# Understanding Climatological Influences on Hurricane Activity: The AIR Near-term Sensitivity Catalog





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## Restrictions and Limitations



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# Introduction

For the 2006 hurricane season, AIR will offer three stochastic catalogs for its U.S. hurricane model: the standard catalog, which is based on over 100 years of historical data and over 20 years of research and development; a near-term sensitivity catalog, which reflects recent research on the influence of sea surface temperatures (SSTs) on near-term (~5 year) hurricane activity; and a 2006 seasonal hurricane catalog that accounts for the influence of current climate signals on hurricane activity for the upcoming season.

This white paper provides a review of the current state of research on climatological influences on hurricane activity and explains the approach used to create the AIR near-term sensitivity catalog, which quantifies the impact of SST forecasts on insured losses for the next five years.

# Understanding Fluctuations in Hurricane Activity

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

Research into these “cycles” began as long ago as the 1980s. One early researcher was Dr. William Gray at Colorado State University. Dr. Gray promoted the work of oceanographer Wally Broeker, who suggested that there is a global “conveyor belt” that transports warm water from the Pacific through the Indian Ocean and into the Atlantic. Gray and his colleagues identified distinct periods of relative activity and inactivity in ocean circulation over the last 100 years and determined that several important atmospheric phenomena—including hurricanes—correlate with the strength of the conveyor. However, the underlying mechanisms that cause such cycles are still not known.

Forecasting hurricane activity on a short time horizon, such as a year or a few years ahead, is very difficult because of the many climatological factors that influence hurricane activity—and landfall activity in particular—in the North Atlantic.

## Climatological Influences on 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.

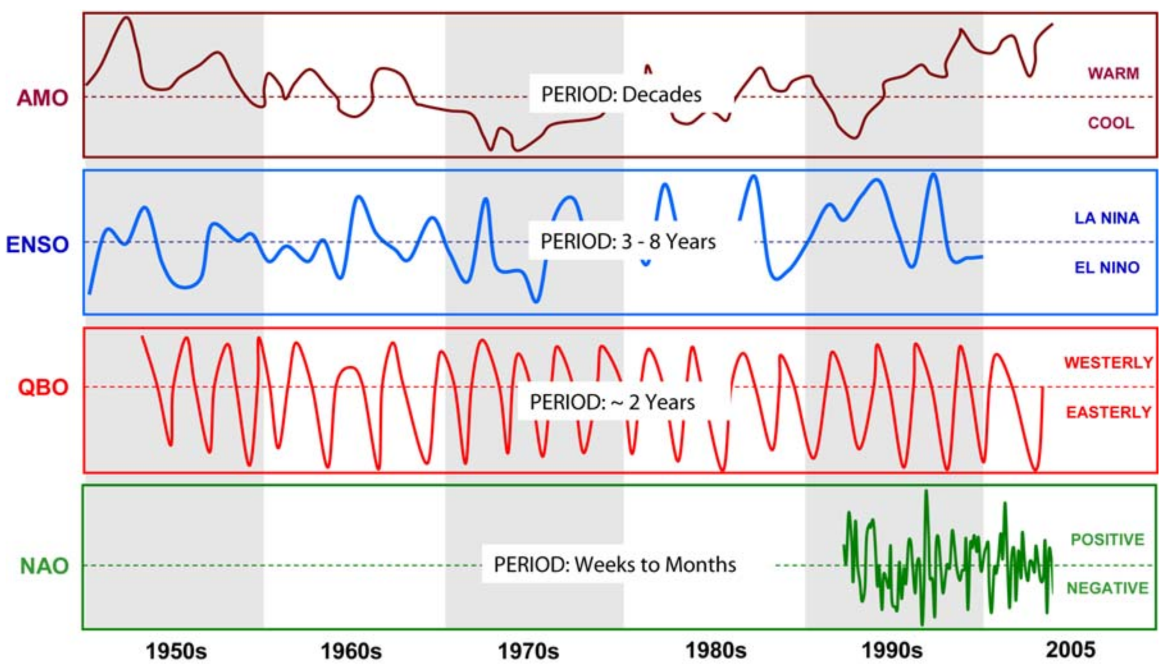
For example, the hurricane “engine” gets its fuel in the form of heat and moisture from the ocean’s surface. The warmer the ocean, the more heat energy is available to tropical storms. The Atlantic Multidecadal Oscillation, or AMO, is a climate signal measuring the change in the sea surface temperature (and salinity) of the North Atlantic. The AMO has received particular attention in light of the last two 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 1 below, 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.

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.

**Figure 1: Periodicity of Climate Signals Affecting Conditions in the Atlantic**



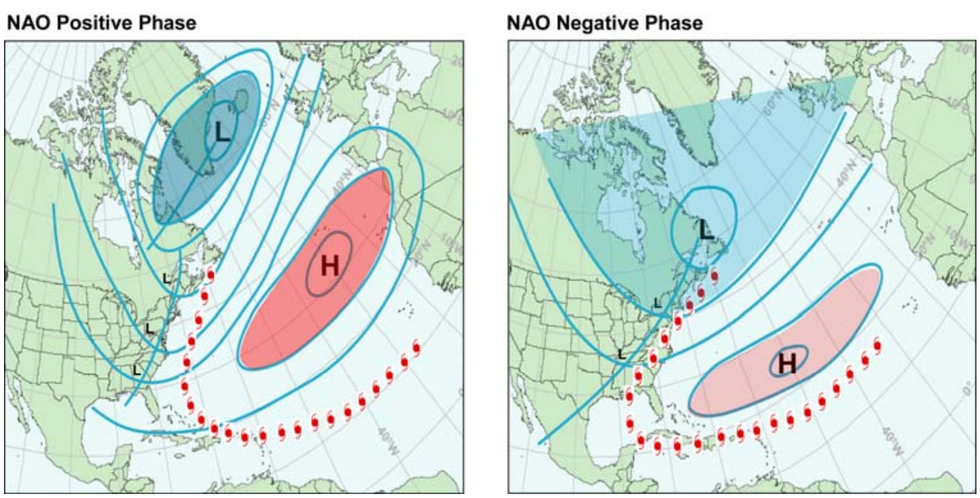

The Quasi-Biennial Oscillation (QBO) is a climate signal that tracks the direction of the equatorial winds in the stratosphere. These currents, which can be more than 20 kilometers above the ocean surface, have been linked to hurricane activity. The hypothesis is that when these winds blow from west 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 1 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.

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 American 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 2).

**Figure 2: The North Atlantic Oscillation (NAO) Impacts Hurricane Tracks**




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.

## Sea Surface Temperatures and Hurricane Activity in the North Atlantic

Over the last 100 years, sea surface temperatures (SSTs) have undergone fluctuations. Some scientists believe these oscillations are periodic—on the order of decades or even multiple decades—and are distinct from any long-term monotonic global warming trend.

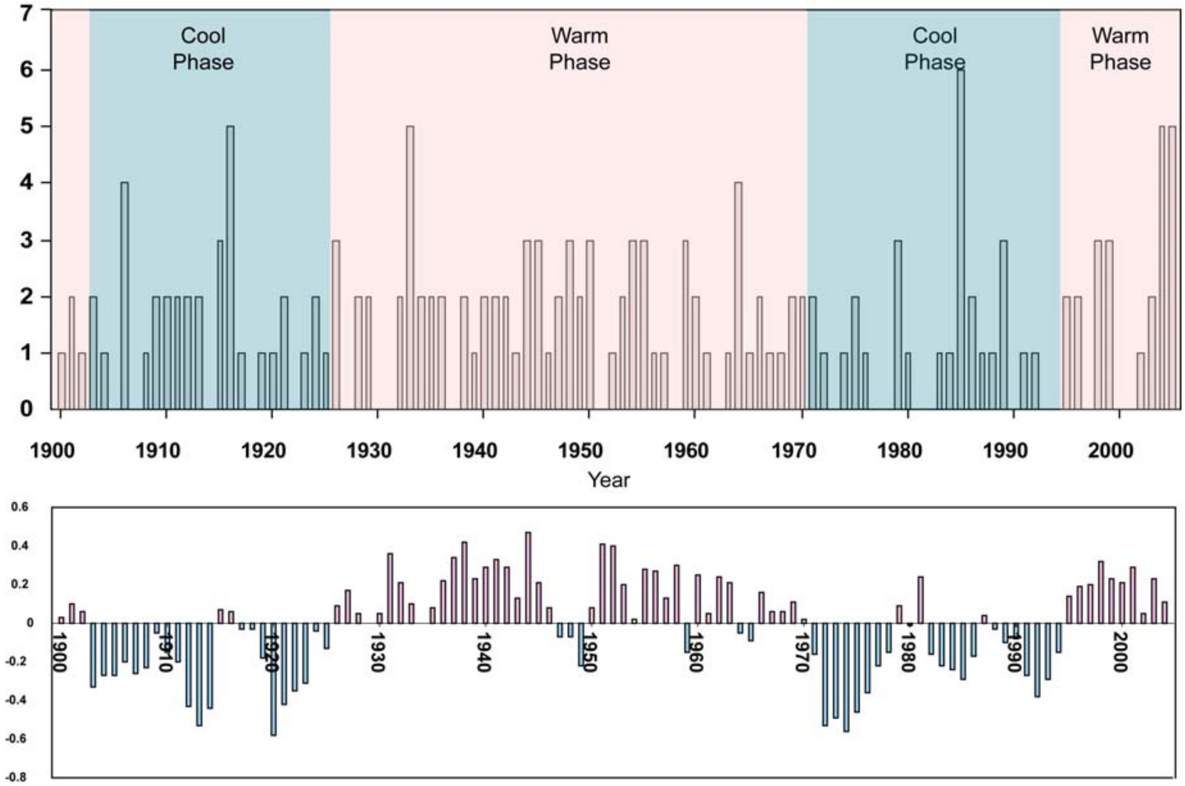
Various theories have been posited as to why these fluctuations occur. However, as yet, there is no clear scientific consensus. One theory suggests that the fluctuations are the variability in the ocean's thermohaline circulation. Another attributes fluctuations to near-decadal cycles of sunspot activity. Other scientists believe that the primary driver of SST fluctuation is the release and subsequent decay of aerosol sulfates produced by episodic volcanic activity (occurring at random) and the initial stages of industrialization.

As SSTs have fluctuated over the last 100 years, so too has hurricane activity in the North Atlantic. Evidence suggests that there is a correlation between the two phenomena—specifically, that increased SSTs are positively correlated with hurricane activity.

Since 1995, the Atlantic basin has been in an active, or warm, phase characterized by elevated SSTs and above long-term average hurricane activity. Some scientists, including those at the National Oceanic and Atmospheric Administration, associate this with the warm phase of the AMO. The AMO is typically theorized to be caused by variability in ocean circulation as influenced by water temperatures and salt content (thermohaline). Its multi-decadal periodicity is explained by the slow response of the ocean and ice sheets to changing air temperature. While the AMO is just one of several measures of Atlantic sea-surface temperature anomalies, other measures are also indicating ocean temperatures above the long-term climatology.

Figure 3 shows the annual frequency of U.S. landfalling hurricanes between 1900 and 2005 relative to the AMO index. The AMO index value represents a temporal reconstruction of SST anomalies averaged over the region of the North Atlantic bounded by $45^o$-$65^o$ North, and $60^o$-$20^o$ West. While it is evident from Figure 3 that a positive index is related to higher frequency, it is far from a perfect correlation. Some years with a positive index have low frequency and other years with a negative index show relatively high frequency. For this reason, and to smooth out the shorter term impacts of other climatological factors discussed earlier in this paper, scientists have more broadly defined warm and cool AMO phases, also illustrated in Figure 3.

**Figure 3: Frequency of Landfalling Hurricanes Relative to the AMO Index**



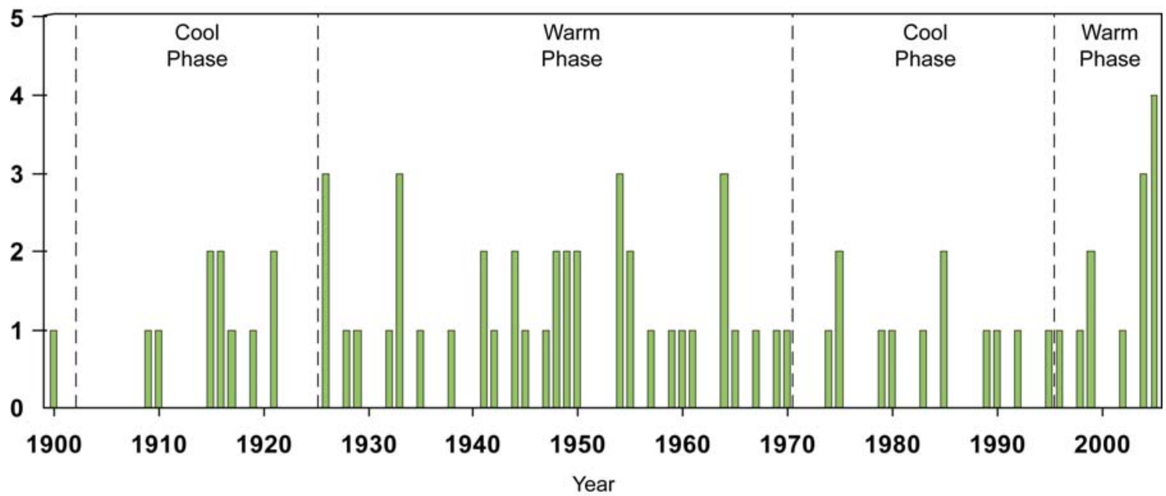

The table that follows shows a few summary statistics that emerge from an analysis of the data.

| | Mean Frequency | 95% Confidence Interval |
|---|---|---|
| Entire period (1900 – 2005) | 1.59 | 1.34 – 1.84 |
| Combined warm phases | 1.82 | 1.49 – 2.15 |
| Combined cool phases | 1.34 | 0.96 – 1.72 |

The size and overlap of the 95% confidence interval shown above indicates the significant uncertainty stemming from the small sample size. Notice that at least half of the confidence intervals for the warm and cool phases fall within the interval for the long run average. Additional uncertainty stems from the fact that we have just one previous complete warm phase from which to extrapolate what may happen in the current, as yet incomplete warm phase.

Figure 4 shows the frequency of major (Saffir Simpson Category 3 and higher) landfalling hurricanes by AMO phase for the period 1900-2005. The difference between the mean frequencies of the two phases is more pronounced, but the 95% confidence intervals are again very wide, indicating a high degree of uncertainty.

**Figure 4: Frequency of Major (≥Cat 3) U.S. Landfalling Hurricanes**




| | Mean Frequency | 95% Confidence Interval |
|---|---|---|
| Entire period (1900 – 2005) | 0.72 | 0.55 – 0.89 |
| Combined warm phases | 0.91 | 0.64 – 1.18 |
| Combined cool phases | 0.45 | 0.25 – 0.65 |

While there is considerable overlap between the confidence intervals for the long-run average and average of the warm phases, the opposite is true for the combined cool phases. That is, the impact of SSTs on major hurricanes during the cool phases seems to be more significant, suggesting that the cooler ocean waters can not provide sufficient energy to result in very intense storms.

## Does the AMO Even Exist? Does It Matter?

Some scientists, including Dr. Kerry Emanuel of MIT, have questioned the very existence of the AMO. These scientists believe surface temperatures in the northern hemisphere are driving SSTs and that the *variability* of SSTs is caused by episodic solar (sunspot) and volcanic activity, as well as the industrial release (and subsequent decay) of aerosol sulfates. They also believe that there is clear evidence of an upward trend in both surface and sea surface temperatures, which is caused by the accumulation of greenhouse gases. However, while they acknowledge the positive correlation between SSTs and hurricane activity in the basin, most scientists believe that the frequency of hurricane *landfalls* is highly dependent on climatological factors unrelated to SSTs, such as the NAO. All of these are areas of active research at AIR.

Despite the large uncertainty regarding the underlying cause of variability in SSTs, many scientists believe we will remain in an active phase of hurricane activity for the next five to ten years. What is much less certain is how that will translate into hurricane landfalls and, ultimately, insured hurricane losses in specific geographical areas.

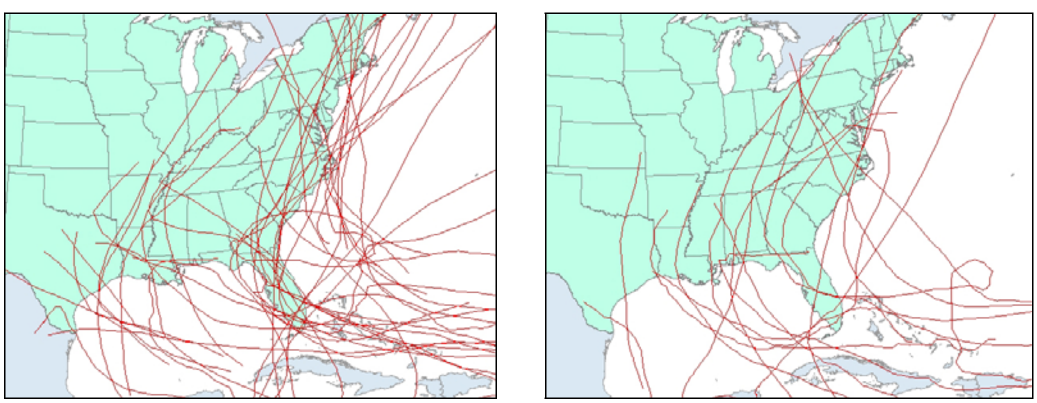
Whether the current active phase is driven by the AMO or some other combination of natural and manmade phenomena, the critical questions for catastrophe modelers are: How long will the current phase last? How does increased activity in the basin translate to changes in the frequency of landfalling hurricanes? How should any increase in the frequency of hurricane landfalls be distributed along the coast? And, ultimately, what is the impact on regional insured loss distributions?

## Quantifying the Impact of SSTs on Landfalling Hurricane Activity

Answers to these questions require forecasts of SSTs for the five year time horizon. Unfortunately, even the most sophisticated climate models can only forecast SSTs twelve months out at best. Scientists must therefore rely heavily on statistical analysis and expert judgment. This is particularly true when attempting to project the elevated risk by geographic location, which becomes necessary in light of current scientific thinking that the change in risk will be different for different coastal regions.

The difficulty of extrapolating from a small sample size is apparent again when we break the data down by region. The figure below contrasts the geographical distribution of hurricane landfalls in the previous and current warm phases. In the previous warm phase, activity was concentrated in the southeast, and in Florida, in particular. So far, in the current warm phase most of the activity has been in the Gulf. Once again, by extrapolating from the historical data it is difficult to determine, with any real confidence, what is likely to occur with respect to hurricane landfalls as we go forward.

**Figure 5: Hurricane Activity in the Previous and Current Warm Phase (1995-2005)**



# Projecting Potential Hurricane Activity and Insured Losses for the Next Five Years

While recognizing the challenges of forecasting hurricane activity for a five-year time horizon based on data characterized by significant uncertainty, AIR has reviewed all the scientific research and conducted extensive internal analyses. In addition, the AIR meteorological and statistical teams have collaborated with Accurate Environmental Forecasting (AEF) to provide such a view of hurricane risk.

Founded in 1998, AEF has developed extensive expertise in numerical weather prediction (NWP) technology to provide clients with scientific information for managing their atmospheric and oceanic natural catastrophe risk. AEF's founders and chief scientists are internationally recognized for their work in modeling the fundamental processes associated with the large scale ocean general circulation on time and space scales relevant to global climate dynamics and extreme ocean weather.

During the mid 1990s, one of AEF's co-founders, Dr. Isaac Ginis, demonstrated that accurate prediction of the sea surface temperature underneath an evolving hurricane is essential to accurate prediction of the hurricane's track and intensity. By 1997, Drs. Ginis, Rothstein, and collaborators had successfully coupled an ocean forecast model to the tropical cyclone forecast model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton. One year later, extensive testing had demonstrated that the new coupled-ocean-atmosphere tropical cyclone forecast model yielded forecasts that were consistently 25% better than those from the original atmosphere only hurricane forecast model. It was adopted by the National Weather Service in 2001, as the nation's first operational coupled-ocean-atmosphere forecast model.

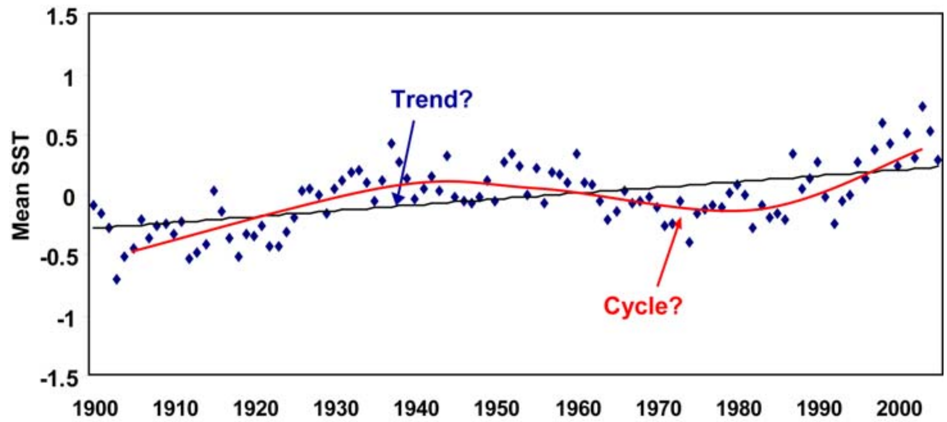
The research undertaken by AIR and AEF has been peer reviewed by Dr. Kerry Emanuel of MIT and Dr. Jim Elsner of Florida State University. Dr. Elsner said, "AIR's approach to estimating near-term (~5 year) hurricane rates, developed in conjunction with proprietary AEF and Climatek technology, includes the latest physical understanding of the causes of fluctuations in hurricane activity and incorporates a sound statistical model." Dr. Emanuel agreed, adding: "The AIR technique is based on sound statistical analysis relating SST anomalies to regional risk from hurricanes."

## Forecasting Sea Surface Temperatures

In order to provide a near-term view of hurricane risk, a forecast of sea surface temperatures is required. For short-term forecasts, climate models, such as general circulation models (GCM) perform quite well. However, the forecast skill of such models deteriorates beyond a few months.

To project hurricane activity for a five year time horizon, scientists rely on statistical modeling techniques, beginning with an analysis of SST anomalies in an attempt to discern any trends and cycles.

**Figure 6: Statistical SST Forecasts Begin with an Analysis of the SST Anomaly Data**




In this analysis two models within the well-accepted ARIMA (autoregressive integrated moving average) class of time series models were employed. The characteristics of each of these models are shown in Figure 7.

AIR and AEF used these models to generate a forecast of SSTs for a five-year window. While the models are quite similar, differences exist in their treatment of the trend. Also, one of the models includes a cyclical component to capture the possible impact of sunspot activity on SSTs. In both cases, any additional periodicity is implicitly captured by serial correlation. To achieve the final SST forecast, a weighted blend of the two was used.

**Figure 7: Two Well Accepted Time Series Models**

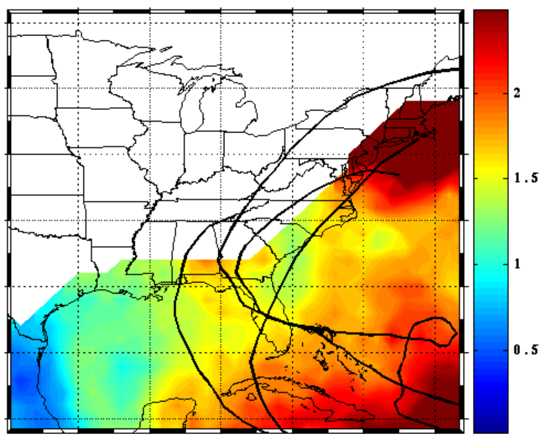
| ARIMA Model with Cycle | AR(2) Model with Trend |
|---|---|
| • Trend is modeled implicitly, since the dependent variable is differenced sea surface temperatures<br>• Cyclical component is added | • Linear trend line is computed<br>• Deviations from trend are modeled using a 2nd order autoregressive model |

Once the five-year forecast of SSTs is generated, a generalized linear model (GLM) was employed to capture the correlation between SST anomalies and hurricane landfalls. The GLM is a scientifically preferred method for computing the regional relationship between climate and hurricane risk. The GLM employed by AIR and AEF is based upon published research by Dr. Elsner and collaborators. The model relates hurricane activity to various climate signals, including SSTs.

The five-year SST forecast is input into the GLM model and the output is used to modify the spatial and intensity distributions of hurricane activity around the U.S. coastline. The GLM computes a hurricane index and associated confidence intervals for the entire U.S. coastline, as well as for individual coastal regions. The index is the ratio between hurricane landfall frequency for a specific climate—i.e., the near-term, or five-year, climate—and hurricane frequency in the long-term average climate. Thus an index of 2.0 should be interpreted to mean that hurricanes are twice as likely to make landfall, and an index of 0.5 means that hurricanes are half as likely.

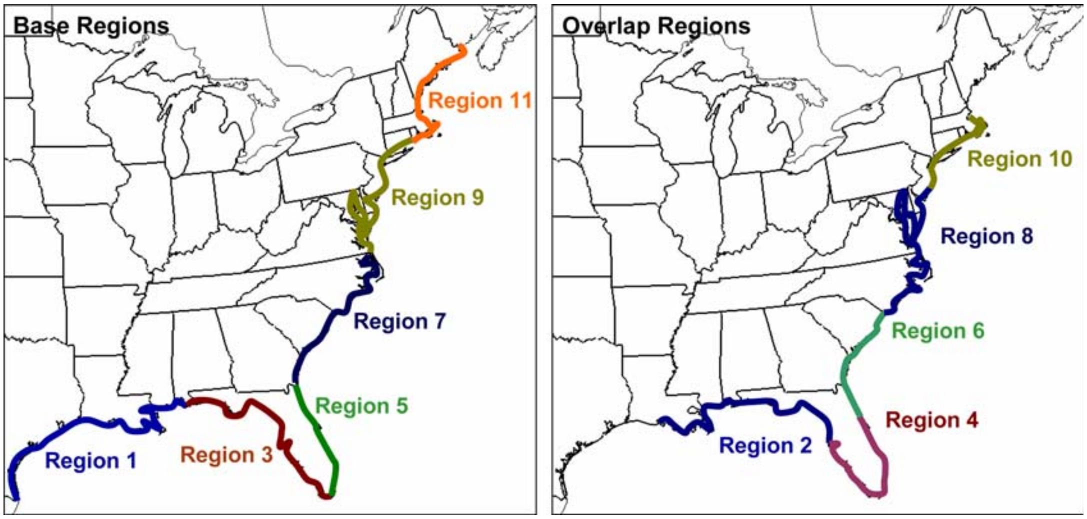
Figure 8 provides a visual representation of the regional hurricane indexes. In this example, hurricane risk is elevated everywhere along the coast, except for the southern Texas coast. It is also apparent from Figure 8 that any forecasted level of hurricane activity will not be uniformly distributed along the coast.

**Figure 8: Sample Hurricane Index for the U.S. Gulf and East Coasts**




For purposes of developing the regional hurricane indexes, AIR's collaborators at AEF divided the coastline into 11 overlapping segments. The map on the left of Figure 9 shows the six "base" regions, which form a continuous line from the border with Mexico to the border with Canada. The "overlap" regions on the right are used to smooth any sudden, discrete jumps in frequency from one base region to the next.

**Figure 9: AEF Regional Definitions**




## Quantifying the Impact of SST Forecasts on Insured Losses

The table below provides the extent to which regional hurricane frequencies over the near-term (resulting from a weighted blend of the ARIMA and AR(2) SST forecast models) deviate from those in the standard AIR U.S. hurricane catalog. The index values have been converted to percent change. Note that the lower end of the 95% confidence bands for all categories of hurricanes is close to no change or in some cases even indicates a decrease in frequency. For major hurricanes only (Category 3 and higher), the confidence intervals are far wider, reflecting the relative sparseness of the historical data and the increased uncertainty.

**Table 1: Deviation in Mean Frequency and Associated Confidence Intervals by Region**

| | All Hurricanes | | Category 3-5 Hurricanes | |
|---|---|---|---|---|
| Region | Mean (%) | 95% Confidence Interval (%) | Mean (%) | 95% Confidence Interval (%) |
| 1 | 1 | -25 - 31 | 16 | -30 - 83 |
| 2 | -3 | -30 - 30 | 8 | -40 - 78 |
| 3 | 18 | -14 - 62 | 18 | -32 - 91 |
| 4 | 25 | -10 - 77 | 36 | -20 - 126 |
| 5 | 32 | -2 - 88 | 34 | -20 - 117 |
| 6 | 40 | 2 - 97 | 78 | 6 - 225 |
| 7 | 32 | 2 - 85 | 82 | -6 - 254 |
| 8 | 31 | 0 - 81 | 80 | 4 - 238 |
| 9 | 44 | 5 - 111 | 54 | -31 - 208 |
| 10 | 32 | -6 - 90 | 40 | -40 - 174 |
| 11 | 39 | -7 - 114 | 43 | -46 - 206 |

## AIR Position on Near-term Catalog Usage

Sea surface temperatures in the North Atlantic basin are currently above the long-term average. Some scientists believe we are currently in a 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 the accumulation of greenhouse gasses and that variability in SSTs is caused by episodic events, such as volcanic activity.

It is the job of scientists to investigate and posit 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., that uncertainty is significant, in part because that particular link has not been the focus of investigation by the scientific community. The statistical models developed by AIR and AEF, and peer reviewed by climate scientists, do suggest a correlation between SSTs and hurricane landfalls, but it is not a strong one. Furthermore, the time horizon and magnitude of this elevated risk and, most importantly, its impact on regional insured losses is still uncertain.

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

AIR believes that the standard model based on over 100 years of historical data and over 20 years of research and development is still the most credible model to use given the uncertainty arising from the sparse data available for projecting the next five years. AIR encourages the use of the near-term catalog developed by AIR and AEF in sensitivity analyses.

# About AIR Worldwide Corporation

AIR Worldwide Corporation (AIR) is a leading risk modeling company helping clients manage the financial impact of catastrophes and weather. Utilizing the latest science and technology, AIR models natural catastrophes in more than 40 countries and the risk from terrorism in the United States. Other areas of expertise include site-specific seismic engineering analysis, catastrophe bonds, and property replacement cost valuation. A member of the ISO family of companies, AIR was founded in 1987 to provide its insurance, reinsurance, corporate and government clients a complete line of risk modeling software and consulting services that produce consistent and reliable results. Headquartered in Boston, AIR has additional offices in North America, Europe and Asia. For more information, please visit www.air-worldwide.com.