SCOR Global P&C

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SCOR Global P&C Guide to Hurricanes: An introduction to quantifying the hazard and managing the peril

Hurricane is one of the most important perils to the insurance industry, representing 42% of all US insured catastrophe losses (Insurance Information Institute, 2013). The US insurance market is the largest in the world, amounting to 34% of the global non-life insurance premiums (AXCO, 2013). The largest natural catastrophe loss worldwide in 2012 was Hurricane Sandy, striking Caribbean islands en route *to the greater New York metropolitan area where it caused record flooding and total insured losses of over US$20 billion.*

Despite the apparent size of this loss, US$20 billion is, in fact, quite close to the US industry average annual loss for hurricane *(Table 1)* and many past hurricanes would cost more if they were to occur today *(Table 2)*. The substantial impact of Atlantic hurricanes has prompted a large volume of scientific research to better understand and predict the phenomenon. With every new event, the insurance industry endeavors to learn from the additional information, and become better prepared by incorporating lessons into Cat modelling *(Info Box 1)*. In this technical newsletter we review physical characteristics, climatology and trends relating to hurricanes and we link this information to its application in the catastrophe models commonly used to quantify the risk.

Table 1. US Annual Average Losses caused by hurricane. PCS losses indexed by SCOR Global P&C.

Scenario/time period	Basis	Loss (US$ billion)
Historical	Model A	13.1
Historical	Model B	11.5
Historical	PCS (30 years)	11.5
Current outlook	Model A	18.5
Current outlook	Model B	13.1
Current outlook	Model C	15.2
Recent past	PCS (1995-2012)	13.0

Table 2. Top 5 hurricane losses 'as-if' they recurred today. Losses calculated by averaging the estimates from multiple Cat models.

Year	Name	As-if Loss (in US$ billion)
1926	Miami, Florida	136
1928	Okeechobee Hurricane, Florida	72
1992	Andrew, Florida	64
1900	Galveston, Texas	57
1947	Fort Lauderdale, Florida	56

Info Box 1

Lessons learned from past hurricanes

1992 Hurricane Andrew: The huge losses demonstrated the need to be prepared for rare but extremely severe hurricanes.

2004 hurricane season: A total of six landfalls occurred, leading to large losses and highlighting the potential for multiple landfalls and 'clustering'. In addition, with four hurricanes affecting Florida, the season illustrated that demand surge can have a large, aggravating impact on losses.

2005 Hurricane Katrina: The extended flooding reminded insurers that storm surge is possibly the most serious threat posed by hurricanes both in terms of human life (WMO, 2007) and in terms of damages (Knutson, et al., 2010). Moreover, the important role engineering (levee design) plays in these situations was highlighted. Casinos floating on barges were swept inland by the surge. These aspects helped emphasize the need for better representation of non-modelled components in Cat models and the need to better understand exposures.

2008 Hurricane Ike: Hurricane Ike re-intensified as an extratropical system after landfall causing large losses due to heavy rains and hurricane-force winds in the Midwest. About 10% of all basin tropical storms are enhanced by their interaction with extratropical systems (Kossin, et al., 2010). The event emphasized that large hurricane losses can occur far beyond coastal areas and for a long time after landfall.

2012 Hurricane Sandy: Sandy set the record for the largest hurricane ever *(Table 4)*. More importantly, it emphasized the need to model more accurately business interruption and storm surge, as well as to track auto physical damage exposure more carefully.

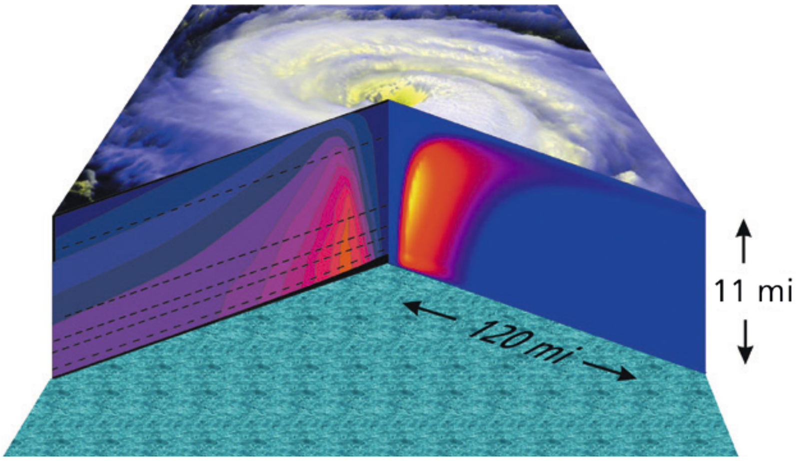
What is a hurricane?

Hurricanes are non-frontal weather systems characterized by cyclonic (counterclockwise) air circulation and thunderstorm activity. They are approximately symmetric with diameters of several hundred miles, and typically encountered in tropical and subtropical North Atlantic waters, north of 10° latitude. For a weather system to qualify as a hurricane, the maximum 1 min average wind speed has to exceed 74 mph* *(Table 3).*

Table 3. Max 1-min wind speed ranges of tropical depressions, tropical storms and the five hurricane categories defined in the Saffir-Simpson hurricane wind scale.

Category	Max 1-min winds (mph)
Tropical depression	< 39
Tropical storm	39-73
Hurricane category 1	74-95
Hurricane category 2	96-110
Hurricane category 3	111-129
Hurricane category 4	130-156
Hurricane category 5	> 156

Figure 1. Cutaway view of a hurricane.



The picture on top is a satellite image of the clouds of Hurricane Fran (1996). The left-hand side depicts the tangential velocity of Hurricane Inez (1966) as measured by aircraft flying at the heights indicated by the dashed lines. The maximum velocity (orange) is 110 mph. The right-hand side shows hurricane vertical velocity estimated by numerical simulation. The maximum velocity (yellow) is 20 mph.
Source: Emanuel, 2003.

Figure 1 depicts the structure of a hurricane. Most hurricanes (and especially the intense ones) have an eye, a circular calm area in the center of the hurricane. In the eye there is *subsidence*[1], which causes cloud-free conditions. Horizontal wind speed in the eye is very low but it increases abruptly close to the eyewall, reaches a maximum at a radius of 6 - 60 mi from the center and decreases slowly thereafter (Emanuel, 2003). Vertical wind speed also increases substantially at the eyewall, leading to a band of clouds extending up to a radius of another 12 - 30 mi beyond the eyewall (Emanuel, 2003). *Major* hurricanes, classified as Saffir-Simpson Category 3, 4 and 5, typically have two (or, in rare cases three) concentric eyewalls following a cycle where the outer eyewall contracts, the inner eye dissipates and a new outer eye is formed.

Characteristics of hurricanes discussed in this and following sections represent “typical” hurricanes. Nevertheless, actual hurricanes differ from their idealized counterparts, often in extreme fashions.

Table 4 summarizes hurricanes and tropical storms that set various records.

As shown in the table, tropical storm Allison stayed over land for an extremely long period of 258 hours. In addition, there have been more than 30 US landfalls whose duration exceeded 4 days. Given that reinsurance contracts in the US market have an hours clause of 3-4 days, insurers may have to take 2 retentions, or potentially claim against a reinstated limit for storms causing damage over a long duration. This would be an issue for hurricanes that remain intense for several days after landfall, a situation that has not appeared historically[2].

Nevertheless, there is no reason to exclude the possibility of a hurricane following a South to North track along the entire eastern seaboard (or East-West along the Gulf of Mexico coast), thereby remaining destructive for an extended period of time. Such atypical events are hardly present even in Cat model event sets that include hundreds of thousands of simulated years. Hence, insurers could be underestimating their exposure to rare but destructive events that have not been modelled and are not sufficiently covered by insurance contracts. The hours clause can also lead to cedants having two retentions for US-Caribbean clash events like Ivan and Wilma.

Table 4. Record breaking hurricanes and tropical storms.

Record	Name	Year	Landfall	Value
Largest number of deaths	Galveston	1900	yes	8,000 approx.
Lowest pressure	Wilma	2005	yes	882 hPa
Largest gale-force wind diameter	Sandy	2012	yes	945 mi
Longest duration	San Ciriaco	1899	yes	27.75 days
Farthest travel	Faith	1966	no	6,850 mi
Highest forward speed	Great New England	1938	yes	70 mph
Longest time over land	Allison	2001	yes	10.75 days

[1] Motion of air from high to low altitude. It typically results in an increase of temperature and a decrease of relative humidity.

[2] Tropical Storm Allison (Table 4) remained over land for several days but only caused severe losses in the first three days after its landfall in Texas.

** 1 mile is equal to 1.6 kilometer.*

How and where are hurricanes created? How do they work once fully developed?

Although the structure of a fully developed hurricane is well understood, the same cannot be said about the conditions that lead to hurricane genesis. One necessary condition is sufficiently high sea surface temperature (at least 79° F*) (Palmen, 1948); the vast amount of energy a hurricane requires (comparable to the global rate of electricity consumption) is provided by the oceans and that available energy depends (among others) on the ocean temperature. High sea surface temperature also tends to increase water vapor close to the surface. Further important conditions are the initial presence of atmospheric instability[3] and convergence. Given the presence of atmospheric instability, warm and moist air close to the surface tends to rise from the surface at higher altitudes because it has lower density than the air around it. During the ascent, air cools and water vapor condenses. Condensation in turn releases heat, which increases local air temperature, decreases local air density and further enhances updrafts. Updrafts contribute to a drop of the atmospheric pressure and therefore intensify cyclonic circulation creating a positive feedback.

Conditions of atmospheric instability and high relative humidity are often encountered in tropical latitudes. Tropical waves[4], a certain form of atmospheric instability, are the starting point for 58% of tropical storms and *minor* (Category 1 and 2) hurricanes and 83% of *major* hurricanes (Emanuel, 1993). A further factor affecting hurricane formation is the existence of a large difference between wind speed and wind direction at low and high altitudes (also known as *wind shear*): strong wind shear disrupts the vertical development of hurricanes. Although the aforementioned environmental conditions are required for the development of a hurricane, they only sometimes lead to one. Hurricane formation, or *cyclogenesis*, is only partly understood and is an active field of scientific research.

An important type of hurricane is the so-called "Cape Verde hurricane". These are tropical storms that form close to the Cape Verde Islands off the west coast of Africa as a result of Tropical Waves and evolve into hurricanes before they reach the Caribbean Sea. Cape Verde hurricanes spend a lot of time in the tropical North Atlantic on their journey from the Cape Verde towards the Caribbean. This often allows them to become very intense. About two Cape Verde hurricanes occur each year on average (Landsea, 2006). According to modelling studies (RMS, 2011), Cape Verde hurricanes occur more frequently in periods of increased North Atlantic sea surface temperature (such as the current period since 1995). Hurricane Ike, a recent and important event for the insurance industry *(Info Box 1),* was a Cape Verde hurricane.

Hurricanes in the Caribbean Sea or in the Gulf of Mexico typically reach lower intensities than their Cape Verde counterparts. Nevertheless, due to their proximity to the US coast, they are more likely to reach it. In the infamous 2005 hurricane season, no less than five hurricanes made landfall in the US, all originating from the Caribbean.

Cyclogenesis in Cat models is modelled as a stochastic process. The probability of a tropical storm genesis event at any location in North Atlantic is estimated as a function of the location and temporally varying meteorological variables (e.g. sea surface temperatures and wind shear at selected areas). The relationship between genesis probability and the aforementioned explanatory variables is in turn determined from historical data (Hall, et al., 2007). It follows that Cat models do not model explicitly the physical mechanisms leading to tropical storm genesis but they do take into account important factors affecting genesis to stochastically simulate the phenomenon. The number of the modelled genesis events and their location tend to match history for a sufficiently large number of simulations (Hall, et al., 2007).

How do hurricanes move?

Hurricane motion is influenced by large-scale atmospheric circulation from genesis to later stages of their lifecycle. In latitudes below 30° N the prevailing wind direction is from East to West (Trade Winds) whereas above 30° N it is towards the East (Westerlies). Hurricanes will typically follow these winds depending on latitude. In addition, their movement has a northward component, which is an indirect result of the earth's rotation around itself (Coriolis Effect). For example, a hurricane that forms in the Eastern Atlantic at 15° N will typically move towards West and North until it reaches about 30° N where it will turn towards East. Hurricane track is not only influenced externally by large-scale atmospheric features but also by the hurricane itself. A number of scientific studies (Holland, 1983; Fiorino, et al., 1989; Smith, 1991) suggest that hurricanes alter atmospheric circulation around them so that they drift northward and westward.

Hurricane forward speed affects the wind speed for a fixed observer on the earth's surface. For example, consider an observer on the East coast observing a hurricane approaching from the East with a typical forward speed of 10 mph: the wind speed on the left-hand side of the observer will be greater than the wind speed on his right hand side by 20 mph and therefore the corresponding coastal areas will not be affected to the same degree.

Atmospheric conditions, including wind, deviate from the climatological expectations at any given time and so do hurricane tracks. A recent example is Hurricane Sandy that turned westwards to the US coast while it was at latitude of about 35° N. Considering typical atmospheric conditions one would have expected the hurricane to move East. Nevertheless, an unusual high-pressure system in the vicinity of Newfoundland made Sandy head towards New Jersey (National Hurricane Center, 2012).

Hurricane tracks in Cat models are calculated using a stepwise algorithm where the track length and direction in each step is derived after superimposing a mean component and a random deviation around it. Both the mean and random displacements depend on the current and the previous position of the storm (Hall, et al., 2007) *as well as related meteorological variables. The relationship between the explanatory variables (current and previous position and meteorology) and track is the result of calibration against historical data.*

What climate patterns influence hurricanes and how?

Hurricane activity is affected by variability in atmospheric and oceanic conditions. As our hurricane description in a previous

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3/ The tendency of the air to rise in the atmosphere can be quantified by atmospheric instability. In an unstable atmosphere, air temperature decreases quickly with height. Instability favors updrafts and therefore the development of hurricanes.

4/ Atmospheric troughs propagating from east to west. In North Atlantic, tropical waves start from West Africa and are also called African Easterly Waves. They are accompanied by cloud cover and thunderstorm activity.

** A temperature difference of one degree Fahrenheit is equal to 5/9 degrees Celsius. To convert a temperature from degrees Celsius to degrees Fahrenheit one subtracts 32 from the Fahrenheit temperature and multiplies by 5/9.*

section suggests, changes in sea surface temperature influence hurricanes. Variability of the Atlantic sea surface temperature in conjunction with hurricane activity has been examined using a number of different sea surface temperature-related climate indices, such as the Atlantic Multidecadal Oscillation (Wang, et al., 2008), the Atlantic Meridional Mode (Vimont, et al., 2007), the Atlantic Warm Pool sea surface temperature (Wang, et al., 2011) and the Main Development Region[5] sea surface temperature (Goldenberg, et al., 2001). Another well-known influence on hurricanes is the El Niño. During El Niño years, upper air circulation in the Caribbean and the Western Tropical Atlantic changes in such a way that wind shear increases and hurricanes are less likely to develop. Conversely, more hurricane activity can be expected in La Niña years. According to Bove et al. (1998), the probability of two or more landfalling US hurricanes is 28%, 48% and 66% during El Niño, neutral and La Nina hurricane seasons respectively. A strong direct linkage between El Niño/La Niña and economic losses has also been identified (Pielke Jr., et al., 1999). Further atmospheric indices influencing hurricane activity include the trade winds at 925 mb (Saunders, et al., 2008), the Indo-Pacific sea surface temperature (RMS, 2011), the sea level pressure in certain parts of the Pacific (Klotzbach, et al., 2013), the Southern Oscillation Index (Villiarini, et al., 2010), the Madden-Julian Oscillation (Kossin, et al., 2010) and the difference between sea surface temperature in the Main Development Region and in the remaining global tropics (Swanson, 2008). These indices are calculated from measurements or other estimates of meteorological variables in several locations around the globe. An overview of some important indices and their locations is provided in the *Info Box 2.* The interactions between the aforementioned atmospheric phenomena and hurricanes are not always well-resolved and can change with time. This complicates understanding and prediction of seasonal hurricane activity.

We will examine the influence of another climatic phenomenon, the North Atlantic Oscillation (NAO) on hurricanes in more detail. NAO can be described as a seesaw of high and low atmospheric pressure between the Azores and Iceland. The Azores High is a broad, stationary area of high atmospheric pressure and anti-cyclonic (clockwise) circulation that tends to block and/or deflect other smaller and more mobile weather systems (such as hurricanes and windstorms) that approach it. The NAO alternates between positive (strong Azores high) and negative (weak Azores high)

5/ The area of North Atlantic bounded by 10° N, 20° N, the West Coast of Africa and Central America.

Info Box 2

Climatic patterns believed to influence hurricanes

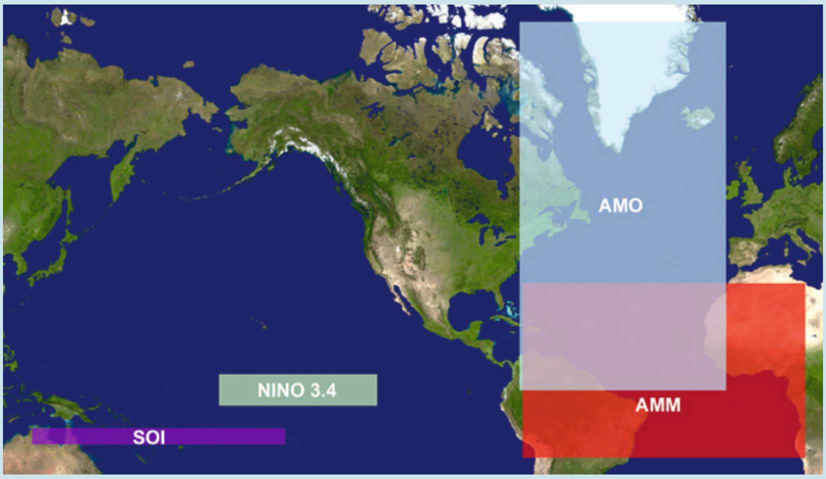
North Atlantic hurricane activity is influenced by climatic patterns that take place in the Atlantic as well as thousands of miles away, in the Pacific and the Indian Ocean. These patterns are quantified using indices, which are calculated by related meteorological variables observed or otherwise estimated at the corresponding locations. The map provides an overview of the geographical locations for the following important climatic patterns:

Atlantic Multidecadal Oscillation (AMO): A periodic variation of the sea surface temperature in the North Atlantic. The period of this variation is approximately 60 years and its peak-to-peak amplitude is about 0.9° FW.

Atlantic Meridional Mode (AMM): Linked variations in the sea surface temperature and various meteorological variables across hemispheres in the Tropical Atlantic, which in turn result from variations in the interaction between low level winds and sea surface temperature in the same area. During a positive phase of the AMM, sea surface temperature, sea level pressure, low-level vorticity (a measure of the local rotation of the air around itself at a certain point) and vertical wind shear in the Tropical Atlantic are all modulated in such a way that hurricane activity is enhanced (Vimont, et al., 2007). The phenomenon has a period of approximately 12-13 years, although considerable irregularities in this variability are introduced by fluctuations in the local weather conditions (Chang, et al., 1997).

Niño 3.4: The El Niño refers to a periodic variation in sea surface temperature in Central and/or Eastern equatorial Pacific. El Niño’s period ranges between 2 and 7 years. Niño 3.4 is an index often used to quantify the El Niño and it is calculated as a spatially averaged sea surface temperature (see *Figure* below for averaging area). NOAA declares an official El Niño event when Niño 3.4 averaged over three months exceeds the 1970-2000 average by 0.9° F or more. Conversely, a negative departure from the 1970-2000 average by 0.9° F or more is defined as a La Niña.

Southern Oscillation Index (SOI): Periodic variation in the sea level pressure difference between Central and Western Pacific. During El Niño, increased sea surface temperature in Central/Eastern equatorial Pacific leads to increased low-level air temperature and to atmospheric instability. This in turn results in below-average sea level pressure in Central/Eastern equatorial Pacific and above-average sea level pressure in Western Pacific. SOI is calculated from the difference in sea level pressure between a meteorological station located in Tahiti and a station located in Darwin, Australia. From the description of SOI it becomes obvious that the phenomenon is strongly coupled to the El Niño and therefore the two climatic patterns are often referred to with the common name El Niño-Southern Oscillation (ENSO).



phases in a way that is almost impossible to predict in a deterministic sense. Scientific evidence suggests that NAO (and other indices related to surface pressure over the North Atlantic) affect hurricane genesis, track and intensity (Wang, et al., 2011; Elsner, et al., 2000; Klotzbach, et al., 2013). *Figure 2* depicts a simple conceptual mechanism that explains to some extent how NAO affects hurricane motion.

A less investigated consequence of NAO is a possible introduction of clustering in hurricane landfalls. The exceptionally destructive hurricane seasons of 2004 and 2005 raised the question: Are there more years with more than one landfall than one would expect by chance? A simple way to detect and quantify the presence of clustering is to compare the mean and the variance of landfalls. In a clustered dataset, the variance is significantly greater than the mean. *Table 5* shows that this is indeed the case for negative NAO years, both for separate US regions and the whole US. An important consequence of clustering is that once a hurricane landfall occurs, the probability of a second one is much higher compared to a scenario without clustering. The conditional probability of having a second hurricane landfall once the first one has occurred is shown in *Table 6,* where the positive and negative NAO cases are shown separately.

Hurricane clustering in Florida, a state with particularly high hurricane risk, is further supported by recent scientific research (Jagger, et al., 2012).

Figure 2. Schematic illustration of a Cape Verde hurricane track in positive (left) and negative (right) NAO conditions. Modified after Wang et al. (2011).

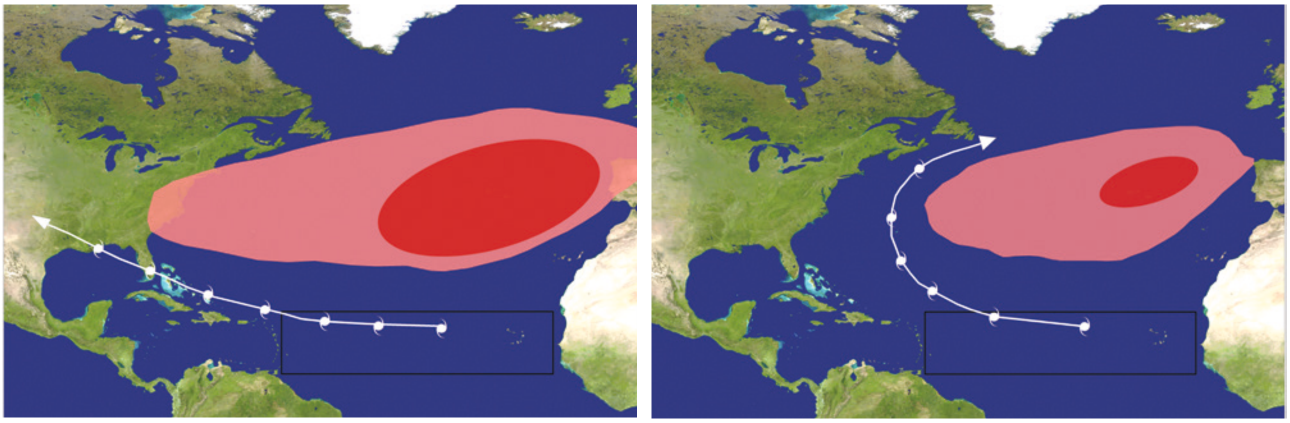


Table 5. Variance-over-mean ratio for hurricane landfalls for various US regions and for years with positive and negative May-June NAO. The May-June NAO average has been shown to affect hurricane activity (Jagger, et al., 2012). Numbers in red indicate ratios significantly greater than one at the 95% level of significance i.e. clustering.

	US	FL	East Coast	Gulf States
All data	1.2	1.2	1.1	1.0
Positive NAO	0.84	0.90	0.90	0.65
Negative NAO	1.5	1.4	1.4	1.3

Table 6. Conditional probability of a second hurricane landfall, given that one landfall has occurred.

	US	FL	East Coast	Gulf States
All data	0.55	0.37	0.27	0.27
Positive NAO	0.47	0.13	0.23	0.14
Negative NAO	0.64	0.61	0.32	0.41

All aforementioned climate patterns have significant components that vary relatively slowly with time and therefore enable the prediction of hurricane activity (albeit with limited skill) months in advance. Nevertheless, hurricane activity also depends strongly on weather conditions at the time the hurricane occurs. These conditions include the steering flow (wind speed at high altitudes), vertical wind shear and relative humidity. Ocean conditions can also have short-term variations with a strong impact on hurricane intensification. The Loop Current is such an example *(see Info Box 3).*

Cat models take into account the recent or projected sea surface temperature in the Atlantic and other basins as well as wind shear to model the number, genesis location and track of tropical storms.

How many hurricanes occur each year? How many landfalls?

A number of different estimates of the yearly average hurricane count can be found in the scientific literature. Given the decreasing accuracy of the hurricane data further back in time, many researchers prefer to exclude data before a certain date. Data records in HURDAT[6], one of the most authoritative sources of hurricane data, start in 1851. Usual cutoff years are 1900, 1950 (aircraft reconnaissance) and 1980 (full availability of high quality satellite data). Thus, data of better quality are kept at the expense of lower quantity. A common problem with hurricane data before 1980 (and even more before 1950, or 1900) is the undercount of basin hurricanes: Before

[6] The official record of North Atlantic basin tropical storms and US landfalls, issued and maintained by the Hurricane Research Division of the US National Oceanic and Atmospheric Administration.

regular satellite observations, it is highly likely that some hurricanes occurred in the Atlantic Basin but were never detected. Various scientific studies suggest methods to correct for the undercount bias by adding extra hurricanes to the historically observed ones (Vecchi, et al., 2012; Landsea, 2007; Chang, et al., 2007). The 1950-2012 average of category 1 to 5 basin hurricanes is 6.3, according to one estimate (Tropical Storm Risk, 2013).

When it comes to hurricane landfalls data accuracy is better because hurricanes making landfall are easier to detect, especially after around 1900, when population density along the US East and Gulf coasts was relatively high. Nevertheless, different approaches still exist. The decision whether a hurricane makes landfall or not and which areas are affected depends on the size of the hurricane, its movement relative to the coast and the configuration of the coastline among others. For example, SCOR Global P&C has analyzed continental US hurricane landfalls between 1900 and 2012 by counting the number of HURDAT hurricane tracks approaching the U.S. coast at a distance less than 20 mi. This method yields an average of 1.7 landfalls per year. The same figure is provided by a model vendor and also the same result is calculated from the HURDAT landfall list. If we only consider the HURDAT landfall list between 1950 and 2012, we obtain 1.5 landfalls per year. Although average landfall statistics from various sources match, there are some differences in the counts of individual landfalls. For example, the center of Hurricane Emily in 1993 approached Cape Hatteras in South Carolina at a minimum distance of about 25 mi while Emily was a category 3 hurricane. This event does not appear in the SCOR Global P&C landfall count as the minimum distance off the coast was always greater than 20 mi. However, the event is included in the HURDAT landfall list because Emily did cause hurricane category 3 winds in coastal areas of South Carolina. *Figure 3* shows a comparison of landfall counts from the aforementioned three sources.

Figure 3. Empirical probabilities of 0, 1, 2, 3 and more than 3 US landfalls in a year using different counts. Based on data from 1900 until 2012.

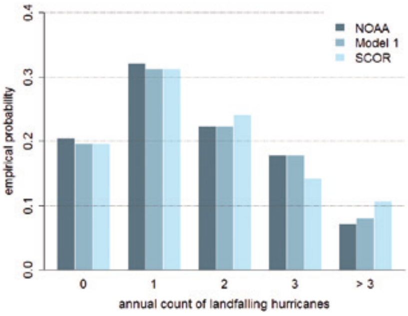
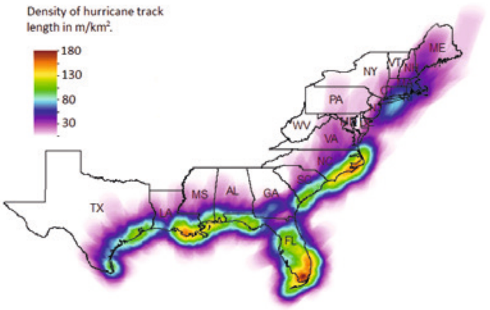
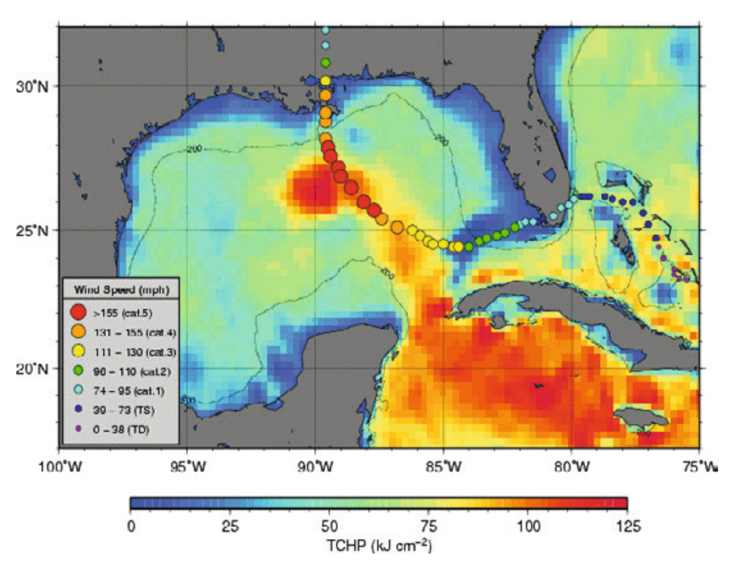


Figure 4 shows the US hurricane landfall density. The states of Florida, Louisiana and North Carolina are the most heavily affected.

Figure 4. SCOR Global P&C analysis of US landfall density for category 1 to 5 hurricanes in the period between 1852 and 2011.
Created by SCOR Global P&C using HURDAT data.





Info Box 3

The Loop Current and hurricanes

The Loop Current is an ocean current originating from the Caribbean and flowing through the Gulf of Mexico. It enters the Gulf passing between the Yucatan Peninsula and Cuba and exits from the Straits of Florida. The exact position of the current in the Gulf of Mexico is variable: it can remain close to the Gulf entrance or it can penetrate nearly up to the coast of Louisiana. Moreover, the current spawns once every 3 to 17 months (Sturges, et al., 2000) an eddy (also called Warm Core Ring) that drifts West until it reaches the coast of Texas or Mexico, a few months up to a year later. Both the current and the Warm Core Ring feature a relatively thick layer of warm water at the surface. This represents conditions which are more favorable for the intensification of hurricanes compared to the rest of the Gulf of Mexico. The Figure above (obtained from NOAA/AOML) shows the Tropical Cyclone Heat Potential (TCHP) in the Gulf of Mexico in August 28, 2005. THCP measures the upper ocean heat content from the surface to the 26°C isotherm. The circles indicate Hurricane Katrina that passed over the Loop Current and a Warm Core Ring and intensified from category 3 to category 5 in just 9 hours.
Katrina made landfall shortly after in the coast of Louisiana. Hurricane Rita that followed almost a month later also intensified as it passed over the Loop Current.
Loop Current forecasts for the next few days (e.g. from NOAA) can be useful for short-range forecasting. Reliable predictions beyond this time horizon are not available and therefore the Loop Current does not feature in seasonal hurricane forecasts. Considering future projections, climate model simulations estimate that the Loop Current will slow down by 20-25 % by the end of the 21st century. This is consistent with the estimated slowdown of the Gulf Stream in the same period (Liu, et al., 2012).

Historical data play an important role in the development and validation of Cat models. As described, there is uncertainty in the basin and landfall hurricane counts, let alone hurricane physical characteristics (such as wind speed, pressure, diameter, etc.) over their lifetime. The uncertainty in the historical data propagates in the Cat models themselves and makes their evaluation more challenging.

Is it possible to forecast hurricanes?

Hurricane forecasts are issued regularly for various timescales and with various degrees of success. The evolution of science and technology behind operational weather forecasting and the improved understanding of the physical characteristics of hurricanes in the last three decades have enabled relatively accurate short range (3-5 day) forecasts (see, for example, the Tropical Weather Outlook of the US National Hurricane Center). Progress has not been equal for all aspects of hurricanes. Today's forecast of a hurricane's position with 72 hours lead time has the same accuracy as a 36-hour forecast 15 years ago. However, there is little improvement in predicting aspects like the maximum hurricane wind speed, fast changes in hurricane intensity and tropical storm genesis (Zhang, 2011). These predictions are invaluable in terms of emergency preparedness and they help protect human life and mitigate economic and insured losses.

Hurricane prediction becomes more challenging and less accurate when lead time increases. Seasonal outlooks issued in late spring and in summer provide estimates about the total number of basin hurricanes and landfalls expected during the season, although they cannot provide information about when and where hurricanes are expected. Two main types of modelling techniques are employed for seasonal outlooks: dynamical and statistical models. Dynamical models use fluid dynamics and thermodynamics equations to predict the number of hurricanes and related quantities into the future. Statistical models use several types of statistical regressions to link future hurricane activity with related explanatory variables (see previous sections for examples of such variables). The accuracy of seasonal outlooks varies but they often represent an improvement over the climatological averages *(Table 7).* Seasonal outlooks issued as early as December are available as well but they tend to have rather poor predictive skill. One of the most prominent teams of hurricane experts, the Tropical Meteorology Project of the Florida State University discontinued their quantitative December outlook in 2012 after recognizing that in the 20 years it was issued, it had not succeeded in achieving real time forecast skill. Because of the high uncertainty of seasonal forecasts, these are not sufficiently credible to substantially modify underwriting behaviour.

Given the limitations of long-range hurricane forecasting, Cat models do not attempt to perform deterministic forecasts, but they provide a probabilistic view of the risk instead. A large number (hundreds of thousands or millions) of theoretical tropical storms are simulated in order to produce an extended range of outcomes. This enables model users to include in their view of risk extremely rare (and often unobserved), but possible, hurricane events.

Table 7. Seasonal predictions for 2012 hurricane activity and observed activity.

Forecasting group	Forecasting method	Issue date	Named Storms + Hurricanes	Hurricanes
FSU COAPS	dynamical	30/5/2012	13 (70% chance of 10-16)	7 (70% chance of 5-9)
NOAA	hybrid	9/8/2012	70% chance of 12-17	70% chance of 5-8
UK Met Office	dynamical	24/5/2012	10 (70% chance of 7-13)	N/A
CSU	statistical	4/4/2012	10	4
Tropical Storm Risk	statistical	23/5/2012	12.7 ± 3.9	5.7 ± 2.7
2012 observed	N/A	N/A	19	10
1995-2012 average	N/A	N/A	15	8

Is hurricane activity changing?

Changes in hurricane activity are difficult to detect due to large natural variability and limited historical data of good quality. Considering global hurricane activity, no significant trend has been observed in the satellite era (IPCC, 2012). A number of scientific studies show that there is an increasing trend in North Atlantic basin hurricanes although the fidelity of hurricane counts (upon which the trends are based) is debated. Increasing hurricane activity in the North Atlantic is also observed by metrics of activity other than hurricane counts such as the Accumulated Cyclone Energy[7]. A recent investigation using a homogeneous record of tide gauge measurements since 1923 estimates a doubling of Katrina-magnitude storm surge events with the warming that occurred in the 20th century (Grinsted, et al., 2013). According to future projections, rainfall associated with tropical cyclones will likely increase (IPCC, 2012). Regarding hurricane landfalls, no significant trend or change-point can be established. From the discussion above (and further scientific investigations not discussed here) it becomes apparent that the evidence of changes in North Atlantic hurricane activity is not incontrovertible and the confidence of future projections is limited. However, we believe there is sufficient evidence for a risk-averse stakeholder to take the possibility of significant future changes into serious consideration.

Unlike long-term trends, change-points in the number of basin hurricanes have been detected (Goldenberg, et al., 2001) and accepted by most scientists. Namely, the average number of category 3, 4 and 5 basin hurricanes increased from 1.6 to 3.8 in the 1965-1994 and 1995-2012 periods respectively. This change has been attributed to the Atlantic Multidecadal Oscillation shifting from a negative to a positive phase in 1995. The causes of this shift are not clear. On the one hand, paleoclimatic evidence suggests that the oscillation is a

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7/ Accumulated Cyclone Energy is a measure of hurricane activity related to the energy a tropical storm uses over its lifetime. Seasonal values are obtained by summing up the values for each individual event.

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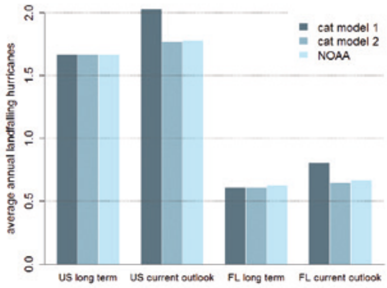
result of internal ocean dynamics (Knudsen, et al., 2011). On the other hand, recent modelling studies postulate that changes in sea surface temperature are a consequence of changes in the emissions and concentrations of natural and anthropogenic aerosol in the last 150 years (Dunstone, et al., 2013). It should be noted here that increased basin activity cannot be directly translated to increased hurricane landfalls. For instance, the recent 2012 season was the third most active on record in terms of basin hurricanes, but it only had two US landfalls. This has been recognized to some extent in vendor Cat models, where the effect of sea surface temperature on hurricane genesis and track is taken into account. In a more forward-looking approach, sea surface temperatures for the next pentad are estimated using dynamical models (which now include aerosol effects) and then the hurricane activity estimates are derived according to the sea surface temperature projections. As mentioned before, the influence of further climatic phenomena, such as the North Atlantic Oscillation and its relation to hurricane clustering should also be considered. In any case, the average yearly hurricane landfalls have increased in the recent period of positive Atlantic Multidecadal Oscillation/above-average sea surface temperature conditions and this change has been reflected on Cat models. *Figure 5* summarizes these changes for the US and for Florida, the most exposed state in terms of hurricane hazard.

Figure 5. Comparison between different estimates of the long-term and current outlook average annual landfalling hurricanes for the US and for Florida.



The long term NOAA observations correspond to the 1900-2011 average whereas the current outlook observations correspond to the 1995-2011 average. The current outlook model estimates refer to future projections of hurricane activity with elevated sea surface temperatures in the North Atlantic.

Outlook

Changes in hurricane activity and its drivers should remain the focus of scientific research over the coming years. In previous sections we briefly mentioned various approaches which seek to describe and predict hurricane activity. On one hand, the multitude of scientific findings incorporated into these approaches indicates how much progress has been made. On the other hand, the lack of consensus between various hurricane models indicates that scientific understanding is incomplete and that important factors affecting hurricanes might still be missing. Capturing the non-stationary nature of the linkages between hurricanes and climatic patterns also remains an important priority. For instance, West African precipitation used to be one of the best predictors of hurricane activity. However, this correlation deteriorated unexpectedly 15-20 years ago (Fink, et al., 2010). The reasons for this are not well understood: natural variability, anthropogenic changes and data inhomogeneity are all believed to play a role. If one accepts that existing predictors of hurricane activity ceased to explain it at some point, one cannot rule out the emergence of new predictors either. While the yearly hurricane landfall rate in the state of Florida is 0.7 since 1995 (and 0.6 since 1900), no landfall has occurred in the 7-year period from 2006 until 2012. Is this a lucky coincidence or has the climatology of hurricane landfalls changed? Identifying the most relevant linkages between climatic patterns and hurricanes and discerning between the natural and anthropogenic drivers of hurricane activity will remain very active fields of scientific research. These developments create a significant potential for changes in the scientific basis of Cat models in the coming years.

Authors:
Dr Iakovos Barmpadimos (ibarmpadimos@scor.com),
Dr Markus Gut (mgut@scor.com), **Jacky Andrich** (jandrich@scor.com),
Tom Linford (tlinford@scor.com), **Ronny Abplanalp** (rabplanalp@scor.com)
and **Dr Kirsten Mitchell-Wallace** (kmitchell-wallace@scor.com).

SCOR Global P&C
5, avenue Kléber - 75795 Paris Cedex 16 - France
Editor: Dominique Dionnet
Tel.: +33 (0)1 58 44 72 62 - Fax: +33 (0)1 58 44 85 22 - ddionnet@scor.com

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