Origin, Distribution, and Timing of Texas Hurricanes: 1851–2006

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Abstract: This paper provides a place-based approach to the organization and analysis of historic hurricane information in the context of informing decision-making in urban planning, disaster management, and mitigation, and natural resource stewardship on the Texas coast. We discuss the climatology of Texas hurricanes by analyzing the spatial and temporal patterns and some aspects of factors that contribute to their observed variability. Finally, we construct scenarios of historic hurricanes that formed and made landfall rapidly on the Texas coastline and suggest that these storms are especially challenging for emergency planners, citizens, and public officials.

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Introduction

The lack of public attention to preparedness for hurricanes and other potentially catastrophic disasters is a persistent phenomenon in American society (Ripley 2006). Despite the availability of exhaustive research on barriers to disaster preparedness and sustained efforts by federal, state, and local emergency managers to educate citizens, repeated surveys document the public's failure to take action (Hurricane Safety Poll 2007). Remarkably, after the intense media attention and public education campaigns associated with the very active hurricane season of 2005 that included the catastrophic impacts of hurricanes Katrina and Rita, the lack of preparedness in Gulf of Mexico states remains apparent in 2007 survey data (AccuWeather 2007).

More than 35 million people choose to live in the coastal counties stretching from North Carolina to Texas, a 244% increase in the resident coastal population between 1950 and 2006 (U.S. Census Bureau 2007). Major metropolitan areas along the southeastern United States and Gulf of Mexico include Miami-Fort Lauderdale, Florida, Tampa-St. Petersburg-Clearwater, Fla., Mobile, Alabama, New Orleans, Louisiana, and Houston-Baytown-Sugar Land, Texas. A recent assessment of the vulnerability of the Greater Houston and Upper Texas coast region to the landfall of a Category 4–Category 5 hurricane suggests both direct and indirect societal impacts significantly greater than those that resulted from hurricanes Katrina and Rita (Blackburn 2007). Cascading impacts from damage to vital oil, natural gas, and petrochemical infrastructure located offshore and in coastal counties of the Upper Texas coast would pose significant consequences for the entire U.S. economy.

In this paper we provide a place-based approach to the organization and analysis of historic hurricane information. Specifically, we aim to provide the basis for constructing risk narratives that are informed by a visual and statistical analysis of historic data on Texas hurricanes. A place-based approach is appropriate because states, counties, and cities share primary responsibilities for disaster management. Private coastal development is largely determined by local regulations, infrastructure, demand, risk, and time value of capital.

Examples of previous attempts to construct hurricane histories include several books at state scales by Williams and Duedall 2002, Barnes 1995,1998, and numerous books and articles on individual major hurricanes (e.g., Galveston 1900, 1938 hurricane, Andrew, Katrina), and a variety of internet resources that provide basic hurricane data records and a few tools for analysis (e.g., Blake et al. 2007). Most of analytical studies on hurricanes are in books and academic journals where the emphasis is on gaining a fundamental understanding of factors that influence the forecasting of track and intensity at the ocean basin scale (e.g., see Emanuel 2005 for a recent review).

With the exception of a recent climatological study of the hurricane history of New York (Vermette 2007), most of the published materials on hurricanes are too demanding of time or technical expertise to meet the requirements of being "usable science" that might inform public planning or private investment in coastal counties and cities. Our metrics for usable science include visual representations of hurricane histories based on state-of the-art data and robust basic statistics, combined with a relatively brief explanatory text that can be understood by a broad range of interested citizens.

This paper provides a comprehensive climatology of Texas hurricanes describing the spatial and temporal patterns and some aspects of factors that contribute to the observed variability. Then,

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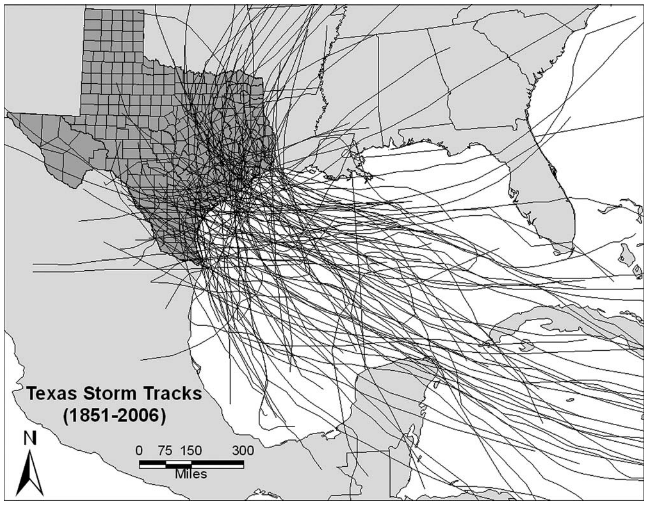

Fig. 1. Historical storm tracks of Texas from 1851 to 2006

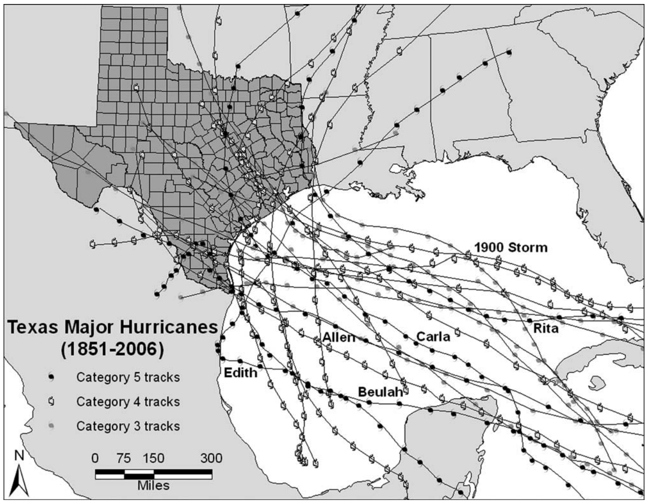

Fig. 2. Storm tracks of Texas major hurricanes (1851–2006)

using historical case studies of hurricanes that rapidly formed and made landfall on the Texas coastline, we suggest that these storms are especially challenging for emergency planners, citizens, and public officials.

Climatology of Texas Hurricanes: 1851–2006

Our Texas hurricane database (Appendix I) was extracted from the National Oceanic and Atmospheric Administration's (NOAA) best track data in the Global Tropical and Extra-tropical Cyclone Climatic Atlas NCDC and FNMOD 1996, and from the Atlantic tracks files provided by the Tropical Prediction Center (UNISYS 2007). 6-h latitude-longitude data and corresponding information for each of the storms were put into ArcGIS for visualization and analysis. Intensities of the storms (i.e., Category 1 through Category 5 hurricanes), as well as tropical storms, are based on the Saffir-Simpson hurricane scale.

Spatial Distribution of Texas Hurricanes

The visualization of tracks from the 104 storms that made landfall in or very near Texas from 1851 through 2006 are presented in Fig. 1. Of these storms, 66 were classified as hurricanes (Table 1) and 24 became major hurricanes (Category 3 or higher). The tracks of major hurricanes are shown separately in Fig. 2.

The hurricane intensity shown in Fig. 2 is based on the maximum wind speeds experienced over its track and does not reflect the intensity at landfall. There is no recorded hurricane that has made landfall on the Texas coast as a Category 5 storm; the deadly 1900 "Galveston Storm" is estimated to have made landfall as a Category 4 hurricane.

Table 1. Frequency of Texas Hurricanes Ranked according to the Saffir-Simpson Scale (1851–2006)

Category	Wind speeds (mph)	Number	%
1	74–95	25	37.88
2	96–110	17	25.76
3	111–130	9	13.64
4	131–155	10	15.15
5	>155	5	7.57
	Total	66	100

The majority of the hurricanes making landfall on the Texas coast (64%) were Category 1 or Category 2, and the rest (36%) were Category 3 and Category 4 hurricanes. Based on their maximum intensities during their ocean track toward the Texas coast—of the major storms, five (21%) were Category 5, 10 (42%) were Category 4 and nine (37%) were Category 3 hurricanes.

During 1851–2006, about half (54%) of all the Texas storms (56 out of 104) formed in the Gulf of Mexico. Of these Gulf-originated storms, five became major hurricanes including four Category 4 and one Category 3 hurricanes. The Category 4 hurricanes were—Bret (1999), Audrey (1957) and two unnamed hurricanes (1945, 1932). In 1983, Alicia, a Category 3 hurricane, caused significant damage in Galveston and the Greater Houston metropolitan area.

Between 1851 and 2006, more than half (56%) of the storms making landfall in Texas hit the Upper Coast with a concentration around the Galveston Bay region. Of these Upper Coast storms, most of them (66%) formed in the Gulf of Mexico. This is in sharp contrast to Louisiana and the Lower Coast of Texas. During this period, 46 storms hit the Lower Texas Coast of which only 18 (39%) storms formed in the Gulf and similarly only 39% of the total storms hitting Louisiana formed in the Gulf of Mexico.

Temporal Distribution of Texas Hurricanes

The official hurricane season in the North Atlantic basin is from June through November. However, the majority of intense hurricanes occur in the three months of August, September, and October (Landsea 1993). Carr (1967) conducted an analysis of 31 hurricanes that affected Texas during 1900–1965. Of these hurricanes, 65% hit the Texas coast in August and September, and 23% made landfall in June at the beginning of the hurricane season.

The monthly distribution of tropical storms and hurricanes that made landfall on the Texas coast between 1851 and 2006 is illustrated in Fig. 3. The majority of the storms hit Texas in August and September (57%), with fewer making landfall in June 22%, July (14.4%), and October (6.7%), similar to the temporal pattern of storm activity previously reported by Carr (1967). The monthly

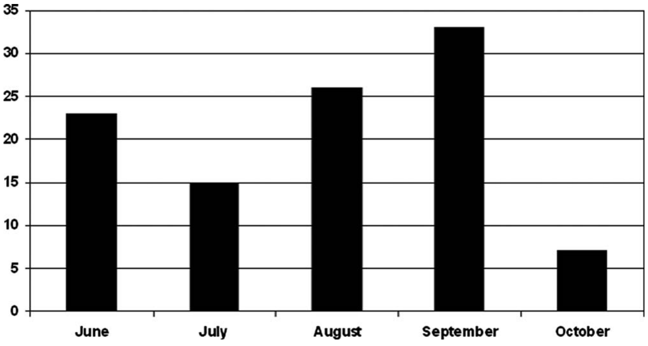

Fig. 3. Monthly distribution of Texas storms (1851–2006)

distribution of major hurricane activity is illustrated separately in Fig. 4. A majority of major hurricanes (83%) made landfall in August and September with relatively few occurrences in June, July and October.

Texas storms that form in the Gulf of Mexico have a significantly different temporal landfall pattern. Gulf-originated storms generally have occurred earlier in the hurricane season than Atlantic hurricanes. June is the busiest month for Gulf-originated storms making landfall in Texas with a total of 18 storms including the Category 4 Hurricane Audrey (Fig. 5).

Conditions Influencing the Variability of Texas Hurricanes

The Atlantic basin is most active during the months of June–November, the traditional "hurricane season." However, considerable temporal variability of hurricanes and tropical storms has been observed in month-to-month and in interannual to interdecadal timescales (Landsea et al. 1999). Much of the long-term variability of Atlantic hurricanes has been attributed to a multidecadal cycle of varying sea-surface temperatures (SSTs) and vertical wind shear referred to as the AMO Index (Goldenberg et al. 2001). Researchers have also examined shorter time variations associated with the El Niño-Southern Oscillation (ENSO) (Bove et al. 1998), the North Atlantic Oscillation (NAO) (Elsner et al. 2000), and a warming of SST's because of increased solar activity (Weng 2005).

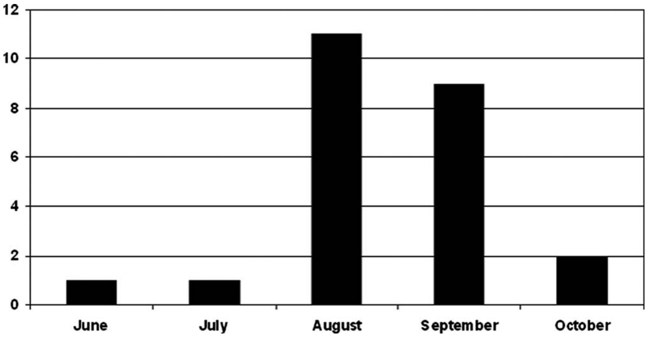

Fig. 4. Monthly distribution of major Texas hurricanes (1851–2006)

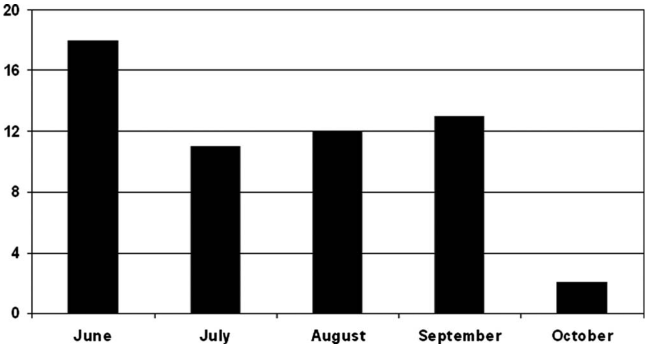

Fig. 5. Monthly distributions of Texas storms formed in the Gulf of Mexico (1851–2006)

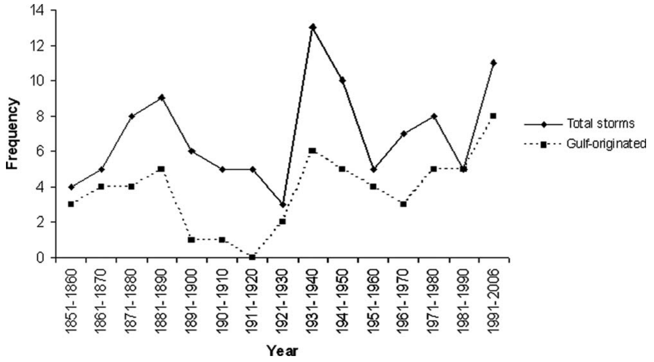

Fig. 6. Frequency of Texas storms in 10-year periods (1851–2006)

SST plays an important role in tropical cyclone genesis. Hurricanes can only form in open ocean areas with a surface temperature greater than 26.5°C (Landsea 1999). This is because the warm ocean water provides sensible heat and water vapor that fuels the intense convection of a hurricane, and if conditions are favorable, a tropical depression develops into a tropical storm, then finally into a hurricane. Thus, SST anomalies in the North Atlantic including the Gulf of Mexico should play a vital role in the variability of Atlantic hurricanes and the storms hitting the Texas coast.

Warm (El Niño) and cold (La Niña)—Southern Oscillation (ENSO) phases are important for low and high rates respectively of Atlantic basin hurricane occurrences. According to Pielke and Landsea (2001), the frequency of hurricanes in the North Atlantic increases during La Niña periods, over that of El Niño periods. During the warm ENSO phase (El Niño) there is anomalously warm water in the equatorial east Pacific. Warm east Pacific water temperatures cause anomalously strong upper tropospheric westerly wind conditions over the tropical Atlantic. Thus, during an El Niño event the tropospheric vertical wind shear is generally increased which inhibits hurricane formation (Gray 1994). Landsea et al. (1999), Tartaglione et al. (2003) and Smith et al. (2007) analyzed the effects of ENSO on U.S. hurricane landfalls at regional scale for the Caribbean, Florida, the Gulf Coast, and the East Coast. The phases of ENSO are defined using the Japan Meteorological Agency (JMA) index and the method of Bove et al. 1998 (Appendix II).

Understanding tropical cyclone variability on interannual to interdecadal timescales is hampered by the relatively short period over which accurate records are available (Landsea et al. 1999). During 1851–2006, the average of tropical storms and hurricanes hitting the Texas coast per year is 0.66, i.e., a storm hits about every 2 years. Fig. 6 shows a comparison of frequencies between the total Texas storms and the Gulf-originated storms in 10-year-periods. In both cases, the strike rate varies considerably over time. Gray (1990) and Landsea and Gray (1992) found that the late 1920s to the 1960s were very active and 1900s to the mid-

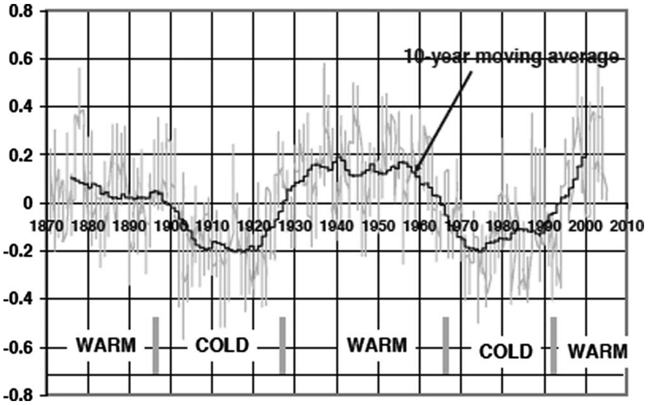

Fig. 7. Oscillations in North Atlantic SST (Source: SFWMD-http://www.sfwmd.gov/newsr/oscillations.gif)

1920s as well as the 1970s to the mid-1980s were quiescent for Atlantic storms. Fig. 6 reflects a similar observation for the storms in Texas and Gulf-originated Texas storms.

The SST anomalies in the North Atlantic influence tropical cyclone variability. SSTs in the genesis regions of tropical cyclone basins have a direct thermodynamic effect on tropical cyclones through their influence on moist static ability (Malkus and Riehl 1960). For the Atlantic basin, warmer than average waters are usually accompanied by lower surface pressures, weaker trade winds, and reduced shear; cooler than average waters are accompanied by higher pressure, stronger trade winds and increased shear (Knaff 1997). Saunders and Harris (1997) provide substantial evidence that Atlantic SSTs are the dominant physical modulator of tropical Atlantic hurricanes (Landsea et al. 1999).

Fig. 7 shows the oscillations in North Atlantic SST (also known as the AMO index), which influences the variation of storm frequencies for the Texas coast. The current warm phase of AMO which began in 1995 has corresponded to the recent rise of landfalls for the Texas coast.

In addition to the thermodynamic variables, changes in the tropical dynamics also play a large role in determining changes in tropical cyclone activity (Landsea et al. 1999). Smith et al. (2007) analyzed the effects of ENSO on U.S. hurricane landfalls at regional scales for Florida, the Gulf Coast, and the East Coast. Regional differences in the effects of ENSO on hurricane landfalls in the Caribbean have also been observed (Tartaglione et al. 2003; Landsea et al. 1999). El Niño (La Niña) decreases (increases) hurricane landfall activity relative to the neutral phase for the entire Caribbean region. There is virtually no difference in the probability of hurricane landfalls in Florida or along the Gulf Coast during ENSO cold versus neutral years but a significant increase is found for the East Coast. Along the Gulf Coast and in Florida the landfall probabilities are reduced for ENSO warm versus neutral phases but nearly identical for the East Coast (Smith et al. 2007).

Table 2 provides the distribution of Texas storms based on their origins in warm, cold ENSO, and neutral phases from 1900 to 2006. In 23 warm ENSO phases, the Texas coast experienced only 11 storms of which 4 originated in the Atlantic and 7 in the Gulf, but in 25 cold ENSO phases, Texas had 20 storms of which 12 originated in the Atlantic and 8 in Gulf. In 59 neutral years, 42 storms hit Texas of which 24 formed in the Gulf. As expected, the rate of storm occurrence for Texas is higher in cold ENSO (La Niña) versus neutral phases and reduced in warm ENSO (El Niño) versus neutral phases.

Table 3. Atlantic and Gulf-Originated Storms in ENSO and Neutral Phases (1900–2006)

Event	Rate of Atlantic-originated storm occurrence per event	Rate of Gulf-originated storm occurrence per event
Warm	0.17	0.30
Cold	0.48	0.32
Neutral	0.31	0.41

In terms of major hurricanes during 1900–2006, all of the Atlantic hurricanes formed either in cold ENSO (La Niña) or in neutral phases. Out of the five major hurricanes that formed in the Gulf of Mexico, three formed during neutral phases and one each formed in warm ENSO and cold ENSO phases.

Table 3 provides a comparison between Atlantic and Gulf-originated storms that hit Texas in ENSO and neutral phases during 1900–2006. In terms of the Gulf-originated storms, the rate of storm occurrence is almost identical for both warm and cold ENSO phases and slightly higher for the neutral phase. This suggests that unlike their effects on Atlantic hurricanes, the warm and cold ENSO conditions have little effect on the Gulf-originated storms.

Summary of Spatial and Temporal Distributions and Conditions Influencing Texas Hurricanes

The Upper Texas Coast is historically more prone to tropical storms and hurricanes than the Lower Texas Coast. About half of the Texas storms formed in the Gulf of Mexico and most of these hit the Upper Coast. The distribution of all tropical storms and major hurricanes hitting Texas shows a peak in August and September. However, Gulf-originated storms and major hurricanes often form early in the hurricane season and actually peak in June.

Oscillations in North Atlantic SST (AMO Index) match well with the year-to-year variability of Texas storms. The effect of ENSO is obvious on Texas storms that originate in the Atlantic. The rate of storm occurrence is higher in cold ENSO versus neutral phases and lower in warm ENSO versus neutral phases. However, the warm and cold ENSO phases have little or no impact on the Gulf-originated storms as the rate of storm occurrence is almost identical in both phases.

Table 2. Distribution of Texas Storms in ENSO Warm, Cold, and Neutral Phases 1900–2006

Event	Total number of years associated with the event	Number of Atlantic-originated storms during the event	Number of Gulf-originated storms during the event	Total Texas storms occurred during the event	Rate of Texas storms occurrence per event
Warm ENSO	23	4	7	11	0.48
Cold ENSO	25	12	8	20	0.80
Neutral	59	18	24	42	0.71

Reconciling Historic Information into Local Decision Making: Case Studies of Texas Hurricanes

The overwhelming emphasis in hurricane education and preparedness information intended for public audiences is on household preparedness actions and evacuation procedures. While these resources are obviously important and undoubtedly useful to citizens, it is clear that alternative sources of information could be informative to both public understanding of hurricane risk factors at specific locations of interest and to a more comprehensive perspective on emergency management and risk management at city and county scales. All too often, hurricane planning is primarily informed by the most recent serious event, or by generic scenarios that do not reflect important regional hurricane characteristics that are "knowable" from historic records.

In this section, we focus on historic hurricanes that pose special challenges to emergency managers because of their rapid formation and landfall on the Texas coastline. Although most of the major hurricanes making landfall on Texas originate in the Atlantic Ocean and give ample time for emergency preparedness, some that form in the Gulf of Mexico have shorter paths and often exhibit relatively fast forward speeds and rapid intensification. Hurricane Rita in 2005 posed an acute evacuation problem in Texas even though it was an Atlantic hurricane because of difficulties in track forecasting and the temporal proximity to the Katrina disaster.

Studies on past hurricane evacuations reveal that individual and household evacuation decisions are influenced by several factors such as interpretation of warning, perception of risk, age of the decision-maker, presence of children or elderly in the household, gender, disability, race and ethnicity, and income (Dash and Gladwin 2007).

Rapid intensification of a hurricane near the coast is the greatest concern of forecasters and emergency officials (Norcross 2007). Studies have shown that people usually do not evacuate in spite of hurricane warning unless it becomes a major hurricane and it might be too late to evacuate when a mandatory evacuation is ordered (e.g., as in the case of Hurricane Alicia in 1983). Balling and Cerveny (2006) studied the tropical cyclone intensification trends and variability in the North Atlantic Basin over the period 1970–2003. They found that in general, tropical cyclone intensification: (a) is higher during the daytime period and during the later months of the storm season; (b) tends to be higher in the western portion of the North Atlantic basin; and (c) is not explained by current month or antecedent SSTs.

Historically, the Upper Coast of Texas has experienced major hurricanes that both moved fast and made landfall within 72 h after forming in the Gulf of Mexico. Based on the experience during the Hurricane Rita evacuation, evacuation times can exceed warning periods making it challenging for decisions in terms of evacuation and emergency planning. The following case study scenarios based on historical data suggest that the Hurricane Rita experience will not be unique and rapidly developing and fast-moving storms deserve special attention by citizens, public officials, and emergency planners.

1932 Texas Hurricane

According to the *Monthly Weather Review* report (Humphreys 1932), the active development of this disturbance occurred in the south-central, or middle, Gulf of Mexico, and its increase in intensity was phenomenally rapid. The track of the 1932 Gulf hurricane that hit the Texas coast with symbols placed at 6 h. intervals is illustrated in Fig. 8. On August 13 06Z (around midnight U.S. time), the 1932 storm reached the status of a Category 1 hurricane about 240 mi away from the coast. The hurricane rapidly gained intensity and became a major hurricane (Category 3) about 100 mi off the coast, and made landfall as a Category 4 hurricane at 00Z (evening U.S. time) on August 14, 1932. The storm killed about 40 people and the damage estimates topped seven million in 1932 U.S. dollars (Humphreys 1932). Freeport, Angleton, and Galveston suffered extensive wind damage, and the inland towns of Brazoria, West Columbia, Damon, and Needville, all in the path of the eye, were also devastated.

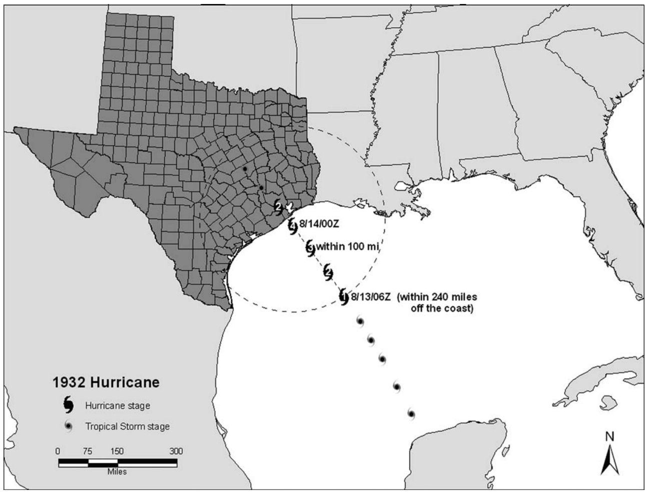

Fig. 8. 1932 Texas Hurricane

The interval between reaching Category 3 status and making landfall as a Category 4 of this 1932 hurricane was only about 6 h. In contrast to hurricanes that form in the Atlantic basin, major Gulf hurricanes often gain strength near the coast and immediately prior to landfall. Existing emergency planning and response tactics do not pay sufficient attention to the potential for rapidly developing storms with very short lead times prior to landfall.

Hurricane Audrey (1957)

Hurricane Audrey was a very fast-moving Gulf hurricane that made landfall on the coast near Texas-Louisiana border in 1957 (Fig. 9). Unlike other major Texas hurricanes, it occurred in June, early in the hurricane season. Audrey was Category 1–Category 2 as it initially moved through the Gulf, and then suddenly gained intensity to a Category 4 hurricane about 125 mi off the coast. Six h later Audrey made landfall as a Category 4 hurricane, providing emergency planners only about 8 h lead time to respond to this significant threat to safety and property.

It was reported that two important factors in hurricane formation—warm SSTs and the proper divergent pattern at high levels—were present during this event. Warming was evident preceding the development of Audrey with the highest SSTs (85°F) in the area where the hurricane formed (Moore et al. 1957).

Audrey caused catastrophic damages of $147 million (1 billion dollars in 2006 USD) in eastern Texas and western Louisiana with 416–550 fatalities (Ross and Blum 1957). It is the sixth deadliest hurricane in the history of the United States. Nearly all the deaths can be attributed to drowning by high tides which was reported more than 12 ft above mean sea level (Moore et al. 1957). The

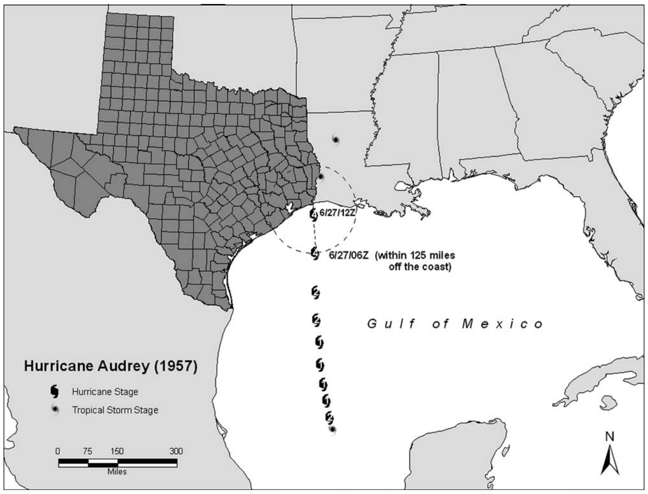

Fig. 9. Hurricane Audrey (1957)

capacity of hurricane Audrey to generate a deadly storm surge was greatly increased by the rapid deepening of the central pressure just prior to landfall.

1945 Texas Hurricane

The track and intensity of another Category 4 Gulf hurricane that hit Texas on August 27, 1945 is illustrated in Fig. 10. The 1945 hurricane became a major hurricane (Category 3) about 35 mi off the lower Texas coast and posed a threat to adjacent land areas. The hurricane subsequently turned, moved along the coast gaining strength, and made landfall near Matagorda Bay as a Category 4 hurricane. Records show that no hurricane of such intensity before paralleled the coast of Texas for so great a distance. Fully two-thirds of the Texas coast and offshore islands were subjected to winds of full hurricane force (Sumner 1946)

The hurricane caused three deaths and the total damage was estimated more than $20 million in 1945. It was reported that prevention of loss of life was made possible by the evacuation of thousands of persons from low-lying areas and from buildings not expected to survive the destructive winds. Buildings were boarded up and other precautionary measures were taken before damaging winds reached the coast (Sumner 1946). This type of hurricane poses very dangerous circumstances because it is difficult to execute mass evacuations over extended areas of coastline in the short time available.

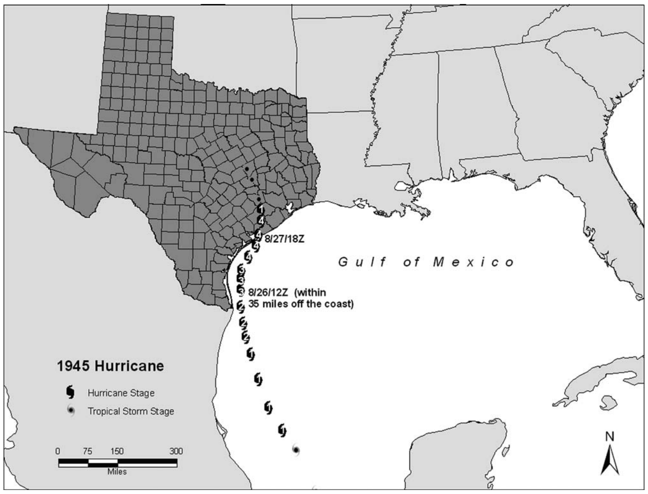

Fig. 10. 1945 Texas Hurricane

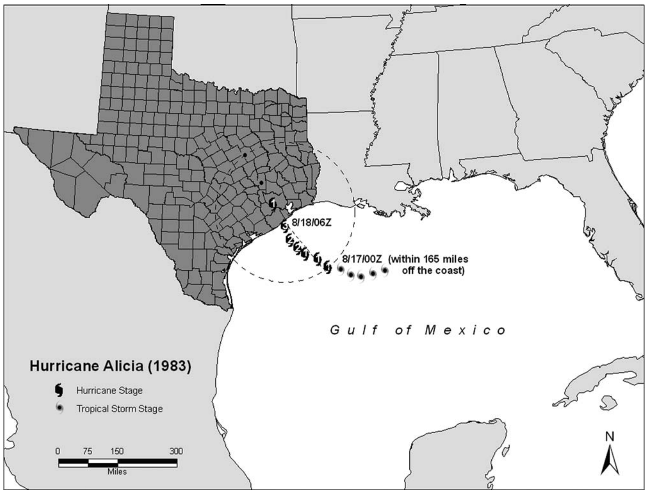

Fig. 11. Hurricane Alicia (1983)

Hurricane Alicia (1983)

Hurricane Alicia was a Category 3 hurricane that made landfall immediately south of Galveston in August, 1983. It seemed relatively harmless as a Category 1 or Category 2 for most of its existence, even as it approached the coast. However, just before landfall Alicia strengthened to a Category 3 hurricane leaving little time for evacuation (Fig. 11).

By hurricane standards, Alicia was only a small to medium-sized Category 3 hurricane at landfall but it became the costliest in Texas history in 1983 with an estimated total damage of nearly $2 billion. Before that Hurricane Carla (1961) which originated in the Atlantic, was the costliest hurricane to strike Texas with an estimated 1983 dollar value of $1.8 billion (Case and Gerrish 1984). Besides the event of Hurricane Rita (2005), which cost about $11 billion in damage and affected several states including Texas, Alicia is still the costliest storm for the State of Texas.

Although Alicia was a Gulf-originated, midsized hurricane; the effect was more severe than Carla and Rita as it struck a more populated area i.e., Houston-Galveston and there was lack of preparation from the authority to protect the citizens. At first, the Galveston Mayor declared that only low-lying areas need to be evacuated. After midnight on August 18 when the situation became worse, a widespread evacuation was finally ordered—but by that time it was impossible for people to drive across the bridges leading to the mainland (Isaacson 1983). It was estimated that 21 people lost their lives, 25 were hospitalized, 3094 were injured and a total of 18,660 families were affected as a result of the hurricane (American Red Cross 1983).

Summary of Gulf Hurricanes Case Studies

Unlike the typical Atlantic hurricanes, Gulf-originated hurricanes are often their strongest when they hit Texas. From the hurricane scenarios discussed in the paper, it is clear that major hurricanes formed in the Gulf can intensify quickly (e.g., 1932 hurricane), can be fast-moving while increasing in strength near landfall (e.g., Audrey), can change direction as approaching the coast (e.g., 1945 hurricane) and gain strength just before landfall (e.g., Alicia and the 1932 hurricane). These hurricane characteristics need to be considered in emergency planning for Texas. (Note: The formation of Gulf hurricane Humberto in September 2007 occurred with almost no warning and actually achieved hurricane status while over land on the Bolivar Peninsula.)

Conclusion

In this paper, we present a comprehensive analysis and interpretation of Texas hurricanes using climatological information and historic case studies with the goal of informing decision-making in urban planning, disaster management and mitigation, and natural resource management. Our results demonstrate that the Upper Texas Coast is more prone to tropical storms and hurricanes than the Lower Texas Coast and that most of the Upper Coast storms originated in the Gulf of Mexico. The ENSO which has a significant influence on Atlantic hurricanes is found to have less influence on storms originating in the Gulf of Mexico. This study shows that Gulf storms that hit the Texas coast may form very early in the hurricane season and can possess unique threats to coastal ecosystems, infrastructure, and people. Special emphasis should be given to preparing proper emergency plans and public education regarding Gulf of Mexico storms that can develop and intensify rapidly with landfall in a matter of hours to a few days. Also, because large-scale evacuations, especially on the Upper Texas Coast, are becoming increasingly more difficult because of population increases and expansions of the built environment, additional, or alternative approaches to protect life and property must be considered. These might include coordinated vertical evacuations at such time that horizontal evacuations become dangerous or impossible and building coastal barriers complete with floodgates to prevent the surge from entering bays and estuaries.

Postscript

On September 13, 2008 Hurricane Ike hit the Upper Texas Coast in Galveston and became the third most destructive hurricane in the United States after Katrina and Andrew. While it was an Atlantic hurricane and mandatory evacuation was issued on time, much of the damage from Ike was caused by its storm surge. The storm was a Category 2 hurricane (110 mph) at landfall; but because of its massive size, Ike had a very high integrated kinetic energy (ironically, its acronym is IKE), which was much more indicative of its surge potential.

Appendix I. Chronological List of All Hurricanes and Tropical Storms Which Affected Texas during 1851–2006

Intensities are based on Saffir-Simpson scale.

SL No.	Year	Month	Maximum intensity	Intensity at landfall	Name
1	1851	June	C1	C1	
2	1854	June	C1	C1	
3	1854	September	C2	C2	"Matagorda"
4	1857	September	C2	TS	
5	1863	September	TS	TS	
6	1865	September	C2	C2	
7	1866	July	C2	C2	
8	1867	October	C2	C2	"Galveston"
9	1869	August	C2	C2	
10	1871	June	TS	TS	
11	1871	June	TS	TS	
12	1874	July	TS	TS	
13	1874	September	TS	TS	
14	1875	September	C3	C3	
15	1879	August	C2	C2	
16	1880	June	TS	TS	
17	1880	August	C4	C3	
18	1881	August	TS	TS	
19	1882	September	C2	C2	
20	1886	June	C2	C2	
21	1886	August	C4	C4	"Indianola"
22	1886	September	C2	C1	
23	1886	October	C3	C3	
24	1887	September	C2	C2	
25	1888	June	C1	C1	
26	1888	July	TS	TS	
27	1891	July	C1	C1	
28	1895	August	C2	C1	
29	1895	October	TS	TS	
30	1897	September	C1	C1	
31	1898	September	TS	TS	
32	1900	September	C4	C4	"Galveston"
33	1901	July	TS	TS	
34	1902	June	C1	TS	
35	1909	June	C2	C2	
36	1909	July	C3	C3	
37	1910	September	C2	C2	
38	1912	October	C2	C2	
39	1913	June	C1	C1	
40	1915	August	C4	C4	"Galveston"
41	1916	August	C3	C3	
42	1919	September	C4	C4	
43	1921	June	C2	C2	
44	1925	September	TS	TS	
45	1929	June	C1	C1	
46	1931	June	TS	TS	
47	1932	August	C4	C4	"Freeport"
48	1933	July	TS	TS	
49	1933	August	C1	C1	
50	1933	September	C3	C3	
51	1934	July	C1	C1	
52	1934	August	C1	C1	
53	1936	June	C1	C1	
54	1936	September	TS	TS	
55	1938	August	C2	C1	
56	1938	October	TS	TS	
57	1940	August	C1	C1	
58	1940	September	TS	TS	
59	1941	September	TS	TS	

SL No.	Year	Month	Maximum intensity	Intensity at landfall	Name
60	1941	September	C1	C1	
61	1942	August	C1	C1	
62	1942	August	C3	C3	
63	1943	July	C1	C1	
64	1945	July	TS	TS	
65	1945	August	C4	C4	
66	1946	June	TS	TS	
67	1947	August	C1	C1	
68	1949	October	C4	C4	
69	1954	June	C1	C1	Alice
70	1957	June	C4	C4	Audrey
71	1958	September	C3	TS	Ella
72	1959	July	C1	C1	Debra
73	1960	June	TS	TS	
74	1961	September	C5	C4	Carla
75	1963	September	C1	C1	Cindy
76	1964	August	TS	TS	Abby
77	1967	September	C5	C3	Beulah
78	1968	June	TS	TS	Candy
79	1970	August	C3	C3	Celia
80	1970	September	TS	TS	Felice
81	1971	September	C1	C1	Fern
82	1971	September	C5	C2	Edith
83	1973	September	TS	TS	Delia
84	1978	July	TS	TS	Amelia
85	1979	July	TS	TS	Claudette
86	1979	September	TS	TS	Elena
87	1980	August	C5	C3	Allen
88	1980	September	TS	TS	Danielle
89	1983	August	C3	C3	Alicia
90	1986	June	C1	C1	Bonnie
91	1989	June	TS	TS	Allison
92	1989	August	C1	C1	Chantal
93	1989	October	C1	C1	Jerry
94	1993	June	TS	TS	Arlene
95	1995	July	TS	TS	Dean
96	1998	August	TS	TS	Charley
97	1998	September	TS	TS	Frances
98	1999	August	C4	C3	Bret
99	2001	June	TS	TS	Allison
100	2002	August	TS	TS	Bertha
101	2002	September	TS	TS	Fay
102	2003	July	C1	C1	Claudette
103	2003	August	TS	TS	Grace
104	2005	September	C5	C3	Rita

Note: C1=Category 1; C2=Category 2; C3=Category 3; C4=Category 4; C5=Category 5; and TS=tropic storm.

Appendix II. ENSO Phases for Hurricane Seasons (June–November) Based on JMA Index and the Method of Bove et al. (1998)

Updated from Smith et al. (2007). Row indicates decade, and column indicates year. W=warm, N=Neutral, and C=cold ENSO phase.

	0	1	2	3	4	5	6	7	8	9
190	N	N	W	C	W	W	C	N	C	C
191	C	W	N	W	N	N	C	N	W	N
192	N	N	C	N	C	W	N	N	N	W
193	W	N	N	N	N	N	N	N	C	N
194	W	N	C	N	C	N	N	N	N	C
195	N	W	N	N	C	C	C	W	N	N
196	N	N	N	W	C	W	N	C	N	W
197	C	C	W	C	C	C	W	N	N	N
198	N	N	W	N	N	N	W	W	C	N
199	N	W	N	N	N	N	N	W	C	C
200	N	N	W	N	N	N	N			

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