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Development of an Extratropical Storm Wind, Wave, and Water Level Climatology for the Offshore Mid-Atlantic

Michael F. Forte and Jeffrey L. Hanson

August 2015



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Development of an Extratropical Storm Wind, Wave, and Water Level Climatology for the Offshore Mid-Atlantic

Michael F. Forte

*Field Research Facility
U.S. Army Engineer Research and Development Center
1261 Duck Rd
Kitty Hawk, NC 27949*

Jeffrey L. Hanson

*Field Research Facility
U.S. Army Engineer Research and Development Center
1261 Duck Rd
Kitty Hawk, NC 27949*

Final report

Approved for public release; distribution is unlimited.

Prepared for Bureau of Safety and Environmental Enforcement
1849 C Street, NW
Washington, D.C. 20240

Abstract

An investigation of the extreme offshore wind, wave, and water level climate in the mid-Atlantic region has been conducted for the U.S. Bureau of Safety and Environmental Enforcement (BSEE). The overall objective of the project is to assist with the development of meteorological and oceanographic (metocean) standards for offshore wind farm design and to establish a 100-year (yr) extratropical wind speed, wave height, and water level climatology for the specific regions of interest.

Measured data from National Data Buoy Center (NDBC) and Scripps Coastal Data Information Program (CDIP) offshore stations were used to evaluate two North Atlantic Ocean hindcasts; the 20 yr U.S. Army Corps of Engineers (USACE) Wave Information Studies (WIS) with kinematically adjusted storm winds and a new 30 yr WAVEWATCH III® hindcast using National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis Reforecast (CFSRR) winds. Four extremal analysis techniques were evaluated on extratropical wind and wave storm extremes that included the empirical simulation technique (EST), the generalized Pareto distribution (GPD), Weibull distribution, and generalized extreme value (GEV) distribution. The WIS hindcast, in conjunction with the EST approach, was selected for use in computation of the 100 yr return period wind speed and wave height extremes for the region.

For identification of a climatological data base for use in computing water level extremes, there is an evaluation of the relevance of extremal water level statistics from a recent coastal storm surge study conducted by USACE for the Federal Emergency Management Agency (FEMA) Region III. The accuracy of the FEMA results is quantified based on water level observations at the USACE Field Research Facility in Duck, NC.

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Preface

This study was conducted for the U.S. Bureau of Safety and Environmental Enforcement (BSEE). The technical monitor was George Hagerman, Center for Energy and the Global Environment, Virginia Tech Advanced Research Institute.

The work was performed by the Coastal Observation and Analysis Branch (CEERD-HFA) of the Flood and Storm Protection Division (CEERD-HF), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Dr. Jeffrey Waters was Chief, CEERD-HFA, and Dr. T. Wamsley was Chief, CEERD-HF. The Deputy Director of ERDC-CHL was Dr. Kevin Barry, and the Director was José E. Sánchez.

Gratitude is expressed to Mark Gravens (U.S. Army Engineer Research Center [ERDC]) for assistance with the EST method application and description; Dr. Jeffrey L. Melby (ERDC) for providing the POT algorithm and helpful insights into extremal analysis; Dr. Robert Jensen and Dr. Tyler Hesser (ERDC) for providing guidance on use of the WIS data; Dr. Arun Chawla (NCEP) for providing the NCEP hindcast data; Dr Heidi Wadman (ERDC) and Dr. Brian Blanton (RENCI) for their contributions to the FEMA RIII project results; Cliff Baron (ERDC) for help in downloading massive amounts of data; and Richie Slocum (ERDC) for help in coding up the EST analysis tools.

LTC John T. Tucker III was Acting Commander, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
fathoms	1.8288	meters
feet	0.3048	meters
inches	0.0254	meters
knots	0.5144444	meters per second
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

1 Introduction

The U.S. Army Corps of Engineers (USACE) has partnered with Virginia Tech Advanced Research Institute, Old Dominion University, and Applied Research Associates, Inc. (ARA) on a study of integrated extreme wind, wave, current, and water level climatology to support standards-based design of offshore wind projects in the North Atlantic Ocean from Cape Hatteras to New York. The study is led by George Hagerman of Virginia Tech Advanced Research Institute and funded by the U.S. Bureau of Safety and Environmental Enforcement (BSEE), whose responsibilities include the development and enforcement of safety and environmental regulations and the permitting of offshore exploration, development, and production.

The objectives of the USACE effort are to (1) propose a methodology for developing extremal wind and wave statistics for extratropical storms in the mid-Atlantic offshore wind farm development areas, (2) apply this methodology to compute extratropical storm 100 yr return period winds and waves, and (3) evaluate the offshore relevance of extremal water levels from recent coastal storm surge study conducted by USACE for the Federal Emergency Management Agency Region III (FEMA RIII).

Hindcasts considered include winds and waves from the USACE Wave Information Studies (WIS) 20 yr Atlantic hindcast, a set of 30 yr reanalysis windfields from the Climate Forecast System Reanalysis (CFSR), a National Oceanographic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) 30 yr wave hindcast forced by the CFSR winds, and the FEMA RIII coastal storm surge study.

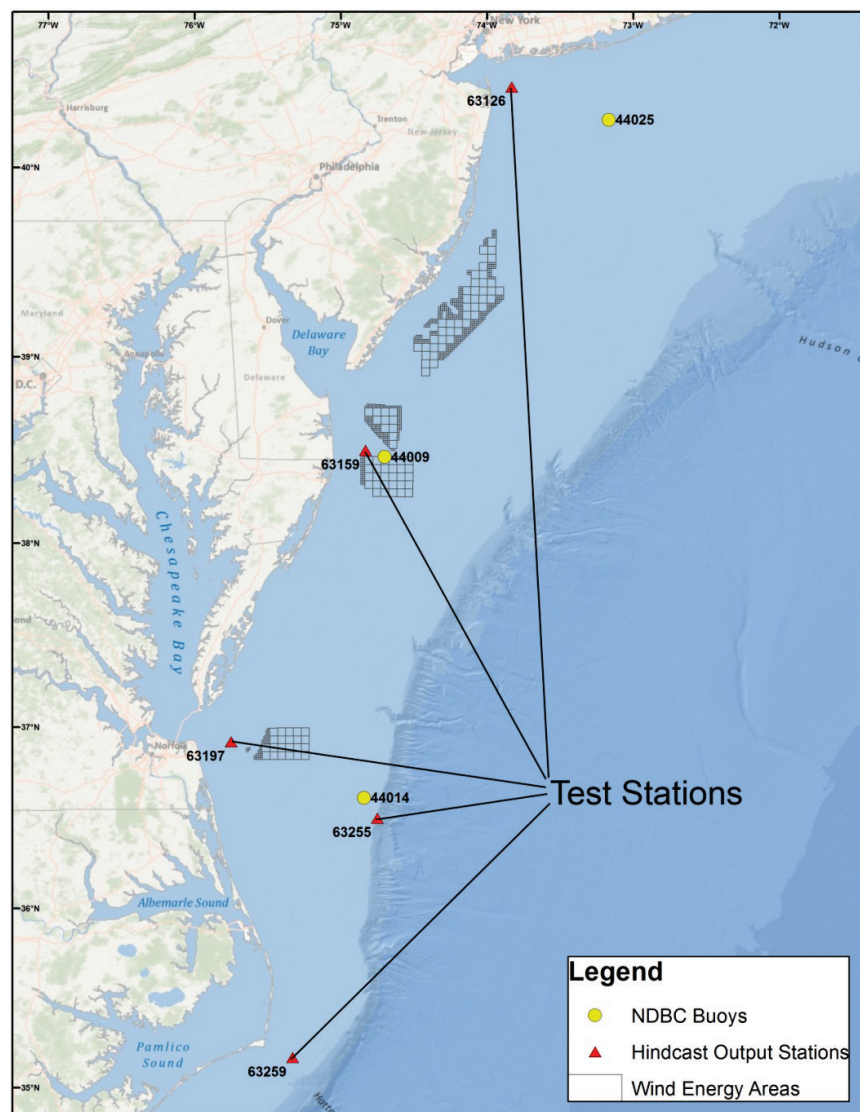
The first objective is focused on developing methodologies and includes the following components:

1. Provide a general statistical evaluation of the WIS, CFSR, and NCEP hindcast wind and wave parameters using selected National Data Buoy Center (NDBC) buoy station data as ground truth.
2. Conduct a detailed evaluation of hindcast wind and wave performance during peak extratropical storm events using the NDBC buoy data as ground truth.

3. Perform a sensitivity study on available wind and wave extremal analysis techniques and recommend an approach for application in this study.
4. Evaluate the relevance of the FEMA RIII extremal water levels for use in the offshore domain of this study.

The wind energy areas of interest, hindcast output points, and NDBC ground truth stations used for the analysis appear in Figure 1.

Figure 1. Project study area showing wind energy areas of interest (light-grey blocks), hindcast output stations (red triangles) also referred to as Test Stations, and NDBC buoy observation stations (yellow circles).



For the second objective, an extremal analysis methodology evaluation for extratropical storm winds and waves was performed at the five Test Stations from the Mid-Atlantic Region using the NCEP 30 yr hindcast.

Resulting extratropical 100 yr wind and wave extremes are provided to BSEE for synthesis with the tropical results, with the goal of producing combined maps of 100 yr extremal statistics for the region. For objective three, the FEMA RIII water level extremes are also provided.

2 Analysis Approach

The offshore extreme wind, wave, and water level study was conducted with the latest available hindcast data, established ground truth observational data, and state-of-the-art processing and analysis techniques. The following sections describe the data and methods used to perform the required analyses.

2.1 Wind and wave data

The candidate wind and wave hindcasts are described below, along with the observational data used as ground truth.

2.1.1 NCEP hindcast

A new 30 yr wind and wave hindcast was available for use by this study. Winds from the CFSR are derived from a 30 yr reanalysis wind data set with a spatial resolution of $0.5 \times 0.5^\circ$ and a temporal resolution of 1 hour (h) (Saha et al. 2010). Initial assessment of the quality of these wind fields indicates that they are equivalent to present operational wind analysis at NCEP (Spindler et al. 2011). A 30 yr wave hindcast, using the third-generation numerical wave model WAVEWATCH III, is under development by the NCEP, in conjunction with a National Oceanographic Partnership Project (NOPP) focused on wave modeling (Tolman et al. 2012). The hindcast is scheduled to be performed in three phases:

- Phase I. Generate a baseline hindcast using the present default WAVEWATCH III model as run at NCEP and the CFSR winds.
- Phase II. Generate a second hindcast using the first NOPP-based physical upgrade for operational wave models at NCEP.
- Phase III. Use the best possible physics from the NOPP project (including shallow water physics) and unstructured grids approaches at the coast to provide a NOPP based consensus optimal 30 yr hindcast.

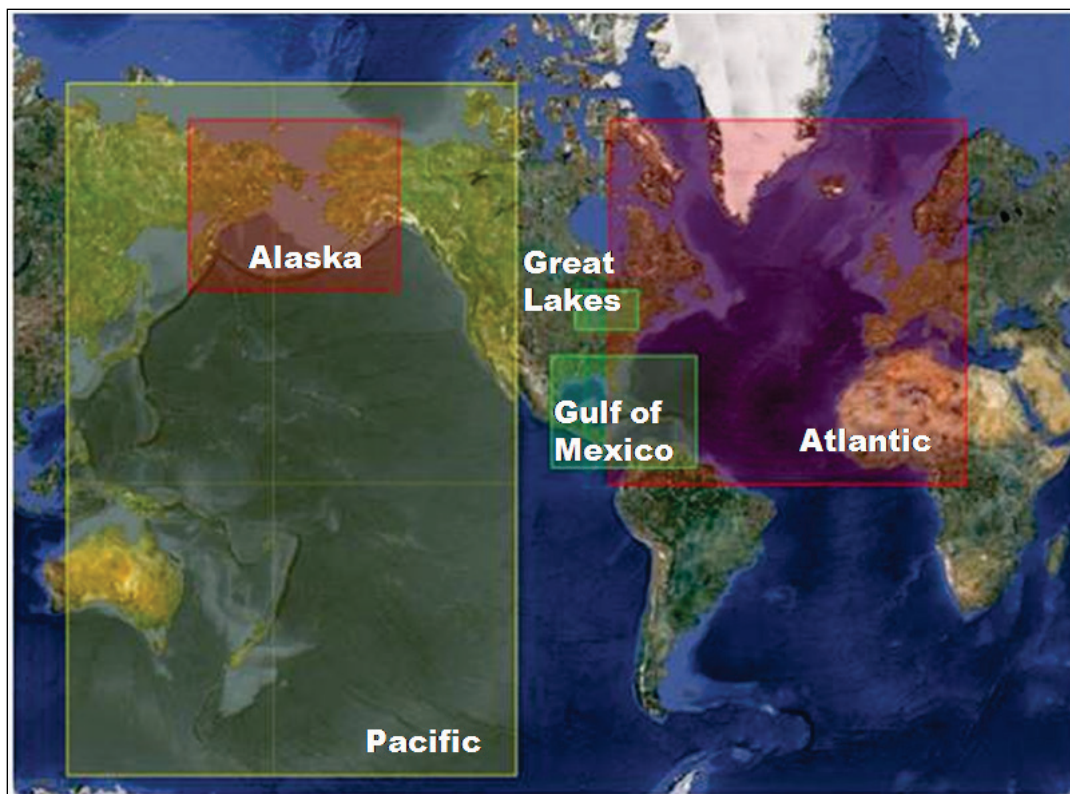
The first phase of this hindcast was completed in October 2011 and is used as part of this study. The hindcast uses the operational NCEP global wave model grids (58-kilometer [km] resolution), including the corresponding higher resolution offshore grids (18 km resolution) and coastal grids

(7.5 km resolution). These grids have been regenerated using the most recent bathymetric data and have been augmented with high-resolution grids for Australia, Iceland, Northern Europe, the Mediterranean, and the Horn of Africa. Wind and spectral wave data have been exported, at 3 hr intervals, at all NDBC buoy locations as well as the USACE WIS hindcast points.

2.1.2 WIS hindcast

The WIS is a USACE-sponsored project that generates consistent, hourly, long-term (20–30 yr) wave climatologies along all U.S. coastlines, including the Great Lakes and U.S. island territories. The WIS program originated in the Great Lakes in the mid 1970s and migrated to the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean. The WIS hindcast domains are depicted in Figure 2. Consistent, high-quality windfields are used to force numerical wave models in each domain. Although the WIS wave modeling technology has kept pace with research advances in model development, the Atlantic Basin domain used in this study was last updated during the years 2003–2004. A new update is underway but was not available for this study.

Figure 2. WIS wind and wave hindcast domains.



Hindcast winds are extracted from high-quality, consistent, neutral stability wind fields at 3 hr intervals on a 0.5-degree (deg) spatial hindcast grid. Wind fields are generated by the marine meteorology group at Oceanweather, Inc. (OWI) using baseline National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) global reanalysis (NRA) 6 hr, 10-meter (m) surface winds on a Gaussian geographic grid (Kalnay et al. 1996). NRA fields are adjusted using QuickSCAT (Q/S) scatterometer winds by linear regressions through quantile-quantile (QQ) plots in 45 deg wind direction sectors. Since extratropical (ET) and tropical cyclone (TC) winds are poorly resolved in the NRA wind fields, the representation of these events is enhanced through application of an interactive objective kinematic analysis (IOKA) by OWI (Cox et al. 1995). The resulting hindcast storms are well resolved in space and time.

The OWI winds were used to drive an Atlantic Basin 20 yr wave hindcast, spanning 1980–1999. The second-generation numerical wave model WISWAVE was employed. WISWAVE is a discrete spectral wave model solving the energy balance equation for the time and spatial variation of a two-dimensional (2D) wave spectrum from wind forcing. The framework of this code is derived from Resio (1981). WISWAVE was modified by Hubertz (1992) to include shallow-water effects. Wind and spectral wave data are output, in 3 hr intervals, at various points around the U.S. Atlantic coastline. Specific output points for the study areas of interest are depicted in Figures 3 and 4. Note that in addition to standard NDBC buoy locations (yellow symbols), hindcast data are also output as a variety of *virtual* buoy locations (red symbols).

Note that USACE recently took delivery of new OWI Atlantic windfields for 2000–2009. This 10 yr wind hindcast will be combined with the previous two decades to produce a new 30 yr Atlantic wave hindcast, likely using an advanced third-generation numerical wave modeling technology for the entire time period. The new wave hindcast product was not available in time for the completion of this study.

Figure 3. NCEP and WIS hindcast output points for offshore New York and New Jersey. Red symbols indicate standard hindcast points. Yellow symbols identify buoy locations.

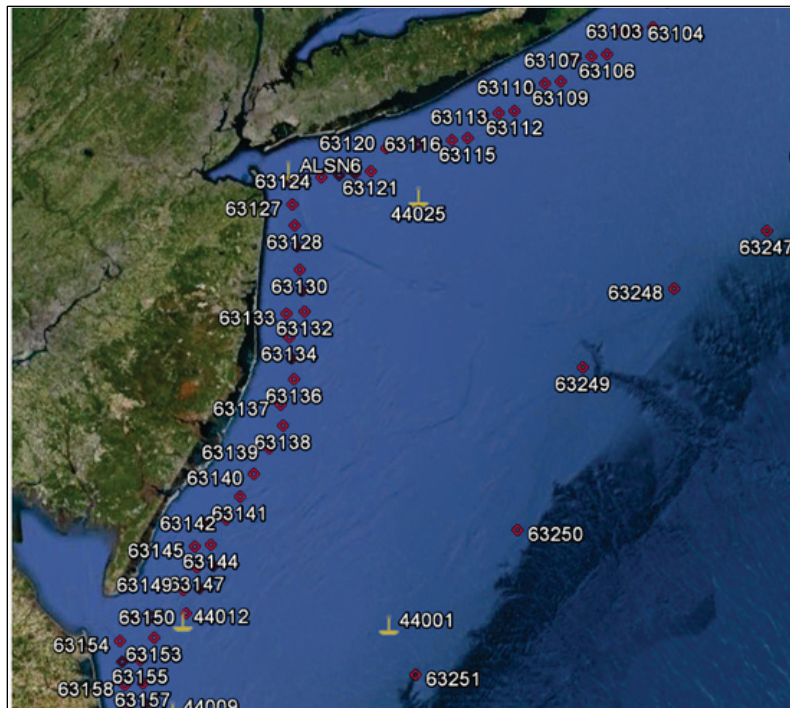
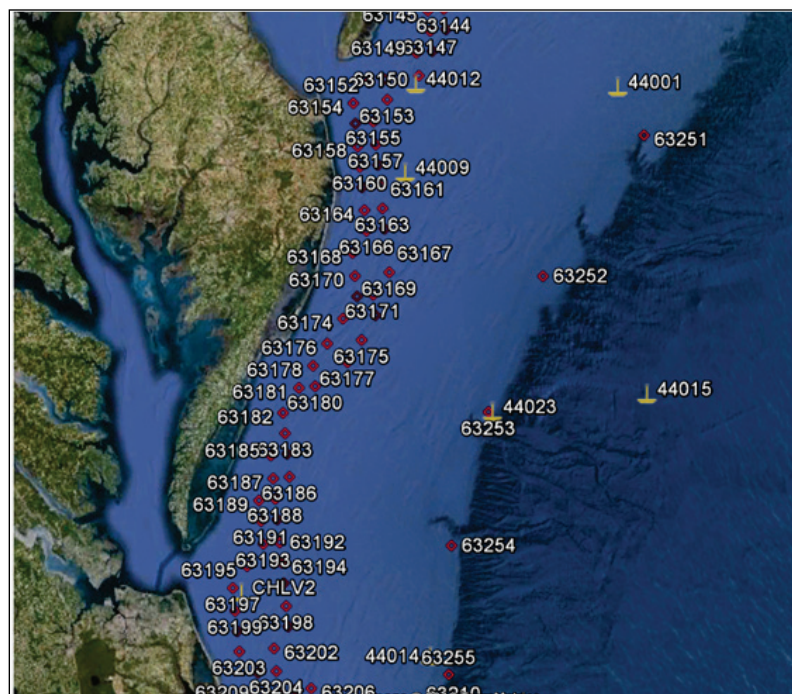


Figure 4. NCEP and WIS HINDCAST output points for offshore Delaware, Maryland, and Virginia. Red symbols indicate standard hindcast points. Yellow symbols identify buoy locations.



2.1.3 NDBC data

Ground truth data are used to quantify the strengths and weaknesses of the proposed hindcast products. During phase 1 of the study, wind and wave ground truth data were obtained from NDBC buoy stations 44009, 44014, and 44025 (Figure 1). These records provide a long-duration, robust set of coincident wind and directional wave observations at each site. For consistency issues, there is only inclusion of data collected with directional wave sensors at the buoy stations. The available time periods are as follows:

- Station 44009: May 1993 – Present
- Station 44014: October 1990 – Present
- Station 44025: April 1991 – Present

Each station has occasional data gaps to coincide with instrument maintenance issues. These gaps can persist from hours to months in duration. This is of minor consequence to the hindcast evaluations, as the hindcast data are time-paired with the existing observation data set. As a result, observational data gaps are mimicked in the hindcast data.

The NDBC scalar-average winds used in this analysis are computed from 10-minute records measured at 5 m height and reported hourly. The winds were adjusted to a 10 m neutral stability reference height following Large and Pond (1981). The NDBC wave spectra are computed from 20-minute time-series records and reported hourly. A detailed description of the NDBC wave measurements is provided by Steele et al. (1992).

2.2 Wind and wave analysis methods

2.2.1 Tropical event removal

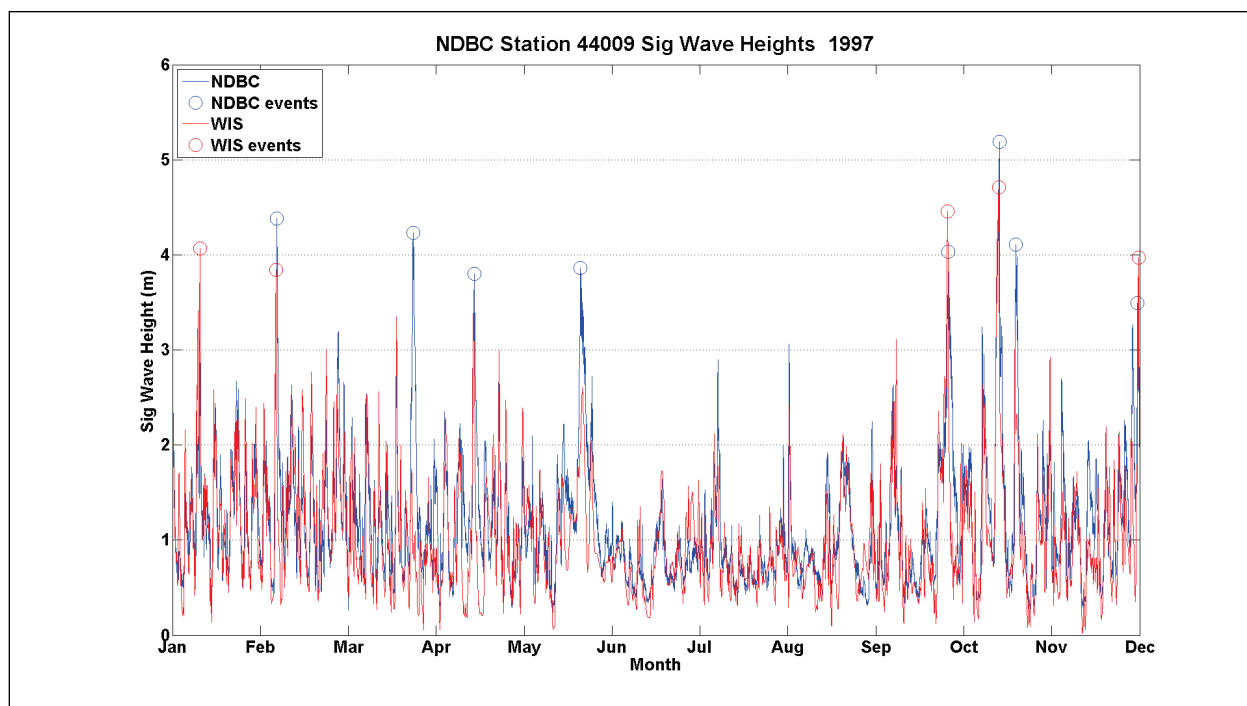
As the wind and wave study is focused on extratropical storms, an algorithm was developed to remove the tropical events from the analysis. Observed and hindcast data segments during tropical storms are identified using the National Hurricane Center's North Atlantic hurricane database (HURDAT). The algorithm employs a search radius from the observation or hindcast geographic position to search the HURDAT database and subsequently removes any coexisting tropical event time period from the data set. For this investigation, a defined radius of 18 deg (approximately 1060 nautical miles) is employed. The large search radius is required after

initial testing showed long-period waves generated from very distant tropical storms not being removed from the record. The tropical storm removal is executed prior to the peaks-over-threshold (POT) analysis described in section 2.2.2 so that the extremal analysis results are not influenced by tropical events.

2.2.2 Peaks-over-threshold (POT) analysis

The wind and wave extremal analysis methods require identification of the event peak conditions. To isolate the peak wind speed and wave height event values, a POT technique was adapted from Thompson et al. (2009). Each peak is associated with a discrete weather event in the observation or hindcast records. The differentiation of discrete events is important so as to not count the contribution from a single weather event more than once in the return period analyses. An example of peak wave events selected during 1997 at NDBC buoy 44009 offshore of Delaware is shown in Figure 5.

Figure 5. Sample baseline wave heights (solid lines) and event peaks (circles) for both NDBC observations (blue) and WIS hindcast (red) at NDBC Station 44009 during 1997.



User inputs to the data-adaptive POT algorithm include a standard deviation multiplier (kh), an interevent time threshold (T), and an optional parameter specifying the desired number of events per year (n). The POT algorithm specifies a wind speed or wave height threshold ($\hat{x}$) as

$$\hat{x} = \bar{x} + \sigma_x * kh$$

Where x specifies the quantity being evaluated at both the hindcast and measurement stations (wind speed U_{10} or wave height H_s) over the time period of interest, $\bar{x}$ is the mean of x , and σ_x is the standard deviation of x over the entire record. When n is specified, the algorithm iterates over kh , using increments of 0.01, until n is satisfied. Furthermore, the algorithm ensures that all events are separated by at least T hours from the nearest event. As recommended by Oceanweather (Swail et al. 2006), an extra-tropical interevent time of $T= 72$ hr was used for all datasets in this study.

2.2.3 Annual maximum series

Annual maximum series (AMS) records were also extracted from the hindcasts for use with the generalized extreme value (GEV) analysis. The most extreme extratropical event was extracted for each year and then rank ordered for use with the GEV.

2.2.4 Hindcast evaluation approach

A comprehensive assessment of hindcast performance at each NDBC buoy site was performed. The model evaluation approach, designed after Hanson et al. (2009), provides a robust statistical analysis of model output using buoy observations as ground truth. The specific processing steps employed in the hindcast evaluations are itemized below:

1. Smooth the NDBC wind and wave data over a 3 hr weighted window. This helps remove sampling noise from the observation set and generates spectra that are most representative of the model results.
2. Remove the TC events from the observational data as described above.
3. Generate sets of 3 hr, time-paired wind and wave observations between the NDBC observations and each hindcast data set. Note that any time gaps in the NDBC data are inserted into the hindcast data sets.
4. Interpolate the NDBC and hindcast directional wave spectra to a common set of frequency and direction bins. This is necessary to ensure that all computed wave parameters are derived from equivalent spectral energy domains. The following bins were used:

- Frequencies: 0.04–0.3 Hz:

0.0400 0.0500 0.0550 0.0600 0.0667 0.0700 0.0800 0.0900
 0.1000 0.1100 0.1200 0.1300 0.1400 0.1500 0.1600 0.1800 0.2000
 0.2500 0.3000
 - Angles: 0–360 at 22.5 deg resolution
5. Compute the following basic descriptors from each interpolated data set (Hanson et al. 2009):
 - wind speed (U_{10} , m/s)
 - wind direction (TWD , degrees clockwise from N)
 - significant wave height (H_s , m)
 - peak period (T_p , s)
 - mean wave period (T_z , s)
 - mean wave direction (D_m , degrees clockwise from N).
 6. For each set of paired (NDBC-Hindcast) parameters, compute the following standard error metrics (Hanson et al. 2009):
 - magnitude parameters (U_{10} , H_s , T_p , T_z): RMS error (RMS), bias, scatter index (SI), regression coefficient (R^2)
 - direction parameters (TWD , D_m): circular correlation ($Cir\ Cor$), circular bias ($Cir\ Bias$).

The above analysis steps were conducted twice on each hindcast data set, using the following as inputs:

- Analysis 1: full set of observations (all available records)
- Analysis 2: peak events.

The peak event analysis was performed on both wind speed and wave height using a threshold of three standard deviations above the mean (section 2.2.2) To allow for spatial variations in wind and wave climate, these thresholds were computed independently on the data from each NDBC buoy station.

2.2.5 Extratropical storm population rank order

The POT output storm populations were ranked ordered from 1- n with 1 being the most extreme event. The return period plotting position was then computed by the following:

$$Rp = \tau + 1 / \vartheta$$

Where Rp is the return period, τ is the number of years, and ϑ is the rank order of event.

2.3 Extremal analysis methods

Four extremal analysis methods were evaluated on the storm series. The GEV, which was used exclusively with the AMS, the generalized Pareto distribution (GPD), Weibull, and the empirical simulation technique (EST) were evaluated for use in computing 100 yr wind speeds and wave heights from the WIS and NCEP hindcasts. A description of each of these methods appears below.

2.3.1 Empirical simulation technique (EST)

The EST (Scheffner et al. 1999) is a life-cycle approach to frequency and error associated risk analysis. Universal applicability of the EST has been demonstrated through implementation to projects located along all coasts of the United States to develop frequency-of-occurrence relationships for storm-related impacts such as storm-surge elevation, vertical erosion of dredged material mounds, and horizontal recession of coastal beaches and dunes. As a result of this demonstrated capability, the EST has been adopted by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, DC, as a recommended approach to developing coastal risk-based design criteria.

The EST utilizes observed and/or computed parameters associated with site-specific historical events as a basis for developing a methodology for generating multiple life-cycle simulations of storm activity and the effects associated with each simulated event. The technique does not rely on assumed parametric relationships but uses the joint probability relationships inherent in the local site-specific database. Therefore, in this approach, probabilities are site specific, do not depend on fixed parametric

relationships, and do not assume parameter independence. Thus, the EST is *distribution free* and nonparametric.

The EST is based on a *bootstrap* resampling-with-replacement, interpolation, and subsequent smoothing technique in which a random sampling of a finite length database is used to generate a larger database. The only assumption is that future events will be statistically similar in magnitude and frequency to past events. The EST begins with an analysis of historical events that have impacted a specific locale. The selected database of events is then parameterized to define the characteristics of each event and the impacts of that event. Parameters that define the storm are referred to as input vectors such as maximum wind speed and wave height. Response vectors define storm-related impacts such as inundation and shoreline/dune erosion. These input and response vectors are then used as a basis for generating life-cycle simulations of storm-event activity. The EST was selected for use in characterizing extratropical storm impacts for the FEMA RIII coastal storm surge study (Hanson et al. 2013). The present study employed a univariate EST analysis where the input vector are total wave height and wind speed and the response vector are total wave height and wind speed.

2.3.2 Generalized Pareto distribution (GPD)

The GPD is a probability density function containing three parameters: shape, scale, and threshold. The GPD has been used to model data in several fields (Castillo and Hadi 1997) and has been applied to develop 100 yr return value estimates for global ocean wind speed and significant wave height (Caires and Sterl 2005). The GPD is commonly used to model the tails of a distribution and allows a continuous range of possible shapes that includes both the exponential and Pareto distributions as special cases. Either distribution can be used to model a particular dataset of exceedence.

2.3.3 Generalized extreme value (GEV) distributions

The GEV distribution is a family of continuous probability distributions developed within extreme value theory that is often used to model the maxima of long (finite) sequences of random variables. Essentially the GEV is the limit distribution of properly normalized maxima of a sequence of independent and identically distributed random variables. The GEV distribution is often used to model the smallest or largest value among a large set of independent, identically distributed random values

representing measurements or observations. As such, it is a common choice for the evaluation of extreme wind and wave climates (for example, see Young et al. 2012).

Use of the GEV defaults to either a Gumbel, Frechet, or Weibull distribution based on the value of a distribution shape parameter K . The GEV results in this study are based on the Frechet distribution. The Weibull distribution is also a commonly used distribution in reliability engineering because of the many shapes it attains for various values of β (slope). Some studies have suggested that the Weibull distribution can provide a good approximation of the probability density function when applied to wind speed data (Monahan 2006). As a result, the Weibull distribution was also evaluated with the hindcast data.

3 Hindcast Evaluation

As the project has multiple wind and wave hindcasts to select from, a thorough comparison is warranted to identify the strengths and weaknesses of each. Furthermore, the NCEP 30 yr hindcast, forced by CSFR 30 yr reanalysis winds, is a rather new product and not yet evaluated in the literature. Hence, this is an opportunity to take a *first look* at the NCEP results in the mid-Atlantic region. As previously described, the hindcasts are evaluated on two levels: a full hindcast assessment and a peak event assessment. All assessments are performed at NDBC directional wave buoy stations 44025, 44009, and 44014 as depicted on Figure 1.

3.1 Full hindcast assessment

The wave climate was assessed over a 10 yr period (1990–1999) for which there is corresponding direction wave buoy, WIS, and NCEP hindcast data. As described previously, hindcast data are time-paired with the NDBC data so that all observational data gaps are represented in the hindcast data as well. Results from the wind speed and significant wave height comparisons at the three stations appear in Figures 6–8. In each of these figures, WIS evaluations are in the left panels, and NCEP evaluations are in the right panels. Wind comparisons are on top, and wave comparisons are on the bottom. As the CFSR winds are included in the NCEP wave hindcast files, they are simply referred to as NCEP winds. In each plot, “Baseline” refers to the NDBC ground truth data, and “Evaluate” refers to the respective hindcast data. Each plot also includes a perfect fit reference line (black), a linear fit through the data (green), and the 95% confidence limits about the linear fits (red). Furthermore, the overall bias and regression coefficient (r^2) are provided for each set of comparisons.

At stations 44025 and 44014, the WIS winds are better correlated with the observations than the NCEP winds. Furthermore, the WIS winds have a substantially smaller bias than the NCEP winds at these stations. At station 44009 the wind results are less distinct. Although the WIS winds are also better correlated with the observations at this site, the NCEP winds exhibit an overall smaller bias and appear to be better correlated in the extremes. In general, however, it can be argued that the IOKA windfield improvements in WIS result in a superior hindcast product.

Figure 6. Station 44025 full hindcast evaluations. See text for explanation.

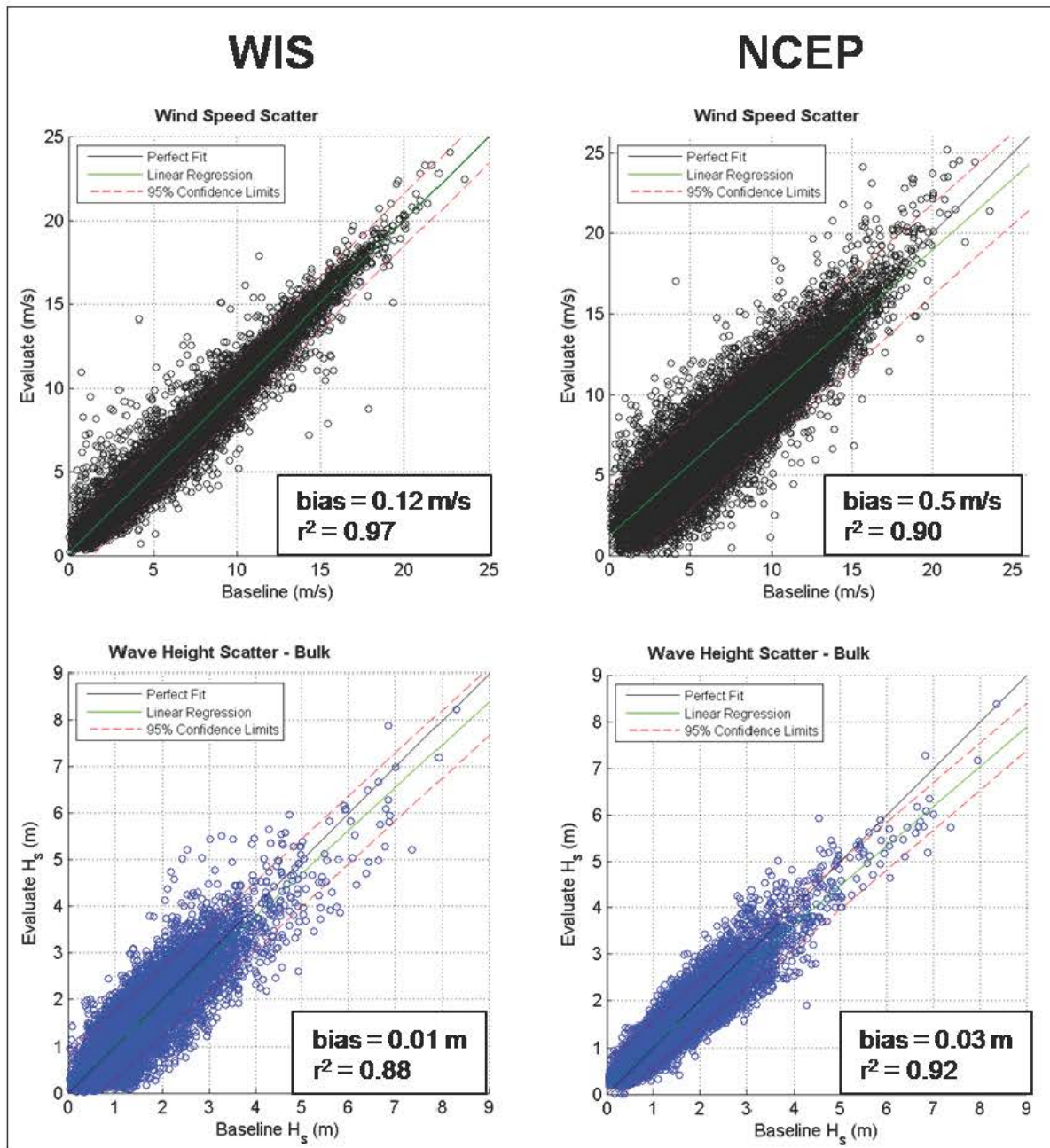


Figure 7. Station 44009 full hindcast evaluations. See text for explanation.

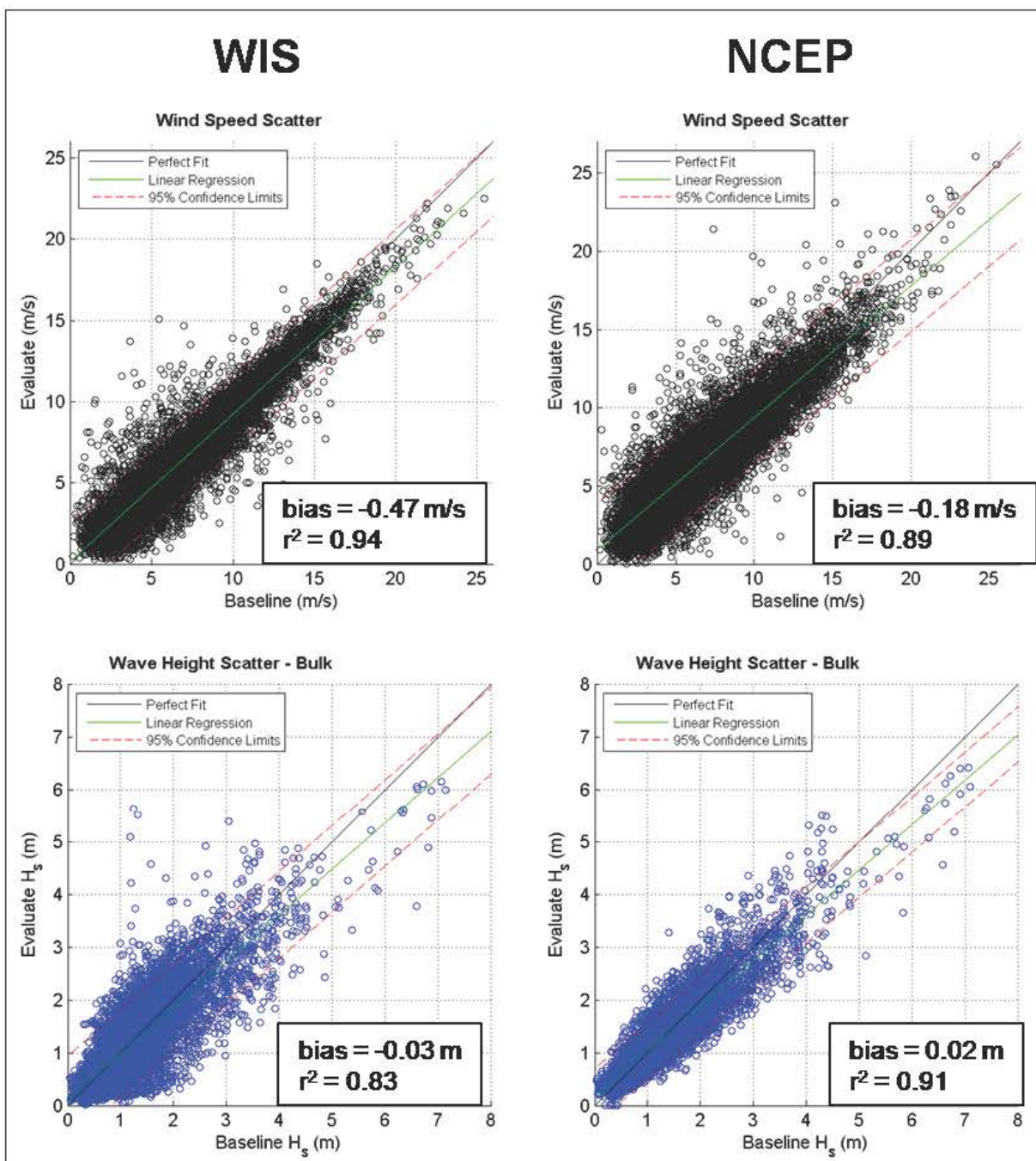
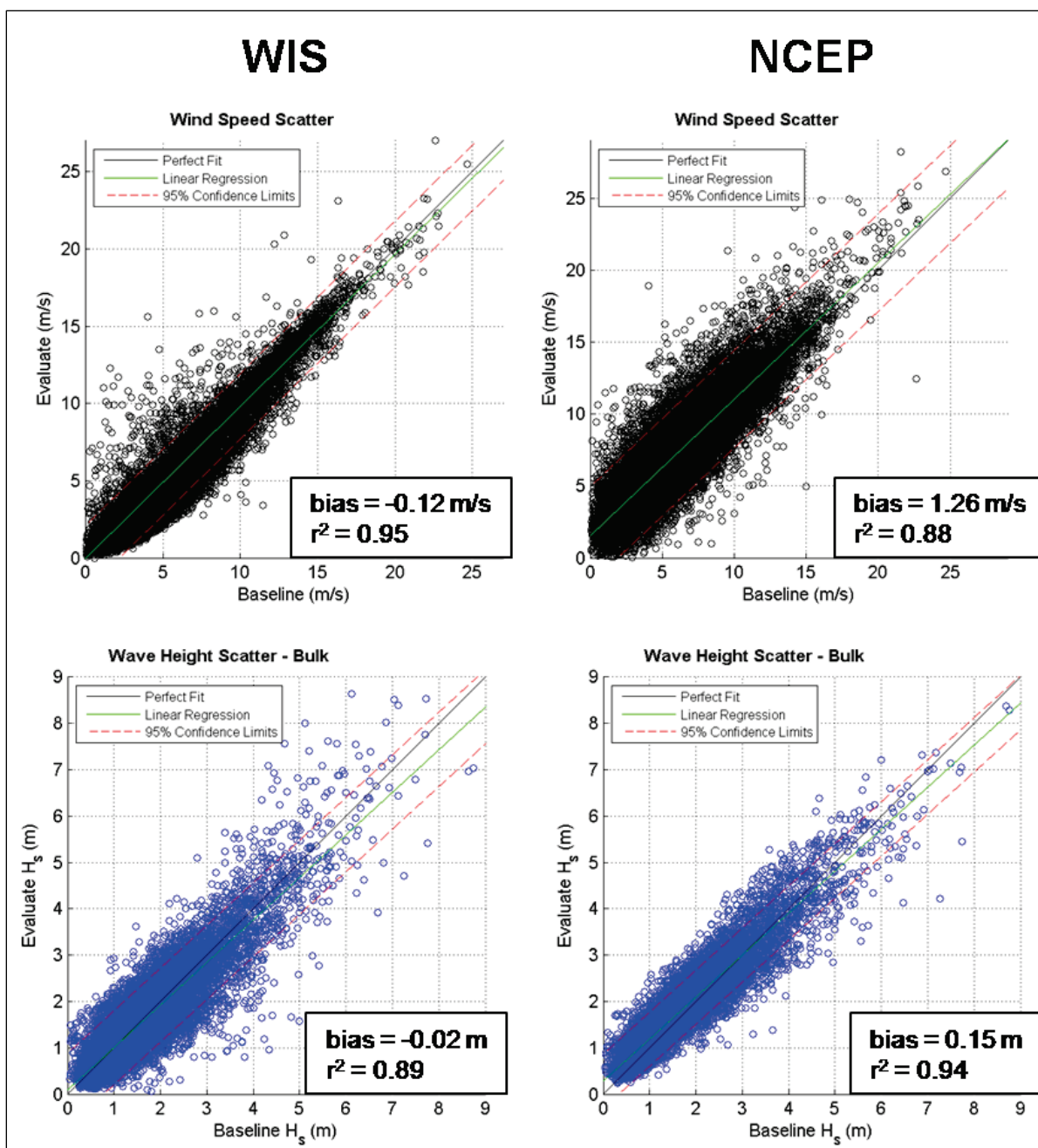


Figure 8. Station 44014 full hindcast evaluations. See text for explanation.



The full-hindcast wave comparisons from Figures 6–8 (lower panels) do not follow the same trend as the winds. The differences between the WIS and NCEP wave heights are less distinct than the wind difference. At each station, the NCEP wave heights are somewhat better correlated with the observations than the WIS results. This difference is most striking at station 44009. The WIS and NCEP overall wave height biases are all quite

small; however, both hindcasts appear to exhibit a negative bias in the extremes at station 44009.

3.2 Peak events

A separate peak event evaluation was performed to determine hindcast strengths and weaknesses in extreme conditions. Sample results from the POT analysis at station 44025 appear in Figure 9. The upper panel compares the observed wind speed time series (solid gray line) to the WIS winds (dashed gray line) for 1990–1999. The solid magenta line shows the POT threshold. Open circles represent the peaks identified in the NDBC record. Each observed peak is matched with the corresponding hindcast peak occurring within ± 6 hr of the observed peak. This generous search window allows for event timing offsets. The lower panel is a similar plot for wave heights. In each record, the time period of the March 1993 *Superstorm* is highlighted. This intense storm, depicted in Figure 10, will be used as an example to highlight differences between observations and hindcasts during a major extreme event.

Figure 9. Wind speed (upper) and wave height (lower) peak selection at station 44025. Horizontal magenta line shows the applied threshold. Open circles depict the selected extremes.

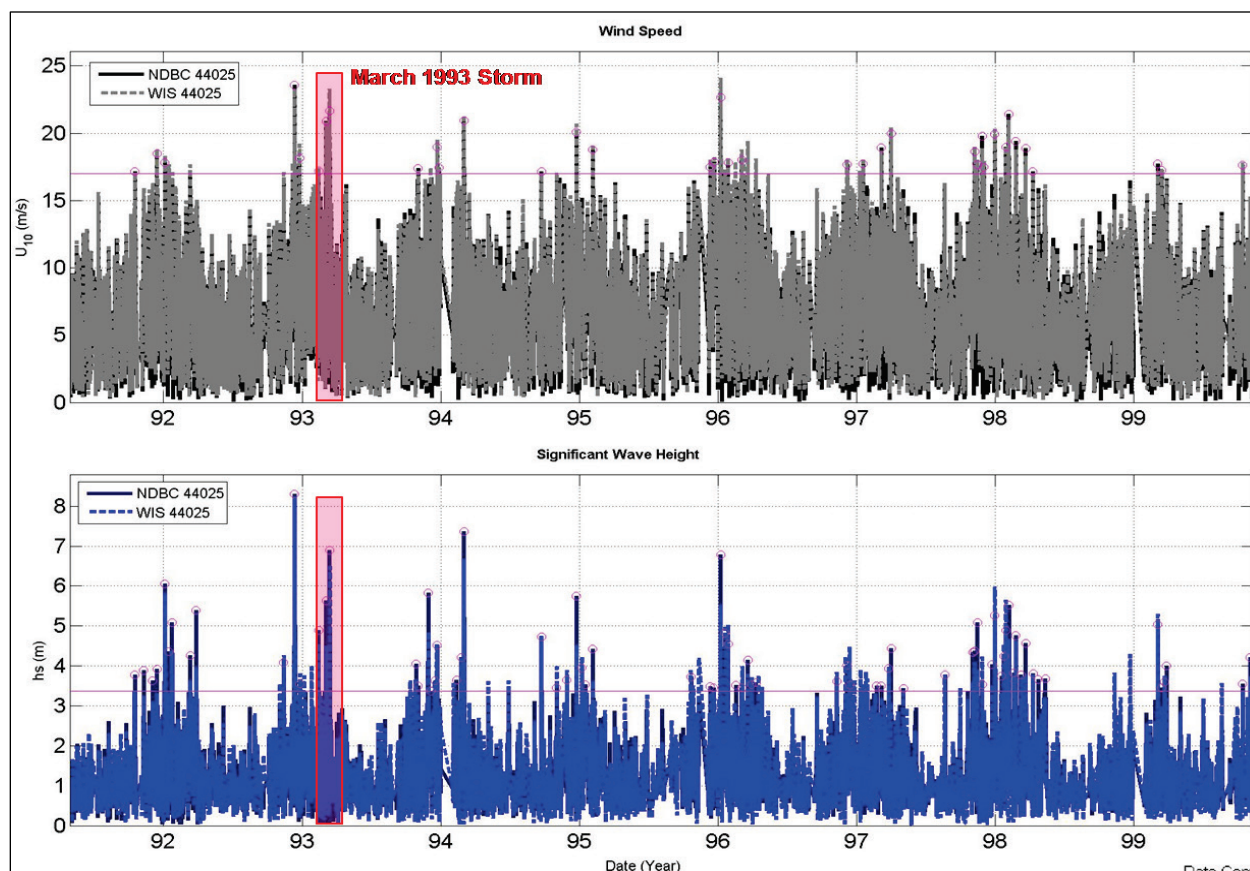
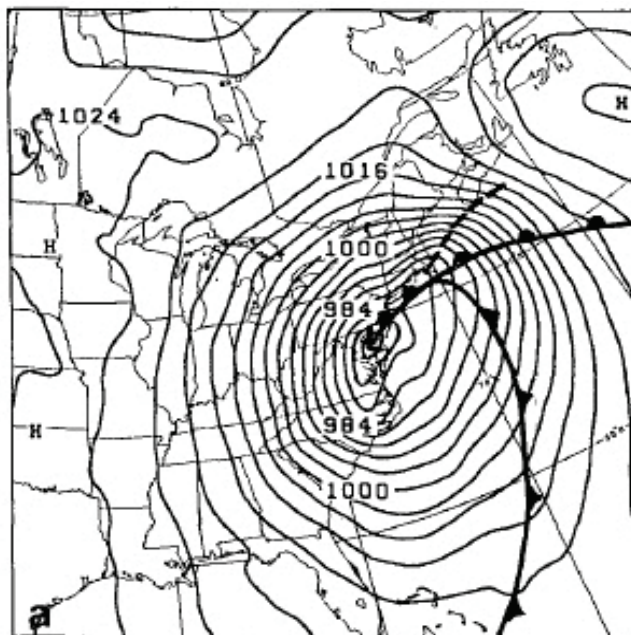


Figure 10. Surface pressure isobars (mbar) for the famous March 1993 *Storm of the Century* that traveled up the U.S. East Coast.



The March 1993 Superstorm, also referred to as *The Storm of the Century* or the *Great Blizzard of 1993*, was a large extratropical storm that occurred on 12–13 March 1993, on the East Coast of North America. It was unique for its intensity, massive size, and wide-reaching effect (Figure 10). Time-series comparisons of observed and hindcast wind speeds and wave heights during the March 1993 storm appear in Figures 11 and 12. The POT threshold (magenta line) is also included on these figures. The WIS winds (Figure 11, upper panel) show good agreement with observed winds over the event period. Furthermore, the WIS wave heights (Figure 11, lower panel) capture the event extremes reasonably well, with hindcast wave heights biased approximately 0.4 m high during the extreme portion of the storm on 13–14 March. At other times, the WIS low wave height conditions generally appear to be biased high.

NCEP winds are not as well correlated with observed winds and generally depict a positive bias throughout (Figure 12, upper panel). A similar trend was observed in the full-hindcast scatter plots of Figure 8. There is a strong positive bias in the NCEP (CFSR) winds at the event peak. As was observed with WIS, NCEP wave heights during this event (Figure 12, lower panel) reasonably capture most of the event peaks during this period; however, NCEP wave heights are approximately 1 m low during the 13–14 March extreme conditions. As with WIS, the NCEP waves also exhibit a positive bias during the low wave height periods.

Figure 11. Comparison of WIS winds and waves to observations at Station 44014 during the March 1993 storm.

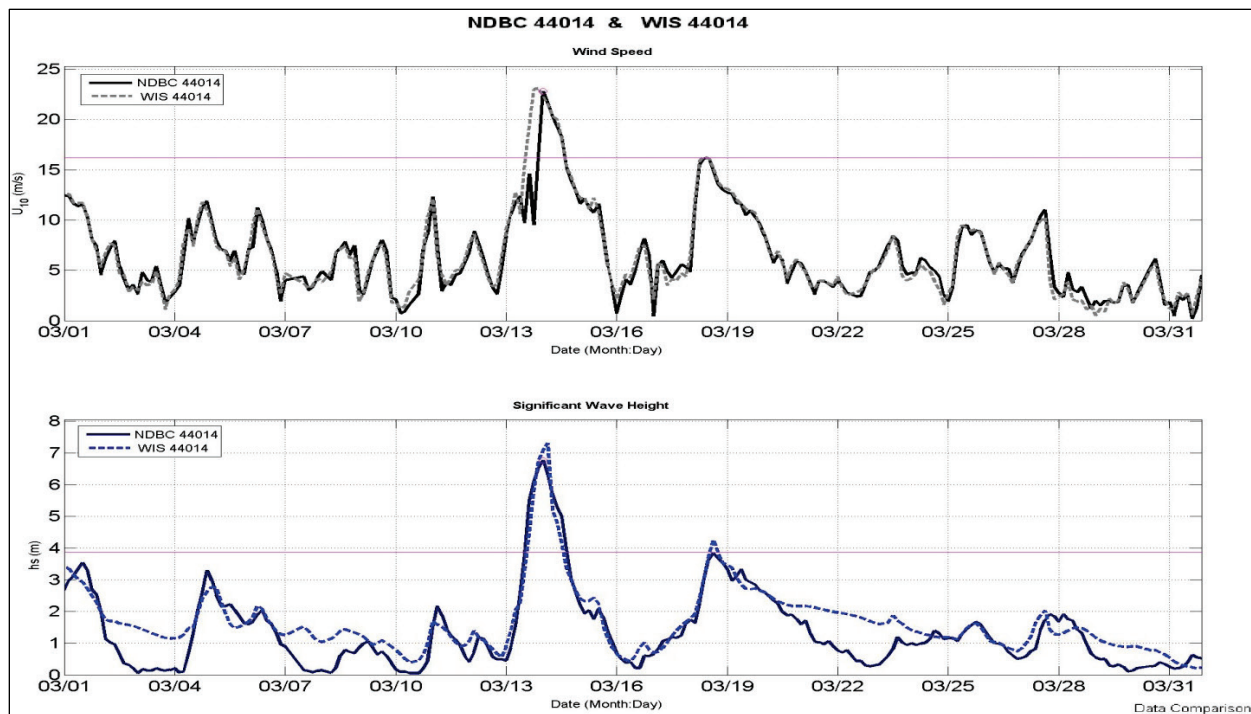
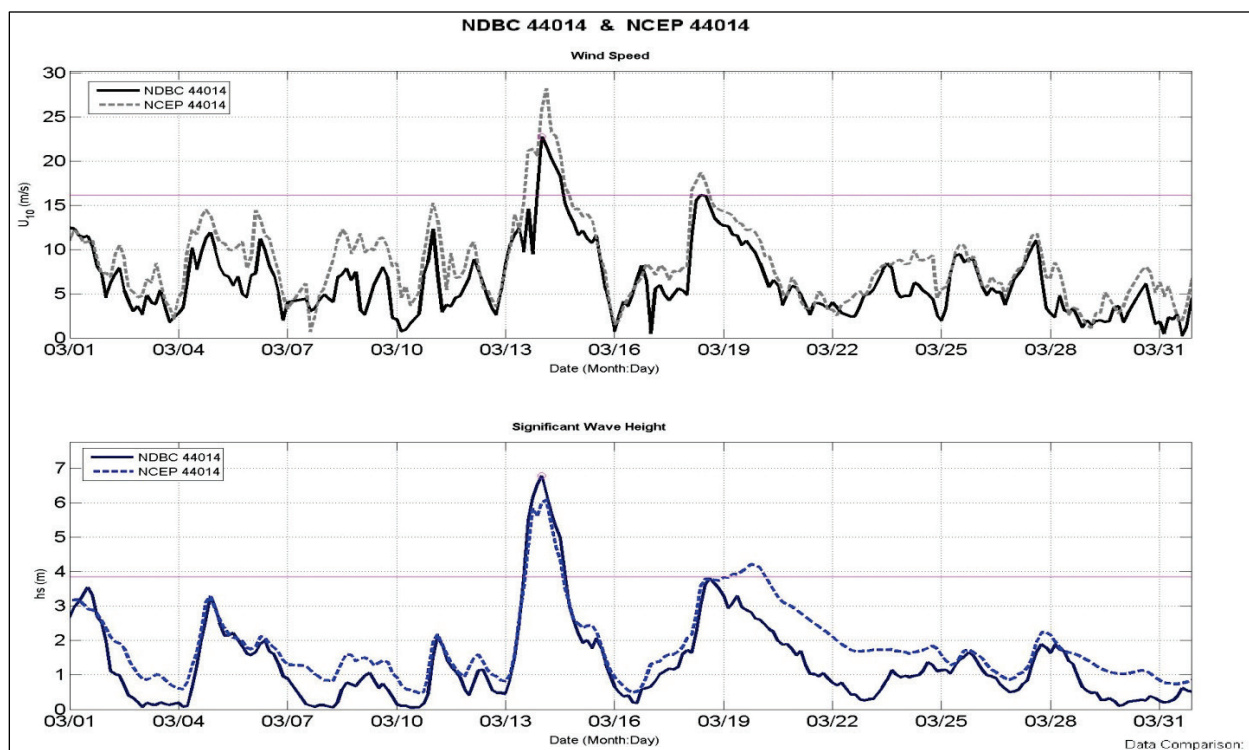


Figure 12. Comparison of CFSR winds and NCEP waves to observations at Station 44014 during the March 1993 storm.



Statistical results from the 10 yr peak event analysis provide detail on hindcast performance during extreme extratropical events such as the March 1993 Superstorm. Results from NDBC stations 44025, 44009, and 44014 appear in Figures 13–15, respectively. The plots include the same features provided in the full-hindcast plots, with the exception that only peak values from extreme extratropical events are included. For winds, the full-hindcast behavior observed above is amplified in the extremes. At stations 44025 and 44014, the WIS winds are clearly superior with very high r^2 values and very small biases. CFSR (NCEP) peak winds exhibit higher scatter and are biased high at each of these two stations. Surprisingly, the quality of both wind hindcasts degrades at station 44009; however, the NCEP winds do a better job of capturing the two most extreme peaks in this 10 yr time period.

The overall extreme wave height performance is very similar for the WIS and NCEP hindcasts (Figures 13–15, lower panels). As with the winds, the hindcasts do best at stations 44025 and 44014. At each station the overall peak wave height bias is low (-0.3 to -0.5); however, the most extreme peaks match the observations quite well. Both WIS and NCEP extreme wave height performance degrades at 44009, as the most extreme hindcast events are now biased low.

Figure 13. Station 44025 peak event evaluations. See text for explanation.

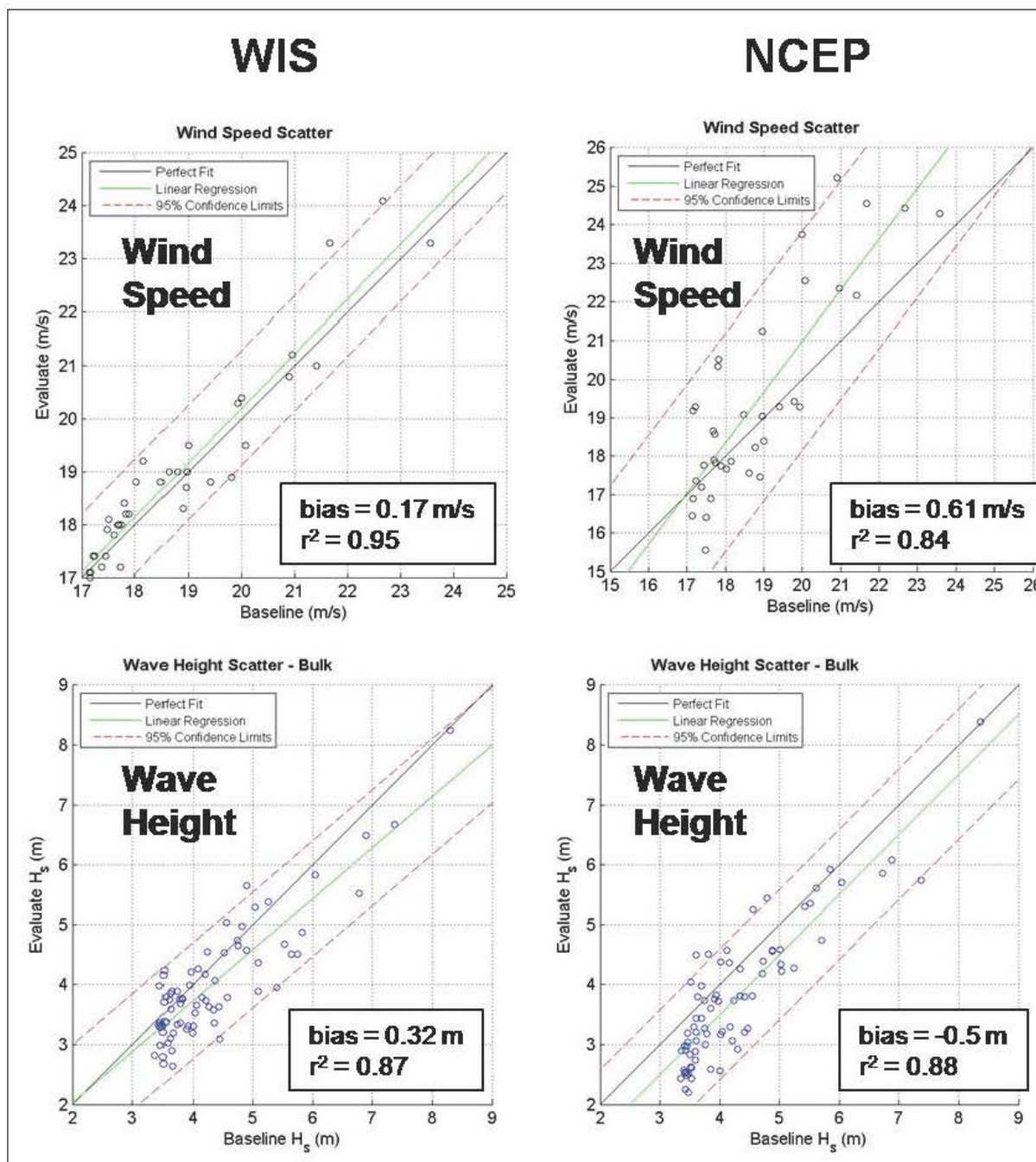


Figure 14. Station 44009 peak event evaluations. See text for explanation.

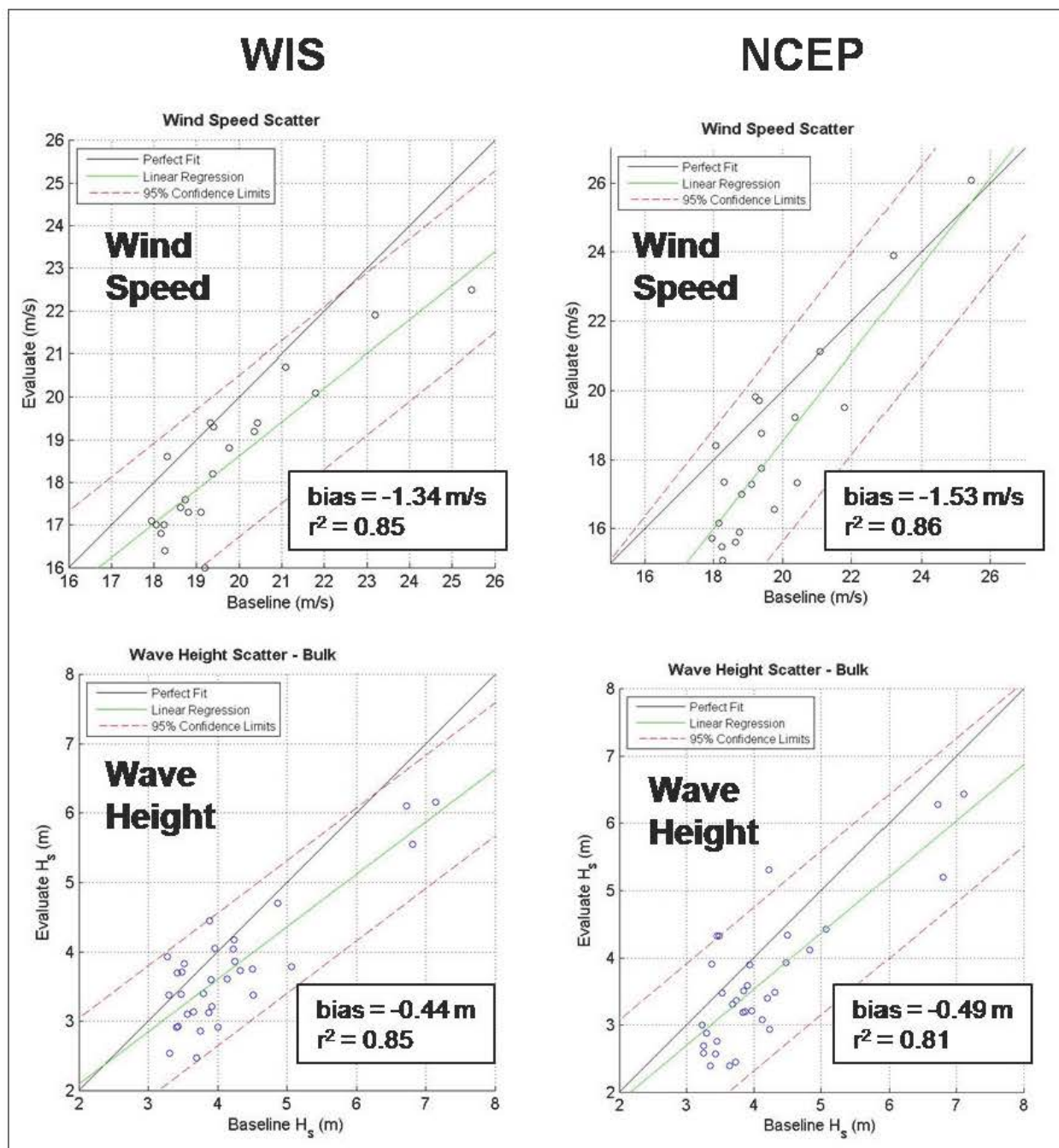
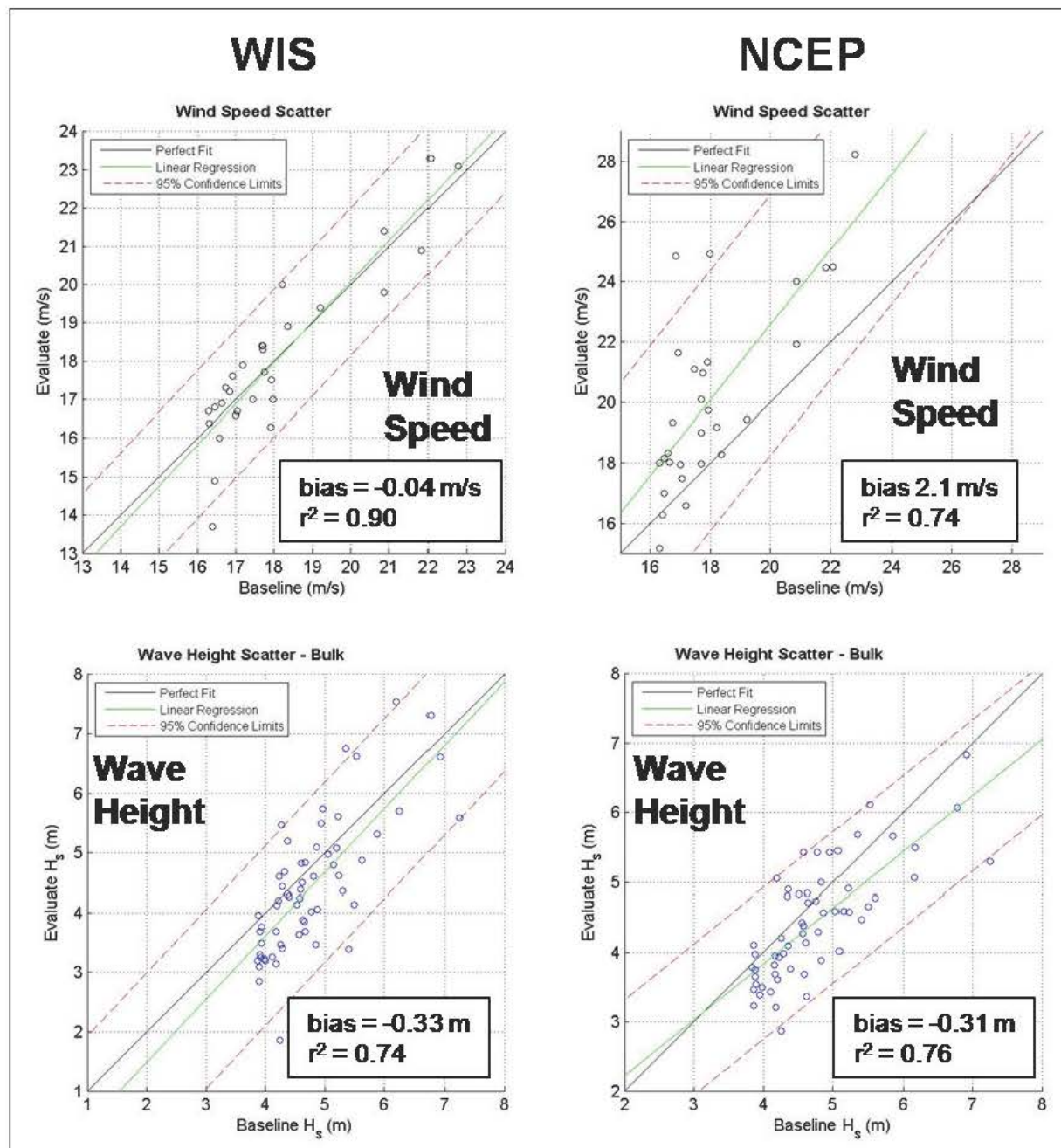


Figure 15. Station 44014 peak event evaluations. See text for explanation.



4 Extratropical Extremal Wind and Wave Estimates

4.1 Method assessment

The extremal analysis method was a qualitative evaluation focused on data fit and the representation of the 100 yr return period or the *tail* of the distribution among four extremal value techniques. The NCEP hindcast for the 30 yr period (1980–2010) was used for this assessment since it was the longest record. Thirty-one extratropical storms were extracted from the hindcast using POT technique for use with all the extremal techniques except the GEV. The GEV technique requires the AMS or largest storm that occurs each year; therefore, 30 extratropical storms were extracted for use with this extremal technique.

The results from the various extremal techniques that were applied to the wave height data at each of the five test stations are shown in Figures 16–20. Each plot contains the POT storm population (black dots), the AMS population (magenta dots), and the various parametric fits (colored lines) including the GEV used only with the AMS population, Weibull, and GPD as well as the nonparametric EST extrapolated out to the 50, 100, and 500 yr wave return periods.

The EST demonstrated a consistent fit to all the data from each storm population at each of the five test stations and demonstrated a steady representation of the return period levels in that it generally passes through the top three to five events. Stations that demonstrated higher variability of the top three events such as 63126 and 63255 were reflected in the EST result by an increased or steeper slope approaching the 50 and 100 yr return period. Conversely, stations that demonstrated a lower variability of the top events such as 63159 and 63259 resulted in a gentler slope. This variability was also represented in the spread of the EST 90% confidence interval (dashed lines) at the higher return periods.

Figure 16. Station 63126 approximately 8 miles east of Sandy Hook, NJ.

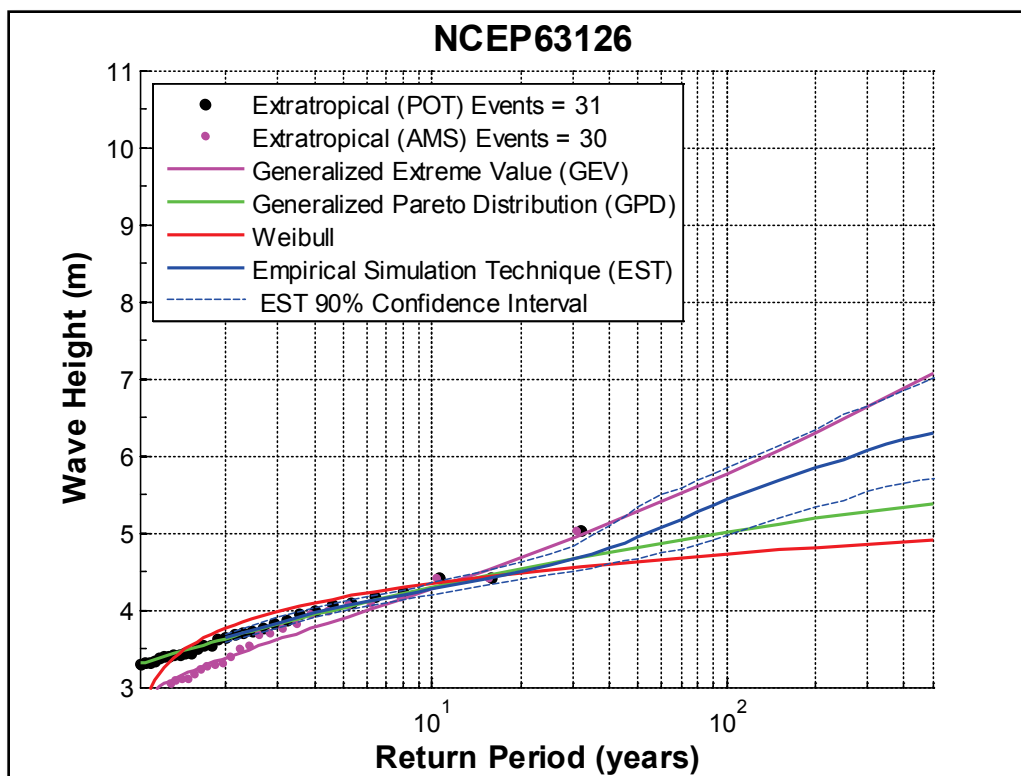


Figure 17. Station 63159 12 miles off the coast of Delaware.

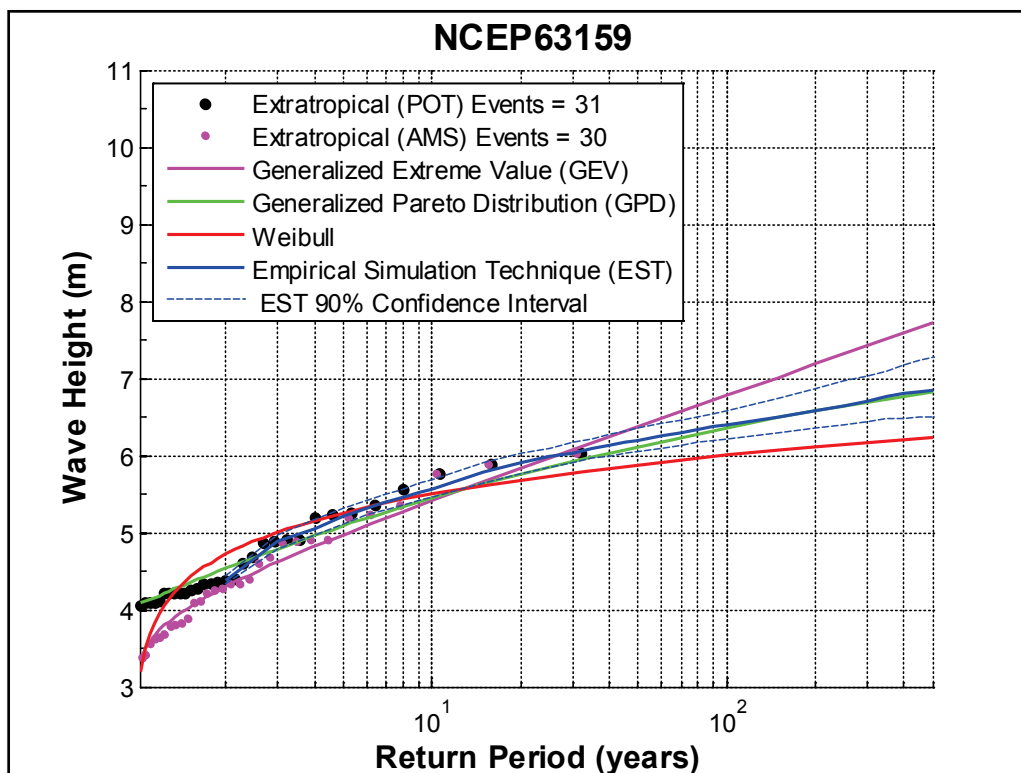


Figure 18. Station 63197 14 miles east of the entrance to Chesapeake Bay.

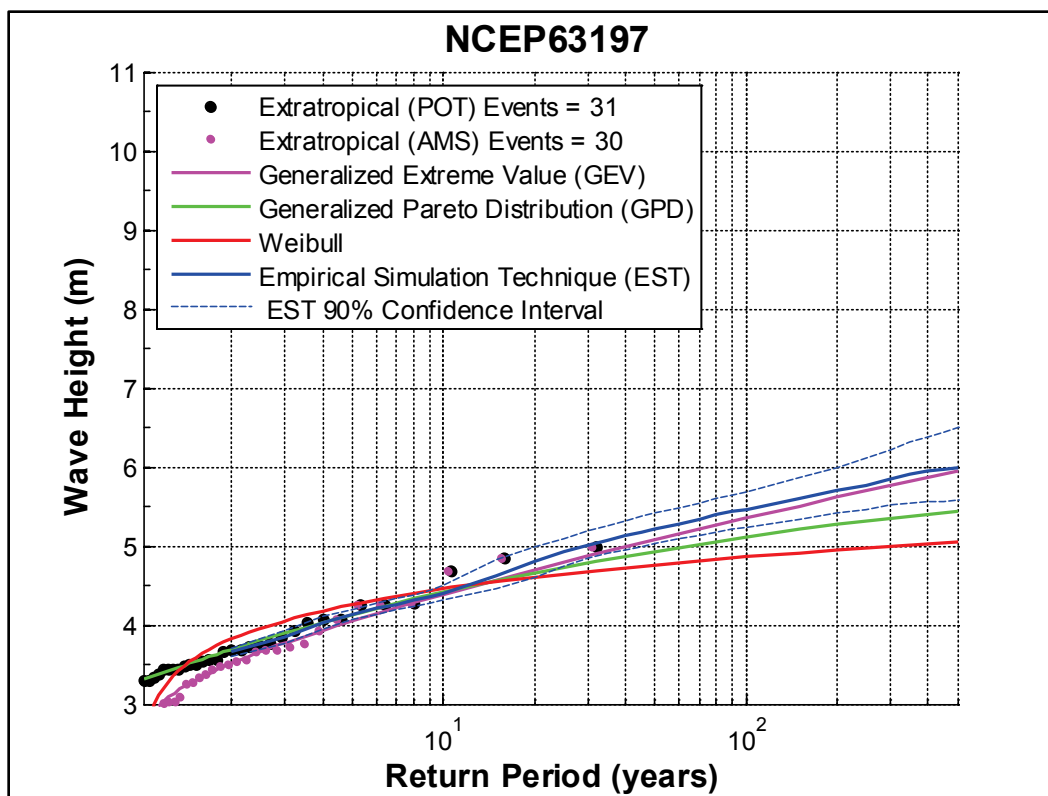


Figure 19. Station 63255 60 miles offshore of NC/VA border.

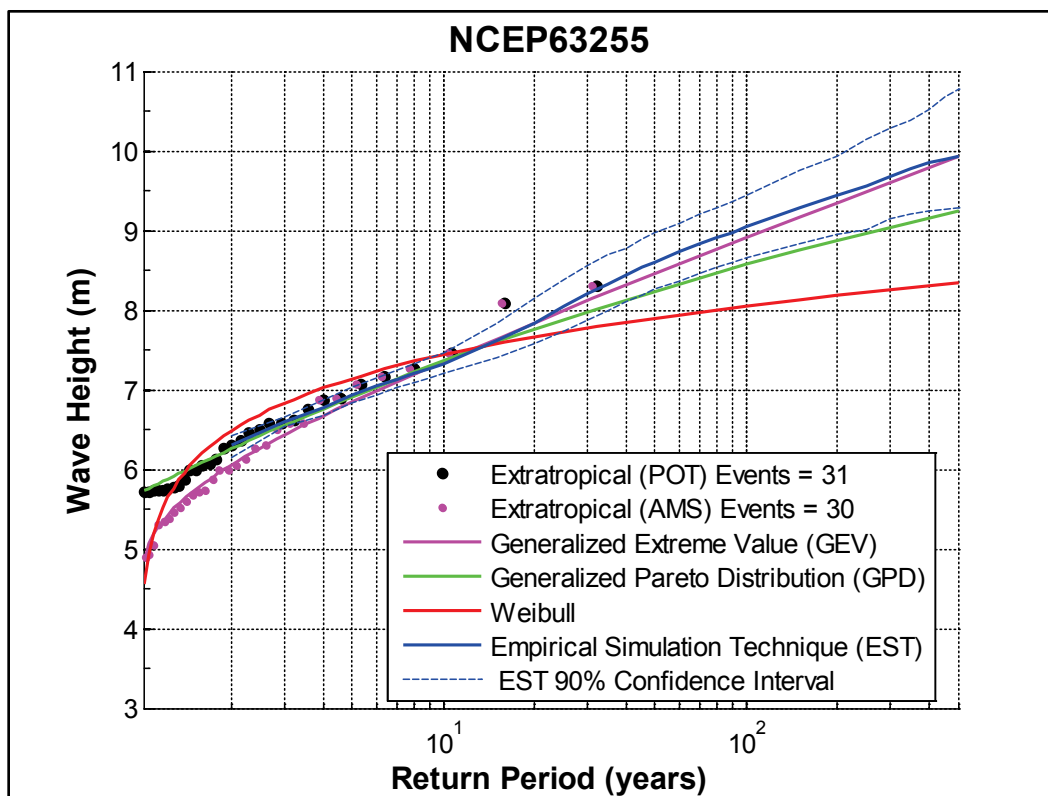
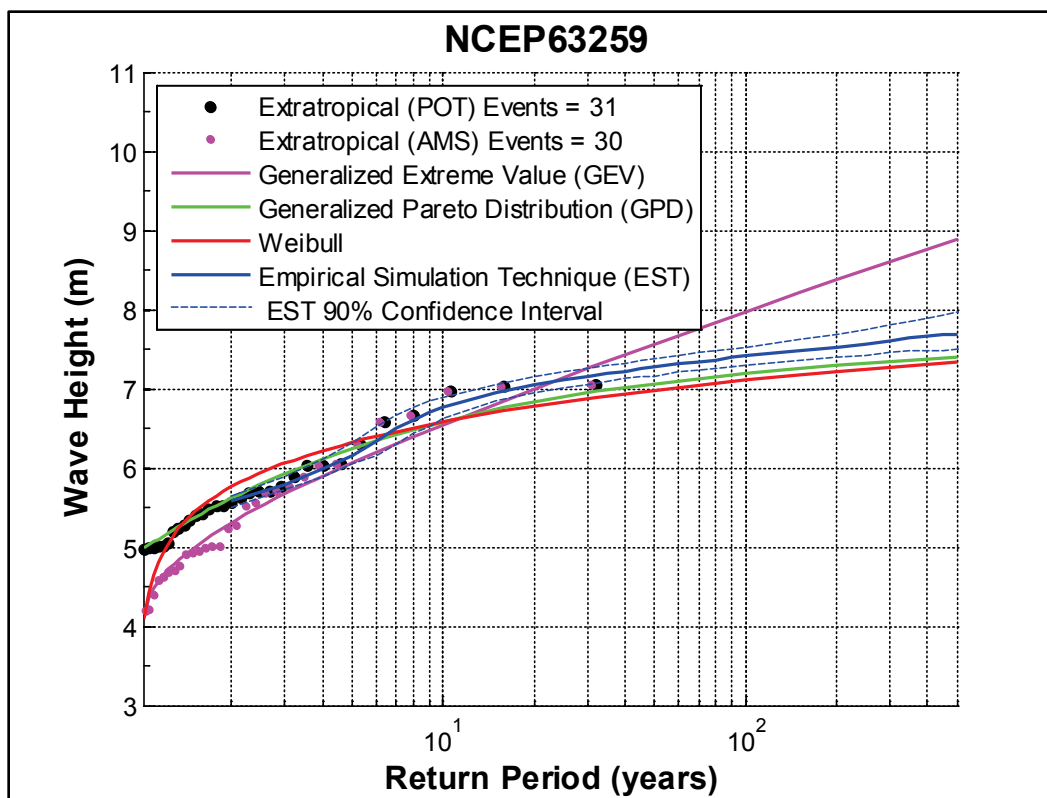


Figure 20. Station 63259 12 miles offshore of Cape Hatteras, NC.



Qualitative inspection of the results suggest that the GPD underperformed the EST in fitting the data and produced lower return periods by up to 0.5 m at all but station 63159, where it matched the EST. The GEV and Weibull techniques showed the most variability both in fitting the data at the extremes and the prediction of the 50 and 100 yr return period levels. A consistent performance was not observed in the GEV data fitting although the GEV predicted a 1–1.5 m higher return period level at three of the five stations than the EST and GPD. The Weibull approach consistently fit the data except for underpredicting the top three events. This resulted the lowest return period levels of the methods tested with differences up to 1 m when compared to the GEV and EST techniques.

The wind and wave return period plots for all test stations are included as Appendixes A and B, respectively.

4.2 Empirical simulation technique (EST) sensitivity testing

A sensitivity study on storm population and its effect on the EST return period levels was performed using the NCEP 30 yr hindcast at the five test locations (red triangles) shown in Figure 1. The POT parameters were

adjusted to achieve three storm populations, high (80–90 storms), mid (30–40 storms), and low (10–20 storms). The interevent time remained constant at 72 hr. The most extreme storms (the top 10 events) were found in each of the populations. The EST was applied to each storm population, and the 50 and 100 yr return period levels were computed. The results are included as Table 1 and indicated that the storm population had little to no impact on the EST computed return period levels. Capturing the top five most extreme events is paramount when applying the EST technique.

Table 1. Results from storm population sensitivity study.

Wave Height Wind Speed					
	Station	50 yr(m)	100 yr(m)	50 yr(m/s)*	100 yr(m/s)
High	NCEP63126	5.0	5.5	21.9	23.0
	NCEP63159	6.2	6.4	27.1	28.0
	NCEP63197	5.3	5.5	25.4	26.0
	NCEP63255	8.6	9.1	29.0	30.4
	NCEP63259	7.3	7.4	32.2	33.7
Mid	NCEP63126	4.5	5.4	21.9	22.9
	NCEP63159	6.2	6.4	27.0	27.9
	NCEP63197	5.2	5.5	25.3	25.8
	NCEP63255	8.6	9.0	28.9	30.3
	NCEP63259	7.3	7.4	32.1	33.7
Low	NCEP63126	4.9	5.4	21.8	22.9
	NCEP63159	6.2	6.4	27.0	27.9
	NCEP63197	5.2	5.4	25.3	25.8
	NCEP63255	8.6	9.1	28.9	30.3
	NCEP63259	7.3	7.4	32.1	33.6

*m/s = meters per second

5 Extratropical 100 yr Return Period Results

The WIS hindcast was selected due to its superior winds and competitive extremal wave heights with NCEP. The EST was run on all of the WIS output stations within the BSEE study shown in Figure 21. The extratropical 100 yr return period levels were computed for both significant wave height and wind speed with results shown in Figures 23 and 24 respectively. The results of the 100 yr wave heights and wind speeds are discussed in the following.

5.1 Wave height 100 yr recurrence interval

The 100 yr recurrence interval significant wave heights were calculated at 122 WIS hindcast stations contained within the project area with the results displayed in Figure 22. The highest 100 yr wave height in the study area was found south of Cape Hatteras near the continental shelf break with a value of 14.5 m. The lowest 100 yr wave height was found 15 miles offshore of Virginia/Maryland state line with a value of 5.4 m. The 100 yr mean wave height was 7.3 m with a standard deviation of 1.5 m. The 100 yr wave height results depicted by Figure 22 show a general trend of higher values along the outer edge of the continental shelf, as wave energy is lost due to bottom friction up on the shelf. Furthermore, there is evidence of higher wave heights near coastal capes (Cape Hatteras, Cape May) with lower values along concave portions of coastline. These results are likely attributed to wave refraction patterns around a cusped coast. As shown in Figure 23, wave refraction results in energy focusing around coastal promontories and energy spreading along concave coastlines. Furthermore, higher 100 yr wave heights were also found along the northern coast of New Jersey. These higher levels are likely related to intensified extratropical storms in higher latitudes that result in greater wind speeds and wave heights.

Figure 21. WIS hindcast output locations (black dots) and wind energy areas (grey squares).

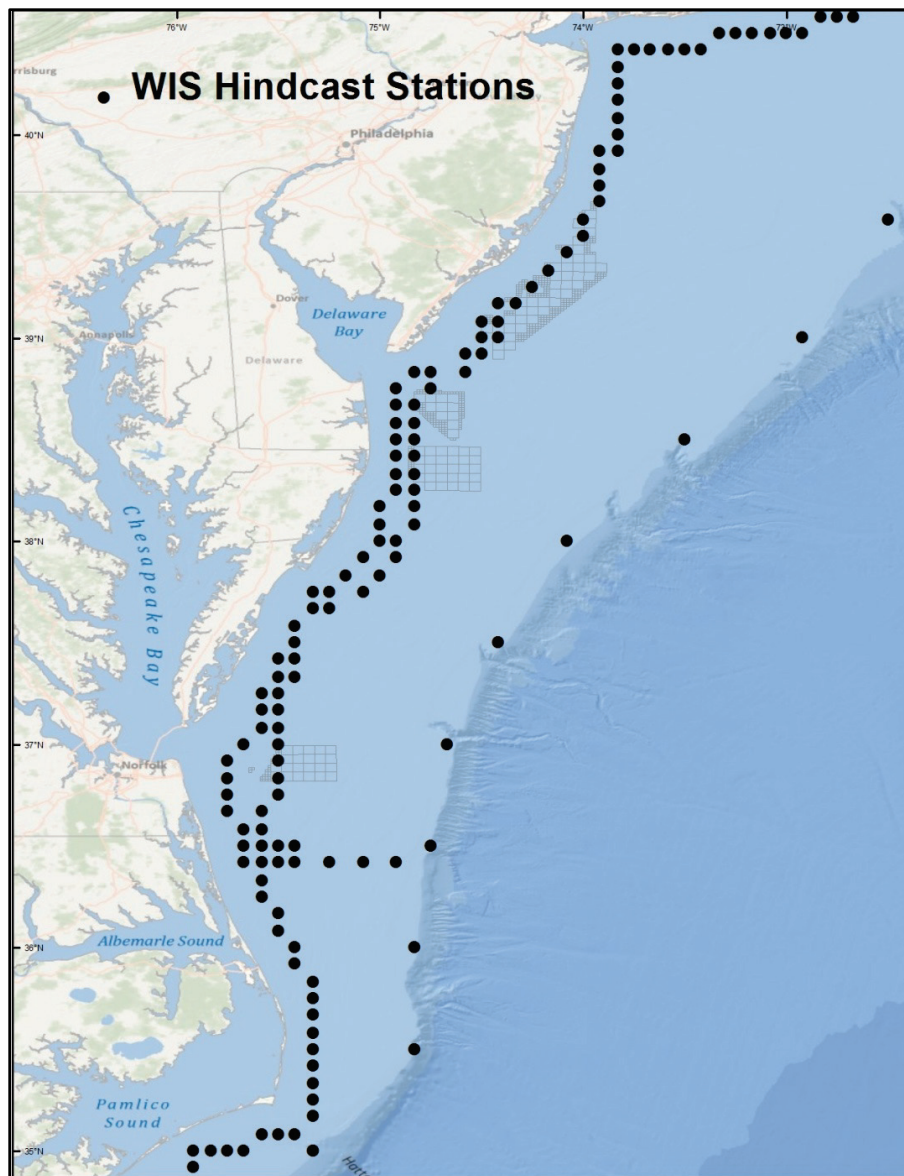


Figure 22. Extratropical 100 yr recurrence interval significant wave heights (m) derived from WIS hindcast.

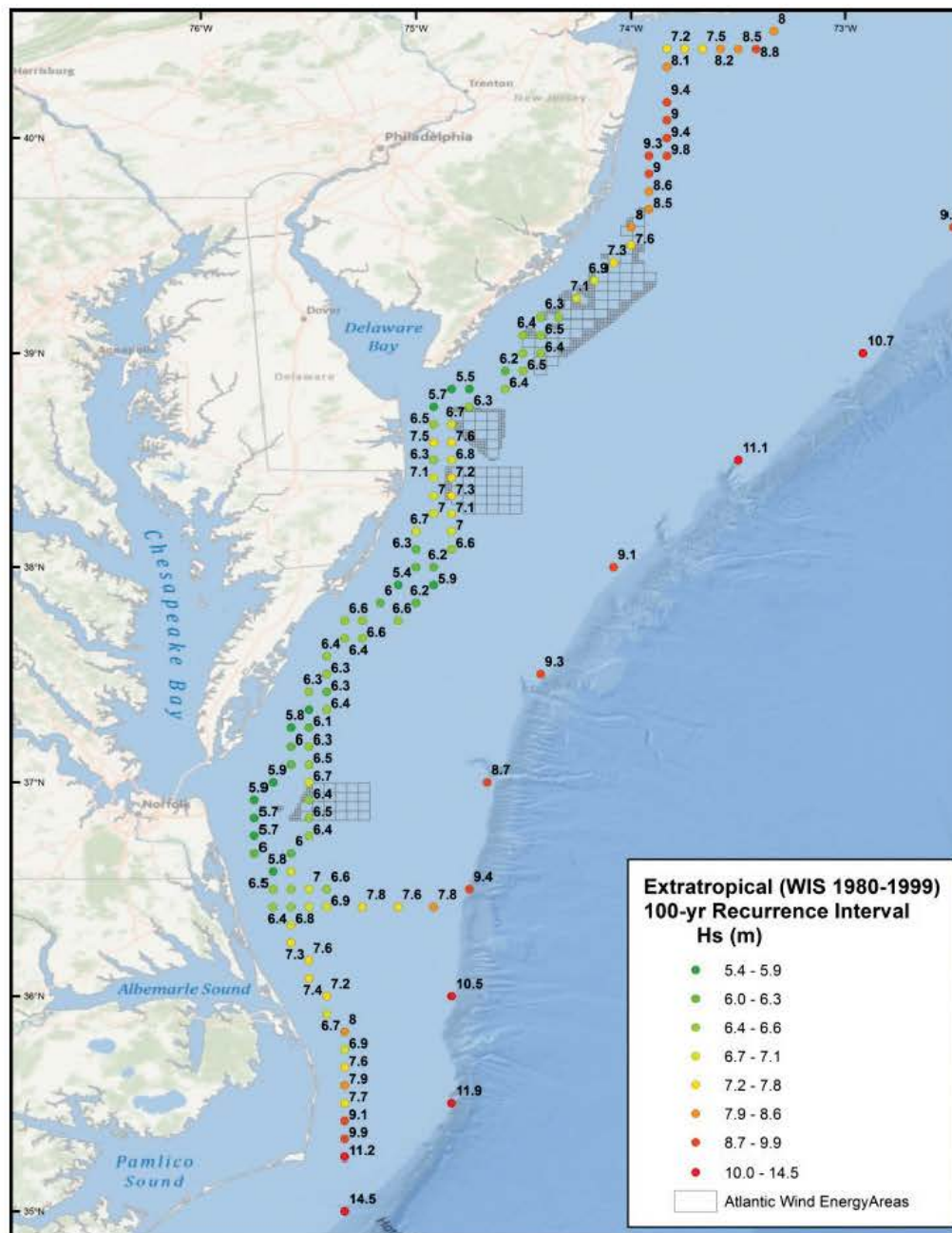
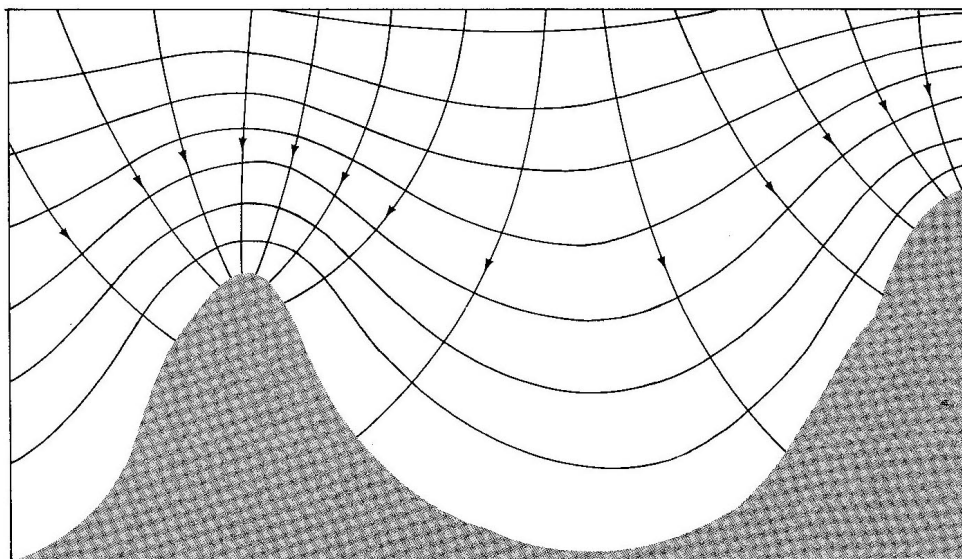


Figure 23. Wave refraction focusing energy along convex areas of coastline and defocusing energy along concave areas of coastline (Knauss 1997).

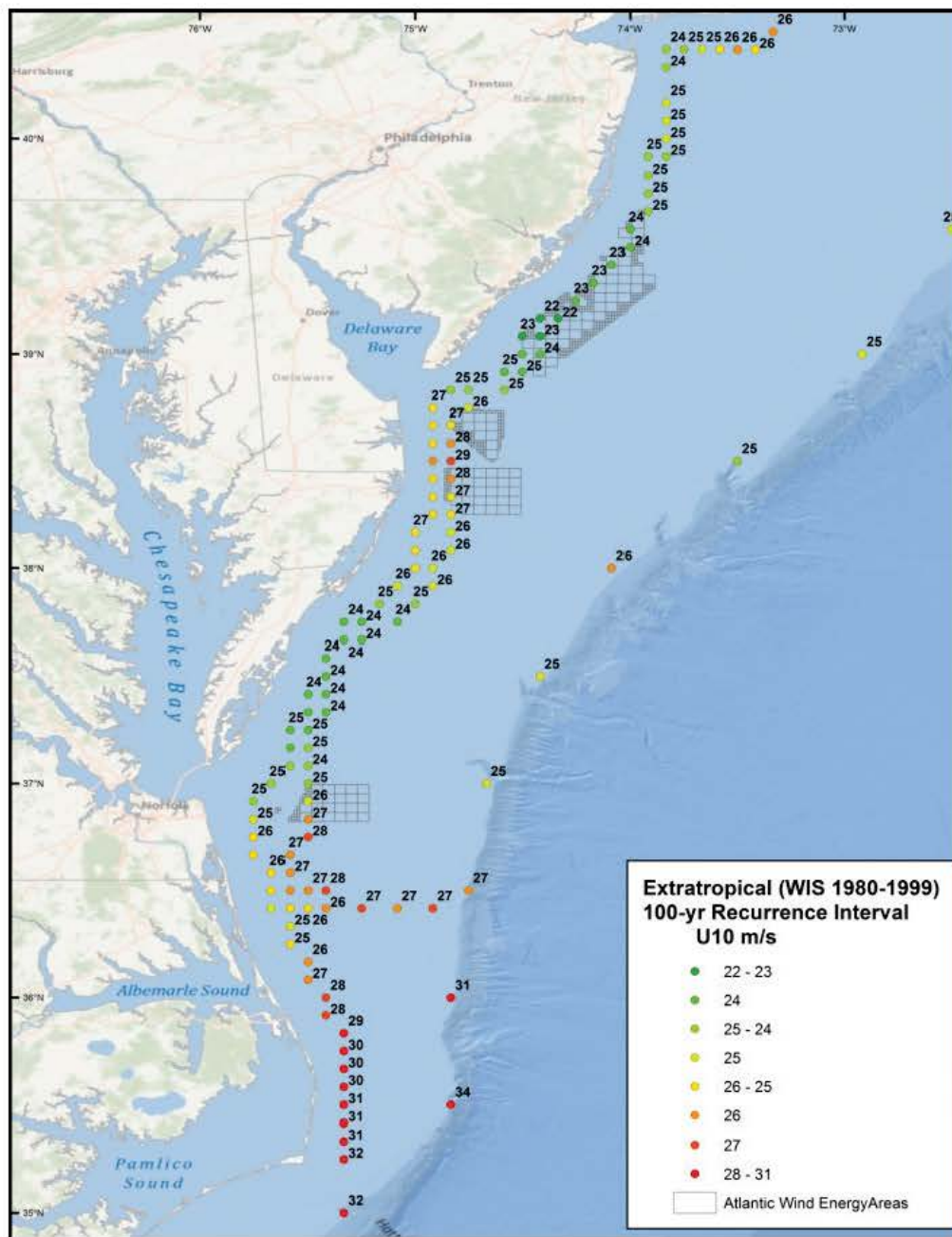


5.2 Wind speed 100 yr recurrence interval

The 100 yr wind speed recurrence interval was calculated at 122 WIS hindcast stations contained within the project area. The highest 100 yr wind speed (34 m/s) was found along the continental shelf break offshore of Cape Hatteras, NC. The lowest 100 yr wind speed (22 m/s) was found off of southern New Jersey. The 100 yr mean wind speed was 26 m/s with a standard deviation of 2 m/s.

The higher 100 yr wind speeds are found along the Outer banks of North Carolina with values ranging from 26–32 m/s and in Northern New Jersey with 100 yr values of 24–26 m/s. A third area with higher wind speeds was found offshore the Northern Maryland and Delaware Coast with 100 yr wind speed values of 26–29 m/s as shown in Figure 24. The higher 100 yr wind speeds in this area are the result of two powerful extratropical storms occurring on 27–29 January and 4–6 February 1998 detailed in Ramsey et al. (1998). These two storms generated winds in excess of 27 m/s and were the top two ranked wind events in the WIS extratropical hindcast.

Figure 24. Extratropical 100 yr Recurrence Interval wind speed (m/s) derived from WIS hindcast.



6 Water Level Assessment

To assess the relevance of the FEMA RIII coastal modeling results for use in the present study, hindcast and observed water levels at the Duck National Ocean Service (NOS) tide station (Station 8651370) are examined. Details on the FEMA hindcasts, NOS observations, and comparison results follow.

6.1 FEMA storm surge modeling

The FEMA RIII office has initiated a study to update the coastal storm surge elevations within the states of Virginia, Maryland, and Delaware, and the District of Columbia, including the Atlantic Ocean, Chesapeake Bay (including its tributaries), and the Delaware Bay. This effort is one of the most extensive coastal storm surge analyses to date, encompassing coastal floodplains in three states and including the largest estuary in the United States. The end-to-end storm surge modeling system includes the Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters (ADCIRC) for simulation of 2D hydrodynamics. ADCIRC was dynamically coupled to the unstructured numerical wave model Simulating WAVes Nearshore (unSWAN) to calculate the contribution of waves to total storm surge (Blanton et al. 2011). The combined modeling system is referred to as PADCSWAN. A seamless modeling grid was developed to support the storm surge modeling efforts with a minimum nearshore horizontal resolution of 30 m (Forte et al. 2011). The modeling system validation consisted of a comprehensive tidal calibration followed by a validation using carefully reconstructed wind and pressure fields from three major flood events for the Region III domain: Hurricane Isabel (September 2003), Hurricane Ernesto (September 2006), and extratropical storm Ida (November 2009). Model skill was assessed by quantitative comparison of model output to wind, wave, water level, and high water mark observations (Hanson et al. 2012). The modeling system was then used to compute 25, 50, 100, and 500 yr extremal water levels for the Region III domain (Hanson et al. 2013).

The NOS network of water level stations is ideal for validating the FEMA RIII coastal water level hindcasts. The NOS stations used for the FEMA validation appear in Figure 25. Peak water level results, from all three validation storms and at each of the NOS stations, appear in Figure 26. The overall water level results depict a negligible bias of 0.02 m and a very

small root-mean-square (RMS) error of 0.16 m. As a result of these small errors, the coastal storm surge modeling system was certified as ready to perform the extremal analyses required by FEMA (Hanson et al. 2012).

The FEMA storm surge modeling system was run on 29 reconstructed extratropical storms and 156 synthetic hurricanes (Vickery et al. 2012). Statistical analyses for each storm set were computed separately. The EST method (described above) was employed to compute the extratropical storm extremal water levels. The joint probability method (JPM) was used to compute the tropical extremes. Extremal results from both sets were then synthesized to compute the total 25, 50, 100, and 500 yr return period water levels. Results from the 100 yr calculation appear in Figure 27. Note in these figures that the statistical analysis was only performed in the Region III domain. Although the storm selection was optimized for this region, model output exists for the entire mid-Atlantic seaboard.

Figure 25. NOS measurement stations used to validate the FEMA RIII coastal water level hindcasts.

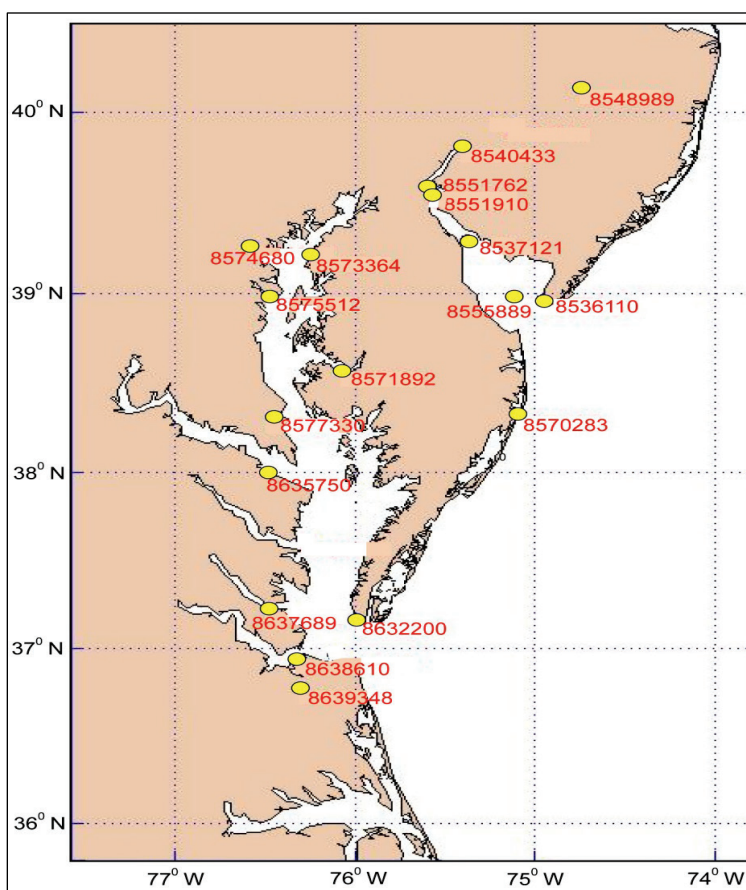


Figure 26. Summary comparison of observed and hindcast peak water levels at the NOS water level stations for all three FEMA RIII validation storms.

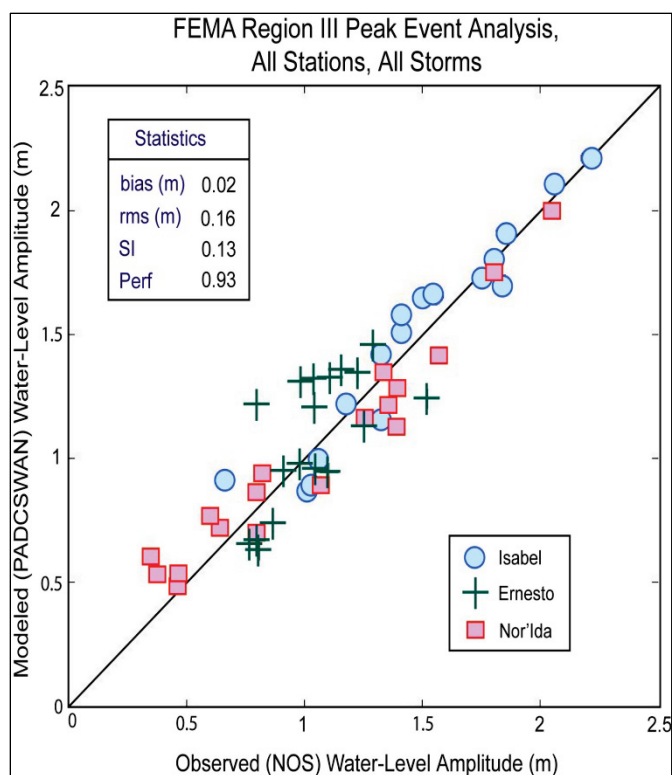
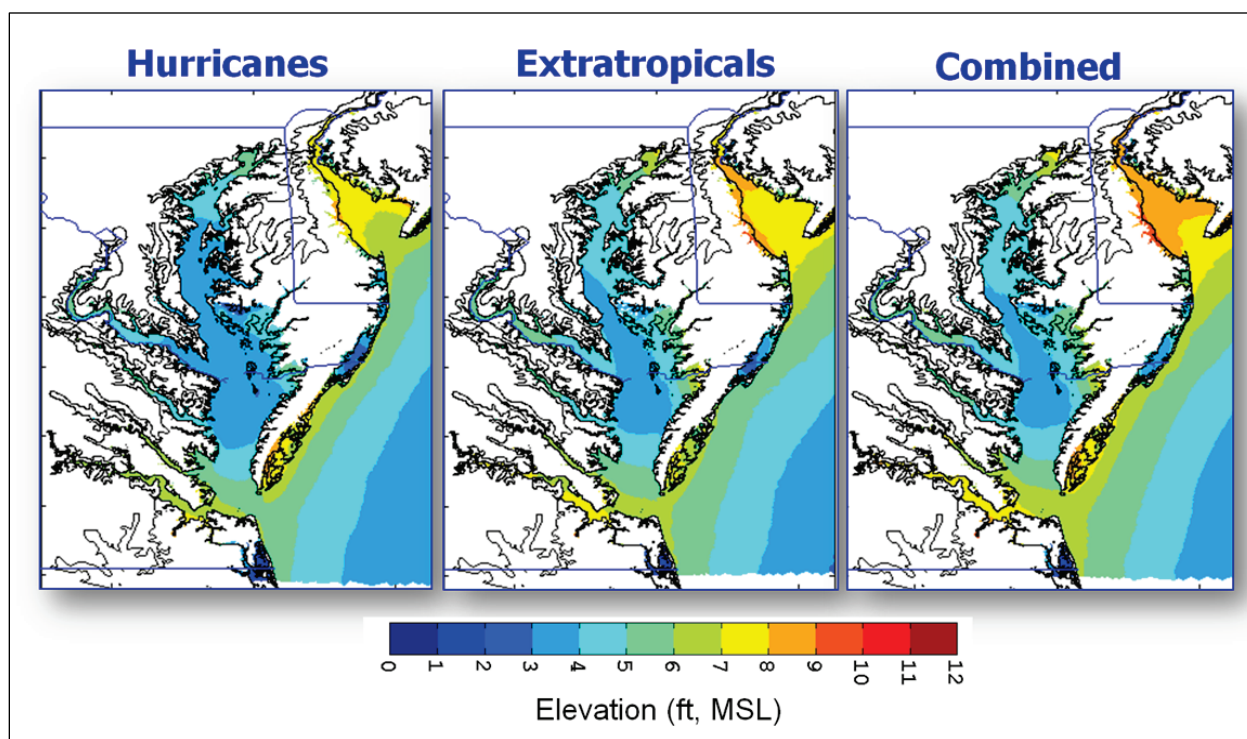


Figure 27. FEMA RIII 100 yr water levels (MSL) for hurricanes, extratropical storms, and all events (synthesis).
Note: Water elevations are in feet.



6.2 National Ocean Service (NOS) Duck water level assessment

Although the FEMA RIII water level hindcast results are encouraging, there are no ground truth water level stations in the offshore domain of this study. Hence, the relevance of the FEMA extremal water levels in the offshore domain requires further investigation. Of all the available NOS stations in the region, the Duck station located at the USACE Field Research Facility (FRF) is the farthest offshore and hence more relevant to the present study. As depicted in Figure 28, the station is located at the end of the FRF pier (36 11 N, 74 44.8 W), located 560 m from shore in a water depth of 7 m. Although this station is south of the FEMA RIII study area, the high resolution model domain sufficiently covered this region. This allows an evaluation of FEMA hindcast water levels in an open ocean setting.

Figure 28. U.S. Army Corps of Engineers Field Research Facility pier which hosts the Duck water level station.



Hindcast water levels from each of the FEMA RIII validation storms were extracted for comparison with observed levels at Duck. Results for Extratropical Storm Ida, Hurricane Ernesto, and Hurricane Isabel appear in Figures 29–31, respectively. Peak hindcast water levels for Extratropical Storm Ida are 0.2–0.3 m higher than observed levels of 1.3 m (Figure 29). Peak hindcast water levels for Hurricane Ernesto agree very closely with observed levels of approximately 0.6 m (Figure 30). Peak hindcast water levels for Hurricane Isabel are 0.3–0.4 m higher than observed levels of approximately 1.3 m (Figure 31). For storms Ida and Isabel, the water level hindcast errors at Duck are greater than the overall RMS error of 0.16 m exhibited by the modeling system in the Region III domain (Figure 27). This is likely a result of the Duck station being outside the primary

modeling domain of interest (Region III) where model mesh resolution was concentrated. Hence, the conclusion is that caution should be exercised in using the FEMA RIII results outside the primary modeling domain of interest as shown in Figure 27.

Figure 29. Comparison of FEMA RIII water level hindcast (blue) with observed water levels (red) during Extratropical Storm Ida (November 2009) at Duck.

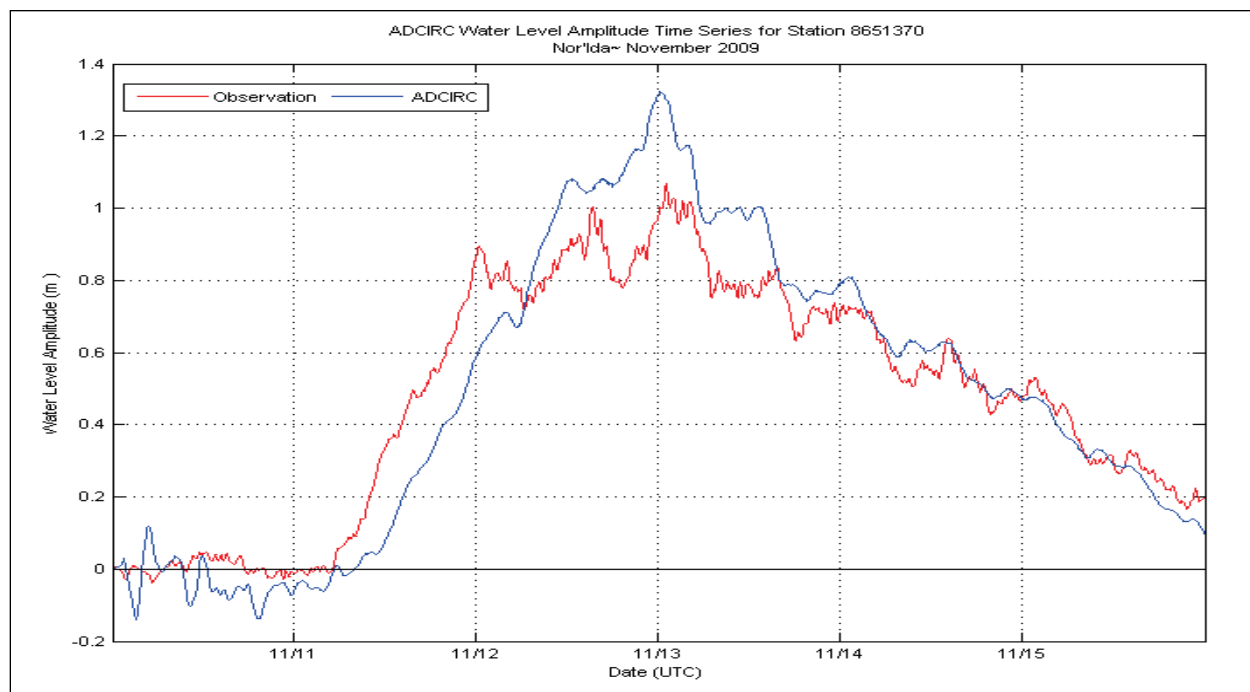


Figure 30. Comparison of FEMA RIII water level hindcast (blue) with observed water levels (red) during Hurricane Ernesto (September 2006) at Duck.

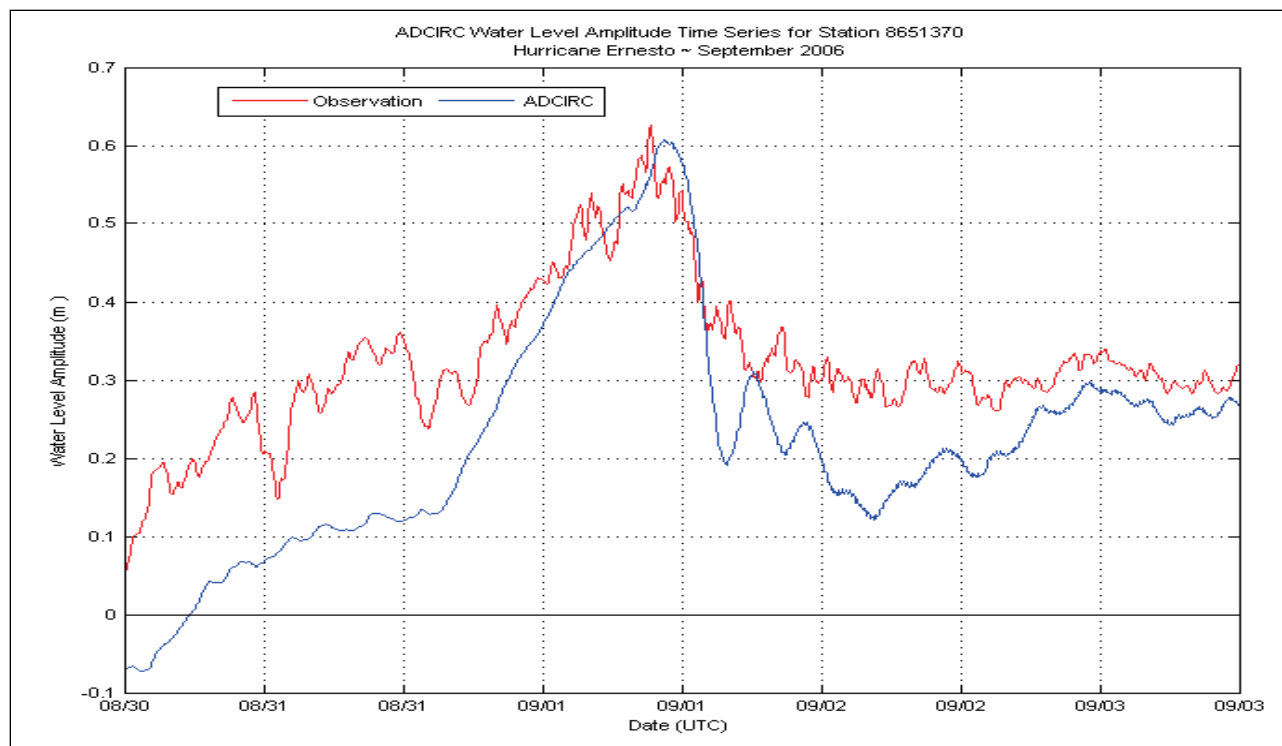
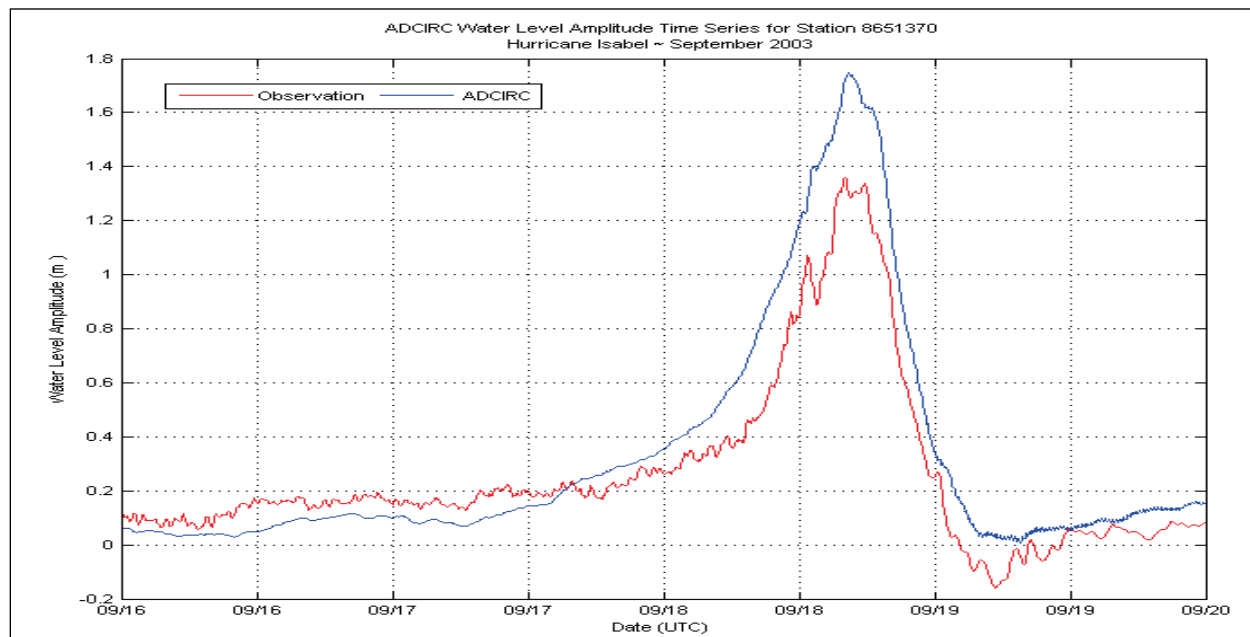


Figure 31. Comparison of FEMA RIII water level hindcast (blue) with observed water levels (red) during Hurricane Isabel (September 2003) at Duck.



7 Conclusions

The primary USACE objectives of study were to (1) evaluate available wind and wave hindcast databases, (2) propose a methodology for developing extremal wind speed and wave height statistics for extratropical storms in the mid-Atlantic offshore wind farm development areas, and (3) investigate the relevancy of FEMA RIII storm surge modeling for specifying water level extremes in the mid-Atlantic offshore areas of interest. A summary of the key findings and conclusions in each area appears in the following sections.

7.1 Hindcast assessments

A wind and wave assessment of WIS, CFSR, and NCEP hindcasts for 1990–1999 was performed at mid-Atlantic NDBC buoy stations 44025, 44009, and 44014 (Figure 1). Key results from the hindcast assessments are the following:

- WIS winds are superior at 44025 and 44014 with NCEP winds biased high at these stations.
- Hindcast wind quality degrades at 44009 with both WIS and NCEP exhibiting a low bias. NCEP winds are superior at the two most extreme values at this station.
- WIS and NCEP wave heights at 44025 and 44014 are very similar and reasonably well correlated with somewhat better performance in each at 44025. At each station, the overall peak wave height bias is low (-0.3 to -0.5); however, the most extreme peaks match the observations quite well.
- Both WIS and NCEP extreme wave height performance degrades at 44009, as the most extreme hindcast events are biased low.

The WIS hindcast was selected for the present study of offshore extremes. Overall, the WIS winds are superior to the CFSR winds; this is likely a result of the IOKA storm enhancements performed by Oceanweather, Inc. After completion of this study, an additional decade (2000–2009) has been added to the WIS hindcast, using IOKA winds and WAVEWATCH III modeling technology. Furthermore, the NCEP reanalysis hindcast will likely be rerun with improved WAVEWATCH III source terms, as a result of the ongoing NOPP project developments. Both of these advances will require an additional round of Hindcast Evaluations in order to finalize

the extratropical extremal wind and wave statistics required for offshore development.

7.2 Wind and wave extremes

An extremal analysis methodology evaluation for extratropical storm winds and waves was performed at five selected locations from the mid-Atlantic region. The EST demonstrated better fits to the data than the GEV, GPD, and Weibull. In addition, the EST represented the tails of the distribution mimicking the slope of the top three to five events. A storm population sensitivity analysis using the EST showed that varying the population of input storms had little to no impact to the 50 and 100 yr return period levels and that the principal driver of the EST return period was accurately capturing the top five most extreme storm events.

7.3 FEMA Region III (RIII) water level extremes

The FEMA RIII coastal storm surge study produced 100 yr extremal water level statistics for extratropical storms, hurricanes, and combined events. Although the assessment of FEMA RIII water levels to NOS gages within the study area shows excellent model performance, these are primarily non-open coast measurement sites. Furthermore, the return period calculation domain was limited to the specific Region III geography (Figure 27).

An assessment of FEMA RIII water levels was performed using observations at Duck, NC, to determine the relevance of FEMA results to open ocean regions outside of the Region III domain. The validation storms included Extratropical Storm Ida (2009), Hurricane Ernesto (2006), and Hurricane Isabel (2003). The results are mixed in that moderate (~0.6 m) water levels during Hurricane Ernesto are captured quite well by the FEMA study, whereas hindcast water levels for the more extreme Extratropical storm Ida and Hurricane Isabel (~1.0 and 1.3 m, respectively) are biased high by 0.2–0.4 m. Hence the FEMA hindcast results appear to represent a conservative estimate of extremal water levels during large events in an open ocean setting outside the primary Region III domain of interest.

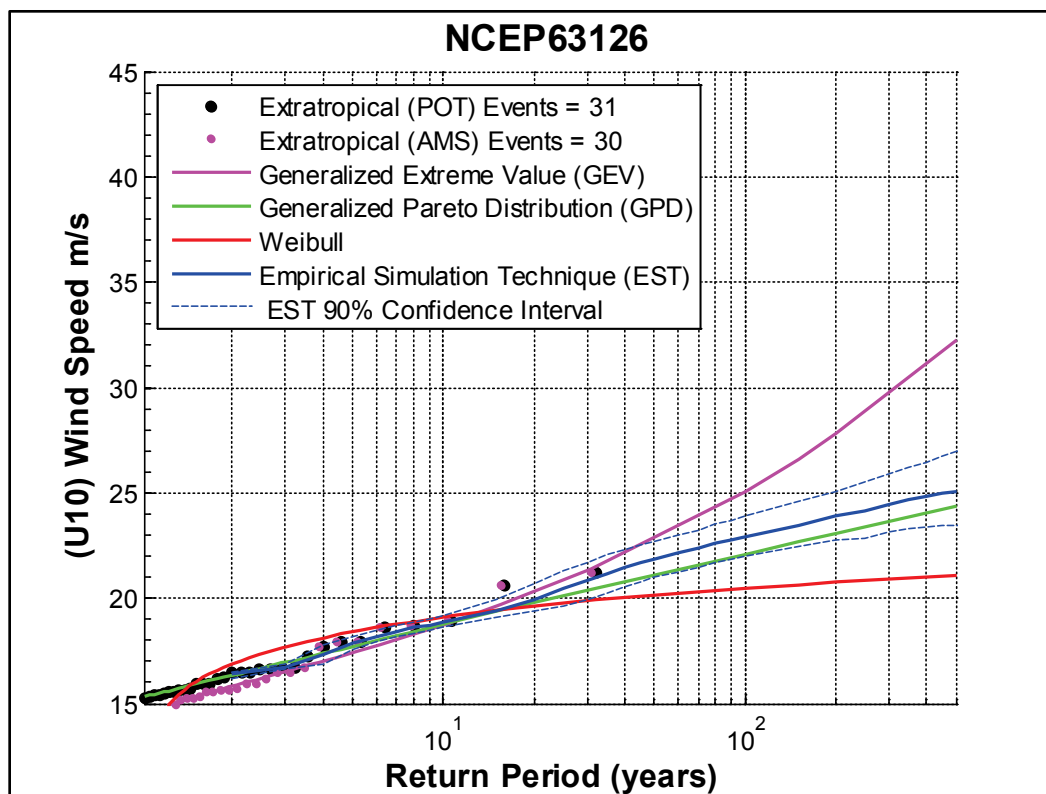
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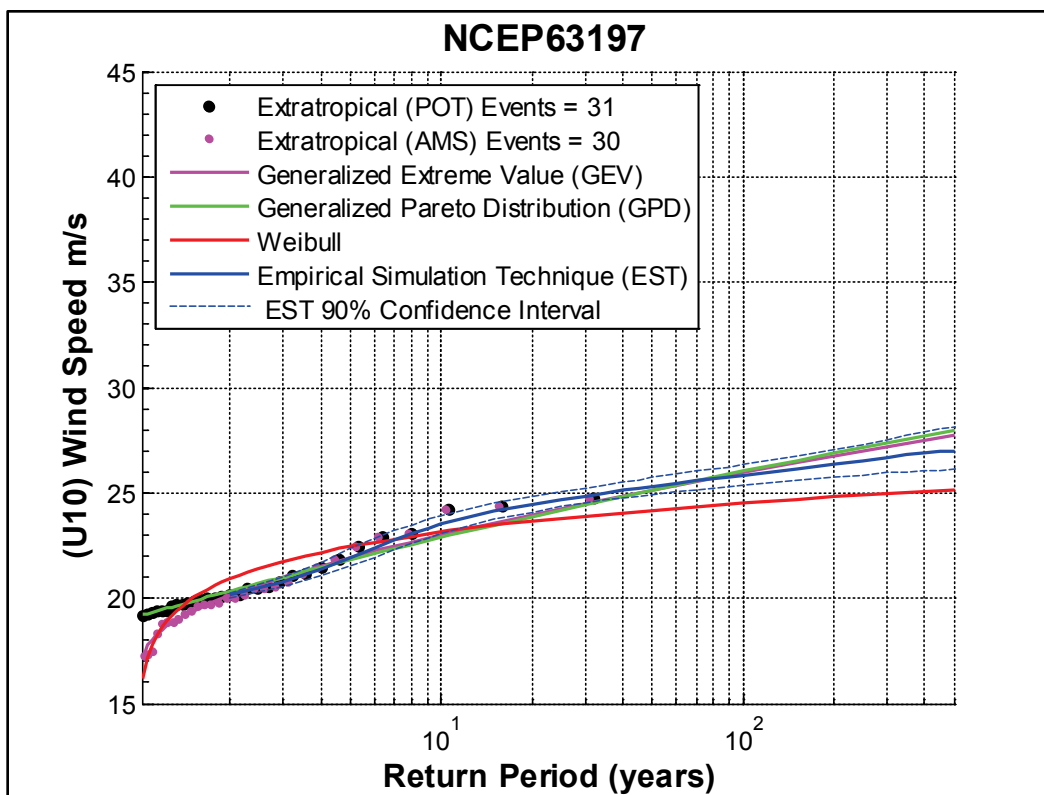
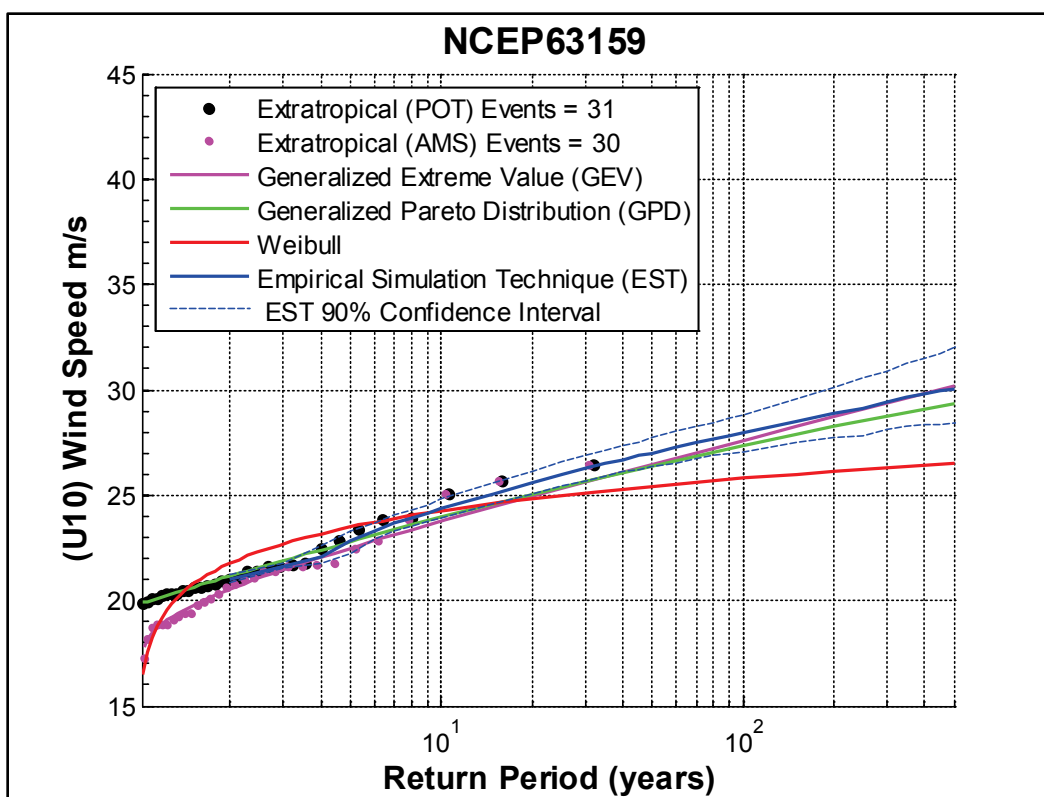
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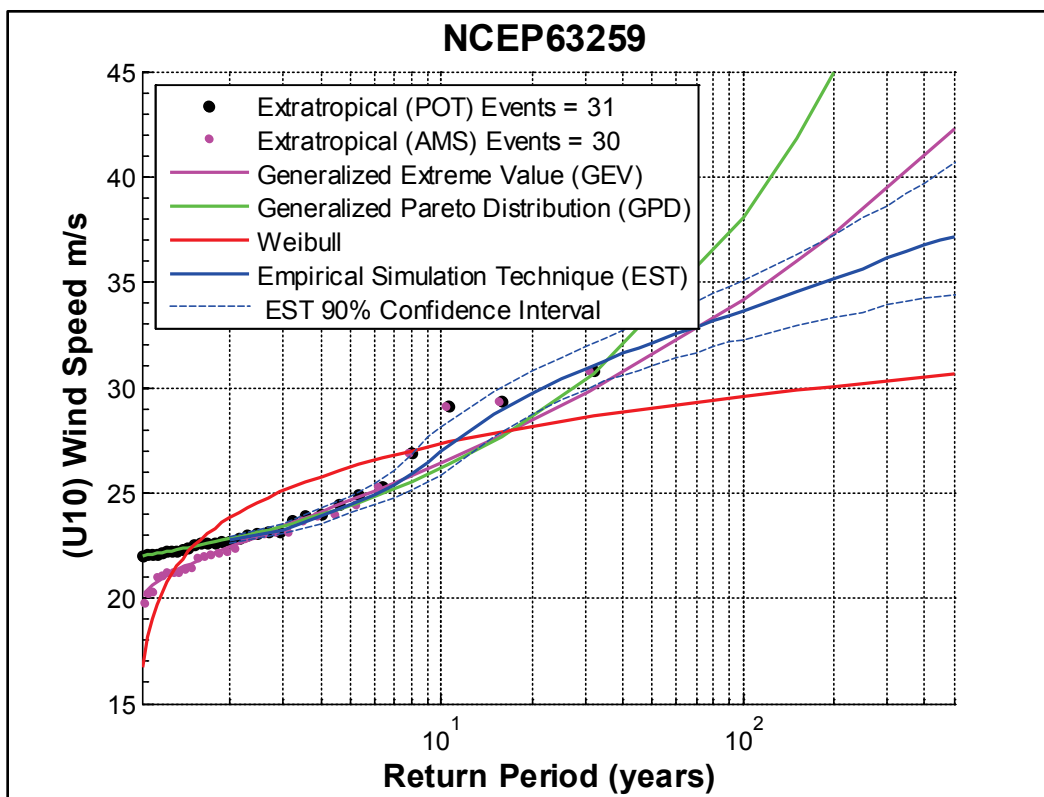
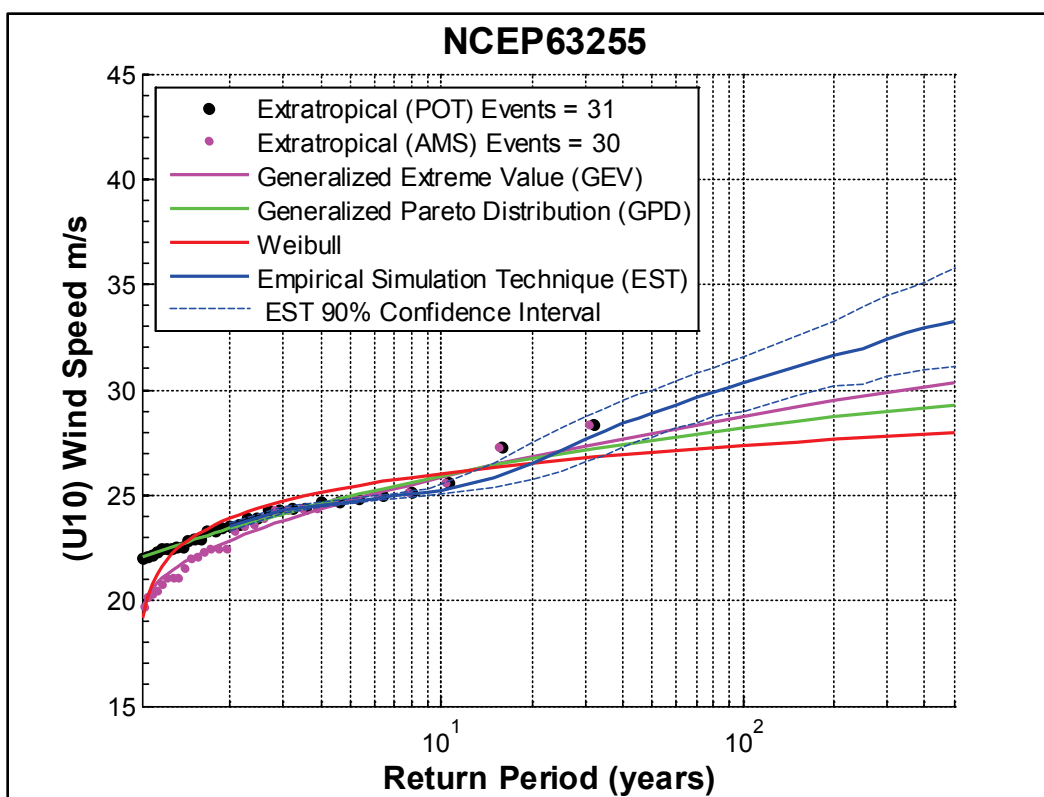
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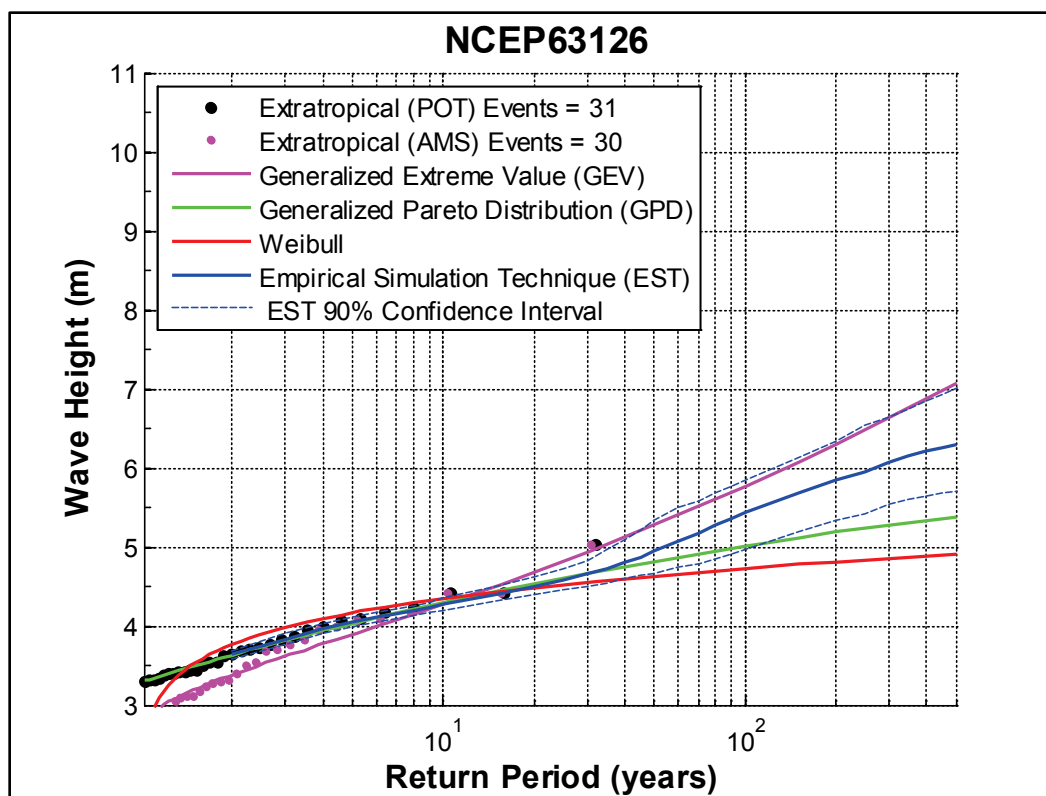
Appendix A: Extratropical Wind Speed Return Periods from 5 NCEP 30 yr (1980–2010) Hindcast Output Stations

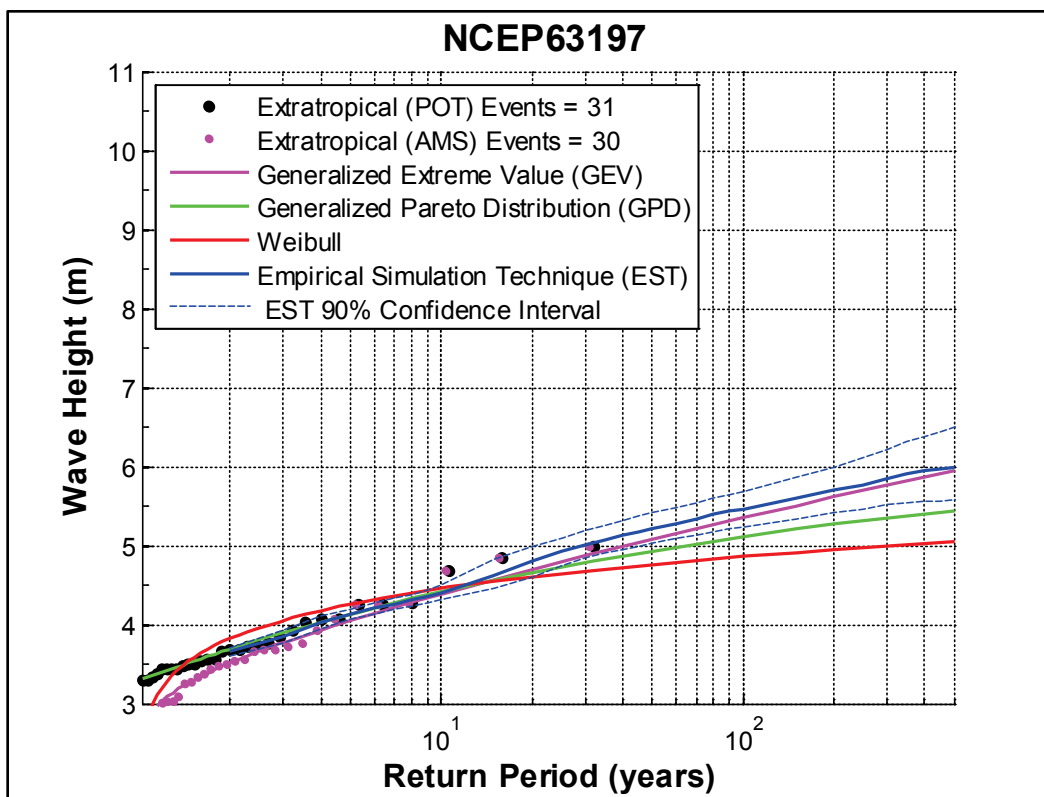
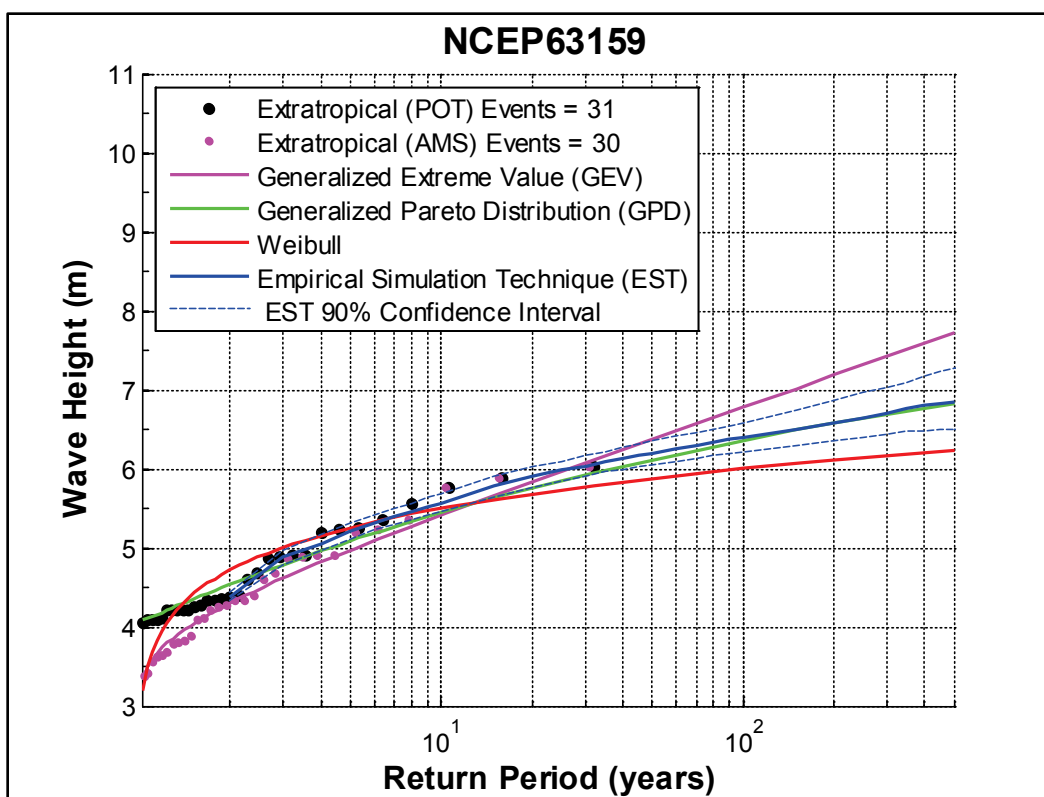


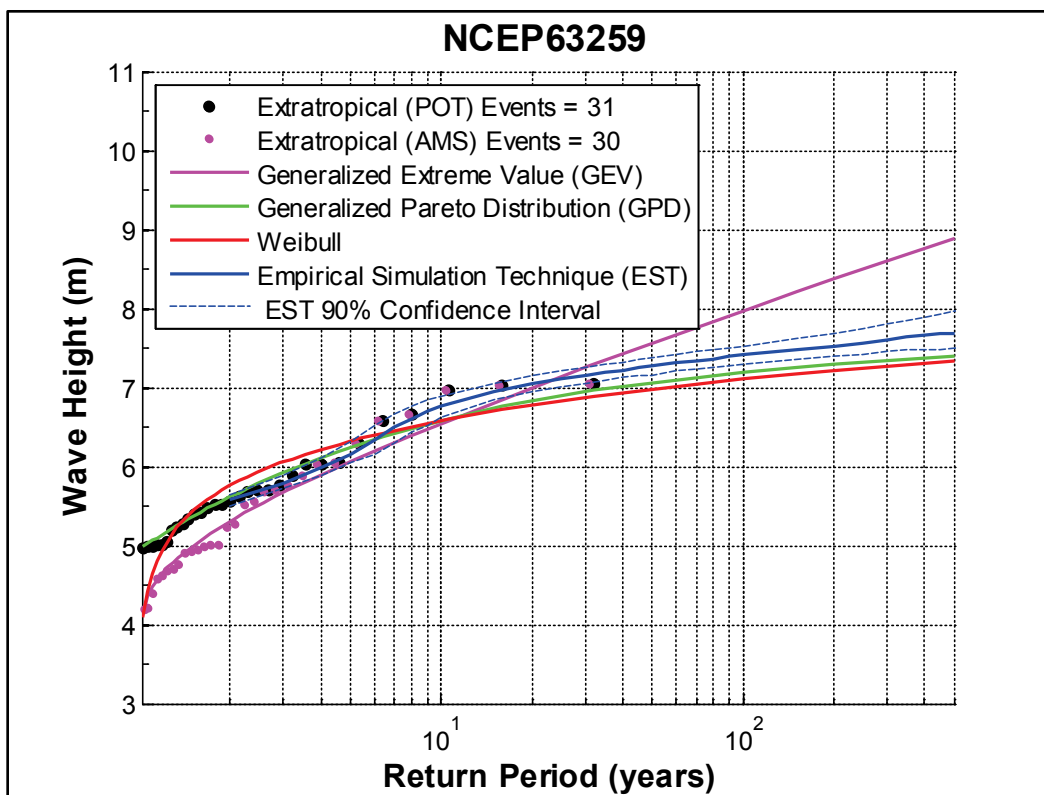
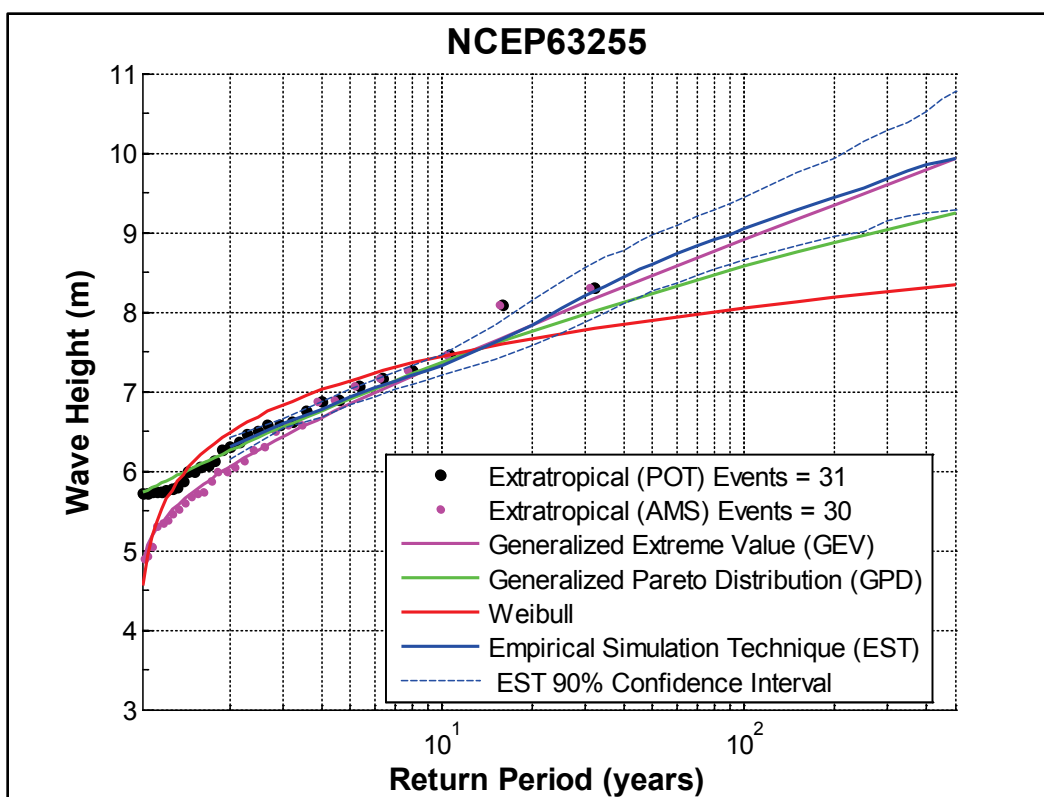




Appendix B: Extratropical Wave Height Return Periods from Five NCEP 30 yr (1980–2010) Hindcast Output Stations







REPORT DOCUMENTATION PAGE

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1. REPORT DATE August 2015		2. REPORT TYPE Technical		3. DATES COVERED (2011-2013)	
4. TITLE AND SUBTITLE Development of an Extratropical Storm Wind, Wave, and Water Level Climatology for the Offshore Mid-Atlantic				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Michael F. Forte, Jeffrey L. Hanson				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Michael F. Forte, Jeffrey L. Hanson USACE ERDC -CHL-COAB 1261 Duck Road, Duck, NC 27949				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CHL TR-15-11	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Bureau of Safety and Environmental Enforcement (BSEE) 1849 C Street, NW Washington, D.C. 20240				10. SPONSOR/MONITOR'S ACRONYM(S) BSEE	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT An investigation of the extreme offshore wind, wave, and water level climate in the mid-Atlantic region has been conducted for the U.S. Bureau of Safety and Environmental Enforcement (BSEE). The overall objective of the project is to assist with the development of meteorological and oceanographic (metocean) standards for offshore wind farm design and to establish a 100-year (yr) extratropical wind speed, wave height, and water level climatology for the specific regions of interest. Measured data from National Data Buoy Center (NDBC) and Scripps Coastal Data Information Program (CDIP) offshore stations were used to evaluate two North Atlantic Ocean hindcasts; the 20 yr U.S. Army Corps of Engineers (USACE) Wave Information Studies (WIS) with kinematically adjusted storm winds and a new 30 yr WAVEWATCH III [®] hindcast using National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis Reforecast (CFSRR) winds. Four extremal analysis techniques were evaluated on extratropical wind and wave storm extremes that included the empirical simulation technique (EST), the generalized Pareto distribution (GPD), Weibull distribution, and generalized extreme value (GEV) distribution. The WIS hindcast, in conjunction with the EST approach, was selected for use in computation of the 100 yr return period wind speed and wave height extremes for the region. For identification of a climatological data base for use in computing water level extremes, there is an evaluation of the relevance of extremal water level statistics from a recent coastal storm surge study conducted by USACE for the Federal Emergency Management Agency (FEMA) Region III. The accuracy of the FEMA results is quantified based on water level observations at the USACE Field Research Facility in Duck, NC.					
15. SUBJECT TERMS Winds Waves			Hindcasts Extremal Statistics North Atlantic Ocean		100 yr return periods extratropical storms
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 61	19a. NAME OF RESPONSIBLE PERSON Michael F. Forte
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 252.261.6840 ext.228