On the Relationship between North Atlantic Sea Surface Temperatures and U.S. Hurricane Landfall Risk

PETER S. DAILEY, GERHARD ZUBA, GRETA LJUNG, IOANA M. DIMA, AND JAYANTA GUIN

AIR Worldwide Corporation, Boston, Massachusetts

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ABSTRACT

In the recent literature, considerable attention has been paid to the relationship between climate signals and tropical cyclone activity. Much of the research has focused on Atlantic Ocean basin activity while less attention has been given to landfall frequency and the geographic distribution of risk to life and property. However, recent active seasons like 2004 and 2005 and the resulting damage and economic loss have generated significant interest in the relationship between climate and landfall risk. This study focuses on sea surface temperatures (SST) and examines modulation of landfall activity occurring in anomalously warm-SST seasons. The objective of the study is to evaluate the effect of warmer ocean conditions on U.S. landfall risk. The study is broken into two parts—statistical and physical. The statistical analysis categorizes historical hurricane seasons as either warm or cool and then estimates shifts in landfall frequency under these two climate modes. The analysis is carried out for overall U.S. landfall risk and then for logical subregions along the U.S. coastline. The climatological behavior for warm-SST conditions is developed across the intensity spectrum, from weak tropical storms to major hurricanes, using wind speed as an intensity measure. The analysis suggests that landfall risk is sensitive to SST conditions but that sensitivity varies by region and intensity. The uncertainty associated with these estimates is discussed. The physical analysis is carried out to understand better why landfall risk is not affected uniformly along the U.S. coastline and to reinforce the reasonability of the statistical results. The study involves a detailed examination of the complete life cycle of historical storms. Results indicate that storms making landfall along the East Coast have different genesis and intensification characteristics relative to storms making landfall along the Gulf Coast. As SSTs warm, the genesis pattern shifts, greatly influencing regional landfall risk. Further, hurricane landfalls may react not only to warm-SST conditions, but also to the effect of ocean temperature anomalies on the atmosphere's general circulation. There are implications that complex feedback mechanisms play a role in modulating the probability of landfall, especially from certain parts of the Atlantic basin. Such physical theories provide added confidence in statistical estimates of elevated risk for certain breeds of tropical cyclones.

1. Introduction

Prediction of future hurricane activity is challenging because of complex interactions among climatological factors influencing the evolution of tropical cyclones (TC). For example, it is well known that two key factors in storm genesis and intensification are the favorable effects of sensible and latent heat derived from the ocean's surface layer (e.g., Emanuel 2005a) and detrimental effects of vertical wind shear in the troposphere (e.g., Elsberry and Jeffries 1996; Emanuel et al. 2004; Emanuel 2005a). Models have shown that, even in the absence of significant shear, sea surface temperatures (SST) must be sufficiently warm to support cyclogenesis and intensification (e.g., Chan et al. 2001).

Some of the latest research has shown that the ocean's "dynamic topography," derived from satellite-based altimetry measurements, can serve as a proxy for the upper ocean's heat content (Goni et al. 1997). Tropical cyclone heat potential, which is a measure of *upper-layer* ocean temperature, rather than SSTs, is more highly correlated with TC intensification, especially episodic and rapid intensification, as was observed in Hurricanes Opal and Katrina (Shay et al. 2000; Scharroo et al. 2005). Because hurricanes effectively mix cooler ocean waters below the surface, shallow layers of warmth can quickly dissipate, whereas

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Corresponding author address: Peter S. Dailey, AIR Worldwide Corp., 131 Dartmouth St., Boston, MA 02116.
E-mail: pdailey@air-worldwide.com

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deeper layers of warmth provide a sustained reservoir of energy for developing TCs. Reliable dynamic topography is only available starting in the early 1990s. Despite the lack of a sufficiently robust 3D thermal profile of the Atlantic Ocean, researchers have demonstrated that an incrementally warmer ocean surface leads to a climatological increase in hurricanes' potential intensity (Emanuel 2005b) and observed tropical cyclone activity (Saunders and Lea 2008).

Historical data show that SSTs in the North Atlantic undergo fluctuations around a long-term average in phases that can last several decades. The nature, cause, and periodicity of these fluctuations are a subject of debate (e.g., Mehta 1998; Xue et al. 2003; Dima and Lohmann 2007). In particular, the examination of long-term trends specifically attributable to anthropogenic forcings has lead to a wide range of conclusions (e.g., Landsea 2005; Webster et al. 2005; Emanuel 2005b; Elsner and Jagger 2006; Elsner et al. 2006; Pielke et al. 2005).

However, it is generally recognized that interannual fluctuations in SSTs are related to fluctuations in TC activity levels at various time scales over multiple seasons (Shapiro and Goldenberg 1998). Others have shown that there exists a relationship between warm Atlantic SSTs and the seasonal power dissipated by hurricanes (Emanuel 2005b) as well as the seasonal frequency of major hurricanes (Webster et al. 2005).

Other climate signals are known to impact tropical cyclone activity, such as the following:

- El Niño–Southern Oscillation (ENSO) quantifies SST anomalies in the Pacific Ocean off the coast of Peru. These anomalies alternate over an approximate 3–8-yr cycle, with a cold phase (La Niña) and warm phase (El Niño). Work by Gray (1984), Goldenberg and Shapiro (1996), Shapiro (1987), and others has shown that the presence of El Niño (La Niña) can have a mitigating (enhancing) effect on Atlantic hurricane frequency, mainly owing to its influence on Atlantic wind shear.
- The North Atlantic Oscillation (NAO), an atmospheric pressure pattern over the Atlantic Ocean, quantifies pressure differences between the Azores and Iceland. Scientists have observed that the large-scale general circulation associated with the NAO steers North Atlantic tropical cyclones in a characteristic pattern to the west and eventually to the north. The subtropical high, when it is stronger or in a more southwesterly position, can cause hurricanes to approach closer to the U.S. coastline before turning north, thereby increasing their likelihood of making landfall (e.g., Elsner et al. 2006). Unlike ENSO, the orientation and strength of the NAO fluctuates on an intraseasonal time scale.
- The Atlantic Meridional Mode (AMM) integrates several local factors relevant to hurricane activity such as SSTs, wind shear, stability, and sea level pressure (Kossin and Vimont 2007). The AMM, which is thought to excite Atlantic TC variability on a multidecadal time scale, is correlated with several activity metrics (frequency, duration, and intensity) and may provide insight into the physical underpinnings of what has been traditionally referred to as the Atlantic Multidecadal Oscillation (e.g., Kerr 2000).

In addition to these large-scale climate influences, other more local and episodic factors can also play a role in year-to-year activity. For example, windstorms over the Sahara Desert that episodically transport dust over the Atlantic can block sunlight and dry the lower troposphere, thereby reducing ocean temperatures (Lau and Kim 2007) and inhibiting convection and precipitation in tropical disturbances (Dunion and Velden 2004). Also, while large-scale climate shifts occur, so do local gradients change, and both can influence observed activity levels (Kossin and Vimont 2007).

Although many of these climate signals are useful in seasonal forecasting (e.g., Gray et al. 1992; Hess et al. 1995; Elsner and Jagger 2006; Jagger et al. 2008), their predictive skill decreases significantly beyond a season. For example, ENSO has a period that is too short to be useful for estimating hurricane activity over a 5-yr time horizon, and the periodicity of the NAO is much too short and irregular to be useful. For these reasons, SSTs have been identified as a useful predictor of hurricane risk in the near term, defined here as the period extending several years into the future (e.g., Griffies and Bryan 1997). Other robust multidecadal signals, such as the AMM, may be equally useful in such analyses (Kossin and Vimont 2007).

Substantial research has focused on the relationship between known climate mechanisms and the ingredients for hurricane formation and development, but far less has related such mechanisms to landfall activity. It may seem obvious that increases in TC activity lead to corresponding increases in landfall risk simply because of an increased opportunity for landfall. However, quantifying the relationship between changes in basin activity (frequency, duration, and intensity) and changes in landfall risk is a challenge, in large part because of data issues; landfall data are sparse and basin data are less dependable during the presatellite era. To determine the sensitivity of landfall risk to climate, one must establish a baseline of landfall climatological data (e.g., Brettschneider 2008). Lyons (2004) stratified the

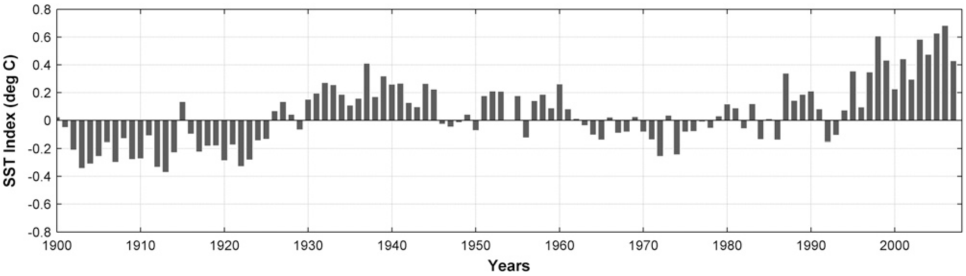


FIG. 1. SST anomalies time series (HadSST2; °C).

historical record to examine how the most active and least active seasons compare in terms of landfall frequency. He found that a projection inferring—from a forecast of number of storms in the Atlantic basin—how many TCs will make landfall in the United States lacks skill, explaining just 18% or less of U.S. landfall variability. It is certain that much of the remaining variability can be explained through complex feedback processes interacting on different scales, which in turn affect the large-scale atmospheric circulation and ultimately the movement and evolution of individual storms.

This paper will focus on the relationship between SSTs in the Atlantic basin and the frequency of TCs that make landfall along the U.S. coastline. SSTs are currently above their long-term average and have been since about 1995, and many scientists believe that Atlantic SSTs will continue to remain elevated for several years. The impact of above-average SSTs on U.S. hurricane landfall frequency will be examined with the objective of estimating its effect on U.S. landfall risk. Modulated risk will be identified for several coastal regions.

There are many useful applications of such an analysis. Saunders and Lea (2005) linked predictions of U.S. hurricane activity to forecasts of insured damage and loss. Emanuel et al. (2006) provided a statistical deterministic approach to hurricane risk assessment. Jagger et al. (2008) developed models to predict hurricane damage using preseason values of Atlantic SST combined with the NAO and Southern Oscillation index as predictor variables. In addition, various planning, preparation, and mitigation strategies within the emergency management and insurance domains can obtain guidance from such estimates.

2. Data and methods

The analysis uses TC information from the North Atlantic Best Track Dataset (HURDAT) available from the National Hurricane Center (Jarvinen et al. 1984). Here, the focus is on activity during the period from 1900 to 2007. For SSTs, the analysis is based on the Hadley Centre data: HadSST2 (Rayner et al. 2006). The average of the SST anomalies during the hurricane-season months—from June through November—is used to quantify annual variability for the period considered. The seasonal Hadley SST anomaly data series is shown in Fig. 1. Anomalies were computed over most of the northern Atlantic Ocean (5°–70°N and 10°E–100°W). The time series shows multidecadal periods in which anomalies have been persistently cooler or warmer than average. For purposes of this analysis, years in which SST anomalies are greater than or equal to 0 are considered to be *warm years* and all other years are considered to be *cool years*. Over the 108 seasons from 1900 to 2007, there are 60 years that are warm and 48 years that are cool.

Different approaches can be used to evaluate hurricane frequency as a function of SST. One approach is to use a Poisson regression (e.g., McCullagh and Nelder 1989) that relates the logarithm of the annual rate of hurricane landfalls λ to a linear function of SST:

$$\log(\lambda) = \beta_0 + \beta_1 \times \text{SST}. \tag{1}$$

A model of this form was used by Elsner and Jagger (2006) to predict seasonal hurricane activity. In their model, multiple predictor variables including SST were included, and a Bayesian approach was used to make inferences about the unknown regression coefficient β. Having developed a model of this form, forecasts of the SST can then be imputed into the model to produce estimates of near-term landfall risk. The benefits of this approach in developing such an estimate of risk rely on the ability to skillfully forecast SST anomalies over a multiseason time horizon. However, forecasts of ocean temperatures beyond a year are subject to significant uncertainties. Because coupled ocean–atmosphere dynamical models have limited skill in predicting SST be-

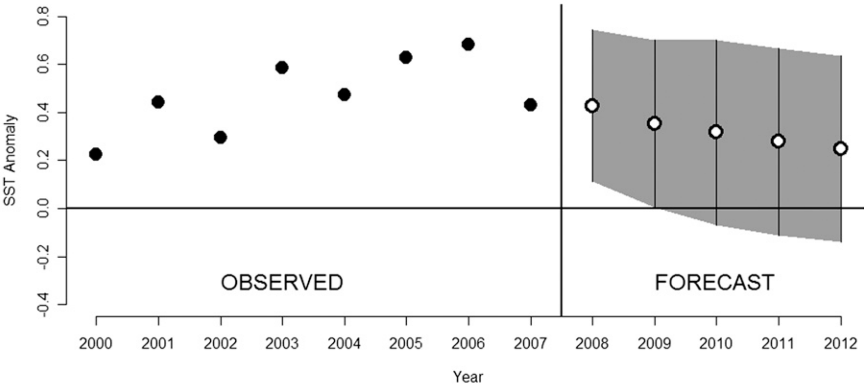


FIG. 2. Forecast Atlantic SST anomalies using an autoregressive [AR(2)] model. The shaded area represents the 95% uncertainty in the forecast.

yond a year (e.g., Goswami and Shukla 1991), various statistical approaches have proven to be useful alternatives, although they also are subject to significant uncertainties.

This aspect is illustrated in Fig. 2, which shows observed Atlantic SST anomalies from 2002 to 2007 and point forecasts of anomalies for the next 5 years, generated using an autoregressive time series model of order 2 or AR(2). Such a model relates the SST at any given time to SST values at two previous times, thereby accounting for temporal correlation. The forecast shown is for the North Atlantic basin. The 95% prediction intervals around the point estimates are indicated by vertical bars. The prediction intervals are large and, with the exception of the 2008 forecast, include the possibility that SSTs could turn anomalously cool in the 5-yr window. The wide intervals indicate that multiple season point forecasts of SST are highly uncertain.

In more recent work, linear inverse modeling techniques have shown some skill in projecting long-term SST fluctuations in the Pacific basin (Alexander et al. 2008). Kossin and Vimont (2007) found that such techniques can also be applied to the AMM and used to project tropical conditions relevant to basin activity. However, the uncertainty associated with such long-term forecasts is also likely to be large, in part because of the temporal growth of error in the highly nonlinear atmosphere–ocean system.

Thus, rather than using SST as a predictor variable, this paper takes a more straightforward approach and conditions the analysis on the assumption that SSTs will remain warmer than the long-run average over the next several years. The impact of SST is then quantified by comparing the average annual landfall frequency during warm years with the average long-term landfall frequency. The results are expressed in the form of a tropical cyclone index (TCI), which is computed as the ratio of frequency given the SST condition to the climatological (long term) frequency:

$$\mathrm{TCI} = \frac{\text{Annual mean landfall frequency for warm years}}{\text{Annual mean landfall frequency for all years}}. \tag{2}$$

The TCI can also be computed based on cool-year frequency. For purposes of this study, a landfall occurs whenever a storm explicitly crosses the U.S. coastline or crosses the Florida Keys or the Outer Banks of North Carolina. One TC may enter into the landfall count several times because it may cross the U.S. coastline more than once. Landfalling storms are considered from 1900 to 2007 because, throughout this period, the U.S. Atlantic coastline was well inhabited and it is highly unlikely that a landfall went unobserved. This is in contrast to a later analysis involving Atlantic basin counts in which special care is taken to consider the potential for undercounting in the early part of the historical record. Unless otherwise noted, landfall intensity is based on the best available information, which typically is HURDAT 6-hourly wind speed, linearly interpolated to 1 h.

The TCI can be estimated for the entire U.S. coastline or for a smaller subregion and can be estimated at any intensity level. For example, a TCI of 1.10 calculated for warm years would indicate that under warm-SST conditions the frequency of landfall is expected to be 10% higher than under average climatological conditions (considering all years, both cool and warm). Of course, uncertainty in the TCI estimate is highest for regions with low frequency. Such uncertainty can be quantified using bootstrapping (e.g., Efron and Tibshirani 1994). The method involves creating many new datasets by sampling with replacement from the observed data. The size of each sample is equal to that of the original

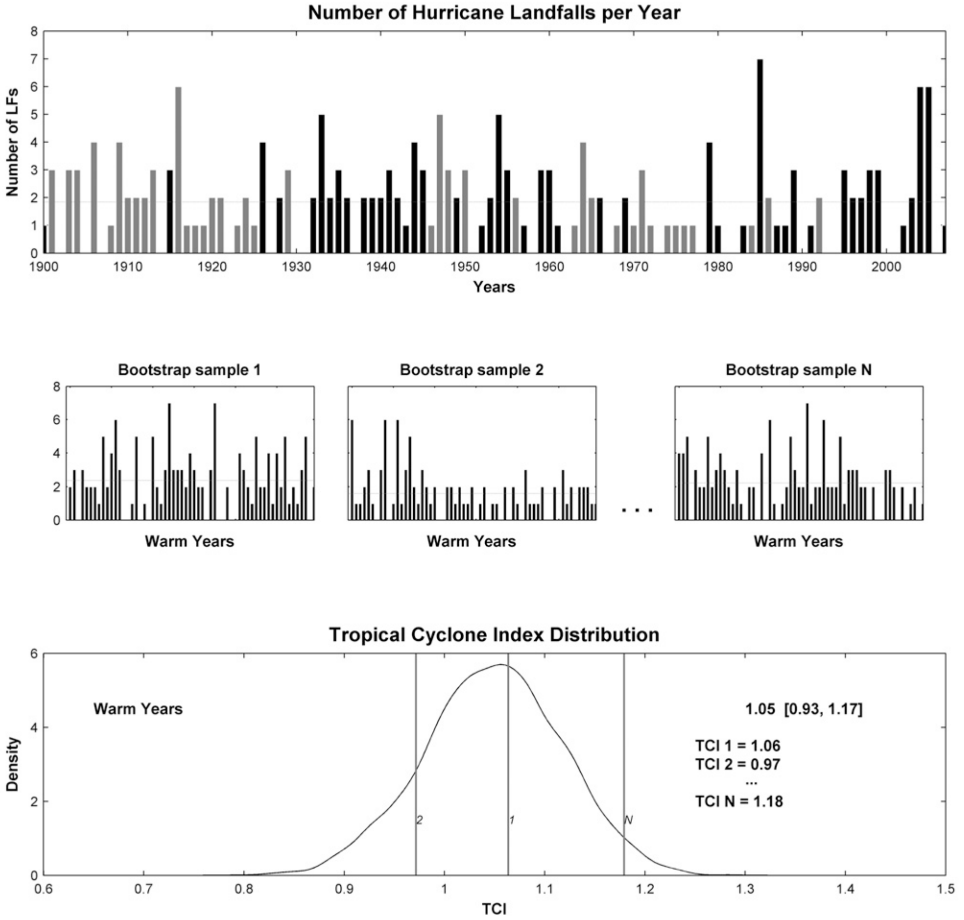


FIG. 3. Estimation of the TCI using U.S. hurricane landfall frequency. (top) For each year from 1900 to 2007, the number of hurricanes making landfall along the U.S. coastline is determined, designated by warm years (black) and cool years (gray). (middle) Warm-year bootstrap samples, and (bottom) the resulting bootstrap distributions of the TCI.

dataset, and the TCI value associated with each sample is computed using (2). TCI values will vary from sample to sample and eventually will populate a bootstrap distribution when the procedure is carried out a large number of times (in this analysis, 5000 times). In this paper, the bootstrap distribution is referred to as the ‘‘TCI distribution.’’ When the number of samples increases, the mean converges to the TCI based on the historically observed frequency. The 90% confidence interval is computed using the 5th and 95th percentile of the bootstrap distribution. A Gaussian kernel density estimate is used for estimation and visualization of the probability density functions of the TCI distributions.

An illustration of the method is shown in Fig. 3. Here, we estimate the warm-year TCI distribution for tropical cyclones making U.S. landfall as hurricanes. The top panel shows the frequency of hurricane landfalls from 1900 to 2007, with black (gray) bars showing observations occurring in warm (cool) years. The middle panel shows three randomly drawn bootstrap samples, using data from warm years. The warm-year TCI for each sample is determined by dividing the mean number of warm-year landfalls in the sample by the mean number of landfalls in all years (which includes both warm- and cool-year landfalls). The values obtained for this example are 1.06, 0.97, and 1.18, respectively. With many such drawings, a bootstrapped distribution is formulated, as displayed in the bottom panel. The figure indicates the mean TCI for U.S. hurricane landfall activity under warm SSTs and also the uncertainty in the TCI estimate. The interpretation is that the frequency of U.S. hurricane landfalls is elevated by 5% in warm-SST years, and that at the 90% confidence interval is bounded by a decrease of 7% and an increase of 17%. Such distributions, which will be shown for a variety of region and intensity combinations, allow for a more complete explanation of the SST climate signal.

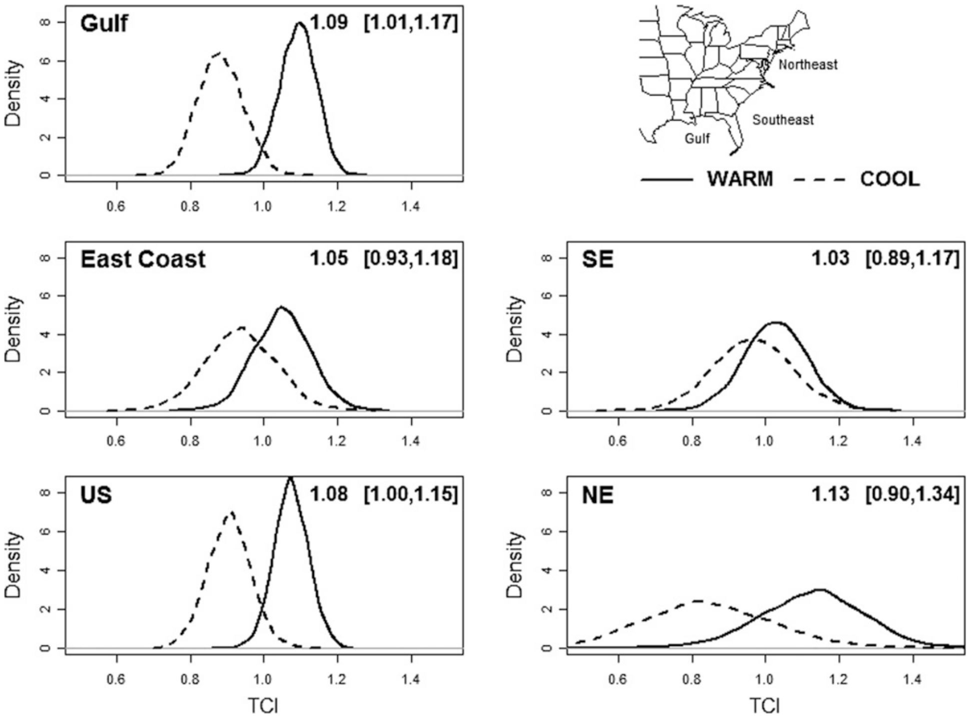


FIG. 4. TCI distributions for all named storm landfalls for cool- (dashed) and warm- (solid) SST years. The mean value of the warm-SST distribution is given In the upper-right corner of each panel, with the 90% confidence interval in brackets. (top right) The region definitions used throughout this paper, showing the Gulf, the Southeast, and the Northeast coasts. The East Coast region is an aggregate of the Northeast and Southeast regions.

3. Results of statistical analysis

Beginning with all named landfalling storms, sampling distributions of the estimated TCI values for both warm years (solid lines) and cool years (dashed lines) are shown in Fig. 4. The spread of the distributions reflects uncertainty in the estimated TCI while the separation between warm- and cool-year distributions reflects the "strength" of the SST signal in influencing landfall frequency. Figure 4 provides results for the United States as a whole and separately for the Gulf and East Coasts. Because roughly two-thirds of historical U.S. landfalls have occurred along the Gulf Coast, the U.S. distribution is effectively a weighted combination of the Gulf (½) and East Coast (⅓) distributions. The East Coast is further divided into Southeast and Northeast regions, as shown in the upper-right panel, with the vast majority of East Coast landfalls occurring in the Southeast. For each coastal region, the estimated mean value of the warm-year TCI is provided along with the associated 90% confidence interval (upper-right corner of each panel).

The distributions in Fig. 4 show that the strongest signal is in the Gulf region, as evidenced by minimal overlap in the respective cool- and warm-year distributions. In addition, both end points of the 90% confidence interval constructed for warm years exceed 1.0, indicating a statistically significant increase in storm frequency. There is also evidence of significantly increased frequency for the United States as a whole. However, for the East Coast and its two subregions, there is little evidence of increased landfall during periods of warm SSTs. In the Northeast region, where historical landfall frequency is relatively low, the distributions are both very wide—reflecting a high level of uncertainty in the impact of anomalous SSTs.

Figure 5 shows the results of the same analysis but carried out for tropical storms only (winds at landfall between 34 and 63 kt; 1 kt $\approx$ 0.5 m s^{-1}). The signal in the Gulf region is stronger, with an estimated 14% increase in tropical storm landfalls during warm years relative to the long-term average. With a TCI of 0.93, tropical storm landfalls in the Southeast region are 7% *less* frequent in warm years relative to the average. Based on the 90% confidence interval, this reduction is not significant.

The picture changes considerably if tropical storms are excluded from the analysis, using only storms that

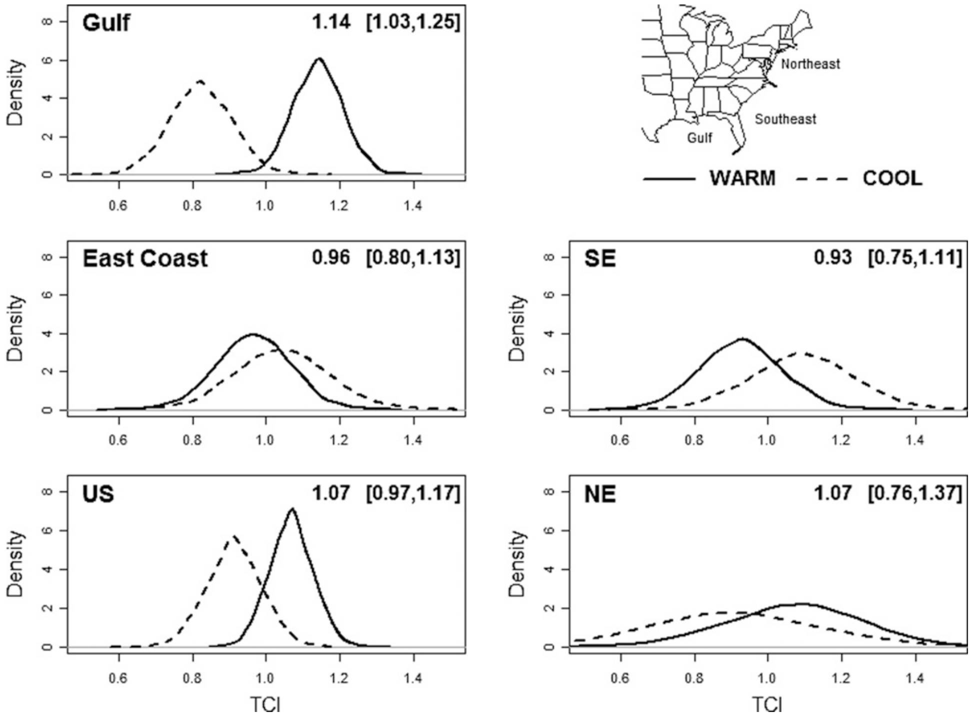


FIG. 5. As in Fig. 4, but for landfalls at tropical storm strength.

make landfall at hurricane strength, as shown in Fig. 6. Of interest is that the signal along the Gulf Coast, which was significant for all landfalling storms (see Fig. 4) and for tropical storms (see Fig. 5), is no longer significant. With a TCI value of 0.98, there is very little difference between warm and cool years in the frequency of *hurricane* landfalls along the Gulf Coast. Hence, the dominant impact of SSTs on Gulf landfalls is for increased frequency of weaker events. However, for the Southeast region, a strong positive signal is noticeable and is nearly significant. Warm-SST years produce an estimated increase of 14% in hurricane landfalls along the coast from the southern tip of Florida to Cape Hatteras. Combined with earlier results, this would suggest that tropical cyclones that make landfall in the Southeast during warm years are more likely to arrive as hurricanes than as tropical storms. Again, for the Northeast region, the distributions are wide, reflecting a high degree of uncertainty that is attributable to the low rate of landfalling hurricanes.

Thus far, the statistical analysis reveals that during years of warm SSTs the Gulf Coast is likely to experience more frequent tropical storm landfalls but little increase in hurricane landfalls. The pattern is reversed in the Southeast region, which is likely to experience more frequent storms of hurricane strength in warm years. In the Northeast region, the signal is too weak to draw any meaningful conclusions. The same analyses of landfall frequency have been performed by Saffir–Simpson category. The patterns held and were more pronounced: namely, the signal in the Gulf region is strong for tropical storms and weak hurricanes and almost disappears for strong hurricanes. The signal is strongest in the Southeast region, especially for major hurricanes (Saffir–Simpson category 3–5). Many storms that *do* make landfall along the Southeast coast of the United States originate near the Cape Verde Islands, off the coast of Africa. Their long journey over the tropical Atlantic increases the likelihood that these storms will arrive as intense storms. The relationship of warm SSTs to this breed of tropical cyclone is further discussed in section 4.

Because the boundaries of the Saffir–Simpson scale are somewhat arbitrary, we have also analyzed the TCI as a continuous function of storm intensity. To obtain a representative sample for a particular wind speed, the data are grouped into centered 20-kt bins. For example, to compute the TCI for 80-kt winds at landfall, all landfalling storms with landfall maximum wind speeds between 70 and 90 kt are included in the sample. The analysis is then repeated using a moving window in steps of 0.5 kt.

The results are shown first for the entire U.S. coastline (Fig. 7). The solid gray line shows the computed TCI as a function of wind speed, and the dashed gray lines represent the corresponding 90% confidence in-

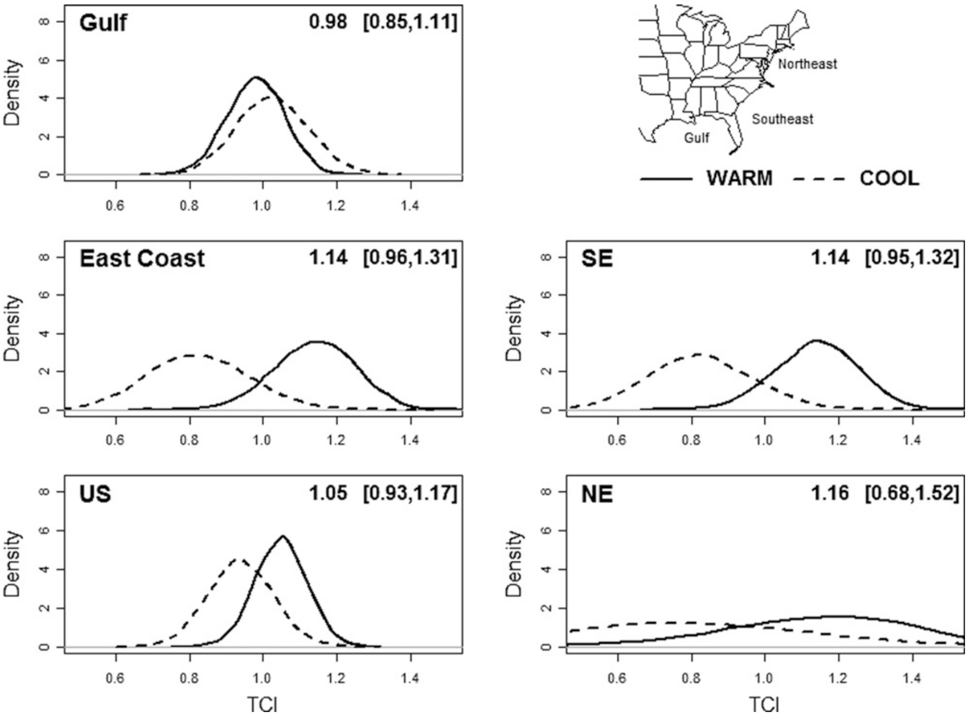


FIG. 6. As in Fig. 4, but for landfalls at hurricane strength.

terval. Black solid and dashed lines show the same but after having smoothed the TCI across the intensity spectrum using the locally weighted polynomial regression and scatterplot smoothing technique (LOWESS; Cleveland 1981). Note that the confidence interval widens as hurricane intensity increases, reflecting the relative sparseness of historical data as landfall intensity increases. The pattern for subhurricane force winds (<64 kt) confirms our earlier finding that warm SSTs contribute to more frequent tropical storm landfalls. The signal is weaker for minor hurricanes but begins to amplify as intensity increases, although the lower

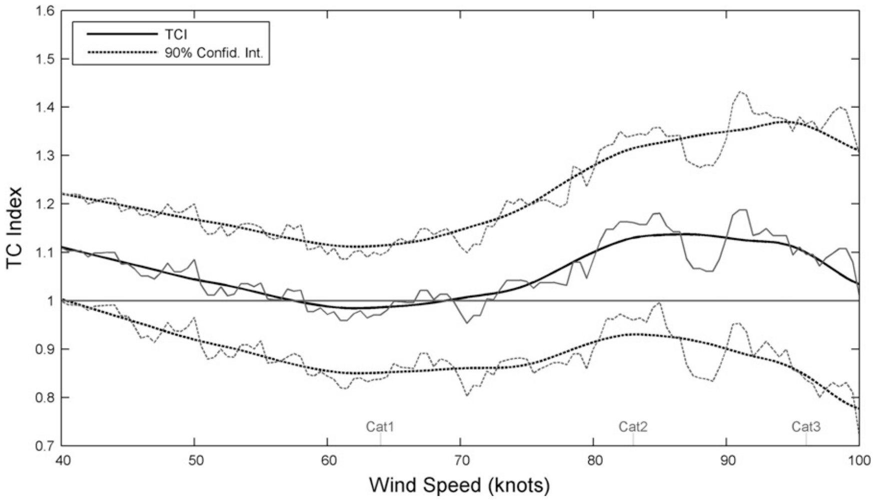


FIG. 7. TCI as a function of landfall wind intensity for the entire U.S. coastline. To estimate the TCI for landfalls at a given wind speed, all storms with maximum landfall sustained winds within ±10 kt are considered. The solid gray line indicates the mean estimate of TCI across the wind intensity spectrum. The black solid line is a smoothed version of the same line. The gray (black) dashed lines show the corresponding raw (smoothed) 90% confidence interval.

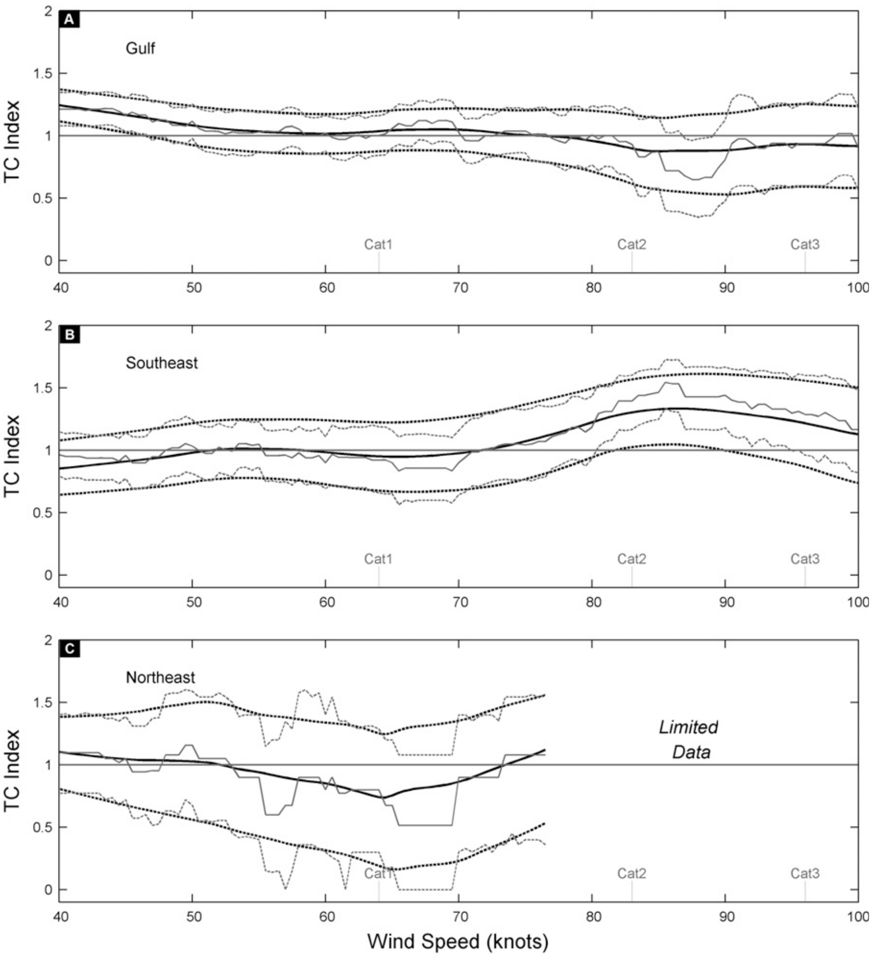


FIG. 8. As in Fig. 7, but for the analyzed subregions.

bound of the confidence interval remains below 1.0. Figure 8 shows the results of the same analysis but stratified by region. Once again, the strongest signals are for tropical storms and weak hurricanes in the Gulf region and for stronger hurricanes in the Southeast region. The TCI grows in the Southeast region with increasing intensity, but the uncertainty grows as well. The Southeast signal, however, may indicate not only that the impact of warm SSTs is strongest in this region but that it influences the frequency of major hurricanes the most. As expected, the results are uncertain for the Northeast region, and the data sample is insufficient to produce robust TCI estimates beyond marginal hurricane intensity.

4. Physical mechanisms influencing landfall risk

We will now discuss physical theories for the SST-induced shifts in landfall risk revealed through the statistical analysis. The focus is on the question, Are there physical mechanisms and/or feedbacks at work in warm-SST years that make it more or less likely for Atlantic storms to intensify and reach the U.S. coastline? It is well known that the atmosphere's translation of thermodynamic forcings (e.g., warmer-than-average ocean temperatures) to dynamical systems (e.g., tropical cyclones) is often indirect and nonlinear. Recent modeling studies that investigated how long-term anthropogenic climate change may affect Atlantic tropical activity indicate that internal feedbacks and global teleconnections may counteract the direct influence of a warmer ocean on tropical cyclogenesis (Vecchi and Soden 2007).

To examine the physical relationship between basin and landfall activity, one can begin by computing the probability of a storm making landfall from the Atlantic basin, both climatologically and under anomalous SST conditions. This analysis was carried out using data from the reanalysis period (from 1948 to present), because storm detection in the basin is considered to be

TABLE 1. Landfall proportion based on landfall counts at different intensities, showing the proportion of named historical storms that make landfall to total number of storms formed in the basin, over the 1948–2007 time period. Top count in each cell is the number of landfalls at a given wind speed or higher. The bottom count is the number of storms in the basin for all warm years and all cool years. Landfall proportion (included in parentheses) is the ratio of the landfall count to the basin storm count for different landfall wind speeds. Note that the third data column, with a threshold of 89 kt, takes advantage of a larger number of strong hurricanes than what is reflected in the fourth data column.

	Landfalls ≥ 34 kt	Landfalls ≥ 64 kt	Landfalls ≥ 89 kt	Landfalls ≥ 96 kt
Warm-SST years	154/453 (34.0%)	73/453 (16.1%)	29/453 (6.4%)	20/453 (4.4%)
Cool-SST years	61/191 (31.9%)	30/191 (15.7%)	14/191 (7.3%)	12/191 (6.3%)

dependable over this time (Vecchi and Knutson 2008). For purposes of this paper, *landfall probability* is estimated by the proportion of storms that make landfall to storms that form in the basin. Table 1 shows U.S. landfall proportion for storms of various intensities. The first data column shows that the historical proportion of storms making landfall at tropical storm strength or greater is 34.0% in warm-SST years and is slightly smaller in cool years. The second column shows that landfall proportion at hurricane strength or higher is about 16.1% in warm years, whereas the cool-year proportion is slightly smaller. For stronger hurricanes, as shown in the third (≥89 kt) and fourth (major hurricane strength) columns, the cool-year proportion is higher than the warm-year proportion. Note that the sample size is small for the proportions computed in the second through fourth data columns. For example, there have only been 30 landfalling hurricanes since 1948 in cool years, and only 12 of them have reached major hurricane status. Although this simple analysis, based on data for the entire United States, does not pass conventional tests of statistical significance, it still raises two questions: 1) Does the landfall proportion in warm-SST years have a physical explanation that may become more obvious under more extreme SST conditions? 2) Are there regions within the Atlantic basin or regions along the U.S. coastline in which warm-SST conditions bring about larger, more significant changes in local landfall probability? It is possible, for example, that destructive interference is rendering a weak signal because it results from the weighted combination of two regional signals of opposite sign.

To examine the problem more closely, it is helpful to approach landfall from a physical perspective. Given that a TC has formed in the basin, landfall probability is dependent on three fundamental factors: *genesis* (where the storm is born), *intensification and decay* (the intensity life cycle), and *tracking* (the storm's ability to approach the coastline). Indeed, Lyons (2004) found that a large portion of landfall variability is related to where TCs form and the orientation of steering currents relative to the U.S. coastline. Modulation of any one of these landfall characteristics can bring about significant changes in landfall probability and in turn the proportion of storms making landfall.

Figure 9 shows the spatial distribution of storm genesis location, along with corresponding contours of genesis density, for all tropical cyclones in the North Atlantic. Genesis for all tropical storms and hurricanes is considered because subsequent intensification under environmental conditions along their path occurs somewhat independently. The spatial distribution is based on a 2D isotropic Gaussian kernel density, with a bandwidth (i.e., radius of influence) that is optimized using cross validation. Further details can be found in Hall and Jewson (2005). However, the radius of about 200 km, which was obtained through optimization, is roughly doubled in Fig. 9 to draw attention to larger-scale features in the genesis pattern. The top panel shows the climatological genesis pattern with two known ''hot spots'' within the Gulf of Mexico and along the so-called main development region (MDR; see Emanuel 2005a). The relative scarcity of genesis in the vicinity of the Caribbean Islands can be explained by this region's high vertical wind shear and strong teleconnection to ENSO (Aiyyer and Thorncroft 2006). The historical record used here may have deficiencies prior to the presatellite era, but the genesis pattern does not dramatically change when data prior to 1970 are eliminated. The genesis region most sensitive to data from 1948 to 1969 is in the eastern Atlantic where the initial portion of some storm tracks was likely missed by ship reports and buoys.

The middle panel shows that under warm-SST conditions genesis in the Gulf of Mexico increases while genesis in the Atlantic basin shifts greatly eastward across the MDR and away from the U.S. coastline. This finding has several implications. First, storms that form in the Gulf region are already close to the coastline and there is little time for a storm to intensify before reaching land. If genesis density here concentrates under warm SSTs, we expect increased frequency of mostly weak storms making landfall in the Gulf region. Note that this does not account for Gulf landfalls that origi-

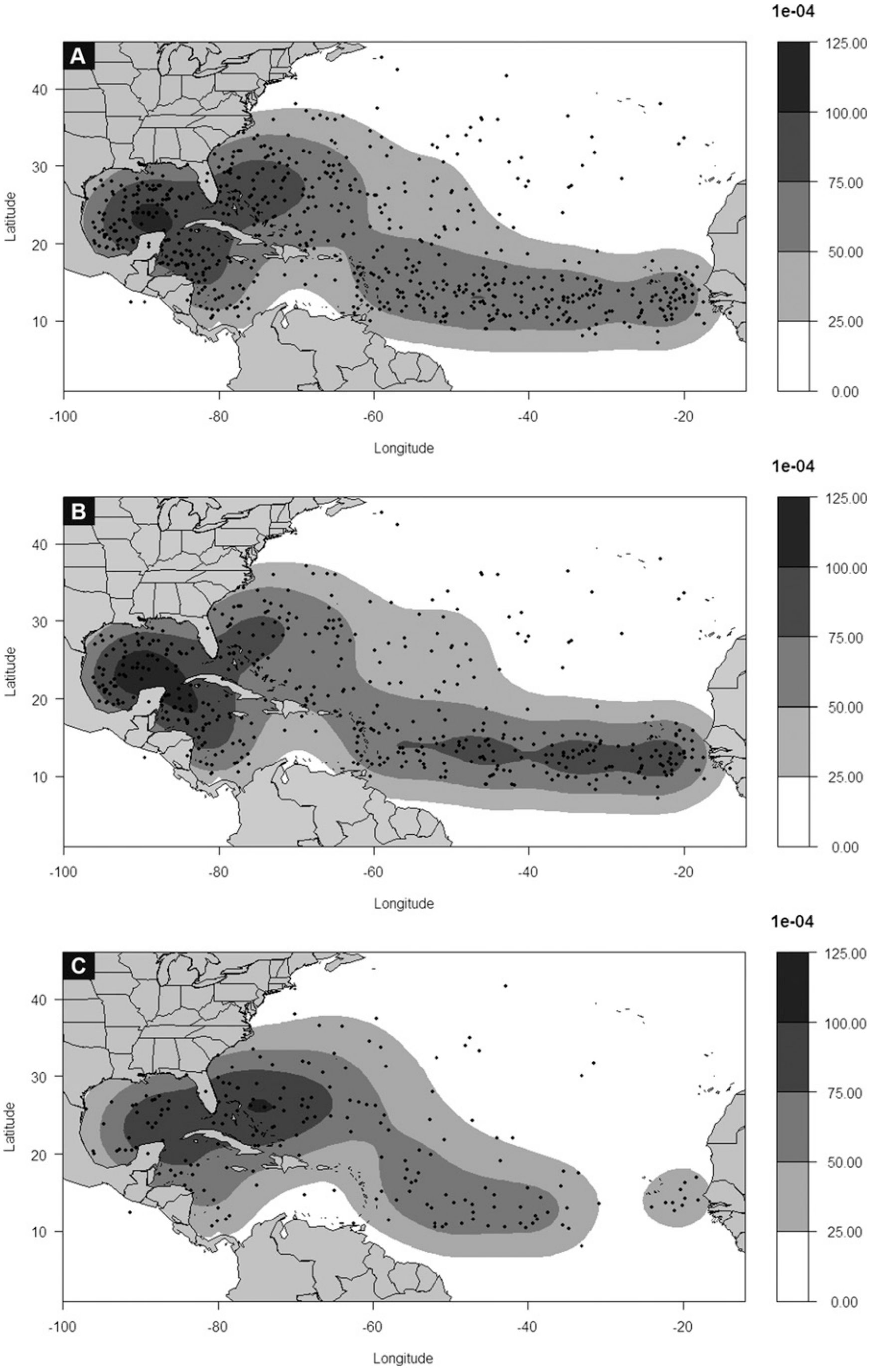


FIG. 9. Spatial distribution and density of genesis for all tropical cyclones (1948–2007). Each dot represents a historical starting point for a TC that eventually reaches at least tropical storm strength. Grayscale contours show the climatological mean genesis density (genesis points per square kilometer per year; 1e-04 label indicates that the values on the scale should be multiplied by 10^{-4} to get the actual value) for (top) all years, (middle) warm years, and (bottom) cool years.

nate outside the Gulf genesis region, although these are less frequent. Overall, the genesis pattern is reduced during cool years (Fig. 9, bottom panel), with the most pronounced decrease observed in the MDR.

To study further the relationship of genesis to landfall, we estimate the conditional probability of a storm making landfall as a hurricane (at ≥64 kt) given its genesis region. For this purpose, we use an indicator variable and assign a tag value of 1 or 0 to each genesis point depending respectively on whether or not the storm later made landfall at hurricane strength. To estimate the likelihood that a TC forming at some location will make landfall, we use the tagged historical genesis points within some radius surrounding that location. To find the best value for the radius of influence (standard deviation of the isotropic Gaussian smoothing kernel), we use a cross-validation optimization technique (Hall and Jewson 2005).

The result is shown in Fig. 10. The top panel shows the climatological probability of landfall at hurricane strength. The middle (bottom) panel shows the same, but using data only from warm- (cool-) SST years. The warm-SST panel indicates that storms forming in the Gulf region have a slightly lower probability of making hurricane landfall under those conditions. The statistical analysis shows that under warm SSTs a large increase in tropical storm and weak hurricane landfalls in the Gulf region can be theorized to result from a significant rise in Gulf genesis, which increases the frequency of storms undergoing short-lived intensification before striking land. Another interesting result is that storms forming off the coast of Africa have a high likelihood of making landfall as a hurricane, partly explained by these storms' long trek across the Atlantic Ocean. Such a long life cycle can translate into an increased chance of intensifying to hurricane and perhaps major hurricane strength prior to striking land. During cool years (bottom panel in Fig. 10) the probability of hurricane landfall is elevated in the Gulf region and in the vicinity of the eastern Caribbean islands and is considerably reduced in much of the MDR.

To demonstrate better the spatial distribution of Atlantic TC intensification, the probability of a storm reaching hurricane strength at any point in its life cycle is shown in Fig. 11. Note that there is an increased likelihood of storms that form off the African coast and in the MDR to reach hurricane strength under warm-SST conditions, at which locations most storms already do so climatologically. The intensification pattern over the remainder of the MDR does not change dramatically with warm SSTs, although there is a slight decrease in the Gulf of Mexico.

As noted earlier, uncertainties exist in genesis and intensity, especially in the eastern Atlantic, during the presatellite era (1948–69). It is unlikely that storms were missed during this period (Vecchi and Knutson 2008), but it is more likely that tracks or intensities were misestimated, leading to uncertainties in Figs. 9–11. It is reassuring to note that the ratio of warm and cool years in the pre- and postsatellite periods is comparable so that the potential for a presatellite bias in the warm- and cool-year patterns is about equal. Further, the patterns do not qualitatively change when presatellite data are excluded from the analysis.

On a regional basis, hurricanes forming in the eastern Atlantic tend to make landfall along the Southeast coast rather than the Gulf Coast or the Northeast coast (not shown). This leads us to theorize that the strong statistical signal in the TCI for the Southeast region (Fig. 6) is especially sensitive to the following shifts in the eastern Atlantic under warm-SST conditions: 1) increased genesis frequency and 2) increased probability of hurricane intensification prior to landfall, which when combined lead to an increased frequency of hurricane and major hurricane landfalls.

When focusing on subregions, we find that the proportion of storms making landfall from the eastern Atlantic increases during warm years, but that it is not statistically significant. The proportion decreases in the western Atlantic, and the 90% confidence interval shows statistical significance. To illustrate this, a hurricane landfall probability index is introduced. First, the ratio of storms that make hurricane landfall along the U.S. coastline to the total number of storms originating from an Atlantic subregion is computed for all years, warm years, and cool years. The ratios for warm and cool years are divided by the proportion of hurricane landfalls for all years. Thus, an index value of 1.0 indicates that landfall proportion from this region of the Atlantic is equal to the climatological mean.

The results are shown in Fig. 12 in the form of kernel density estimates of sampling distributions obtained through bootstrapping, similar to the approach used to estimate TCI distributions. The distribution mean and 90% confidence interval are shown in the upper-right of each panel. The top panel shows distributions of the hurricane landfall probability index for the entire Atlantic basin where warm and cool indices have practically the same mean value and do not deviate significantly from climatological values. When the data are analyzed for subregions, the signal in the western Atlantic is not only significant, but the reduction in probability is dramatic—on the order of 30%. There appears to be a small increase in mean landfall probability in the eastern Atlantic (bottom panel), but a lack of data and uncertainties in this part of the basin make it difficult to draw a conclusion. These results indicate that the basinwide insensitivity to landfall probability under warm- and cool-SST conditions is partly driven by cancellation between a decrease in the western Atlantic and an increase in the eastern Atlantic.

Because neither genesis frequency (Fig. 9) nor hurricane intensification (Fig. 11) in the western Atlantic region is dramatically affected by warm-SST condi-

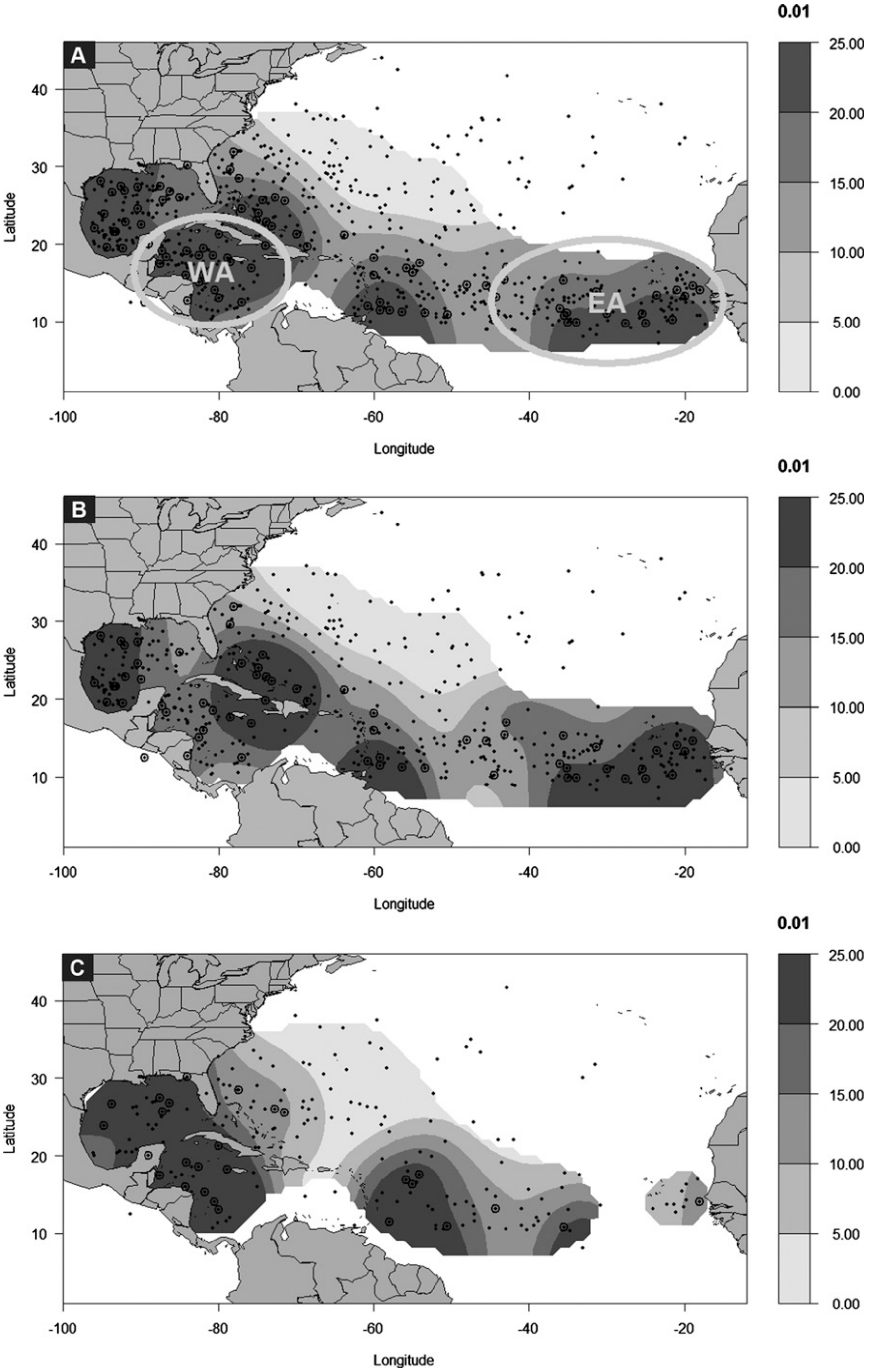


FIG. 10. Estimated probability of hurricane landfall. Circled points indicate storms that eventually make U.S. landfall as a hurricane. The contouring was limited to the shaded genesis density areas in Fig. 9 (0.01 label indicates that the values on the scale should be multiplied by 10^{-2} to get the actual value). (top) Climatological probability of hurricane landfall from genesis regions across the Atlantic. (middle), (bottom) As at top, but using data stratified by warm and cool years, respectively.

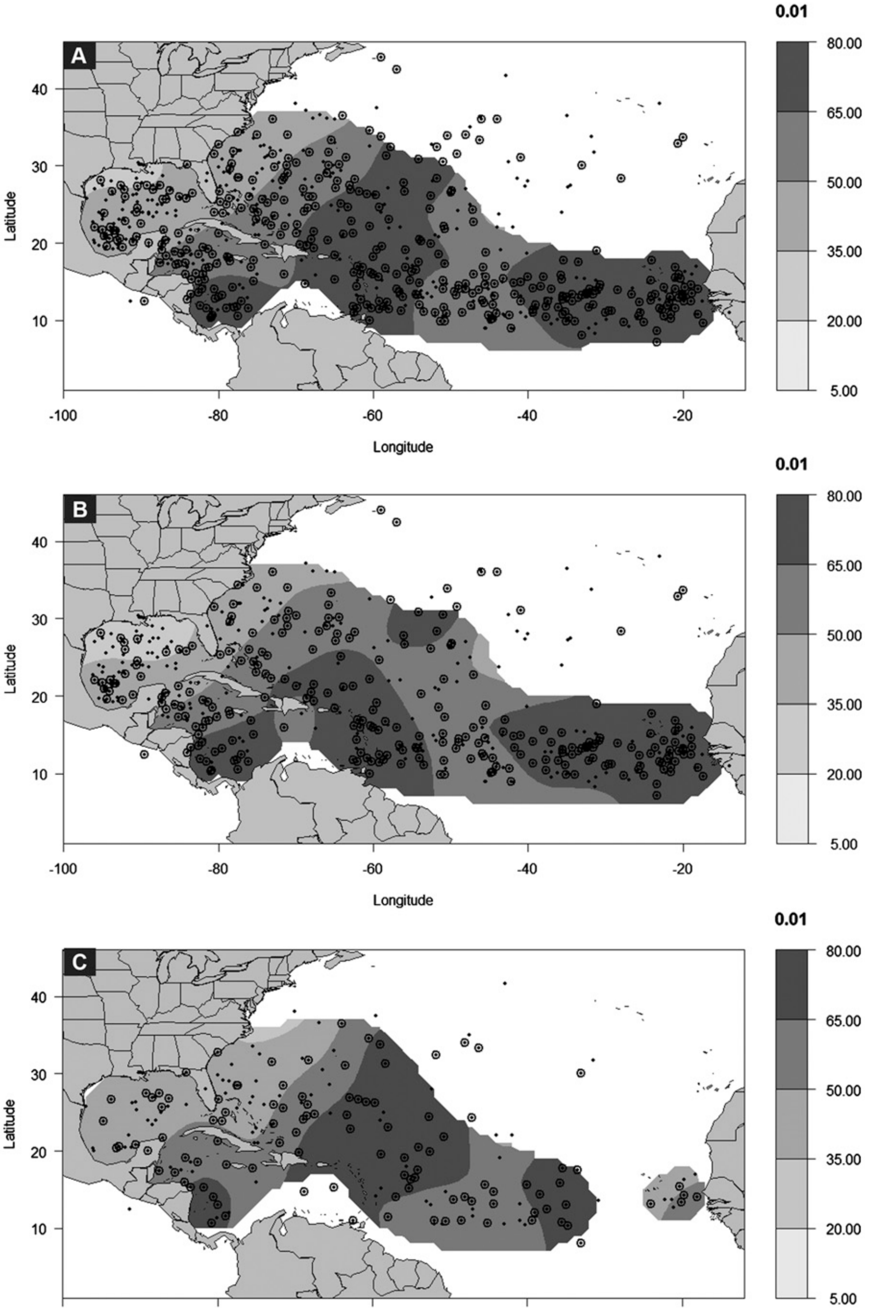


FIG. 11. As in Fig. 10, but estimated probability of TCs reaching hurricane intensity. Circled points indicate storms that eventually achieved hurricane strength but did not necessarily make landfall at that strength.

tions, it is possible that the drop in landfall probability for this breed of storm is caused by changes in tracking that are due to the feedback of warm SSTs on the atmospheric circulation. The influence of typical warm-SST conditions on the strength of the subtropical high pressure center can be significant, and this can have an important effect in the western Atlantic. First, slight increases in track curvature can shift storms away from entering the Gulf of Mexico, where the probability of making landfall is high, out to the Atlantic basin, where the probability of landfall is lower. Also, slight decreases in curvature can take storms that otherwise

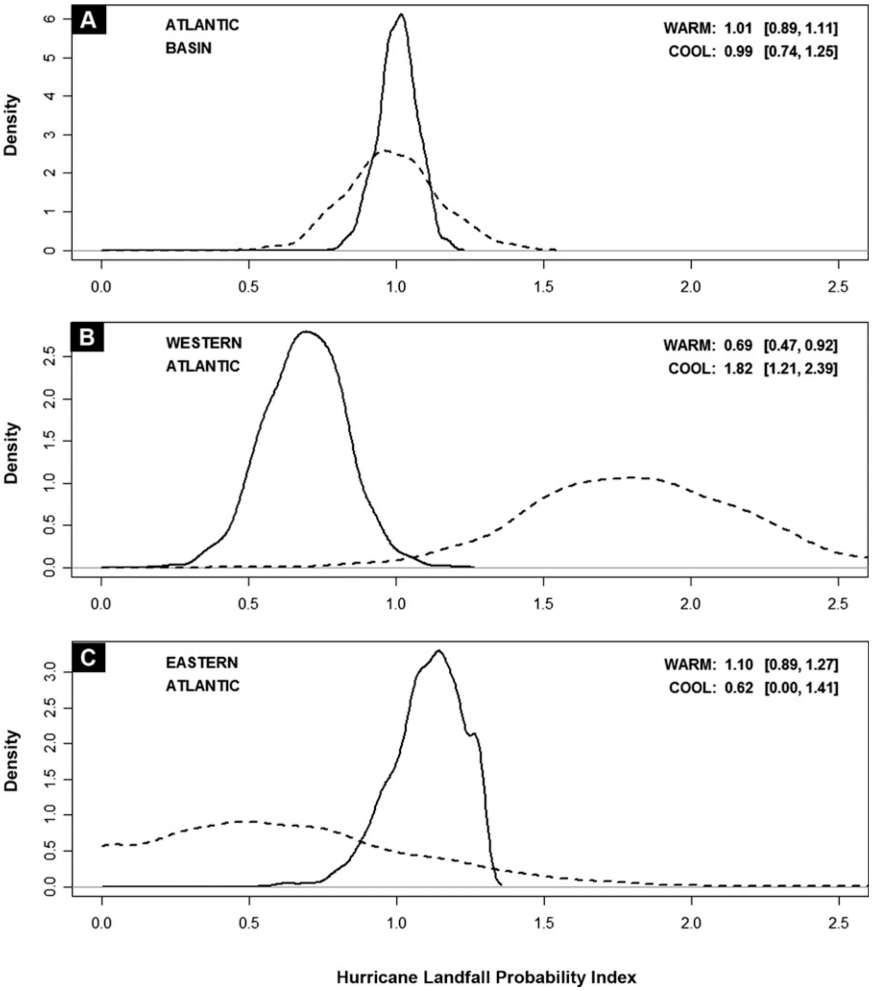
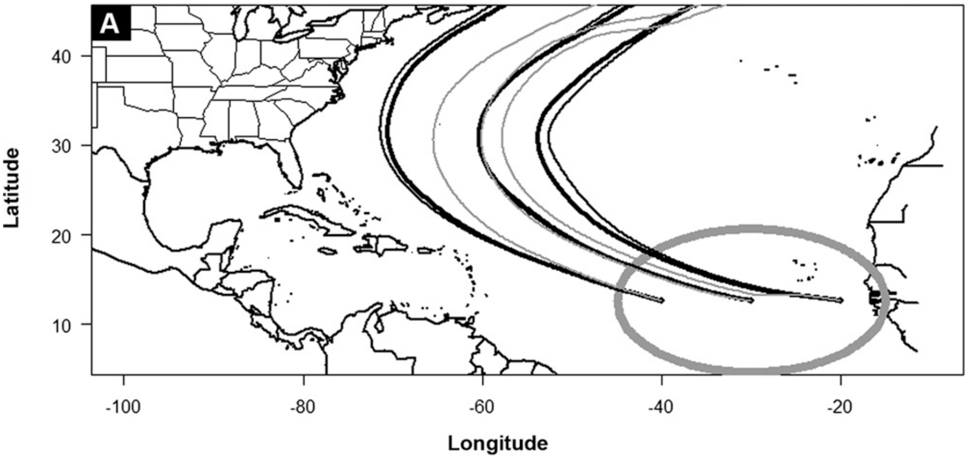


FIG. 12. Sampled distributions of the bootstrapped hurricane landfall probability index for the (top) entire Atlantic basin and the (middle) western and (bottom) eastern Atlantic genesis regions in cool- (dashed) and warm- (solid) SST years. An index value of 1.0 represents U.S. hurricane landfall probability equal to the climatological mean.

would have made landfall along the Gulf Coast and track them toward Mexico. Examination of the historical record shows that the western Atlantic breeds storms with qualitatively different track characteristics under warm-SST conditions.

To examine this aspect of landfall risk further, the Hall and Jewson (2006) technique was used to compute a ‘‘mean climatological track’’ based on the propagation vector (speed and direction) from all historical tracks originating from each genesis region. Figure 13 shows the result from select locations within the eastern Atlantic (EA) and western Atlantic (WA) genesis regions. The thick black lines show that storms originating in the western Atlantic tend to propagate toward the Gulf and Southeast Coasts. The thin black (gray) line is computed for storm tracks occurring in warm (cool) years. There is some indication that warm-SST years correspond to more disperse tracks such that they propagate more westward from the west part of the WA and more eastward from the east part of the WA. The same is shown for the EA genesis region. Here, the anomaly is similar in that warm SSTs seem to impart a premature curvature to the north, in particular from the Cape Verde Islands. Of interest is that a stronger thermodynamic forcing (warmer SSTs) seems to induce more variability in storm tracks, and this can have a profound effect on landfall risk for portions of the coastline that are highly dependent on genesis from certain parts of the Atlantic.

If warm SSTs do feed back onto steering currents, and this significantly affects the movement of storms, then one should be able to observe that relationship. We have analyzed the correlation between Atlantic mean sea level pressure and SST anomalies using data



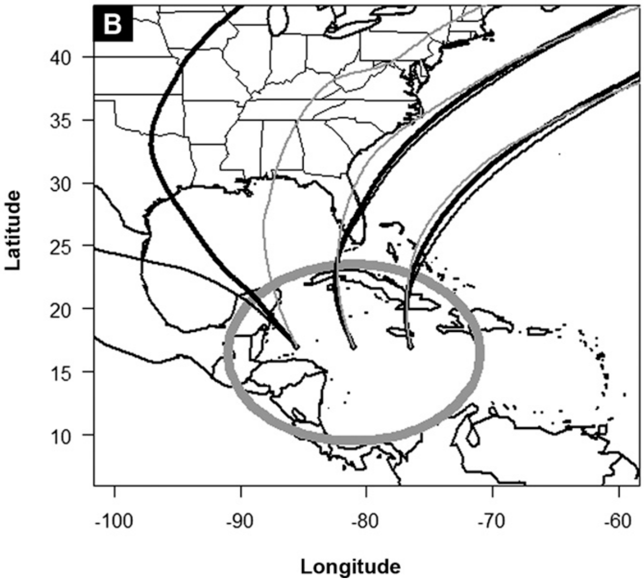


FIG. 13. Climatological mean tracks for TCs originating in two select genesis regions. The thick black line indicates the mean trajectory of storms originating from the (top) western Atlantic and (bottom) eastern Atlantic regions discussed in the text. Tracks are computed using the technique described in Hall and Jewson (2006) as applied to genesis and probability fields. The thin black (gray) line is based on historical tracks originating from each genesis region in warm (cool) years.

from 1948 to 2007 (not shown). Anomalies were computed over a region centered on the mean summer position of the semipermanent subtropical high, which partly controls the movement of TCs in the basin. The correlation is small but is statistically significant, indicating an important though weakly forced impact of warm SSTs on the atmospheric circulation. The correlation coefficient is negative, indicating that as the ocean warms the subtropical high weakens and the atmosphere's control over storm movement is diminished. This may not only explain the more northerly movement shown for storms originating over parts of the MDR, but also the increased variability in track direction under stronger SST forcing. The relationship of tracks to changes in climate requires further research, in particular to address the statistical significance of shifts in movement and to carry out a thorough analysis for genesis regions that strongly influence landfall risk. Of note is that additional studies of how the general circulation itself is affected by local SST anomalies in the tropical Atlantic Ocean and how such changes may feed back onto ocean anomalies will help to solidify or to disprove these theoretical relationships. The implications are important because what may be latent under historically warm SST conditions could become more apparent in a more strongly forced climate.

Beyond changes in steering patterns, there are other reasons why landfall risk along the Gulf Coast is sensitive to changes in SST. For example, the western Atlantic is especially prone to high levels of vertical wind shear and known teleconnections to ENSO (Aiyyer and Thorncroft 2006). Further, the presence of the Caribbean Islands can complicate the direct effects of climate on storm development. Also, storms undergoing initial development in the WA from the depression stage are particularly susceptible to the unique characteristics of this genesis zone. As a consequence, ocean–atmosphere dynamics in the western Atlantic may act as a ‘‘tipping point’’ for U.S. landfall risk—exhibiting a high sensitivity to local conditions for landfall risk, especially under the influence of strong ocean anomalies.

5. Sensitivity analyses

Several sensitivity analyses were carried out to assure that the results of this study are robust. These include testing the sensitivity of TCI distributions to 1) the SST time series, 2) the definition of the area over which SST anomalies are averaged, 3) the exclusion of one season of landfall data, and 4) the exclusion of bypassing hurricanes (which skirt the coastline without explicitly making landfall). The qualitative conclusions reached in section 3 were not affected by these stress tests. When the TCI distributions were estimated using a different intensity measure—central pressure (CP) at landfall—the results did change. The mean TCI for the Gulf region was significantly higher in warm years using CP, especially for stronger hurricanes. This may be the result of a regional bias in the relationship between CP and maximum wind speed and requires further analysis. Still, with CP as an intensity measure, the signal along the Southeast coast was strongest among the analysis regions.

In addition, patterns of genesis density and landfall probability (shown in Figs. 9–11) were determined to be largely invariable as a function of 1) the exclusion of genesis data for one season, 2) the exclusion of data from the presatellite era, 3) the choice of SST anomaly and assignment of cool and warm years, and 4) the choice of optimal radius of influence. The results in section 4 of this study are most sensitive in parts of the Atlantic basin where genesis frequency is low and, for this reason, Figs. 10 and 11 have been masked in areas where the data sample is deemed insufficient for probability estimation. Note that some storm tracks may have been missed prior to 1970, especially over the eastern Atlantic. In general, landfall probability estimates are most sensitive in parts of the Atlantic where genesis is sparse and along parts of the U.S. coastline where landfalls are infrequent.

6. Summary

This study examines the relationship between warm Atlantic SSTs and U.S. landfall activity. Unlike most previous investigations in which the focus has been on activity over the Atlantic Ocean, this study focuses on how the basin’s response to warm SSTs translates to landfall frequency and landfall probability.

Rather than being conditioned on point forecasts of SSTs, which are subject to significant levels of uncertainty, the analysis is conditioned on the assumption that the currently elevated SSTs are likely to remain elevated above climatological levels for several seasons. However, while SSTs are the preferred predictor of hurricane risk over a multiseason horizon, secondary factors can still play an important role in determining hurricane activity from one season to the next. To gain a more complete understanding of these complexities, the dynamical system is also examined. Shifts in genesis and changes in storm evolution, both intensification and track, can regionally focus the effects of warm ocean temperatures, but not always in an intuitive way. Potential deficiencies in data for the Atlantic basin, especially during the presatellite era, are acknowledged.

The statistical analysis shows that the risk of TC landfall along the Gulf Coast is significantly elevated in a warm-SST climate, but frequency is mainly enhanced for tropical storm and weak hurricane landfalls. The physical explanation is that storms that form in the Gulf of Mexico contribute strongly to the landfall risk along the Gulf Coast, and these storms have a reduced opportunity to intensify before making landfall. This is a climatological statement; there are many exceptions in the historical record, including longer-lived storms that form outside the Gulf and storms that form within the Gulf but undergo rapid intensification.

The statistical analysis also shows that the risk of hurricane landfall along the Southeast coast is significantly elevated under warm-SST conditions, and the frequency is mainly enhanced for hurricane and especially strong hurricane landfalls. The physical explanation is more complex than for the Gulf Coast because of contributions to risk in the Southeast region from a diverse area of Atlantic basin genesis. What is clear is that storms that make landfall along the Southeast coast typically originate from the open Atlantic and have a longer expanse of ocean over which to develop and intensify.

The low frequency of landfalling events along the Northeast coast of the United States makes it difficult to extend the analysis to this region. To complicate matters further, the risk of landfall in New England is partly driven by storms that have made initial landfall along another part of the coastline or are disrupted by unfavorable conditions in the midlatitudes. This combination of low frequency combined with a diverse origin of landfall renders the Northeast as the most challenging region for such an analysis. Stochastic models may provide additional guidance.

The combined results of the statistical and physical analyses explain what is noticeable in the historical data: the percentage increase in basinwide activity in warm-SST years does not directly translate into a proportional increase in U.S. landfalls, both by region and by intensity. Local hurricane risk along the U.S. coastline is sensitive to its dominant genesis region and the response of genesis to warm SSTs, as well as large-scale shifts in the tracking patterns imparted by a warm ocean. This paper highlights some of these relationships to SST, and there are other important climate factors such as ENSO that may have equally strong influence.

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