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A review of the climatological characteristics of landfalling Gulf hurricanes for wind, wave, and surge hazard estimation

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ABSTRACT

The climatological characteristics of landfalling Gulf of Mexico hurricanes are presented, focusing on the basic parameters needed for accurately determining the structure and intensity of hurricanes for ocean response models. These include the maximum sustained wind, radius of maximum winds, the Holland-*B* parameter, the peripheral or far-field pressure, the surface roughness and coefficient of drag, and the central pressure for historical hurricanes in the Gulf.

Despite evidence of a slight increase in the annual number of named storms over the past 50 years, presently there is no statistically significant trend in tropical storms, hurricanes, or major hurricanes in the Gulf of Mexico. In addition, the long-term variability of tropical cyclones in the Gulf reflects the observed variability in the Atlantic basin as a whole. Analyses of hurricane winds from multiple sources suggest the presence of a bias toward overestimating the strength of winds in the HURDAT dataset from 7% to 15%. Results presented comparing HURDAT with other sources also show an overestimation of intensity at landfall, with an estimated bias of ~10%.

Finally, a review of recent studies has shown that hurricane frequencies and intensities appear to vary on a much more localized scale than previously believed. This exacerbates the sampling problem for accurate characterization of hurricane parameters for design and operational applications.

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1. Introduction

Given the devastating impacts from hurricanes that occurred in the Gulf of Mexico in 2004 and 2005, scientific interest in the observed characteristics of these storms has greatly expanded. 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., Briggs, 2008; Keim et al., 2007; Jagger and Elsner, 2006; Webster et al., 2005; Emanuel, 2005), 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). The purpose of this article is to provide an overview of available information related to hurricane climatology (frequency and intensity) in the Gulf of Mexico, evaluate the utility of the information for ocean response modeling, and to provide a quantitative description of hurricane characteristics in the Gulf of Mexico that can be used for a variety of engineering applications.

The observed long-term variability of tropical cyclones was addressed in the recent Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007), along with the recent Climate Change Science Program (CCSP) Synthesis and Assessment Report (SAP) 3.3 on climate and weather extremes (CCSP, 2008). In addition, the World Meteorological Organization's (WMO) Interagency Working Group on Tropical Cyclones released an additional assessment of the impacts of climate change on tropical cyclone frequencies and intensities (WMO, 2006). All of these reports have attempted to address whether there has been a quantifiable increase in the number of hurricanes in the Atlantic basin tied to global warming, but, as documented by Landsea (2007) and Aberson (2009), various data problems have inhibited the ability of researchers to address this fundamental concern.

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. In this article we will review prior research and 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

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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 parameters must be integrated over time steps that are compatible with the particular model in question.

An important point to make here is that ocean response models used in operational applications today are driven by winds which represent averages over 15–20 min, or so, and that these models should not be driven by maximum wind speeds over some time interval developed for other applications. Therefore, all wind inputs to these models should represent average winds over the model time-step at a common reference level (10 m) above the water surface. For model time steps less than 15 min, it is assumed that interpolated values from longer-term averages suffice for driving these models.

2. Historical perspective

2.1. Annual activity in the Gulf of Mexico

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 (Gray, 1984).

Fig. 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-year 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 (Fig. 1a), the longer-term variability is similar to the Atlantic Basin as a whole. Numerous studies (i.e., Goldenberg et al., 2001; Webster et al., 2005; 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; Trenberth and Shea, 2006) based on long-term variations in sea-surface temperatures (SST). The associated atmospheric variations have been referred to as the Tropical Multi-decadal Mode (TMM; Bell and Chelliah, 2006) based on the EOF analyses of atmospheric 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.

2.2. Evolution of observations

During the first half of the twentieth century information on the position and intensity of hurricanes and tropical storms was provided almost exclusively by observations from ships and land-based meteorological stations (Fig. 2). Since the middle of the twentieth century there have been several significant advances in the operational platforms and measurement technology used for observing tropical cyclone characteristics. These improvements in observations have had a direct impact on the data used for determining the long-term variability of tropical storms and hurricanes, and have a discernible change on the historical statistics. These improvements in observations have primarily involved aircraft field programs and remote sensing technology, such as the deployment of polar and geostationary satellite platforms and the Next Generation Weather Radar Network (NEXRAD), but also the initiation of routine aircraft reconnaissance and improved instrumentation aboard these aircraft (see Fig. 2). The following sub-sections summarize these significant changes in observational technologies and retrieval algorithms.

2.2.1. Aircraft reconnaissance

The advent of routine aircraft reconnaissance officially occurred in 1947 by the USAF (Uhlhorn and Black, 2003), although reconnaissance flights did occur before this during WWII.[2] In 1976, the National Oceanic and Atmospheric Administration (NOAA) began routine reconnaissance missions (Aberson et al., 2006) using specially outfitted P-3 aircraft,[3] significantly increasing the number of missions and the airborne observational capabilities. Extensive instrumentation aboard these aircraft allow for the collection of a suite of measurements related to hurricane intensity and structure (Aberson et al., 2006). The advent of dropsondes for measuring the vertical pressure profile occurred in the early 1970s, and more recently since 1997 routine GPS dropwindsonde profiles (Hock and Franklin, 1999) have provided the best direct measurements of PBL structure and storm intensity available, and their use has become routine on reconnaissance flights (for a more detailed overview of the instrumentation onboard the NOAA P-3 aircraft see Aberson et al. (2006)).

2.2.2. Satellite platforms

Another major change in observing technology was the deployment of polar and geostationary satellite platforms that began in the 1960s, with further advances during the 1970s, 1980s and 1990s as more sophisticated sensors have been deployed on

[1] Major or *intense* hurricanes are those that reach Category 3 or higher on the Saffir–Simpson scale ($\geq$96 kt).

[2] According to the Hurricane Hunters Association, hurricane hunting began on a dare in the middle of World War II, when Lt. Col. Joe Duckworth took an AT-6 *Texan* training aircraft into the eye of a hurricane. For further details please see http://www.hurricanehunters.com/aboutus.html.

[3] NOAA used a C-130 for hurricane research before and during the first few years of P-3 operations in the 1970s (Aberson et al., 2006).