

# **Developing a Framework for Modeling Texas Coast Waves and Validation Final Report**

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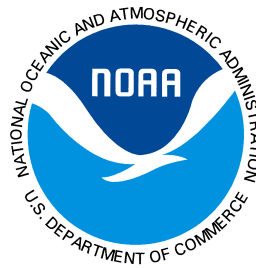
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## Contents

|                                                                         |     |
|-------------------------------------------------------------------------|-----|
| Project Summary .....                                                   | iii |
| 1. Introduction .....                                                   | 1   |
| 2. Study region.....                                                    | 4   |
| 3. Datasets.....                                                        | 5   |
| 4. Methodology.....                                                     | 6   |
| 4.1 Parametric hurricane model and blending (Task 2) .....              | 7   |
| 4.2 Historical Storm Selection (Task 3).....                            | 10  |
| 4.3 Wave Model setup (Task 3).....                                      | 12  |
| 5. Model Validation (Task 4).....                                       | 14  |
| 5.1 Wave Model Validation for Hurricane events.....                     | 14  |
| 5.2 Spotter Buoy Deployment and Data Collection.....                    | 17  |
| 5.3 Wave Model Validation Using Spotter Buoy Observations .....         | 20  |
| 6. Extreme Wave Value Statistics (Task 5) .....                         | 21  |
| 6.1 Extreme Value Analysis Methodology .....                            | 22  |
| 6.2 Results and discussion.....                                         | 24  |
| 7. Sensitivity study (Task 6).....                                      | 27  |
| 7.1 Storm and model parameters, baseline simulations .....              | 27  |
| 7.2 Methodology of estimating Sensitivity index (at each location)..... | 28  |
| 7.3 Estimated sensitivity matrix (results).....                         | 30  |
| 8. Summary and final remarks.....                                       | 35  |
| References .....                                                        | 37  |
| Appendix.....                                                           | 41  |



## Project Summary

The objective of this study is to generate reliable wave information along the Texas coast by developing a robust wave modeling framework that integrates high-resolution, up-to-date bathymetry, state-of-the-art reanalysis wind fields, and their refinement using appropriate parametric hurricane models. The outcomes of this work will improve the understanding of coastal wave characteristics through hindcast simulations of hurricane-induced wave conditions and enable probabilistic estimation of extreme wave events. These results are intended to support coastal management, hazard assessment, and resilience planning.

NCEP's CFSv2 (version 2) provides relatively higher spatial resolution compared to ECMWF's ERA5 dataset. However, ERA5 offers a much longer temporal coverage (1940–present) than CFSv2 (2011–present) and is more widely used in ocean and wave modeling applications. ERA5 generally provides reliable and accurate representation of moderate wind conditions, but it tends to underestimate extreme wind speeds during hurricanes in the Gulf of America. The inner-core structure of hurricanes is also not well resolved in either dataset. The use of the parametric hurricane model by Holland (1980), with some modifications, incorporating quadrant-specific wind radii information from best-track datasets such as HURDAT2, provides a simple and effective method to enhance and correct reanalysis wind fields under hurricane conditions.

The SWAN wave model with ST6 physics (third-generation formulation) provides improved estimates of wave parameters when forced with modified wind fields under hurricane conditions, compared to the default setup. The Komen physics formulation serves as an alternative and performs better under fair-weather conditions.

Hindcast wave simulations of about 56 historical hurricanes (up to 2024), and extreme value analysis at 100 coastal locations in water depths of 6–10 m and 18–20 m along the Texas coast, using the Generalized Extreme Value Distribution, indicate significant spatial variability in coastal vulnerability. Higher probabilities of extreme wave occurrence are observed along the southern Texas coast, especially near Corpus Christi.

While the extreme value analysis indicates greater vulnerability along the southern Texas coast, the sensitivity analysis, based on variations in wind forcing and key wave model parameters (bottom friction coefficient and depth-induced breaking parameter), shows higher modeling uncertainty along the northern Texas coast. This increased sensitivity is likely associated with the wider continental shelf in the northern region. In this study, this region is identified as a suitable zone for selecting optimal locations for buoy deployment.

**Participating students:**

Tasnim Islam, Sohail Ansari, Taseen Faiyaz, Josh Joubert

**Presentations (conferences):**

Islam, T., Nayak, S., Figlus, J., Xu, C., and Panchang, V., (2026). Texas nearshore SWAN wave simulation and field data, 39<sup>th</sup> International Conference on Coastal Engineering (ICCE, COPRI-ASCE), May 17-22, 2026

**Manuscripts:**

Nayak, S., Islam, T., Taseen, M. A. F., Ansari, S., Xu, C., Panchang, V. and Figlus, J., (2026). Comparative evaluation of wind forcing and source term schemes for simulations of Hurricane waves in the Gulf of Mexico. (under review)

Islam, T., Nayak, S., Figlus, J., Xu, C., and Panchang, V. High-resolution nearshore wave modeling along the Texas coast: Implementation and Field Validation. (In preparation)

Islam, T., Nayak, S., Figlus, J., Xu, C., and Panchang, V. Sensitivity of environmental and model parameters in wave modeling along the Texas coast. (In preparation)

## LIST OF FIGURES

|                                                                                                                    |    |
|--------------------------------------------------------------------------------------------------------------------|----|
| Figure 1 Study region and computational domains .....                                                              | 4  |
| Figure 2 (a) Hurricane Ida (b) Maximum wind speed during its lifecycle in the GoA, 6 hourly, ..                    | 9  |
| Figure 3 Wind speeds (spatial, over GoA) (a) Modeled, (b)ERA5 and (c) Blended ERA5.....                            | 9  |
| Figure 4 Wind speed comparison, during Ida (a) 42003 (b) 42084 .....                                               | 10 |
| Figure 5 Hurricane Ida and Ike, with NDBC stations and wave gauges U, V and W .....                                | 15 |
| Figure 6 Comparison of significant wave height ( $H_s$ ) and mean wave period ( $T_m$ ) during Hurricane Ida. .... | 15 |
| Figure 7 Comparison of significant wave height ( $H_s$ ) and mean wave period ( $T_m$ ) during Hurricane Ike. .... | 16 |
| Figure 8 Comparison of $H_s$ , (a) at gauge U (b) at gauge V and (c) at gauge W.....                               | 16 |
| Figure 9 Map of instrument locations for the field measurement campaign.. ....                                     | 18 |
| Figure 10 Schematic of Spotter wave buoy deployment setup. ....                                                    | 18 |
| Figure 11 Wind rose during Campaign 1 .....                                                                        | 19 |
| Figure 12 Spotter buoy comparisons.....                                                                            | 20 |
| Figure 13 Coastal locations .....                                                                                  | 21 |
| Figure 14 $H_s$ Return levels.....                                                                                 | 25 |
| Figure 15 Top panels fitted probability density functions. Bottom panel Q-Q plots .....                            | 26 |
| Figure 16 $H_s$ return levels for regions: D2 and D3.....                                                          | 26 |
| Figure 17 MAPE-SI for environmental parameters.....                                                                | 27 |
| Figure 18 MAPE-SI for model parameters .....                                                                       | 33 |
| Figure 19 NRMSE-SI for environmental parameters .....                                                              | 34 |
| Figure 20 NRMSE- SI for model parameters .....                                                                     | 34 |
| Figure 21 Optimal buoy location.....                                                                               | 35 |

## LIST OF TABLES

|                                                                              |    |
|------------------------------------------------------------------------------|----|
| Table 1 List of hurricanes that made landfall along the Texas coast .....    | 11 |
| Table 2 List of hurricanes that made landfall along the Louisiana coast..... | 12 |
| Table 3 SWAN model inputs and configurations.....                            | 14 |
| Table 4 Spotter buoy location details.....                                   | 17 |
| Table 5 Sensitivity Index ( <i>MAPE</i> , based on peak <i>Hs</i> ) .....    | 30 |
| Table 6 Sensitivity Index ( <i>NRMSE</i> ), based on ( <i>Hs</i> ).....      | 31 |

# 1. Introduction

Ocean waves are a primary driver of coastal dynamics, influencing sediment transport, shoreline morphology, storm surge dynamics, and the stability of coastal ecosystems. Their influence intensifies markedly during extreme events such as hurricanes (tropical cyclones), when large waves significantly amplify coastal hazards, including inundation, erosion, and damage to coastal infrastructure. Along the Texas coast, hurricane-induced impacts have historically resulted in extensive infrastructure losses and economic disruption. Between 1980 and 2024, approximately 16 major hurricane events have produced cumulative damage exceeding \$200-\$300 billion, accounting for more than half of the state's total disaster-related losses (NOAA-NCEI, 2025). These impacts are occurring in a region of rapidly increasing exposure: the Gulf Coast of Texas currently supports about 7.3 million residents, nearly 25% of the state's population with continued growth projected (U.S. Census Bureau, 2020; Texas Comptroller of Public Accounts, 2022). Given this rising vulnerability, accurate information, characterization of nearshore wave conditions during extreme events is essential for coastal hazard assessment, infrastructure design, shoreline management, and resilience planning.

Moored buoys provide high-quality, in-situ measurements of wave parameters (e.g., significant wave height, period, and direction) and serve as the primary source of real-time and historical observations. However, the spatial coverage of these buoy-networks is limited. The National Data Buoy Center (NDBC) maintains roughly 55 directional wave buoys across the entire Gulf of America, yet only some provide continuous, modern records, and only few are deployed along the extensive Texas coast. This sparse observational network constrains the characterization of near-shore wave conditions. While satellite-based remote sensing (e.g., altimeters and Synthetic Aperture Radar) offers broader spatial coverage, but their applicability in coastal regions is limited by reduced accuracy near the land-sea boundary, coarse temporal sampling, and swath constraints. As a result, numerical wave modeling stands as the primary mechanism for generating spatially and temporally continuous wave fields.

In response to these data gaps, numerous academic and institutional initiatives have focused on hindcasting the Texas nearshore wave climate, characterizing long-term near-shore wave conditions, essential for sediment transport, shoreline evolution, and coastal hazard assessment. Recent frameworks, including the Texas Coastal Resiliency Master Plan (TCRMP, 2023) led by the Texas General Land Office (TGLO) in partnership with the Harte Research Institute, as well as foundational studies by Dietrich et al. (2011) and Vijayan et al. (2023), underscore the critical role of high-resolution wave models in resolving complex processes across the wide Texas continental shelf and barrier island systems.

One of the most comprehensive recent efforts was undertaken by HR Wallingford (2020; hereafter HRW, Knaapen, M et al., 2026) for the TGLO, primarily aimed at estimating the sediment budget along the Texas coastline. Recognizing that reliable nearshore wave conditions are fundamental

for calculating littoral drift and shoreline evolution, the study first evaluated the suitability of several widely used long-term wave hindcast datasets, including Climate Forecast System Reanalysis (CFSR), Wave Information Studies (WIS), and European Centre for Medium-Range Weather Forecasts' ERA5, before developing its own dedicated wave modeling framework. As this effort closely preceded the present study and represents one of the relevant regional wave hindcast applications for the Texas coast, its methodology and key findings provide important context for the developments presented herein.

HRW rejected CFSR wave hindcast dataset, despite its relatively high spatial resolution due to its restricted temporal range (1979–2009), which omitted critical modern storm events. WIS was deemed unsuitable because its offshore stations were too far from the coast to resolve nearshore transformations, and its simulations exhibited systematic directional biases. While ERA5 data is widely accepted globally, its native spatial resolution ( $\sim 0.25^\circ$ ) proved too coarse to resolve shallow-shelf dynamics and intricate coastal features. To overcome this, HRW deployed the third-generation spectral wave model TOMAWAC (Benoit, 1996) on an unstructured mesh forced by ERA5 winds. To bypass the computational burden of multi-decadal simulation, they ran TOMAWAC in a stationary mode for representative conditions and used the output to train a Gaussian Process Emulator (GPE) to reconstruct the long-term wave history.

While highly effective for long-term climatology and sediment budgeting, the HRW stationary emulator framework possesses limited capacity to replicate transient, rapidly evolving physics such as shifting wind fields, swell propagation, non-linear wave-wave interactions, and hurricane-induced non-stationary wave growth. These limitations become critical during severe storms, where time-dependent wave growth and transformation govern peak hazard characteristics.

To bridge these operational gaps, the present project, titled “*Developing a Framework for Modeling Texas Coast Waves and Validation*,” establishes a robust, non-stationary coastal wave modeling framework. A core component of this project focuses on capturing hurricane-induced extreme wave fields across the Texas nearshore through targeted hindcast simulations of major storms spanning 1940 to 2024.

Crucially, the accuracy of any wave hindcast relies on the accuracy of its driving atmospheric forcing. Atmospheric reanalysis products like CFSR and ERA5 regularly exhibit systematic deficiencies during hurricanes, frequently underestimating core wind speeds due to coarse spatial resolution and smoothed pressure gradients (Hodges et al., 2017; Belmonte Rivas & Stoffelen, 2019). To resolve this, parametric hurricane wind models are employed to mathematically reconstruct the inner core structure, which is subsequently blended with background reanalysis winds (e.g., Mazyak & Shafieefar, 2022). The accuracy of these parametric models depends not only on the underlying empirical formulations but also on the effective use of observed hurricane best-track data to represent storm intensity, size, and asymmetry. A key objective of this project is to evaluate existing parametric hurricane wind models, identify the most suitable one, and maximize the use of hurricane best-track information from the HURDAT2 database maintained by

National Oceanic and Atmospheric Administration (NOAA) and the National Hurricane Center (NHC).

Furthermore, selecting an appropriate wave model and tuning its physical parameterizations is essential. While third-generation basin-scale models like WAM and WAVEWATCH III excel in deep water, their source terms are not primarily optimized for the shallow-water processes that govern coastal zones. For the Texas shelf, the Simulating WAVes Nearshore (SWAN) model, developed by Delft University of Technology, is a suitable choice and is also operationally used by National Oceanic and Atmospheric Administration for coastal wave applications. SWAN incorporates key nearshore processes, including shoaling, refraction, depth-induced wave breaking, bottom friction, wave–current interactions, and nonlinear triad wave interactions, which are essential for accurate shallow-water wave simulations.

A major challenge, however, is the selection of an optimal set of physical parameterizations for reliable wave prediction. The performance of different physics formulations can vary significantly across regions and under different meteorological conditions. Therefore, careful evaluation and calibration of the model physics are necessary to ensure accurate wave simulations for both fair-weather and hurricane conditions.

In summary, developing a comprehensive coastal wave modeling framework demands systematic calibration across multiple components: reanalysis wind selection, parametric hurricane wind blending, and spectral wave physics optimization. Equally important is the characterization of the resulting wave fields through appropriate analysis techniques, including extreme value analysis and sensitivity assessments of wave response to uncertainties in storm forcing and model parameterizations. To achieve this, the present study establishes an integrated framework for the Texas coast through the following key objectives:

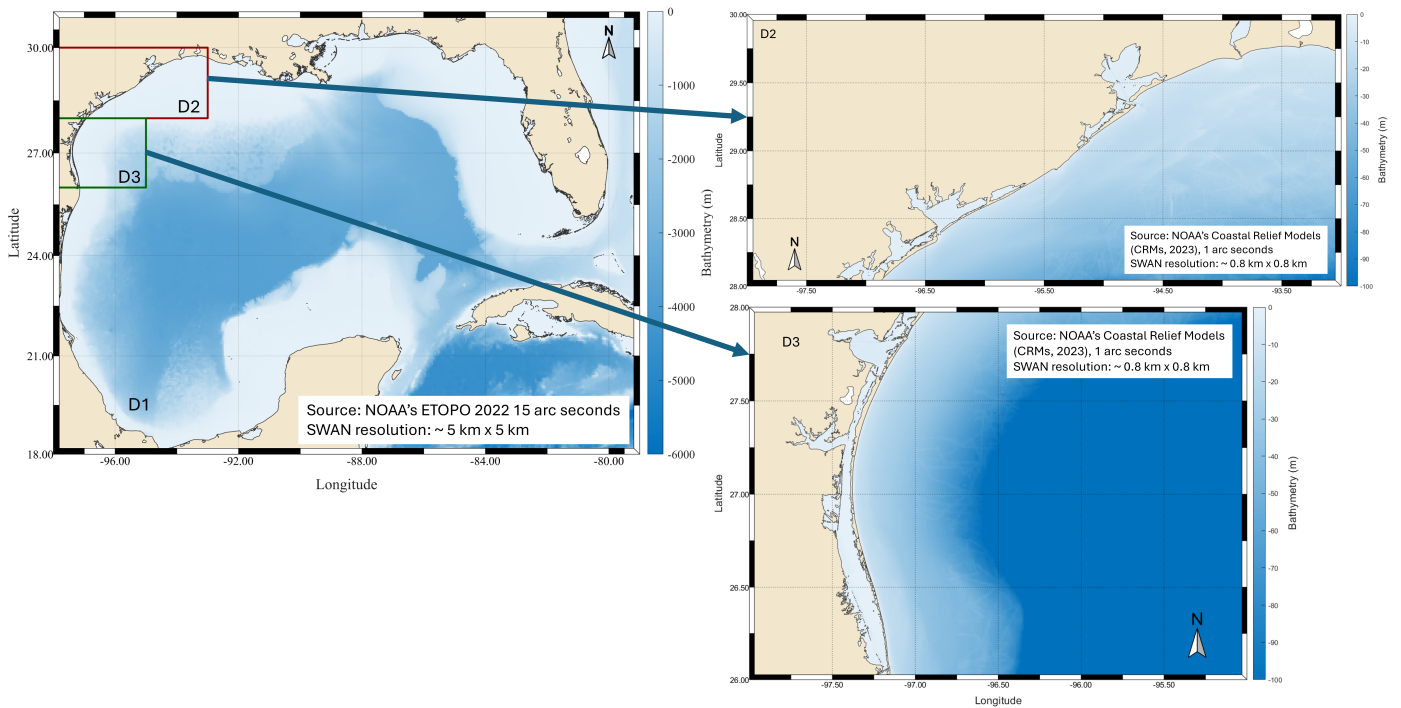
- **Evaluation** of CFSR’s (CFSv2) and ERA5 wind fields for regional coastal wave modeling.
- **Reconstruction** of historical hurricane wind fields utilizing HURDAT2 data and parametric wind models.
- **Configuration and validation** of the SWAN wave model.
- **Multi-decadal hindcasting** of hurricane-generated wave fields from 1940 to 2024.
- **Characterization** of extreme wave conditions and return levels at selected nearshore locations.
- **Sensitivity assessment** of coastal wave predictions to varying wind forcing and wave model physics parameterizations.

The remainder of this report is organized as follows: Section 2 describes the geographical study area and computational domains. Section 3 details the atmospheric reanalysis products, storm databases, and observational datasets utilized. Section 4 presents the comprehensive methodological framework, parametric model, wind blending, and SWAN configuration. Section 5 details the model validation against recent fair-weather field data collected by our team and

historical NDBC buoy data during hurricane events. Section 6 presents the extreme wave analysis (EVA), results. Section 7 presents the model sensitivity metrics and discusses the vulnerability of specific nearshore sectors. Finally, Section 8 summarizes the major conclusions.

## 2. Study region

Although this study focuses on the nearshore waters of the Texas coast, accurate simulation of coastal wave conditions requires representation of wave generation and propagation across the wider Gulf of America (GoA). Hurricane-generated waves can originate far from the Texas shelf and propagate over large distances before reaching the coast. Therefore, a nested-domain approach was adopted (Fig. 1). The outer domain (D1) covers the entire GoA, extending from 98°W to 79°W and from 18°N to 31°N. Two higher-resolution inner domains were defined along the Texas coast: D2 (Galveston domain), spanning 98°W–93°W and 28°N–30°N, and D3 (Corpus Christi domain), spanning 98°W–95°W and 26°N–28°N. Bathymetry for the domains and additional details of the model grids and spatial resolutions are provided in Section 3 and 4.



*Figure 1 Study region and computational domains*



### 3. Datasets

To force and validate the wave model simulations, this study relies on four main types of data: bathymetry, atmospheric forcing, hurricane best-track records, and wave observations. Wherever possible, we prioritized the use of datasets produced and maintained by NOAA and its affiliated agencies to ensure consistency, reliability, and long-term data availability. A brief description of the datasets and their sources is provided below.

- **Bathymetry:** Bathymetric data were obtained from two sources to represent the different spatial scales of the modeling domains. For the basin-scale Gulf of America domain (D1, Fig. 1), bathymetry was derived from the ETOPO 2022 Global Relief Model (NOAA-NCEI, 2022). ETOPO 2022 is NOAA’s latest global topographic–bathymetric dataset and provides gridded elevation data at a spatial resolution of 15 arc-seconds, making it suitable for large-scale wave simulations over the Gulf of America.

For the higher-resolution coastal domains (D2 and D3, Fig. 1), bathymetry was obtained from the NOAA-NCEI Coastal Relief Models (CRMs). The CRMs integrate topographic and bathymetric data to produce elevation models spanning both onshore and offshore environments within the U.S. coastal zone. These datasets are provided at a spatial resolution of 1 arc-second and are generated by merging multiple high-resolution sources, including digital elevation models (DEMs) from the U.S. Geological Survey (USGS) and NCEI’s continuously updated DEM products. The higher spatial resolution of the CRM dataset enables a more accurate representation of nearshore bathymetry and continental shelf morphology, which are critical for simulating wave transformation processes such as shoaling, refraction, and depth-induced breaking.

- **Reanalysis data (wind forcing):** The reanalysis wind fields used to drive the wave model in this study are obtained from NOAA-NCEP’s CFSv2 (v2 stands for version 2) and ECMWF’s ERA5. Both wind products provide hourly wind data, with spatial resolutions of  $0.2045^\circ \times 0.2045^\circ$  for CFSv2 and  $0.25^\circ \times 0.25^\circ$  for ERA5 and.

The CFSv2 reanalysis employs a three-dimensional variational (3D-Var) data assimilation scheme based on grid-point statistical interpolation (GSI) with 64 hybrid sigma-pressure vertical levels, extending up to a model top of 0.02 hPa, offering a detailed vertical resolution of the atmosphere. It serves as an extension to the earlier CFSv1 system, which covered the period from 1979 to 2010. CFSv2 continues from 2011 to the present (Saha et al., 2010, 2014).

ERA5 is the fifth-generation global climate reanalysis developed by ECMWF, covering the period from January 1940 to present. ERA5, which replaces ECMWF’s ERA-interim, uses a four-dimensional variational (4D-Var) data assimilation technique within the ECMWF

Integrated Forecast System (IFS), specifically cycle CY41R2, with 137 hybrid sigma-pressure (model) levels in the vertical, up to a top level of 0.01 hPa. ERA5 incorporates observations from a wide range of sources, with the number increasing from around 750,000 per day in 1979 to nearly 24 million per day by 2018 (Hersbach et al., 2020).

**Note:** Because CFSv2 and CFSv1 wind products are only available from 1992 to the present, they were not employed in the long-term hurricane-induced wave simulations. Nevertheless, they were used in selected validation cases to assess performance relative to ERA5 forcing. For simulations corresponding to the 2024–2025 Spotter observations, CFSR forcing was adopted owing to its higher spatial resolution.

- **Surface currents:** Surface currents are included as input forcing in specific coastal validation simulations. These hourly current fields, featuring a spatial resolution of  $13\text{ km} \times 13\text{ km}$ , were extracted from the Hybrid Coordinate Ocean Model of the Gulf of America (HYCOM-TSIS 1/100° Gulf of America Reanalysis dataset, Barth et al., 2024)
- **Hurricane best track information:** To generate hurricane wind fields in the selected parametric hurricane model, historical best-track data were obtained from the HURDAT2 database, which is maintained by the National Hurricane Center (NHC) under NOAA. This database provides official post-storm reanalysis records of tropical, subtropical, and extratropical cyclones. It contains comma-delimited data at six-hour intervals including storm coordinates, minimum central pressure, and maximum sustained surface winds. For modern entries, it also provides wind radii for 34, 50, and 64-knot thresholds across four geographical quadrants. These metrics provide the spatial and physical dimensions needed to initialize the parametric wind equations (NHC, 2021).
- **Wave Observations for Model Validation:** Wave observations used for model validation were obtained from two sources. Spotter buoys deployed and maintained as part of this project (described in Section 5.2) and observations from the National Data Buoy Center (NDBC), operated by the National Weather Service of NOAA, were utilized. Specifically, wave measurements from NDBC stations 42001, 42002, 42003, 42012, 42019, 42020, 42035, 42036, 42040, 42055, and 42084 were used to evaluate model performance under both fair-weather and hurricane conditions.

## 4. Methodology

The methodology encompasses the enhancement of wind intensity in reanalysis data through parametric modeling approach, along with the careful selection of appropriate wave model physics. First, parametric hurricane model and wind-blending technique is discussed (Section 4.1),

followed by the list of selected hurricanes (Section 4.2), and the SWAN wave model setup, configurations, and key physics options (Section 4.3).

## 4.1 Parametric hurricane model and blending (Task 2)

Following an extensive literature review on parametric hurricane models and preliminary analysis, a flexible approach was adopted based on the parameters available for a particular hurricane from the HURDAT2 database.

The most widely used Holland (1980) model (although modified in various ways) is adopted in this study. In this model, pressure is described by a rectangular hyperbola as a function of radius, and the radial wind profile is derived from the pressure field assuming cyclostrophic balance.

$$P(r) = P_c + (P_n - P_c) \exp^{-(R_{max}/r)^B} \quad (1)$$

$$V(r) = \sqrt{\frac{100 B}{\rho} \left(\frac{R_{max}}{r}\right)^B (P_n - P_c) \exp^{-(R_{max}/r)^B} + \left(\frac{rf}{2}\right)^2} - \frac{rf}{2} \quad (2)$$

where  $P(r)$  is the surface pressure at a distance  $r$  from the hurricane center,  $P_n$  is the ambient surface pressure,  $P_c$  is the central pressure,  $R_{max}$  is the radius of maximum winds,  $B$  is a hurricane shape parameter,  $\rho$  is air density,  $f$  is the Coriolis parameter, and  $V(r)$  is the wind velocity at a distance  $r$  from the hurricane center. The formulations that we used for  $P_c$  and  $R_{max}$ , if these parameters were not provided in the HURDAT2 database, are:

$$P_c = 1021.36 - 0.36V_{max} - (V_{max}/20.16)^2 \quad (\text{Knaff et al., 2007}) \quad (3)$$

$$R_{max} = 46.6e^{-0.0155 V_{max} + 0.0169 \phi}, \quad \phi = \text{latitude} \quad (\text{Willoughby et al., 2010}) \quad (4)$$

$$B = \frac{V_{max}^2 \rho e}{100(P_n - P_c)} \quad (\text{Holland, 1980}) \quad (5)$$

$$f = 2\Omega \sin \phi \quad (6)$$

Following (Xie et al., 2006), the asymmetric hurricane wind field is constructed using quadrant-specific wind radii ( $R_{64}, R_{50}$  and  $R_{34}$ , where  $R_{64}, R_{50}$  and  $R_{34}$ , denoting the maximum radial extents of 64-, 50-, and 34-knot winds, respectively) from the HURDAT2 database. An optimized  $R_{max}$  is then determined for each quadrant by fitting a truncated Fourier series (Eq. 7), with coefficients  $a_i$  and  $b_i$  determined from the fit. This allows  $R_{max}(\theta)$  to be expressed as a function of azimuthal angle at every grid point. Subsequently, surface pressure and wind velocity are calculated as functions of both radial distance ( $r$ ) and azimuthal angle ( $\theta$ ), capturing the asymmetry in the wind field.

$$R_{max}(\theta) = a_0 + a_1 \cos \theta + b_1 \sin \theta + a_2 \cos 2\theta + b_2 \sin 2\theta \quad (7)$$

$$P(r, \theta) = P_c + (P_n - P_c) \exp^{-(R_{max}(\theta)/r)^B} \quad (8)$$

$$V(r, \theta) = \sqrt{\frac{100 B}{\rho} \left( \frac{R_{max}(\theta)}{r} \right)^B (P_n - P_c) \exp^{-(R_{max}(\theta)/r)^B} + \left( \frac{rf}{2} \right)^2} - \frac{rf}{2} \quad (9)$$

Blending techniques range from simple interpolation to more advanced methods that define a transition zone where parametric and reanalysis wind fields are merged, retaining the parametric model near the core and ERA5 or CFSv2 farther out. Here, methodology of Liu and Sasaki (2019) is adopted, incorporating a blending radius  $R$  and a transition bandwidth  $R_b$ . In this generalized blending scheme, the parametric wind field ( $V(r, \theta)$ ) is applied within the inner region ( $r \leq R$ ), while ERA5 or CFSv2 ( $V_{ERA5}, V_{CFSv2}$ ) data are used in the outer region ( $r \geq R + R_b$ ). Between these zones ( $R < r < R + R_b$ ), the two wind fields are smoothly interpolated to ensure a seamless transition.

$$V_B = \begin{cases} V(r, \theta) & (r \leq R) \\ \frac{2R-r}{R} V(r, \theta) + \frac{r-R}{R} V_{ERA5/CFSv2} & (R < r < R + R_b) \\ V_{ERA5/CFSv2} & (r \geq R + R_b) \end{cases} \quad (10)$$

where  $V_B$  is the resultant blended wind velocity. It is important to note that the selection of  $R$  and  $R_b$  significantly influences the accurate representation of the hurricane core. In our initial tests, setting  $R = R_{max}$  and  $R_b = 2R_{max}$  often failed to adequately capture the hurricane core. This was primarily because, in most cases,  $R_{max}$  was less than 27 km, the same as the spatial resolution of ERA5/CFSv2, resulting in insufficient replacement of the core wind field. To address this, we adjusted the parameters to  $R = 2R_{max}$  and  $R_b = 4R_{max}$ , which yielded better results in representing the core of the hurricane.

### Discussion of some results of parametric hurricane model and blending.

We briefly present an assessment of ERA5 and CFSv2 winds during Hurricane Ida (2021). By applying parametric modeling and blending techniques, we demonstrate the resulting structural improvements in the wind fields.

Hurricane Ida traversed the Gulf of America between 27 and 30 August 2021, rapidly intensifying from 29 to 30 August (Fig. 2 a). While the HURDAT2 database reports peak winds of 45–65 m/s, ERA5 and CFSv2 captured peak winds of only 32 m/s and 44 m/s, respectively, failing to match HURDAT2 intensities. An along-track, 6-hourly comparison of the maximum wind speeds is illustrated in Figure 2b. Both reanalysis datasets underestimate peak hurricane wind speeds, with ERA5 exhibiting the largest deficit.

Figure 3 illustrates this discrepancy during a period of peak intensity on 29 August at 09:00 UTC. The spatial plots contrast the asymmetric structure of the Holland-generated winds with the original ERA5 grid. While the original ERA5 wind speed (Fig. 3b) was only 29 m/s compared to the HURDAT2 peak of 63 m/s (Fig. 3a), the blended Holland-ERA5 field successfully captures

the true intensity (Fig. 3c), reaching the 63 m/s threshold. (similar blending was performed for CFSv2 but is not shown here for brevity).

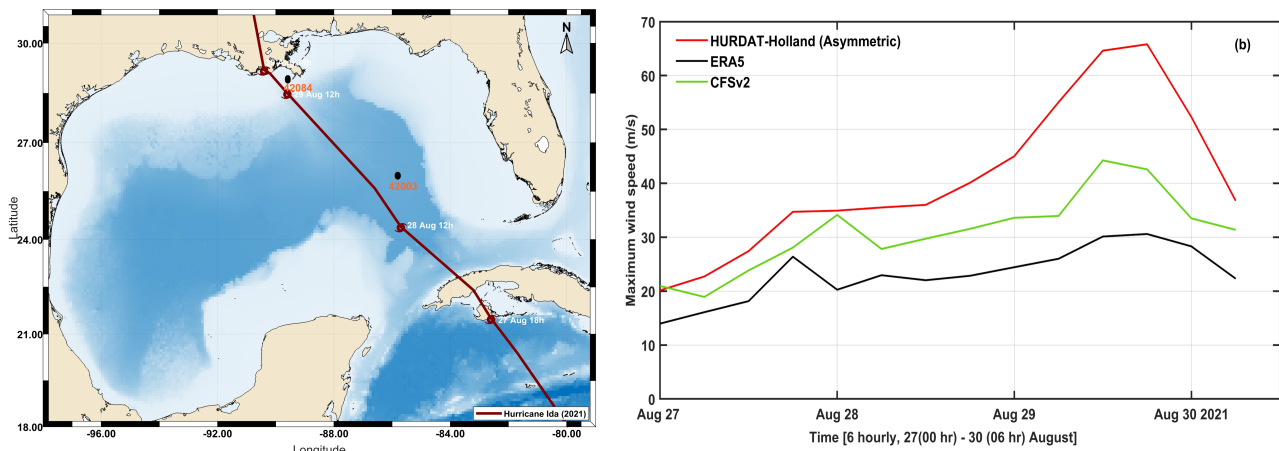


Figure 2 (a) Hurricane Ida (b) Maximum wind speed during its lifecycle in the GoA, 6 hourly,

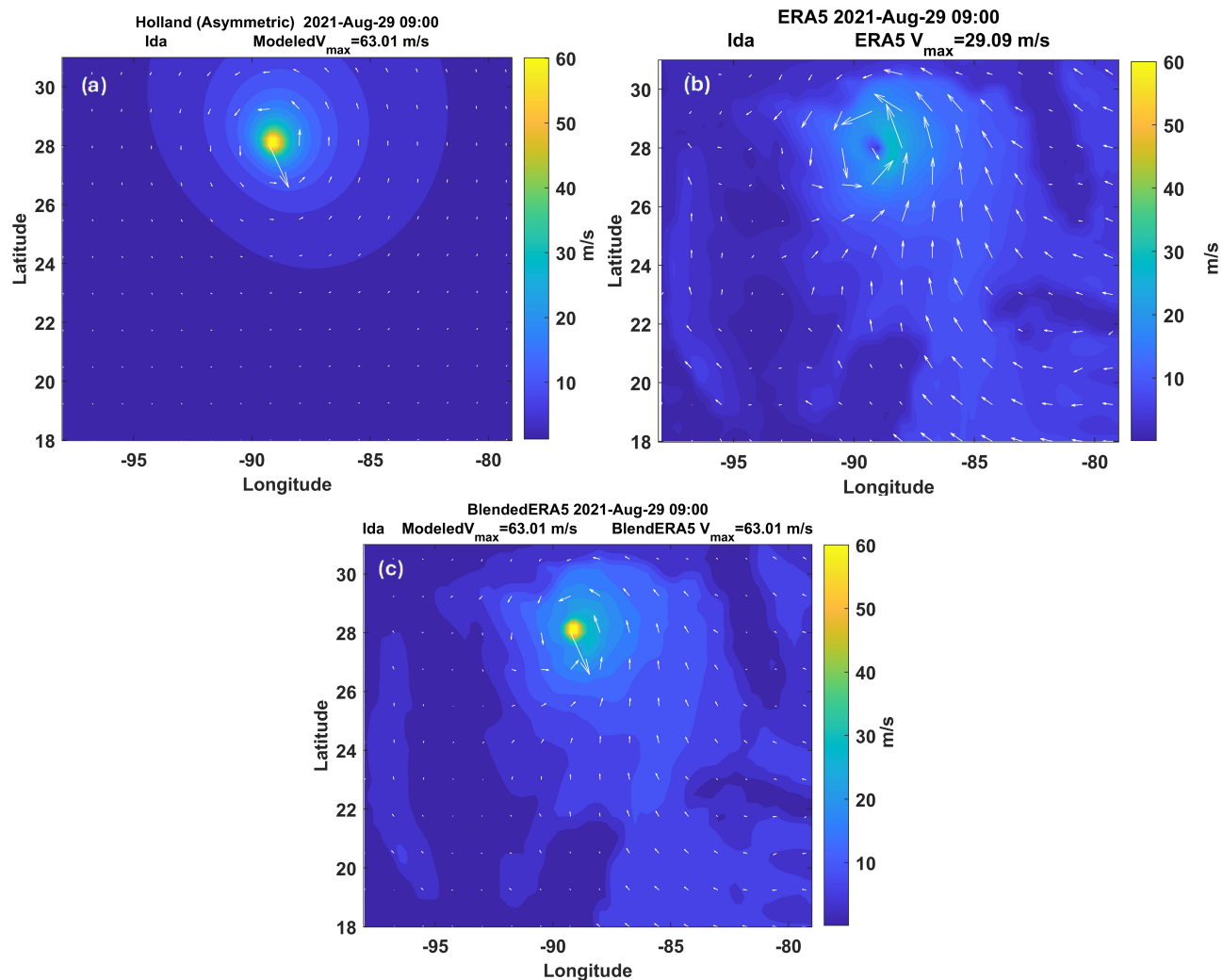


Figure 3 Wind speeds (spatial, over GoA) (a) Modeled, (b) ERA5 and (c) Blended ERA5

At buoy 42003 (Fig. 4a), ERA5 agrees well with observations throughout the event. In contrast, CFSv2 captures lower wind speeds but substantially overestimates peak values. The blending procedure slightly reduced CFSv2 peak winds while causing negligible changes to the ERA5 field.

Figure 4b illustrates the distinct impact of blending on both datasets at station 42084. While wind observations are missing due to the severe storm conditions, continuous wave measurements are available. Wave modeling results forced by these blended winds show strong agreement with observations, as discussed in Section 5.1.

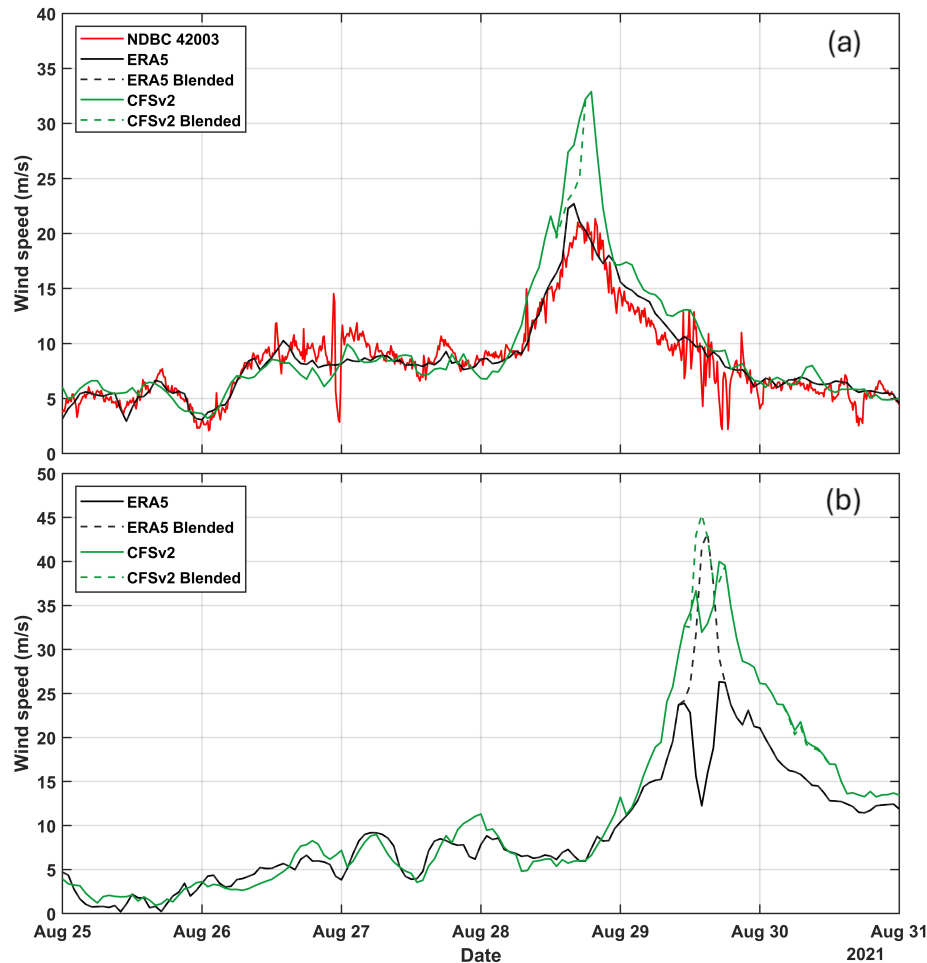


Figure 4 Wind speed comparison, during Ida (a) 42003 (b) 42084

## 4.2 Historical Storm Selection (Task 3)

To generate reliable long-term wave information along the Texas coast, a set of 56 hurricanes was selected based on the following criteria: each storm made landfall along the Texas or Louisiana coast, had a minimum sustained wind speed of at least 60 knots, and a maximum central surface pressure of 1000 hPa. Tables 1 and 2 below list the selected hurricanes that made landfall along

the Texas or Louisiana coast, including details such as the year, minimum surface pressure, and maximum wind speeds.

*Table 1 List of hurricanes that made landfall along the Texas coast*

| Year | Name      | Category | Minimum Pressure (mb/hPa) | Maximum Wind speed (knots) | Dates             |
|------|-----------|----------|---------------------------|----------------------------|-------------------|
| 2024 | Beryl     | 5        | 932                       | 145                        | 28 June - 11 July |
| 2021 | Nicholas  | 1        | 991                       | 65                         | 12 Sep - 17 Sep   |
| 2020 | Hanna     | 1        | 973                       | 80                         | 23 Jul - 26 Jul   |
| 2017 | Harvey    | 4        | 937                       | 115                        | 16 Aug - 02 Sep   |
| 2008 | Ike       | 2        | 950                       | 95                         | 01 Sep - 15 Sep   |
| 2008 | Dolly     | 1        | 967                       | 75                         | 20 Jul - 27 Jul   |
| 2007 | Humberto  | 1        | 985                       | 80                         | 12 Sep - 14 Sep   |
| 2005 | Rita      | 3        | 937                       | 100                        | 18 Sep - 26 Sep   |
| 2003 | Claudette | 1        | 963                       | 80                         | 07 Jul - 17 Jul   |
| 1999 | Bret      | 3        | 951                       | 100                        | 18 Aug - 25 Aug   |
| 1989 | Jerry     | 1        | 983                       | 75                         | 12 Oct - 16 Oct   |
| 1989 | Chantal   | 1        | 986                       | 70                         | 30 Jul - 03 Aug   |
| 1986 | Bonnie    | 1        | 990                       | 75                         | 23 Jun - 28 Jun   |
| 1983 | Alicia    | 3        | 962                       | 100                        | 15 Aug - 21 Aug   |
| 1980 | Allen     | 3        | 945                       | 100                        | 31 Jul - 11 Aug   |
| 1971 | Fern      | 1        | 979                       | -                          | 03 Sep - 13 Sep   |
| 1970 | Celia     | 4        | 944                       | 120                        | 31 Jul - 05 Aug   |
| 1967 | Beulah    | 3        | 940                       | 100                        | 05 Sep - 24 Sep   |
| 1961 | Carla     | 4        | 931                       | 125                        | 03 Sep - 18 Sep   |
| 1959 | Debra     | 1        | 980                       | 75                         | 22 Jul - 27 Jul   |
| 1957 | Audrey    | 3        | 946                       | 110                        | 24 Jun - 29 Jun   |
| 1949 | Unnamed   | 2        | 965                       | 95                         | 27 Sep - 07 Oct   |
| 1947 | Unnamed   | 1        | 984                       | 70                         | 09 Aug - 27 Aug   |
| 1945 | Unnamed   | 3        | 963                       | 100                        | 24 Aug - 29 Aug   |
| 1943 | Unnamed   | 2        | 967                       | 90                         | 25 Jul - 30 Jul   |
| 1942 | Unnamed   | 3        | 950                       | 100                        | 17 Aug - 31 Aug   |
| 1941 | Unnamed   | 3        | 942                       | 110                        | 11 Sep - 27 Sep   |
| 1940 | Unnamed   | 2        | 972                       | 85                         | 03 Aug - 10 Aug   |

*Table 2 List of hurricanes that made landfall along the Louisiana coast*

| Year | Name     | Category | Minimum Pressure (mb/hPa) | Maximum Wind speed (knots) | Duration        |
|------|----------|----------|---------------------------|----------------------------|-----------------|
| 2024 | Francine | 2        | 972                       | 90                         | 8 Sep- 14 Sep   |
| 2021 | Ida      | 4        | 931                       | 130                        | 26 Aug - 04 Sep |
| 2020 | Zeta     | 3        | 970                       | 100                        | 24 Oct - 30 Oct |
| 2020 | Delta    | 2        | 970                       | 85                         | 04 Oct - 11 Oct |
| 2020 | Laura    | 4        | 939                       | 130                        | 20 Aug - 29 Aug |
| 2019 | Barry    | 1        | 993                       | 65                         | 10 Jul - 16 Jul |
| 2017 | Nate     | 1        | 983                       | 65                         | 03 Oct - 11 Oct |
| 2012 | Isaac    | 1        | 966                       | 70                         | 20 Aug - 01 Sep |
| 2008 | Gustav   | 2        | 954                       | 90                         | 25 Aug - 05 Sep |
| 2005 | Katrina  | 3        | 920                       | 110                        | 23 Aug - 31 Aug |
| 2005 | Cindy    | 1        | 991                       | 65                         | 03 Jul - 11 Jul |
| 2002 | Lili     | 1        | 963                       | 80                         | 21 Sep - 04 Oct |
| 1997 | Danny    | 1        | 984                       | 70                         | 16 Jul - 27 Jul |
| 1992 | Andrew   | 5        | 922                       | 150                        | 16 Aug- 28 Aug  |
| 1988 | Florence | 1        | 984                       | 70                         | 07 Sep - 11 Sep |
| 1985 | Juan     | 1        | 971                       | 75                         | 26 Oct - 01 Nov |
| 1985 | Danny    | 1        | 987                       | 80                         | 12 Aug - 20 Aug |
| 1979 | Bob      | 1        | 986                       | -                          | 09 Jul - 16 Jul |
| 1977 | Babe     | 1        | 995                       | -                          | 03 Sep - 09 Sep |
| 1974 | Carmen   | 3        | 952                       | -                          | 29 Aug - 10 Sep |
| 1971 | Edith    | 2        | 978                       | -                          | 05 Sep - 18 Sep |
| 1969 | Camille  | 5        | 900                       | 150                        | 14 Aug - 22 Aug |
| 1965 | Betsy    | 4        | 946                       | 115                        | 27 Aug - 13 Sep |
| 1964 | Hilda    | 2        | 959                       | 90                         | 28 Sep - 07 Oct |
| 1960 | Ethel    | 1        | 980                       | 80                         | 12 Sep - 17 Sep |
| 1956 | Flossy   | 1        | 974                       | 80                         | 20 Sep - 03 Oct |
| 1948 | Unnamed  | 1        | 983                       | 70                         | 01 Sep - 06 Sep |
| 1947 | Unnamed  | 4        | 943                       | 115                        | 07 Sep - 26 Sep |

### 4.3 Wave Model setup (Task 3)

The third-generation spectral wave model SWAN, version 41.51, was used in this study. Developed at Delft University of Technology, SWAN is designed for nearshore applications and is capable of simulating wave generation, propagation, and transformation through nonlinear triad and quadruplet interactions, refraction, shoaling, reflection, diffraction, and energy dissipation due to whitecapping, depth-induced breaking, and bottom friction (Booij et al., 1999). The model solves the spectral action balance equation using a third-order implicit numerical scheme. Detailed descriptions of the governing equations and numerical implementation can be found in the SWAN scientific and technical documentation (The SWAN Team, 2024).



The outer model domain (D1; Fig. 1), covering the Gulf of America (GoA), was discretized using a uniform computational grid with a spatial resolution of approximately 5 km in both horizontal directions (Table 3). Two nested coastal domains, D2 and D3 (Fig. 1), were established with a higher spatial resolution of approximately 0.8 km (800 m) to better resolve wave transformation processes over the Texas continental shelf and nearshore waters. The SWAN model was configured with 36 directional bins spanning the full 360° directional spectrum at 10° intervals and 31 logarithmically spaced frequencies ranging from 0.05 to 1.0 Hz (Table 3). Simulations were performed with a time step of 1 h. Wave propagation was solved using the first-order upwind propagation scheme (backward in space and backward in time), with a maximum of 25 iterations per computational time step. In addition to wind forcing, surface currents were included in the simulations. Although current magnitudes were generally weak (typically  $\sim 0.035 \text{ m s}^{-1}$ ), their effects on wave propagation were accounted for throughout the modeling period.

With respect to wave physics, the SWAN model was initially evaluated for Hurricanes Ida (2021) and Harvey (2017) using the default third-generation formulation of van der Westhuysen et al. (2007), which combines the wind-input formulation of Yan (1987), a saturation-based whitecapping dissipation scheme, and the wind drag relation of Wu (1982). Validation against observations from 12 NDBC stations showed that this baseline configuration consistently underestimated peak significant wave heights ( $H_s$ ) near the hurricane tracks, regardless of whether the original or blended wind fields were used.

To improve model performance, additional source-term parameterizations were tested, including the Komen et al. (1994) formulation and seven configurations of the ST6 source-term package (Rogers et al., 2012; Zieger et al., 2015). The sensitivity analysis conducted for Hurricanes Ida and Harvey demonstrated that the ST6 parameterizations provided the best performance under hurricane conditions, particularly in reproducing peak  $H_s$ . Although the Komen formulation yielded the best overall statistical agreement with observations, it frequently underestimated the highest wave conditions. Comprehensive error statistics for all physics configurations and wind-forcing scenarios are provided in Appendix 1.

Based on these results, the ST6 configuration S7 (Table 3) was selected for the long-term hurricane hindcast simulations using both the original and blended ERA5 wind fields. Under fair-weather conditions, however, the Komen formulation showed better agreement with observations than both the default and ST6 configurations when forced with CFSv2 winds. Accordingly, the Komen formulation was adopted for fair-weather simulations and validation against the Spotter buoy observations. All simulations included nonlinear wave–wave interactions (quadruplets and triads), depth-induced breaking, and bottom friction. The final model configurations are summarized in Table 3.

Table 3 SWAN model inputs and configurations

| Inputs (forcings) to SWAN                         |                                                                                  |                        |         |         |         |                         |                         |
|---------------------------------------------------|----------------------------------------------------------------------------------|------------------------|---------|---------|---------|-------------------------|-------------------------|
|                                                   | Source                                                                           | Spatial resolutions    |         |         |         | Temporal resolutions    |                         |
| <b>Bathymetry</b>                                 |                                                                                  |                        |         |         |         |                         |                         |
| D1                                                | ETOPO22                                                                          | 5 km × 5 km            |         |         |         | -                       |                         |
| D2 and D3                                         | NOAA CRM                                                                         | 0.8 km × 0.8 km        |         |         |         | -                       |                         |
| <b>Winds</b>                                      |                                                                                  |                        |         |         |         |                         |                         |
| CFSv2                                             | NCEP                                                                             | 0.2045° × 0.2045°      |         |         |         | Hourly                  |                         |
| ERA5                                              | NCMWF                                                                            | 0.25° × 0.25°          |         |         |         | Hourly                  |                         |
| <b>Currents</b>                                   |                                                                                  |                        |         |         |         |                         |                         |
| HYCOM                                             | HYCOM                                                                            | 0.12° × 0.12°          |         |         |         | 3 Hourly                |                         |
|                                                   |                                                                                  |                        |         |         |         |                         |                         |
| <b>SWAN Model configurations</b>                  |                                                                                  |                        |         |         |         |                         |                         |
| <b>Frequency</b>                                  | 31 logarithmically spaced frequencies ranging from 0.05 to 1.0 Hz                |                        |         |         |         |                         |                         |
| <b>Directions</b>                                 | 36 directional bins spanning the full 360° directional spectrum at 10° intervals |                        |         |         |         |                         |                         |
| <b>Time step</b>                                  | 1 Hour                                                                           |                        |         |         |         |                         |                         |
| <b>SWAN Physics options<br/>(with parameters)</b> |                                                                                  |                        |         |         |         |                         |                         |
| <b>Fair weather</b><br>Winds-CFSv2                | Komen                                                                            | All default parameters |         |         |         |                         |                         |
| <b>Hurricane events</b>                           |                                                                                  |                        |         |         |         |                         |                         |
| Winds-ERA5                                        | ST6                                                                              | [a1sds]                | [a2sds] | [p1sds] | [p2sds] | <b>Drag<br/>Formula</b> | <b>Wind<br/>scaling</b> |
|                                                   | S7                                                                               | 5.7E-7                 | 8.0E-6  | 4.0     | 4.0     | HWANG                   | 32                      |

## 5. Model Validation (Task 4)

The wave model framework was validated under both extreme hurricane and ambient fair-weather conditions. Section 5.1 presents hurricane-event validation followed by sections 5.2 and 5.3 discussing the deployment of three Spotter buoys, data processing, and validation results from the Spotter buoy observations.

### 5.1 Wave Model Validation for Hurricane events

For the hurricane event simulations, model performance was evaluated against wave observations across 12 NDBC stations (Fig. 5) spanning multiple historical storms; however, for brevity, only results focusing on Hurricanes Ida (2021) and Ike (2008), forced with ERA5 (E-S7) and its blended version (EB-S7) are presented here. Comparisons are shown for NDBC stations 42003 and 42084 during Hurricane Ida and station 42035 during Hurricane Ike, as these locations were closest to the storm tracks and best illustrate the effects of wind-field blending. For Hurricane Ike, wave comparisons are also presented at three additional wave gauges U, V and W (shown in Fig. 8).

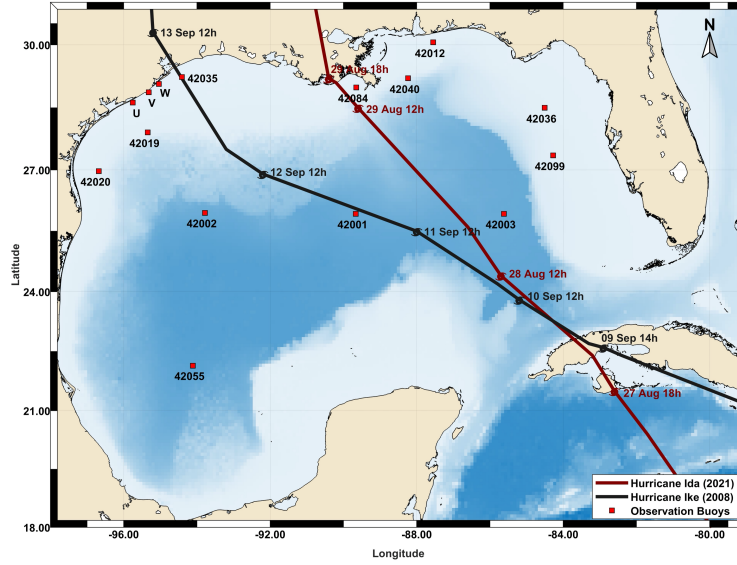


Figure 5 Hurricane Ida and Ike, with NDBC stations and wave gauges U, V and W

## Hurricane Ida (2021)

Figure 6 presents a side-by-side comparison of significant wave height ( $H_s$ ) and mean wave period ( $T_m$ ) yielded from the forcing of ERA5 and blended ERA5 with S7 parametrizations (E-S7 and EB-S7). The top panels (Fig. 6a and 6b) correspond to station 42003, while the bottom panels (Fig. 6c and 6d) for station 42084. As previously noted, (in Fig 4a), the blending process introduced negligible changes at station 42003; nearly identical  $H_s$  (Fig. 6a) and mean period (Fig. 6b). However, at station 42084, the E-S7 severely underestimates the peak  $H_s$ , by approximately 4 m relative to observations. This underestimation is largely resolved by EB-S7 (Fig. 6c), which also yields a modest improvement in the simulated mean wave period (Fig. 6d).

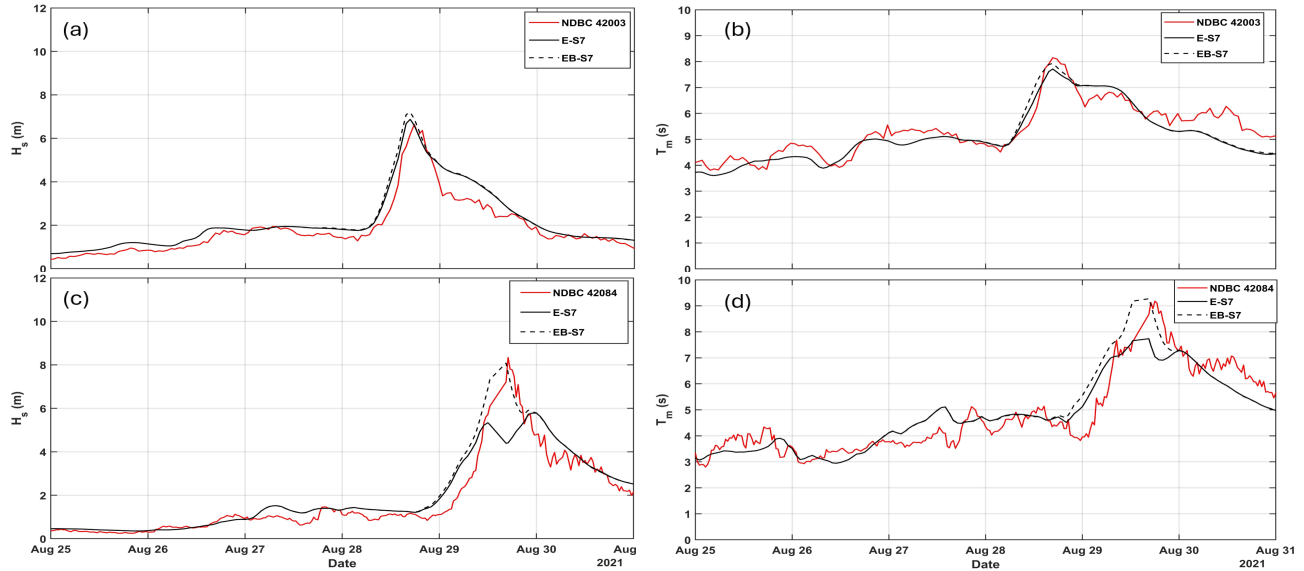


Figure 6 Comparison of significant wave height ( $H_s$ ) and mean wave period ( $T_m$ ) during Hurricane Ida. Panels show (a)  $H_s$  and (b)  $T_m$  at station 42003, and (c)  $H_s$  and (d)  $T_m$  at station 42084.

## Hurricane Ike (2008)

During Hurricane Ike, minor corrections in  $H_s$  (Fig. 7a) and  $T_m$  (Fig. 7b) were observed from EB-S7 at station 42035.

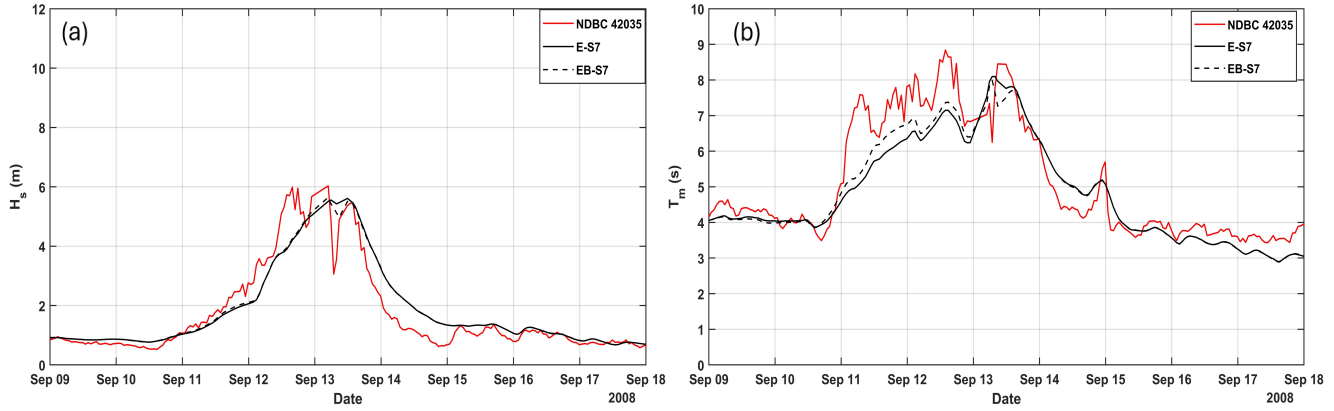


Figure 7 Comparison of significant wave height ( $H_s$ ) and mean wave period ( $T_m$ ) during Hurricane Ike.  
(a)  $H_s$  and (b)  $T_m$  at station 42035

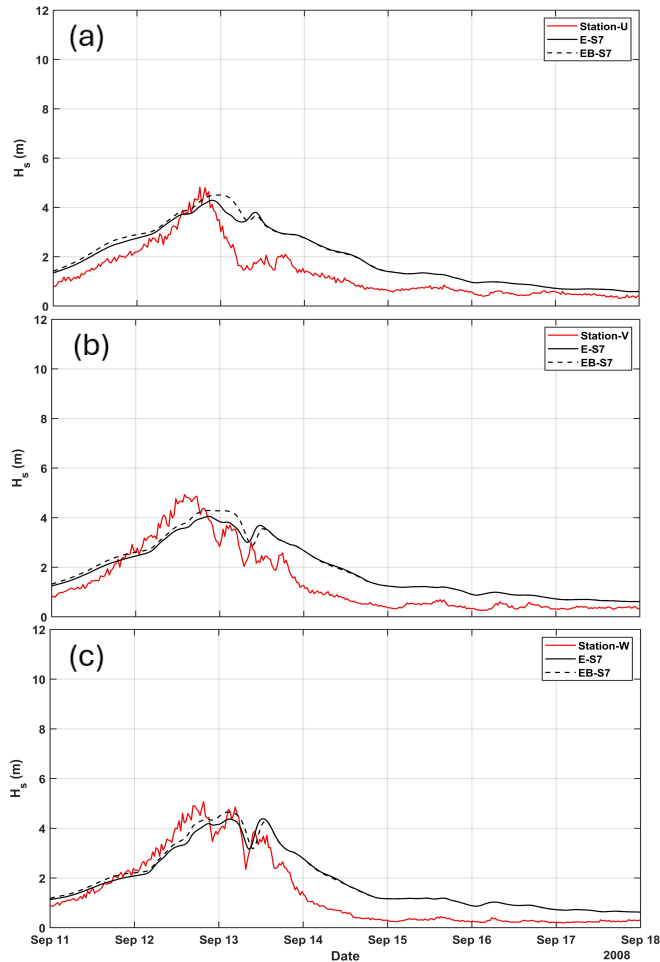


Figure 8 Comparison of  $H_s$ , (a) at gauge U (b) at gauge V and (c) at gauge W

Similar minor corrections are also seen with the results from wave gauges U, V, and W presented in Figures 8a, 8b, and 8c, respectively. Note that  $T_m$  observations were unavailable at these gauge locations and are therefore omitted.

## 5.2 Spotter Buoy Deployment and Data Collection

Validation under fair-weather conditions was conducted using in-situ wave measurements collected from Spotter buoys deployed in the nearshore region of Galveston Island from November 16 to December 11, 2024 (Campaign 1). The deployment and subsequent data collection procedures were executed as follows:

Three Sofar Spotter wave buoys (Sofar, 2025) were placed offshore of Galveston Island (Spot\_1, Spot\_2, Spot\_3) to capture incident wave conditions during the measuring campaign (Table 4, Fig. 9). One was placed around 1.2 miles offshore (Spot\_1), and the second 3.2 miles offshore (Spot\_2) along the same transect to assess wave transformation. The third Spotter (Spot\_3) was placed further down the beach, approximately 3.2 miles offshore of San Luis Pass (SLP).

The Spotters compute directional wave spectra at 30–60 min intervals from their local displacement measured using satellite GPS. They also record their geographical position, sea surface temperatures, barometric pressure, and estimated windspeed derived from the measured wave spectra (Sofar, 2019). Spotters can connect through satellite or cellular towers to transmit data to the Spotter dashboard (<https://spotter.sofaroccean.com/dashboard-v2>), allowing for real-time tracking, remote viewing and download of high-level data. Spotters were deployed via vessel, with an indirect mooring system, as recommended by Sofar (2022), to allow for more freedom of movement. A schematic and photo of the Spotter deployment setup is given in Figure 10.

Moderate winds ( $>6$  m/s) were present for most of the deployment window, largely driven by strong northerly cold fronts, leading to high wind-wave activity. See Figure 11 for a representative wind rose plot produced with data measured at nearby Scholes Airport on Galveston Island.

*Table 4 Spotter buoy location details.*

| <b>Buoy</b>   | <b>Latitude; Longitude</b> | <b>Distance from shoreline</b> | <b>S/N</b> |
|---------------|----------------------------|--------------------------------|------------|
| <b>Spot_1</b> | 29.173840; -94.948235      | ~1.2 miles                     | 31679C     |
| <b>Spot_2</b> | 29.150085; -94.930845      | ~3.2 miles                     | 31700C     |
| <b>Spot_3</b> | 29.066743; -95.069186      | ~3.2 miles                     | 31698C     |

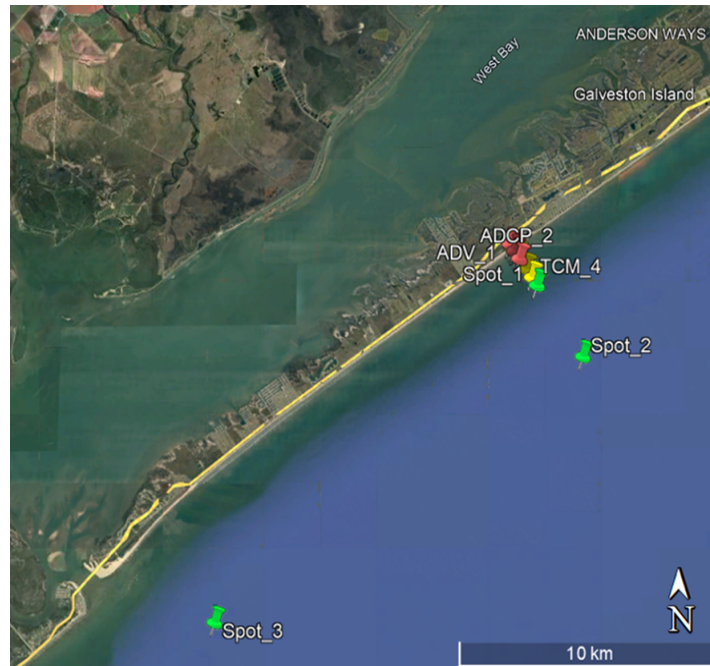


Figure 9 Map of instrument locations for the field measurement campaign. Spotter buoy locations are marked by green pins.

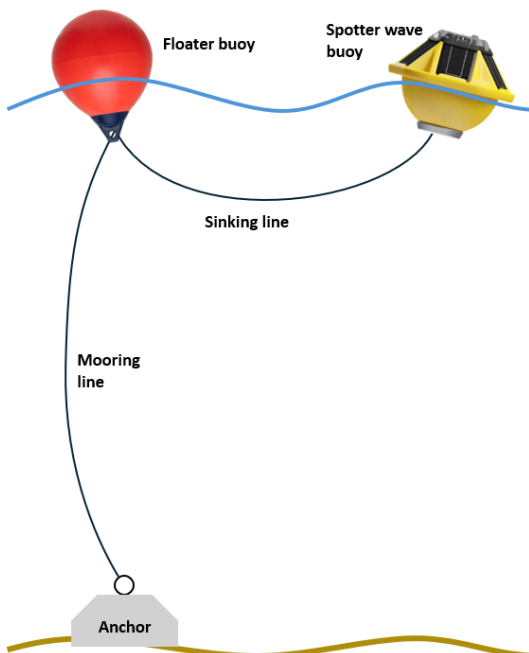


Figure 10 Schematic of Spotter wave buoy deployment setup (left) and pre-deployment instrument mounting setup (right) for Spotter wave buoys (yellow) with rope lines, anchors, and floater buoys (red).



Windrose Plot for [GLS] GALVESTON/SCHOLES  
Obs Between: 19 Nov 2024 12:52 AM - 10 Dec 2024 11:52 PM America/Chicago

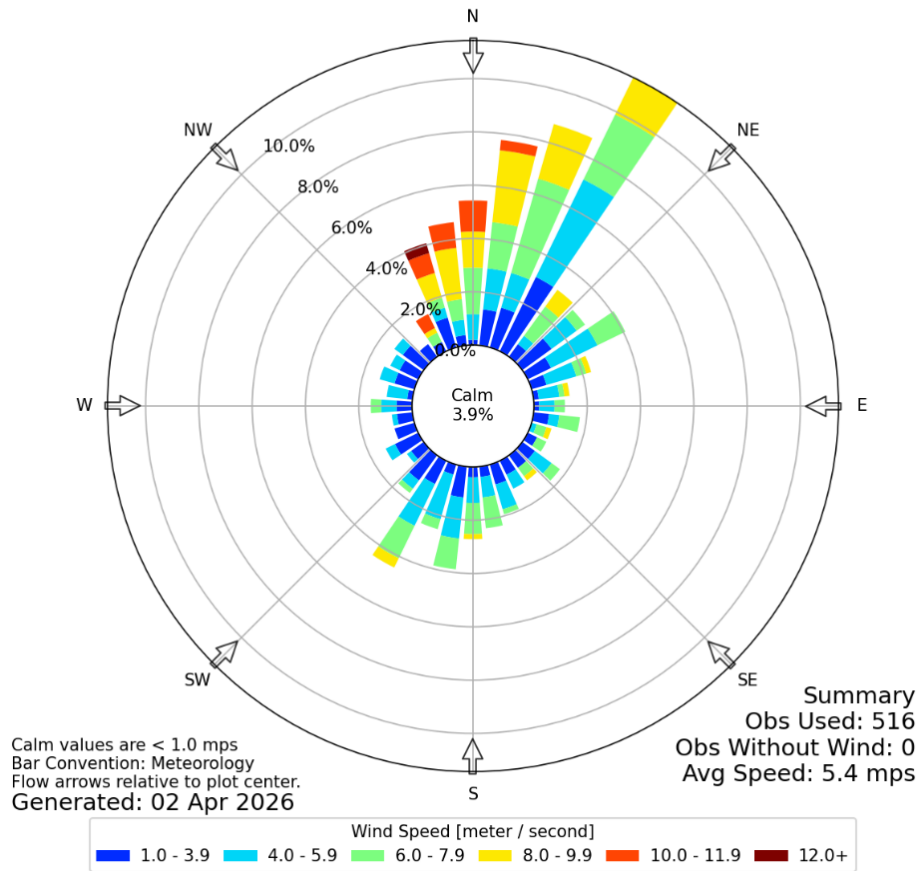


Figure 11 Wind rose during Campaign 1 at Galveston Scholes Airport sourced from Iowa Environmental Mesonet (2026).



### 5.3 Wave Model Validation Using Spotter Buoy Observations

The three Spotter buoys are located between 1 to 2 km offshore at depths ranging from 9 to 12 m. Under fair-weather conditions, significant wave heights in this region remain low, with observed peak  $H_s$  values ranging between 1.2 and 1.6 m across the deployment sites. As previously discussed, an evaluation of the various physics parameterizations revealed that the Komen scheme reproduced  $H_s$  and  $T_m$  closer to the observations than the default formulation. Comparisons of  $H_s$  and  $T_m$  derived from the simulations forced by CFSv2 winds with the Komen scheme and the default formulation are presented in Figure 12.

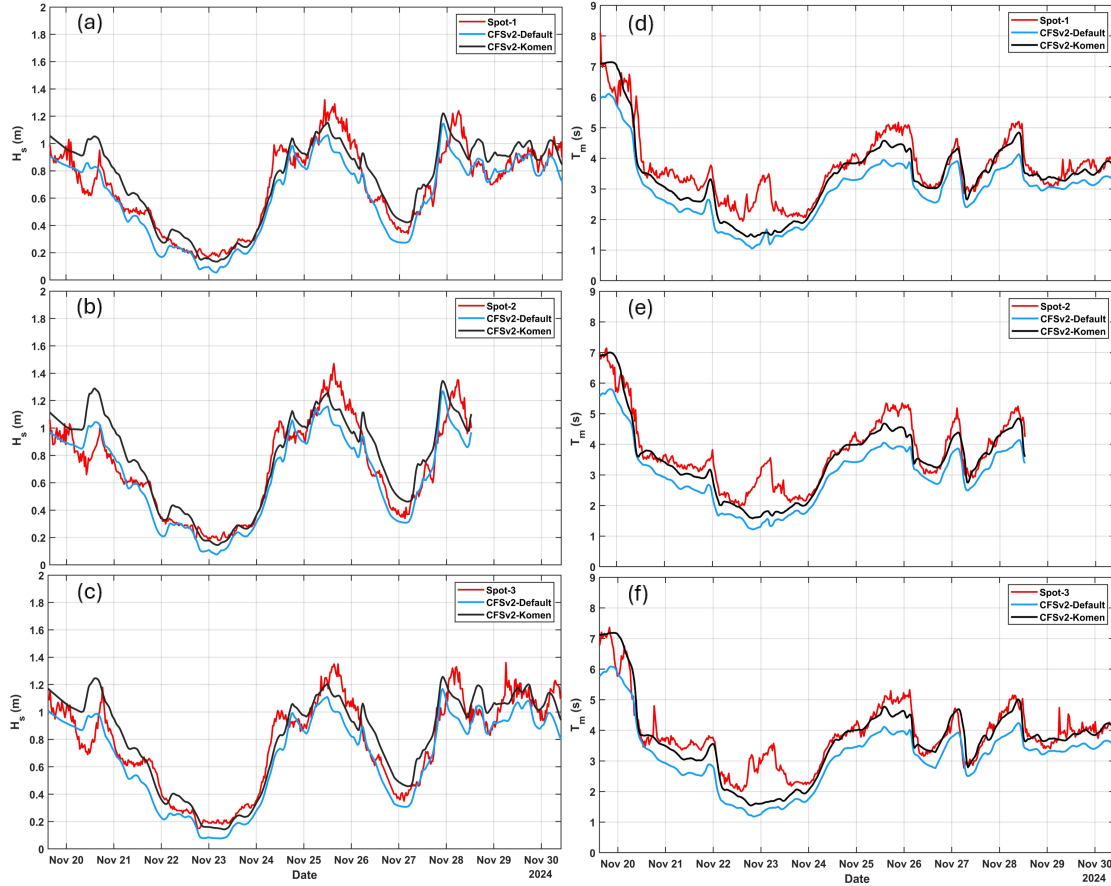


Figure 12 Comparison of simulated and observed  $H_s$  and  $T_m$  at the Spotter buoys. Panels (a)–(c) show  $H_s$  comparisons for Spotter-1, Spotter-2, and Spotter-3, respectively, while panels (d)–(f) show the corresponding  $T_m$  comparisons for Spotter-1, Spotter-2, and Spotter-3.

The default scheme exhibits a consistent negative bias, systematically underestimating both  $H_s$  and  $T_m$  across all buoy locations and throughout the simulation period. The bias is particularly evident during peak wave events, such as those occurring around 25 and 28 November. During the highest-energy conditions ( $H_s > 1.0$  m and  $T_m > 4.0$  s), the CFSv2–Komen configuration reproduces the observed  $H_s$  peaks much more accurately, whereas the default scheme underestimates them. Although the Komen formulation also slightly underestimates peak  $T_m$  values, it represents a considerable improvement over the default configuration.



## 6. Extreme Wave Value Statistics (Task 5)

Following validation and selection of the optimal wave model configuration, hindcast simulations were performed for all hurricanes that affected the Texas coast during the period 1940–2024. The 56 hurricane events considered in this study are listed in Section 4.2. Because CFSR (including CFSv1 and CFSv2) wind fields are only available from 1992 onward, the long-term hindcast simulations were forced using ERA5 winds combined with the hurricane wind-field blending approach described earlier.

The primary objective of these simulations was to quantify extreme wave conditions and assess the relative vulnerability of different coastal segments along the Texas coast. To this end, 100 locations were selected for extreme value analysis (Fig. 13). Of these, 51 nearshore locations (23 within the Galveston domain, D2, and 28 within the Corpus Christi domain, D3) were situated in water depths ranging from 6 to 10 m. The remaining 49 locations (22 in D2 and 27 in D3) were in intermediate water depths of approximately 18–22 m. The geographic coordinates and depths of all locations are provided in Appendix 2.

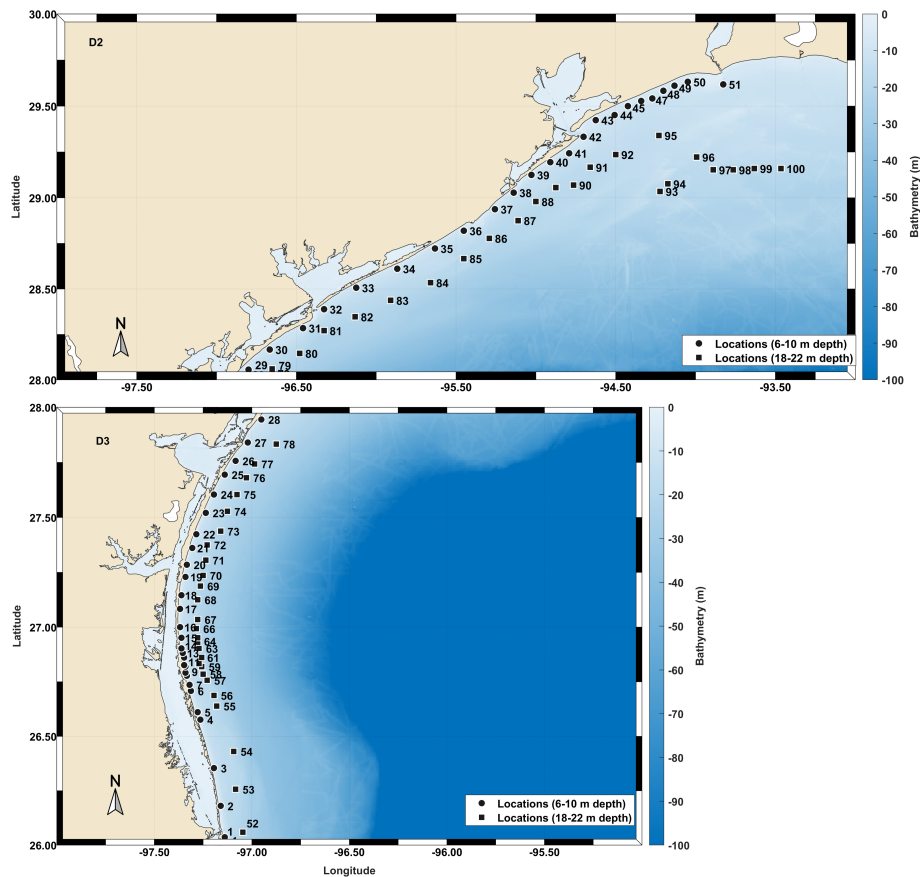


Figure 13 Coastal locations

For each hurricane simulation, significant wave height and other relevant wave parameters were extracted at these locations throughout the storm duration to construct a long-term hurricane-wave database. The extreme value analysis methodology based on the Generalized Extreme Value (GEV) distribution is described below in Section 6.1, followed by the discussion of return-level estimates in Section 6.3.

## 6.1 Extreme Value Analysis Methodology

Extreme value analysis (EVA) is widely used to quantify the probability and magnitude of rare and severe environmental events. Among the various EVA techniques, the two most commonly applied approaches are the Generalized Extreme Value (GEV) distribution and the Generalized Pareto Distribution (GPD). Both methods are theoretically well established and have been extensively used in hydrology, meteorology, oceanography, and coastal engineering for estimating design extremes and return levels.

The GEV approach is based on the block maxima method, in which the maximum value within a predefined block of time (e.g., annual maxima, seasonal maxima, or monthly maxima) is extracted and fitted to a GEV distribution. In contrast, the GPD approach follows the peaks-over-threshold (POT) framework, where all independent events exceeding a suitably selected threshold are retained and modeled using a GPD. Because the POT method utilizes more extreme observations than the block-maxima approach, it is often considered statistically efficient when a sufficiently large sample of threshold exceedances is available.

The reliability of both GEV and GPD models depends strongly on the quantity and quality of the available extreme-event data. In the present study, the available dataset consists of only 56 hurricane-induced maximum significant wave heights ( $H_s$ ) at each location, derived from 56 historical hurricanes affecting the study area. Furthermore, these events are irregularly distributed in time and do not correspond to conventional annual or seasonal block maxima. Although the POT/GPD framework is, in principle, well suited for event-based datasets that are not associated with regular time blocks, its successful application requires a sufficiently large sample of independent exceedances and a carefully selected threshold.

Several threshold-selection tests were conducted during the analysis. However, owing to the limited sample size, the estimated GPD parameters were found to be highly sensitive to the chosen threshold. Small changes in threshold level resulted in large variations in the fitted parameters and return-level estimates, occasionally producing unrealistic or physically implausible values. Such instability indicates that the available sample is insufficient to support a robust threshold-based analysis and that the resulting estimates are highly dependent on threshold selection.

Consequently, a GEV-based framework was adopted for the final analysis. Since our data (storm maxima) represent discrete storm events (occur irregularly) rather than annual maxima, a conventional annual-block maxima approach is inappropriate. Instead, we adopt a compound Poisson-GEV framework, a well-established method in marine hindcasting for independent

stochastic events (Todorovic & Zelenhasic, 1970; Jonathan & Ewans, 2013). Parameters are estimated via Maximum Likelihood Estimation (MLE) with confidence intervals derived via the delta method, following Coles (2001). The fitted distributions were subsequently used to characterize the probability distribution of hurricane-induced extreme wave heights and derive annual return-level estimates. The estimation of annual return levels involved the following steps:

### **Step 1: Extraction of hurricane maximum wave heights**

For each hurricane and each location, the maximum significant wave height ( $H_s$ ) was extracted from the SWAN simulations. This resulted in a sample of (N=56) independent hurricane maximum wave heights:

### **Step 2: Fitting the GEV distribution**

A GEV distribution was fitted to the hurricane maxima using MLE. The cumulative distribution function (CDF) of the GEV distribution is

$$F(H_s) = \exp\left(-\left(1 + \xi \frac{H_s - \mu}{\sigma}\right)^{-\frac{1}{\xi}}\right) \quad (11)$$

where  $H_s$  is the random variable (maximum significant wave heights),  $\mu$  is location parameter,  $\sigma$  is scale parameter and  $\xi$  is shape parameter.

### **Step 3: Define annual return periods**

The annual return periods considered in this study are:  $T = 20, 50, 100 \text{ years}$

The corresponding annual exceedance probability is:  $AEP = \frac{1}{T}$

Therefore  $AEP_{20} = 0.05$ ,  $AEP_{50} = 0.02$  and  $AEP_{100} = 0.01$ ,

### **Step 4: Estimate Hurricane occurrence rate**

The mean hurricane occurrence rate was calculated from the historical record:

$$\lambda = \frac{85 \text{ years}}{56 \text{ hurricanes}} = 0.659$$

This means that, on average, about 0.66 hurricanes affect the study area each year.

### **Step 5. Convert annual probability to storm probability**

Because the GEV is fitted to hurricane events rather than annual maxima, the annual exceedance probability must be converted into an equivalent hurricane-event exceedance probability.

Assuming hurricane occurrences follow a Poisson process:

$$AEP = 1 - e^{-\lambda p_{storm}} \quad (12)$$

where  $p_{storm}$  is probability that an individual hurricane exceeds a specified wave height.

Rearranging eq. (12): 
$$p_{storm} = -\frac{\ln(1-AEP)}{\lambda}$$

This equation converts a 20-, 50-, or 100-year probability into the equivalent exceedance probability per hurricane event.

### Step 6. Determine equivalent storm return period

The equivalent return period expressed in terms of hurricane occurrences is

$$R_{storm} = \frac{1}{p_{storm}} \quad (13)$$

In our case, using  $\lambda = 0.66$ , annual return period of 20 years is equivalent to 12.9 storms that means a 20-year return level corresponds approximately to a wave height exceeded once every 13 hurricanes. Similarly, a 50-year return level corresponds approximately to a wave height exceeded once every ~33 hurricanes, and a 100-year return level corresponds approximately to a wave height exceeded once every ~66 hurricanes.

### Step 7. Estimate annual return levels

The non-exceedance probability corresponding to the storm exceedance probability is

$$q = 1 - p_{storm} \quad (14)$$

The annual return level is then obtained from the fitted GEV distribution:

$$H_T = F^{-1}(q) \quad (15)$$

where,  $H_T$  is return wave height associated with return period  $T$

### Step 8. Estimate confidence intervals

Uncertainty in the return levels was quantified using:

$$95\%CI = H_T \pm 1.96 \times SE \quad (16)$$

where, SE is the standard error obtained using the delta method.

## 6.2 Results and discussion

Annual return levels of significant wave height ( $H_s$ ) were estimated for all 100 coastal locations. For brevity, the discussion focuses on the 51 nearshore locations located in water depths of 6–10 m. Return-level estimates for all 100 locations are included in the Appendix 3.

Figure 14 displays the 20-, 50-, and 100-year return levels alongside their corresponding 95% confidence intervals (indicated by vertical error bars) for these 51 nearshore locations. Given the constraints of the relatively small sample size, consisting of 56 historical storm events spanning

an 85-year period (1940–2024), the 100-year return level estimates inherently carry higher statistical uncertainty and should be interpreted with caution. Nevertheless, spatial variations are distinct; locations 26 through 30 consistently exhibit elevated return level estimates across all three recurrence intervals. The maximum values are observed at location 29, situated near Corpus Christi, where the 20-, 50-, and 100-year return levels reach 4.8 m, 6.5 m, and 8.2 m, respectively.

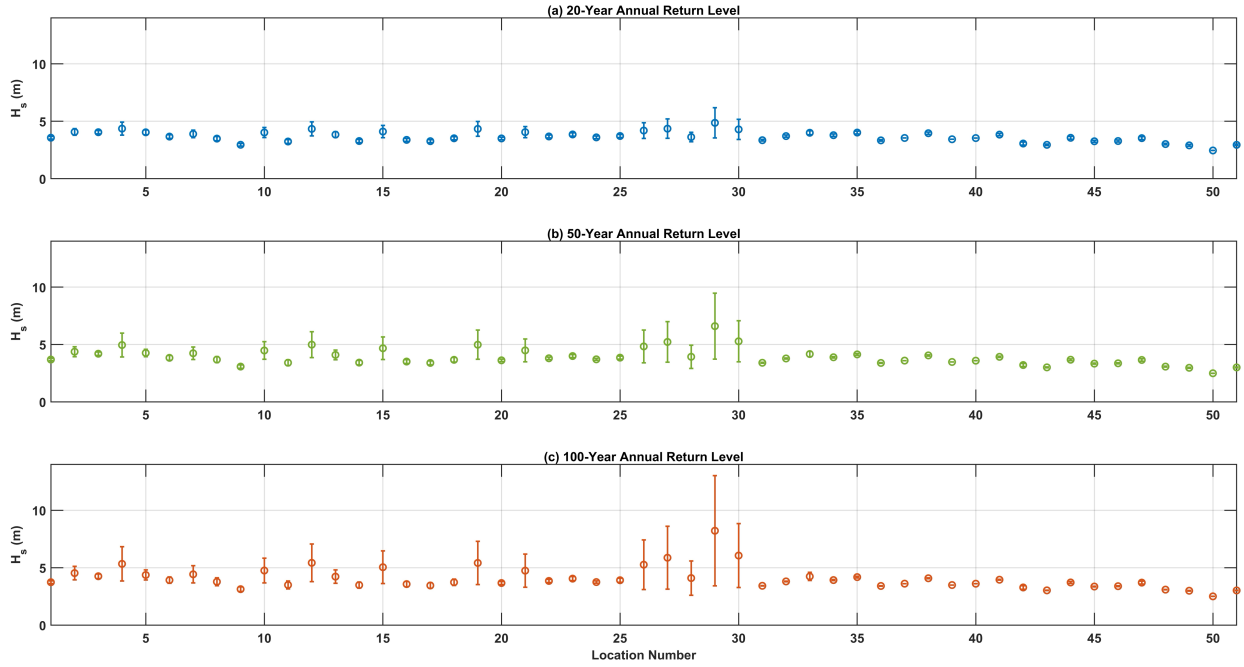


Figure 14  $H_s$  Return levels

The fitted probability density functions (PDFs) and quantile-quantile (Q-Q) plots for corresponding locations 26 through 29 demonstrate a satisfactory overall goodness-of-fit for the lower and intermediate quantiles (Fig. 15). However, distinct spatial variations emerge in the upper tails. Locations 27 and 29 exhibit positive shape parameters ( $\xi = 0.01$  and  $\xi = 0.28$ , respectively), characteristics of heavy-tailed Fréchet distributions. At these sites, the empirical data deviate below the 1:1 Q-Q reference line at the highest quantiles, indicating that the theoretical return levels extrapolate beyond the maximum wave heights observed in the 85-year historical record. Conversely, location 28 displays a negative shape parameter ( $\xi = -0.34$ ), signifying a bounded Weibull-type distribution where wave heights appear physically limited, likely due to localized shallow-water bathymetric constraints or sheltering effects. At few locations (not shown here) while the GEV model overestimates the lower-tail dispersion (yielding physically unrealistic negative theoretical bounds), it provides a highly accurate fit for the upper-tail extremes, which is the primary focus of the return-level study.

Figure 16 shows the estimated 20-, 50-, and 100-year return levels based on regionally aggregated maxima for the Galveston and Corpus Christi coastal domains.

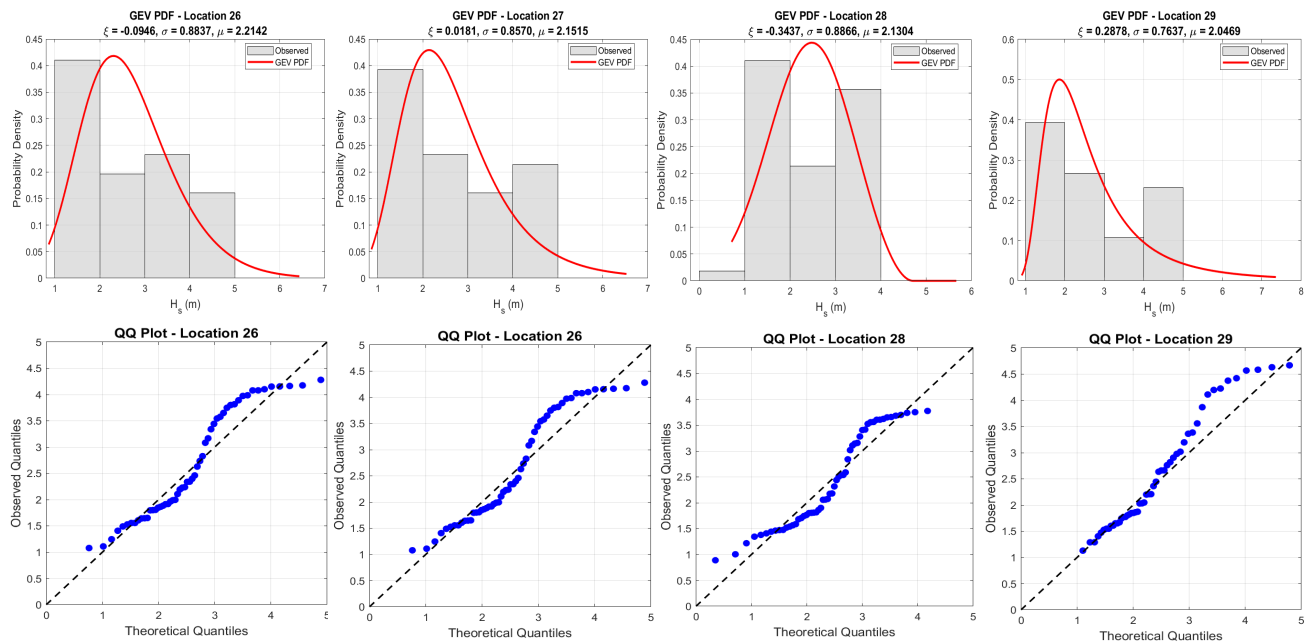


Figure 15 Top panels fitted probability density functions. Bottom panel Q-Q plots

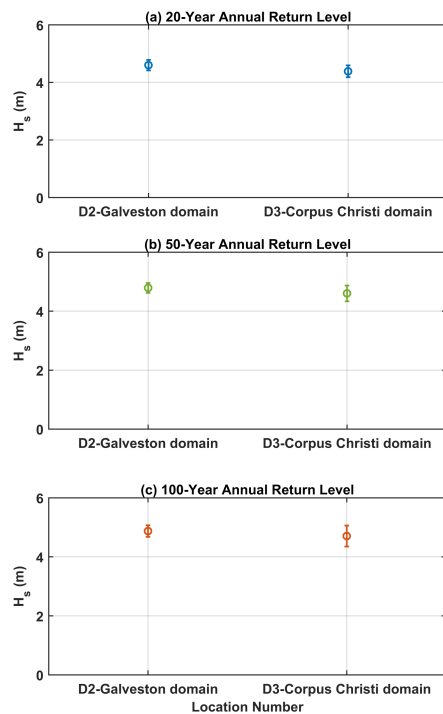


Figure 16  $H_s$  return levels for regions: D2 and D3

## 7. Sensitivity study (Task 6)

The final objective of this study was to assess the sensitivity of coastal wave responses to uncertainties in both hurricane characteristics and numerical model parameters. The analysis aims to identify nearshore locations where wave predictions are particularly sensitive to these uncertainties and where future field measurements, such as buoy deployments, would be most beneficial for improving model reliability and reducing prediction uncertainty.

The assessment was based on the same nested-domain wave modeling framework used in the extreme value analysis, employing SWAN simulations forced with blended ERA5 wind fields. However, the analysis was restricted to 28 historical hurricanes whose tracks passed in close proximity to the Texas coast, making them the most relevant events for evaluating coastal sensitivity. Details of the selected hurricanes are provided in Table 1. The analysis was conducted at the same set of locations considered in the extreme value assessment, comprising 51 nearshore stations and 49 intermediate-depth stations (Fig. 13).

Section 7.1 describes the storm and model parameters considered in the sensitivity analysis, along with the corresponding baseline simulations used for each parameter variation. The sensitivity metrics and methodological framework are presented in Section 7.2, followed by a discussion of the results in Section 7.3.

### 7.1 Storm and model parameters, baseline simulations

For the sensitivity assessment, wind forcing was treated as the sole storm (environmental) parameter, while the model parameters were limited to the bottom friction coefficient and the depth-induced breaking parameter, based on prior testing and analysis.

Because wind forcing represents an external environmental driver, whereas the bottom friction and breaking parameters arise from empirical and semi-empirical model formulations, combining all three into a single sensitivity index is not physically meaningful. In addition, each parameter was perturbed over distinct ranges and percentages, consistent with values reported in the literature, rather than applying a uniform perturbation that could yield unrealistic scenarios.

Accordingly, sensitivity at each location was quantified using two separate indices: (i) an environmental sensitivity index derived from wind forcing, and (ii) a model sensitivity index obtained as the combined contribution of the bottom friction and depth-induced breaking parameters.

The baseline simulation setup, used as the reference for estimating variability/sensitivity due to parameter changes, is described below, along with the corresponding parameter ranges and discrete values considered.

## A. Storm (environmental) parameters

### Winds

**Baseline simulations:** Each hurricane was simulated using ERA5 wind fields blended with the parametric hurricane model.

**Perturbed winds/Varying winds:** The blended ERA5 winds for each hurricane were randomly varied within  $\pm 30\%$ , at each grid point and each time step. Simulations with these perturbed wind fields were then compared against the baseline simulations.

## B. Wave model parameters

### i) Bottom friction coefficient.

**Baseline simulations:** Each hurricane was simulated using the original blended ERA5 wind fields, with bottom friction represented by the Hasselmann-JONSWAP formulation and a coefficient of  $0.019 \text{ m}^2/\text{s}^3$ , as recommended for the Gulf of Mexico (SWAN User Manual; Huang et al., 2013).

**Coefficient variations:** Two different bottom friction coefficients were adopted:  $0.038 \text{ m}^2/\text{s}^3$  (SWAN default) and  $0.01 \text{ m}^2/\text{s}^3$ , representing approximately  $\pm 50\%$  variation around the baseline value.

### ii) Depth induced breaking parameter

**Baseline simulations:** Each hurricane was simulated using the original blended ERA5 wind fields, with depth induced breaking based on Battjes and Janssen (1978) formulation with breaking parameter equal to 0.73, as recommended default in SWAN (SWAN User Manual; Huang et al., 2013).

**Parameter variations:** Based on Battjes and Stive (1985), the lower and upper bounds of the parameter range: 0.6 and 0.8 were adopted (approximately  $\pm 14\%$  variation around the baseline value).

## 7.2 Methodology of estimating Sensitivity index (at each location)

Based on a review of established sensitivity analysis methodologies (e.g., Andrea Saltelli et al., 2008; Francesca Pianosi et al., 2016; Ranatunga et al., 2017), two complementary metrics were adopted as representative sensitivity indices (SI): (i) the Mean Absolute Percentage Error (MAPE), based on peak significant wave heights, which reflects extreme response sensitivity (useful in design conditions, hazard assessment etc.) and (ii) the Averaged Normalized Root Mean Square Error ( $\overline{NRMSE}$ ) based on daily mean significant wave heights ( $\overline{H_s}$ ), capturing time-integrated or bulk response sensitivity. The formulations are described below



### i. Mean Absolute Percentage Error (*MAPE*)

At a given location  $i$ , the Absolute Percentage Error (*APE*) associated with a perturbation in parameter  $A$  is first computed for the peak significant wave height, relative to the corresponding baseline simulation, as:

$$APE_{i,j}(A) = \left| \frac{H_{sP(A)}^{peak} - H_{sB}^{peak}}{H_{sB}^{peak}} \right| \times 100 \quad (17)$$

where,  $H_{sP(A)}^{peak}$  denotes the peak significant wave height at location  $i$ , obtained from the simulation with parameter  $A$  perturbed, and  $H_{sB}^{peak}$  is the corresponding peak value from the baseline simulation for the  $j^{\text{th}}$  hurricane.

The sensitivity index at location  $i$  is then defined as the mean of  $APE_{i,j}$  values across all  $N$  hurricanes:

$$MAPE_i(A) = \sum_{j=1}^N \frac{APE_{i,j}(A)}{N} \quad (18)$$

### ii. Averaged Normalized Root Mean Square Error (*NRMSE*)

At a given location over the full duration of each hurricane event. We first compute the Root Mean Square Error (*RMSE*, Eq.19), then normalize it to obtain the *NRMSE* (Eq. 20) and finally estimate average  $\overline{NRMSE}$  (Eq. 21) to derive the sensitivity index.

**Step 1:** The *RMSE* of the daily mean  $\overline{H_s}$  for hurricane  $j$ , corresponding to a perturbation of parameter  $A$ , at location  $i$ , is first computed and is defined as follows:

$$RMSE_{i,j}(A) = \sqrt{\frac{1}{n} \sum (\overline{H_{sP(A)}} - \overline{H_{sB}})^2} \quad (19)$$

where,  $\overline{H_{sP(A)}}$  denotes the daily mean significant wave height at location  $i$ , obtained from the simulation with a perturbation applied to parameter  $A$ ,  $\overline{H_{sB}}$  denotes the corresponding daily mean significant wave height at location  $i$  from the baseline simulation for the  $j^{\text{th}}$  hurricane, and  $n$  represents the number of days in the hurricane event.

**Step 2:** The Normalized Root Mean Square Error (*NRMSE*) for the  $j^{\text{th}}$  hurricane at location  $i$  corresponding to a perturbation of parameter  $A$  is then computed by normalizing the *RMSE* with the range of the daily mean  $\overline{H_s}$ , defined as the difference between the maximum and minimum values from the baseline simulation of the  $j^{\text{th}}$  hurricane. The corresponding formula is given below:

$$NRMSE_{i,j}(A) = \frac{RMSE_{i,j}(A)}{\max(\overline{H_{sB}}) - \min(\overline{H_{sB}})} \quad (20)$$

where,  $\max(\bar{H}_{sB})$  and  $\min(\bar{H}_{sB})$  denote the maximum and minimum values, respectively, of the daily mean SWH from the baseline simulation.

**Step 3.** The  $NRMSE$  associated with parameter  $A$  is averaged across all hurricane events at location  $i$ .

$$\overline{NRMSE}_i(A) = \sum_{j=1}^N \frac{NRMSE_{i,j}(A)}{N} \quad (21)$$

where,  $N$  is the total number of hurricanes. This average  $\overline{NRMSE}$  is then used as the sensitivity index (SI) to quantify the relative influence of a parameter at a given location, considering all hurricanes included in the analysis. Higher SI values indicate a stronger impact of the parameter at that location, whereas lower values correspond to a weaker influence.

### 7.3 Estimated sensitivity matrix (results)

Using the methodology described in Section 7.2, sensitivity indices associated with environmental and model parameters were computed for each coastal location using both  $MAPE$  and  $\overline{NRMSE}$  metrics. The results are summarized in Table 5 ( $MAPE$ -based sensitivity index) and Table 6 ( $NRMSE$ -based sensitivity index).

In these tables, the first column lists the coastal locations (by index), the second column represents the sensitivity index due to the environmental parameter (wind), and the third column represents the model sensitivity index, obtained as the combined contribution of the bottom friction coefficient and the depth-induced breaking parameter. The highlighted locations correspond to those exhibiting the highest sensitivity. The variation of these indices with respect to location, for the 6–10 m and 18–22 m depth ranges, is presented in the subsequent figures.

*Table 5 Sensitivity Index (MAPE, based on peak  $H_s$ )*

| Locations | MAPE-SI<br>Environmental | MAPE-SI<br>Model | Locations | MAPE-SI<br>Environmental | MAPE-SI<br>Model | Locations | MAPE-SI<br>Environmental | MAPE-SI<br>Model |
|-----------|--------------------------|------------------|-----------|--------------------------|------------------|-----------|--------------------------|------------------|
| 1         | 3.124                    | 7.141            | 16        | 2.684                    | 8.488            | 31        | 2.673                    | 10.594           |
| 2         | 3.403                    | 6.859            | 17        | 2.605                    | 8.658            | 32        | 2.682                    | 10.766           |
| 3         | 3.373                    | 7.321            | 18        | 2.612                    | 8.370            | 33        | 2.571                    | 10.558           |
| 4         | 3.952                    | 6.554            | 19        | 3.246                    | 7.165            | 34        | 2.056                    | 11.195           |
| 5         | 3.392                    | 7.219            | 20        | 2.392                    | 8.472            | 35        | 2.341                    | 11.253           |
| 6         | 2.786                    | 7.707            | 21        | 2.809                    | 7.638            | 36        | 2.006                    | 12.622           |
| 7         | 2.823                    | 7.306            | 22        | 2.668                    | 8.288            | 37        | 2.260                    | 12.409           |
| 8         | 2.632                    | 7.993            | 23        | 3.190                    | 8.179            | 38        | 2.767                    | 12.141           |
| 9         | 2.286                    | 8.918            | 24        | 2.654                    | 8.655            | 39        | 2.290                    | 13.714           |
| 10        | 2.828                    | 7.062            | 25        | 3.120                    | 8.655            | 40        | 2.638                    | 13.749           |
| 11        | 2.435                    | 8.493            | 26        | 3.320                    | 8.201            | 41        | 3.398                    | 13.171           |
| 12        | 2.870                    | 6.841            | 27        | 3.329                    | 8.485            | 42        | 2.388                    | 13.532           |
| 13        | 2.704                    | 7.535            | 28        | 2.825                    | 9.774            | 43        | 1.614                    | 15.775           |

|    |       |       |  |    |       |       |  |    |       |        |
|----|-------|-------|--|----|-------|-------|--|----|-------|--------|
| 14 | 2.303 | 8.574 |  | 29 | 3.325 | 7.737 |  | 44 | 2.983 | 14.690 |
| 15 | 2.838 | 7.215 |  | 30 | 2.994 | 9.391 |  | 45 | 2.823 | 15.545 |

| Locations | MAPE-SI<br>Environmental | MAPE-SI<br>Model |  | Locations | MAPE-SI<br>Environmental | MAPE-SI<br>Model |  | Locations  | MAPE-SI<br>Environmental | MAPE-SI<br>Model |
|-----------|--------------------------|------------------|--|-----------|--------------------------|------------------|--|------------|--------------------------|------------------|
| 46        | 3.380                    | 15.149           |  | 65        | 3.712                    | 3.053            |  | 84         | 3.669                    | 4.343            |
| 47        | 4.163                    | 14.401           |  | 66        | 3.934                    | 3.357            |  | 85         | 3.985                    | 5.427            |
| 48        | 2.526                    | 16.053           |  | 67        | 3.919                    | 3.141            |  | 86         | 5.589                    | 5.564            |
| 49        | 2.700                    | 16.060           |  | 68        | 4.049                    | 3.182            |  | 87         | 4.769                    | 5.591            |
| <b>50</b> | 2.242                    | <b>16.890</b>    |  | 69        | 4.257                    | 3.138            |  | 88         | 5.585                    | 6.631            |
| 51        | 2.796                    | 15.432           |  | 70        | 4.618                    | 3.092            |  | 89         | 5.256                    | 7.550            |
| 52        | 3.712                    | 3.420            |  | 71        | 4.252                    | 3.275            |  | 90         | 5.149                    | 7.132            |
| 53        | 4.655                    | 3.699            |  | 72        | 3.753                    | 3.763            |  | 91         | 4.448                    | 8.285            |
| 54        | 4.312                    | 2.886            |  | 73        | 4.015                    | 2.922            |  | 92         | 4.365                    | 8.986            |
| 55        | 4.192                    | 2.950            |  | 74        | 4.082                    | 3.213            |  | 93         | 4.923                    | 5.916            |
| 56        | 4.108                    | 2.873            |  | 75        | 4.059                    | 3.257            |  | 94         | 4.375                    | 6.184            |
| 57        | 4.028                    | 2.959            |  | 76        | 4.051                    | 3.439            |  | 95         | 4.528                    | 10.497           |
| 58        | 4.015                    | 3.072            |  | 77        | 4.341                    | 3.655            |  | 96         | 4.709                    | 8.123            |
| 59        | 3.947                    | 2.947            |  | 78        | 3.980                    | 3.404            |  | 97         | 4.480                    | 6.431            |
| 60        | 3.878                    | 3.315            |  | 79        | 3.869                    | 4.068            |  | 98         | 5.694                    | 5.923            |
| 61        | 3.776                    | 3.034            |  | 80        | 3.530                    | 3.805            |  | 99         | 5.373                    | 5.839            |
| 62        | 3.807                    | 2.869            |  | 81        | 4.262                    | 4.112            |  | <b>100</b> | <b>5.732</b>             | 5.289            |
| 63        | 3.712                    | 3.040            |  | 82        | 3.918                    | 4.466            |  |            |                          |                  |
| 64        | 3.571                    | 3.161            |  | 83        | 3.256                    | 4.369            |  |            |                          |                  |

Table 6 Sensitivity Index ( $\overline{NRMSE}$ ), based on ( $H_s$ )

| Locations | $\overline{NRMSE}$ -SI<br>Environmental | $\overline{NRMSE}$ -SI<br>Model |  | Locations | $\overline{NRMSE}$ -SI<br>Environmental | $\overline{NRMSE}$ -SI<br>Model |  | Locations | $\overline{NRMSE}$ -SI<br>Environmental | $\overline{NRMSE}$ -SI<br>Model |
|-----------|-----------------------------------------|---------------------------------|--|-----------|-----------------------------------------|---------------------------------|--|-----------|-----------------------------------------|---------------------------------|
| <b>1</b>  | <b>0.059</b>                            | 0.047                           |  | 18        | 0.053                                   | 0.049                           |  | 35        | 0.043                                   | 0.052                           |
| 2         | 0.056                                   | 0.043                           |  | 19        | 0.053                                   | 0.042                           |  | 36        | 0.043                                   | 0.061                           |
| 3         | 0.055                                   | 0.045                           |  | 20        | 0.054                                   | 0.049                           |  | 37        | 0.041                                   | 0.058                           |
| 4         | 0.055                                   | 0.039                           |  | 21        | 0.053                                   | 0.044                           |  | 38        | 0.040                                   | 0.055                           |
| 5         | 0.054                                   | 0.042                           |  | 22        | 0.053                                   | 0.048                           |  | 39        | 0.040                                   | 0.067                           |
| 6         | 0.053                                   | 0.045                           |  | 23        | 0.053                                   | 0.046                           |  | 40        | 0.039                                   | 0.067                           |
| 7         | 0.053                                   | 0.042                           |  | 24        | 0.051                                   | 0.050                           |  | 41        | 0.037                                   | 0.062                           |
| 8         | 0.053                                   | 0.047                           |  | 25        | 0.050                                   | 0.048                           |  | 42        | 0.037                                   | 0.082                           |
| 9         | 0.053                                   | 0.059                           |  | 26        | 0.051                                   | 0.044                           |  | 43        | 0.036                                   | 0.088                           |
| 10        | 0.053                                   | 0.041                           |  | 27        | 0.049                                   | 0.045                           |  | 44        | 0.036                                   | 0.075                           |
| 11        | 0.053                                   | 0.051                           |  | 28        | 0.049                                   | 0.053                           |  | 45        | 0.036                                   | 0.082                           |
| 12        | 0.052                                   | 0.039                           |  | 29        | 0.051                                   | 0.044                           |  | 46        | 0.036                                   | 0.082                           |
| 13        | 0.052                                   | 0.043                           |  | 30        | 0.050                                   | 0.049                           |  | 47        | 0.035                                   | 0.078                           |
| 14        | 0.052                                   | 0.052                           |  | 31        | 0.050                                   | 0.054                           |  | 48        | 0.035                                   | 0.092                           |
| 15        | 0.052                                   | 0.041                           |  | 32        | 0.047                                   | 0.053                           |  | 49        | 0.035                                   | 0.095                           |

|    |       |       |  |    |       |       |  |    |       |       |
|----|-------|-------|--|----|-------|-------|--|----|-------|-------|
| 16 | 0.053 | 0.051 |  | 33 | 0.046 | 0.052 |  | 50 | 0.036 | 0.110 |
| 17 | 0.053 | 0.055 |  | 34 | 0.044 | 0.054 |  | 51 | 0.035 | 0.092 |

| Locations | <i>NRMSE</i> -SI<br>Environmental | <i>NRMSE</i> -SI<br>Model |  | Locations | <i>NRMSE</i> -SI<br>Environmental | <i>NRMSE</i> -SI<br>Model |  | Locations | <i>NRMSE</i> -SI<br>Environmental | <i>NRMSE</i> -SI<br>Model |
|-----------|-----------------------------------|---------------------------|--|-----------|-----------------------------------|---------------------------|--|-----------|-----------------------------------|---------------------------|
| 52        | 0.058                             | 0.030                     |  | 69        | 0.052                             | 0.024                     |  | 86        | 0.041                             | 0.029                     |
| 53        | 0.056                             | 0.029                     |  | 70        | 0.053                             | 0.024                     |  | 87        | 0.040                             | 0.030                     |
| 54        | 0.055                             | 0.025                     |  | 71        | 0.053                             | 0.025                     |  | 88        | 0.040                             | 0.034                     |
| 55        | 0.054                             | 0.024                     |  | 72        | 0.052                             | 0.026                     |  | 89        | 0.038                             | 0.038                     |
| 56        | 0.053                             | 0.024                     |  | 73        | 0.050                             | 0.023                     |  | 90        | 0.037                             | 0.036                     |
| 57        | 0.054                             | 0.024                     |  | 74        | 0.050                             | 0.024                     |  | 91        | 0.035                             | 0.041                     |
| 58        | 0.054                             | 0.024                     |  | 75        | 0.050                             | 0.024                     |  | 92        | 0.035                             | 0.045                     |
| 59        | 0.054                             | 0.024                     |  | 76        | 0.049                             | 0.024                     |  | 93        | 0.037                             | 0.031                     |
| 60        | 0.054                             | 0.025                     |  | 77        | 0.050                             | 0.024                     |  | 94        | 0.036                             | 0.032                     |
| 61        | 0.053                             | 0.024                     |  | 78        | 0.048                             | 0.023                     |  | 95        | 0.034                             | 0.052                     |
| 62        | 0.053                             | 0.023                     |  | 79        | 0.049                             | 0.029                     |  | 96        | 0.036                             | 0.039                     |
| 63        | 0.053                             | 0.024                     |  | 80        | 0.047                             | 0.027                     |  | 97        | 0.036                             | 0.033                     |
| 64        | 0.053                             | 0.024                     |  | 81        | 0.048                             | 0.028                     |  | 98        | 0.037                             | 0.031                     |
| 65        | 0.053                             | 0.024                     |  | 82        | 0.046                             | 0.027                     |  | 99        | 0.037                             | 0.031                     |
| 66        | 0.054                             | 0.025                     |  | 83        | 0.044                             | 0.026                     |  | 100       | 0.038                             | 0.030                     |
| 67        | 0.054                             | 0.024                     |  | 84        | 0.042                             | 0.025                     |  |           |                                   |                           |
| 68        | 0.052                             | 0.024                     |  | 85        | 0.041                             | 0.028                     |  |           |                                   |                           |

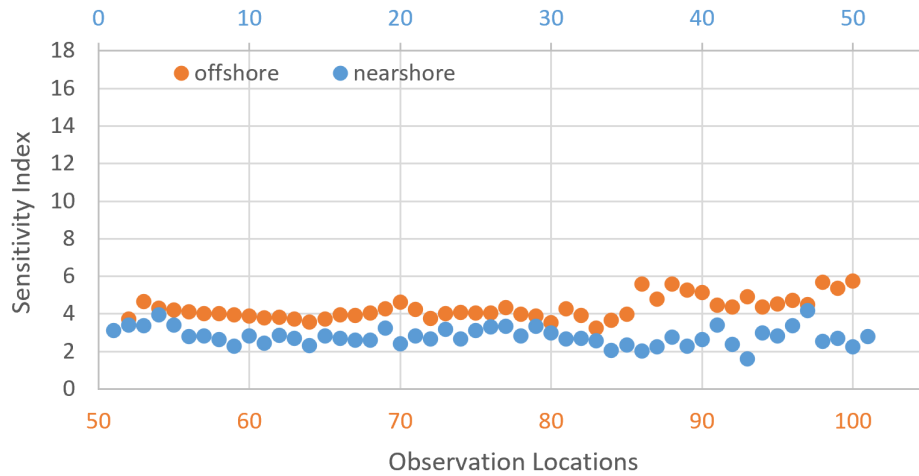


Figure 17 MAPE-SI for environmental parameter (winds), offshore (18–22 m water depth) and nearshore (6–10m depth); the numbers on X-axis (top and bottom) are the coastal locations in numbers (Table. 5)

MAPE-based sensitivities (percentage error) due to wind variations are smaller than those associated with variations in model parameters (Fig. 17 and 18). The sensitivity due to wind remains relatively consistent between nearshore (6–10 m depth) and offshore (18–22 m depth) locations, showing little depth dependence. In contrast, sensitivities arising from the combined effects of bottom friction and depth-induced breaking exhibit pronounced variation with depth,

clearly indicating strong depth dependence (Fig. 18). Higher sensitivity is observed in shallower waters.

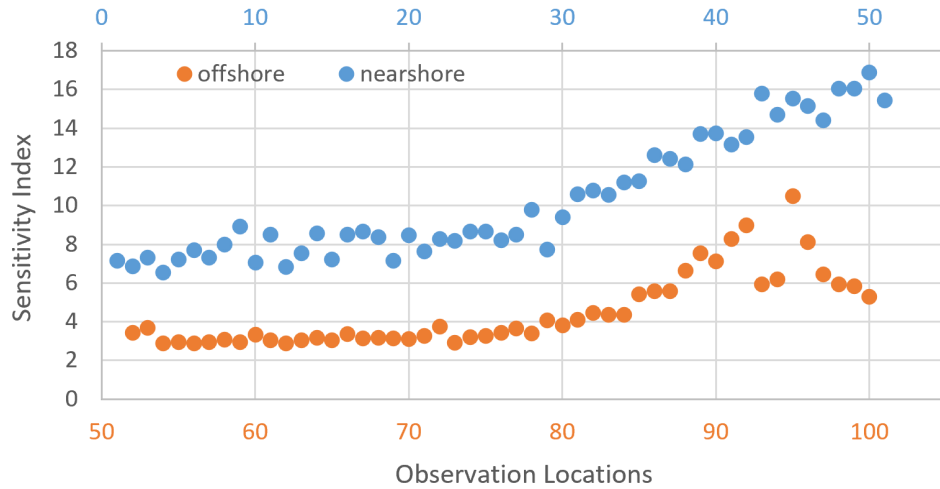


Figure 18 MAPE-SI for model parameters (bottom friction and breaking parameter), offshore (18-22 m water depth) and nearshore (6-10m depth); the numbers on X-axis (top and bottom) are the coastal locations in numbers (Table. 5)

Based on Table 5 and Figures 17 and 18, Location 50 (longitude  $-94.04$ , latitude  $29.63$ ), situated in  $\sim 6$ – $10$  m water depth, shows the highest sensitivity to variations in model parameters.

Turning to the NRMSE-based sensitivities (Fig. 19 and 20), the patterns observed in the MAPE analysis, particularly for model parameter variations, are consistently reproduced in Figure 20, although expressed in non-percentage terms. Sensitivities due to wind variations remain relatively small and show negligible differences between nearshore and offshore locations (Fig. 19). In contrast, sensitivities associated with model parameters again exhibit a clear dependence on water depth, with higher values in shallower regions. Consistent with the MAPE results, Location 50 (Fig. 20) shows the highest sensitivity, further indicating that model sensitivity increases with decreasing water depth, potentially due to the extended continental shelf in the northern region.

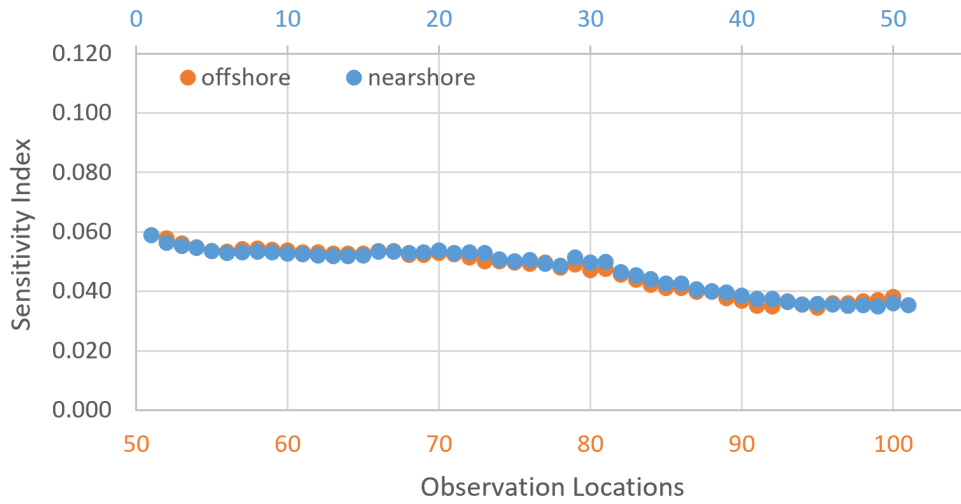


Figure 19 NRMSE-SI for environmental parameter (winds), offshore (18-22 m water depth) and nearshore (6-10m depth); the numbers on x-axis (top and bottom) are the coastal locations in numbers (Table. 6)

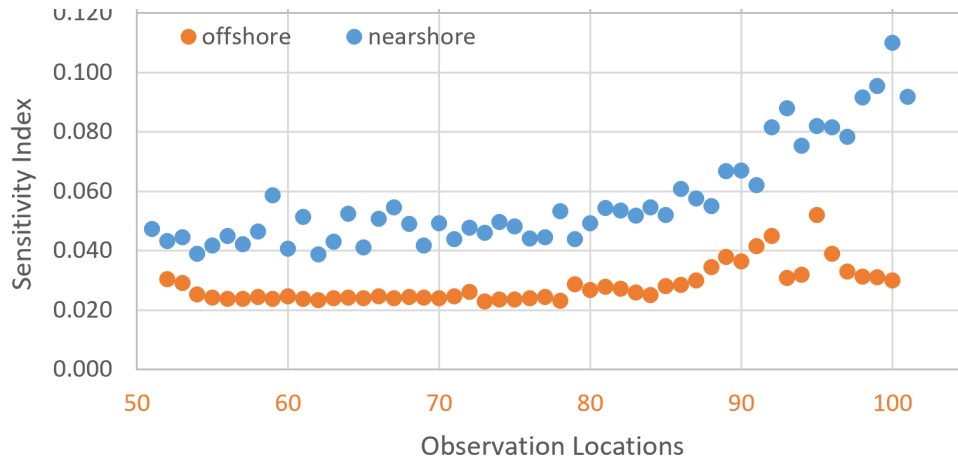


Figure 20 NRMSE- SI for model parameters (bottom friction and breaking parameter), offshore (18-22 m water depth) and nearshore (6-10m depth); the numbers on x-axis (top and bottom) are the coastal locations in numbers (Table. 6)

Based on the combined analysis of wind and model parameter variations using both MAPE- and NRMSE-based sensitivity indices, Location 50 (encircled in Fig 21), near McFaddin National Wildlife Refuge on the upper Texas coast, is identified as the optimal site for buoy installation. This location exhibits the highest modeling uncertainty, likely influenced by shallow-water depth effects.

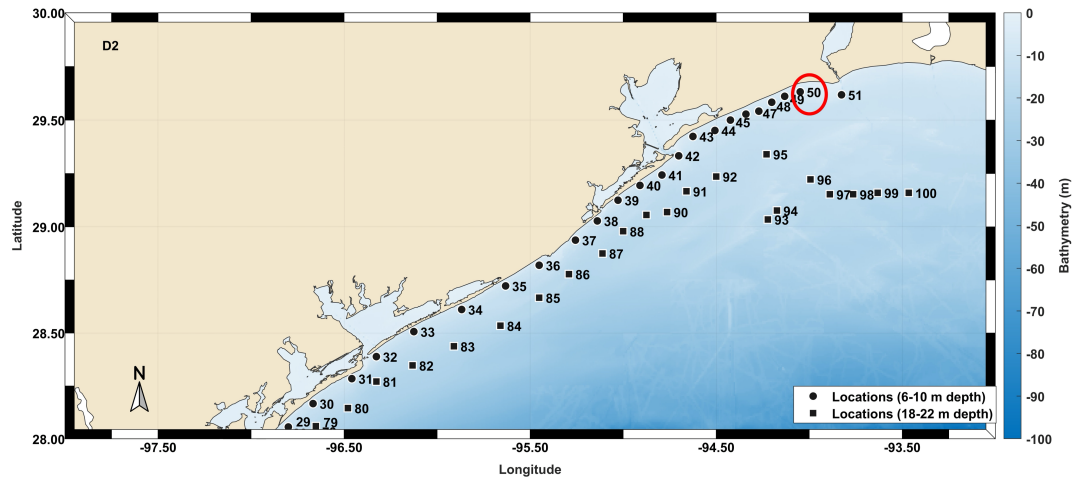


Figure 21 Optimal buoy location

## 8. Summary and final remarks

This study presents a comprehensive long-term wave hindcast for the Texas coast using the SWAN model, analyzing 56 Gulf of America hurricanes from 1940 to 2024. To resolve the typical underestimation of hurricane winds in reanalysis datasets, a parametric hurricane model was utilized for dynamic adjustments. Extensive testing of physical parameterizations and forcing datasets established a highly optimized, dual-approach methodology: ST6 physics coupled with ERA5 data was selected for hurricane-induced wave simulations due to its accuracy in capturing peak significant wave heights (SWH), while Komen physics paired with high-resolution CFSv2 data was utilized for fair-weather conditions.

Output data across 100 localized coastal stations were analyzed using a modified Generalized Extreme Value (GEV) distribution. The Extreme Value Analysis (EVA) identified the Corpus Christi region as highly vulnerable to extreme wave heights. Additionally, a rigorous sensitivity study evaluating uncertainties in wind inputs, bottom friction, and depth-induced breaking coefficients revealed that coastal areas north of Galveston are particularly sensitive to these environmental and model parameter variations.

### Final Remarks

This work stands out for its methodological rigor, specifically the adaptive pairing of wave physics (ST6 vs. Komen) and wind forcing (ERA5 vs. CFSv2) to match specific weather conditions. By refusing a "one-size-fits-all" modeling approach, the hindcast achieves a higher degree of accuracy across both extreme events and fair weather.

**Targeted Risk Management:** The definitive identification of Corpus Christi's vulnerability to extreme wave heights provides an actionable metric for prioritizing local coastal defense and infrastructure planning.

Model Uncertainty Awareness: The sensitivity mapping north of Galveston serves as a critical caveat for future engineers and forecasters, highlighting a regional zone where slight variations in wind or physical parameters can drastically alter wave predictions.

Overall, this study delivers high-fidelity, highly localized wave climate data that is essential for robust coastal engineering, hazard mitigation, and long-term resilience planning along the Texas Gulf Coast.



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# Appendix

## Appendix 1. Summary of error statistics for all model configurations forced by ERA5, CFSR, and their blended versions.

Table I. Statistics of Hs (driven by ERA5) validation dataset at 42019 and 42020 for Harvey and 42003, 42040 and 42084 for Ida.

| Buoy ID | Schemes     | ERA5 (E)     |       |      |      | ERA5-Blended (EB) |       |      |      |
|---------|-------------|--------------|-------|------|------|-------------------|-------|------|------|
|         |             | Corr. coeff. | Bias  | RMSE | IoA  | Corr. coeff.      | Bias  | RMSE | IoA  |
| 42019   | Default (W) | 0.98         | -0.32 | 0.43 | 0.96 | 0.97              | -0.24 | 0.40 | 0.97 |
|         | Komen (K)   | 0.98         | -0.16 | 0.32 | 0.98 | 0.97              | -0.09 | 0.31 | 0.98 |
|         | ST6-2 (S2)  | 0.97         | -0.19 | 0.42 | 0.96 | 0.96              | -0.12 | 0.39 | 0.97 |
|         | ST6-7 (S7)  | 0.98         | 0.19  | 0.32 | 0.98 | 0.97              | 0.27  | 0.43 | 0.97 |
| 42020   | Default (W) | 0.94         | -0.41 | 0.62 | 0.91 | 0.96              | -0.40 | 0.58 | 0.92 |
|         | Komen (K)   | 0.95         | -0.24 | 0.51 | 0.94 | 0.96              | -0.23 | 0.46 | 0.95 |
|         | ST6-2 (S2)  | 0.94         | -0.26 | 0.58 | 0.91 | 0.96              | -0.26 | 0.53 | 0.93 |
|         | ST6-7 (S7)  | 0.94         | 0.10  | 0.40 | 0.96 | 0.96              | 0.10  | 0.35 | 0.97 |
| Ida     |             |              |       |      |      |                   |       |      |      |
| 42003   | Default (W) | 0.91         | -0.41 | 0.60 | 0.92 | 0.91              | -0.40 | 0.60 | 0.92 |
|         | Komen (K)   | 0.90         | -0.22 | 0.51 | 0.94 | 0.90              | -0.21 | 0.51 | 0.94 |
|         | ST6-2 (S2)  | 0.89         | -0.26 | 0.56 | 0.92 | 0.89              | -0.25 | 0.55 | 0.93 |
|         | ST6-7 (S7)  | 0.89         | 0.09  | 0.56 | 0.94 | 0.90              | 0.11  | 0.58 | 0.94 |
| 42040   | Default (W) | 0.97         | -0.34 | 0.54 | 0.97 | 0.97              | -0.33 | 0.53 | 0.97 |
|         | Komen (K)   | 0.96         | -0.15 | 0.46 | 0.98 | 0.96              | -0.14 | 0.46 | 0.98 |
|         | ST6-2 (S2)  | 0.95         | -0.29 | 0.62 | 0.96 | 0.96              | -0.28 | 0.60 | 0.96 |
|         | ST6-7 (S7)  | 0.96         | 0.16  | 0.55 | 0.97 | 0.96              | 0.18  | 0.56 | 0.97 |
| 42084   | Default (W) | 0.91         | -0.37 | 0.64 | 0.93 | 0.94              | -0.32 | 0.53 | 0.96 |
|         | Komen (K)   | 0.91         | -0.19 | 0.56 | 0.94 | 0.93              | -0.14 | 0.48 | 0.96 |
|         | ST6-2 (S2)  | 0.91         | -0.27 | 0.63 | 0.92 | 0.95              | -0.24 | 0.49 | 0.96 |
|         | ST6-7 (S7)  | 0.91         | 0.04  | 0.55 | 0.95 | 0.95              | 0.10  | 0.49 | 0.97 |

Table II. Statistics of Hs (driven by CFSv2) validation dataset at 42019 and 42020 for Harvey and 42003, 42040 and 42084 for Ida.

| Buoy ID | Physics options | CFS (C)      |       |      |      | CFS-Blended (CB) |       |      |      |
|---------|-----------------|--------------|-------|------|------|------------------|-------|------|------|
|         |                 | Corr. coeff. | Bias  | RMSE | IoA  | Corr. coeff.     | Bias  | RMSE | IoA  |
| 42019   | Default (W)     | 0.96         | -0.12 | 0.45 | 0.97 | 0.96             | -0.07 | 0.47 | 0.97 |
|         | Komen (K)       | 0.97         | 0.05  | 0.43 | 0.97 | 0.97             | 0.09  | 0.46 | 0.97 |
|         | ST6-2 (S2)      | 0.97         | -0.02 | 0.31 | 0.98 | 0.97             | 0.01  | 0.32 | 0.98 |
|         | ST6-7 (S7)      | 0.97         | 0.39  | 0.69 | 0.94 | 0.97             | 0.44  | 0.76 | 0.93 |
| 42020   | Default (W)     | 0.93         | -0.26 | 0.56 | 0.95 | 0.93             | -0.26 | 0.55 | 0.95 |
|         | Komen (K)       | 0.94         | -0.09 | 0.48 | 0.96 | 0.94             | -0.08 | 0.47 | 0.96 |
|         | ST6-2 (S2)      | 0.94         | -0.14 | 0.45 | 0.96 | 0.94             | -0.13 | 0.44 | 0.97 |
|         | ST6-7 (S7)      | 0.94         | 0.25  | 0.69 | 0.94 | 0.94             | 0.26  | 0.70 | 0.94 |
| Ida     |                 |              |       |      |      |                  |       |      |      |
| 42003   | Default (W)     | 0.91         | -0.08 | 0.85 | 0.90 | 0.91             | -0.12 | 0.73 | 0.92 |
|         | Komen (K)       | 0.90         | 0.13  | 0.85 | 0.90 | 0.90             | 0.09  | 0.74 | 0.92 |
|         | ST6-2 (S2)      | 0.90         | 0.04  | 0.65 | 0.93 | 0.90             | 0.01  | 0.60 | 0.94 |
|         | ST6-7 (S7)      | 0.90         | 0.48  | 1.19 | 0.84 | 0.90             | 0.44  | 1.06 | 0.86 |
| 42040   | Default (W)     | 0.96         | 0.02  | 0.83 | 0.95 | 0.96             | 0.01  | 0.81 | 0.96 |
|         | Komen (K)       | 0.96         | 0.23  | 0.86 | 0.95 | 0.96             | 0.22  | 0.84 | 0.95 |
|         | ST6-2 (S2)      | 0.97         | 0.01  | 0.51 | 0.98 | 0.97             | 0.00  | 0.50 | 0.98 |
|         | ST6-7 (S7)      | 0.96         | 0.57  | 1.22 | 0.92 | 0.96             | 0.56  | 1.20 | 0.92 |
| 42084   | Default (W)     | 0.95         | -0.01 | 0.68 | 0.95 | 0.95             | 0.00  | 0.71 | 0.95 |
|         | Komen (K)       | 0.94         | 0.17  | 0.70 | 0.94 | 0.94             | 0.18  | 0.73 | 0.94 |
|         | ST6-2 (S2)      | 0.94         | 0.01  | 0.51 | 0.97 | 0.95             | 0.02  | 0.51 | 0.97 |
|         | ST6-7 (S7)      | 0.94         | 0.41  | 0.94 | 0.91 | 0.95             | 0.43  | 0.99 | 0.91 |

Table III. Comparison of modeled peak Hs vs. observed peak Hs at selected buoys.

| Obs. Peak H <sub>s</sub> | Harvey |       |       |       | Ida   |       |       |        |       |       |
|--------------------------|--------|-------|-------|-------|-------|-------|-------|--------|-------|-------|
|                          | 42019  |       | 42020 |       | 42003 |       | 42040 |        | 42084 |       |
|                          | 7.0 m  |       | 7.3 m |       | 6.6 m |       | 8.2 m |        | 8.3 m |       |
| Wind forcing             | EB     | CB    | EB    | CB    | EB    | CB    | EB    | CB     | EB    | CB    |
| Default (W)              | 5.0 m  | 7.5 m | 4.8 m | 6.6 m | 5.9 m | 8.8 m | 6.3 m | 11.3 m | 6.7 m | 8.9 m |
| Komen (K)                | 5.2 m  | 7.6 m | 4.9 m | 7.0 m | 6.0 m | 8.8 m | 6.4 m | 11.0 m | 6.2 m | 8.5 m |
| ST6-2 (S2)               | 4.3 m  | 6.2 m | 4.5 m | 6.3 m | 4.9 m | 7.0 m | 5.2 m | 8.9 m  | 5.8 m | 7.3 m |
| ST6-7 (S7)               | 5.8 m  | 8.5 m | 6.0 m | 8.8 m | 6.8 m | 9.9 m | 7.1 m | 12.0 m | 7.6 m | 9.7 m |

EB- Blended ERA5 and CB-Blended CFSv2

## Appendix 2. Details of the nearshore and offshore locations

| Location | Respective domain name<br>index | Longitude | Latitude | Depth (m) |
|----------|---------------------------------|-----------|----------|-----------|
| 1        | D3-1                            | -97.13    | 26.02    | 7.80      |
| 2        | D3-2                            | -97.15    | 26.18    | 8.99      |
| 3        | D3-3                            | -97.19    | 26.35    | 9.43      |
| 4        | D3-4                            | -97.26    | 26.57    | 10.48     |
| 5        | D3-5                            | -97.27    | 26.61    | 9.39      |
| 6        | D3-6                            | -97.31    | 26.70    | 8.11      |
| 7        | D3-7                            | -97.31    | 26.73    | 8.99      |
| 8        | D3-8                            | -97.33    | 26.77    | 7.58      |
| 9        | D3-9                            | -97.34    | 26.79    | 5.94      |
| 10       | D3-10                           | -97.34    | 26.81    | 9.49      |
| 11       | D3-11                           | -97.34    | 26.82    | 6.86      |
| 12       | D3-12                           | -97.34    | 26.86    | 10.24     |
| 13       | D3-13                           | -97.35    | 26.88    | 8.72      |
| 14       | D3-14                           | -97.36    | 26.90    | 6.79      |
| 15       | D3-15                           | -97.36    | 26.95    | 9.57      |
| 16       | D3-16                           | -97.36    | 27       | 7.17      |
| 17       | D3-17                           | -97.36    | 27.08    | 6.87      |
| 18       | D3-18                           | -97.36    | 27.14    | 7.81      |
| 19       | D3-19                           | -97.34    | 27.22    | 10.51     |
| 20       | D3-20                           | -97.33    | 27.28    | 7.86      |
| 21       | D3-21                           | -97.30    | 27.36    | 9.58      |
| 22       | D3-22                           | -97.28    | 27.42    | 8.30      |
| 23       | D3-23                           | -97.23    | 27.52    | 9.18      |
| 24       | D3-24                           | -97.19    | 27.60    | 8.22      |
| 25       | D3-25                           | -97.13    | 27.69    | 8.81      |
| 26       | D3-26                           | -97.08    | 27.75    | 10.07     |
| 27       | D3-27                           | -97.02    | 27.84    | 10.82     |
| 28       | D3-28                           | -96.95    | 27.94    | 8.89      |
| 29       | D2-1                            | -96.81    | 28.02    | 12.34     |
| 30       | D2-2                            | -96.66    | 28.16    | 10.89     |
| 31       | D2-3                            | -96.45    | 28.28    | 7.84      |
| 32       | D2-4                            | -96.32    | 28.38    | 9.45      |
| 33       | D2-5                            | -96.12    | 28.50    | 10.43     |
| 34       | D2-6                            | -95.86    | 28.61    | 9.56      |
| 35       | D2-7                            | -95.63    | 28.72    | 10.24     |
| 36       | D2-8                            | -95.45    | 28.81    | 8.29      |
| 37       | D2-9                            | -95.25    | 28.93    | 8.35      |
| 38       | D2-10                           | -95.13    | 29.02    | 9.47      |
| 39       | D2-11                           | -95.02    | 29.12    | 8.26      |
| 40       | D2-12                           | -94.90    | 29.19    | 8.73      |

|    |       |        |       |       |
|----|-------|--------|-------|-------|
| 41 | D2-13 | -94.79 | 29.24 | 9.90  |
| 42 | D2-14 | -94.70 | 29.33 | 8.19  |
| 43 | D2-15 | -94.62 | 29.42 | 7.50  |
| 44 | D2-16 | -94.50 | 29.45 | 9.62  |
| 45 | D2-17 | -94.42 | 29.5  | 8.50  |
| 46 | D2-18 | -94.34 | 29.52 | 8.59  |
| 47 | D2-19 | -94.27 | 29.54 | 9.60  |
| 48 | D2-20 | -94.20 | 29.58 | 7.77  |
| 49 | D2-21 | -94.13 | 29.61 | 7.70  |
| 50 | D2-22 | -94.04 | 29.63 | 6.44  |
| 51 | D2-23 | -93.82 | 29.61 | 7.41  |
| 52 | D3-29 | -97.09 | 26.04 | 19.44 |
| 53 | D3-30 | -97.08 | 26.25 | 19.19 |
| 54 | D3-31 | -97.09 | 26.43 | 20.53 |
| 55 | D3-32 | -97.18 | 26.63 | 20.59 |
| 56 | D3-33 | -97.19 | 26.68 | 20.51 |
| 57 | D3-34 | -97.22 | 26.75 | 20.05 |
| 58 | D3-35 | -97.25 | 26.78 | 20.15 |
| 59 | D3-36 | -97.25 | 26.81 | 20.15 |
| 60 | D3-37 | -97.27 | 26.83 | 19.22 |
| 61 | D3-38 | -97.26 | 26.86 | 20.22 |
| 62 | D3-39 | -97.25 | 26.86 | 21.17 |
| 63 | D3-40 | -97.27 | 26.90 | 20.12 |
| 64 | D3-41 | -97.27 | 26.93 | 19.73 |
| 65 | D3-42 | -97.27 | 26.95 | 20.93 |
| 66 | D3-43 | -97.28 | 26.99 | 19.31 |
| 67 | D3-44 | -97.27 | 27.03 | 20.87 |
| 68 | D3-45 | -97.27 | 27.12 | 20.25 |
| 69 | D3-46 | -97.26 | 27.18 | 20.58 |
| 70 | D3-47 | -97.25 | 27.23 | 20.78 |
| 71 | D3-48 | -97.23 | 27.30 | 20.16 |
| 72 | D3-49 | -97.22 | 27.37 | 18.45 |
| 73 | D3-50 | -97.15 | 27.43 | 21.24 |
| 74 | D3-51 | -97.12 | 27.52 | 20.05 |
| 75 | D3-52 | -97.07 | 27.60 | 19.85 |
| 76 | D3-53 | -97.02 | 27.68 | 19.68 |
| 77 | D3-54 | -96.98 | 27.74 | 19.34 |
| 78 | D3-55 | -96.87 | 27.83 | 20.58 |
| 79 | D2-24 | -96.65 | 28.03 | 19.14 |
| 80 | D2-25 | -96.47 | 28.14 | 20.33 |
| 81 | D2-26 | -96.32 | 28.27 | 20.69 |
| 82 | D2-27 | -96.13 | 28.34 | 20.45 |
| 83 | D2-28 | -95.90 | 28.43 | 20.05 |



|     |       |        |       |       |
|-----|-------|--------|-------|-------|
| 84  | D2-29 | -95.65 | 28.53 | 20.13 |
| 85  | D2-30 | -95.45 | 28.66 | 19.03 |
| 86  | D2-31 | -95.29 | 28.77 | 19.45 |
| 87  | D2-32 | -95.11 | 28.87 | 19.66 |
| 88  | D2-33 | -95    | 28.97 | 18.12 |
| 89  | D2-34 | -94.87 | 29.05 | 17.33 |
| 90  | D2-35 | -94.76 | 29.06 | 18.66 |
| 91  | D2-36 | -94.65 | 29.16 | 16.65 |
| 92  | D2-37 | -94.5  | 29.23 | 15.52 |
| 93  | D2-38 | -94.22 | 29.03 | 19.19 |
| 94  | D2-39 | -94.17 | 29.07 | 18.96 |
| 95  | D2-40 | -94.22 | 29.34 | 14.18 |
| 96  | D2-41 | -93.99 | 29.22 | 15.26 |
| 97  | D2-42 | -93.88 | 29.15 | 18.02 |
| 98  | D2-43 | -93.76 | 29.15 | 19.01 |
| 99  | D2-44 | -93.63 | 29.15 | 18.15 |
| 100 | D2-45 | -93.46 | 29.15 | 19.32 |

### Appendix 3. EVA results

#### Nearshore EVA

| Location | Annual<br>Return<br>Period in<br>Years | Equivalent<br>Storm<br>Return<br>Period | Return Level<br>(meters) | CI_Low<br>(meters) | CI_High<br>(meters) |
|----------|----------------------------------------|-----------------------------------------|--------------------------|--------------------|---------------------|
| 1        | 20                                     | 12.8442                                 | 3.5641                   | 3.4455             | 3.6827              |
| 1        | 50                                     | 32.6107                                 | 3.6843                   | 3.5839             | 3.7847              |
| 1        | 100                                    | 65.5524                                 | 3.7333                   | 3.6154             | 3.8512              |
| 2        | 20                                     | 12.8442                                 | 4.0677                   | 3.7823             | 4.3532              |
| 2        | 50                                     | 32.6107                                 | 4.3686                   | 3.9327             | 4.8045              |
| 2        | 100                                    | 65.5524                                 | 4.5295                   | 3.9454             | 5.1135              |
| 3        | 20                                     | 12.8442                                 | 4.0449                   | 3.8981             | 4.1918              |
| 3        | 50                                     | 32.6107                                 | 4.1926                   | 4.044              | 4.3411              |
| 3        | 100                                    | 65.5524                                 | 4.254                    | 4.0565             | 4.4514              |
| 4        | 20                                     | 12.8442                                 | 4.3587                   | 3.7921             | 4.9253              |
| 4        | 50                                     | 32.6107                                 | 4.9498                   | 3.9128             | 5.9867              |
| 4        | 100                                    | 65.5524                                 | 5.3342                   | 3.8412             | 6.8273              |
| 5        | 20                                     | 12.8442                                 | 4.0359                   | 3.8231             | 4.2486              |
| 5        | 50                                     | 32.6107                                 | 4.2582                   | 3.9361             | 4.5804              |
| 5        | 100                                    | 65.5524                                 | 4.3647                   | 3.9258             | 4.8035              |
| 6        | 20                                     | 12.8442                                 | 3.6638                   | 3.5009             | 3.8266              |
| 6        | 50                                     | 32.6107                                 | 3.8359                   | 3.6257             | 4.0461              |
| 6        | 100                                    | 65.5524                                 | 3.9155                   | 3.6398             | 4.1911              |
| 7        | 20                                     | 12.8442                                 | 3.8947                   | 3.5683             | 4.2211              |
| 7        | 50                                     | 32.6107                                 | 4.233                    | 3.6907             | 4.7754              |
| 7        | 100                                    | 65.5524                                 | 4.424                    | 3.6777             | 5.1702              |
| 8        | 20                                     | 12.8442                                 | 3.4881                   | 3.3059             | 3.6703              |
| 8        | 50                                     | 32.6107                                 | 3.6806                   | 3.4215             | 3.9396              |
| 8        | 100                                    | 65.5524                                 | 3.7757                   | 3.433              | 4.1184              |
| 9        | 20                                     | 12.8442                                 | 2.95                     | 2.834              | 3.0659              |
| 9        | 50                                     | 32.6107                                 | 3.0722                   | 2.9209             | 3.2235              |
| 9        | 100                                    | 65.5524                                 | 3.1282                   | 2.9279             | 3.3285              |
| 10       | 20                                     | 12.8442                                 | 4.021                    | 3.5851             | 4.4568              |
| 10       | 50                                     | 32.6107                                 | 4.474                    | 3.7071             | 5.241               |
| 10       | 100                                    | 65.5524                                 | 4.7531                   | 3.6708             | 5.8353              |
| 11       | 20                                     | 12.8442                                 | 3.2348                   | 3.068              | 3.4015              |
| 11       | 50                                     | 32.6107                                 | 3.4088                   | 3.1563             | 3.6614              |
| 11       | 100                                    | 65.5524                                 | 3.4949                   | 3.1545             | 3.8354              |
| 12       | 20                                     | 12.8442                                 | 4.3352                   | 3.7245             | 4.9459              |
| 12       | 50                                     | 32.6107                                 | 4.9843                   | 3.8555             | 6.113               |
| 12       | 100                                    | 65.5524                                 | 5.423                    | 3.7819             | 7.0642              |
| 13       | 20                                     | 12.8442                                 | 3.8365                   | 3.5863             | 4.0868              |
| 13       | 50                                     | 32.6107                                 | 4.0909                   | 3.6677             | 4.5142              |
| 13       | 100                                    | 65.5524                                 | 4.222                    | 3.6374             | 4.8066              |
| 14       | 20                                     | 12.8442                                 | 3.2769                   | 3.1413             | 3.4125              |
| 14       | 50                                     | 32.6107                                 | 3.4189                   | 3.2239             | 3.6138              |
| 14       | 100                                    | 65.5524                                 | 3.4836                   | 3.2166             | 3.7507              |
| 15       | 20                                     | 12.8442                                 | 4.1037                   | 3.5669             | 4.6404              |

|    |     |         |        |        |         |
|----|-----|---------|--------|--------|---------|
| 15 | 50  | 32.6107 | 4.6682 | 3.6839 | 5.6526  |
| 15 | 100 | 65.5524 | 5.0413 | 3.6194 | 6.4633  |
| 16 | 20  | 12.8442 | 3.3779 | 3.2504 | 3.5054  |
| 16 | 50  | 32.6107 | 3.5109 | 3.3393 | 3.6825  |
| 16 | 100 | 65.5524 | 3.5696 | 3.3335 | 3.8056  |
| 17 | 20  | 12.8442 | 3.2637 | 3.1402 | 3.3872  |
| 17 | 50  | 32.6107 | 3.3923 | 3.2167 | 3.568   |
| 17 | 100 | 65.5524 | 3.4492 | 3.2038 | 3.6946  |
| 18 | 20  | 12.8442 | 3.5157 | 3.3753 | 3.656   |
| 18 | 50  | 32.6107 | 3.6621 | 3.4615 | 3.8626  |
| 18 | 100 | 65.5524 | 3.7272 | 3.4479 | 4.0064  |
| 19 | 20  | 12.8442 | 4.3331 | 3.6876 | 4.9786  |
| 19 | 50  | 32.6107 | 4.9782 | 3.7059 | 6.2505  |
| 19 | 100 | 65.5524 | 5.4136 | 3.5284 | 7.2987  |
| 20 | 20  | 12.8442 | 3.5028 | 3.3873 | 3.6183  |
| 20 | 50  | 32.6107 | 3.6171 | 3.513  | 3.7213  |
| 20 | 100 | 65.5524 | 3.6638 | 3.5303 | 3.7974  |
| 21 | 20  | 12.8442 | 4.0526 | 3.5743 | 4.5309  |
| 21 | 50  | 32.6107 | 4.4833 | 3.4928 | 5.4737  |
| 21 | 100 | 65.5524 | 4.742  | 3.2941 | 6.19    |
| 22 | 20  | 12.8442 | 3.675  | 3.5507 | 3.7993  |
| 22 | 50  | 32.6107 | 3.7964 | 3.6899 | 3.9029  |
| 22 | 100 | 65.5524 | 3.8456 | 3.7103 | 3.9808  |
| 23 | 20  | 12.8442 | 3.8496 | 3.7073 | 3.992   |
| 23 | 50  | 32.6107 | 3.9894 | 3.8557 | 4.1231  |
| 23 | 100 | 65.5524 | 4.0469 | 3.8694 | 4.2243  |
| 24 | 20  | 12.8442 | 3.5955 | 3.4776 | 3.7135  |
| 24 | 50  | 32.6107 | 3.7047 | 3.6209 | 3.7884  |
| 24 | 100 | 65.5524 | 3.7473 | 3.6463 | 3.8482  |
| 25 | 20  | 12.8442 | 3.7142 | 3.5764 | 3.8519  |
| 25 | 50  | 32.6107 | 3.8508 | 3.7181 | 3.9835  |
| 25 | 100 | 65.5524 | 3.9074 | 3.732  | 4.0829  |
| 26 | 20  | 12.8442 | 4.1904 | 3.5082 | 4.8727  |
| 26 | 50  | 32.6107 | 4.8276 | 3.3957 | 6.2595  |
| 26 | 100 | 65.5524 | 5.2623 | 3.1011 | 7.4236  |
| 27 | 20  | 12.8442 | 4.3545 | 3.5096 | 5.1994  |
| 27 | 50  | 32.6107 | 5.2198 | 3.4503 | 6.9892  |
| 27 | 100 | 65.5524 | 5.8682 | 3.1307 | 8.6056  |
| 28 | 20  | 12.8442 | 3.6223 | 3.2128 | 4.0318  |
| 28 | 50  | 32.6107 | 3.927  | 2.9156 | 4.9384  |
| 28 | 100 | 65.5524 | 4.0957 | 2.6009 | 5.5906  |
| 29 | 20  | 12.8442 | 4.8621 | 3.5461 | 6.1781  |
| 29 | 50  | 32.6107 | 6.5951 | 3.7188 | 9.4714  |
| 29 | 100 | 65.5524 | 8.2179 | 3.4191 | 13.0167 |
| 30 | 20  | 12.8442 | 4.2909 | 3.4176 | 5.1642  |
| 30 | 50  | 32.6107 | 5.2756 | 3.4892 | 7.062   |
| 30 | 100 | 65.5524 | 6.0576 | 3.2721 | 8.843   |
| 31 | 20  | 12.8442 | 3.3491 | 3.2754 | 3.4228  |
| 31 | 50  | 32.6107 | 3.4048 | 3.3693 | 3.4403  |
| 31 | 100 | 65.5524 | 3.4231 | 3.4036 | 3.4427  |
| 32 | 20  | 12.8442 | 3.7069 | 3.6136 | 3.8002  |

|    |     |         |        |        |        |
|----|-----|---------|--------|--------|--------|
| 32 | 50  | 32.6107 | 3.7793 | 3.7341 | 3.8245 |
| 32 | 100 | 65.5524 | 3.8035 | 3.7778 | 3.8293 |
| 33 | 20  | 12.8442 | 3.9966 | 3.8283 | 4.1648 |
| 33 | 50  | 32.6107 | 4.1656 | 3.9267 | 4.4046 |
| 33 | 100 | 65.5524 | 4.2376 | 3.883  | 4.5923 |
| 34 | 20  | 12.8442 | 3.7847 | 3.678  | 3.8914 |
| 34 | 50  | 32.6107 | 3.8842 | 3.8221 | 3.9464 |
| 34 | 100 | 65.5524 | 3.921  | 3.8732 | 3.9688 |
| 35 | 20  | 12.8442 | 4.0141 | 3.8883 | 4.1398 |
| 35 | 50  | 32.6107 | 4.1339 | 4.0547 | 4.2131 |
| 35 | 100 | 65.5524 | 4.1796 | 4.1079 | 4.2514 |
| 36 | 20  | 12.8442 | 3.3349 | 3.2672 | 3.4026 |
| 36 | 50  | 32.6107 | 3.3899 | 3.3569 | 3.423  |
| 36 | 100 | 65.5524 | 3.4081 | 3.3894 | 3.4268 |
| 37 | 20  | 12.8442 | 3.5432 | 3.5432 | 3.5432 |
| 37 | 50  | 32.6107 | 3.5933 | 3.5933 | 3.5933 |
| 37 | 100 | 65.5524 | 3.609  | 3.609  | 3.609  |
| 38 | 20  | 12.8442 | 3.9574 | 3.8573 | 4.0576 |
| 38 | 50  | 32.6107 | 4.0472 | 3.9939 | 4.1005 |
| 38 | 100 | 65.5524 | 4.0786 | 4.0433 | 4.114  |
| 39 | 20  | 12.8442 | 3.4311 | 3.4311 | 3.4311 |
| 39 | 50  | 32.6107 | 3.4751 | 3.4751 | 3.4751 |
| 39 | 100 | 65.5524 | 3.4889 | 3.4889 | 3.4889 |
| 40 | 20  | 12.8442 | 3.5344 | 3.5344 | 3.5344 |
| 40 | 50  | 32.6107 | 3.5885 | 3.5885 | 3.5885 |
| 40 | 100 | 65.5524 | 3.6053 | 3.6053 | 3.6053 |
| 41 | 20  | 12.8442 | 3.8356 | 3.7305 | 3.9407 |
| 41 | 50  | 32.6107 | 3.922  | 3.8702 | 3.9737 |
| 41 | 100 | 65.5524 | 3.9518 | 3.9177 | 3.9859 |
| 42 | 20  | 12.8442 | 3.0591 | 2.9223 | 3.1959 |
| 42 | 50  | 32.6107 | 3.2078 | 3.0717 | 3.3439 |
| 42 | 100 | 65.5524 | 3.2775 | 3.123  | 3.4319 |
| 43 | 20  | 12.8442 | 2.946  | 2.879  | 3.0129 |
| 43 | 50  | 32.6107 | 3.0043 | 2.9701 | 3.0386 |
| 43 | 100 | 65.5524 | 3.0243 | 3.003  | 3.0456 |
| 44 | 20  | 12.8442 | 3.558  | 3.4399 | 3.6762 |
| 44 | 50  | 32.6107 | 3.6699 | 3.5908 | 3.749  |
| 44 | 100 | 65.5524 | 3.7131 | 3.6292 | 3.797  |
| 45 | 20  | 12.8442 | 3.2558 | 3.1703 | 3.3412 |
| 45 | 50  | 32.6107 | 3.3309 | 3.2861 | 3.3758 |
| 45 | 100 | 65.5524 | 3.3573 | 3.3265 | 3.3882 |
| 46 | 20  | 12.8442 | 3.2775 | 3.1874 | 3.3676 |
| 46 | 50  | 32.6107 | 3.3587 | 3.3094 | 3.4081 |
| 46 | 100 | 65.5524 | 3.388  | 3.3507 | 3.4252 |
| 47 | 20  | 12.8442 | 3.5278 | 3.401  | 3.6547 |
| 47 | 50  | 32.6107 | 3.6502 | 3.5479 | 3.7525 |
| 47 | 100 | 65.5524 | 3.6989 | 3.5707 | 3.8272 |
| 48 | 20  | 12.8442 | 3.0127 | 2.9415 | 3.0839 |
| 48 | 50  | 32.6107 | 3.0703 | 3.0355 | 3.1051 |
| 48 | 100 | 65.5524 | 3.0896 | 3.0695 | 3.1097 |
| 49 | 20  | 12.8442 | 2.8991 | 2.8234 | 2.9749 |

|    |     |         |        |        |        |
|----|-----|---------|--------|--------|--------|
| 49 | 50  | 32.6107 | 2.968  | 2.9264 | 3.0096 |
| 49 | 100 | 65.5524 | 2.9927 | 2.9623 | 3.0232 |
| 50 | 20  | 12.8442 | 2.4534 | 2.4534 | 2.4534 |
| 50 | 50  | 32.6107 | 2.4906 | 2.4906 | 2.4906 |
| 50 | 100 | 65.5524 | 2.5019 | 2.5019 | 2.5019 |
| 51 | 20  | 12.8442 | 2.9434 | 2.8766 | 3.0101 |
| 51 | 50  | 32.6107 | 2.9979 | 2.9654 | 3.0303 |
| 51 | 100 | 65.5524 | 3.0164 | 2.9964 | 3.0364 |

#### Offshore EVA

| Location | Annual<br>Return<br>Period in<br>Years | Equivalent<br>Storm<br>Return<br>Period | Return Level<br>(meters) | CI_Low<br>(meters) | CI_High<br>(meters) |
|----------|----------------------------------------|-----------------------------------------|--------------------------|--------------------|---------------------|
| 52       | 20                                     | 12.8442                                 | 6.0611                   | 4.4773             | 7.6449              |
| 52       | 50                                     | 32.6107                                 | 8.186                    | 4.9089             | 11.4631             |
| 52       | 100                                    | 65.5524                                 | 10.1192                  | 4.8188             | 15.4197             |
| 53       | 20                                     | 12.8442                                 | 6.2523                   | 4.7088             | 7.7957              |
| 53       | 50                                     | 32.6107                                 | 8.249                    | 5.0878             | 11.4102             |
| 53       | 100                                    | 65.5524                                 | 10.0077                  | 4.9529             | 15.0624             |
| 54       | 20                                     | 12.8442                                 | 6.5183                   | 4.7363             | 8.3004              |
| 54       | 50                                     | 32.6107                                 | 8.9477                   | 5.1798             | 12.7156             |
| 54       | 100                                    | 65.5524                                 | 11.2183                  | 5.0276             | 17.4091             |
| 55       | 20                                     | 12.8442                                 | 6.259                    | 4.4737             | 8.0444              |
| 55       | 50                                     | 32.6107                                 | 8.7542                   | 4.9032             | 12.6053             |
| 55       | 100                                    | 65.5524                                 | 11.1582                  | 4.7297             | 17.5867             |
| 56       | 20                                     | 12.8442                                 | 6.2515                   | 4.4387             | 8.0643              |
| 56       | 50                                     | 32.6107                                 | 8.8096                   | 4.8721             | 12.7471             |
| 56       | 100                                    | 65.5524                                 | 11.3015                  | 4.6915             | 17.9115             |
| 57       | 20                                     | 12.8442                                 | 6.2159                   | 4.3689             | 8.0628              |
| 57       | 50                                     | 32.6107                                 | 8.8471                   | 4.7942             | 12.8999             |
| 57       | 100                                    | 65.5524                                 | 11.4438                  | 4.5877             | 18.2999             |
| 58       | 20                                     | 12.8442                                 | 6.1342                   | 4.3193             | 7.9492              |
| 58       | 50                                     | 32.6107                                 | 8.7129                   | 4.7328             | 12.6929             |
| 58       | 100                                    | 65.5524                                 | 11.2524                  | 4.5246             | 17.9803             |
| 59       | 20                                     | 12.8442                                 | 6.0825                   | 4.2542             | 7.9109              |
| 59       | 50                                     | 32.6107                                 | 8.7033                   | 4.6599             | 12.7468             |
| 59       | 100                                    | 65.5524                                 | 11.3136                  | 4.434              | 18.1931             |
| 60       | 20                                     | 12.8442                                 | 6.1196                   | 4.3598             | 7.8794              |
| 60       | 50                                     | 32.6107                                 | 8.5802                   | 4.7716             | 12.3889             |
| 60       | 100                                    | 65.5524                                 | 10.9575                  | 4.5861             | 17.3289             |
| 61       | 20                                     | 12.8442                                 | 6.2918                   | 4.3852             | 8.1983              |
| 61       | 50                                     | 32.6107                                 | 9.0099                   | 4.7898             | 13.2301             |
| 61       | 100                                    | 65.5524                                 | 11.7101                  | 4.5308             | 18.8894             |
| 62       | 20                                     | 12.8442                                 | 6.378                    | 4.4182             | 8.3378              |

|    |     |         |         |        |         |
|----|-----|---------|---------|--------|---------|
| 62 | 50  | 32.6107 | 9.1928  | 4.8313 | 13.5544 |
| 62 | 100 | 65.5524 | 12.0121 | 4.5595 | 19.4648 |
| 63 | 20  | 12.8442 | 6.3291  | 4.4025 | 8.2557  |
| 63 | 50  | 32.6107 | 9.077   | 4.8053 | 13.3487 |
| 63 | 100 | 65.5524 | 11.8106 | 4.5354 | 19.0857 |
| 64 | 20  | 12.8442 | 6.2912  | 4.3606 | 8.2219  |
| 64 | 50  | 32.6107 | 9.0467  | 4.7435 | 13.35   |
| 64 | 100 | 65.5524 | 11.7989 | 4.4451 | 19.1526 |
| 65 | 20  | 12.8442 | 6.3116  | 4.3259 | 8.2974  |
| 65 | 50  | 32.6107 | 9.1826  | 4.7046 | 13.6605 |
| 65 | 100 | 65.5524 | 12.0957 | 4.3736 | 19.8178 |
| 66 | 20  | 12.8442 | 6.2956  | 4.3623 | 8.2288  |
| 66 | 50  | 32.6107 | 9.054   | 4.7459 | 13.3621 |
| 66 | 100 | 65.5524 | 11.8084 | 4.4475 | 19.1693 |
| 67 | 20  | 12.8442 | 6.3917  | 4.3678 | 8.4156  |
| 67 | 50  | 32.6107 | 9.3247  | 4.7549 | 13.8946 |
| 67 | 100 | 65.5524 | 12.3081 | 4.4183 | 20.1979 |
| 68 | 20  | 12.8442 | 6.3496  | 4.3239 | 8.3753  |
| 68 | 50  | 32.6107 | 9.2707  | 4.6691 | 13.8723 |
| 68 | 100 | 65.5524 | 12.2454 | 4.2755 | 20.2153 |
| 69 | 20  | 12.8442 | 6.3754  | 4.367  | 8.3838  |
| 69 | 50  | 32.6107 | 9.2609  | 4.7274 | 13.7944 |
| 69 | 100 | 65.5524 | 12.1801 | 4.3636 | 19.9967 |
| 70 | 20  | 12.8442 | 6.4609  | 4.3886 | 8.5331  |
| 70 | 50  | 32.6107 | 9.4453  | 4.7251 | 14.1655 |
| 70 | 100 | 65.5524 | 12.4881 | 4.3001 | 20.676  |
| 71 | 20  | 12.8442 | 6.3716  | 4.3544 | 8.3889  |
| 71 | 50  | 32.6107 | 9.262   | 4.6887 | 13.8353 |
| 71 | 100 | 65.5524 | 12.1904 | 4.2862 | 20.0945 |
| 72 | 20  | 12.8442 | 6.1515  | 4.2545 | 8.0484  |
| 72 | 50  | 32.6107 | 8.8204  | 4.5538 | 13.0871 |
| 72 | 100 | 65.5524 | 11.4799 | 4.1613 | 18.7986 |
| 73 | 20  | 12.8442 | 6.5921  | 4.4265 | 8.7578  |
| 73 | 50  | 32.6107 | 9.7199  | 4.7198 | 14.72   |
| 73 | 100 | 65.5524 | 12.944  | 4.1922 | 21.6959 |
| 74 | 20  | 12.8442 | 6.5651  | 4.3642 | 8.7661  |
| 74 | 50  | 32.6107 | 9.7616  | 4.622  | 14.9011 |
| 74 | 100 | 65.5524 | 13.0936 | 4.0253 | 22.1618 |
| 75 | 20  | 12.8442 | 6.6971  | 4.3632 | 9.031   |
| 75 | 50  | 32.6107 | 10.1209 | 4.5639 | 15.6779 |
| 75 | 100 | 65.5524 | 13.7591 | 3.8183 | 23.6999 |
| 76 | 20  | 12.8442 | 6.6694  | 4.2693 | 9.0695  |
| 76 | 50  | 32.6107 | 10.2167 | 4.3937 | 16.0397 |
| 76 | 100 | 65.5524 | 14.0515 | 3.4982 | 24.6048 |
| 77 | 20  | 12.8442 | 6.7075  | 4.2493 | 9.1658  |

|    |     |         |         |        |         |
|----|-----|---------|---------|--------|---------|
| 77 | 50  | 32.6107 | 10.3655 | 4.3472 | 16.3838 |
| 77 | 100 | 65.5524 | 14.3601 | 3.3788 | 25.3414 |
| 78 | 20  | 12.8442 | 7.1261  | 4.2201 | 10.0321 |
| 78 | 50  | 32.6107 | 11.5931 | 4.0538 | 19.1325 |
| 78 | 100 | 65.5524 | 16.7587 | 2.4141 | 31.1033 |
| 79 | 20  | 12.8442 | 6.6126  | 4.102  | 9.1232  |
| 79 | 50  | 32.6107 | 10.4384 | 4.1119 | 16.7649 |
| 79 | 100 | 65.5524 | 14.7541 | 2.9552 | 26.5531 |
| 80 | 20  | 12.8442 | 6.9568  | 4.2763 | 9.6373  |
| 80 | 50  | 32.6107 | 11.01   | 4.2179 | 17.8021 |
| 80 | 100 | 65.5524 | 15.5805 | 2.8821 | 28.2789 |
| 81 | 20  | 12.8442 | 7.1422  | 4.3174 | 9.967   |
| 81 | 50  | 32.6107 | 11.4179 | 4.1964 | 18.6394 |
| 81 | 100 | 65.5524 | 16.2714 | 2.6912 | 29.8517 |
| 82 | 20  | 12.8442 | 7.1604  | 4.4568 | 9.864   |
| 82 | 50  | 32.6107 | 10.9593 | 4.2004 | 17.7182 |
| 82 | 100 | 65.5524 | 15.0387 | 2.6497 | 27.4277 |
| 83 | 20  | 12.8442 | 7.0967  | 4.6232 | 9.5702  |
| 83 | 50  | 32.6107 | 10.2805 | 4.3081 | 16.253  |
| 83 | 100 | 65.5524 | 13.4534 | 2.8982 | 24.0086 |
| 84 | 20  | 12.8442 | 7.1015  | 4.8722 | 9.3309  |
| 84 | 50  | 32.6107 | 9.7814  | 4.6143 | 14.9484 |
| 84 | 100 | 65.5524 | 12.2616 | 3.4692 | 21.0539 |
| 85 | 20  | 12.8442 | 6.5038  | 4.8548 | 8.1527  |
| 85 | 50  | 32.6107 | 8.3153  | 4.7178 | 11.9129 |
| 85 | 100 | 65.5524 | 9.8088  | 4.016  | 15.6015 |
| 86 | 20  | 12.8442 | 6.5901  | 4.9717 | 8.2085  |
| 86 | 50  | 32.6107 | 8.3466  | 4.8549 | 11.8383 |
| 86 | 100 | 65.5524 | 9.7661  | 4.1961 | 15.3361 |
| 87 | 20  | 12.8442 | 6.4939  | 5.1366 | 7.8512  |
| 87 | 50  | 32.6107 | 7.932   | 5.1377 | 10.7264 |
| 87 | 100 | 65.5524 | 9.0149  | 4.7057 | 13.3241 |
| 88 | 20  | 12.8442 | 6.1351  | 5.0183 | 7.2518  |
| 88 | 50  | 32.6107 | 7.2682  | 5.0107 | 9.5257  |
| 88 | 100 | 65.5524 | 8.0661  | 4.6611 | 11.4711 |
| 89 | 20  | 12.8442 | 5.8532  | 4.9939 | 6.7124  |
| 89 | 50  | 32.6107 | 6.7285  | 5.091  | 8.3661  |
| 89 | 100 | 65.5524 | 7.3     | 4.9098 | 9.6902  |
| 90 | 20  | 12.8442 | 5.9427  | 5.0834 | 6.8021  |
| 90 | 50  | 32.6107 | 6.8651  | 5.3081 | 8.422   |
| 90 | 100 | 65.5524 | 7.4773  | 5.2325 | 9.7221  |
| 91 | 20  | 12.8442 | 5.516   | 4.7781 | 6.2539  |
| 91 | 50  | 32.6107 | 6.3007  | 4.9822 | 7.6193  |
| 91 | 100 | 65.5524 | 6.8072  | 4.923  | 8.6914  |
| 92 | 20  | 12.8442 | 5.1494  | 4.6989 | 5.6     |

|     |     |         |        |        |        |
|-----|-----|---------|--------|--------|--------|
| 92  | 50  | 32.6107 | 5.6305 | 4.9296 | 6.3313 |
| 92  | 100 | 65.5524 | 5.8997 | 4.9536 | 6.8459 |
| 93  | 20  | 12.8442 | 5.9121 | 5.397  | 6.4272 |
| 93  | 50  | 32.6107 | 6.5047 | 5.8051 | 7.2044 |
| 93  | 100 | 65.5524 | 6.8514 | 5.9611 | 7.7416 |
| 94  | 20  | 12.8442 | 5.7916 | 5.2569 | 6.3264 |
| 94  | 50  | 32.6107 | 6.4125 | 5.6745 | 7.1505 |
| 94  | 100 | 65.5524 | 6.7839 | 5.8392 | 7.7286 |
| 95  | 20  | 12.8442 | 4.6627 | 4.3401 | 4.9852 |
| 95  | 50  | 32.6107 | 5.0135 | 4.5761 | 5.4509 |
| 95  | 100 | 65.5524 | 5.1979 | 4.6344 | 5.7613 |
| 96  | 20  | 12.8442 | 5.2023 | 4.8436 | 5.561  |
| 96  | 50  | 32.6107 | 5.5986 | 5.1294 | 6.0678 |
| 96  | 100 | 65.5524 | 5.8101 | 5.2171 | 6.4031 |
| 97  | 20  | 12.8442 | 5.801  | 5.2493 | 6.3527 |
| 97  | 50  | 32.6107 | 6.4342 | 5.6449 | 7.2235 |
| 97  | 100 | 65.5524 | 6.8162 | 5.7889 | 7.8434 |
| 98  | 20  | 12.8442 | 5.972  | 5.3437 | 6.6004 |
| 98  | 50  | 32.6107 | 6.6962 | 5.7626 | 7.6297 |
| 98  | 100 | 65.5524 | 7.1479 | 5.9124 | 8.3834 |
| 99  | 20  | 12.8442 | 5.9385 | 5.3395 | 6.5375 |
| 99  | 50  | 32.6107 | 6.6273 | 5.7486 | 7.506  |
| 99  | 100 | 65.5524 | 7.0521 | 5.8965 | 8.2076 |
| 100 | 20  | 12.8442 | 6.2534 | 5.5293 | 6.9774 |
| 100 | 50  | 32.6107 | 7.101  | 5.9979 | 8.204  |
| 100 | 100 | 65.5524 | 7.6507 | 6.1733 | 9.1281 |