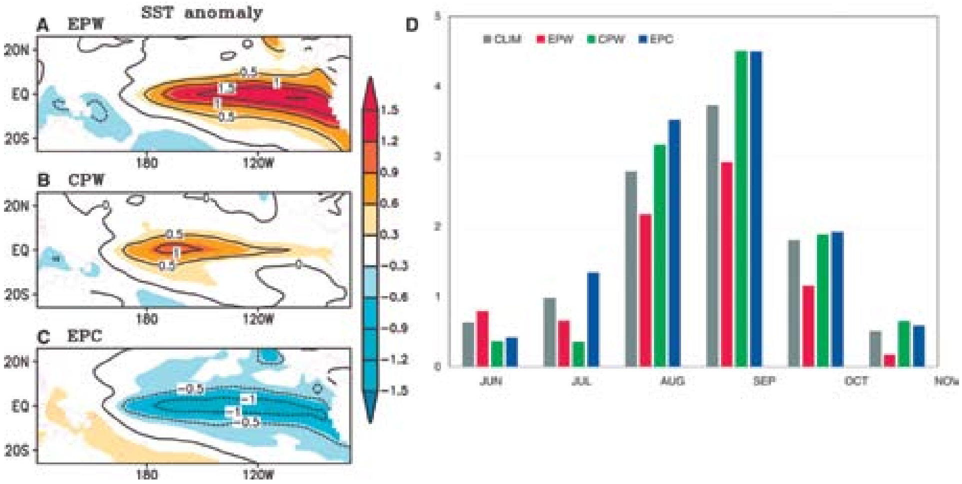


Figure 11

Composites of sea surface temperature (SST) anomalies (contours interval is 0.5°C) according to Kim et al. (2009) during the August to October period for (A) Eastern Pacific Warming (EPW), (B) Central Pacific Warming (CPW), and (C) Eastern Pacific Cooling (EPC). The average number of North Atlantic tropical cyclones per month from June to November is shown in (D) for climatology (grey bar), EPW (red), CPW (green), and EPC (blue). The time series has been de-trended to eliminate the effects of decadal variability or climate trends.

Courtesy: Science.

Writing in the Journal of Climate and looking at the longer, historical time scale **G. Vecchi**[58] and **T. Knutson**, of the Geophysical Fluid Dynamics Laboratory, Princeton, examine the relationships between North Atlantic (NA) tropical cyclone activity and SSTs. Vecchi and Knutson attempt to produce a historical metric for tropical cyclone activity for the period 1878-2006 by estimating the number of storms missed in the era before satellite observations. They find a highly significant increase (+~4.2 storms century $^{-1}$) in storm numbers for 1900-2006. However, the estimate for storm frequency for 1878-2006 is weakly positive, not statistically significant and dependant on highly uncertain numbers for the late 19th century. An unexpected finding is a highly significant decrease in storm duration for 1878-2006, but this is subject to greater uncertainties. The relationship of these findings to increased SSTs in the development region of North Atlantic cyclones and other factors at work remain unclear.

In a note, also in *Journal of Climate*, **P. Klotzbach**[51] and **W. Gray**, of Colorado State University, also report results of a historical analysis back to 1978. They find a ‘remarkable agreement’ between NA SST, sea level pressure (SLP) anomalies and multi-decadal variability in both Atlantic storm activity and the frequency of landfall in the United States. The frequency of landfalling storms along the US East Coast and Florida peninsula is correlated with phases of the Atlantic Multidecadal Oscillation (AMO) in SSTs.

Further to the last point **P. Dailey**[46] and co-workers from AIR Worldwide Corporation, Boston, Massachusetts, writing in the Journal of *Applied Meteorology and Climatology*, focus on where and how SSTs influence the location of US landfall of storms. The results of their two part, statistical and physical, study indicate East Coast land-falling storms have a different genesis region and intensification characteristics compared to Gulf Coast land-falling storms **(Figure 12)**. Warming SSTs and shifting genesis regions and intensification patterns may strongly influence regional landfall risk, with profound implications for the distribution of the risk to life and property.

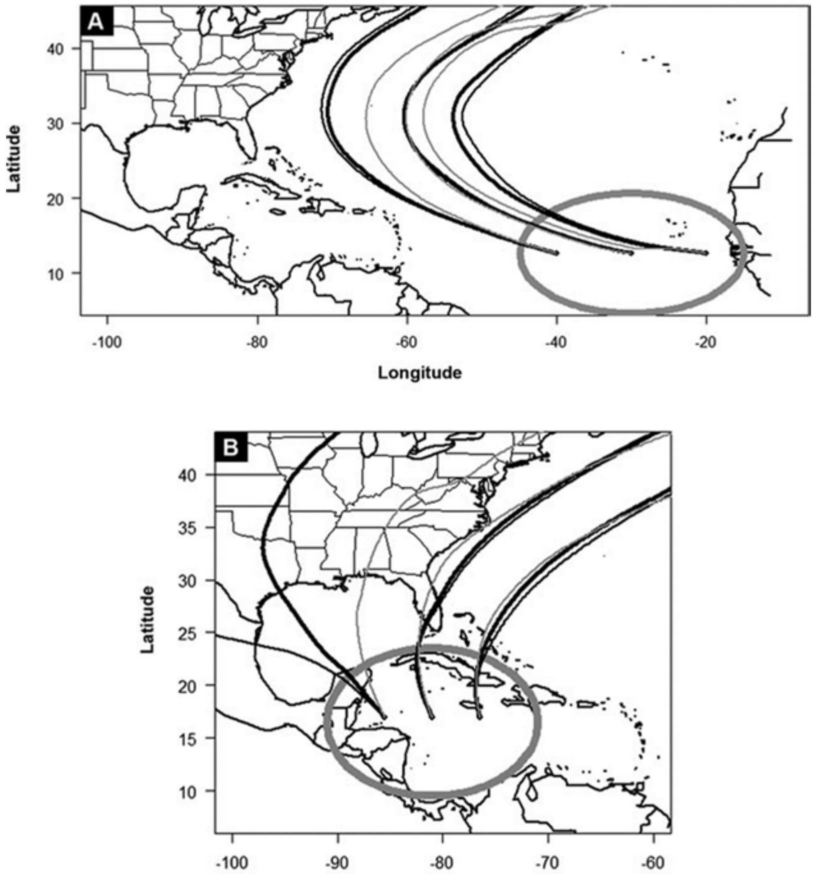


Figure 12

Climatological mean tracks for tropical cyclones originating in two select genesis regions according to Dailey et al. (2009). The thick black line indicates the mean trajectory of storms originating from the (top) western Atlantic and (bottom) eastern Atlantic regions discussed in the text. The thin black (grey) line is based on historical tracks originating from each genesis region in warm (cool) years.

Reprinted with permission of the American Meteorological Society.

The above papers focus their analyses on the Northern Hemisphere tropical cyclone season and we now turn to a paper on Southern Hemisphere storms, in which similar themes are apparent. **H. Ramsey**[54], and co-workers from the University of Oklahoma, report in the *Journal of Climate* the results of a study of various large-scale environmental factors on the inter-annual variability of tropical cyclones in the Australasian region. Ramsey and colleagues provide a brief but useful review of the previous literature on tropical cyclone climatology for Australasia and then go on to analyse a 1970-2006 "best-track" dataset for the satellite observation era. They find large correlations between Niño-3.4 and Niño-4 region SSTs in the Pacific and seasonal numbers of tropical cyclones. The correlations are greatest during August to October, immediately preceding the Australasian tropical cyclone season, and are potentially useful predictors as early as July. Correlations with local SSTs in the region where these cyclones are born north of Australia are found to be much weaker. However, low-level vorticity and tropospheric vertical wind shear in this genesis region are found to be strongly influenced by central Pacific SSTs via an 'atmospheric bridge'- an idea for which the authors provide a conceptual model **(see Figure 13)**. Intriguingly, correlations between SSTs and cyclone activity are increased by combining tropical Pacific SST and sub-tropical North Atlantic SSTs even several months prior to the cyclone season, hinting at teleconnections from far afield. Finally, the authors find an apparent decline in annual numbers of all tropical cyclones since 1970, but not for storms with central SLPs of below 965 hPa.

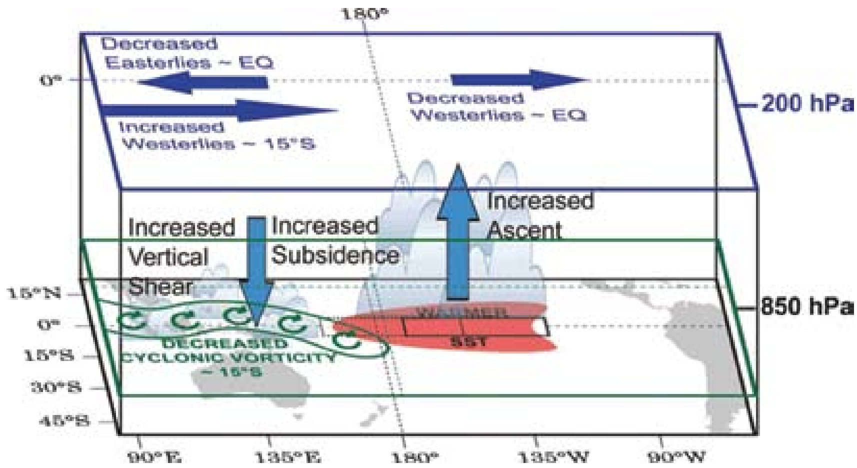


Figure 13

Schematic from Ramsey et al. (2008) showing the connection between anomalously warm Sea Surface Temperature in the Niño-3.4 and Niño-4 regions (pink shading) associated with El Niño events and the corresponding atmospheric response: increased 200-hPa zonal westerly winds (blue horizontal arrows) around 15°S resulting in increased vertical shear of the zonal wind, co-located with decreased 850-hPa relative cyclonic vorticity (green) associated with a weakened monsoon trough over the Australian region. Light blue vertical arrows indicate anomalous subsidence over the northern Australian region and anomalous ascent over the central equatorial Pacific.

Compared to the North Atlantic, North West Pacific and Australasian regions, studies of East Asian tropical cyclone climatology have received less attention. The two following studies seek to address this imbalance. **Z. Zuki**[60], and **A. Lupo**, University of Missouri, Columbia, in the *Journal of Geophysical Research (Atmospheres)* study tropical storm activity impacting Malaysia for the period 1960-2006. Motivated by two particularly costly and deadly storms- 'Greg' and 'Vamei', that struck in December 1996 and December 2001- they show that indeed November and December are the most active months in this region. Their dataset from the Joint Typhoon Warning Center (JWTC) shows a slight but statistically insignificant increasing trend in activity for the period 1960-2006. Study of the inter-annual variability shows there was more cyclone activity in La Niña years compared to El Niño years. La Niña years were associated with warmer SSTs, relatively weak tropospheric vertical wind shear, greater moisture, and stronger low-level cyclonic vorticity in the study region. Regardless of whether SSTs were warmer or cooler non-active years tended to have more low-level anti-cyclonicity, even weaker wind shear and less moisture and these were mostly El Niño years. Longer term variability, such as linkage to the Pacific Decadal Oscillation (PDO), was not found.

J. Chan[44] and **M. Xu**, in the *International Journal of Climatology*, perform one the first comprehensive studies of landfalling tropical cyclones in the East Asian region, i.e. China, Vietnam, the Philippines, the Korean peninsula and Japan. Their dataset from the JTWC covers 1945-2004 and again they find no significant overall trend in cyclone numbers using a wavelet analysis. They do find significant inter-annual and decadal variability which is well correlated with the total number of cyclones in the North West Pacific region on a multi-decadal time scale. Detailed analysis is left to a second paper, not yet published.

Tropical Cyclones: hazards, prediction and warning

The authors of many of the above papers are only too aware of the limitations of their historical datasets. The record available for risk assessment in, for instance, the North Atlantic basin only goes back ~150 years whereas reinsurers need to consider far longer return periods in their calculations. In a paper in *Natural Hazards* **J. Rumpf**[56] and **V. Schmidt**, of the Institute of Stochastics at Ulm University, and co-workers from Munich Re attempt a different approach to assess the probability and intensity of landfalling storms in the North Atlantic. Using a basin-wide Monte-Carlo simulation they create a synthetic dataset of storm tracks which they claim is more comprehensive than the available historical data and, they argue, provides a better basis for assessing landfall probability, especially in areas of low landfall frequency. In this approach the fluctuations of inter-annual, decadal and multi-decadal variability are neglected in order to capture the statistics of the historical dataset as a whole, in this case for the period 1900-2005, and enable the calculation of the return periods of a large number of 'wind impacts' at any one location affected by tropical cyclones.

The concern underlying all these recent studies is that human-induced climate change is influencing the course of weather and climate variability and related trends in insurance losses. **R. Crompton**[45] and **K.J. McAneney**, of the Risk Frontiers Natural Hazards Research Centre at Macquarie University, Sydney address this point directly in a paper in the journal *Environmental Science & Policy*. Using the Natural Disaster Event List from The Insurance Council of Australia they normalise the weather related losses to estimate the insured loss that would be incurred if these events were to occur under 2006 societal conditions. For instance, they include a factor adjusting for the influence of improved building standards in cyclone prone areas since the early 1980s- this is a marked advance on previous studies. In summary they suggest their evidence shows that societal factors- for instance the increased number and value of dwellings- are the reason for increased insurance losses in Australia and find no impact of human-induced climate change during the time period of their study. They find improved building standards have effectively reduced risk and cyclone related losses in recent years and conclude, on an optimistic note, that “Employing both mitigation and adaptation contemporaneously will benefit society now and into the future”.

An important aspect of hazard mitigation is accurate and timely forecasting of tropical cyclones. The leading centre for tropical cyclone prediction in the Northern Hemisphere is the National Hurricane Center (NHC), based in Miami, Florida. In a paper published in *Weather and Forecasting* **E. Rappaport**[55] and colleagues from the NHC comprehensively review the current status of the United States’ hurricane warning program highlighting recent progress, current limitations and the challenges ahead- all this in the light of the recent extremely active hurricane seasons of 2004 and 2005. Looking forward to the next 10 years Rappaport and co-authors identify key areas for progress, namely 1) improvements in global and regional forecast systems to reduce errors in storm track and intensity guidance; 2) optimisation and enhancement of observing capabilities not only for operational, forecasting purposes but also for advancing research; 3) expanding and enhancing the forecast tools required to apply and add value to the guidance from the numerical models and the observing systems.

Multi-season forecasting is addressed by **J. Elsner**[48] of The Florida State University, and co-authors, in a paper in the *Journal of Climate*. They have developed an improved statistical algorithm to predict North Atlantic hurricane activity out to 5 yrs. The results indicate that forecast skill over the period 1997-2005 is improved over persistence and previous multi-season forecasts. A major caveat is that the technique does not, at present, account for fluctuations such as ENSO.

Finally, in this section, we conclude with a paper which tackles a grey area in our fundamental understanding of hurricanes and the extreme winds and damage they produce- the Hurricane Boundary Layer (HBL). **P. Zhu**[59], of the Florida International University, Miami, writing in the *Journal of Geophysical Research (Atmospheres)* proposes a conceptual model for the structure of the updrafts and downdrafts that bring the hurricane winds to the surface. Operating the National Centers for Atmospheric Research (NCEP) Weather Research and Forecasting (WRF) model in Large Eddy Simulation (LES) mode he investigates the structure of Hurricane Ivan’s boundary layer on landfall along the Gulf Coast in 2004. The use of extremely high resolution, real data, so-called ‘large eddy resolving’ simulations (grid point spacing of order ~100m) is a new area of research which will test our understanding of how hurricanes interact with the changing surface roughness and heat and moisture fluxes on making landfall, increase our understanding of how localised wind damage is produced and will lead to better parameterizations of the HBL in numerical models thus improving the prediction of storm intensity.

Extratropical Storms

A major windstorm, ‘Klaus’, struck Western Europe during the winter of 2009 (see **Aon Benfield 2009**[43]). On the night of 23 January and into the 24 January sustained winds up to 170 kph and gusts over 200 kph were recorded across southern France and northern Spain leaving at least 27 dead, millions of homes without electricity and extensive damage to property and infrastructure. Estimated losses range up to EUR2.5 billion. A few weeks later a second strong, but less damaging storm, 'Quinten', struck north-western France. 'Klaus' is likely to be the most damaging windstorm to strike Western Europe since 'Lothar' and 'Martin' in 1999.

Windstorms in Europe in recent decades have been extremely costly to insurers and two papers in a special issue of the *International Journal of Climatology* (**Alexander, L.V.**[41] et al. Eds.), 2009) devoted to "Climate extremes: progress and future directions" will be of interest to the industry. **R. Allan**[42] of the Hadley Centre, Exeter (UK), and co-authors, examine extreme storms across the British Isles during the autumn and winter months from 1920 to 2004. They find a significant correlation of storminess in the autumn months (October, November, December) with the Azores-Iceland North Atlantic Oscillation (NAO) index, but not with the Gibraltar-SW Iceland NAO index. A weaker linkage to ENSO is detected. In the winter months (January, February, March) significant correlation with both NAO indices is found but this fluctuates over the period of the dataset. Interestingly, and importantly, extreme storms in the autumn and winter months appear to be linked to different physical mechanisms. Such a study helps put recent western European storms in perspective and emphasises the role played by inter-decadal to multi-decadal fluctuations in natural climate variability.

In another study of historical storminess in the European region, **E. Hanna**[49] of the University of Sheffield, and colleagues, examine trends in surface pressure back to 1830, as a proxy for Atlantic and Northwest European storminess and climate variation over the period. Writing in the *Journal of Climate*, they use these records to demonstrate the existence of periods of increased storminess around 1900 and during the early 1990s, with a relatively quiet period between the 1930s and 1960s. They also note that there is little evidence that the mid- to late-nineteenth century was any less stormy than at present, and observe that there is no sign – as yet – of a sustained enhanced storminess signal associated with global warming.

Of direct interest and importance to the reinsurance industry is the paper by **P.M. Della-Marta**[47] and colleagues from MeteoSwiss, Zurich. Using the European Centre for Medium Range Forecasting (ECMWF) ERA-40 reanalysis they estimate, using Extreme Value Analysis techniques, the return periods of a catalogue of 200 of the most prominent European windstorms. This seems to be a significant step forward; however the authors conclude with remarks on the challenges of further developing the statistical methodology and overcoming the inherent limitations of current historical datasets.

Severe local storms- tornado formation

The first part of a major field program, 'Vortex-2', designed to investigate severe local storms and tornado formation has taken place this spring in the Plains of the American Mid-West. However, 2009 was a quiet tornado season after two very active years, including the devastating Greensburg, Kansas tornado in May, 2007. The researchers may collect further data during the second leg of Vortex-2 in spring 2010.

A key aim of field experiments like Vortex-2 is to obtain data which will throw light on why some, but by no means all, rotating thunderstorms – 'supercells' – produce tornadoes and how the near surface storm environment influences tornadogenesis. Finding a canonical theory for tornado formation has proved elusive but two papers published in *Geophysical Research Letters* may well prove to be important pieces of the jigsaw puzzle. Both focus on the influence of cloud microphysics on the rear flank downdraft (RFD) and cold pool generation in supercell storms. RFDs in supercell storms have long been thought to be crucial to the evolution of low-level storm rotation. **N. Snook**[57] and **M. Xue**, of the Center for Analysis and Prediction of Storms at the University of Oklahoma, use idealized supercell simulations to investigate influences on cold pool (the rain cooled storm downdraft) intensity and the low-level storm dynamics. Tornadic circulations occur in their simulations only when the cold pool strength is relatively weak and just so in order to provide the dynamic lift and vertical stretching of low-level air parcels that support tornadogenesis.

Reporting the results of a complementary study in *Geophysical Research Letters*, **D. Lerach**[52] of Colorado State University, and co-researchers, also describe the use of idealised simulations to show that storm environments polluted by aerosols produced stronger RFDs, weaker cold pools and tornadoes. Clean environments were less favourable for tornadogenesis. Further study of these processes is likely to be of importance in improving the cloud microphysical parameterisations in the next generation of storm scale forecast models.

Sources and further reading

41. Alexander, L.V. et al. (Eds.) 2009 Special Issue: Climate Extremes: progress and future directions. *International Journal of Climatology* **29**, 317 – 459.

42. Allan, R., Tett, S. & Alexander, L.V. 2009 Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* **29**, 357-371.

43. AON Benfield 2009 Event Recap Report: Windstorm Klaus – Jan. 23-24, 2009. Available at: http://www.aon.com/about-aon/intellectual-capital/attachments/reinsurance/Event_Recap_Report_Windstorm_Klaus.pdf.

44. Chan, J. C. L. & Xu, M. 2009 Inter-annual and inter-decadal variations of landfalling tropical cyclones in East Asia. Part I: time series analysis. *International Journal of Climatology* **29**, 285-1293. doi: 10.1002/joc.1782.

45. Crompton, R. P. & McAneney, K. J. 2008 Normalised Australian insured losses from meteorological hazards: 1967-2006. *Environmental Science and Policy* **11**, 371-378.

46. Dailey, P. S. et al. 2009 On the Relationship between North Atlantic Sea Surface Temperatures and U.S. Hurricane Landfall Risk. *Journal of Applied Meteorology and Climatology* **48**, 111-129.

47. Della-Marta, P.M. et al. 2009 The return period of wind storms over Europe. *International Journal of Climatology* **29**, 437-459.

48. Elsner, J. B. et al. 2008 Improving multiseason forecasts of north Atlantic hurricane activity. *Journal Of Climate* **21**, 1209—1219.

49. Hanna, E. et al. 2008 New insights into North European and North Atlantic surface pressure variability, storminess and related climatic change since 1830. *Journal of Climate* **21**, 6739 – 6766.

50. Kim, H-M, Webster, P.J. and Curry, J. A. 2009 Impact of Shifting Patterns of Pacific Ocean Warming on North Atlantic Tropical Cyclones. *Science* **325**, 77-80.

51. Klotzbach, P. J. and Gray, W. M. 2008 Multidecadal Variability in North Atlantic Tropical Cyclone Activity. *Journal of Climate* **21**, 3929-3935.

52. Lerach, D.G., Gaudet, B.J and Cotton, W.R. 2008 Idealized simulations of aerosol influences on tornadogenesis. *Geophysical Research Letters* **35**. doi:10.1029/2008GL035617.

53. Maue, R. N. 2009 Northern Hemisphere tropical cyclone activity. *Geophysical Research Letters* **36**. doi:10.1029/2008GL035946.

54. Ramsay, H. A. et al. 2008 Interannual variability of tropical cyclones in the Australian region: Role of large-scale environment. *Journal Of Climate* **21**, 1083-1103.

55. Rappaport, E. N. et al. 2009 Advances and Challenges at the National Hurricane Center. *Weather and Forecasting* **24**, 395-419.

56. Rumpf, J. et al. 2008 Tropical Cyclone Hazard Assessment Using Model-based Track Simulation. *Natural Hazards* **48**, 383-398.

57. Snook, N. and Xue, M. 2008 Effects of microphysical drop size distribution on tornadogenesis in supercell thunderstorms. *Geophysical Research Letters* **35**. doi:10.1029/2008GL035866.

58. Vecchi, G. A. & Knutson, T. R. (2008), 'On estimates of historical north Atlantic tropical cyclone activity', *Journal Of Climate* **21**, 3580--3600.

59. Zhu, P. 2008 Simulation and parameterization of the turbulent transport in the hurricane boundary layer by large eddies. *Journal of Geophysical Research-Atmospheres* **113**. doi:10.1029/2007JD009643.

60. Zuki, Z. M. and Lupo, A. R. 2008 Interannual variability of tropical cyclone activity in the southern South China Sea. *Journal of Geophysical Research-Atmospheres* **113**. doi:10.1029/2007JD009218.

6. CLIMATE CHANGE

Over the past three years the climate change issue has risen to the very top of the political agenda, and is now widely recognised as the greatest threat to society at large and to a fully-functioning and sustainable global economy. Both the US and UK have published new, detailed, studies addressing climate change impacts on the respective nations (see at: http://www.globalchange.gov and http://www.ukcip.org.uk), while the United States Geological Survey has issued a report on abrupt climate change and its potential impacts that certainly helps to concentrate the mind (see at: http://www.usgs.gov/global_change/). Ahead of the critical COP15 UN Climate Change Conference, to be convened in Copenhagen in December to address the issue of a post-Kyoto greenhouse gas emissions agreement, the Climate Science Congress, held in the same city in March, produced a particularly sobering synthesis report on future prospects (see at: http://climatecongress.ku.dk/). Notwithstanding, however, the enormous research effort focusing on our changing climate and its implications, there is still a great deal that we cannot be certain of, or are unable to quantify. One area that still triggers high emotions within certain elements of the climate science community relates to how, or even whether, a warmer world will affect the number and intensity of tropical cyclones, and this contentious area is addressed in the following section.

Climate change and tropical cyclone activity

Despite very quiet Atlantic hurricane seasons over the last two years, the debate continues about whether episodes of recent elevated hurricane activity in the North Atlantic are driven by climate change or are simply a reflection of a natural cycle. Advocates of both sides of the argument present their results in a series of papers published in a new book on *Hurricanes and Climate Change*, edited by **J. Elsner** and **T. Jagger**[69] of Florida State University. The papers are the result of an international summit on hurricanes and climate change that attracted more than 70 scientists to the Greek island of Crete in 2007 to debate the issue. **Elsner**[67], an advocate of a role for climate change in recent tropical cyclone activity, addresses the often turbulent discussions at the summit in a paper in the *Bulletin of the American Meteorological Society*. Here he succinctly gets to the heart of the problem: studies have shown that tropical cyclones are becoming more powerful, most notably in the North Atlantic, with the increase correlated with a rise in sea-surface temperature (SST). Is this temperature rise, however, a consequence of anthropogenic climate change resulting in increases in radiative forcing due to accumulating greenhouse gases in the atmosphere, or to natural climate variations? While a warmer ocean might be expected to spawn and nurture tropical cyclones more easily, increasing wind shear in a warmer world would be expected to breaking up storms more effectively. Critically, Elsner observes that although the question of whether changes in tropical cyclone intensity can be attributed to anthropogenic climate change remains open, based upon data models of extreme winds, the difference in hurricane intensity for storms near the US coast between globally warm and cool years is consistent in both sign and magnitude with theory and simulations. The corollary of this is that apparent discrepancies between numerical model results and observations probably reflect a reliance on data analysis rather than data models. Elsner also reports the results of storm deposit studies presented at the summit that suggest there were fewer Atlantic hurricanes when the northern hemisphere was cooler during the so-called Little Ice Age (15th – 19th centuries). This he suggests, however, could reasonably be explained – at a specific location - by a change in hurricane tracks rather than abundance. Finally, and perhaps most significantly, Elsner notes that results presented from a number of high-resolution models were consistent with the occurrence of stronger tropical cyclones in a warmer world, while storm numbers were predicted to fall overall.

In an important and insightful paper in the journal *Science*, **G. Vecchi**[77] of the US National Oceanic and Atmospheric Administration, and co-authors, zero-in on future prospects for Atlantic hurricanes in a carbon-enriched world, noting that alternative interpretations of the relationship between SST and hurricane activity result in very different pictures. On the one hand, a simple link between absolute SST and Atlantic hurricane activity, would result in a situation, by 2100, in which even a quiet year would be comparable to 2005, when four hurricanes made US landfall resulting in losses in excess of USD100 billion **(Figure 14 top)**. On the other, if Atlantic hurricane activity is modulated by the Sea Surface Temperature in the tropical Atlantic main development region (where most hurricanes grow) *relative* to the tropical mean SST, the picture would be far less dramatic. Between 1946 and 2007, this ‘relative SST’ is as well correlated with Atlantic hurricane activity as the absolute SST, but looking ahead relative SST is not projected to experience a significant upward trend as the tropics as a whole warm **(Figure 14 bottom)**. A future wherein Atlantic hurricane activity is controlled by relative SST would, therefore, be comparable to the recent past, with periods of more and less intense activity relative to present-day conditions – due to natural climate variability – but with little or no longer-term trend.

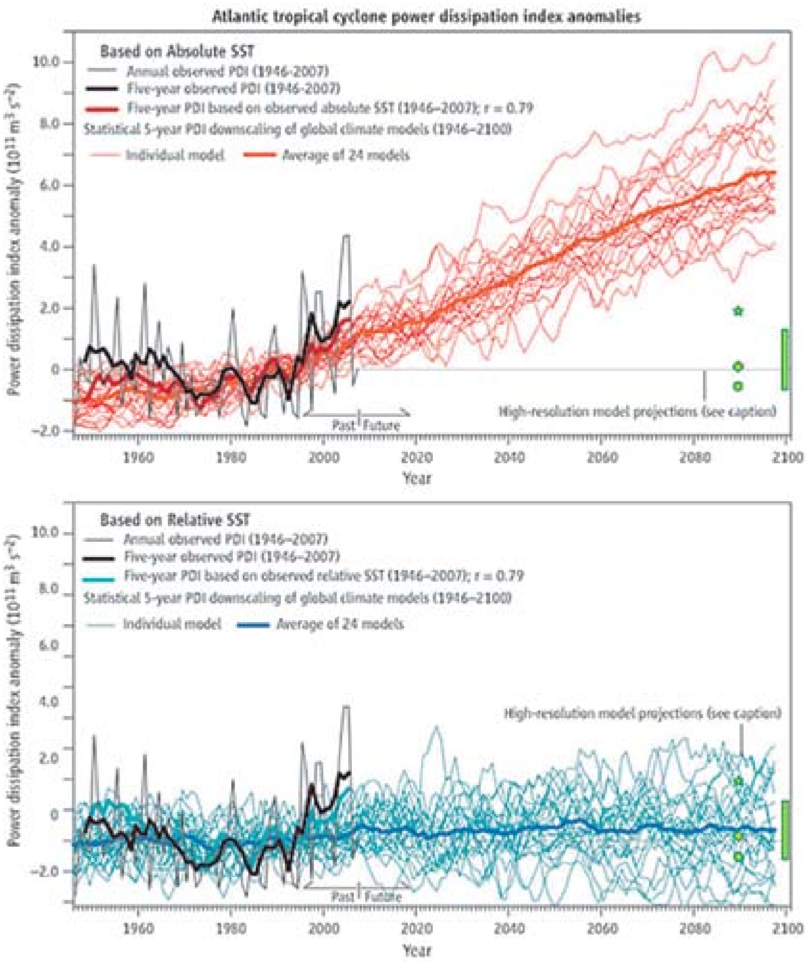


Figure 14

Past and extrapolated changes in Atlantic hurricane activity. Observed hurricane power dissipation index (PDI) anomalies are regressed onto observed absolute and relative Sea Surface Temperature over the period from 1946 to 2007, and these regression models are used to build estimates of PDI from output of global climate models for historical and future conditions. Anomalies are shown relative to the 1981 to 2000 average (2.13 × 10^{11} m^3 s^{-2}). The green bar denotes the approximate range of PDI anomaly predicted by the statistical/dynamical calculations. The other green symbols denote the approximate values suggested by high-resolution dynamical models. Sea Surface Temperature indices are computed over the region 70°W-20°W, 7.5°N-22.5°N, and the zero-line indicates the average over the period from 1981 to 2000.

Courtesy: Science.

Sea-surface temperatures in tropical cyclone spawning grounds are also addressed by **N. P. Gillett**[71] of the University of East Anglia’s Climatic Research Unit, and co-researchers. In a paper in *Geophysical Research Letters*, Gillett and colleagues provide evidence from modelling in support of a clear anthropogenic influence on ocean warming in both the North Atlantic and Western North Pacific cyclogenesis regions. The authors conclude that greenhouse gas increases due to human activities are probably the main cause of warming in these regions. In the case of the Atlantic, they note that their findings disagree with the idea that warming in the Atlantic Cyclogenesis Region is driven by natural cycles such as the Atlantic Multi-decadal Oscillation. Writing in *Theoretical & Applied Climatology*, **P. A. Steenhof**[75] and **W. A. Gough** of the University of Toronto also examine Atlantic SST, this time in the context of the resurgence of hurricane activity that started in 1995.

The authors use a range of different measures of hurricane activity to examine the influence of SST in the main development region of Atlantic hurricanes. In one approach, they take the 10 warmest years and the 10 coolest years between 1941 and 2006, and identify a significant statistical relationship between SST and hurricane activity. In a second element of the study the authors identify a significant correlation between SST and all measures of hurricane activity **(Figure 15)**. For reasons addressed in the aforementioned paper by Vecchi and colleagues, however, Steenhof and Gough are ambivalent about whether or not the established link between recent Atlantic SST and hurricane activity will translate into increased hurricane activity in a warmer world.

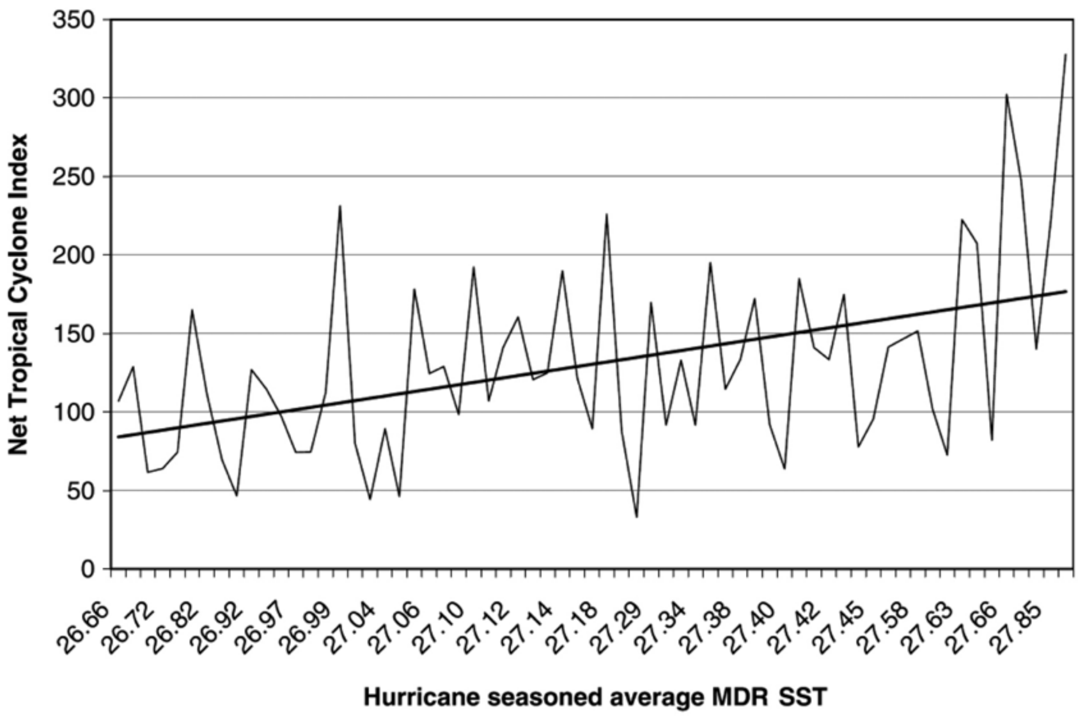


Figure 15

Steenhof and Gough (2008) demonstrate a statistically-significant relationship between Sea Surface Temperature in the Main Development Region and hurricane activity in the Atlantic Basin. This positive correlation is illustrated by a change in total hurricane activity in the Atlantic Basin in association with changing SSTs in the MDR.

Courtesy: Theoretical & Applied Climatology.

Staying with the influence of sea-surface temperature, **K. Arpe**[61] of Germany's Max Planck Institute for Meteorology and **S. Leroy** of Brunel University in the UK, examine, in *Quaternary International*, the impact of local SST on Atlantic hurricanes. They also address the potential effects of other phenomena affecting hurricane development in the North Atlantic, including ENSO (El Niño – Southern Oscillation) and the stratospheric QBO (Quasi-Biennial Oscillation). Arpe and Leroy note that elevated local SST, increases in the latent heat flux from the oceans to the atmosphere, a westerly airstream in the tropical stratosphere (which reduced the occurrence of strong easterly phases of the QBO), and a more moist, unstable stratification of the atmosphere, all lead to more frequent or more intense hurricanes. In contrast, increased vertical wind shear or a drier atmosphere will lead to fewer North Atlantic hurricanes. Arpe and Leroy pick out wind shear as a critical determinant that they conclude has a dominant influence, even over tropical SST. Looking ahead, they speculate that increased wind shear in a warmer world could counteract the tendency for higher SSTs to trigger increased Atlantic hurricane activity.

Looking more broadly at tropical cyclone activity across the globe, **S. Gualdi**[72] of the Istituto Nazionale di Geofisica e Vulcanologia in Bologna, Italy, and co-workers, use the results of a study using a high-resolution, coupled-circulation model, to predict how global warming will affect tropical cyclone activity in the major ocean basins. Writing in the *Journal of Climate*, Gualdi and colleagues demonstrate that the study predicts a substantial general reduction in tropical cyclone frequency as the concentration of atmospheric carbon dioxide is doubled and quadrupled, particularly for the North Atlantic and tropical western North Pacific regions. In the former, hurricane activity appears to be suppressed by a more stable atmosphere and by – as suggested in the previous paper – stronger vertical wind shear.

AON BENFIELD UCL Hazard Research Centre

The study also predicts that tropical cyclones will generate more rainfall and – despite the expansion pole-ward of warmer SSTs – will remain confined to the tropics.

Whether or not tropical cyclones will eventually expand their traditional 'hunting grounds' – bearing in mind that Atlantic hurricanes have struck both Brazil and Spain in recent seasons **(Figure 16)** – there may already be evidence that the Atlantic hurricane season is getting longer. Writing in *Geophysical Research Letters*, **J. P. Kossin**[73], of the University of Wisconsin, looks at the timing of Atlantic hurricanes in recent years. He notes that in 2007, storms occurred in both May and December, while the following year, four tropical storms – two of hurricane status – occurred in July. Similarly, 2005 saw anomalous activity both early and late in the season. Examining observed historical trends in the annual distribution of North Atlantic tropical storm formation events, and their relationship with tropical Atlantic SST, Kossin detects an apparent tendency towards more common early and late season storms that correlates with higher SST. Currently, however, the uncertainties in the correlation are high and the author makes the point that although storm formation dates have been changing over the historical record, the observed trends cannot be used to reliably predict future changes to the season.

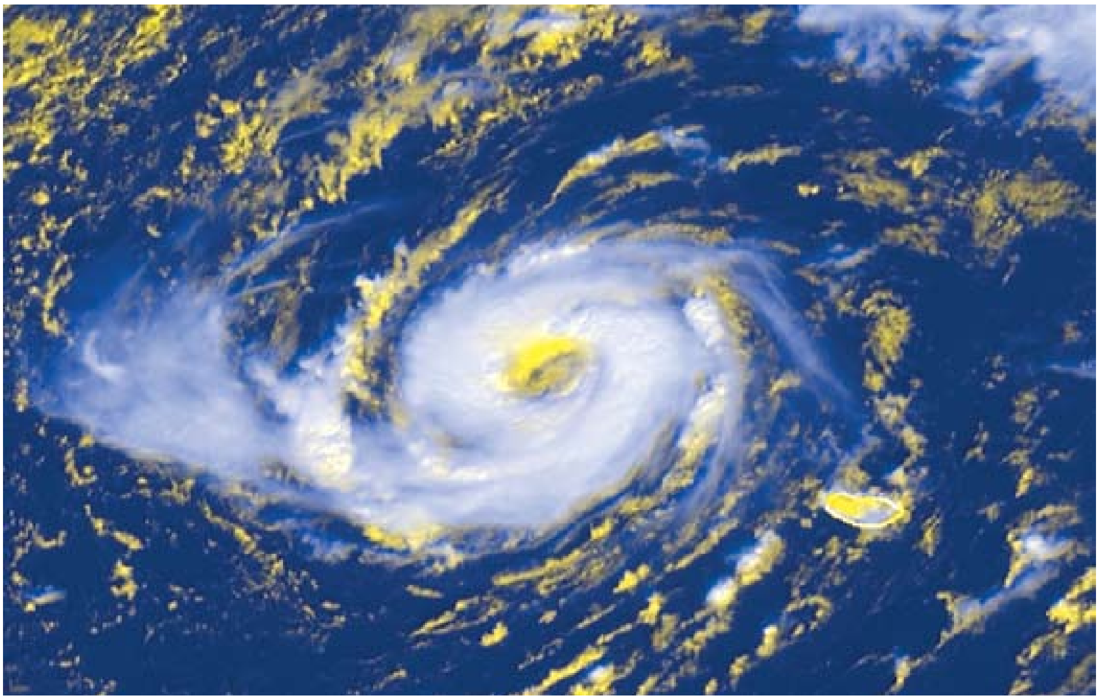


Figure 16

Hurricane Vince close to Madeira in October 2005.

Courtesy: EUMETSAT.

In addition to the season getting longer, it also seems that Atlantic hurricanes are getting stronger, along with tropical cyclones in other ocean basins. Writing in *Nature*, **J. Elsner**[68] of Florida State University, and colleagues, confirm a 30-year trend that shows tropical cyclones in the Atlantic getting progressively stronger, in line with SST rises in the Atlantic region and elsewhere. By analysing homogeneous satellite wind-speed data they also show that a comparable trend can be seen in the rest of the tropics. The authors demonstrate a significant overall upward trend for wind-speeds in the most powerful tropical cyclones, which they also recognise in the very strongest storms over each ocean basin, and most noticeably in the North Atlantic. As explanation, Elsner and his co-researchers, note that their results are consistent with the simple and straightforward idea that as the oceans warm they have more energy to convert to tropical cyclone wind.

While the prospect of more powerful tropical cyclones is a concern, this only becomes a real problem when and if such storms make landfall. For the US, this is an issue tackled by **K. Coughlin**[63] and colleagues at Risk Management Solutions and Germany's Alfred Wegener Institute in Bremerhaven. The authors note that the fraction of Atlantic hurricanes that make landfall in the US is a measure of the relationship between landfalling and basis hurricane numbers. Using statistical tests, they go on to establish that there is a significant change in the proportion of Atlantic hurricanes that struck the US coastline between the first and second halves of the 20th century, relative to hurricane activity in the Atlantic Basin as a whole; supposedly an artefact of a paucity of basin observations in the earlier period. After 1948, however, Coughlin and co-workers analysis reveals no change in the proportion of Atlantic hurricanes striking the US coast, despite significant changes in the total number of hurricanes. They note, however, that there probably are changes – to some degree – in both the proportion and number of landfalling hurricanes, but that both are masked by the fact that the scarcity of landfalling hurricanes means that there are insufficient data to resolve potential changes. Notwithstanding this, the authors conclude that by assuming that the proportion of landfalling hurricanes is constant, information about the total number of hurricanes in the Atlantic Basin can be used to make more accurate forecasts of US landfalling hurricane activity in the future.

Climate change and extra-tropical cyclones

As with tropical cyclones, a lively debate is ongoing about whether climate change will mean more and/or more intense windstorms outside the tropics, and in particular across the European region. The issue of extra-tropical cyclones in a warmer world is reviewed in *Theoretical & Applied Climatology* by **U. Ulbrich**[76] of the Freie Universität Berlin, and co-authors, who acknowledge at the start that it is not easy to present a common viewpoint of extra-tropical cyclones, their variability and trends, either in the real world or in global climate model (GCM) studies. Nevertheless, the authors arrive at conclusions that broadly support the findings of the 2007 IPCC (Intergovernmental Panel on Climate Change) 4th Assessment report, namely that global warming will shift storm tracks towards the poles in both hemispheres (most noticeably in the southern hemisphere) and drive greater storm activity at higher latitudes. More specifically, two regions of high cyclonic activity are predicted in the northern hemisphere; one over the North Pacific and the other over the North Atlantic, with a secondary region of elevated activity over the Mediterranean. Broadly-speaking, a fall in winter cyclone numbers is projected, although a rise in the number of intense cyclones is forecast across the NE Atlantic, the British Isles and the North Pacific. In the southern hemisphere, the existing southward band of cyclonic activity is predicted to move further south, leading to reduced cyclonic activity around 50º S and increased activity around 60º S.

In a paper in *Geophysical Research Letters*, **P. M. Della-Marta**[65] of MeteoSwiss and **J. G. Pinto** of the University of Cologne, look ahead to the potential impact of a warmer climate on winter storms over the North Atlantic and Europe. For two IPCC emissions scenarios (A1B – more optimistic and A2 – less optimistic), the authors quantify changes in storm frequency and intensity across the region, in terms of return periods. By 2100, under both scenarios, they show that both the minimum central pressure (CP) and the maximum vorticity (VOR) of North Atlantic storms are projected to remain unchanged compared to the present day. For the British Isles – North Sea – western Europe area, however, shorter return periods for VOR of all intensities are apparent as early as 2040. Although they speculate that the changes may be unrealistically large, with a 50 (20) year event projected to become a 9 (5.5) year event under both scenarios, Della-Marta and Pinto suggest that the likely consequences are a higher incidence of damaging wind events across Europe.

Climate change, extreme wind events and tornadoes

It might seem intuitively reasonable that a warmer, more dynamic atmosphere will be characterised by more extreme winds, but the true situation is far more complex. Writing in *Geophysical Research Letters*, **G. Gastineau**[70] and **B. J. Soden** of the Rosenstiel School for Marine and Atmospheric Science in Miami, use a multi-model ensemble of coupled climate model simulations to investigate changes in the frequency of occurrence of extreme windstorm events in response to anthropogenic global warming. The authors conclude that a weakening of large-scale atmospheric circulation results in a reduction in the frequency

AON BENFIELD UCL Hazard Research Centre

of the most extreme wind events over the tropics. Conversely, however, they found that the strongest near-surface wind events increased in frequency at higher latitudes, as the mid-latitude storm tracks migrated towards the poles. As a consequence of higher moisture contents in the lower troposphere, the frequency of the heaviest precipitation events was also projected to increase.

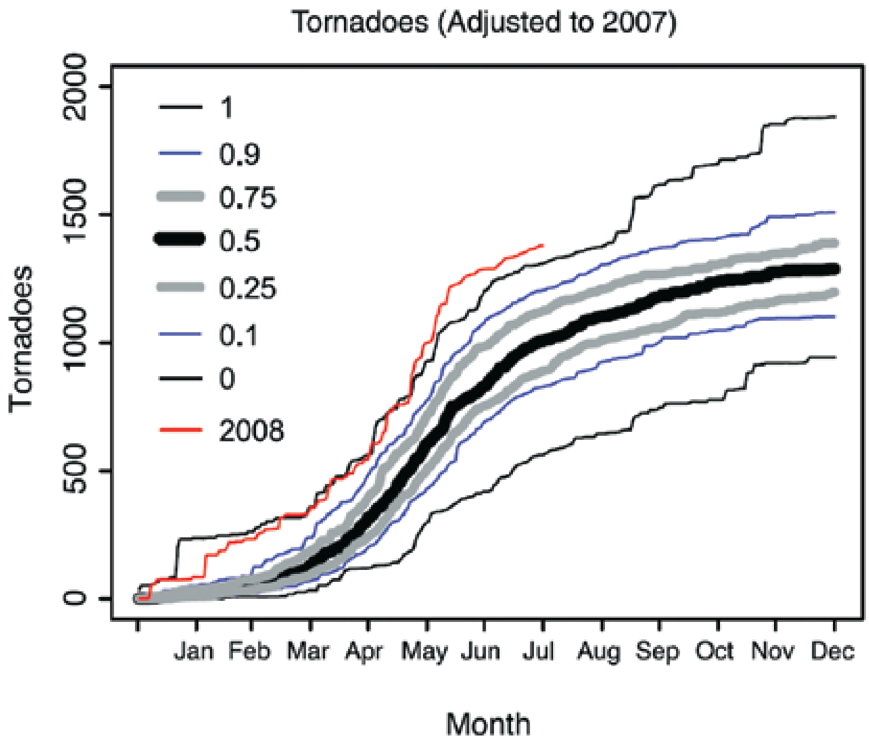


Figure 17

Average yearly patterns of tornado occurrence in the United States based on 1954–2007 data. The annual totals were fit with a linear regression in time and adjusted to 2007 values to account for changes in tornado monitoring and other factors through time. The progression of each year was then scaled to fit the adjusted annual total, and quantiles (the grey, blue, thin black, and thick black curves) were calculated for each day of the year from those adjusted series. 2008's tornado count (red) is shown for comparison.

Courtesy: American Geophysical Union.

It has often been speculated that climate change may drive more of the severe thunderstorms that spawn destructive tornadoes, but is this the case, and if so can a climate change signal already be recognised? This issue is examined by **N. S. Diffenbaugh**[66] of Purdue University, and colleagues, in a paper in *Eos*, who look at trends in US tornado activity in an attempt to unravel a climate change signal **(Figure 17)**. The authors note that the number of reported tornadoes in the US has been rising, on average, by about 14 a year over the past century, although this may well reflect an inconsistent reporting record rather than a true, progressive rise. Surprisingly, the numbers of the most damaging tornadoes (F2 – F5) have actually fallen over the past 50 years, although again this may be an artefact. The authors note that tornado activity may be affected by natural climate variations associated, for example, with ENSO or shifts in the jet stream. A climate change effect could also make itself felt, although this could go either way – resulting in more or fewer tornadoes. Looking ahead, Diffenbaugh and his co-authors note that higher greenhouse gas concentrations in the atmosphere are projected to increase the incidence of severe thunderstorms in the US, and therefore opportunities for tornado formation, but this is not a robust forecast. In conclusion, the jury remains out in relation to whether global warming will bring more tornadoes or suppress their formation.

Climate change, precipitation and flooding

One of the broadly accepted tenets of climate change is that it will result in more extreme precipitation events and increased flood risk and, indeed, this trend is already detectable in some parts of the world. The detail remains, however, to be determined, and the resolution of predictive models – although improving all the time – remains less than desirable. Here, the findings of three papers relating to future European precipitation and flood risk in a warmer world are presented. In the first, **J. Kysely**[74] and **R. Beranova**, of the Institute of Atmospheric Physics in Prague, examine the effects of climate change on extreme precipitation events in central Europe. Writing in *Theoretical & Applied Physics*, the authors note that although the hydrological cycle is predicted to intensify and becomes increasingly volatile, large uncertainties remain, in particular in relation to the seasonal and spatial variability of future precipitation changes. To address this, Kysely and Beranova evaluate scenarios of changes in extreme precipitation events in 24 future climate runs of 10 regional climate models, focusing on a part of the Czech Republic where local conditions make future projections difficult using global models. The authors conclude that heavy precipitation events are likely to increase in winter, with summers generally drier. Uncertainties are large, but the broad pattern matches recently observed trends, lending weight to the conclusions. Unsurprisingly, Kysely and Beranova conclude that their findings raise expectations of significantly elevated peak river discharges and increased flood risk.

Looking at the broader picture, **R. Dankers**[64] and **L. Feyen** of the Joint Research Centre at Ispra (Italy) use high-resolution climate simulations to examine the impact of climate change on flood hazard across the continent. In the *Journal of Geophysical Research*, the authors note that by 2100, under IPCC emissions scenario A2, extreme discharge levels in many European rivers may increase in both frequency and magnitude **(Figure 18)**. In some rivers in the west, and in parts of eastern Europe, for example, 100 year floods could occur every 50 years or less. In contrast, flood hazard appeared to be reduced in rivers in central and southern Europe, and in the north-east.

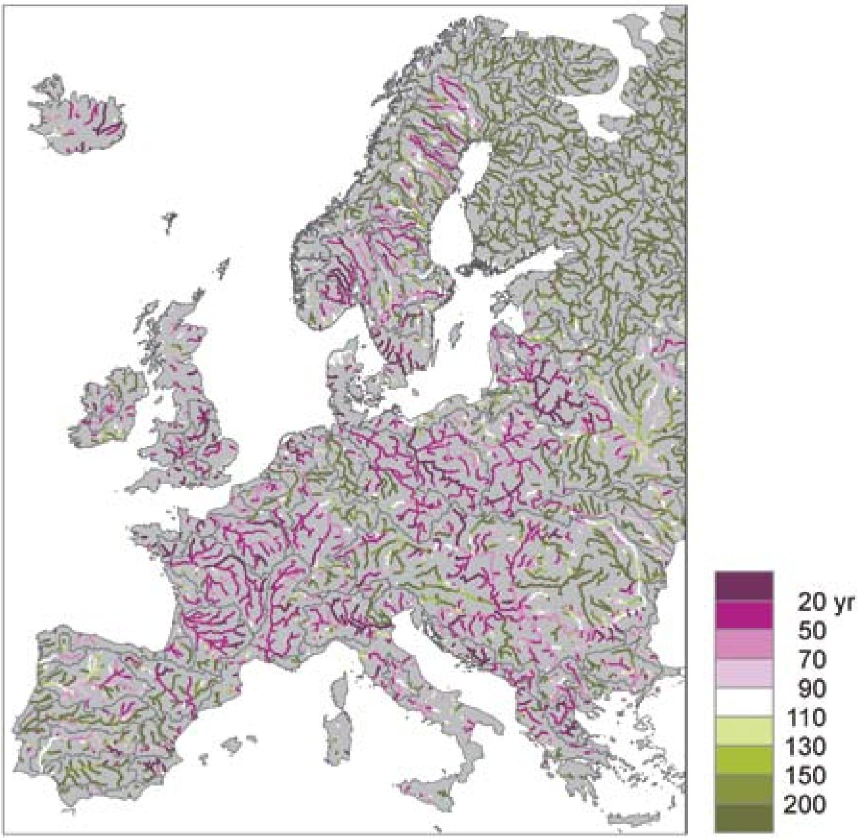


Figure 18

Change in recurrence of a 100-year flood in the control run of the H12A2 Intergovernmental Panel on Climate Change (IPCC) emissions scenario. In some rivers in the west, and in parts of eastern Europe, for example, 100 year floods could occur every 50 years or less. In contrast, flood hazard appeared to be reduced in rivers in central and southern Europe, and in the north-east.

Courtesy: American Geophysical Union.

Continuing the pan-European flood hazard theme, **J. L. Barredo**[62], also of the Joint Research Centre at Ispra, evaluates flood losses in Europe between 1970 and 2006. Writing in *Natural Hazards & Earth Systems Sciences*, Barredo presents an assessment of flood losses in 31 European nations, normalised to current societal conditions and taking account of a range of factors at country level, including population changes, wealth and inflation. Despite some perceptions to the contrary, the author concludes that no climate-change signal is detectable in flood loss trends, with an observed increase in flood losses over the period explainable purely by changes in societal factors.

Sources and further reading

61. Arpe, K. et al. 2009 Atlantic hurricanes – testing impacts of local SSTs, ENSO, stratospheric QBO – implications for global warming. *Quaternary International* **195**, 4 – 14.

62. Barredo, J. L. 2009 Normalised flood losses in Europe 1970 – 2006. *Natural Hazards & Earth Systems Sciences* **9**, 97 – 104.

63. Coughlin, K. et al. 2009 A relationship between all Atlantic hurricanes and those that make landfall in the USA. Q. *Journal of the Royal Meteorological Society* **135**, 371 – 379.

64. Dankers, R. & Feyen, L. 2008 Climate change impact on flood hazard in Europe: an assessment based on high-resolution climate simulations. *Journal of Geophysical Research* **113**. doi:10.1029/2007JD009719.

65. Della-Marta, P. M. & Pinto, J. G. 2009 Statistical uncertainty of the changes in winter storms over the North Atlantic and Europe in an ensemble of transient climate simulations. *Geophysical Research Letters* **36**. doi:10.1029/2009GL038557.

66. Diffenbaugh, N. S., Trapp, R. J. and Brooks, H. 2008 Does global warming influence tornado activity? *Eos* **89**, 553 – 554.

67. Elsner, J. B. 2008 Hurricanes and Climate Change. *Bulletin of the American Meteorological Society* **89**, 677--679.

68. Elsner, J. B.; Kossin, J. P. & Jagger, T. H. 2008 The increasing intensity of the strongest tropical cyclones. *Nature* **455**, 92--95.

69. Elsner, J. B. & Jagger, T. H. 2008 Hurricanes and Climate Change. Springer. Berlin. 380pp.

70. Gastineau, G. & Soden, B. J. 2009 Model projected changes of extreme wind events in response to global warming. *Geophysical Research Letters* **36**. doi:10.1029/2009GL037500.

71. Gillet, N. P. et al. 2008 Attribution of cyclogenesis region sea surface temperature change to anthropogenic influence. *Geophysical Research Letters* **35**. doi:10.1029/2008GL033670.

72. Gualdi, S. et al. 2008 Changes in tropical cyclone activity due to global warming: results from a high-resolution coupled general circulation model. *Journal of Climate* **21**, 5204 – 28.

73. Kossin, J. P. 2008 Is the North Atlantic hurricane season getting longer? *Geophysical Research Letters* **35**. doi:10.1029/2008GL036012.

74. Kysely, J. et al. 2009 Climate-change effects on extreme precipitation in central Europe: uncertainties of scenarios based on regional climate models. *Theoretical & Applied Climatology* **95**, 361 – 374.

75. Steenhof, P. A. 2008 The impact of tropical sea-surface temperatures on various measures of Atlantic tropical cyclone activity. *Theoretical and Applied Climatology* **92**, 249 – 255.

76. Ulbrich, U., Leckebusch, G. C. & Pinto, J. G. 2009 Extra-tropical cyclones in the present and future climate: a review. *Theoretical and Applied Climatology* **96**, 117–131.

77. Vecchi, G. A. et al. 2008. Climate Change: whither hurricane activity? *Science* **322**, 687 – 89.

Notes

AON BENFIELD UCL
Hazard
Research
Centre

Acknowledgements

The following are gratefully acknowledged for suggesting or highlighting papers considered worthy of mention in HRSR2009: Dr. Erik Ruettener (PartnerRe), Dr. Malcolm Haylock (PartnerRe), Dr. Michael Ewald (PartnerRe), Dr. Paul Della-Marta (PartnerRe), Dr. Richard Dixon (Aon Benfield), Adam Podlaha (Aon Benfield), Dr. Francisco Lorenzo (Aon Benfield).

Contact:
www.abuhrc.org
e: info@abuhrc.org
t: +44 (0)20 7679 3637
f: +44 (0)20 7679 2390

AON BENFIELD

PartnerRe