Tellus (2007), 59A, 499–510
Printed in Singapore. All rights reserved

TELLUS

Atlantic basin, U.S. and Caribbean landfall activity rates over the 2006–2010 period: an insurance industry perspective

By MANUEL LONFAT[1]*, AUGUSTE BOISSONNADE[2] and ROBERT MUIR-WOOD[3],
[1]*RMS Ltd., 30 Monument Street, London EC3R 8NB, UK;* [2]*RMS Inc., 7015 Gateway Blvd, Newark, CA, USA;*
[3]*RMS Ltd., 30 Monument Street, London EC3R 8NB, UK*

(Manuscript received 31 August 2006; in final form 26 February 2007)

ABSTRACT

Atlantic hurricane activity has been particularly high since 1995, with nine seasons recording more hurricanes than the long-term average. The recognition that current activity is not the same as the long-term historical average means that, for the purpose of catastrophe risk assessment, we need to be explicit as to the time period over which expected activity is evaluated. We have chosen to explore activities over a 5-yr forward looking time window, which bounds the range of business applications for which catastrophe loss models are employed. This time horizon is also shorter than the pattern of past multidecadal periods of high and low activity.

The methodology used to assess activity rates for the next 5 yr contains a blend of statistical analyses and an expert elicitation. A panel of experts was convened to discuss expected levels of activity for the next 5 yr across the Atlantic, along the U.S. and Caribbean coasts. The results indicate hurricane activities along the U.S. coast are expected to be between 20 and 35% higher than the long-term average, depending on storm intensity. The implementation of these findings has included work to determine how increases are distributed by track type and by region, and the impacts on expected losses.

1. Introduction

Hurricane activity in the Atlantic basin has shown a marked increase since 1995. Over those last 12 yr, the number of hurricanes has surpassed the long-term average in nine seasons. The 1997 and 2002 seasons were affected by warm conditions of the El Niño Southern Oscillation (ENSO). The relatively low activity of 2006 has also been linked to an El Niño episode by various agencies, such as the National Oceanic and Atmospheric Administration (NOAA). The heightened activity over the last decade has been particularly apparent in the number of major hurricanes (those with winds above 111 mph, classified as Category 3 or above intensity (Cat 3–5) on the Saffir–Simpson scale), with an annual average of 3.9 storms since 1995, compared to 2.7 in the period from 1950 to 2006. Smaller increases have been observed in the record of all hurricanes, yet annual averages are 8.2 and 6.1 over the same periods.

The latest increase in basin activity has previously been attributed to multidecadal cyclical variations in conditions that affect hurricane development (Goldenberg et al., 2001; Elsner et al., 2000), principally changes in sea-surface temperature (SST). In fact, fluctuations in the numbers of past hurricanes are evident over decadal time-scales. The period from 1970 to 1994, for example, experienced a trough in activity levels, while the 1950s and part of the 1960s showed raised levels of activity. Scientific views have however recently emerged that these SST increases are being affected by global climate change and therefore may not revert back to the long-term pre-1990s averages. Trenberth raised the question in 2005 (Trenberth, 2005) of the possible link between the increase in North Atlantic basin hurricane activity and global warming. Recent work on Atlantic and global distributions of tropical cyclones has also shown an increase in the power dissipation of hurricanes between 1970 and 2004 using data both from the historical storm tracks (Emanuel, 2005a) and from the National Center for Environmental Predictions (NCEP) reanalysis project (Sriver and Huber, 2006), as well as an increase in the number and duration of the most severe storms (Webster et al., 2005). Webster et al. (2005) document that the proportion of the most severe storms has increased over the past three decades; but the total number of all tropical cyclones worldwide has not changed significantly.

Causes of recent increases in activity are however still the focus of an intense debate, with several papers notably highlighting issues around the completeness and accuracy of the Atlantic and

*Corresponding author.
e-mail: Manuel.Lonfat@rms.com.
DOI: 10.1111/j.1600-0870.2007.00242.x

global tropical cyclone records (Landsea et al., 2004a; Emanuel, 2005b; Landsea, 2005; Kahamori et al., 2006; Klotzbach, 2006; Landsea et al., 2006; Velden et al., 2006), while other publications further discuss the reasons for the current levels of activity (Trenberth, 2005; Webster et al., 2005; Anthes et al., 2006; Chan, 2006; Curry et al., 2006; Elsner, 2006: Elsner et al., 2006; Hoyos et al., 2006; Pielke et al., 2006; Trenberth and Shea, 2006). A recent publication by Mann and Emanuel (2006) hypothesizes that the reduced Atlantic hurricane activity of the 1970s and 1980s can be linked to higher Eastern U.S. aerosol emissions during that period, rather than to a multidecadal oscillation in SSTs. It is however generally agreed within the research community that Atlantic basin tropical storm activity will likely remain elevated for the next 10 or more years, with possible large volatility from year to year.

In November 2006, the World Meteorological Organization (WMO) released a statement on tropical cyclones and climate change (WMO, 2006), which was the result of discussions among more than 100 forecasters and scientists, meeting at the WMO-sponsored International Workshop on Tropical Cyclones (IWTC-VI), held in Costa Rica. The consensus opinion was that no definitive position can yet be taken on how climate change impacts tropical cyclones. No single tropical cyclone can be directly linked to global warming although global warming may impact the distribution of all cyclones. The statement acknowledges that in a warming climate, it is likely that peak wind speeds and rainfall will show some increase. The document also notes that 'it is well established (for the North Atlantic) that SST is one of the factors impacting on the number and severity of cyclones. No such in-situ relationship has been established for the other cyclone basins'.

For the assessment of catastrophe loss, it is important to understand possible changes in the frequency and intensity distributions of U.S. landfalling storms, including the distribution of the number of storms, their intensities and the regionalization of their tracks. Between 1995 and 2003, heightened activity of the most intense 'major' Cat 3–5 hurricanes in the basin did not convert into higher activity of intense storms at landfall, but during 2004 and 2005 the high basin activity has transposed into elevated U.S. impacts. The large increase in the number of U.S. landfalls particularly impacted Florida and the coastal communities of the Gulf of Mexico.

Looking back, the U.S. coastline has experienced past periods of heightened and reduced activity, similar to those described for the basin. Reduced activity was observed from 1970 to 1994, with an annual average of 1.2 landfalling hurricanes, of which 0.5 were major Cat 3–5 storms. From the 1930s to the 1960s, those numbers were 1.8 and 0.8, respectively, and they increased to 2.2 and about 0.85 over the last 12 yr, including the high Cat 3–5 activity experienced in 2004 and 2005.

The traditional approach for modelling the expected activity rate of hurricanes for risk assessment has been to employ the average over the period extending from the present to as far back as the data is considered complete (this period extends generally back to at least 1900 for U.S. landfalling hurricanes). The risk is then modelled stochastically by simulating hurricanes across the basin and at any location along the U.S. coastline, conditioned by the historical baseline activity. The assumption of using the average of the historical record to represent the risk over the next few years holds as long as there are neither trends in activity nor evidence that we are currently in an extended period of heightened or reduced activity. The record shows however that there have been prolonged periods of rates significantly different from the long-term average and a clear demonstration that we are now within one of these elevated periods. Faced with the evidence that the long-term average is no longer appropriate for assessing risk over the next few years, we need to explore alternative ways to assess hurricane activity. Changes in activity over multi-year periods and their consequences for risk assessment were highlighted by Pielke and Landsea (1999). In other areas of hazard analysis, where there is evidence for time varying behaviour, it is commonplace to employ methods that do not use long-term averaging. For example, on many major faults earthquake probabilities are estimated conditional on the last time a significant earthquake occurred.

Before describing the approach employed here, it is useful to apply some definitions. We define 'short-term' as the prediction of activity for the coming hurricane season, and 'medium-term' as the average risk perspective across several hurricane seasons in the future. Both short- and medium-term perspectives are dynamic by nature and need to be re-assessed on an annual basis. The medium-term perspective is more specifically defined here as a window covering the next 5 yr. There are both scientific and business reasons for choosing the 5-yr horizon. The variance of predictions over 5 yr is smaller than that of seasonal forecasts, in part because of the way that the variations accompanying the state of the El Niño are implicitly accounted for, as 5 yr nears the average period of one ENSO cycle. Predictions at longer timescales, such as 10 or 20 yr are also found to be less skillful, given the observed multidecadal variability. Five yr also bound most business applications within the insurance industry, whether it is planning for capital allocation or for transferring financial risk through Catastrophe Bonds, for example.

For many business applications, the perspective provided by short-term seasonal risk is too volatile, changing month by month as the season approaches even while most contracts are only written annually. Several groups provide seasonal predictions of Atlantic activity either with statistical (Landsea et al., 1998; Jagger et al., 2002; Klotzbach and Gray, 2003, 2004; Blake and Gray, 2004; Elsner and Jagger, 2004; Klotzbach and Gray, 2004; Saunders and Lea, 2005) or dynamical methods (Thorncroft and Pytharoulis, 2001; Vitart and Stockdale, 2001). Those forecasts generally show significant skill at the beginning of the season and with a few months lead (Owens and Landsea, 2003). However the remaining volatility even at short lead times, and issues such as the low skill in forecasting ENSO before the March–April spring barrier (Lloyd-Hughes et al., 2004) make it difficult to use seasonal forecast outputs across much of the business planning and contract negotiation of the insurance industry that takes place during the winter prior to the hurricane season. It would also be very difficult, for example, for insurance regulators to deal with hurricane insurance rate filing based on seasonal forecasts that could vary from year to year by more than 100%. For example, some seasonal forecasts for 2006 predicted more than two Cat 3–5 to make a U.S. landfall, or nearly 300% above the long-term baseline.

To our knowledge, the only methods reported in a peer-review journal for predicting U.S. hurricane activities at longer time-scales are those in Elsner et al. (1998) and Elsner and Bossak (2001). In Elsner and Bossak (2001), the authors document a Bayesian analysis technique to predict activity over decadal time-scales. Results provided in their paper illustrate that statistical methods derived only from climatological information can lead to serious underestimation or overestimation if breaks or trends in the data are not properly identified. For example, a 5-yr forecast issued in 2000 indicated a probability of less than 3% of observing 15 or more landfalls in the U.S. over a 5-yr period, and less than a 1% chance of observing eight or more Cat 3–5 storms thru 2005. These results show that much work is needed in forecasting at these time-scales. Given the potential for different interpretations of the available data by the members of the scientific community, a carefully prepared elicitation of experts in the field can produce valuable data.

In view of the recent evidence for high activity observed both in the Atlantic basin and along the U.S., in October 2005 RMS convened a panel of experts and asked them to develop an understanding of expected hurricane activities over the medium term 5-year (2006–2010) period. The next sections provide an overview of catastrophe loss models, describe the data that was used in this analysis and the process of expert elicitation, that is, how expert opinions were elicited. Findings from the elicitation for the expected U.S. levels of activity were used for setting activity rates in the RMS U.S. hurricane model in the May 2006 model update. Lessons learned were applied to a second expert elicitation in October 2006 for use in assessing the medium term 5 yr (2007–2011).

2. Structure of catastrophe loss models

Catastrophe loss models are used by the insurance and financial services community to price and manage catastrophic risks. These models comprise four modules:

1. A stochastic module that includes a comprehensive population of events in a region (such as the tracks and intensities of hurricanes) along with their respective probabilities.
2. A hazard module that defines the strength of the hazard agent – such as windspeed – at each location in the path of each stochastic event.
3. A vulnerability module that links the level of damage and loss of buildings and their contents to the hazard parameter, using damage curves.
4. The financial module that calculates how the losses become affected by the financial structure of insurance and reinsurance contracts.

This paper addresses the parametrizationAuthor: Please check the suggested running head for correctness. of a core component of the first stochastic module of a hurricane catastrophe model, that is, the assessment of the frequency of occurrence and intensity distribution. A detailed review of the application of catastrophe models can be found in Grossi et al. (2005).

Catastrophe models are used by insurers and reinsurers to estimate the price for risk of single properties and portfolios of multiple policies. The model will however be just one component in the pricing decisions taken by insurers and reinsurers. Competition within the market can play an important role on rate setting. In the case of U.S. hurricanes, state insurance regulators may also constrain what prices can be charged. The market also has access to various model providers, and many participants do integrate the risk perspectives from various sources in their decision making process. In the current period of higher hurricane activity and losses, modellers have been increasingly asked to make their parametrization processes more transparent. One of the goals of this manuscript is to describe the process for assessing frequency and intensity of hurricanes in the Atlantic basin and in the U.S., when approaches calibrated against long-term historical data are not solely used.

3. Data sets

We use the HURDAT historical catalogue to study the distribution of hurricanes within the basin and the U.S. catalogue of landfalling storms for landfall frequencies. Both data sets are available at NHC (http://www.nhc.noaa.gov). For the purpose of this analysis, the data is partitioned into category 1–2 (Cat 1–2) storms, defined on the Saffir–Simpson scale as those with maximum 1-min sustained wind speeds between 74 and 110 mph, and ‘severe’ category 3–5 storms (Cat 3–5) - those with maximum winds equal or above 111 mph. It is the severe storms that contribute the large majority of damage and insurance losses. Fig. 1 shows time series of Atlantic and U.S. Cat 3–5 activity since 1900. The red curves are 5-yr centred moving averages.

The HURDAT data set has traditionally been used to assess the risk associated with hurricanes in the U.S. and the Caribbean. The historical record is likely incomplete however, particularly in the earlier periods of the record. For the period prior to 1950, the number of storms, their duration and intensity may not be fully known across the whole Atlantic basin. In the U.S., while it is inconceivable that a hurricane could have been completely missed, along the low population density coastlines of the Gulf of Mexico or Florida it is possible that the maximum intensity of a storm could have been underestimated, in particular prior to

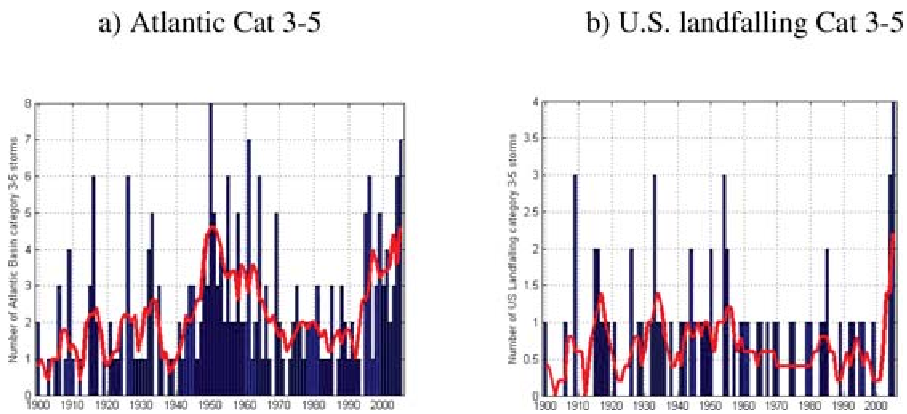

Fig. 1. Atlantic and U.S. activity of Cat 3–5 from 1900 to present. The blue bars represent the number of counts and the red line is a 5-yr running mean across the time series.

1900. Over the last year, issues related to the completeness and accuracy of the historical data sets have been an important component of the debates concerning the impact of global warming on hurricanes (Pielke et al., 2005, 2006). Landsea et al. (2004a) have undertaken a reanalysis of the entire HURDAT database, leading to a number of revisions in recent years (see, for example, Dunion et al., 2003; Chenoweth and Landsea, 2004; Landsea et al., 2004b). This analysis is not yet completed, but cannot be expected to supplement missing data when no observations exist.

Questions can therefore be asked about the validity of methods that give equal weight to the whole historical data set for risk assessment, both because of the evidence for shifts in activity through time and also because of reliability and completeness questions associated with older parts of the data set. As discussed in the introduction, there are alternative scientific theories regarding the cause of the current heightened Atlantic activity, which themselves assign different weights to which periods of the historical record are considered germane to predicting current activities.

4. The elicitation of expert opinions

In this context of uncertainty, both in the quality of the data and in the physical drivers of activity, one approach to supplement the information contained in the historical record is to use a formal process of expert elicitation. This method is standard practice in social sciences and risk assessment in engineering fields when analysing earthquake and other geological hazards, for example, but is rare in applied meteorology. There is a large body of literature on expert elicitation: as, for example, ‘Use of Technical Expert Panels: Applications to Probabilistic Seismic Hazard Analysis, by Budnitz et al. (1998), or the NUREG/CR 6372 report, “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts.” by Budnitz et al. (1997). More recently, Coppersmith et al. (2005) presented the results of a formal expert elicitation for assessing the likelihood of a catastrophic volcanic explosion.

The elicitation process involves the gathering of experts at a special workshop, where relevant scientific issues can be presented, and differences in individual interpretations of the data are examined and explored. The scope of the workshop is to characterize the distribution of interpretations from a representative, theoretically exhaustive, set of the scientific community. The goal is to develop a probability distribution of interpretations that represent the opinion of the community regarding the validity of each interpretation and how well it represents all the available data. It could be said that the goal of an expert elicitation is to develop a group consensus on the distribution of alternative interpretations but definitively not to reach a consensus on models or a model. The results of the elicitation can be expressed in terms of preferences for specific modelling methodologies, or as a set of weights assigned to various alternative procedures. Weights can be derived using various techniques, the most powerful ones involving the use of probabilistic approaches, such as a Bayesian framework (e.g. Clemen and Winkler, 1999).

The workshop is chaired by an independent facilitator (one or a team of individuals) who structures the discussions and helps the experts to focus on the core issues. The facilitator must remain neutral during the discussions, so the evaluations are those of the group of experts only. Before the meeting, the facilitator arranges for the distribution of informational material to the experts, who are encouraged to bring and present any additional materials they deem relevant to the questions being addressed. After the meeting, the facilitator prepares a report and circulates it to the experts for comment and approval. The final report is the workshop’s output deliverable. An important component of the expert elicitation is to ensure that the information provided by each expert is self-consistent with the interpretation of the data and that the assumptions made by each expert are understood by all experts participating in the elicitation.

For these reasons, a set of questions are defined and proposed to the experts. For each question, experts agree on the exact meaning of that question and what data sets are relevant to be used for providing answers. If models are used in providing information, they should be clearly defined and agreed upon among the experts. More details on the principles of elicitation and methodologies that have been developed to analyse the findings of an elicitation can be found in Ayyub (2000) and Cook (1991), for example.

The first such workshop to develop a 5-yr perspective on hurricane activity rates was conducted mid-October 2005. The following scientists were present at the meeting, covering a range of expertise in the field of tropical cyclones: Professor Jim Elsner (Florida State University, expert in modelling hurricane climatology and activity), Professor Kerry Emanuel (Massachusetts Institute of Technology, expertise across various fields of hurricane research, including climatology), Tom Knutson (NOAA Geophysical Fluid Dynamics Laboratory, expert in hurricane climate modelling) and Professor Mark Saunders (University College London, expert in seasonal forecasting). They were asked to discuss several questions pertinent to the use of hurricane climatology in a risk assessment context and to address specifically the following questions:

(1) What is the expected basin activity of Cat 1–5 and Cat 3–5 over the next 5 yr?
(2) What is the expected U.S. landfall activity of Cat 1–5 and Cat 3–5 over the next 5 yr?
(3) What can we expect for the activity of Cat 1–5 and Cat 3–5 in the Caribbean over the next 5 yr?
(4) How much longer can we expect the recent activity levels to persist?

Experts were provided with the HURDAT data (for reference) and basic statistics of activities derived from the hurricane time series, prior to the meeting. Experts also brought their own analyses, for dissemination and discussion. The statistics that were provided by RMS included means and standard deviations of annual activities over various time periods, as well as some background information on the definition of activity rates within the RMS U.S. Hurricane and Caribbean models, including how hurricanes are divided into types according to their origin, and that the model considers the whole track of the storm not just where it makes landfall. However, no information was provided relating to how decisions around activity rates become converted into financial outputs. The information was summarized in a short presentation delivered at the beginning of the elicitation meeting. An RMS analyst was also present, to provide technical support to the experts with any statistics and analyses of the historical data that they requested. The analyst's function was only to provide results upon request, rather than have any participation in the discussions. RMS also provided a mediator and, with the agreement of the experts, the proceedings of the meeting were recorded. The role of the mediator was solely to introduce the questions to the experts and to clarify the questions in response to requests from the experts.

5. Results from the elicitation workshop

Experts were first asked to consider the activity of Cat 1–5 and Cat 3–5 hurricanes within the whole Atlantic for the next 5 yr. All experts agreed that the activity is currently above the long-term average, and that the elevated levels of activity are expected to continue for a time period of at least 10–15 yr, so for a period significantly longer than the 5-yr medium term perspective. At the same time, it was recognized that not all individual years in the next decade are expected to be more active than average, as the seasonal activity depends on various climatological factors, such as the state of ENSO.

When quantifying the level of basin activity over the next 5 yr, experts converged on the best representation being that given by a mixed baseline approach, assigning a 90% weight to the activity of the period since 1995 and a 10% weight to the 'long-term baseline'. It was agreed that to assess the activity over the entire Atlantic basin, it is best to restrict the long-term baseline to the period starting in 1950 since when the offshore data is more likely to be comprehensive and reliable. Annual mean activity rates of Cat 1–5 and Cat 3–5 hurricanes from 1995 to 2005 and for the whole 1950 to 2005 period are shown in Table 1. The 90%:10% mix of baselines approach yields 8.2 Cat 1–5 per year, 3.9 of those storms expected to attain Cat 3–5.

The experts also agreed that this approach would be appropriate for considering medium term activity in the Caribbean (CB) region, as the islands are mostly affected by storms forming deep in the tropics (from easterly waves) and those storms of equatorial Atlantic origin comprise most of the incremental storms in periods of heightened activity. In order to calibrate activities, the CB region was defined from all those storms crossing a series of boxes surrounding the islands, as shown in Fig. 2. Table 2 shows the 1950–2005 and the 1995–2005 mean annual CB activity rates, as well as the 2006–2010 expected activity of Cat 1–5 and Cat 3–5 based on the 90%:10% rule.

The experts were then asked to discuss methodologies for assessing medium term activity rates at U.S. landfall. Two independent methods were employed. First, experts assigned probabilities of exceedance to various key activity rate measures for Cat 1–5 and Cat 3–5 hurricanes at landfall, including the average activity between 1900 and 2005, and the mean over the 1995–2005 period. Those averages are shown in Table 3. For the purpose of assessing these probabilities, the assumption was made that the annual number of storms impacting the U.S. follows a

Table 1. Mean annual Atlantic activity of Cat 1–5 and Cat 3–5 over the 1950–2005 and the 1995–2005 periods

Averaging period	Cat 1–5	Cat 3–5
1950–2005	6.2	2.7
1995–2005	8.5	4.1
90% (1995–2005) + 10% (1950–2005)	8.2	3.9

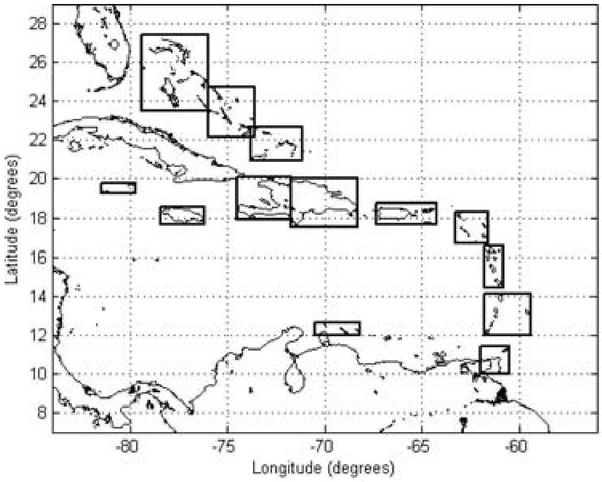

Fig. 2. Boxes used to derive the Caribbean activity.

Table 2. Mean annual of Cat 1–5 and Cat 3–5 across the Caribbean islands over the 1950–2005 and the 1995–2005 periods

Averaging period	Cat 1–5	Cat 3–5
1950–2005	1.0	0.5
1995–2005	1.8	0.9
90% (1995–2005) + 10% (1950–2005)	1.7	0.9

Table 3. Mean annual of Cat 1–5 and Cat 3–5 at U.S. landfall over the 1900–2005 and the 1995–2005 periods

Averaging period	Cat 1–5	Cat 3–5
1900–2005	1.7	0.7
1995–2005	2.4	0.9

Poisson distribution. (Sensitivity tests were later performed to test this assumption against the actual variance/mean ratios of the historical record of annual activities.) The approach yielded several 'expected landfalling activity rates' for each expert, for both the activity of Cat 1–5 and Cat 3–5 storms. The rates were combined using several alternative averaging techniques, from a simple linear average of all expert estimates to a weighted approach, in which the weights were inversely proportional to the spread in opinions of each expert. The average rates of U.S. landfalling storms were near 2.1 for all Cat 1–5 storms, and 0.9 for Cat 3–5. The spread in individual expert assessment was around 10% for Cat 1–5, and less than 5% for Cat 3–5. Results generated with the different averaging schemes yielded estimates within a few percentage points of one another, and therefore the choice of averaging scheme did not have a significant impact on the final results. Those rates correspond to a 35% increase in the activity of the most severe storms. Subtracting the rate of Cat 3–5 from the total population of Cat 1–5 storms, we obtain a 20% increase in the activity of the weaker Cat 1–2 hurricanes, compared to the long-term baseline.

The second methodology involved comparing activity in the basin to the activity observed at landfall for the most critical Cat 3–5 hurricanes. Figure 3 shows the basin to U.S. landfall 'conversion rate' of Cat 3–5 storms, namely the proportion of basin Cat 3–5 hurricanes that reach the U.S. coastline as Cat 3–5 intensities. This measure is computed across the data since 1950, as a 5-yr running mean of the ratio of U.S. to basin Cat 3–5 hurricanes. The mean conversion rate since 1950 is about 27%. The variance around this mean is large, particularly in the last 25 yr of the record. One striking feature, however, is the anomalously low conversion of Atlantic Cat 3–5 between 1995 and 2003, when only about 10% of Cat 3–5 reached the U.S. coast. Over the last 2 yr, the conversion rate has increased again, and has been significantly larger than the long-term average. Over a period of decades, we do expect the conversion to converge towards the long-term mean, therefore to be between 20 and 30%. Using the result from the '90%:10%' (1995–2005 : historical) mix of baselines approach for determining the expected annual number of Atlantic Cat 3–5 storms gives 3.9 per year (Table 1), and allied with the 27% conversion rate, yields about 1 Cat 3–5 at landfall per season. This estimate is close to that generated with the first approach and provides confirmation that estimates from the first method are appropriate.

6. Additional research

Before proceeding with employing the results from the elicitation into the RMS U.S. & Caribbean Hurricane catastrophe loss models, a number of additional issues were explored by asking the following questions:

(1) How do the U.S. targets provided by the elicitation compare with the observed distribution of U.S. hurricane activity rates?

(2) Is there a statistical correlation between the whole Atlantic activity and the number of hurricanes expected to make landfall in the U.S.?

(3) Can we derive further information regarding the regionalization of activity within the U.S.?

6.1. Comparison of elicitation and U.S. historical rates

To evaluate how the U.S. targets derived from the elicitation compare to the historical catalogue, we construct the distribution of 5-yr running means from the 1900 to 2005 historical U.S. landfall database, for both Cat 1–2 and Cat 3–5 storms. Figure 4 shows the probability density function of 5-yr running means for the Cat 3–5 storms, plotted relative to the long-term mean. The 35% increase in activity lies well within the historical distribution, with about 20% of all 5-yr means computed from

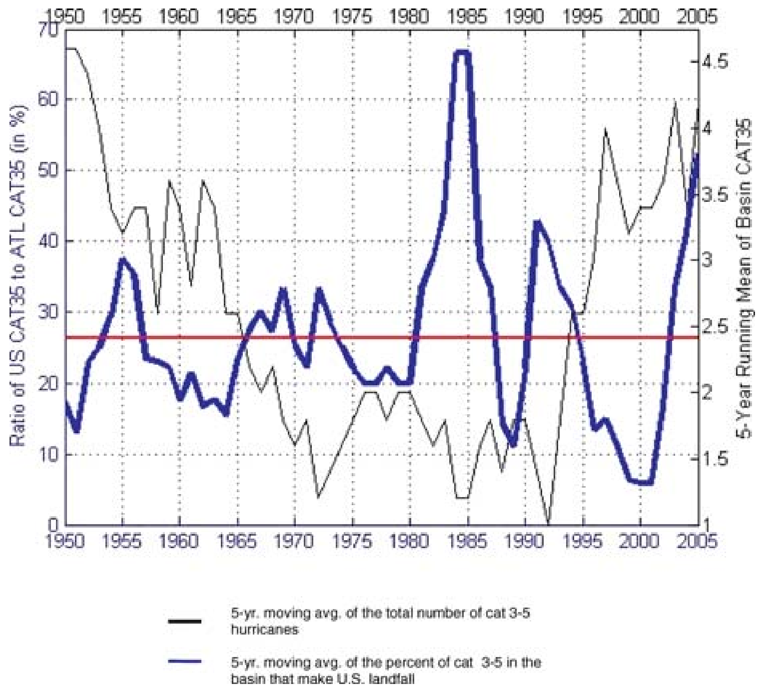

Fig. 3. Five-year running average of Cat 3–5 Atlantic hurricanes (black line) and the ratio of hurricanes making U.S. landfall as a Cat 3–5 (blue line) since 1950. The red line marks the average ratio of Atlantic basin to U.S. landfall Cat 3–5 across this period.

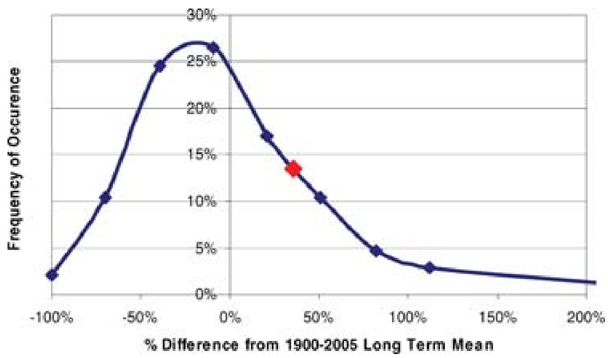

Fig. 4. Normalized distribution of 5-yr running means of (a) Cat 1–5 and (b) Cat 3–5 for the U.S. landfalling activity. The red dot on each distribution marks the location on the distribution of the expected all-U.S. activity, used as target for the implementation in our 2005 model update.

the last 106 yr record being larger than this value. Similar results were found for the activity of Cat 1–2 storms.

We further conducted a bootstrap analysis of 5-yr means generated from the historical record, for both U.S. Cat 1–5 and Cat 3–5 hurricanes. A bootstrap simulation consists of a set of new time series derived from the original record by randomly permuting its elements. In our case, we use data from 1900 to 2005 to first derive 1 million permutations of its elements as a bootstrap data set. For each permutation, we compute the average of the 5-yr mean distribution. This data set shows a mean value of 1.67 (0.63) for Cat 1–5 (Cat 3–5), near the actual means of the 1900–2005 period of 1.70 (0.66). We then generate a second simulation using data at U.S. landfall from years ranked in the Atlantic basin as active under the multidecadal oscillation (AMO) theory, that is, years from 1926 to 1969, with the addition of 1995–2005. The average values rise significantly, to 2.1 (0.83) for Cat 1–5 (Cat 3–5) storms. Targets obtained from the elicitation process are within a third of a standard deviation of the expected values from the bootstrap analysis.

Since this analysis, the Atlantic basin experienced the below average 2006 season. Particularly, the activity shut down early in the season (in September) and after early threats to the U.S. in the form of two tropical storm landfalls, the remaining storms tracked well to the East of the U.S. and Caribbean regions. These patterns are generally consistent with those observed during seasons affected by El Niño. In September 2006, NOAA released a statement announcing the onset of a weak El Niño event, which has since then been acknowledged by various agencies, such as the World Meteorological Organization (WMO). It is important to note that the analysis presented here is a perspective of risk over a 5-yr period. The occurrence of an El Niño episode in 2006 was within the bounds of our perspective, as at the time of this analysis, experts were considering the possibility of an El Niño event to occur within the 5-yr period of interest (2006–2011).

6.2. *Correlation between Atlantic and U.S. activity*

The correlation between Atlantic basin and U.S. activity over individual seasons is relatively weak, as tracks of individual storms are affected by specific climatological conditions that may vary from one season to another. However, it might be reasonable to expect changes in average activities detected along the U.S.

coast, to coincide with changes in the basin activity as a whole when averaged over a few years. To investigate this hypothesis, the average number of Cat 1–5 and Cat 3–5 U.S. landfall conditional of at least 7 Cat 1–5 storms in the basin is computed. Seven Cat 1–5 storms is just over the long-term average (defined as 1950 to present) annual number of hurricanes developing within the Atlantic basin. When at least seven hurricanes were observed in the basin between 1900 and 2005, nearly 2.2 (1.1) Cat 1–5 (Cat 3–5), respectively, made a U.S. landfall. Those numbers decreased to 1.2 and 0.5 for years with six or less hurricanes developing within the basin. Nine of the last 12 yr on record had more than seven hurricanes within the basin, and in about 80% of those years, at least two storms made a U.S. landfall. Compared to previous periods, an anomalous number of those were Cat 1–2, partially as a result of rapid weakening of some storms approaching the U.S. coastline, such as Floyd in 1999, for example. Two El Niño years since 1995 (1997 and 2002) displayed low basin activity (e.g. three and four storms) and only one U.S. landfall each. In 2006, five hurricanes developed and no U.S. landfall occurred.

6.3. *Regionalization of activity*

The activity that was concentrated in Florida and the Gulf of Mexico during 2004 and 2005 raises the issue of the regionalization of activity. Florida specifically, which since 1900 experienced nearly 40% of all U.S. landfalls, has gone through periods of heightened and reduced activity. Figure 5 shows a time series of Cat 1–5 storms that have affected Florida since 1900. The average annual activity rate in Florida over the last 106 yr is 0.65, but it has averaged 1.09 since 1995, while it was 0.24 for the period extending from 1970 to 1994. In all the decades prior to 1970, back to 1930 rates were above the long-term mean, except for the 1960s, when many of the U.S. landfalling storms affected the East coast, North of Florida.

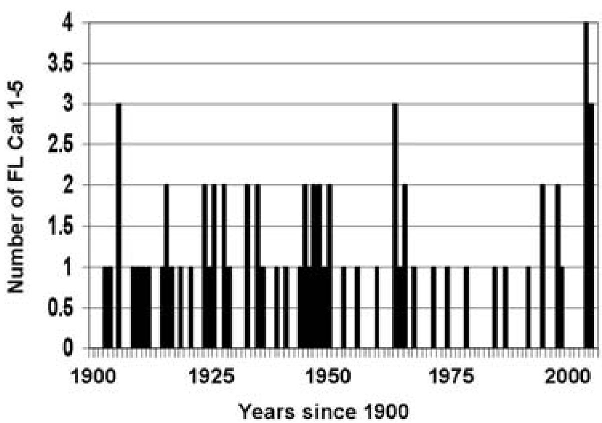

Fig. 5. Annual number of Cat 1–5 hurricanes affecting Florida since 1900.

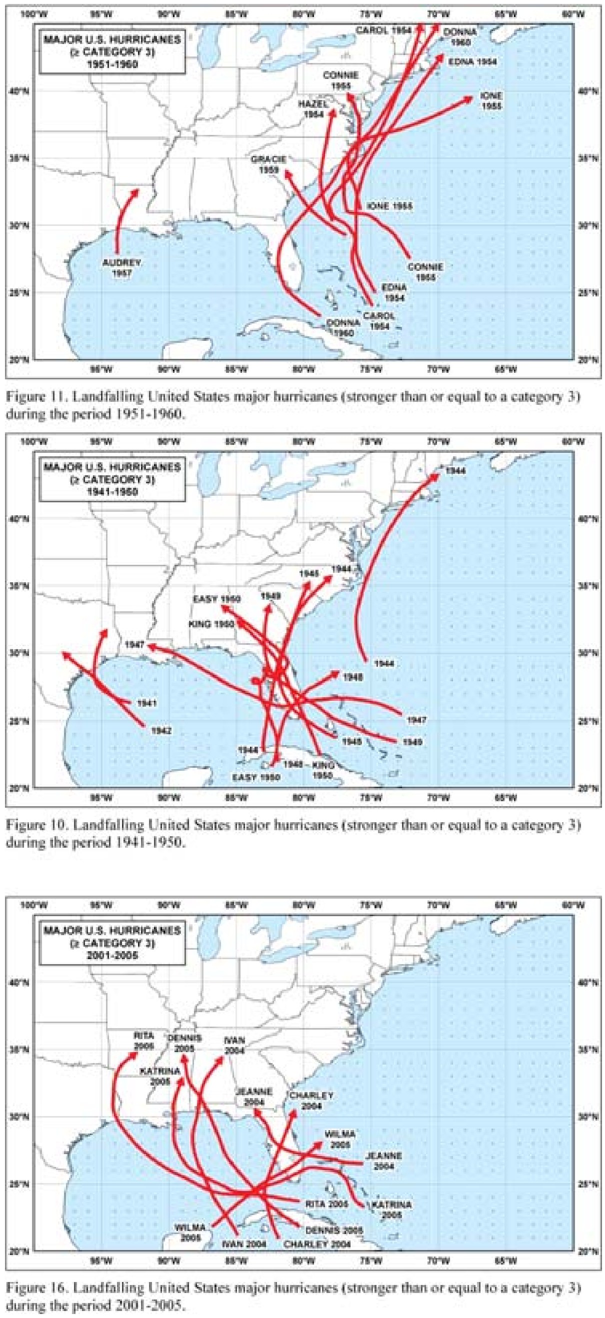

Fig. 6. Track of Cat 3–5 landfalling storms in the 1940s, 1950s and the period from 2000 to 2005 (plots from http://www.nhc.noaa.gov/Deadliest_Costliest.shtml)

Shifts in activity between regions of the U.S. coastline over decadal time-scales are documented in NHC's report on the 'deadliest, costliest, and most intense U.S. tropical storms' (http://www.nhc.noaa.gov/Deadliest_Costliest.shtml). Figure 6 shows activity during the 1940s, 1950s and in the last 5 yr. During the 1940s, most severe storms (defined as Cat 3–5 in the report) hit states along the Gulf of Mexico and Florida, while during the 1950s many severe storms affected the Carolinas and regions further to the Northeast. During the last 5 yr, and particularly the last 2 yr, storms have mostly impacted Florida and the Gulf of Mexico. There is as yet no simple climatological explanation for this decadal migration in activity of the most severe hurricanes. A relationship between the distribution of hurricane tracks and the phase of the North Atlantic Oscillation (NAO) has been documented (Elsner, 2003). However, the NAO index does not show consistency in sign over such time periods.

Despite the patterns qualitatively described above, regionalization cannot easily be demonstrated from the U.S. landfall storm population, because of the small amount of data available, in particular, in the Northeast U.S. where a direct landfalling hurricane is observed about once a decade and none has occurred since Hurricane Bob in 1991. Yet, the region is also vulnerable to grazing storms and storms making a secondary landfall after having impacted the Southern states. Hence, we have investigated regionalization in activity by studying the populations of Cat 1–2 and Cat 3–5 hurricanes in larger offshore areas including the Gulf of Mexico and a region encompassing the coast of the U.S. mid-Atlantic and Northeast. Those regions are depicted in Fig. 7.

Figure 8 shows the 5-yr running-mean time series of Cat 1–2 and Cat 3–5 storms within each of these two regions. The activity of Cat 1–2 in both regions is positively correlated. During years of heightened activity, the number of Cat 1–2 storms increases everywhere near the U.S. coastlines. The activity of the Cat 3–5 hurricanes does not follow the same pattern and instead Gulf and Northeast regions show a negative correlation. Elevated Gulf activity tends to be accompanied by weaker activity in the Northeast.

Over the period since 1950, the activity near the U.S. has switched back and forth between those regions. Figure 9 shows the contribution of Cat 3–5 storm activity in the Gulf of Mexico region to that summed across both the Gulf of Mexico and Northeast regions (defined in Fig. 7). Periods of heightened activity in one or the other region have shown evidence for autocorrelation persisting for up to a decade. This behaviour seems to be only partially linked to changes in SSTs, as SSTs in the main development region (MDR) and the Gulf of Mexico have shown continuous increases over the last 30 yr. In contrast to the early

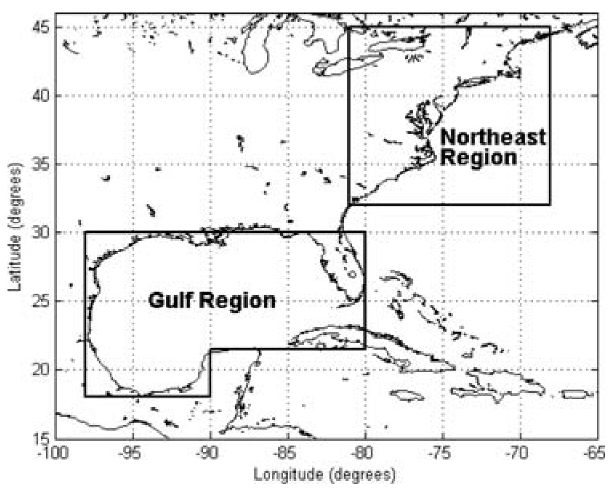

Fig. 7. Regions used in the study of regionalization in U.S. activity.

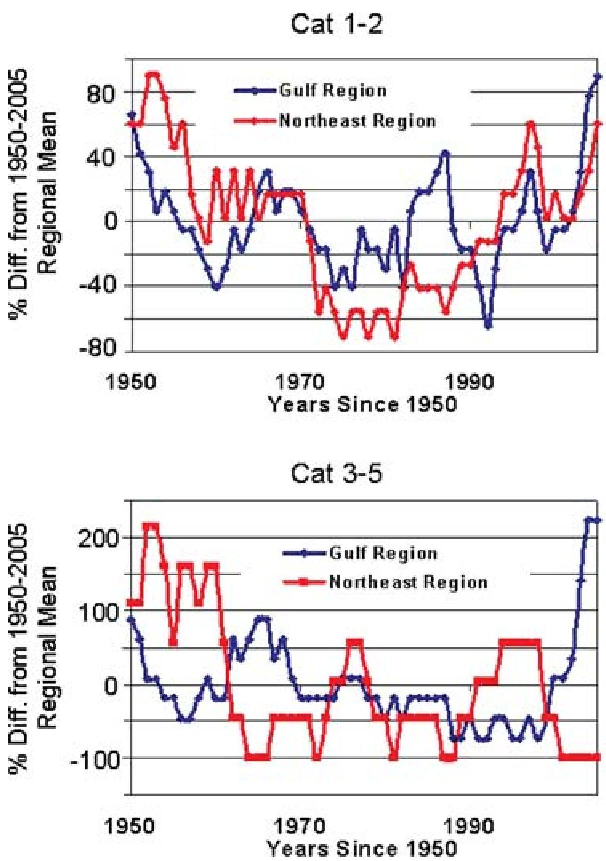

Fig. 8. Time series of 5-yr running means of the activity with the regions shown in the previous figure: (a) Cat 1–2 and (b) Cat 3–5.

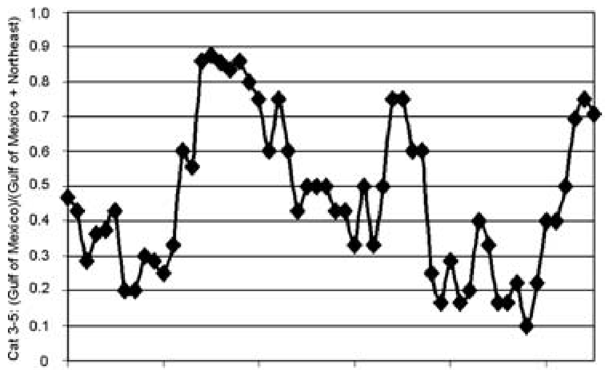

Fig. 9. Ratio of 5-yr centred running means of Gulf of Mexico Cat 3–5 to Gulf of Mexico + Northeast Cat 3–5. Regions are defined in Fig. 7.

1950s when high activity in the basin corresponded with a period when intense storms tracked towards the Northeast, since 2000 Cat 3–5 hurricanes have almost exclusively occurred in the Gulf of Mexico and Florida. Hence this regionalization does not simply correspond with the phases of the AMO: and it would not be appropriate to employ the landfall regionalization of the 1950s to represent expected activities over the medium term.

7. Lessons learned from the elicitation of expert opinions

The 2005 elicitation workshop offered several lessons. The elicitation was organized as the first step in a new approach to hurricane activity rate assessment in the Atlantic basin and the U.S. region. It was found that leading scientists within the community were willing to share their expertise, and therefore very constructive evaluations of alternative interpretations were offered during the meeting and in the period that followed. However, within the time limitations of the meeting it was only possible to make an assessment of overall basin and U.S. activity, while questions of regionalization of activity were left for the research phase.

Using those lessons, the methodology presented in this manuscript was revisited. A second elicitation of experts was organized toward the end of the 2006 hurricane season to provide an update to the medium term perspective on activity rates, covering the period 2007–2011. In this update several aspects were improved. First, a larger panel of experts was convened, now composed of seven experts, including again Kerry Emanuel, Thomas Knutson and Mark Saunders, but also Suzana Camargo (from the International Research Institute of Columbia University), John Knaff (from the NOAA/Colorado State University Cooperative Institute for Research in the Atmosphere-CIRA), James Kossin (University of Wisconsin) and Frédéric Vitart (ECMWF). The panel was extended in such a way to include additional expertise on seasonal forecasting, ENSO predictability and its impact on hurricane activity, the use of numerical models to assess annual variability in hurricane counts, and also expertise in data quality control.

A number of statistical models were also developed at RMS after the first elicitation to evaluate the U.S. activity over a 5-yr period, and the variability around this prediction. Some of those models studied relationships between Atlantic SST and hurricane activity in the basin. We also developed models based solely on historical time series, and researched in depth the statistics of the conversion of activity in the basin into U.S. landfalls. The methodologies underlying each of these models, as well as their outputs, were all presented at the second elicitation.

The meeting lasted an entire day which allowed the investigation of questions related to the regionalization in activity and the expected activity at decadal time-scales. The second elicitation yielded results for the Atlantic basin and U.S. activity that were very similar (within 1–2% for most key metrics) to those of the first elicitation.

8. Discussions and conclusions

Figure 10 shows the increases in hurricane frequencies in the U.S. by region resulting from the implementation of this work on activities, taking into consideration how increased activities have been distributed among the hurricane tracks of different origins (both for Cat 1–2 and Cat 3–5). Changes are shown in comparison to the activity rates of the long-term 1900–2005 baseline. Frequencies are increased across the entire model, but not uniformly. The largest increases occur in the southeast (the

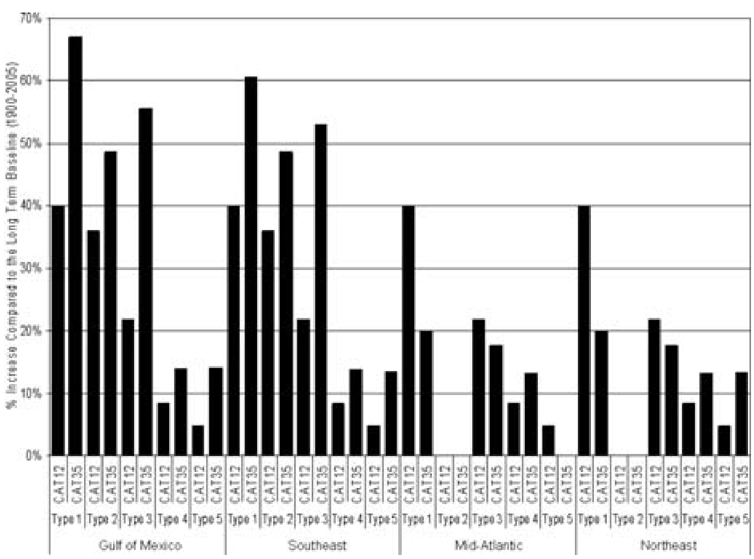

Fig. 10. Relative changes (compared to the 1900–2005 baseline) in activity rates of Cat 1–2 and Cat 3–5 across U.S. regions. The model classifies storms into five types: Type 1 and 2 are storms forming in the deep tropics out of easterly waves and tracking either towards the Eastern U.S. states or the Gulf, Type 3 storms form in the vicinity of the Bahamas, (e.g. Hurricane Katrina-2005), Type 4 are storms forming in the Caribbean region and Type 5 are of Gulf of Mexico origin. The Gulf is defined as the region extending from the border with Mexico to Key West, the Southeast as the region from Southeast Florida to Cape Hatteras. The Northeast is the region North of New York to the border with Canada. Numbers in parentheses behind are model gates.

region encompassing Georgia, South and North Carolina) and the east coast of Florida. Increases are larger in the activity rates of the most severe storms. Those results are consistent with what was described in the earlier sections of this paper. Particularly, Florida has experienced significant decadal changes in activity of both Cat 1–2 and Cat 3–5 storms and is currently in a period of heightened activity. Increases relative to the historic baseline for first landfalls are smaller in the Gulf of Mexico and much smaller in the mid-Atlantic and the northeast. In agreement with the regionalization results described above, when included within the catastrophe loss models the largest impacts are in Florida and the southeast. As for the activity rates, the impact on losses of assessing risk with a medium term perspective varies regionally, but generally ranges between 15 and 25% increase at 50–100-year return periods. The impact of our analysis on losses in the Northeast is more significant than would be implied by the activities of first landfalling storms, as nearly two-thirds of the northeast annual average loss comes from events first impacting the southern states.

As mentioned above, the process was repeated and extended in 2006, including the development of a suite of statistical models. Results from those models, as well as proceedings of the second elicitation will be documented in an additional manuscript.

9. Acknowledgments

The authors would like to thank Roger Pielke, Jr., and the additional anonymous reviewer for their time and valuable input to this manuscript.

References

Anthes, R. A., Corell, R. W., Holland, G., Hurrell, J. W., McCracken, M. C. and co-authors. 2006. Hurricanes and global warming potential linkages and consequences. *Bull. Amer. Meteor. Soc.* **87,** 623–628.

Ayyub, B. 2000. *Elicitation of Expert Opinions for Uncertainty and Risks*. CRC Press, New York, pp. 328.

Blake, E. S. and Gray, W. M. 2004. Prediction of August Atlantic basin hurricane activity. *Wea. Forecast.* **19,** 1044–1060.

Budnitz, R. J., Apostolakis, G., Boore, D. M., Cluft, C. L., Coppersmith, K. J. and co-authors. 1997. *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts*. NUREG/CR-6372, Volume 1, Washington, DC: U.S. Nuclear Regulatory Commission. TIC: 235076

Budnitz, R. J., Apostolakis, G., G., Boore, D. M., Cluff, L. S., Coppersmith, K. J. and co-authors. 1998. Use of technical expert panels: applications to probabilistic seismic hazard analysis. *Risk Analysis* **18**(4), 463–469.

Chan, J. C. L. 2006. Comment on "Changes in tropical cyclone number, duration, and intensity in a warming environment". *Science* **311,** 1713b.

Chenoweth, M. and Landsea, C. 2004. The San Diego Hurricane of 2 October 1858. *Bull. Amer. Meteor. Soc.* **85,** 1689–1697.

Clemen, R. T. and Winkler, R. L. 1999. Combining probability distributions from experts in risk analysis. *Risk Analysis* **19,** 187–203.

Cook, R. M. 1991. *Experts in Uncertainty: Opinion and Subjective Probability in Science*. Oxford University Press, Oxford, pp. 321.

Coppersmith, K. J., Nieman, J. K., Perman, T. R., Youngs, R., Perry, F. and co-authors. 2005. *Update to the Probabilistic Volcanic Hazard Analysis*, Yucca Mountain, Nevada. American Geophysical Union, Fall Meeting 2005, abstract #V31E-07

Curry, J. A., Webster, P. J. and Holland, G. J. 2006. Mixing politics and science in testing the hypothesis that greenhouse warming is causing a global increase in hurricane intensity. *Bull. Amer. Meteor. Soc.* **87,** 1025–1037.

Dunion, J. P., Landsea, C. W., Houston, S. H. and Powell, M. D. 2003. A reanalysis of the surface winds for Hurricane Donna of 1960. *Mon. Wea. Rev.* **131,** 1992–2011.

Elsner, J. B. 2003. Tracking hurricanes. *Bull. Amer. Meteor. Soc.* **84,** 353–356.

Elsner, J. B. 2006. Evidence in support of the climate change-Atlantic hurricane hypothesis. *Geo. Res. Lett.* **33,** L16705.

Elsner, J. B., Niu, X. and Tsonis, A. A. 1998. Multi-year prediction model of North Atlantic hurricane activity. *Meteorol, Atmos. Phys.* **68,** 43–51.

Elsner, J. B., Jagger, T. and Niu, X. 2000. Changes in the rates of North Atlantic major hurricane activity during the 20th Century. *Geo. Res. Lett.* **27,** 1743–1746.

Elsner, J. B. and Bossak, B. H. 2001. Bayesian analysis of U.S. hurricane climate. *J. Climate* **14,** 4341–4350.

Elsner, J. B. and Jagger, T. H. 2004. A hierarchical Bayesian approach to seasonal hurricane modeling. *J. Climate* **17,** 2813–2827.

Elsner, J. B., Tsonis, A. A. and Jagger, T. H. 2006. High frequency variability in hurricane power dissipation and its relationship to global temperature. *Bull. Amer. Meteor. Soc.* **87,** 763–768.

Emanuel, K. 2005a. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436,** 686–688.

Emanuel, K. 2005b. Emanuel replies. *Nature* **438,** E13–E13.

Goldenberg, S. B., Landsea, C. W., Mestas-Nuñez, A. M. and Gray, W. M. 2001. The recent increase in Atlantic hurricane activity: causes and implications. *Science* **293,** 474–479.

Grossi, P., Kunreuther, H. and Patel, C. C. 2005. *Catastrophe Modeling: A New Approach to Managing Risk*. Springer, New York, pp. 245.

Hoyos, C. D., Agudelo, P. A., Webster, P. J. and Curry, J. A. 2006. Deconvolution of the factors contributing to the increase in global hurricane intensity. *Sciencexpress*, doi:10.1126,science.1123560.

Jagger, T. H., Niu, X. and Elsner, J. B. 2002. A space-time model for seasonal hurricane prediction. *Int. J. Climatology* **22,** 451–465.

Kamahori, H., Yamazaki, N., Mannoji, N. and Takahashi, K. 2006. Variability in intense tropical cyclone days in the western North Pacific. *SOLA* **2,** 104–107, doi:10.2151/sola.2006-027.

Klotzbach, P. J. 2006. Trends in global tropical cyclone activity over the past twenty years (1986–2005). *Geophys. Rev. Lett.* **33,** L10805, 1–4.

Klotzbach, P. J. and Gray, W. M. 2003. Forecasting September Atlantic Basin tropical cyclone activity. *Wea. Forecast.* **18,** 1109–1128.

Klotzbach, P. J. and Gray, W. M. 2004. Updated 6–11-month prediction of Atlantic Basin seasonal hurricane activity. *Wea. Forecast.* **19,** 917–934.

Landsea, C. W. 2005. Meteorology: hurricanes and global warning. *Nature* **438,** E11–E12.

Landsea C. W., Bell, G. D., Gray, W. M. and Goldenberg, S. B. 1998. The extremely active 1995 Atlantic hurricane season: environmental conditions and verification of seasonal forecasts. *Mon. Wea. Rev.* **126,** 1174–1193.

Landsea, C. W., Anderson, C., Charles, N., Clark, G., Dunion, J., Fernandez-Partagas, J., Hungerford, P., Neumann, C. and Zimmer, M. 2004a. The Atlantic hurricane database re-analysis project: Documentation for the 1851–1910 alterations and additions to the HURDAT database. In: *Hurricanes and Typhoons: Past, Present and Future* (eds R. J. Murnane and K.-B. Liu). Columbia University Press, New York, 177–221.

Landsea, C. W., Franklin, J. L., McAdie, C. J., Beven, J. L. II, Gross, J. M. and co-authors. 2004b. A reanalysis of hurricane Andrew's intensity. *Bull. Amer. Meteor. Soc.* **85,** 1699–1712.

Landsea, C. W., Harper, B. A., Hoaru, K. and Knaff, J. A. 2006. Can we detect trends in extreme tropical cyclones? *Science* **313,** 452–454.

Lloyd-Hughes, B., Saunders, M. A. and Rockett, P. 2004. A consolidated CLIPER model for improved August-September ENSO prediction skill. *Wea. Forecast.* **19,** 1089–1105.

Mann, M. E. and Emanuel, K. A. 2006. Atlantic hurricane trends linked to climate change. *EOS* **87,** 233, 238, 241.

Owens, B. F. and Landsea, C. W. 2003. Assessing the skill of operational atlantic seasonal tropical cyclone forecasts. *Wea. Forecast.* **18,** 45–54.

Pielke, R. A. and Landsea, C. W. 1999. La Niña, El Niño, and Atlantic hurricane damages in the United States. *Bull. Amer. Meteor. Soc.* **80,** 2027–2033.

Pielke, R. A., Jr., Landsea, C. W., Mayfield, M., Laver, J. and Pasch, R. 2005. Hurricanes and global warming. *Bull. Amer. Meteor. Soc.* **86,** 1571–1575.

Pielke, R. A., Jr., Landsea, C. W., Mayfield, M., Laver, J., Pasch, R. 2006. Reply to "Hurricanes and global warming potential linkages and consequences". *Bull. Amer. Meteor. Soc.* **87,** 628–631.

Saunders, M. A. and Lea, A. S. 2005. Seasonal prediction of hurricane activity reaching the coast of the United States. *Nature* **434,** 1005–1008.

Sriver, R. and Huber, M. 2006. Low frequency variability in globally integrated tropical cyclone power dissipation. *Geophys. Res. Lett.* **33,** L11705.

Thorncroft, C. and Pytharoulis, I. 2001. A dynamical approach to seasonal prediction of Atlantic tropical cyclone activity. *Wea. Forecast.* **16,** 725–735.

Trenberth, K. 2005. Uncertainty in Hurricanes and Global Warning. *Nature* **308,** 1753–1754.

Trenberth, K. and Shea, D. J. 2006. Atlantic hurricanes and natural variability in 2005. *Geophys. Rev. Lett.* **33,** L12704.

Velden, C., Harper, B., Wells, F., Beven, J. L. II, Zehr, R. and co-authors. 2006. The Dvorak tropical cyclone intensity estimation technique: a satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.* **87,** 1195–1210.

Vitart, F. and Stockdale, T. N. 2001. Seasonal forecasting of tropical storms using coupled GCM integrations. *Mon. Wea. Rev.* **129,** 2521–2537.

Webster, P. J., Holland, G. J., Curry, J. A. and Chang, H.-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309,** 1844–1846.

WMO 2006. *Statement on Tropical Cyclones and Climate Change*, Available at http://www.wmo.ch/web/arep/arep-home.html.