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SAND2021-11825
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Assessing and mapping extreme wave height along the Gulf of Mexico coast

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ABSTRACT

The effect of extreme waves on the coastal community includes inundation, loss of habitats, increasing shoreline erosion, and increasing risks to coastal infrastructures (e.g., ports, breakwaters, oil and gas platforms), important for supporting coastal resilience. The coastal communities along the US Gulf of Mexico are very low-lying, which makes the region particularly vulnerable to impacts of extreme waves generated by storm events. We propose assessing and mapping the risks from extreme waves for the Gulf of Mexico coast to support coastal resiliency planning. The risks will be assessed by computing n-year recurring wave height (e.g., 1, 5, 50, 100-year) using 32-year wave hindcast data and various extreme value analysis techniques including Peak-Over-Threshold and Annual Maxima method. The characteristics of the extreme waves, e.g., relations between the mean and extreme wave climates, directions associated with extreme waves, will be investigated. Hazard maps associated with extreme wave heights at different return periods will be generated to help planners identify potential risks and envision places that are less susceptible to future storm damage.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
O&M	Operation and Maintenance
US	United States
NOAA	National Oceanic and Atmospheric Administration
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
POR	Period of Record
WWIII	Wave Watch III
SWAN	Simulating WAves Nearshore
EEZ	Exclusive Economic Zone
HPC	High Performance Computing
POT	Peak-Over-Threshold
AM	Annual Maxima
GDP	Generalized Pareto Distribution

1. INTRODUCTION

Resilience is important everywhere as all communities face some form of natural threats such as flooding, droughts, and earthquakes. Coastal areas have additional hazard risks from extreme storms and tend to be more densely populated, which makes the ability of a community to "bounce back" after these hazardous events particularly important in those locations. Many coastal regions are experiencing increasing risk due to inundation, coastal erosion, and wetland loss. Extreme storms are one of the natural disasters contributing to these risks and the great losses to human society. Extreme events have also threatened the operation and maintenance (O&M) and survival of nearshore and offshore infrastructures such as marine energy devices, oil and gas platforms. The increasing frequency of catastrophic storms with global warming and sea-level rise has unprecedented impacts on the people, infrastructure, and ecology of coastal regions, which have brought increased attention to the need to increase the resiliency of coastal communities.

The Gulf of Mexico coast of the United States (US) has been subject to numerous catastrophic storms. According to National Oceanic and Atmospheric Administration (NOAA), the occurrence of the Atlantic basin tropical storms increased by 100% for the last 30-year period and the number of storms passing through the Gulf of Mexico coast significantly increased [1]. In addition, the coastal communities along the Gulf of Mexico are very low-lying where more than 7,000 square miles of the Gulf Coast is below 5 feet in elevation (Figure 1-1) whereas 91 feet waves were recorded in the Gulf of Mexico when 2004 Hurricane Ivan headed toward shore [2]. These low-lying areas include vital infrastructure assets such as residential buildings, rail lines, ports, airports, and electric power plants that are essential to the local and national economy. The increasing number of extreme events in these low-lying coastal areas makes the region particularly vulnerable to the impacts of storms and threatens millions of people, local businesses, the overall resiliency of the natural systems and coastal infrastructure. In addition, numerous oil platforms are located under the influence of storms, and oil production has been significantly affected by the storm attack. Hurricane Katrina and later Hurricane Rita in 2005 jointly shut in at least 163 million barrels of production over 298 days [3].

Assessing and characterizing extreme wave conditions is one of the most important tasks for the prevention and mitigation of storms and protection of the infrastructures in coastal areas. Extreme conditions in coastal/ocean engineering and science are often described in terms of return significant wave height with corresponding return periods. The significant wave height is the mean wave height (trough to crest) of the highest third of the waves and the return period is the average time interval between successive storm events of the design wave being equaled or exceeded. For example, a 50-year extreme significant wave height is the significant wave height, which could be expected to be equaled or exceeded, on average, once during a 50-year time period. Needs for the analysis of extreme significant wave height arise in many branches of engineering implementations including energy development, design of offshore structures (e.g., breakwater and seawalls), and marine navigation. In most cases, a 100-year extreme significant wave height is chosen on the basis of design waves for maritime structures [4]. In marine energy, the 50-year extreme wave height [5] and the relative risk ratio, the 50-year extreme wave height normalized by the mean wave height [5,6], have been proposed as an indicators of project risk. In addition, the International Electrotechnical Commission (IEC) recommends a design standard for wave energy converters that requires 50-year extreme significant wave height for building design load cases for the wave energy converter [7]. In addition, these extreme significant wave heights have been used as a proxy to investigate coastal hazards such as run-up, inundation, and wave-induced coastal erosion.

(a) (b)

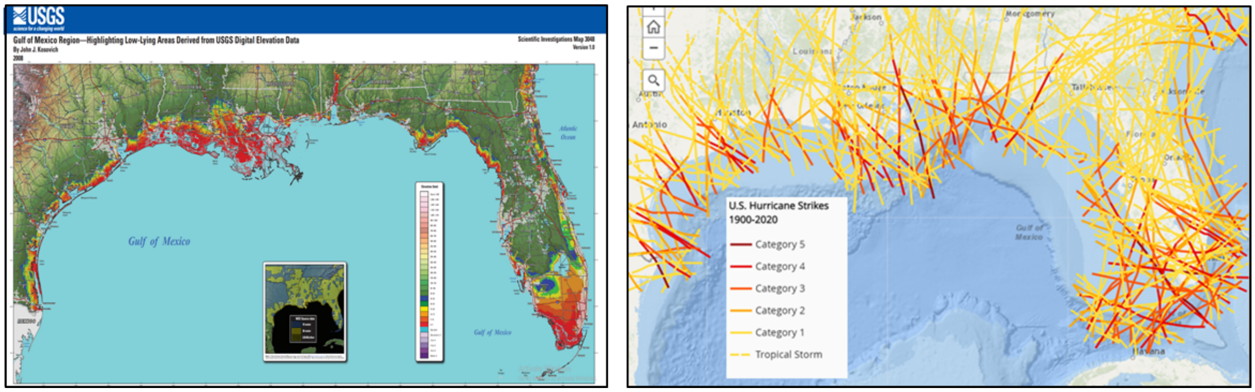

Figure 1-1. (a) Gulf of Mexico region highlighting low-lying areas derived from USGS digital elevation data [8] (b) Characteristic paths and categories of historical hurricanes in the Gulf of Mexico.

Because wave data spanning periods as long as 100 years are rarely available the extreme significant wave height needs to be predicted from wave height data with a shorter time series based on estimates of the underlying probability distribution functions [9]. More extreme events during the return periods can be extrapolated from tails of extreme distribution functions generated from the finite duration data. This approach can be subject to statistical uncertainty due to the small sample population [10] and the International Organization for Standardization (ISO) recommends using periods of record (POR) at a quarter of the desired return period [11]. For instance, wave data with a period longer than 25 years is recommended for 100-year extreme wave height prediction.

However, wave data sources with sufficient spatial resolution and coverage and temporal coverage to perform the extreme wave height analysis are not broadly available. Although satellite data provide wave height more than 30 years, their coarse spatial resolutions (order of 0.1 – 1.0 °) limit its applications [9]. Wave measurements from buoy networks are site-specific and lack the spatial and temporal fidelity to predict regional extreme wave climates. Only a few buoy stations provide the wave data for more than 20 years for the US [12].

Wave hindcast generated from numerical wave models (e.g., Wave Watch III (WWIII) and Simulating WAves Nearshore (SWAN)), which numerically integrate the wave energy balance equation and represent wave physics is an alternative source for the wave data when validated with measurement data [13]. Model hindcasts have provided significant benefits by addressing the noted limitations of the spatial resolution, coverage, and period of record from the measurements. 32-year wave hindcast from global wave models, e.g., ERA5 global reanalysis (Hersbach et al., 2020) and

Global WWIII [14], are currently available at a coarse spatial resolution (0.5° x 0.5°). For the US Exclusive Economic Zone (EEZ), a 32-year wave hindcast was generated by the WWIII with a finer spatial resolution of 4 arc-minutes [15]. Although these hindcasts have been widely adopted for wave analysis and ocean engineering design, their application has been limited to deep waters as their models did not resolve nearshore wave physics, e.g., complicated wave interactions, effects of bathymetric gradients that significantly affect the wave climates in shallow water [16]. This motivated the development of regional high-resolution SWAN models to generate 32-year hindcasts with resolutions of 200 to 300 m for the US nearshore waters. These ongoing US wave hindcast efforts, jointly carried out by the Sandia National Laboratories and Pacific Northwest National Laboratory, are designed to upgrade US wave energy resource assessment and characterization with more accurate wave statistics [17].

The Water Power Technologies at Sandia National Laboratories has developed and validated a high-resolution SWAN model for the Gulf of Mexico with a spatial resolution of 200 m and a computational mesh of over 5.7 million grid points. We ran the model and generated 32-year (1979-2010) wave hindcast data (e.g., 3-hourly significant wave height at all grid points) using Sandia's HPC resource[18]. By leveraging the benefits of this high-fidelity wave hindcast data, we propose assessing and mapping the risks from extreme waves for the US Gulf of Mexico coast to support coastal resiliency planning. The risks will be assessed by computing n-year extreme wave height (e.g., 1, 5, 50, 100-year) using various extreme value analysis techniques including Peak-Over-Threshold (POT), and Annual Maxima (AM) method. Hazard maps associated with extreme wave heights at different return periods will be generated to help planners identify potential risks and envision places that are less susceptible to future storm damage.

2. DATA SOURCE

The 32-year hindcast was generated by the third generation phase-averaged SWAN (v.41.10) on an unstructured mesh encompassing the Gulf of Mexico. In this simulation, SWAN considers the main physical processes in the generation and propagation of waves in both deep and shallow waters, e.g., whitecapping dissipation, non-linear wave interaction, bottom friction, shallow water wave breaking, and triad. The main feature of unstructured mesh is the 200 m resolution within 20 km of the coastline for the entire Gulf of Mexico. Such a high-resolution mesh requires a huge number of computational grid points (more than 5.7 million) that makes the use of parallel processing for simulation inevitable. Hence, simulations for the long-term hindcast were run on Sandia's high-performance computing resources (Chama cluster), which consists of almost 1,232 nodes, each with a 16-core 2.6 GHz Intel processor and 64 GB of RAM. The simulation of a single month takes approximately 30 hours of wall time on 640 of these cores.

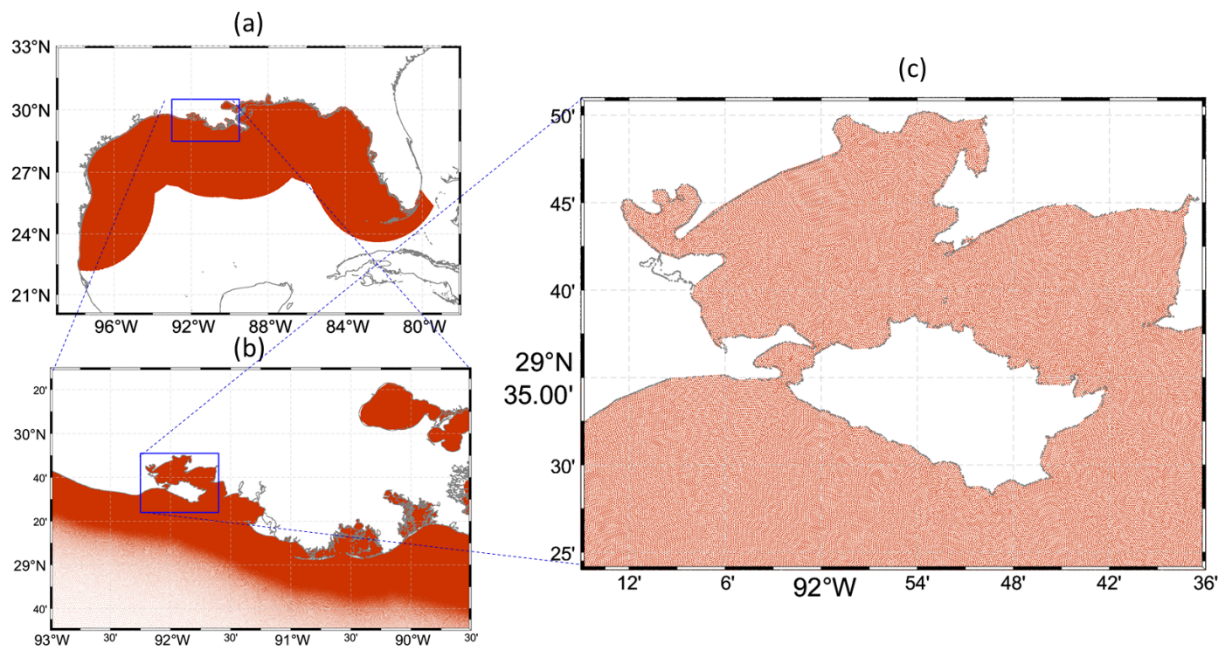

Figure 2-1. Locations of bulk wave parameters generated by the high-resolution SWAM Model. Data points include all computational grids within the EEZ along the Gulf of Mexico.

Three types of outputs are archived from the model hindcast: (a) hourly frequency-directional wave spectra at limited points, (b) 3 hourly bulk wave parameters (e.g., significant wave height, energy period, wave power, spectral width) at each grid point, and (c) hourly spectral partitioned bulk wave parameters at limited points. In the present work, n-year extreme significant wave heights ($H_{s(n)}$) at all grid points are computed using 3 hourly significant wave heights (H_s) for the 32-year period spanning from 1979 to 2010. To the author's knowledge, this high-fidelity data set is of the highest quality available for the study area given its spatial and temporal coverage with the high-spatial resolution. At 30 years or more, this data set exceeds minimum requirements for estimating extreme significant wave heights with return periods up to 100 years. Ahn et al. (2021) extensively validated the hindcast and reported that the modeled significant wave height, the data source of the present work, agrees well with those derived from buoy measurements (r ≈ 0.93 for fifteen buoy stations)[19].

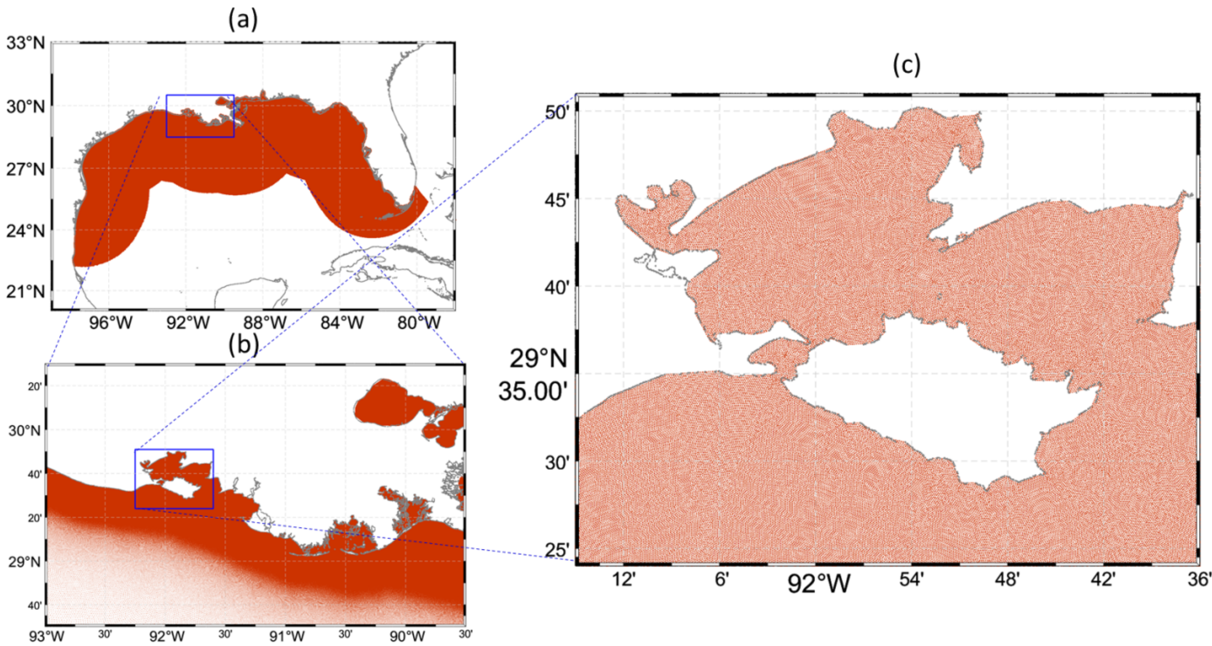

Figure 2-2. A sample of model validations reported in Ahn et al. (2021) [19]**. (left) Time series comparison of measured (black) and modeled (red) H_s at NDBC buoy 42036 (Gulf of Mexico). (right) Scattered diagram of measured (x-axis) and modeled (y-axis) H_s during a validation period (January 2007 to December 2009) where the blue-line is a 1:1 line and the red-dashed line is a linear slope.**

3. METHODOLOGY

Two main approaches for practical extreme value analysis will be applied to estimate the extreme significant wave height. The AM method will be applied to estimate $H_{s(5)}$, $H_{s(50)}$, and $H_{s(100)}$. The AM method fits the yearly maxima H_s to a Gumbel distribution [13], which is simple to implement and requires no user inputs that can introduce user bias. The Gumbel distribution is given by:

$$F(x) = exp\left\{exp\left[-\frac{x-U}{A}\right]\right\} \quad (1)$$

where x is the annual maximum significant wave height and U and A are location and scale parameters related to the mean $\mu = U + 0.557A$ and standard deviation $\sigma = 1.283A$ of the Gumbel variable. It requires at least 20-year of data points [13].

Goda, (2010) recommended the POT method for low return periods, below 5-years. The POT method will be applied to estimate $H_{s(1)}$ using the Generalized Pareto Distribution (GDP) model, which has been broadly applied for extreme wave height estimations. The cumulative distribution function of the GPD with zero shape parameter is given by:

$$F(x) = 1 - exp\left[-\frac{x-\mu}{\sigma}\right] \quad (2)$$

where x is the extreme significant wave height associated with an individual storm event, μ is the threshold of significant wave height filtering the sample population and σ is the mean value of the excess $(x-\mu)$ [20]. The threshold needs to be high enough to be characterized as a tail sample by the GPD model, while low enough to maintain enough population of samples to ensure a robust model fit. As the threshold value selection is subjective and can introduce user bias [10], a threshold value that provides the best fit to the modeled GPD is determined using quantile-quantile plots.

4. KEY DELIVERABLES

- Mean wave climates for the Gulf of Mexico will be assessed and characterized by analyzing 32-year mean H_s , wave energy, and direction containing the largest wave energy. Investigating spatial variations of the mean wave climates provides useful information to coastal communities and infrastructures.

- Extreme significant wave heights, $H_{s(1)}$, $H_{s(5)}$, $H_{s(50)}$, and $H_{s(100)}$, will be estimated at every grid point using AM and POT method. In addition, directions associated with $H_{s(n)}$ will be assessed by estimating directionally resolved $H_{s(n)}$ to identify where these hazardous waves will come from. Relations between extreme wave climates ($H_{s(n)}$ and corresponding direction) and mean wave climates (mean H_s and associated direction) will be investigated to characterize the degree that the coastal communities and infra-structures will face the risks relative to normal conditions. Sandia's High Performance Computing will be utilized in the computation.

- Geographic contours of $H_{s(n)}$ will be mapped to envision areas that are vulnerable to or less susceptible to future storm damage.

The result will be a data set detailing risk factors by region which can be used to inform the construction of new infrastructure, and the retrofitting of old infrastructure, reducing the risk of storm damage to the most susceptible low-lying coastal communities.

5. PRELIMINARY RESULTS

Figure 5-1 shows a 32-year mean H_s within the EEZ of the Gulf of Mexico. The waters along the eastern Gulf of Mexico exhibit a relatively small mean H_s than the western and central waters as the eastern waters are sheltered by the Florida peninsula from the southeasterly wind system that generated the most waves for this region [21]. Figure 5-1 (b) shows the geographic distribution of maximum H_s for a 32-year period of record where paths of four historical extreme hurricane events are identified. This historical record reveals that the majority of low-lying areas (Figure 1-1 (a)) and offshore platforms were exposed to these extreme hurricane events.

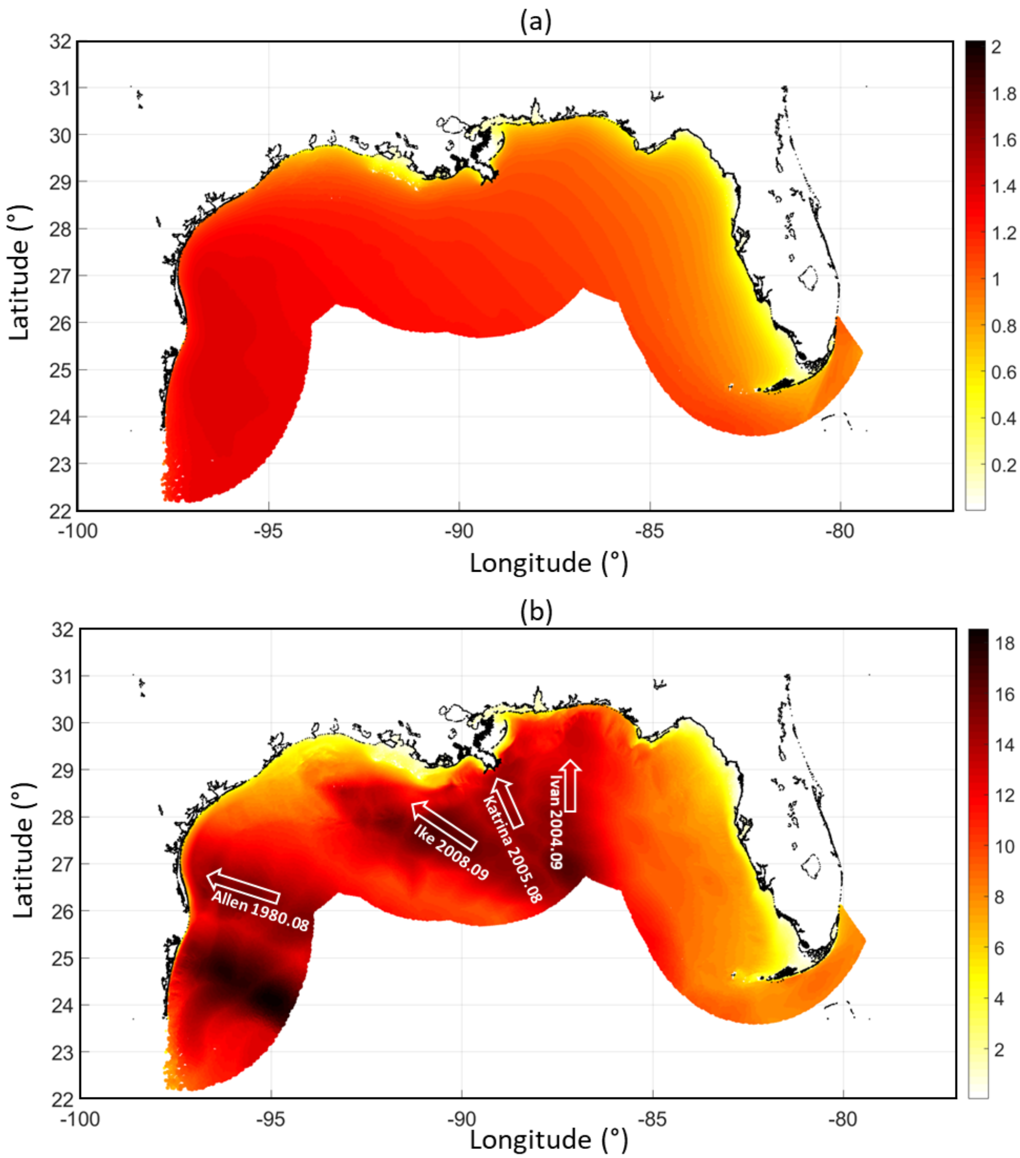

Figure 5-1. Geographical distribution of (a) 32-year mean H_s (in meter) and (b) 32-year maximum H_s (in meter).

Figure 5-2 shows the 32-year maximum H_s near (a) New Orleans, LA, and (b) Panama City, FL. The offshore of New Orleans exhibited higher maximum H_s exceeding 15 m associated with the hurricane Katrina (2005) than that of Panama City (around 10 m associated with the hurricane Ivan(2004)). For waters along the shoreline, however, much higher maximum H_s were recorded along the waters near Panama City than the New Orleans.

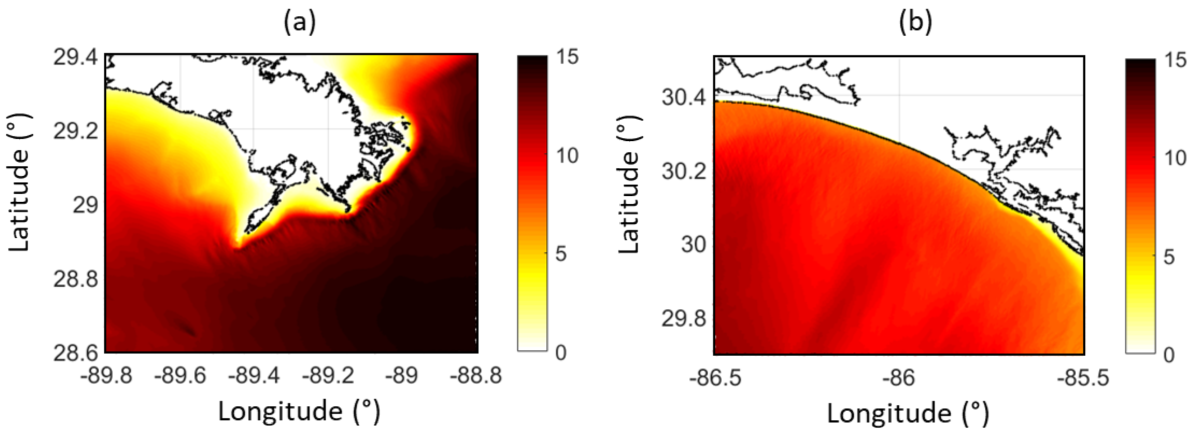

Figure 5-2. 32-year maximum H_s (in meter) near (a) New Orleans, LA and (b) Panama City, FL.

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