Climatological Influences on Hurricane Activity: The AIR Warm SST Conditioned Catalog

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Executive Summary

AIR Worldwide provides two views of U.S. hurricane risk in the form of stochastic catalogs for its U.S. hurricane model:

- A *Standard* catalog, which reflects hurricane risk under average climate conditions, and;
- A *Warm Sea Surface Temperature (Warm SST)* catalog, which reflects hurricane risk under warmer-than-average sea-surface temperature conditions.

Each of these catalogs incorporates the latest scientific research and has undergone extensive peer review by leading scientists to provide a credible estimate of U.S. hurricane risk. Together, they provide the most scientifically advanced and sound approach to assessing U.S. hurricane risk available today.

This paper reviews the current state of research on climatological influences on hurricane activity, explains in detail the approach used to create AIR's Warm SST catalog, and addresses the role of these catalogs in a robust approach to assessing catastrophe risk. Key points discussed in the document include:

- The Warm SST catalog assesses hurricane risk based on years in which SSTs were above the long term, or climatological, mean and therefore provides a measure of expected risk for any season or seasons in which the Atlantic is warmer than average.
- The rigorously scientific approach taken by AIR in developing the Warm SST catalog incorporates original research that advances the state of scientific knowledge and leverages the considerable expertise of a sizeable and highly credentialed staff of meteorologists and climate scientists. The research embodied in the catalog has been accepted for publication in a forthcoming issue of the peer-reviewed *Journal of Applied Meteorology and Climatology* and as a book chapter in *Hurricanes and Climate Change* (Springer). As such, the methodology used by AIR is completely transparent to both the user of the model and to the wider scientific community. Perhaps even more importantly, it is entirely reproducible.
- Findings from research undertaken by AIR scientists indicate that during years in which SSTs are warmer than the long-term average, the U.S. Gulf and East Coasts experience more frequent tropical cyclone landfalls. The findings further indicate that tropical cyclone *intensity at landfall* is also affected by warm ocean conditions and the effect varies by region.
- In particular, the Gulf Coast is likely to experience more frequent landfalls of *tropical storms*, but little increase in the number of *hurricane* landfalls. The pattern is different for

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the Southeast, which is likely to experience more frequent storms of hurricane strength. In the Northeast, the relationship between warm SSTs and hurricane landfalls is too weak to draw a clear conclusion.

- Overall, the difference (increase) in the mean frequency between the Warm SST catalog and AIR's Standard catalog for U.S. hurricane landfalls is between 5% and 10%, but varies—in some cases outside this range— depending on the geographical region and measure of intensity considered in the analysis.
- While sea-surface temperatures are a significant indicator of hurricane risk over a five-year time horizon, secondary factors can still play an important role in determining hurricane activity from season to season, and thus they also play a role in the heightened uncertainty in *any* climate conditioned catalog. For example, despite the warmer-than-average SSTs in the Atlantic in 2006 and 2007, the El Niño Southern Oscillation (ENSO) cycle and the Saharan Air Layer (SAL) mitigated what had been forecast to be highly active seasons.

AIR offers its Warm SST catalog as a supplement to, rather than a replacement for, its Standard catalog of Atlantic hurricane activity. In providing two catalogs instead of one, AIR is promoting the idea of using multiple views of risk—what is often referred to as an ensemble approach. It is well known in the scientific community that several credible, albeit different "opinions" of what the future may hold (the "ensemble") is always preferable to a single opinion. Weather and climate forecasts across the world are based on multiple runs of numerical models—or multiple opinions—that provide a measure of where the opinions agree and where they differ. By providing two catalogs with its U.S. Hurricane Model, AIR encourages clients to assess variability and uncertainty, which are fundamental to managing risk.

AIR is committed to explaining to its clients how the two catalogs are developed, how they differ, and how they can be used to optimize risk management. Because both are developed using sound scientific principles, together they constitute the most advanced and reliable U.S. hurricane model available on the market today.

Introduction

AIR Worldwide provides two views of U.S. hurricane risk in the form of stochastic catalogs for its U.S. hurricane model:

- A *Standard* catalog, which reflects hurricane risk under average climate conditions, and;
- A *Warm Sea Surface Temperature (WWST)* catalog, which reflects hurricane risk under warmer-than-average sea-surface temperature conditions.

Each of these catalogs incorporates the latest scientific research and has undergone extensive peer review by leading scientists to provide a credible estimate of U.S. hurricane risk. Together, they provide the most scientifically advanced and sound approach to assessing U.S. hurricane risk available today.

This paper reviews the current state of research on climatological influences on hurricane activity, explains in detail the approach used to create AIR's Warm SST catalog, and addresses the role of these catalogs in a robust approach to assessing catastrophe risk.

Using Sea Surface Temperatures to Develop a Climate Conditioned View of Atlantic Hurricane Activity

A statistical analysis of Atlantic hurricane activity since 1900 concludes that basin activity is positively correlated with SST anomalies; the warmer the ocean, the higher the storm count. This makes physical sense because warm ocean temperatures are the primary fuel source for tropical cyclones.

Another closely correlated climate signal is the El Niño Southern Oscillation (ENSO). The ENSO+ phase (also known as El Niño) reduces counts of Atlantic storms. This also makes physical sense because the El Niño condition, which is characterized by anomalously warm SSTs over much of the tropical Pacific, also produces elevated levels of wind shear in parts of the Atlantic where tropical cyclones form—and wind shear inhibits tropical cyclone development.

While ENSO is secondary to SSTs in the degree of correlation, it is particularly important because upward trends in global temperatures may imply that both Atlantic SSTs and Pacific SSTs are increasing in unison. If the frequency of El Niño episodes increases because of rising Pacific SSTs, any existing correlation between El Niño and Atlantic SSTs might be altered. This is an area of future research at AIR.

While warm SSTs and ENSO conditions may persist for more than a year, other climate signals, such as the North Atlantic Oscillation (NAO), oscillate at a very high frequency (on the order of days to weeks) and are thus more aptly termed "weather signals" rather than "climate signals."

NAO is of particular interest not because of its correlation with the level of activity in the Atlantic, but rather as a predictor of the path that storms take. This has obvious implications for the probability that storms will make landfall. Because NAO is highly unpredictable on a seasonal time scale, however, it is of limited use.[1]

Therefore, the obvious starting point for developing a hurricane climatology conditioned on climate is to focus on the relationship between hurricanes and the most strongly correlated climate signal: sea surface temperatures.

Quantifying the Impact of Warm SSTs on Landfalling Hurricane Risk

It is AIR's intent that the methodology it employs in this relatively new area of research be completely transparent and reproducible. Therefore, the original research described herein has been submitted, and subsequently accepted for publication in the peer-reviewed *Journal of Applied Meteorology and Climatology*[2], and as a book chapter in *Hurricanes and Climate Change* (Springer).

Methodology

There are several challenges in estimating hurricane risk conditioned on any climate condition. The most important is the small sample of U.S. landfalling hurricanes contained in the historical record. The mean annual frequency of landfalling hurricanes is only about 1.7 per year, thus the record since 1900 only includes about 180 events.[3] That period is then further stratified into warm-SST and cool-SST years in order to study how landfall risk is modulated by warm SSTs. Doing so reduces the sample size still further.

The difficulty of extrapolating from a small sample is also apparent when we break the data down by region. Figure 3 contrasts the geographical distribution of hurricane landfalls during two periods of extended warm SSTs—from 1930 to 1960 in the left-hand panel and the current warm period beginning in 1995 in the right. In the earlier warm period, landfall activity was concentrated in the southeast—and in Florida, in particular. Since 1995, landfall activity has been more uniformly distributed along the Gulf and Southeast coasts. Of course, the current sample is still quite sparse and extrapolating from it carries its own risks; that is, it is difficult to determine

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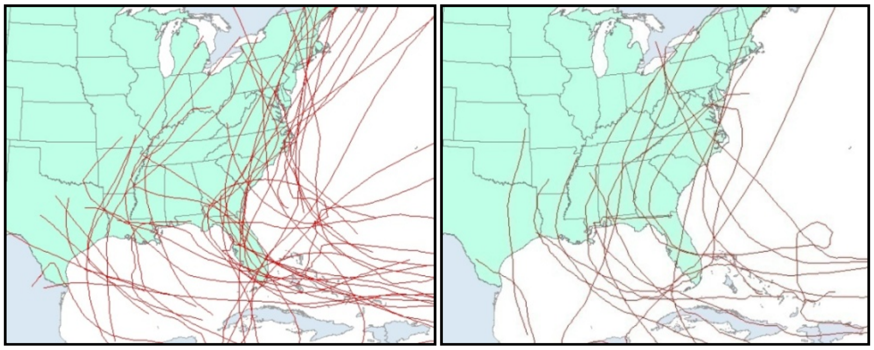
[1] See Appendix B for further details on various climate signals and their relationship with hurricane activity.
[2] An abstract of the article is available online here: http://ams.allenpress.com/perlserv/?request=get-pdf&doi=10.1175%2F2008JAMC1871.1.
[3] Data is available from NOAA for tropical cyclones dating back to the mid 1800s. However, there are several difficulties with pre-1900 data, including the possibility that parts of the U.S. coastline may not have been sufficiently inhabited to have recorded a landfalling hurricane. Also, there may be biases in intensity estimates for very old storms, even though the track and landfall location may be fairly clear. Wind speed data for very old storms is also quite sparse.

with a high degree of confidence what is likely to occur with respect to hurricane landfalls going forward, even assuming future conditions will be warm.

Figure 1. Hurricane Activity in Warm Years 1930-1960 (left) and 1995-2005 (right)



In order to quantify the impact of warm SSTs on regional U.S. landfall risk, the historical record of landfalling hurricanes was stratified into warm-year and cool-year seasons (based on the anomaly time series shown in Appendix B, Figure 7). A bootstrap distribution[4] was then developed to estimate the expected (mean) change in frequency associated with a warm ocean condition, and the confidence level surrounding that mean estimate.

The metric used is referred to as the Tropical Cyclone Index, or TCI, and is defined as follows:

$$\text{TCI} = \frac{\text{Annual mean landfall frequency for warm years}}{\text{Annual mean landfall frequency for all years}}$$

By repeatedly sampling landfall frequency from warm years, one can develop a TCI distribution at any level of intensity and for any region. The process is illustrated in Figure 2.

The top panel shows the historical record of U.S. landfalling hurricanes, with cool years in gray and warm years in black. Bootstrap samples are repeatedly drawn from the historical record, and the TCI for each sample is computed. For example, as shown in the middle panel, the first sample produces a hurricane landfall frequency that is 6% higher than the historical average, resulting in a TCI value of 1.06. The TCI for the second sample is 0.97 indicating a 3% reduction in landfall frequency for this sample of warm-year activity.

As this sampling process is repeated, the mean TCI for all samples will approach the value computed using the actual historical record. After about 5,000 repetitions, a mean value of 1.05 is reached, as shown in the bottom panel of Figure 2, which represents the full distribution of sample draws.

[4] Bootstrapping is a non-parametric method for estimating the sampling distribution of a statistical parameter.

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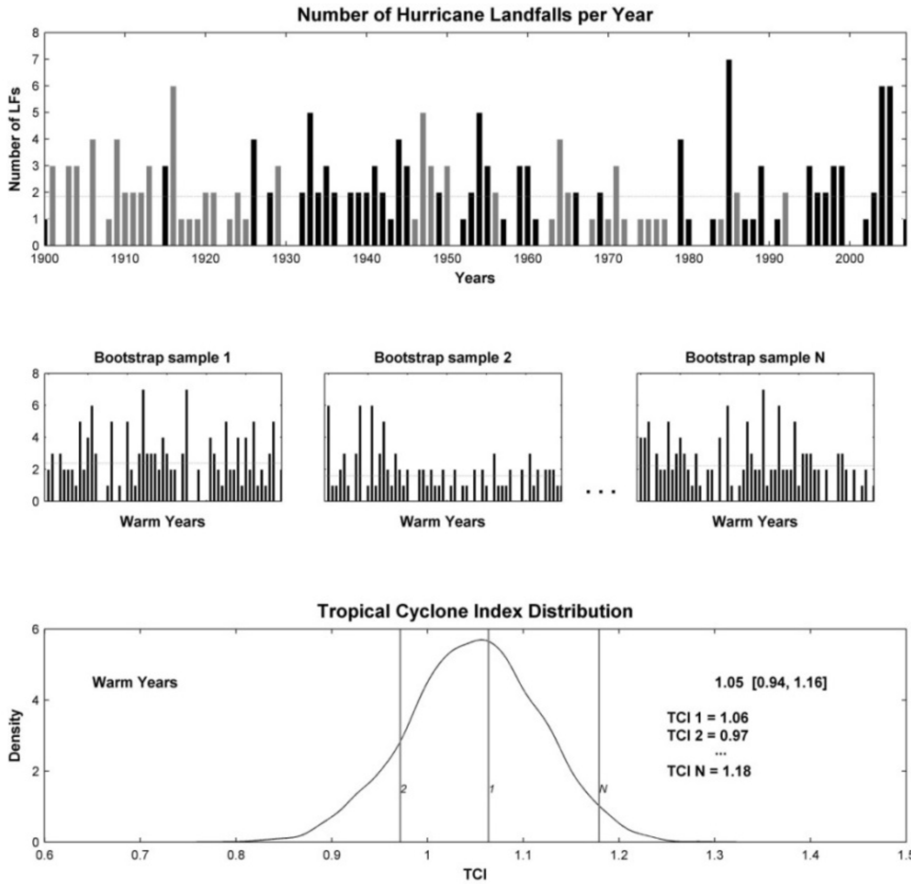
Figure 2: Technique Used to Develop a TCI Distribution for the Entire U.S.



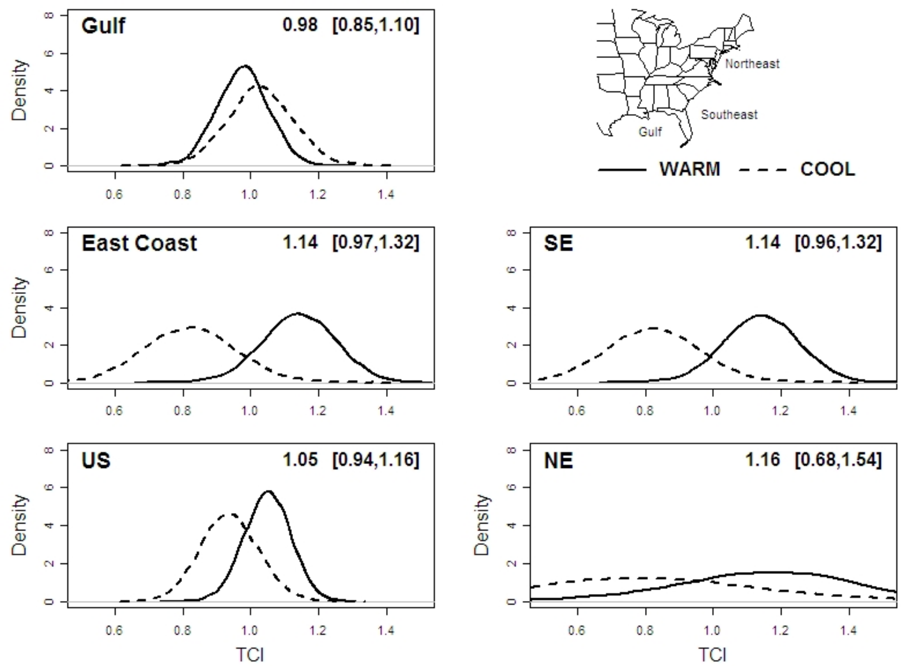
Such bootstrapped distributions are particularly useful in highlighting not only the *expectation* under warm SSTs, which in this case indicates a 5% increase in U.S. hurricane landfalls, but also the confidence around that estimate. The 90% confidence interval for this distribution ranges from the 5th percentile at a TCI of 0.94 to the 95th percentile at a TCI of 1.16. That is, one can say with 90% confidence that, on average, the effect of warm Atlantic SSTs on U.S. hurricane landfalls falls somewhere between a 6% decrease and a 16% increase.

Following the technique described above, AIR scientists estimated the relationship between warm SSTs and U.S. landfall risk for three coastal regions across the full, continuous spectrum of tropical cyclone intensity. The three regions are:

- Gulf (from Texas to Florida Keys)
- Southeast (from Florida Keys to Cape Hatteras)
- Northeast (from Cape Hatteras to Maine).

The results indicate that the effects of warm SSTs do indeed vary regionally, and the differences are statistically significant. In fact, the application of an across-the-board increase of 5% based on the mean TCI for the entire coastline would produce biases in estimated risk. The regional analysis is shown in Figure 3.

Figure 3: TCI Distributions for U.S. Coastal Regions under Warm and Cool SST Conditions



For reference, the U.S. TCI distribution from Figure 3 is shown in the bottom left panel. The dotted line in each panel represents the cool-SST counterpart to the warm-year TCI. The more the warm and cool distributions separate, the stronger is the correlation between warm SSTs and hurricane landfalls. When the analysis is carried out for Gulf Coast landfalls, the results (shown in the upper left panel) indicate that hurricane frequency is largely insensitive to warm SST conditions—that is, there is little difference in *hurricane* landfall frequency between warm and cool years. When the Gulf Coast data is analyzed across the full spectrum of intensity, the largest impact of warm SSTs is on tropical storms and weak, or marginal, hurricanes.

For the East Coast, the impact is larger and more significant. Nearly the entire 90% confidence interval is above 1.0, indicating a statistically significant increase in hurricane landfall activity in this region under warm ocean conditions. The expectation is for a mean increase of 14%, and as much as a 32% increase at the end of the 90% confidence interval.

The mean TCI for the Southeast increases with increasing intensity, indicating that the SST signal is particularly strong here and has its largest impact on strong hurricanes. This conclusion makes physical sense because most storms that make landfall along the Southeast coast at hurricane strength develop over the open Atlantic and therefore have a long expanse of ocean over which to travel and intensify. As SSTs grow warmer, this breed of storm is expected to become even more intense and maintain that strength to landfall. This is in contrast to the Gulf coast where many hurricane landfalls originate within the Gulf of Mexico and have little time to intensify before making landfall.

The East Coast was further divided into Southeast and Northeast regions. Upon inspection of Figure 3, it is clear that the primary impact of warm SSTs is along the Southeast coastline. There are very few historical landfalls along the Northeast U.S., rendering wide TCI distribution with no statistical significance.

It is worthwhile noting that the sharp increases in Southeast hurricane landfall frequency are tempered from the perspective of the entire U.S. because, historically, two-thirds of hurricane landfalls occur along the Gulf Coast. This explains why the mean TCI for the entire U.S., at 1.05, is much lower than the mean TCI of 1.14 for the Southeast alone.

TCI distributions were computed for other regions to cross-check these results and to determine where the statistical significance is strongest. For example, the state of Florida was treated as a separate region and both coasts of Florida were compared to the TCI results for their respective regions. The TCI for Florida's west coast was very similar to that of the Gulf region, but Florida's east coast had a lower mean TCI than that of the Southeast. Given these indications, the Southeast was further divided into Southeast/Florida and Southeast/Carolinas, and TCI estimates for these sub-regions were computed and incorporated into the AIR Warm SST catalog.

Once the analysis was completed and the sensitivities understood, the AIR research team developed a set of mean regional TCIs by storm region and intensity. Although the analyses were carried out across the full intensity spectrum, the results have been summarized here by Saffir-Simpson category for simplicity. Since the low frequency of hurricane landfalls in the Northeast makes it difficult to draw statistically sound conclusions, changes along this part of the U.S. coastline are restricted to coastal segments adjoining the Southeast for a smooth transition from one region to the next.

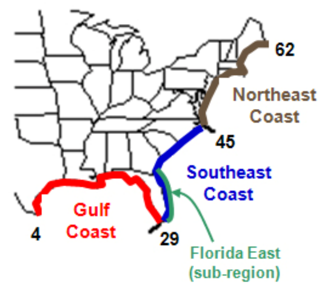
Frequency adjustments in the Warm SST catalog reflect the expected impact on U.S. hurricane landfall frequency of the "*typical*" warm-SST year under current climate conditions.

Figure 4 shows the extent to which regional hurricane frequencies in the Warm SST catalog deviate from the Standard catalog. TCI (Tropical Cyclone Index) values have been converted to percent change. Note the 90% confidence intervals are not reflected in the catalog adjustments, but care has been taken to ensure than the mean TCI is applied where there is a combination of statistical significance and meteorological support for such adjustments.

Figure 4: TCIs for U.S. Coastal Regions[5]

REGION	COASTAL SEGMENTS	CAT	FREQUENCY ADJUSTMENTS	
Gulf Coast	04 to 28	1	6.0%	
		2	1.2%	
		3	1.1%	
		4	15.0%	
		5	15.1%	
Southeast Coast	29 to 44	1	15.0%	15.0%
Florida East	29 to 35	2	15.3%	10.2%
		3	29.4%	10.4%
		4	29.1%	15.2%
		5	27.7%	14.8%
Northeast Coast	45 to 62	1	1.1%	
		2	1.2%	
		3	1.1%	
		4	0.9%	
		5	0.0%	

Regional Definitions



Sensitivity and Stress Tests

Several sensitivity tests were carried out to verify regions and storm intensities where the strongest correlations exist between hurricane landfall and warm SSTs. For example, stress tests examined the sensitivity of the results to (a) the addition of data for one more season, (b) the addition of storms that bypass the coast without making landfall, (c) the treatment of multiple landfalling hurricanes as separate events, (d) the use of a different landfall intensity measure (central pressure instead of wind speed), and (e) the addition of different coastal regions (e.g., the Florida coastline). The results of these sensitivity analyses indicate that the results of the study are robust and dependable.

Results were most sensitive to the choice of using the wind speed at landfall versus the central pressure at landfall. This analysis showed that, for the Gulf region, larger increases in frequency are indicated, especially for strong hurricanes. This is likely the result of a unique relationship in the Gulf between wind speed and central pressure, and merits further study. For the entire U.S. coastline, the analysis indicates an increase in frequency of hurricane landfalls under warm SSTs closer to 10%. In the end, the frequency adjustments incorporated into the Warm SST catalog reflect a balance between the TCI analyses using wind speed and the analyses using central pressure at landfall.

[5] Frequency adjustments are based on a balance of statistical significance, signal strength, scientific literature, stability across regions and AIR's latest body of hurricane climate research.

In addition, a physics-based analysis of where storms form, how they intensify, and where they track was carried out in parallel with the statistical TCI analysis. The results of this research have been accepted for publication in the peer-reviewed *Journal of Applied Meteorology and Climatology*. Preliminary results of the physical analysis not only reinforce the statistical analysis, but have also identified portions of the Atlantic where the life cycle of tropical cyclones is particularly sensitive to warm SSTs.

As AIR's climate research program goes forward, the combination of statistical and physical analysis will continue to play a role. Not only do physical analyses establish increased confidence in the statistical results, but they also reveal the most important storm development mechanisms relating to climate.

Peer Review of AIR's Approach By Leading Scientists

In addition to that performed by reviewers for the *Journal of Applied Meteorology and Climatology*, AIR's research into hurricane landfall risk under a regime of warm SSTs has been rigorously peer reviewed by several respected scientists in the field, including MIT's Dr. Kerry Emanuel, Dr. James Elsner at Florida State University and Dr. Timothy Hall from NASA/GISS. Here are brief excerpts from their reviews:

> "[AIR follows a] wise strategy, allowing one to make inferences about the effect of very basic SST variability on hurricane activity without unduly stressing the statistical significance of results based on the limited best track data"
>
> *Dr. Kerry Emanuel, MIT*

> "I agree with AIR's decision to switch from an SST point forecast to a category forecast (warmer vs. colder) for its near-term catalog.[6] SST has a significant influence on TC landfall rates, but the forecasts are not reliable enough to warrant precision beyond broad categories. Overall, I judge AIR's North American tropical cyclone (TC) analysis to be sound and of high quality."
>
> *Dr. Timothy Hall, NASA/GISS*

> "The AIR model uses an autoregressive model to justify a warm/cold epoch, but it does not predict the magnitude of the anomaly. This is a reasonable approach given the large uncertainty in 5-year predictions of SST."
>
> *Dr. James Elsner, Florida State University*

[6] For a discussion of the change in methodology between AIR's "near-term" catalog in Version 8.0 of the U.S. Hurricane Model and the Warm SST catalog in Versions 9.0 and 10.0, please see Appendix B.

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A Practical and Robust Approach to Risk Assessment

Each of AIR's two U.S. hurricane catalogs incorporates the latest scientific research and has undergone extensive peer review by leading scientists to provide a credible estimate of U.S. hurricane risk. Together, they provide the most scientifically advanced and sound approach to assessing U.S. hurricane risk available today.

In this section we address the role of these catalogs in a robust approach to assessing catastrophe risk.

Sources of Uncertainty

Sea surface temperatures in the North Atlantic basin are currently above the long-term average, and have been since about 1995. Some scientists believe we are currently in the warm phase of the Atlantic Multidecadal Oscillation, a climate signal with an irregular periodicity that spans decades. Others believe that surface temperatures are elevated because of, among other natural mechanisms, the anthropogenic accumulation of greenhouse gasses in the atmosphere, and that additional variability in SSTs is caused by episodic events, such as volcanic activity.

It is the job of scientists to investigate and posit such theories to explain physical phenomena. Competing theories nourish scientific debate, but arriving at a consensus can be a lengthy process. Until a consensus is reached, considerable uncertainty exists.

In the case of the relationship between elevated SSTs in the Atlantic and hurricane *landfalls* in the U.S., the uncertainties are significant in part because that particular link has historically not been the focus of investigation by the scientific community. AIR is doing its part to fill the gap with original, peer-reviewed, and published research. The statistical models developed by AIR do suggest a correlation between Atlantic SSTs and hurricane landfalls for some coastal regions, but even where correlations are significant, they are not strong.

It is worth pointing out that when the AIR U.S. Hurricane Model was first developed and released—back in the 1980s—the Atlantic was in the middle of a prolonged period of cool SSTs and below-average hurricane activity. At that time, AIR encouraged companies to use the Standard model, based on the entire historical record, because it reflected the expected level of risk. If companies had priced based on the below-average activity prevalent at the time, they would have underestimated the long-term risk.

Hurricane seasons like 1992, which occurred under below average ocean temperatures, illustrate that just one major hurricane landfall like Hurricane Andrew can develop, intensify, and make landfall as a major hurricane even under suboptimal SST conditions. The reverse also holds true, namely, that even under favorable conditions driven by a warm Atlantic, hurricane landfall activity can be average or even below average, as they were in 2000, 2001, 2002, 2006 and 2007.

The purpose of a catastrophe model is to estimate current risk. However, focusing on just a few seasons, no matter how recent, can result in an over- or under- estimation of risk.

Another source of uncertainty is recent scientific research that indicates that, in a warming world, the Atlantic may experience two primary effects related to hurricane development. First, a warmer environment may continue to elevate SSTs, thereby providing more fuel for tropical cyclones. Second, there may be a trend for more frequent or more intense El Niño events that may increase wind shear in the Atlantic—an unfavorably condition for tropical cyclone development and intensification. While it is true that warmer SSTs may lead to more frequent hurricane landfalls, elevated wind shear may counteract this effect. Which effect will ultimately dominate is the subject of lively debate.

Robust Risk Assessment Using a Multiple Catalog Based Approach

The relationship between tropical cyclone activity in the Atlantic and the risk of hurricane landfall in the U.S. is an ongoing and extremely active research project at AIR. While one might naturally assume that a given increase in Atlantic basin activity translates directly to a similar level of inflated risk of landfall, the relationship is not so simple. Rather, it is a function of many factors, including where storms form, how they intensify, and the region of interest along the U.S. coastline.

Combining all three areas of research, AIR scientists estimated the relationship between warm SSTs and U.S. landfall risk for three coastal regions across the full spectrum of intensity. The result is the Warm Sea Surface Temperature (Warm SST) catalog, which is provided along with the Standard catalog as part of the AIR U.S. Hurricane Model.

The Warm SST catalog does not forecast risk; instead it estimates the sensitivity of landfall risk to a typical warm ocean condition.

It is well known in the scientific community that several equally credible, though different “opinions” of what the future may hold (what is known as an ensemble) is always preferable to a single opinion. Thus by providing two catalogs with its U.S. Hurricane Model, AIR encourages clients to assess variability and uncertainty, which are fundamental to managing risk.

The use of one or both catalogs is a determination that can only be made by the consumer of the information, each of whom has a unique combination of risk appetite, business case, and regional exposure to risk.

AIR is committed to explaining to its clients how the two catalogs are developed, how they differ, and how they can be used to optimize risk management. Because both are developed using sound scientific principles, together they constitute the most advanced and reliable hurricane model available on the market today.

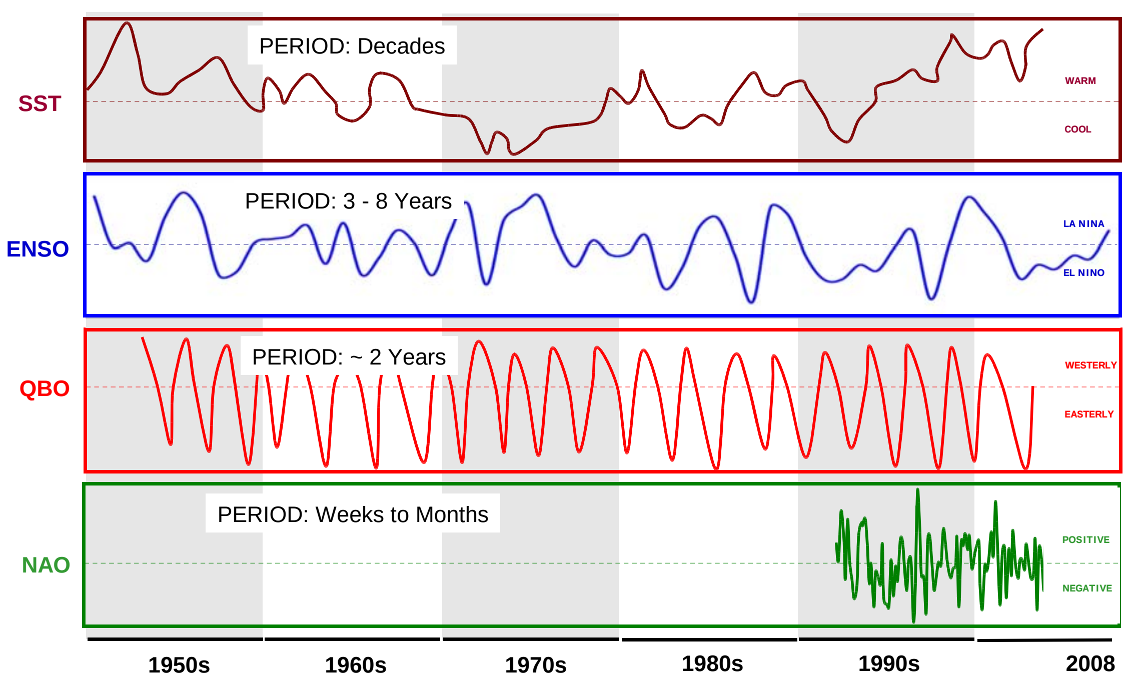
APPENDIX A: Climate Mechanisms that Influence Atlantic Hurricane Activity

There are at least four important mechanisms within earth's environment that affect hurricane activity. These mechanisms are correlated with a variety of climate signals, which are measurements of the natural feedback systems of the earth in its effort to maintain equilibrium. Climate signals are typically presented as a measurement of anomalies, or deviations from the mean.

For example, the hurricane "engine" gets its fuel in the form of heat and moisture from the ocean's surface. The warmer the ocean, the more heat energy is available to tropical storms. The Atlantic Multidecadal Oscillation, or AMO, is a climate signal measuring the change in the sea surface temperature (and salinity) of the North Atlantic. The AMO has received particular attention in light of the 2004 and 2005 hurricane seasons and is thought by some to hold the key to recent elevated levels of hurricane activity.

Because it is a measure of sea surface temperature anomalies, which are correlated with hurricane activity, the AMO has been used to predict near-term hurricane activity. However, as can be seen in Figure 5, its periodicity is the least regular of the climate signals that have been associated with tropical cyclones. Thus forecasts using the AMO are characterized by significant uncertainty.

Figure 5. Periodicity of Climate Signals Affecting Conditions in the Atlantic



The widely known El Niño Southern Oscillation (ENSO) measures temperature anomalies in the Pacific Ocean off the coast of Peru. The effect of ENSO on hurricane activity is well documented and stems from its impact on wind shear over the tropical Atlantic. Wind shear is a measure of how quickly air currents above the ocean surface change with height. Wind shear is generally destructive to hurricanes and can limit a hurricane's potential intensity.

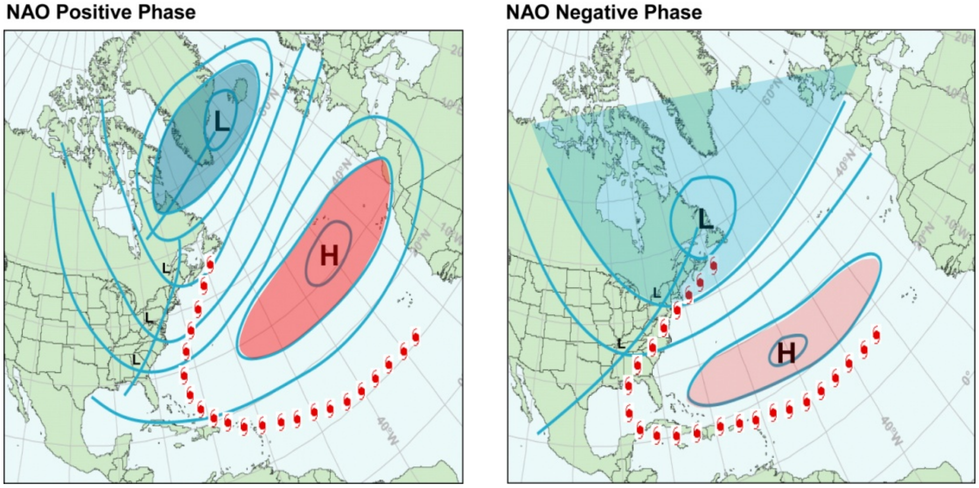
La Niña years are typically characterized by increased activity, while activity is lower in El Niño years. However, the period of ENSO is too irregular to make it very useful for forecasting hurricane activity over a five year time horizon. During that period, the opposing effects of La Niña and El Niño could largely cancel each other out, or the ENSO signal could remain relatively neutral.

The Quasi-Biennial Oscillation (QBO) is a climate signal that tracks the direction of the equatorial winds in the stratosphere. These currents, which can be more than 20 kilometers above the ocean surface, have been linked to hurricane activity. The hypothesis is that when these winds blow from west to east, they have a positive impact on hurricane formation by allowing the storms to more efficiently vent air out the engine's "exhaust".

As Figure 6 shows, the periodicity of the QBO is the most regular. However, while the QBO is the easiest signal to forecast, it has the weakest correlation with hurricane activity.

Figure 6: The North Atlantic Oscillation (NAO) Impacts Hurricane Tracks

NAO Positive Phase **NAO Negative Phase**



Finally, air currents at a level a few kilometers above the ocean surface steer tropical storms. These currents respond to the distribution of atmospheric pressure. In particular, an area of high pressure in the mid-Atlantic known as the "Bermuda High"—closely related to the North Atlantic Oscillation (NAO)—tends to steer tropical storms to the west and eventually to the north.

In particular, when the Bermuda High is in a more southwesterly position, hurricanes are more likely to make landfall than when the high is further north and east, off the northern African Coast (Figure 6).

Because the NAO has a significant impact on atmospheric steering currents and therefore hurricane tracks, it is theoretically a valuable metric for forecasting the geographical distribution of hurricane *landfall* locations. However, the NAO varies in response to the atmospheric pressure distribution over the Atlantic, which changes on a very short time scale (weeks to months). Thus the predictability of the NAO decays quickly, rendering it virtually useless for forecasting hurricane activity five years out.

Of the four climate signals most closely correlated with hurricane activity, recent scientific research has focused on the AMO because it is the only signal whose period spans more than five years.

Very recent research is beginning to unravel the complexities of how multiple climate factors combine to influence tropical activity. A new climate signal, known as the Atlantic Meridional Mode or AMM, is based not on a single observed factor like SST or SLP, but on a hybrid of combined factors weighted on their relevance to the tropical cyclone development. By combining SST anomalies with levels of wind shear and other important physical mechanisms that foster and inhibit TC development, the AMM almost acts as a multi-factor metric regressed on a combination of ocean and atmosphere factors that influence activity.

Integrated metrics like the AMM are also more physically explainable and relates more closely to aspects of risk that are commonly studied such as frequency, intensity, duration, and track. This is not surprising since AMM explains more variance in the factors that underlie storm development. More work is needed, but as the research matures, scientists will be better able to relate hurricane activity to climate, and eventually improve on predictions beyond a year.

APPENDIX B: Change in AIR's Methodology for Assessing Near-term Hurricane Risk

AIR first introduced an alternative catalog for assessing near-term hurricane risk in Version 8.0 of its U.S. hurricane model. This Appendix examines first the motivation for the development of an alternative U.S. hurricane catalog, reviews the prior methodology implemented in Version 8.0 and explains the motivation for the change in approach implemented in Versions 9.0 and 10.0.

Motivation for the Development of an Alternative U.S. Hurricane Catalog

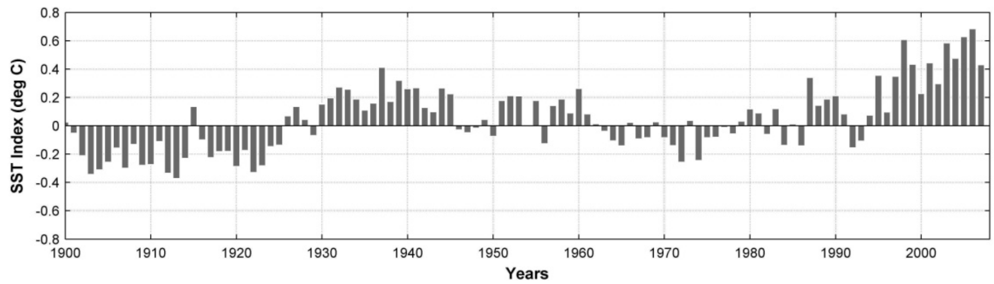
Hurricanes are well understood meteorological phenomena. Hundreds of scientists have for decades studied their formation and subsequent life-cycles. It is also widely accepted that hurricane activity—in terms of both frequency and intensity—has fluctuated over the past 100 years, with alternating periods of low and high activity.

Research into these fluctuations began decades ago, starting in the 1980s. One of the earliest researchers was Dr. William Gray at Colorado State University. At the time, Dr. Gray promoted the work of oceanographer Wally Broeker, who put forward the theory that there is a global "conveyor belt" that transports warm water from the Pacific through the Indian Ocean and into the open Atlantic. Gray and his colleagues identified distinct periods of relative activity and inactivity in this conveyor, or ocean circulation, over the last 100 years that resulted in periods of anomalously warm or anomalously cool SSTs in the Atlantic. They further determined that several important atmospheric phenomena—including hurricanes—correlate with the strength of the conveyor. The cycle, which is theorized to last for several decades, has been branded the Atlantic Multidecadal Oscillation, or AMO.

Figure 7 shows the historical record of SST anomalies measured over most of the northern Atlantic Ocean starting in 1900. Values greater than zero indicate warm ocean temperature anomalies. At first glance, there do appear to be extended periods of warm and cool temperatures, but the historical record is short and there is significant uncertainty in extrapolating beyond it.

Since Gray's work, other researchers active in the field of hurricane dynamics have tied extended periods of ocean warmth to a combination of trends in the solar cycle, episodic events like volcanic eruptions, and increases in aerosols from the burning of fossil fuels. The study of how anthropogenic, or human-induced, effects are realized in the environment is a complex area of research on its own. Still, while some would argue that the Atlantic undergoes cyclical periods of high and low activity, others would counter that there is no physical basis to support the idea of a multi-decadal cycle. Instead, this group would argue that climate change today is being driven by the continual release of greenhouse gases, and this will continue to warm the oceans of the world.

Figure 7: North Atlantic Sea Surface Temperature (SST) Anomalies (Jun-Nov)



Despite the debate, two facts remain. First, the North Atlantic has been warmer than the long-term average every year since the mid-1990s.[7] Second, whether the current climate state is being driven by the warm phase of the AMO or is induced through global warming, it is *likely* that the Atlantic will remain warm in the near future. Oceans have enormous volume and heat capacity, which results in thermal inertia. That is, oceanic systems do not undergo rapid change.

If one knew with 100% certainty that SSTs in the coming years would remain warm, then it is reasonable to estimate hurricane risk conditioned on hurricane activity that has occurred under warm ocean conditions. Recognizing this, AIR embarked on a research program to study the impacts of warm SSTs on Atlantic hurricane activity and U.S. hurricane landfall activity, in particular.

However, while such an analysis is useful, it must be cautioned that a stochastic catalog built to reflect risk under the warm SST condition will have more uncertainty than one built on the entire historical record, including both warm and cool years, for a variety of reasons. First and foremost, a hurricane climatology built on years that have been anomalously warm—roughly half the full historical record—will be inherently less certain because it is based on a smaller data sample.

It should also be noted that conditioning estimates of hurricane risk on a climate signal such as warm ocean temperatures implicitly assumes that *all other relevant climate factors are held constant*. Yet there are several other climate oscillations that are known to impact hurricane risk in the Atlantic, including but not limited to ENSO (El Niño Southern Oscillation), NAO (North Atlantic Oscillation), and SAL (Saharan Air Layer).[8] The sensitivity of hurricane activity to these other factors can, in some seasons, overcome the effect of warm SSTs. For example, it is well recognized

[7] This also holds for Atlantic SSTs during the months of the hurricane season. The anomalies in Figure 7 were computed during the months of the hurricane season (June to November) and indicate a persistently warm Atlantic since about 1995.

[8] For further details on climate mechanisms that influence Atlantic hurricane activity, please see Appendix A.

that despite warmer than average Atlantic SSTs in 2006 and 2007, those years saw average or below average levels of activity due to the combined effects of these and other climate factors.

Finally, in terms of actual usage of a warm SST-conditioned catalog, it is *not* known with 100% certainty that the Atlantic will remain anomalously warm. Therefore, there is uncertainty in the very decision as to whether to base risk management decisions on a climate conditioned catalog.

For all of these reasons, AIR has consistently offered its catalog for assessing hurricane risk in the near-term as a supplement to, rather than a replacement for, its standard catalog.

Methodology Employed in the Development of the Version 8.0 "Near-term" Catalog

In April 2006, AIR released a "near-term catalog" of stochastic storms in Version 8.0 of its U.S. Hurricane Model. The methodology used to create AIR's first climate-conditioned catalog was to *forecast* Atlantic SST anomalies for the next 5 years, and then correlate the anomalies to changes in landfall risk along the U.S. coastline. The resulting catalog, which was released in Version 8.0 of the AIR U.S. Hurricane Model, represented the potential for increased hurricane risk over the five year period from 2007 to 2011—the "near term."

Frequency changes based on an SST forecast, which projected a warmer than average Atlantic for the entire 5-year period, were estimated for 11 sections of the U.S. coastline, and intensity changes were estimated for each category in the Saffir-Simpson scale. The near-term catalog was then generated by populating a stochastic catalog with more frequent draws of landfalling storms. In some regions, where frequency increases were most pronounced for intense hurricanes, the impact on insured loss was dramatic.

That catalog represented the potential for increased hurricane risk over the five year period from 2007 to 2011 and was based on a specific *forecast* of what sea surface temperatures (SSTs) in the North Atlantic were likely to be over that period.

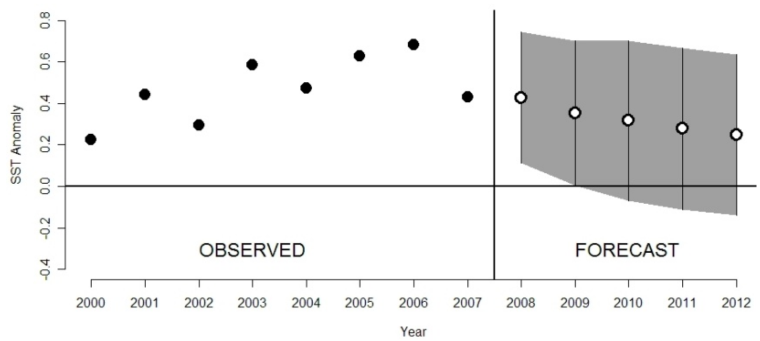
Motivation for the Change in Methodology and the Adoption of a "Warm SST" Catalog

The primary motivation for a change in the methodology used to develop a climate-conditioned hurricane catalog was the recognition of the considerable uncertainties inherent in any multiple-year forecast of SSTs. Other minor changes were motivated by a re-examination of the sensitivity of frequency increases by region and by intensity.

Quantifying the Uncertainties in Near-term Forecasts

For Version 8.0, AIR researched the best available techniques available to forecast SST anomalies beyond a season. It is known that numerical weather prediction (NWP) models lack skill in such forecasts beyond about 9 months. One approach for multi-season forecasts involves the use of autoregressive models, which rely on the correlation of current anomalies to those observed in prior seasons. Such a technique applied to the Atlantic reveals that significant correlations persist with a lag of up to 3 years. Thus, an autoregressive model which projects anomalies based on two time lags (i.e., an AR2 model) can be applied. Applying an AR2 model to the time series of Atlantic SST anomalies produces the forecast shown in Figure 8. While Figure 8 does suggest that the Atlantic will remain warmer than average over the next five years, the 95% confidence bounds (shown in gray) are quite wide around the point forecasts.

Figure 8: Sea Surface Temperature (SST) Anomalies Projected Using an Autoregressive Forecast Technique



This and other subsequent research led to the conclusion that the level of uncertainty in a 5-year SST forecast is too large to merit the inclusion of a forecast in a climate conditioned hurricane catalog, as had been done for the Version 8.0 release. However, while confidence in the SST point forecasts is low, the confidence intervals around the projected anomalies are largely positive at this point in the observed record.

While it is difficult to predict just how warm the Atlantic will be for the next five years, as of 2007, one can say with more confidence that the Atlantic will remain warmer-than-average in the coming years.

Understanding the Sensitivity of Frequency Increases by Region and by Intensity

With respect to the regional analysis performed by AIR, it was determined that rather than the original 11 regions incorporated in the Version 8.0 release, three larger regions would allow for more robust estimates because each would be based on a larger sample size. (Some of the original 11 coastal regions had little historical landfall data, and were therefore leading to a higher level of uncertainty in the correlation to SSTs.) In addition, the three newly-defined coastal regions have a more logical physical connection to generation of storms in the basin.

Further, while the Saffir-Simpson scale is a useful convention for characterizing individual events, it is more useful to analyze the influence of climate on a continuous spectrum of tropical cyclone intensity. This approach was also implemented in the version 9.0 and 10.0 catalogs.

In Summary

A significant portion of the higher uncertainty embodied in the version 8.0 near-term catalog stemmed from the uncertainty in the multi-year SST point forecasts on which it was based (that is, forecasts that the Atlantic will be anomalously warm by some *specific* number of degrees).

Therefore, in 2007, AIR developed a catalog conditioned not on *point* forecasts, but instead on the broader, scientifically-accepted projection that sea-surface temperatures are likely to remain elevated for the next several years.

While the changes to the definitions of region and intensity did not materially affect the methodology used to generate the climate conditioned catalog, the replacement of an SST forecast with a more confident warm SST condition is an important one. To emphasize the importance of the change, AIR renamed the catalog from the "Near-term" catalog to the "Warm SST Conditioned" catalog. The new name better reflects its meaning—which is an estimate of risk under typical warm ocean conditions, not a forecast of risk over the near term.

Simply put, the new approach was adopted because there is more certainty in the statement that SSTs will be warmer than average over the next five years than that they will be warmer by a specific number of degrees. An added benefit of this approach is that the inclusion of one additional season of hurricane landfall experience will not significantly change estimates of climate-conditioned risk and the Warm SST catalog will yield more stable results going forward.

About AIR Worldwide Corporation

AIR Worldwide Corporation (AIR) is the scientific leader and most respected provider of risk modeling software and consulting services. AIR founded the catastrophe modeling industry in 1987 and today models the risk from natural catastrophes and terrorism in more than 50 countries. More than 400 insurance, reinsurance, financial, corporate and government clients rely on AIR software and services for catastrophe risk management, insurance-linked securities, site-specific wind and seismic engineering analyses, and property replacement cost valuation. AIR is a member of the ISO family of companies and is headquartered in Boston with additional offices in North America, Europe and Asia.