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# A Climatology of Tropical Storm and Hurricane Strikes to Enhance Vulnerability Prediction for the Southeast U.S. Coast

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## ABSTRACT

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A simple model of the average swath of tropical storm and hurricane-force winds to the right and left of storm centers is developed and utilized to evaluate the geographical and temporal distribution of storm strikes at "point locations" along the subtropical coast of the United States. The specific area of study is from South Padre Island, Texas, to Cape Hatteras, North Carolina. The time of record is 100 years from 1901 through 2000. The analysis illustrates the great geographical variability with high frequencies of tropical storm and hurricane strikes in southeastern Louisiana, southern Florida, and eastern North Carolina. Coastlines with lower frequency strikes are located along the western coastline of the Gulf of Mexico in southern Texas, the northeastern coastline of the Gulf in Florida from near Apalachicola southward to St. Petersburg, and especially along the South Atlantic coast from Daytona Beach, Florida, northward to the vicinity of Charleston, South Carolina. Temporal variability is great and significant, however, and with the exception of the northern Gulf Coast, most coastal sites have experienced pronounced clusters of strikes separated by tens of years with very few strikes. The occurrences of tropical storm and hurricane events over the Gulf of Mexico are related to La Niña, neutral, and El Niño seasons, but the clusters of strike events and longer runs of seasons with minimal activity cannot be explained on the basis of ENSO indices alone. Our findings have important implications for storm clusters and vulnerability prediction along coasts.

**ADDITIONAL INDEX WORDS:** *Coastal erosion, Gulf of Mexico, Atlantic Ocean, ENSO, return periods, storm clusters*

## INTRODUCTION

The most commonly used approach to quantifying hurricane strikes and recurrence intervals along coastlines involves spatial scales at regional, state and county levels (see recent reviews in ELSNER and KARA, 1999). While this approach has provided critical information on the recurrence probabilities over segments of the coasts, it is well known that the impacts of hurricanes and tropical storms along coasts clearly transcends political boundaries and is extremely variable over relatively short distances. This fact was recognized by SIMPSON and LAWRENCE (1971) when they calculated the number of years between occurrences of tropical cyclones for the Gulf and Atlantic coasts of the U.S. at 80 km (50 mi) increments alongshore. This length was based on the generalization that maximum winds often extend 80 km (50 mi) to the right of the eye of a severe hurricane and thus when added to an 80 km (50 mi) segment where the eye made landfall, would constitute a total impact length of 160 km (100 mi). While this approach generally allows for a higher resolution data set than a county by county-based approach, it remains of limited use for coastal cities, towns, or infrastructure in the private sector, and predicting vulnerability to hurricanes. The focus of this paper is the evaluation of strikes at points along the coast rather than for segments in order to provide a more realistic appraisal of the frequency and return periods of particular places. In addition, graphics of the geographic and temporal patterns of storm strikes over the last 100 years are provided.

## BACKGROUND

In the United States studies of the geographical patterns of tropical storm and hurricane strikes are based on the atlas of storm tracks compiled by the National Hurricane Center (NHC) of the National Oceanic and Atmospheric Administration (NOAA). The latest edition includes seasonal maps of storm tracks over the Atlantic, Caribbean, and Gulf of Mexico from 1871 through 1992 (NEUMANN *et al.,* 1993), with published supplemental updates. A four times daily listing of all

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storms including latitude and longitude positions, central pressures, maximum winds, and the well-known Saffir/Simpson scale of intensity classes and damage potential for each season beginning with 1901 is also now available on the world-wide web.

The classic study of recurrences of hurricane strikes along the Atlantic and Gulf coasts from Maine to Texas was presented by SIMPSON and LAWRENCE (1971). Hurricane strikes across the coastlines were compiled for coastal segments 80 km (50 miles) in length, with an adjustment for strikes in the adjacent segment to the right in order to "smooth" geographical patterns along the coasts. Their storm track data set included 85 years from 1886 through 1970. Figure 1 represents the SIMPSON and LAWRENCE (1971) analysis in terms of average return periods between hurricanes for each coastal segment. The inner number represents average return periods in years for all hurricanes, and the outer number average return periods for severe hurricanes, defined as having maximum winds greater than 200 kph (124 mph); this definition results in a slight underestimate of return periods of Saffir/Simpson categories 3, 4, and 5, which require winds greater than 179 kph (111 mph). Minimum return periods for all hurricanes was 6 years in southeastern Florida, and 7 years in southeastern Texas and along the central Gulf Coast from southeastern Louisiana eastward to western segments of the Florida Panhandle. Blank boxes indicate no hurricane strikes in those coastal segments. Return periods for severe hurricane strikes were shortest again in southeastern Florida with minima of 14 years from near Miami northward to Palm Beach.

In a technical memorandum published by NOAA, all hurricane direct strikes and major hurricane strikes by states were compiled for the years between 1900 and 1995 (HEBERT *et al.,* 1995). This compilation has little practical application other than comparisons among the states, regardless of the length of coastlines. With its very long coastline, Florida led all of the states in both categories.

ELSNER and KARA (1999) reanalyzed hurricane strikes by counties from Maine to Texas for 97 years from 1900 through 1996. Their analysis incorporated all hurricanes and only major hurricanes, categories 3 through 5, in terms of average return periods, and average wait times in years between strikes. Since hurricane events sometimes occur as clusters, average wait time can be a very different statistic than average return periods, but return periods are most familiar to the public. For all hurricanes their minimum return period was 4 years for Monroe County, Florida, a county that extends for more than 224 km (140 miles) from Key West to Key Largo; for major hurricanes the minimum was 11 years, again for Monroe County.

Particularly for the private sector, however, the potential for recurring storm damage and estimates of strike return periods are most relevant for short segments of beaches and coasts and specific structures such as homes, condos, hotels, and business infrastructure. The double segments of SIMPSON and LAWRENCE (1971), 160 km (100 miles), are often much too long, and the strike counts by counties by ELSNER and KARA (1999) are truncated by political boundaries. We propose, instead, a simple but more realistic strike model, adjusted for storm intensity in terms of surface winds and storm surges, and the typical asymmetric extension of storm winds to the right of storm tracks in the northern hemisphere (SIMPSON and RIEHL, 1981), and nearby offshore storms that affect the coasts but do not cross the coasts.

## STRIKE MODEL METHODOLOGY

Tropical storms and hurricanes are normally much smaller geographically when compared to the major frontal storms of the higher latitudes (HSU, 1988). Storm winds and precipitation associated with major midlatitude cyclones can sometimes extend over an area as much as 1,600 km (1,000 miles) across, but the swath of hurricane-force winds in very intense, although small hurricanes may be less than 100 km (60 miles) across (SIMPSON and RIEHL, 1981). The coastal extent of destructive winds of the two category 5 hurricanes that have crossed the United States coastline since 1900, the Florida Keys Labor Day storm in 1935 and Hurricane Camille on the Louisiana and Mississippi Gulf Coasts in 1969, was very restricted. The eye of the 1935 hurricane in the Florida Keys was only 13 km (8 miles) in diameter (BARNES, 1998), and the swath of hurricane-force wind gusts as Hurricane Camille came onshore was only 160 km (100 miles) across (Climatological Data for Louisiana, 1969). Largest diameters, however, are often associated with category 3 storms, but there is great variation in the diameter of hurricane-force winds in individual hurricanes, with extreme winds usually limited to the narrow ring around the eye-wall (SIMPSON and RIEHL, 1981). PIELKE and PIELKE (1997) have recently illustrated the range of storm diameters from midgets to giants. Typically, the right-front quadrant of a hurricane generates the strongest storm winds, so that hurricane-force winds normally extend much farther to the right than to the left of the eye along the storm track (SIMPSON and RIEHL, 1981).

The higher storm surges are also normally to the right of the storm tracks, with damaging surges often extending well beyond the extent of destructive hurricane winds. During Hurricane Opal in 1995, a category 3 storm just before landfall, the destructive storm surge extended more than 290 km (180 miles) along the coast of the Florida Panhandle from Pensacola Beach eastward to Wakulla County (STONE *et al.,* 1996; BARNES, 1998). Detailed compilations of storm surge elevations associated with hurricanes along the Louisiana coast indicate typical elevations of 3 meters (10 feet) extend far to the right of the storm tracks, but with very low surges, occasionally even negative elevations, to the left of the tracks (U.S. ARMY CORPS OF ENGINEERS, 1972; STONE *et al.,* 1993; GRYMES and STONE, 1995).

The atlas of tropical storm and hurricane tracks (NEUMANN *et al.,* 1993) provides estimates of the Saffir/Simpson category of each storm at landfall, but there are normally very few standardized and well-calibrated wind observations along the coasts in the vicinity of these strikes. In order to compile categories of storm strikes at locations in the vicinity of landfalls, it is necessary to develop a simple model of the average diameter of storm categories. The models of typical storm-wind patterns in SIMPSON and RIEHL (1981) were

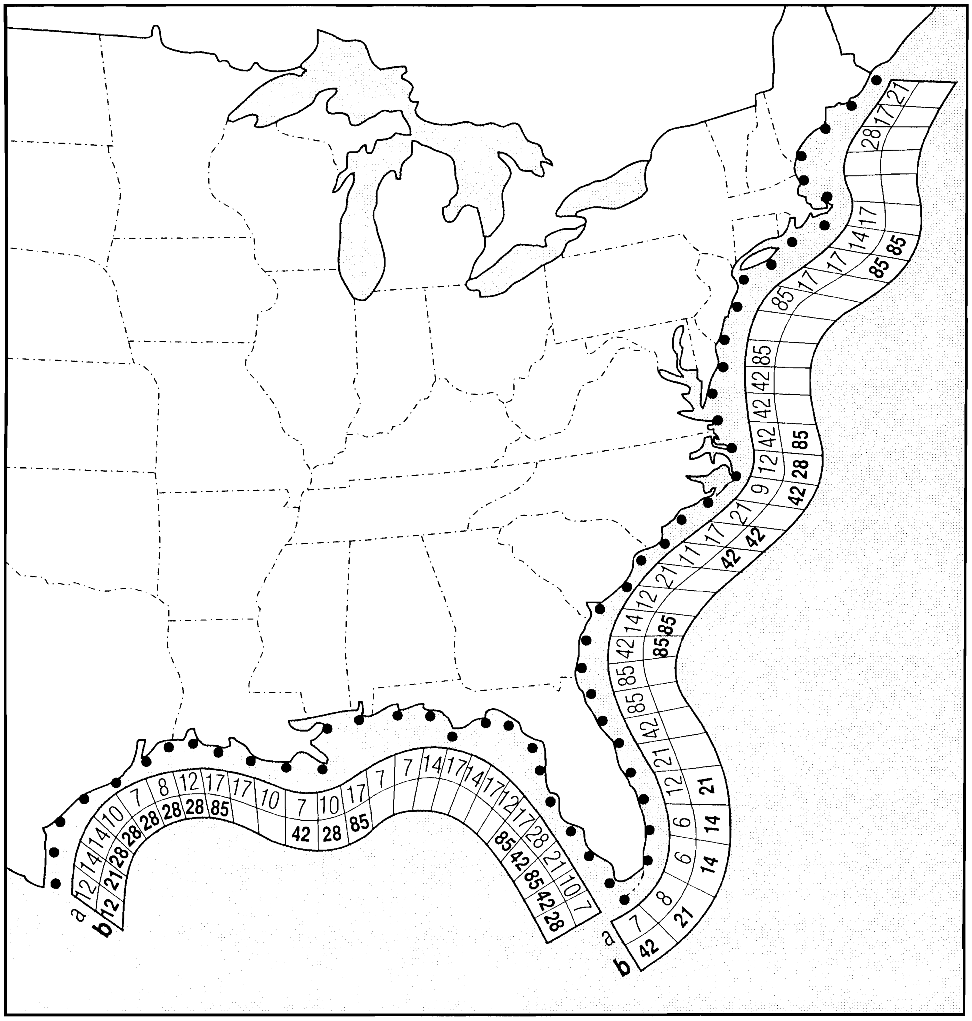

Figure 1. Average return periods for all hurricanes (a) and severe hurricanes (b) for 80 km coastal segments 1886–1970 (adapted from SIMPSON and LAWRENCE, 1971.)

most helpful for the development of the standardized strike models in Figure 2.

Figure 2 illustrates the simple tropical storm and hurricane strike model developed in this study. For tropical storms, the effects of tropical storm winds and surges are shown to extend outward from the center for 80 km (50 miles) to the right and 40 km (25 miles) to the left of the storm track. For category 1 and 2 hurricanes, the effects of winds of hurricane strength and surges extend outward from the eye 80 km (50 miles) to the right and 40 km (25 miles) to the left; the effects of tropical storm force winds and surges extend outward an additional 80 km (50 miles) to the right and 40 km (25 miles) to the left. Similarly, for major hurricanes, categories 3 through 5, the effects of at least category 3 winds and surges extend 80 km (50 miles) to the right and 40 km (25 miles) to the left of the track, with the effects of hurricane-force winds and surges an additional 80 km (50 miles) to the right and 40 km (25 miles) to the left; hence, the width of the effects of hurricane-force winds parallel with the track is 240 km (150 miles). Again, the effects of tropical storm force winds extend an additional 80 km (50 miles) to the right and 40 km (25 miles) to the left of the track. The dimensions of this simple model were set to approximate "average-size" hurricanes described in DUNN and MILLER (1960), SIMPSON and RIEHL (1981), and ELSNER and KARA (1999).

This model was applied to the tropical storm and hurricane tracks from 1901 through 2000 at 32 coastal communities along the subtropical Atlantic and Gulf coasts of the United States from South Padre Island (Brownsville, Texas) to Cape Hatteras, North Carolina, a coastline of more than 3,500 km (2170 miles) in length. Locations and place names are shown in Figure 3. The selected coastal communities are associated with well-known coastal cities, seaports, and beach resorts, and they are not equally spaced along the coastlines. The compilation is for landfall at "point-locations" on the beaches of the coastal communities, most often located on barrier is-

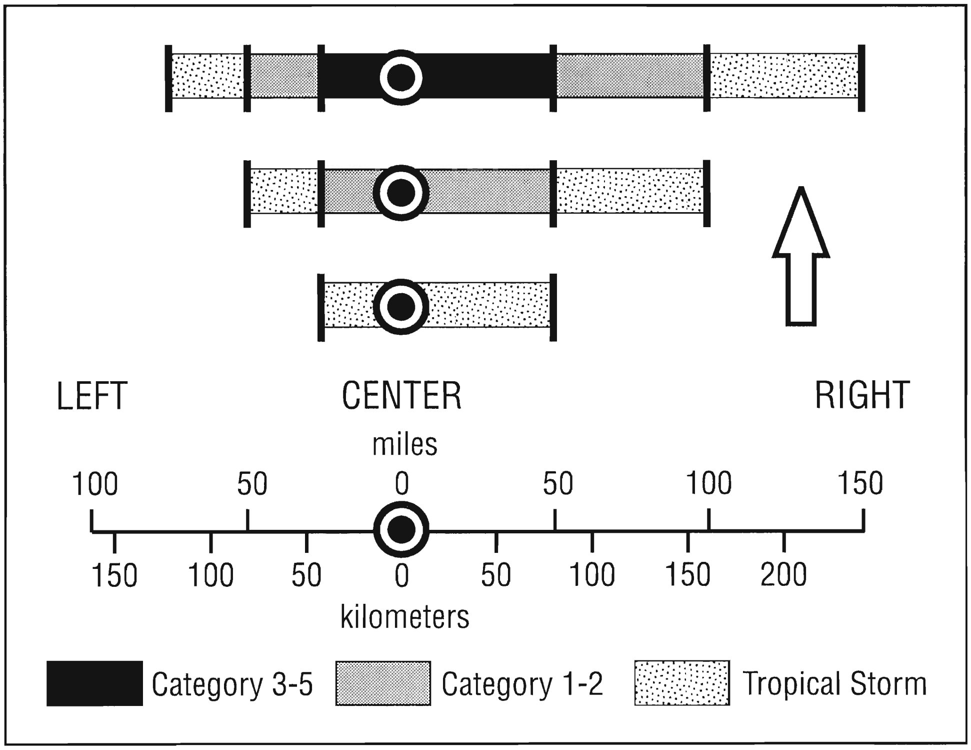

Figure 2. Representative swaths for tropical storms, and Saffir/Simpson hurricanes categories 1–2, and 3–5 sustained winds, with the direction of movement shown in the diagram.

lands. Recurrence of tropical storm and hurricane force winds at the much better known nearby cities, usually sheltered from the immediate coast, will of course be much lower.

## TEMPORAL AND GEOGRAPHIC PATTERNS OF STORM STRIKES

The temporal and geographic patterns of tropical storm and hurricane strikes are presented in Figure 4. For specific coastal communities this figure illustrates temporal patterns on the vertical axes, and geographical patterns along the coasts on the horizontal axes. The figure provides a summary overview of the geographical and temporal patterns of tropical storm and hurricane strikes in the Twentieth Century from Texas to North Carolina.

Beginning with Texas, among the more striking features of this figure are the lower frequencies of strikes along the southeast Texas coast southwest of Galveston during the last 3 decades. This also includes no major hurricane strikes at Port Aransas (Corpus Christi) since 1934, and only 1 hurricane strike at Cameron, Louisiana (Lake Charles), since Hurricane Audrey in 1957. The obvious cluster of 6 tropical storms and 7 hurricanes at Galveston between 1932 and 1949 and their impacts is of interest; less intensive clusters of events are evident at some of the sites to the east and north, especially in southern Florida and North Carolina. In addition, the most catastrophic hurricane strike in the history of the United States, the Galveston hurricane of 1900, is just off the figure by 1 year. The model also illustrates the very high frequency of major hurricanes in southeastern Louisiana, with 7 at Morgan City and 5 at Boothville, near the mouth of the Mississippi River.

Considering the central Gulf Coast from Gulfport, Mississippi, eastward to Apalachicola, Florida, a coastline of approximately 440 km (275 miles), the strike data indicate that the frequency of tropical storm and hurricane strikes decreases from west to east with 31 strikes at Gulfport and 24 at Apalachicola. Similarly, the geographical pattern of all hurricanes also decreases from west to east, with the exception of Gulfport which is partially protected from recurring strikes from the southwest by the Mississippi River delta plain. Major hurricane strikes also decrease from west to east along the central Gulf Coast from the highest frequencies in southeastern Louisiana with the deltaic region protruding southeastward into the Gulf. The maximum of 4 major hurricane strikes occurred at Dauphin Island, Alabama (Mobile), with no major hurricane strikes in the twentieth century to the

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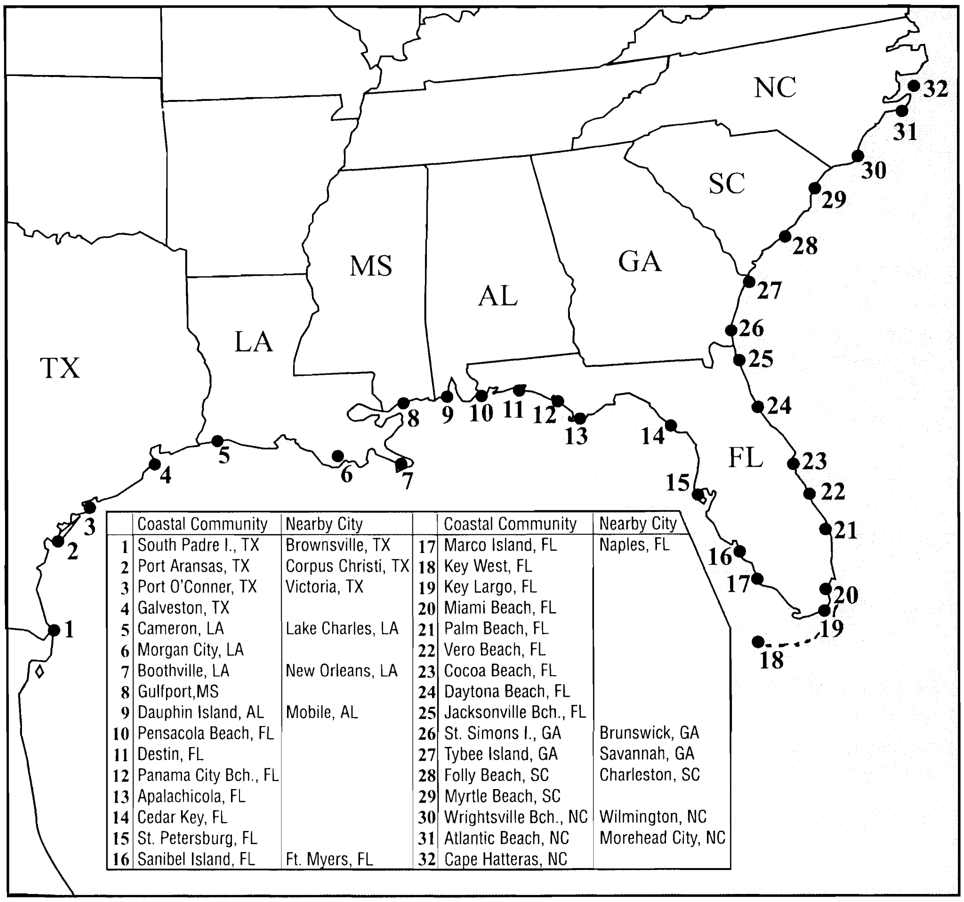
Figure 4. Tropical storm and hurricane strikes South Padre Island, Texas, to Cape Hatteras, North Carolina.



|  | Coastal Community | Nearby City |  | Coastal Community | Nearby City |
|---|---|---|---|---|---|
| 1 | South Padre I., TX | Brownsville, TX | 17 | Marco Island, FL | Naples, FL |
| 2 | Port Aransas, TX | Corpus Christi, TX | 18 | Key West, FL |  |
| 3 | Port O'Conner, TX | Victoria, TX | 19 | Key Largo, FL |  |
| 4 | Galveston, TX |  | 20 | Miami Beach, FL |  |
| 5 | Cameron, LA | Lake Charles, LA | 21 | Palm Beach, FL |  |
| 6 | Morgan City, LA |  | 22 | Vero Beach, FL |  |
| 7 | Boothville, LA | New Orleans, LA | 23 | Cocoa Beach, FL |  |
| 8 | Gulfport,MS |  | 24 | Daytona Beach, FL |  |
| 9 | Dauphin Island, AL | Mobile, AL | 25 | Jacksonville Bch., FL |  |
| 10 | Pensacola Beach, FL |  | 26 | St. Simons I., GA | Brunswick, GA |
| 11 | Destin, FL |  | 27 | Tybee Island, GA | Savannah, GA |
| 12 | Panama City Bch., FL |  | 28 | Folly Beach, SC | Charleston, SC |
| 13 | Apalachicola, FL |  | 29 | Myrtle Beach, SC |  |
| 14 | Cedar Key, FL |  | 30 | Wrightsville Bch., NC | Wilmington, NC |
| 15 | St. Petersburg, FL |  | 31 | Atlantic Beach, NC | Morehead City, NC |
| 16 | Sanibel Island, FL | Ft. Myers, FL | 32 | Cape Hatteras, NC |  |

Figure 3. Location of 32 coastal communities from South Padre Island, Texas, to Cape Hatteras, North Carolina, where tropical storm and hurricane strikes are compiled.

east at Apalachicola, where the sheltering effect of the Florida peninsula diminishes the intensity of storms approaching from the east and southeast.

Figure 4 illustrates the clustering of events and long runs of years with few events along the north central Gulf. At Gulfport, for example, there were 12 tropical storm and hurricane strikes, including 4 hurricanes, one of which was major, during the 16 years between 1901 and 1916. Similarly, at Dauphin Island there were 13 strikes during 17 years between 1901 and 1917, including 6 hurricanes, one of which was classified as major. Figure 4 also illustrates long runs of years with minimal activity. Examples include only 1 hurricane at Gulfport for 42 years between 1927 and 1968, and no hurricanes for 30 years between 1942 and 1971 at Apalachicola.

The record of tropical storm and hurricane strikes along the west coast of Florida from Cedar Key south to Key West shows interesting trends. Geographically, the increasing frequency of storm strikes from north to south is obvious. Similar to Apalachicola to the northwest, Cedar Key is also located within the coastal region that is sheltered by the Florida peninsula, thereby mitigating the intensity of storm strikes approaching from the east and south. At Cedar Key the model indicates that there have been only 3 hurricane strikes during the twentieth century, only one of which was classified as major.

The variable distribution of storm strikes through time is a very significant characteristic of Florida's west coast. At Cedar Key, for example, 14 tropical storm and hurricane strikes occurred between 1932 and 1953, with only 11 additional strikes during the 78 years before and after this intense cluster of activity. Indeed, during the 1920s, 30s, and 40s, St. Petersburg, Fort Myers, and Marco Island experienced very frequent strikes relative to the first 2 and last 5 decades of the twentieth century. At each of these 3 locations more than half of the storm strikes of the century occurred during the 30-year period between 1921 and 1950, and with the exception of Hurricane Andrew in 1992, the model indicates there have been no other major hurricane strikes at these 4 west coast locations for more than 30 years, even 40 years at Sanibel Island. The beaches southward from the Tampa Bay region to Marco Island have been intensively developed during the last 30 years; this strike history indicates that probably very few coastal residents have any memory of hurricane strikes and impacts.

The model record for "offshore" Key West is somewhat different, with relatively frequent tropical storm and hurricane strikes, 28, for the first 70 years; half of these, 14, were of hurricane intensity. Beginning with 1967, however, there was a 20-year period during which only 2 tropical storms occurred. The model also indicates only 2 major hurricane strikes for the 100-year record.

Along the Florida East Coast from Key Largo to Jacksonville Beach, the geographical pattern from south to north is again very obvious, with frequent hurricane strikes northward as far as Vero Beach, and very infrequent strikes northward from Cocoa Beach. There have been no major hurricane strikes from Cocoa Beach northward, and only 4, 3, and 2 hurricane strikes at Cocoa Beach, Daytona Beach, and Jacksonville Beach respectively.

The 30-year period from 1920 to 1950 was by far the most active strike years northward from Key Largo to Vero Beach, very similar to the Florida west coast pattern. At Palm Beach, for example, there were 9 hurricane strikes, of which 4 were major, in 25 years between 1926 and 1950, with most of the activity concentrated in the late 20s and 40s. Since then there have been only 2 hurricane strikes and no major hurricane strikes, during the last 50 years. The only major hurricanes at Key Largo, Miami Beach, and Palm Beach since 1950 have been Hurricane Betsy at Key Largo in 1965 and Hurricane Andrew at Key Largo and Miami Beach in 1992. Again, most of the intensely-developed "Gold Coast" of southeast Florida has not experienced frequent hurricane strikes over the last 50 years.

The low frequency of hurricane strikes in northeastern Florida is continued northward along the coasts of Georgia, with the model indicating no major hurricane strikes north of Vero Beach, Florida, until Folly Beach (Charleston, South Carolina). The model indicates only 1 hurricane strike at St. Simons Island (Brunswick, Georgia), for the entire 100-year record. Geographically, there is an increasing frequency of storm strikes towards the northeast, with more events along the North Carolina coast that protrudes eastward into the Atlantic and is more exposed to storms sweeping northward and northeastward after extended tracks over the open Atlantic.

Unlike southern Florida where there has been an intense clustering of strikes during the 1920s, 30s, and 40s, the primary clustering along the North Carolina coast occurred during the 50s; secondary clusters also occurred there in the early 30s and middle 40s, the early 80s, and again, most recently since 1995. In contrast, the model indicates only 1 hurricane strike at these 7 beach communities in Georgia, South and North Carolina, between 1961 and 1983. This is a remarkable run of years without a single major hurricane strike in the region.

## RETURN PERIODS

Return periods, the long-term average number of years between strikes at a particular coastal location, provide helpful perspectives on the "chances" of strikes in coming seasons. However, the return-period methodology assumes a random distribution of strikes through time, and it does not provide for predictions when the next strike will occur. Nevertheless, the geographical patterns of return periods do provide useful indices of comparative storm threats along the coasts.

Table 1. *Tropical Storm and Hurricane Strikes and Return Periods.*

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| S Padre Is | 16 | 8 | 3 | 6 | 12 | 33 |
| Pt Aransas | 23 | 9 | 2 | 4 | 11 | 50 |
| Pt O'Connor | 26 | 13 | 2 | 4 | 8 | 50 |
| Galveston | 31 | 13 | 3 | 3 | 8 | 33 |
| Cameron | 26 | 5 | 2 | 4 | 20 | 50 |
| Morgan City | 35 | 10 | 7 | 3 | 10 | 14 |
| Boothville | 32 | 16 | 5 | 3 | 6 | 20 |
| Gulfport | 31 | 10 | 2 | 3 | 10 | 50 |
| Dauphin Is | 32 | 15 | 4 | 3 | 14 | 25 |
| Pensacola B | 27 | 14 | 2 | 4 | 7 | 50 |
| Destin | 28 | 10 | 3 | 4 | 10 | 33 |
| Panama City B | 24 | 10 | 2 | 4 | 10 | 50 |
| Apalachicola | 24 | 11 | 0 | 4 | 9 | 100 |
| Cedar Key | 25 | 3 | 1 | 4 | 33 | 100 |
| St Petersburg | 26 | 5 | 1 | 4 | 20 | 100 |
| Sanibel Is | 30 | 8 | 1 | 3 | 12 | 100 |
| Marco Is | 29 | 12 | 3 | 3 | 8 | 33 |
| Key West | 36 | 17 | 2 | 3 | 6 | 50 |
| Key Largo | 27 | 15 | 5 | 4 | 7 | 20 |
| Miami B | 33 | 15 | 2 | 3 | 7 | 50 |
| Palm B | 30 | 13 | 4 | 3 | 8 | 25 |
| Vero B | 25 | 10 | 1 | 4 | 10 | 100 |
| Cocoa B | 26 | 4 | 0 | 4 | 25 | 100 |
| Daytona B | 20 | 3 | 0 | 5 | 33 | 100 |
| Jacksonville B | 20 | 2 | 0 | 5 | 50 | 100 |
| St Simons Is | 10 | 1 | 0 | 10 | 100 | 100 |
| Tybee Is | 18 | 5 | 0 | 6 | 20 | 100 |
| Folly B | 19 | 3 | 1 | 5 | 33 | 100 |
| Myrtle B | 24 | 7 | 2 | 4 | 14 | 50 |
| Wrightsville B | 27 | 11 | 2 | 4 | 9 | 50 |
| Atlantic B | 34 | 10 | 3 | 3 | 10 | 33 |
| Cape Hatteras | 34 | 15 | 3 | 3 | 7 | 33 |

1 = tropical storm and hurricane strikes.
2 = hurricane strikes.
3 = major hurricane strikes.
4 = tropical storm and hurricane return periods in years.
5 = hurricane return periods in years.
6 = major hurricane return periods in years.

In Table 1 the 100-year summary of tropical storm and hurricane strikes and rounded-off return periods for the 32 coastal communities from South Padre Island (Brownsville) to Cape Hatteras are presented. For all 32 coastal communities averaged together, the return period for tropical storms and hurricanes combined is 4 years. Return periods for tropical storms and hurricanes together decrease to 1 every 3 years on the average at coastal communities with the most frequent strikes, the central Gulf Coast, south Florida, and the Cape Hatteras region. Return periods increase to once every 5 to 6 years on average at locations with the fewest strikes, southern Texas and the East Coast from central Florida northward to the southern half of South Carolina.

The average return period for hurricane strikes is 11 years, with return periods of only 6 to 8 years along the western two-thirds of the northern Gulf Coast, Port O'Connor (Victoria, Texas) to Pensacola Beach (Florida), with an anomalous break at Cameron (Lake Charles, Louisiana), southern

Table 2. *Tropical Storms and Hurricanes over the Gulf of Mexico and ENSO Seasons, 1951–2000.*

|  |  | Tropical Storms & Hurricanes |  | Tropical Storms |  | Hurricanes Categories 1–5 |  | Major Hurricanes Categories 3–5 |  |
|---|---|---|---|---|---|---|---|---|---|
|  | Seasons | Events | Per Season | Events | Per Season | Events | Per Season | Events | Per Season |
| El Niño | 11 | 19 | 1.7 | 13 | 1.2 | 6 | 0.5 | 1 | 0.1 |
| Neutral | 30 | 79 | 2.6 | 43 | 1.4 | 36 | 1.2 | 13 | 0.4 |
| La Niña | 9 | 26 | 3.7 | 15 | 1.7 | 14 | 2.0 | 2 | 0.3 |
| Totals | 50 | 124 | 2.6 | 71 | 1.4 | 56 | 1.2 | 16 | 0.3 |

Florida from Marco Island around to Palm Beach, and North Carolina. Return periods of 20 years or more are calculated for Cedar Key and St. Petersburg, Florida, and along the East Coast from Cocoa Beach northward to Folly Beach (Charleston). Because of only 1 hurricane strike at St. Simon Island (Brunswick, Georgia), the return period there is calculated as at least 100 years.

The average return period for major hurricane strikes from South Padre Island (Brownsville) to Cape Hatteras is 50 years. The range is from 20 years or less in southeastern Louisiana and southeastern Florida, only 14 years at Morgan City, Louisiana and 20 years at Key Largo, Florida, to more than 100 years along the East Coast, where there have been no major hurricane strikes at these coastal communities from Cocoa Beach northward to Tybee Island (Savannah, Georgia) during the twentieth century.

For the 32 coastal sites we have compared our estimates of all hurricane return periods in Table 1 with SIMPSON and LAWRENCE (1971) and KARA (1999). When return periods for the 32 sites are averaged, the mean of our estimates for 1901–2000 is 1.5 years shorter, more frequent strikes than SIMPSON and LAWRENCE (1971) for 1886–1970. Variable frequencies of storm activity and coastal strikes may account for much of these differences, which are greatest along the northern Florida and Georgia coasts where hurricane strikes have been most infrequent; one hurricane more or less changes the return period estimate significantly. As an example, for Jacksonville Beach, there was only one hurricane in 1964 in the Simpson and Lawrence data set, giving a return period of 85 years. A second hurricane in 1979 resulted in a return period estimate of 50 years (Table 1).

Our return period estimates in Table 1 average 3.7 years longer, less frequent strikes, than the county estimates by ELSNER and KARA (1999) for 1900–1996, almost the same years for this study. Our return period estimates are longer mostly because of our "point" compilation rather than strikes compiled on a county basis. The greatest differences are for points within larger counties with longer coasts especially along the Florida Keys and the east coast of Florida. Hence, our return period estimates are more realistic relative to storm strike experiences at points along the coasts, however, they do not take into account the highly variable beach exposures to wind and water.

## TEMPORAL VARIABILITY OF STRIKE FREQUENCIES AND THE EFFECTS OF EL NIÑO AND LA NIÑA SEASONS

It is well recognized that there are extended runs of years and decades with more or less frequent tropical storm and hurricane activity over the Atlantic, Gulf, and Caribbean together (ELSNER *et al.,* 1999). The trends in Figure 4 indicate that storm strikes at most of the coastal communities from South Padre Island to Cape Hatteras are not "random" through time, but instead tend to occur in clusters with relatively long runs of years with minimal activity in between. Storm-strike activity tends to be concentrated in one region or another for a few years or even as much as 2 or 3 decades, only then to relocate elsewhere along the coast.

This temporal variability has been greatest along the Atlantic Coast and the West Coast of Florida, as well as the southeast coast of Texas. These coasts have experienced extended runs of frequent storm strikes separated by extended quiet periods. The northern Gulf Coast from Galveston (Texas) eastward to Panama City (Florida), on the other hand, has a strike record that is generally much less variable, with only a few extended periods with little activity.

It is well recognized that sea-surface temperature patterns and atmospheric circulation indices over the tropical Pacific (ENSO) and the North Atlantic oceans significantly impact the seasonal number of tropical storms and hurricanes over the North Atlantic Ocean (GRAY, 1999; PIELKE, JR. and LANDSEA, 1999). Interrelations with Pacific ENSO patterns are best understood. Generally, El Niño seasons are associated with decreasing storm activity and La Niña seasons with increasing activity over the Atlantic Ocean, Caribbean Sea, and the Gulf of Mexico.

In order to evaluate these relationships for the Gulf of Mexico specifically, the standardized monthly ENSO data, sea-level pressure for Tahiti minus Darwin, from 1951 through 2000, were utilized to identify El Niño, neutral, and La Niña seasons. El Niño and La Niña seasons were identified when at least 3 consecutive months between May and November were 1 standard deviation or more below or above the respective long-term means. From 1951 through 2000 11 seasons were identified as El Niño events, 30 as neutral, and 9 as La Niña events. For this analysis all tropical storms and hurricanes making landfall along Gulf of Mexico shores of the United States were compiled by season and Saffir/Simpson categories at landfall from the hurricane track atlas (NEUMANN, *et al.,* 1993) and annual updates by the National Hurricane Center.

Table 2 shows average seasonal tropical storm and hurricane activity over the Gulf of Mexico as related to ENSO events. For tropical storms and hurricanes together, the variation ranged from a seasonal average of 1.7 storms during El Niño seasons, 2.6 storms during neutral seasons, and 3.3 storms during La Niña seasons. For hurricanes only, the seasonal average increased from 0.5 hurricanes during El Niño seasons to 1.7 hurricanes during La Niña seasons. Table 2 also suggests fewer major hurricanes during El Niño seasons, but the limited number of major hurricanes allows only a qualitative generalization among the 3 ENSO classes.

Clearly, more tropical storm and hurricane events can be anticipated during La Niña seasons and fewer during El Niño seasons. These results are relatively similar to other analyses of El Niño and La Niña seasons based on sea-surface temperature departures over the tropical Pacific Ocean in region Niño 3.4 (PIELKE, JR. and LANDSEA, 1999). For 1951 through 1998, 17 El Niño seasons and 14 La Niña seasons were identified, a more "liberal" identification than for Table 2. Nevertheless, when tropical storm and hurricane events over the Gulf of Mexico were compiled according to this organization of seasons, similar frequency relationships by El Niño, neutral, and La Niña seasons were calculated. Hence, the broader interpretation of El Niño and La Niña events does not change significantly the basic relationships set out in Table 2.

## ENHANCING VULNERABILITY PREDICTION

A more advanced understanding of the relationships of sea-surface temperature and atmospheric circulation anomalies with the temporal and geographic variability along the Atlantic and Gulf coasts would be helpful for improved protection of life and property along the beach resorts and coastal cities. This is particularly true for the introduction and management of mitigation policies, and is also essential for the successful prediction of frequencies for the next season and beyond. A considerable effort has been made in recent years in the compilation, analysis, and interpretation of global environmental interactions and seasonal tropical storm and hurricane activity over the Atlantic (ELSNER *et al.,* 1999). In addition to temperature anomalies across the entire Pacific, especially the El Niño and La Niña patterns, North Atlantic properties including sea-surface temperature and salinity patterns, atmospheric pressure distributions, persistent stratospheric winds, and even rainfall regimes in West Africa, have all been shown to be related to the temporal variations of seasonal and decadal tropical storm and hurricane activity over the subtropical Atlantic (GRAY, 1999). As presented in Table 4, beginning with 1995 there has been a sharp increase in tropical storm and hurricane strikes along the central Gulf Coast as well as North and South Carolina. Along the northern Gulf, public concern has increased in recent years because of this clustering effect. There are considerable data indicating recent instability of this coast as one consequence of the clustering of storm events in the 1990s (STONE *et al.,* 1996, STONE 1999).

## SUMMARY

The classis works of SIMPSON and LAWRENCE (1971) on hurricane strikes in the United States have been refined in this study to enhance its applicability to shorter coastal segments. The resultant data are viewed useful for coastal communities in estimating recurring storm damage and strike return periods. While earlier works have provided valuable state-wide and regional statistics on strike probabilities, the spatial resolution is somewhat constrained. While the proposed strike model and resultant data are critical in defining the vulnerability of coastal communities to hurricane impacts, other factors including the geomorphology of coastal areas, degree of coastal stability and population trends are also critical. The recent clustering effect of storms along in particular, the northern Gulf of Mexico, has caused a considerable increase in the number of beach restoration projects which are in various degrees of completion.

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