A Climatology of Landfalling Hurricane Central Pressures Along the Gulf of Mexico Coast

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1. INTRODUCTION AND OVERVIEW

Given the devastating impacts from hurricanes that occurred in the Gulf of Mexico region during the hurricane seasons of 2004, 2005, and 2008, scientific interest in the observed characteristics of these storms has greatly expanded. In particular, the numerous articles that have been written since the 2005 hurricane season and the aftermath of Hurricane Katrina have generally focused on whether there has been a discernable trend in hurricane frequency or intensity (i.e., Webster et al. 2005; Emanuel 2005; Jagger and Elsner 2006; CCSP 2008), along with articles studying future scenarios and projections related to the impact of warming ocean temperatures on future hurricane frequencies and characteristics (i.e., Sirutis et al. 2008; Vecchi and Soden 2007; Knutson and Tuleya 2004).

However, of particular importance to the scientific and coastal engineering community are the kinematic characteristics associated with hurricanes and the air-sea forcing that generates ocean waves and storm surges, since the impacts from these phenomena are of critical importance to emergency managers, coastal engineers, and others with economic, social or ecosystem related interests or management responsibilities along coastal areas. Our intent here is to present the observations related to the characteristics of hurricanes at landfall, but also the modifications of wind field characteristics as these storms approach the coast.

The issue of wind, wave and surge characteristics and their physical development is of particular importance along the northern Gulf of Mexico (GoM) coastline, where the shallow slope of the bathymetry and the topography of the coastal plain have a significant potential for generating destructive storm surges (Irish et al. 2008).

Despite significant progress over the past decade, accurate numerical simulations of hurricane-generated waves and surges remains one of the most difficult aspects of prediction as tropical cyclones approach and eventually impact a stretch of coast. For ocean response modeling, the critical factors include accurate near-surface winds, where the standard is a 10-m (U_{10}) wind speed averaged over 10-min, the wind-forcing as described by the wind stress (τ) and the coefficient of drag (C_D), the radius of maximum winds (R_{max}), as well as the central pressure (C_p) and peripheral pressure (P_o) that help define the differential pressure (ΔP) and therefore the pressure gradient for each storm. All of these factors must be integrated over time steps that are compatible with the particular ocean response model in question.

The purpose of this article is to present an analysis of landfalling hurricane central pressures along the GoM coastline, with special emphasis placed on the climatology of observed central pressures as they approach the coast, make landfall, and "fill" inland. Of wider concern from a coastal hazard perspective is the probable risk of occurrence of hurricanes along different sections of the Gulf of Mexico coast. To illuminate this issue the historical along-shore and off-shore variability of hurricane central pressures will be shown.

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2. ANNUAL GULF HURRICANE ACTIVITY

As the GoM is a sub-basin of the larger North Atlantic, the annual mean frequency of tropical cyclones is significantly less than the Atlantic as a whole. As such, the GoM exhibits pronounced inter-annual variability in the number of tropical storms and hurricanes that are observed during each hurricane season. The observed variability in the GoM has been shown to be well correlated with the phase of the El Niño Southern Oscillation (ENSO), with El Niño years having lower activity and La Niña years having higher activity, and therefore more frequent and stronger tropical cyclones, which is similar to the Atlantic basin as a whole (Gray 1984).

Figure 1 (a-c) shows the annual totals of tropical storms, hurricanes and major hurricanes in the Gulf of Mexico from 1949 through 2008. As summarized in Table 1 we see that, on average over this entire 50-yr time period the GoM experienced just over three tropical storms (~3.2), more than one hurricane (~1.6), and less than one major[1] hurricane (~0.4) each season. Despite an overall increasing trend in the number of tropical storms (see Fig. 1a), the longer-term variability is similar to the Atlantic Basin as a whole. Numerous studies (e.g., Goldenberg et al. 2001; Jagger and Elsner 2006) have shown that there was a period of increased activity in the Atlantic basin during the 1950s and early 1960s, a period of lesser activity in the 1970s through the mid-1990s, and a sharp increase in overall activity since 1995. Several studies have linked these active and inactive periods to the Atlantic Meridional Mode (AMM; Kossin and Vimont 2007; Vimont and Kossin 2007) based on long-term variations in sea-surface temperatures. The associated atmospheric variations have been referred to as the Tropical Multi-decadal Mode (TMM; Bell and Chelliah 2006) derived from EOF analyses of atmospheric pressure fields. However, a recent study by Holland and Webster (2007) contradicts the assertion of active and inactive periods, and suggests that there have been three different epochs of hurricane activity over the past century that reflect a general increase in the ratio of tropical storms to hurricanes in each of these epochs. Therefore, the issue of trends and inter-decadal variability remains an active area of research given the limitations in best track data and the uncertainty in the historical record of Atlantic basin and Gulf of Mexico tropical cyclones (Aberson 2009).

[1] Major or *intense* hurricanes are those that reach Category 3 or higher (≥ 96 kt) on the Saffir-Simpson scale (Simpson 1974).

3. LANDFALL CHARACTERISTICS

Long-term records of the location and intensity of hurricanes that made landfall in the United States extend back to 1851 (Blake et al. 2007; Jarrell et al. 1992). Because of the sparseness of towns and cities before 1900 in some coastal locations along the Southeast, Florida, and Gulf coasts, the data is not of equivalent quality and quantity for all states (Jarvinen et al. 1984). Therefore, the intensities of some historical hurricanes were likely underestimated, or for smaller-sized systems were missed completely. Despite reanalysis efforts in recent years (e.g., Landsea et al. 2008; Landsea et al. 2004) that improved the landfall dataset in the pre-1920 period, significant gaps remain. For example, the official landfall dataset[2] that was developed by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) includes actual intensity estimates from 1851-1920, reflecting the reanalysis efforts that have been conducted covering this period. However, between 1921 and 1979 no official intensity estimates exist for those hurricanes that made landfall, so the mid-point of the Saffir-Simpson scale has been widely used for landfall intensity during that period. Beginning in 1980 more accurate estimates of landfall intensity were determined using a variety of available data, so actual estimates of hurricane intensity at landfall beginning in 1980 are included in the official AOML dataset.

4. CENTRAL PRESSURE

The most reliable estimates of hurricane intensity are obtained from dropsonde profiles of central pressure (C_p), which have been routinely conducted during aircraft reconnaissance starting in the early 1970s. Historically, very few hurricanes have made landfall, or even approached the coast, in the GoM with a central pressure of 920 mb or lower (Fig. 2). The lowest pressure ever estimated at landfall along the Gulf coast, as well as for the entire U.S. coastline, was the 1935 Labor Day hurricane in the Florida Keys had an impressively low pressure of 892 mb at landfall[3]. Since 1960, only two hurricanes have made landfall along the

[2] The official NOAA data for hurricanes that made landfall along the U.S. coast can be found online at: http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512008.txt.

[3] Note that the pressure observation of 892 mb estimated for the 1935 Labor Day hurricane is not included in the HURDAT BT data for this storm.

Gulf coast at or below 920 mb: Hurricane Camille in 1969 made landfall along the Mississippi coast with an estimated C_p of 909 mb, while Hurricane Katrina in 2005 made landfall along the Louisiana coastline at 920 mb (which filled to 928 mb at its second landfall along the Mississippi coast).

Numerous observational studies have shown that those storms that make landfall weaken as the cyclone "fills", due to the increased surface roughness and lack of the storm's primary energy source. Therefore, the cyclone's C_p increases as it dissipates, with the most rapid filling occurring over land. In contrast to the widely held assumption that the decay occurs solely once the hurricane's center of circulation makes landfall, observations in the GoM support the notion that dissipation typically occurs before they reach land. It is important to note that the size of the hurricane also plays an important role with respect to decay prior to landfall, as larger storms will interact with drier continental air earlier than smaller tropical cyclones as they approach landfall. This may be the reason that Hurricane Camille in 1969 did not decay prior to landfall, given its relatively tight circulation as it approached the Mississippi coast.

Figure 3 provides an additional perspective on observed intensity changes associated with landfalling tropical cyclones in the GoM. The analysis shows the changes in wind speed and C_p in the 12-hr immediately prior to landfall. The results suggest the existence of two separate populations in terms of their intensity changes as they approach the coast, since only the weaker storms included in this analysis intensified before landfall (as can be noted for pre-landfall pressures in the range of 980 and higher in this figure), while none of the stronger hurricanes (C_p < 940 mb) increased in strength prior to landfall. In several cases the observed dissipation was only slight (< 5 mb), but typically the stronger hurricanes weakened between 10-20 mb during the 12-hr before landfall occurred, while for those tropical cyclones where C_p > 980 mb the observations showed that intensification occurred prior to landfall.

Finally, Figure 4 illustrates the spatial variability of hurricane C_p return periods along the GoM coast, from the Florida panhandle to eastern Texas. Regardless of the return period chosen (50-yr, 100-yr, or 500-yr) the estimated C_p is lower along the central and eastern Gulf coast than along the western Gulf and Texas coasts. This is primarily due to the observed intensities for hurricanes Camille and Katrina, both of which had the lowest C_p in the GoM since 1960. These results are also consistent with those found in NWS Tech Report 23 (Schwerdt et al. 1979).

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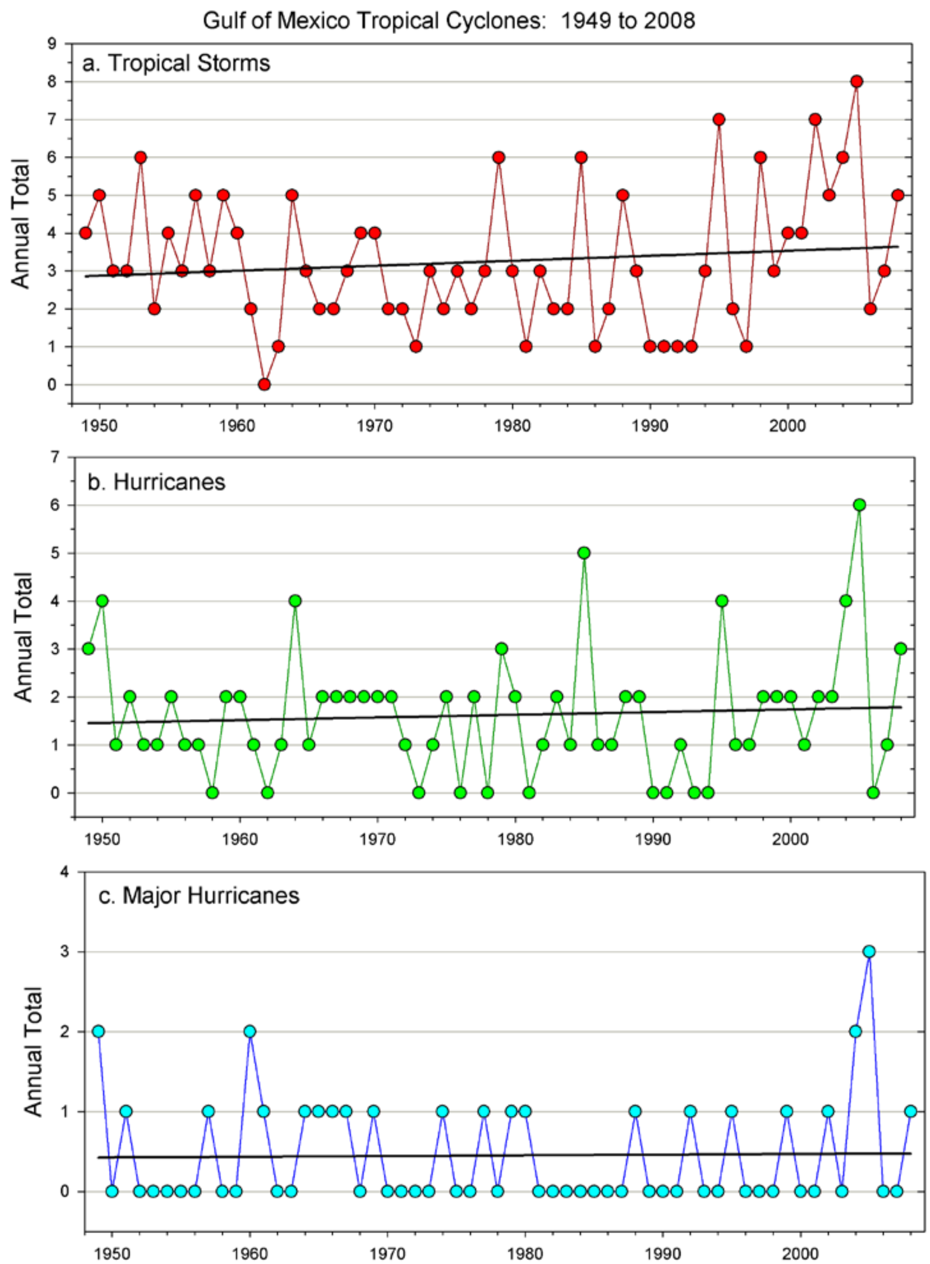

Figure 1. Annual counts of tropical cyclones in the Gulf of Mexico (north of 25°N, and between 80°-100°W) from 1949 to 2008 for: a) Tropical Storms (≥34 kt), b) Hurricanes (≥64 kt), and c) Major Hurricanes (≥96 kt; Category 3 -5 on the Saffir-Simpson scale). Black lines are the linear regression of the trend over the 60-yr period, none of which were statistically significant above the 90% level. Note that the source data were obtained from the NOAA Hurricane Database (HURDAT), except for the 2008 season which was based on preliminary data.

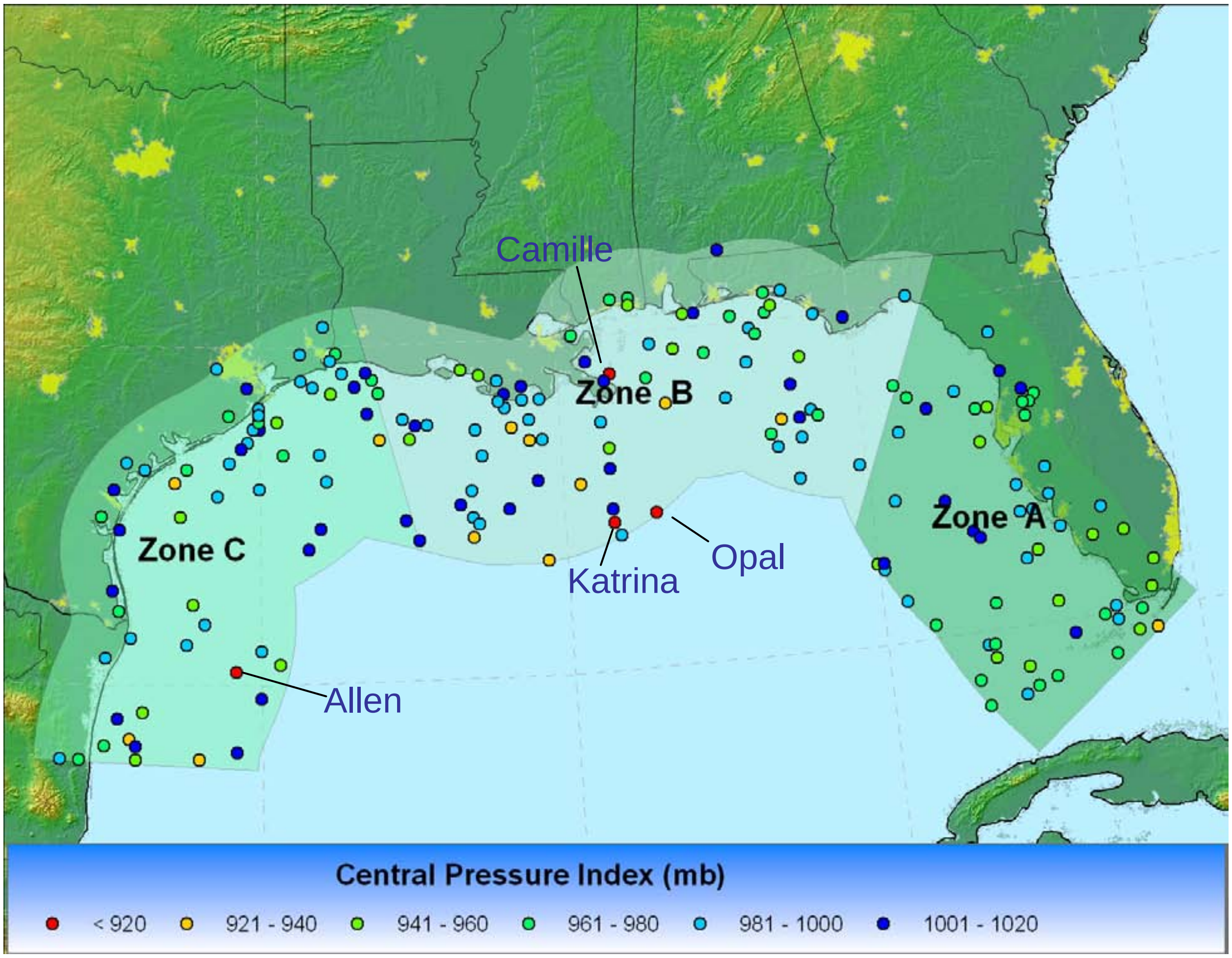

Figure 2. The Central Pressure Index (CPI), which is defined as the lowest central pressure (C_p) in mb reached by a particular hurricane within 150 nautical miles of the coastline, plotted for all hurricanes in the GoM since 1900. Adapted from Schwerdt et al. (1979) and updated using Best Track data from HURDAT through the 2005 season. Highlighted are the four hurricanes that have an estimated or observed (C_p) of 920 mb or below in the GoM: Hurricane Camille in 1969 (909 mb), Hurricane Allen in 1980 (916 mb), Hurricane Opal in 1995 (916 mb) and Hurricane Katrina in 2005 (905 mb). It is important to note that besides Camille, which made landfall at 909 mb, the other three storms weakened from their lowest C_p prior to landfall resulting in a higher C_p at landfall (H Allen 945 mb, H Opal 942 mb, and H Katrina 920 mb).

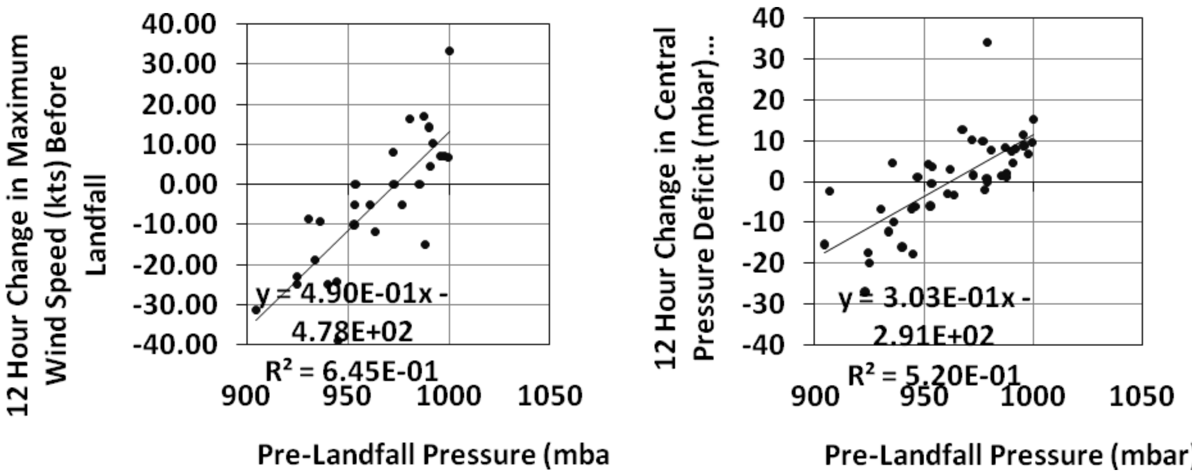

Figure 3. Intensity changes (left) and pressure changes (right) within the last 12-hr before landfall for a subset of landfalling Gulf of Mexico hurricanes (source: NOAA/NWS/NHC).

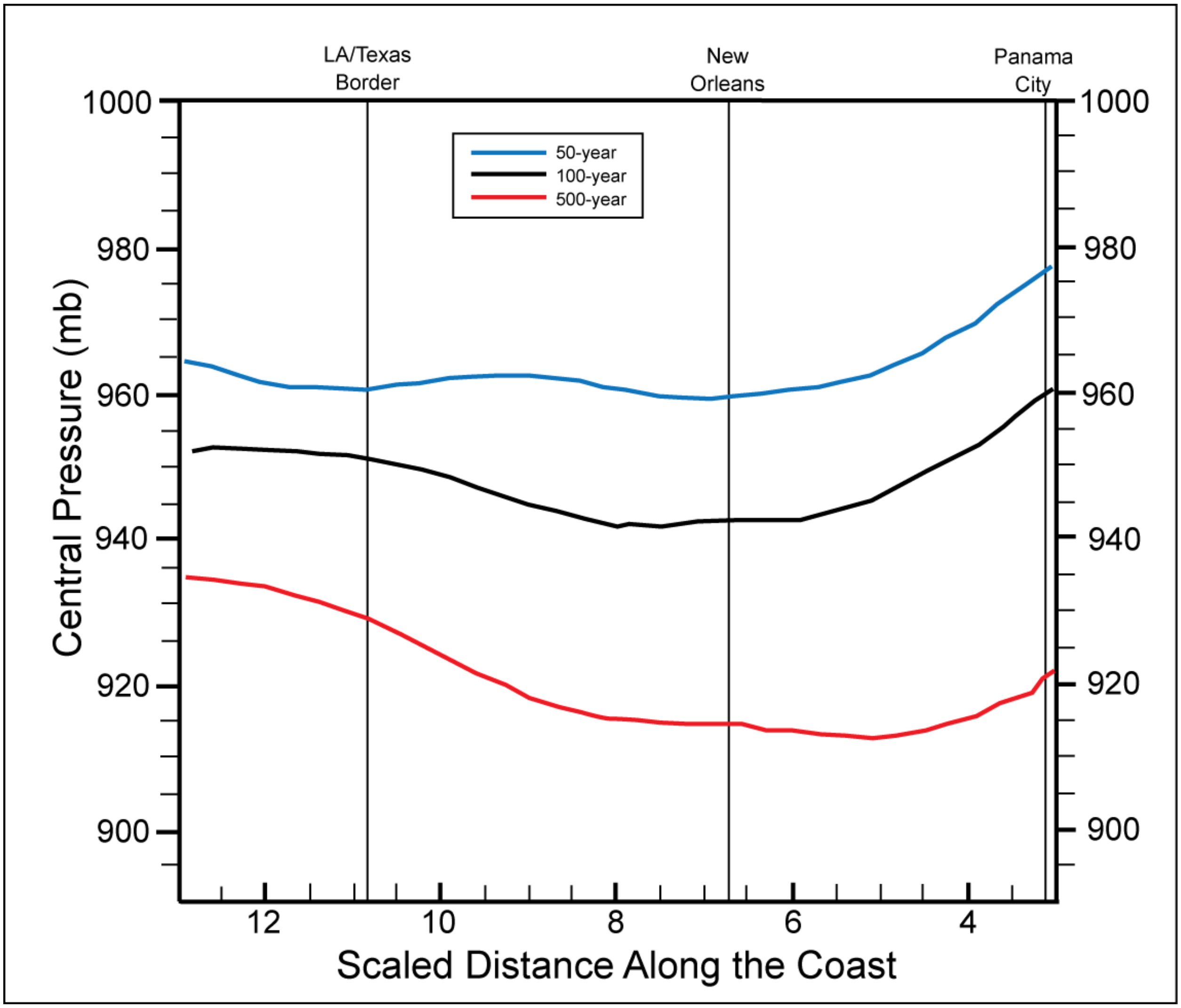

Figure 4. The distribution of 50-yr (blue line), 100-yr (black line), and 500-yr (red line) C_p return periods scaled along the Gulf of Mexico coast from the Florida panhandle to eastern Texas using official NOAA values derived from HURDAT and covering the period 1940 to 2005. Locations along this line can be taken as equivalent to 1^o increments along the coast, with the New Orleans area falling within increment 7 (source: IPET 2008).