Development of an Integrated Extreme Wind, Wave, Current, and Water Level Climatology to Support Standards-Based Design of Offshore Wind Projects

Technology Assessment and Research Project #672

Extratropical Storm Winds, Waves, and Water Levels

APPENDIX B

US Army Corps of Engineers®

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

US Army Corps of Engineers Phase 1 Report

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1. Introduction

The US Army Corps of Engineers (USACE) has partnered with the Virginia Tech Advanced Research Institute, Old Dominion University and the 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 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 purpose of the USACE effort is 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 50- and 100-yr recurrence 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 wind fields from the Climate Forecast System Reanalysis (CFSR), a National Oceanographic and Atmospheric Administration (NOAA) National Centers for

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Environmental Prediction (NCEP) 30-year wave hindcast forced by the CFSR winds, and the FEMA RIII coastal storm surge study.

The USACE contributions to the BSEE study are being conducted in two phases. Phase I is focused on developing methodologies and includes the following objectives:

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 Phase II of 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 Phase I analysis appear in Figure 1.

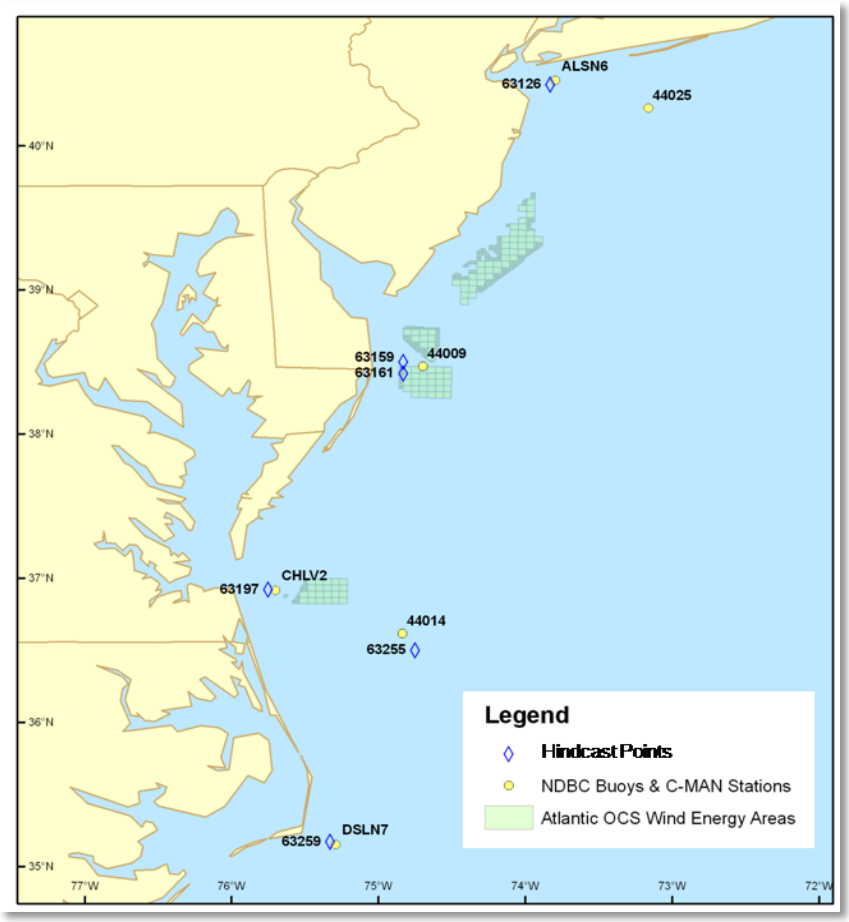

Figure 1. Project study area showing wind energy areas of interest (light green blocks), hindcast output stations (blue diamonds), and ground truth observation stations (yellow circles).

During Phase II, USACE will finalize the extremal wind, wave and water level results. The methods developed during Phase I will be applied to the latest and most appropriate hindcast datasets available. Resulting extratropical 50- and 100-yr wind and wave extremes will be provided to the project team for synthesis with the tropical results, with the goal of producing combined maps of 50-and 100-yr extremal statistics for the region. If deemed appropriate, the FEMA RIII water level extremes will also be 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.

NCEP Hindcast

A new 30-yr wind and wave hindcast is available for use by this study. Winds from the Climate Forecast System Reanalysis (CFSR) are derived from a 30 year reanalysis wind data set with a spatial resolution of $0.5 \times 0.5^{\circ}$ and a temporal resolution of 1 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 3rd-generation numerical wave model WAVEWATCH III, is being performed by the National Centers for Environmental Prediction (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 as is.

Phase II. Generate a second hindcast using the first NOPP based physical upgrade for operational wave models at NCEP.

Phase IIII Using 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 year 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 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-hourly intervals, at all National Data Buoy Center (NDBC) buoy locations as well as the USACE Wave Information Studies hindcast points (see below).

WIS Hindcast

The Wave Information Studies (WIS) is a USACE-sponsored project that generates consistent, hourly, long-term (20-30 years) wave climatologies along all US coastlines, including the Great Lakes and US island territories. The WIS program originated in the Great Lakes in the mid 1970's and migrated to the Atlantic, Gulf of Mexico and Pacific Oceans. The WIS hindcast domains are depicted in Figure 2. Consistent, high-quality windfields are used to force numerical wave models in each domain. Furthermore the wave modeling technology applied, at the time each hindcast was generated, has kept pace with research advances in model development.

Hindcast winds and waves from the Atlantic WIS domain were used in this study. Winds are extracted from high-quality, consistent, neutral stability wind fields at 3-hour intervals on a 0.5-degree 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-hourly, 10-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-year 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 2-D 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-hourly intervals, at various points around the US Atlantic coastline. Specific output points for our 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 a variety of 'virtual' buoy locations (red symbols).

It should be noted that USACE recently took delivery of new OWI Atlantic windfields for 2000-2009. This 10-year wind hindcast will be combined with the previous two decades to produce a new 30-year Atlantic wave hindcast, likely using an advanced third-generation numerical wave modeling technology. Although the winds are available now, it is not clear if the new wave hindcast product will be available in time for the completion of this study.

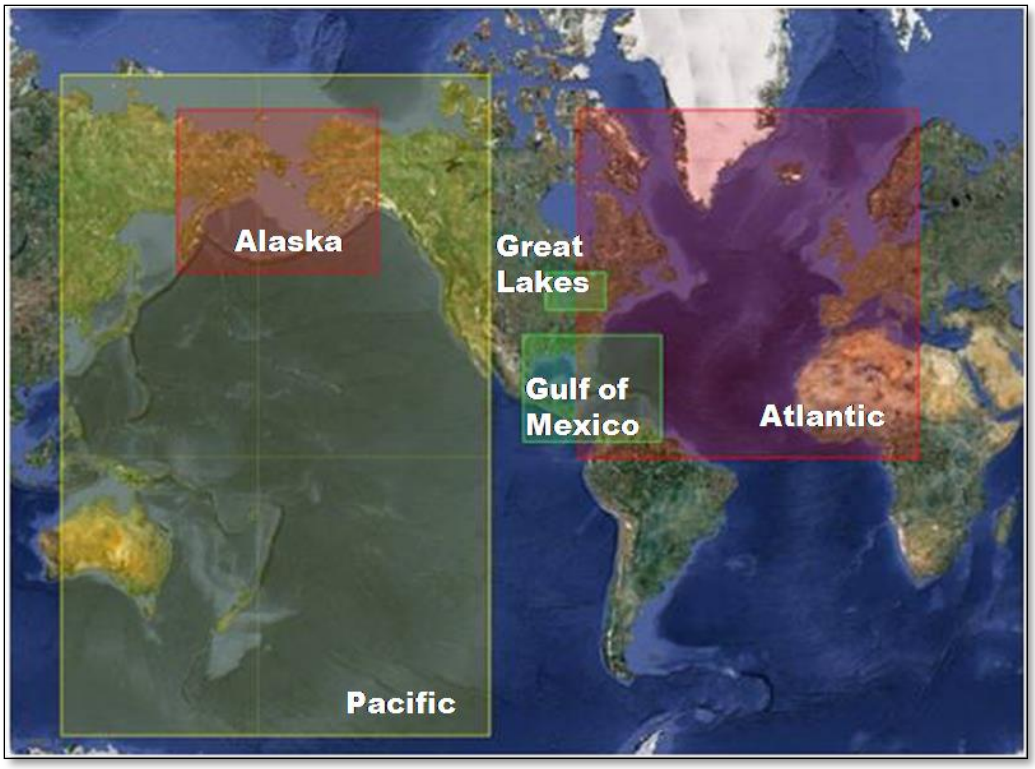

Figure 2. Wave Information Studies (WIS) Wind and Wave Hindcast Domains

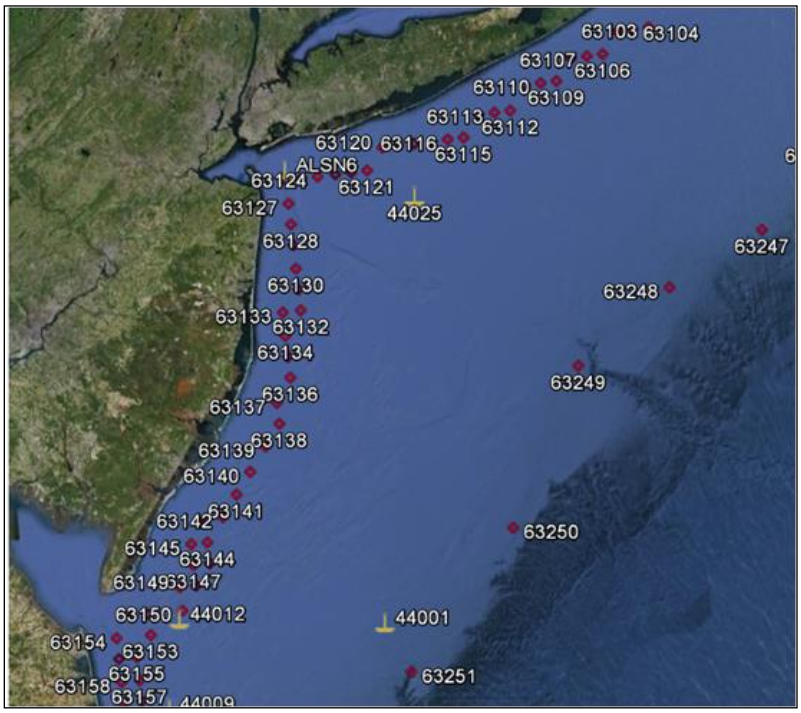

Figure 3. NCEP and WIS Hindcast output points for offshore New York and New Jersey. Red symbols indicate standard hindcast points, Yellow symbols identify buoy locations.

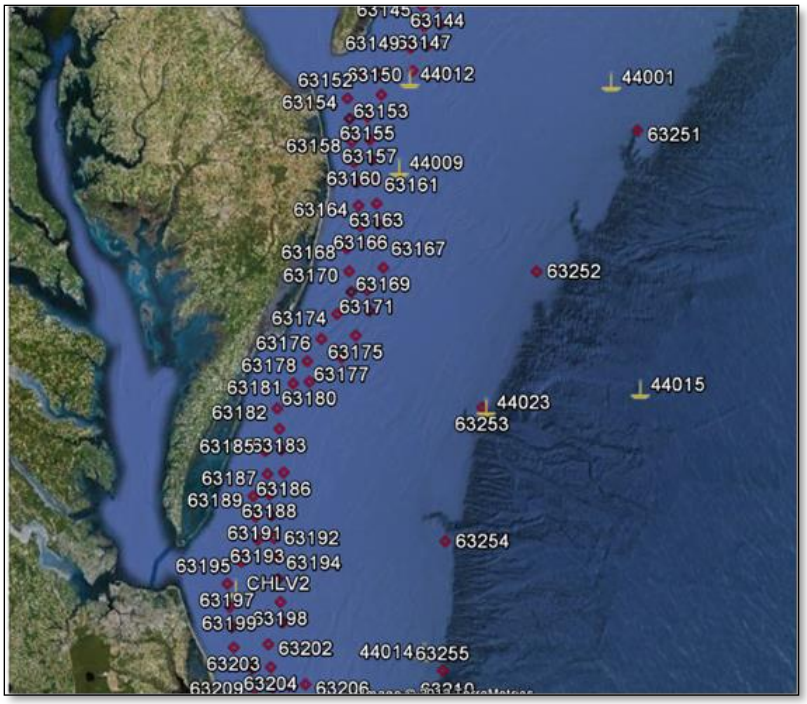

Figure 4. NCEP and WIS Hindcast output points for offshore Delaware, Maryland and Virginia. Red symbols indicate standard hindcast points, Yellow symbols identify buoy locations.

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. These records provide a long duration, robust set of coincident wind and directional wave observations at each site. For consistency issues, we only include data collected with directional wave sensors in the analysis. 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 this analysis, 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

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 remove any co-existing tropical event time period from the data set. For this investigation a defined radius of 18 degrees (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 analysis (see below) so that the extremal analysis results are not influenced by tropical events.

Peaks over Threshold Analysis

The wind and wave extremal analysis methods require identification of the event peak conditions. To isolate peak wind speed and wave height event values a Peaks-Over-Threshold (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 recurrence interval analyses. An example of peak wave events selected during 1997 at NDBC buoy 44009 offshore of Delaware is shown in Figure 5.

User inputs to the data-adaptive POT algorithm include a standard deviation multiplier *kh*, an inter-event 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 (wind speed or wave height) over the time period of interest, $\bar{x}$ is the mean of *x*, and ? ?$_x$ is the standard deviation of x. 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 extratropical inter-event time of T= 72 hours was used for all datasets in this study.

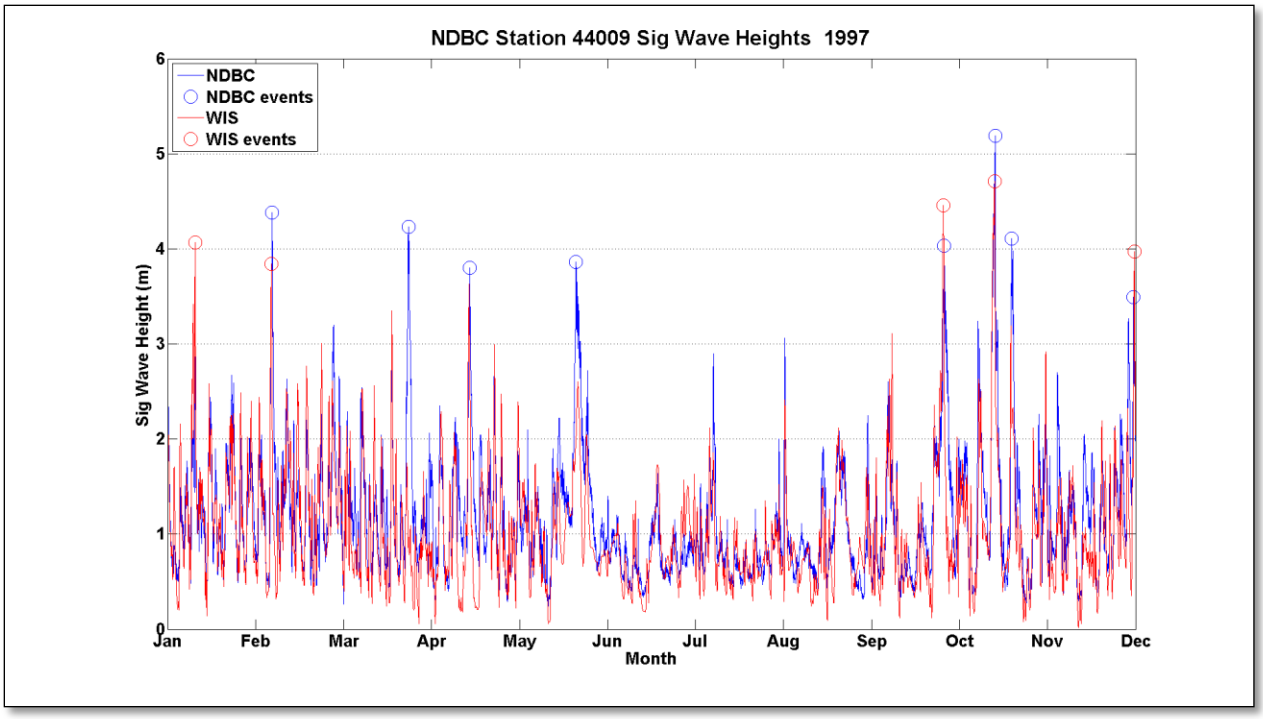

Figure 5. Sample baseline wave heights (solid lines) and event peaks (circles) for both NDBC observations (blue) and WIS hindcast (red) at NDBC Station 44009 during 1997.

Hindcast Validation Approach

A comprehensive assessment of hindcast performance at each NDBC buoy site was performed. The assessment was accomplished using the model evaluation tools in the XWaves ocean wavefield analysis toolbox for Matlab™ (WaveForce, 2012). The XWaves model evaluation module, 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-hour 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 Tropical Cyclone events from the observational data as described above.
3. Generate sets of 3-hourly 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 (U10, m/s)
   - Wind direction (TWD, degrees clockwise from N)
   - Significant wave height (Hs, m)
   - Peak period (Tp, s)
   - Mean wave period (Tz, s)
   - Mean wave direction (Dm, 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 (U10, Hs, Tp, Tz):

   RMS Error (RMS), bias, Scatter Index (SI), Regression coefficient (R^2)

   Direction parameters (TWD, Dm):

   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 3 standard deviations above the mean (see POT description above). To allow for spatial variations in wind and wave climate, these thresholds were computed independently on the data from each NDBC buoy station.

Extratropical Storm Population Rank Order

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

$$Rp = \tau + \frac{1}{\vartheta}$$

Where Rp is the recurrence interval, τ **is the number of years,** and ϑ is the rank order of event.

2.3 Extremal Analysis Methods

Four extremal analysis methods including the Generalized Extreme Value (GEV), The Generalized Pareto Distribution (GPD), Weibull, and the Empirical Simulation Technique (EST) were evaluated for use in computing 100-year wind speeds and wave heights from the WIS and NCEP hindcasts. A description of each of these methods appears below.

Empirical Simulation Technique

The Empirical Simulation Technique (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, 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 Region III Coastal Storm Surge Study (Hanson et. al,2012) The present study employed a univariate EST analysis where the input vector is total wave height and wind speed and the response vector is total wave height and wind speed.

Generalized Pareto Distribution

The Generalized Pareto Distribution (GPD) is a probability density function with the following 3 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-year 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 another 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.

Generalized Extreme Value (GEV) Distributions

The Generalized Extreme Value (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*. Based on this criterion, the GEV results in this study are based on the Frechet distribution. However 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 our hindcast data.

3. Hindcast validation

As the project has multiple wind and wave hindcasts to select from, a through comparison is warranted to identify the strengths and weaknesses of each. Furthermore the NCEP 30-year hindcast, forced by CSFR 30-year 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. Phase II of this study will expand the assessment to include other NDBC stations in the region of interest.

3.1 Full Hindcast Assessment

The wave climate was assessed over a 10-year period (1990-1999) for which we have 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 to 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 data (red). Furthermore the overall bias and regression coefficient (r^2) are provided for each set of comparisons.

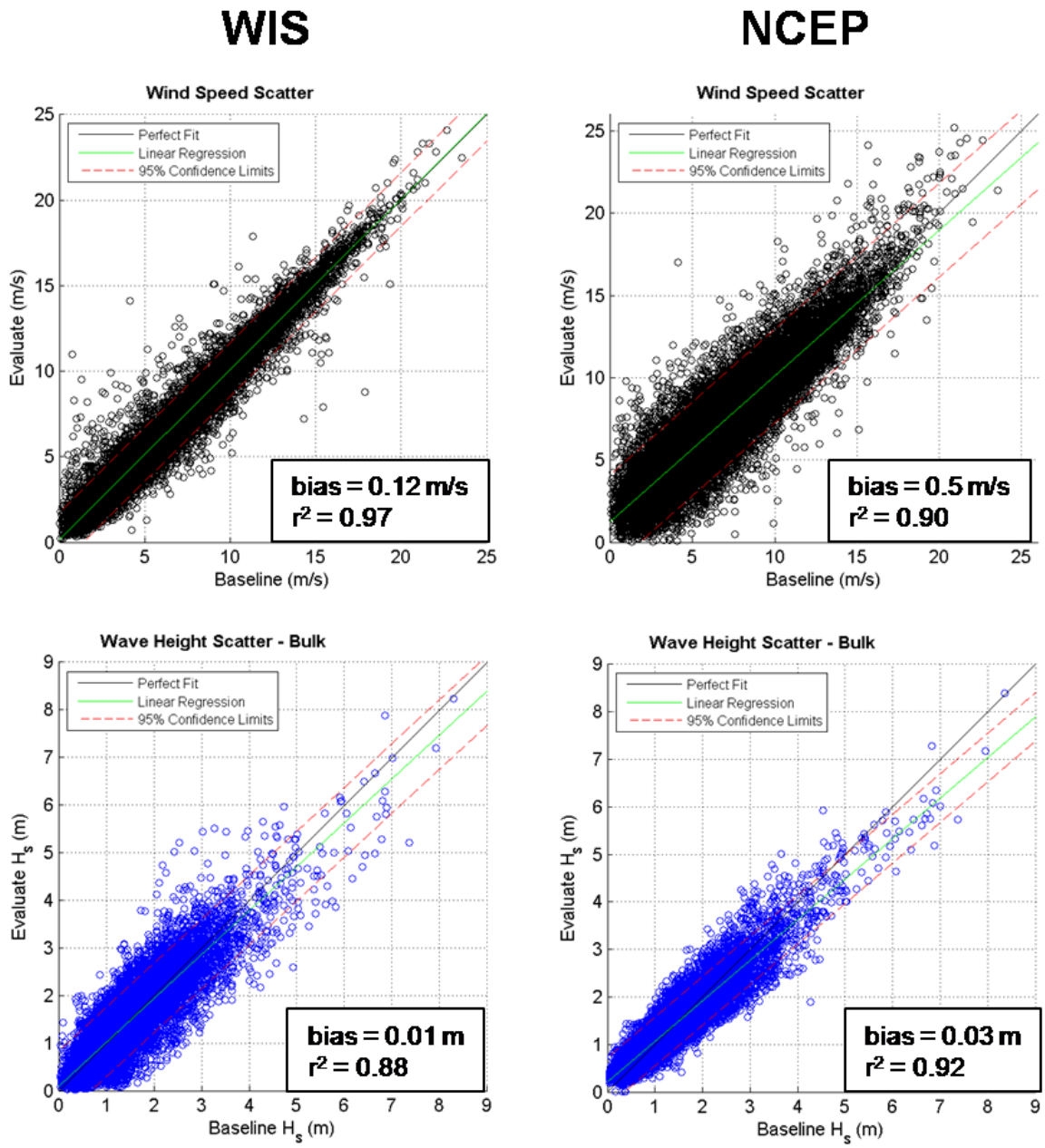

Figure 6. Station 44025 full hindcast evaluations. See text for explanation.

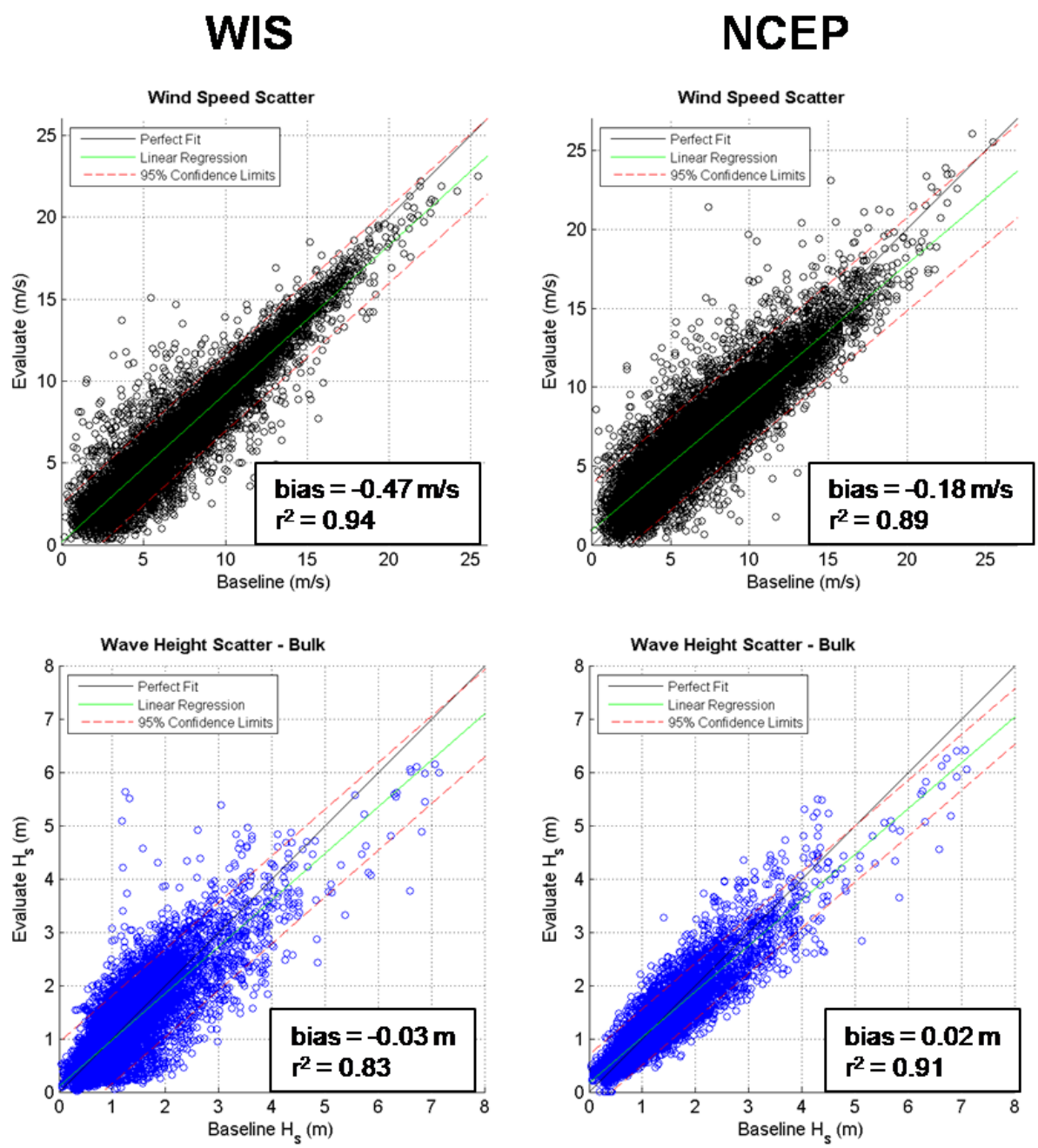

Figure 7. Station 44009 full hindcast evaluations. See text for explanation.

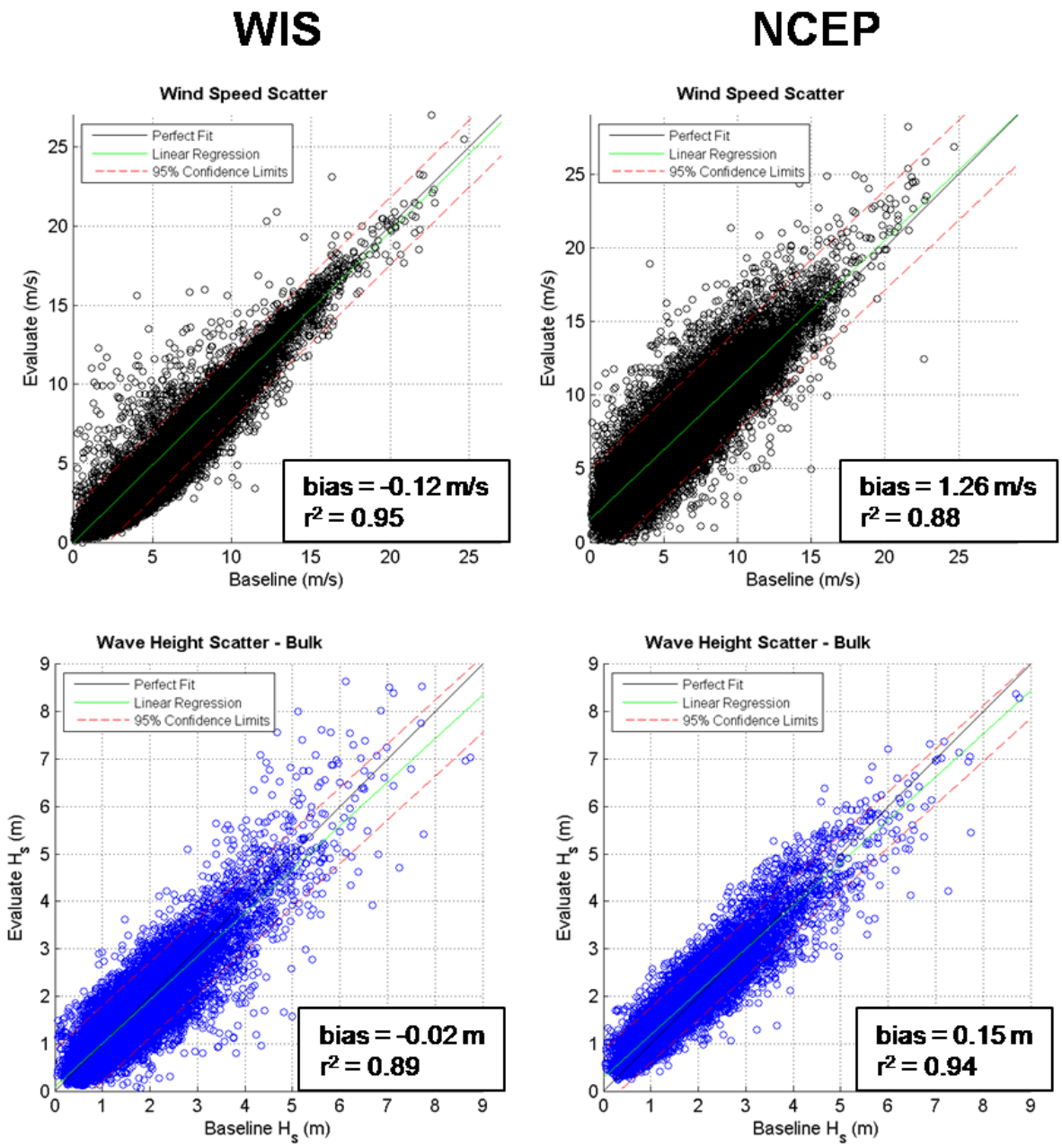

Figure 8. Station 44014 full hindcast evaluations. See text for explanation.

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.

The full-hindcast wave comparisons from Figures 6 to 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-h 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.

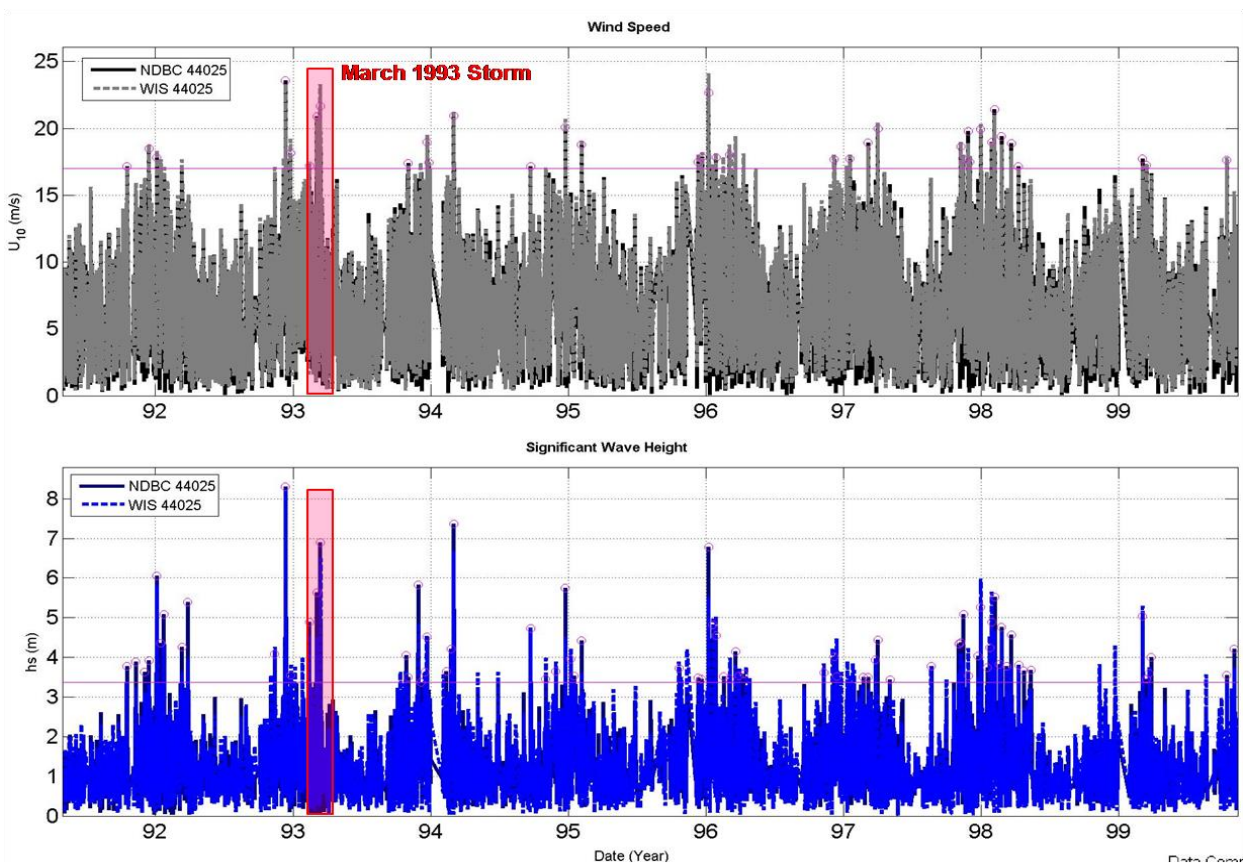

Figure 9. Wind speed (upper) and wave height (lower) peak selection at station 44025. Horizontal magenta line shows the applied threshold. Open circles depict the selected extremes.

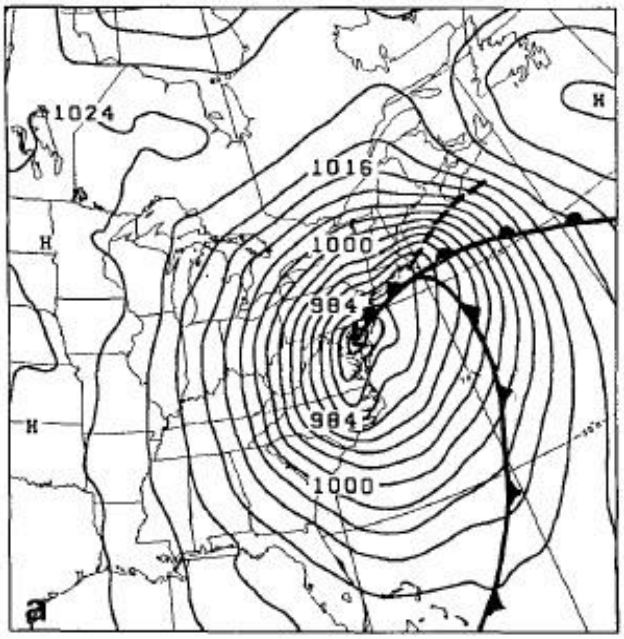

Figure 10. Surface pressure Isobars (mbar) for the famous March 1993 'Storm of the Century' that traveled up the US east coast.

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 March 12–13, 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) and selected peaks (open circles) are 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.

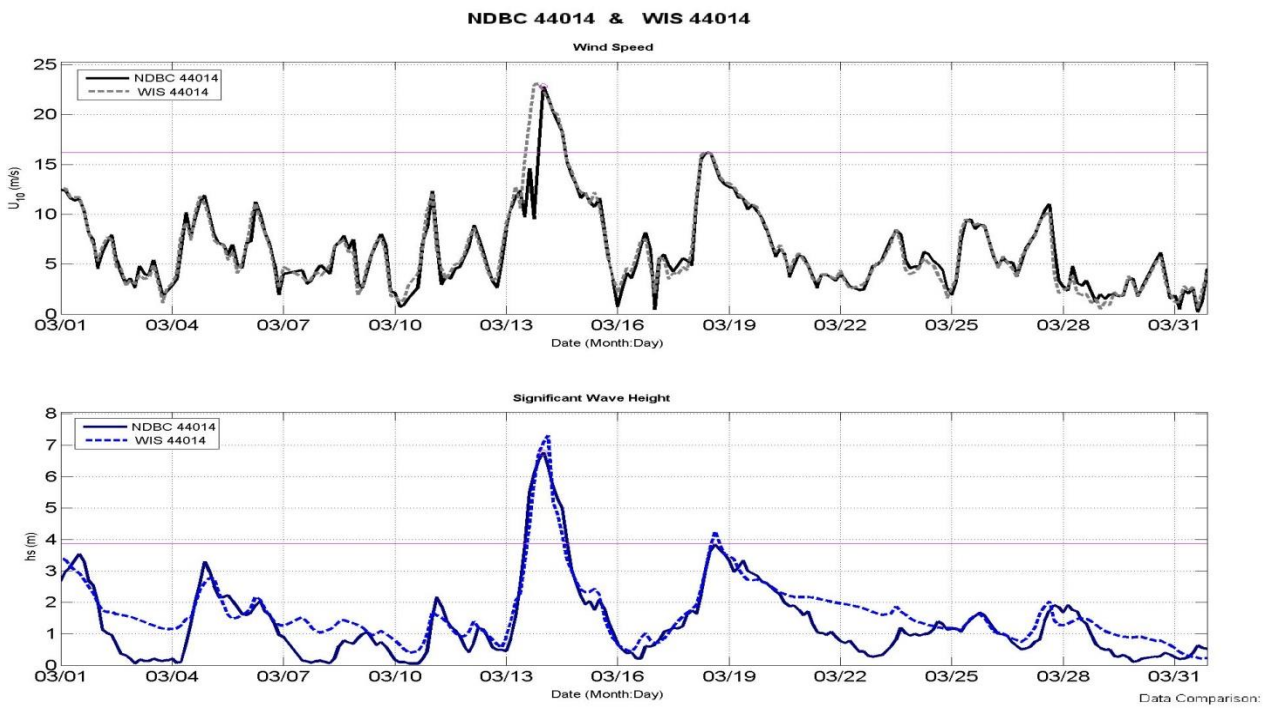

Figure 11. Comparison of WIS winds and waves to observations at Station 44014 during the March 1993 storm

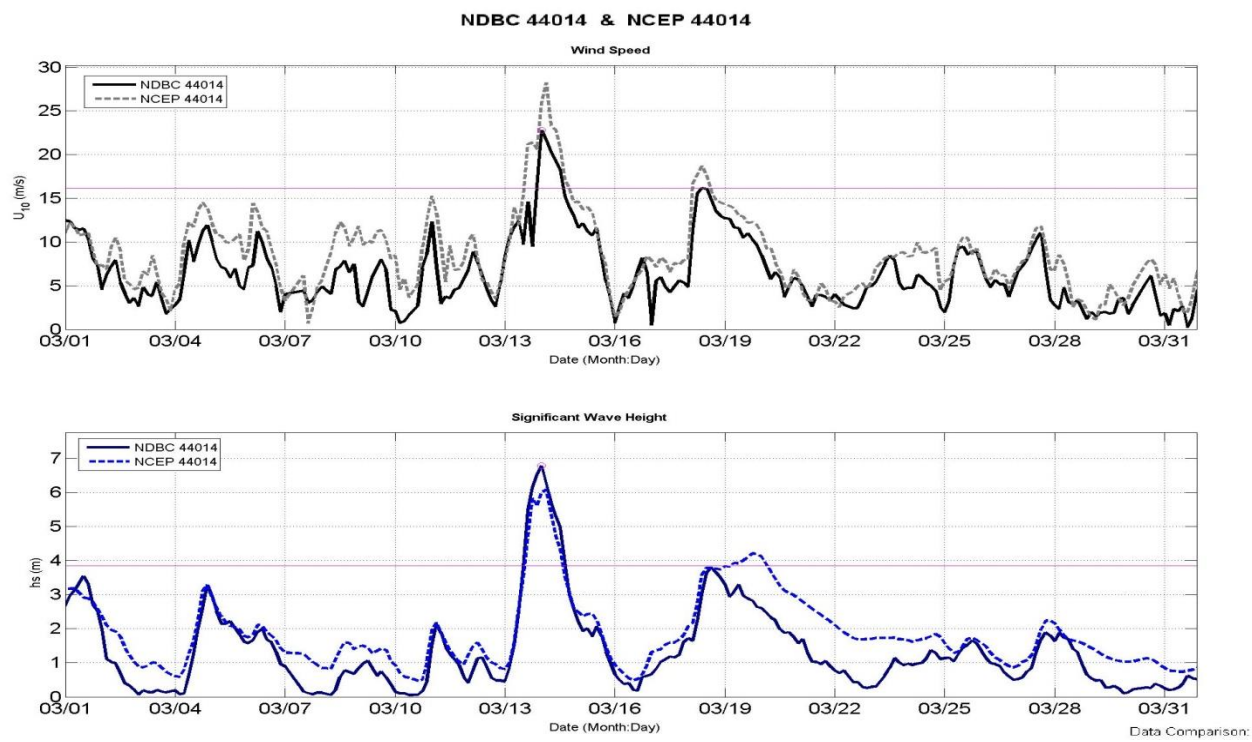

Figure 12. Comparison of CFSR winds and NCEP waves to observations at Station 44014 during the March 1993 storm

Statistical results from the 10-year 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 to 15, respectively. The plots include the same features as was 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 2 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-year time period.

The overall extreme wave height performance is very similar for the WIS and NCEP hindcasts (Figures 13 to 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.

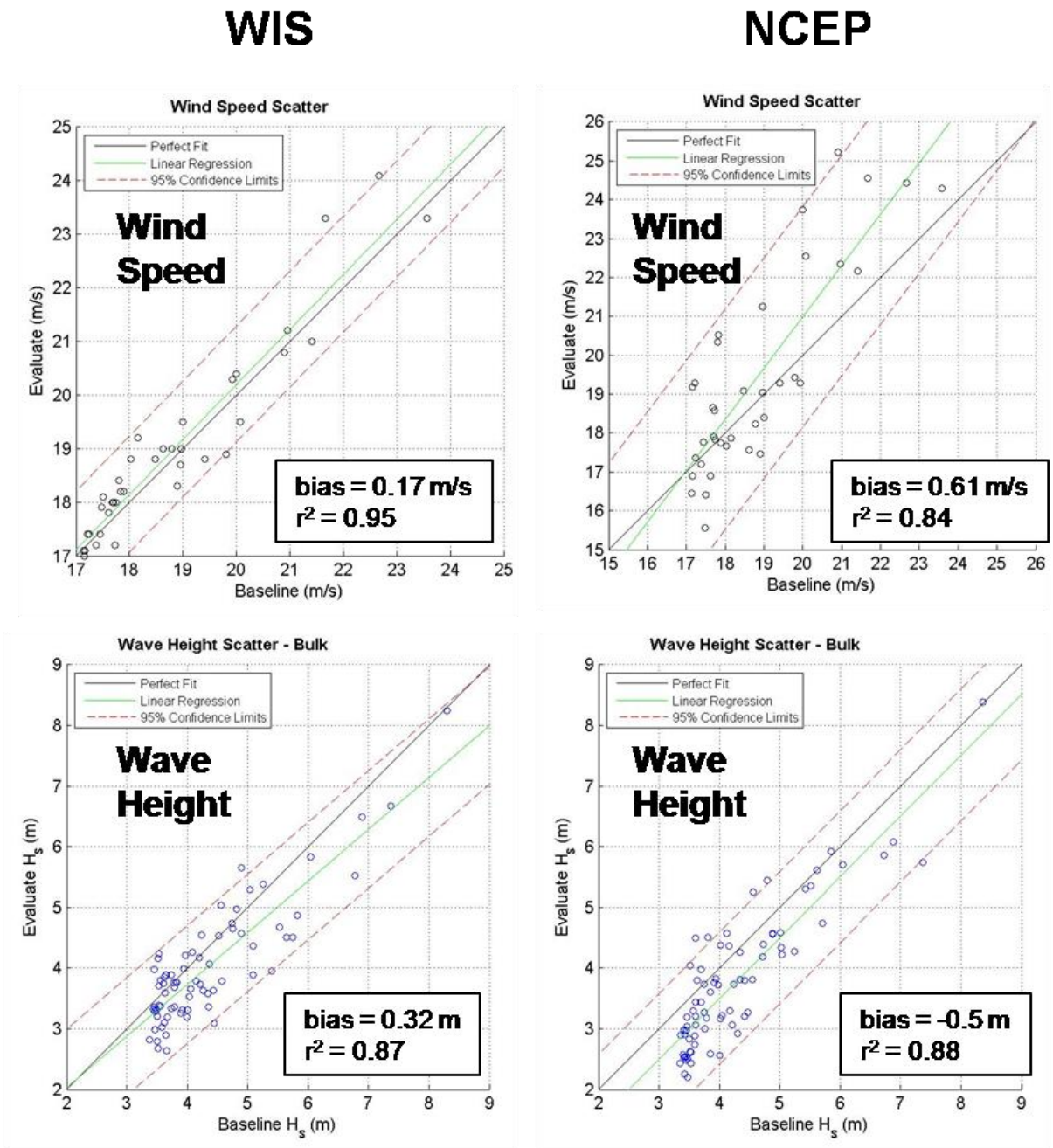

Figure 13. Station 44025 peak event evaluations. See text for explanation.

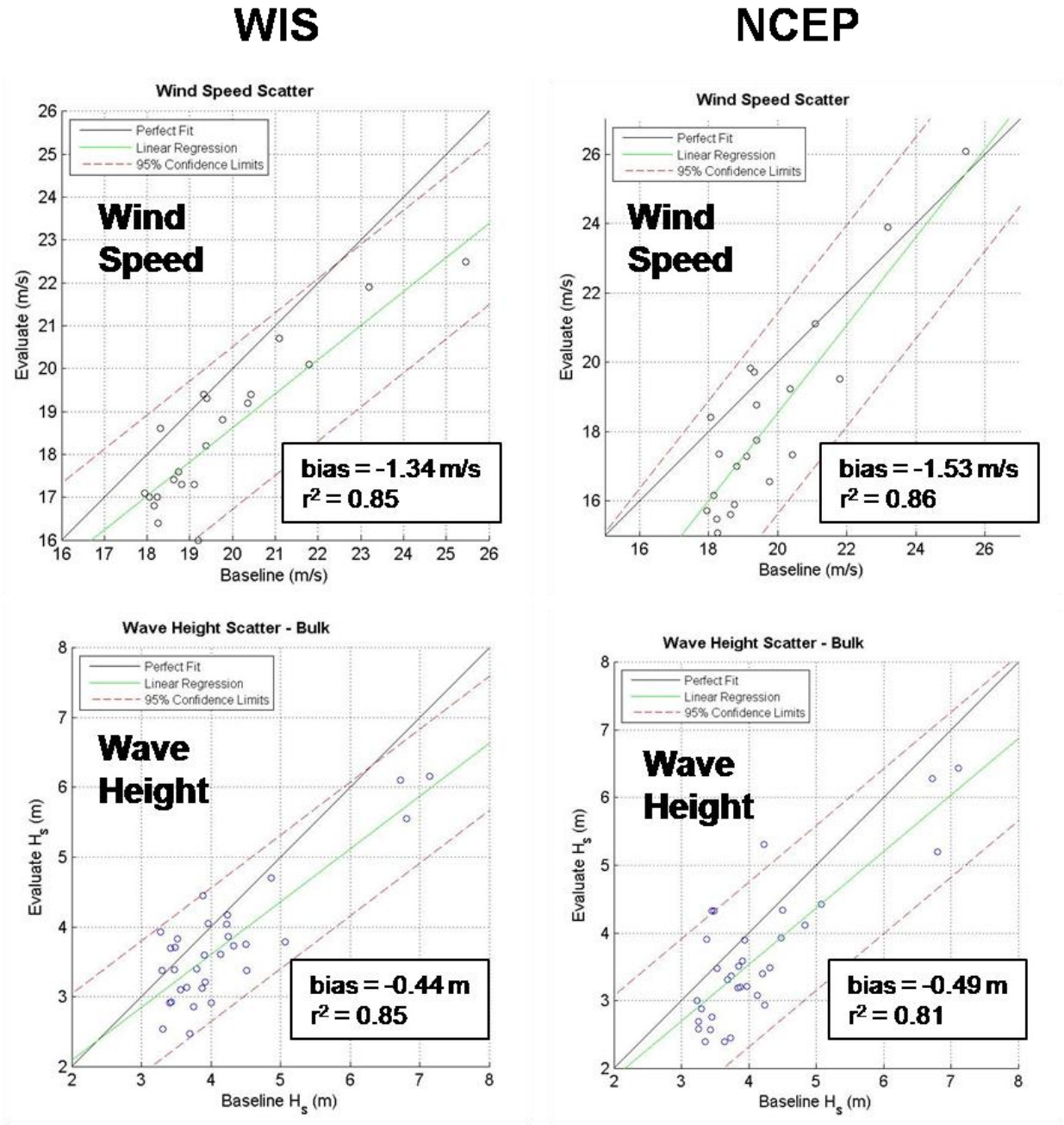

Figure 14. Station 44009 peak event evaluations. See text for explanation.

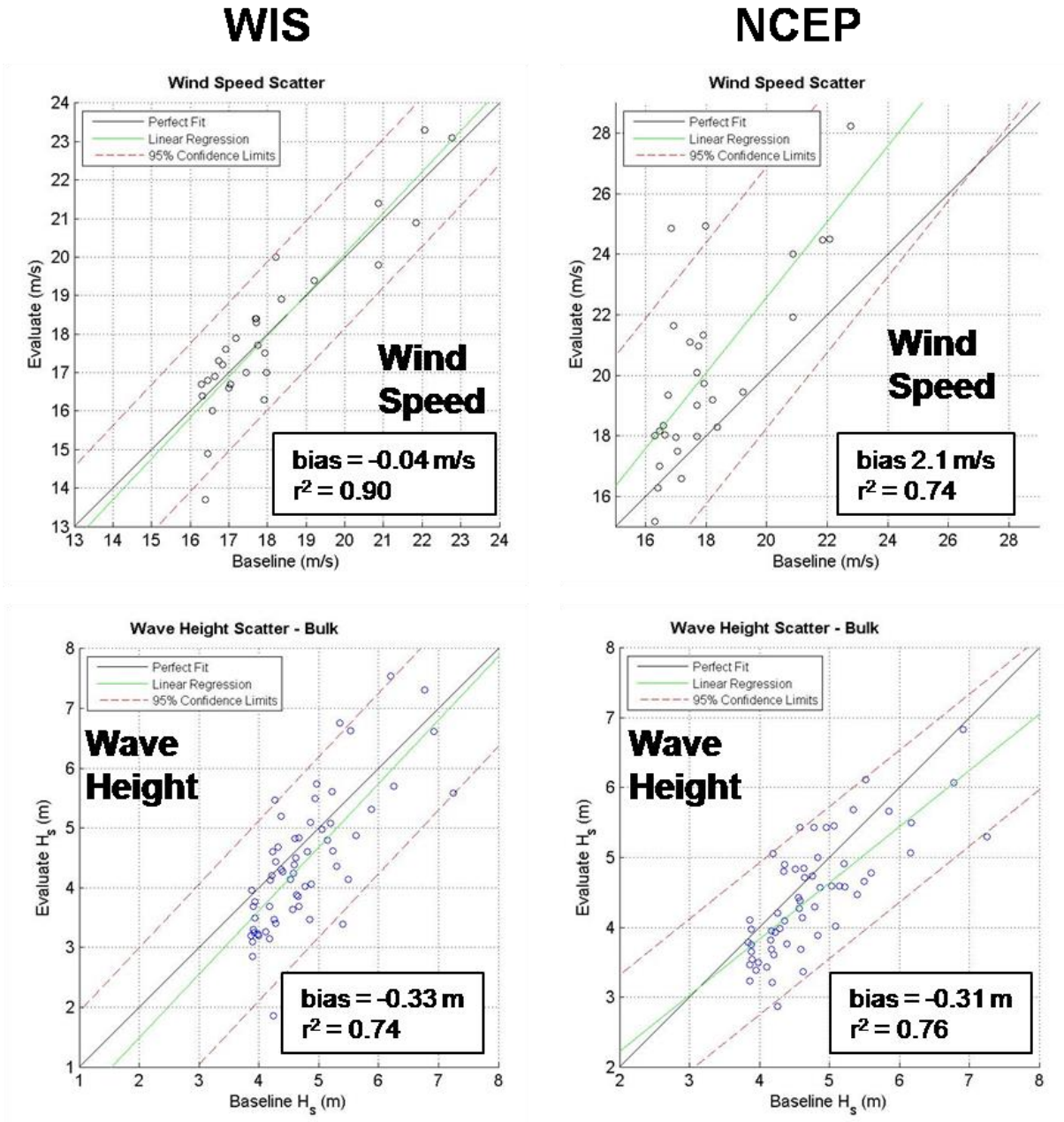

Figure 15. Station 44014 peak event evaluations. See text for explanation.

4. Extratropical Extremal Wind and Wave Estimates

4.1 Method Assessment

The extremal analysis method evaluation focused on data fit and the representation of the 50 and 100-yr recurrence interval or the "tail" of the distribution. The NCEP hindcast for the 30 year period (1980-2010) was used for this assessment since it was the longest record. Figures 16 to 20 display the results from the various extremal techniques that were applied to the data at each of the 5 evaluation stations shown in Figure 1. Each plot contains the storm population (black dots) and the various parametric fits (colored lines) including the GEV, Weibull, and GPD as well as the non-parametric EST extrapolated out to the 50 and 100-yr wave recurrence intervals.

The EST demonstrated a consistent fit to all the data from each storm population at each of the 5 test stations. In addition the EST demonstrated a steady representation of the recurrence interval in that it mimicked the slope of the top 3-5 events. Stations that demonstrated higher variability of the top 3 events such as 63126 and 63255 were reflected in the EST result by an increased or steeper slope approaching the 50 and 100-yr recurrence interval. 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 recurrence intervals. The GPD was ranked 2nd to the EST in fitting the data, however the recurrence intervals came in lower at all but station 63159 where it matched the EST. The GEV and Weibull showed the most variability both in fitting the data at the extremes and the prediction of the 50 and 100-yr recurrence interval. A consistent trend was not observed in the GEV data fitting although the GEV always predicted a higher recurrence interval than the EST and GPD by approximately 1-1.5m at the 100-yr interval. The Weibull showed steady trends of fitting the data except for the top 3 events where it always fell under the data and resulted in the lowest recurrence intervals of all the methods. From this assessment, the EST is clearly the recommended approach for this study. The plots from all stations for both waves and winds are included as Appendix A and B respectively.

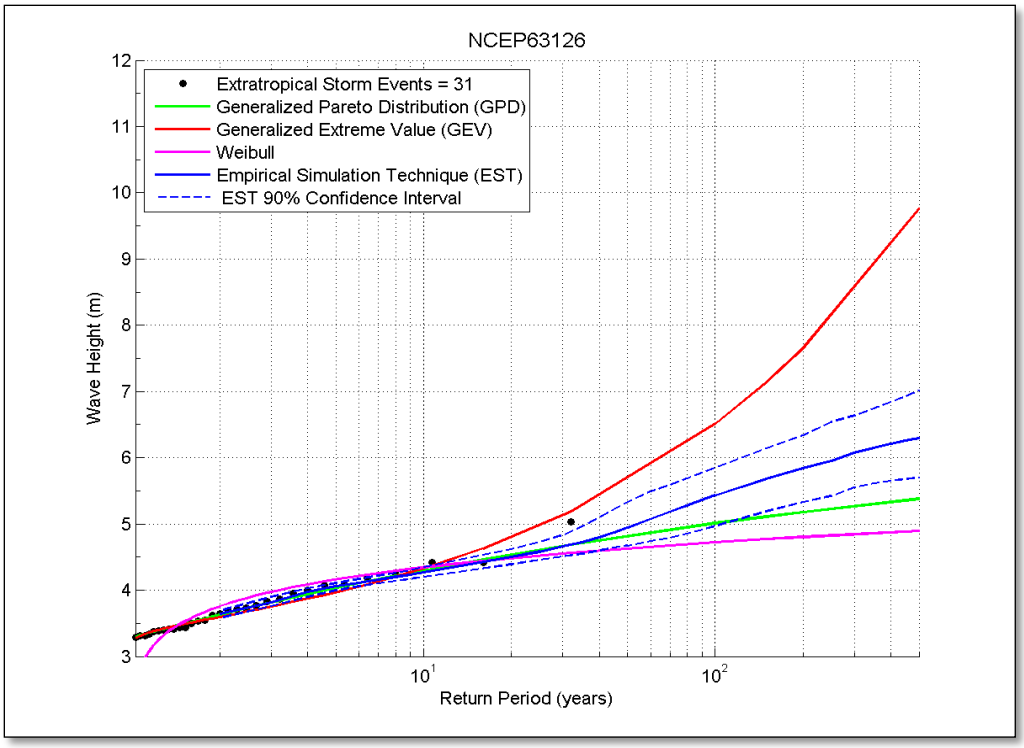

Figure 16. Station 63126 approximately 8 miles East of Sandy Hook NJ

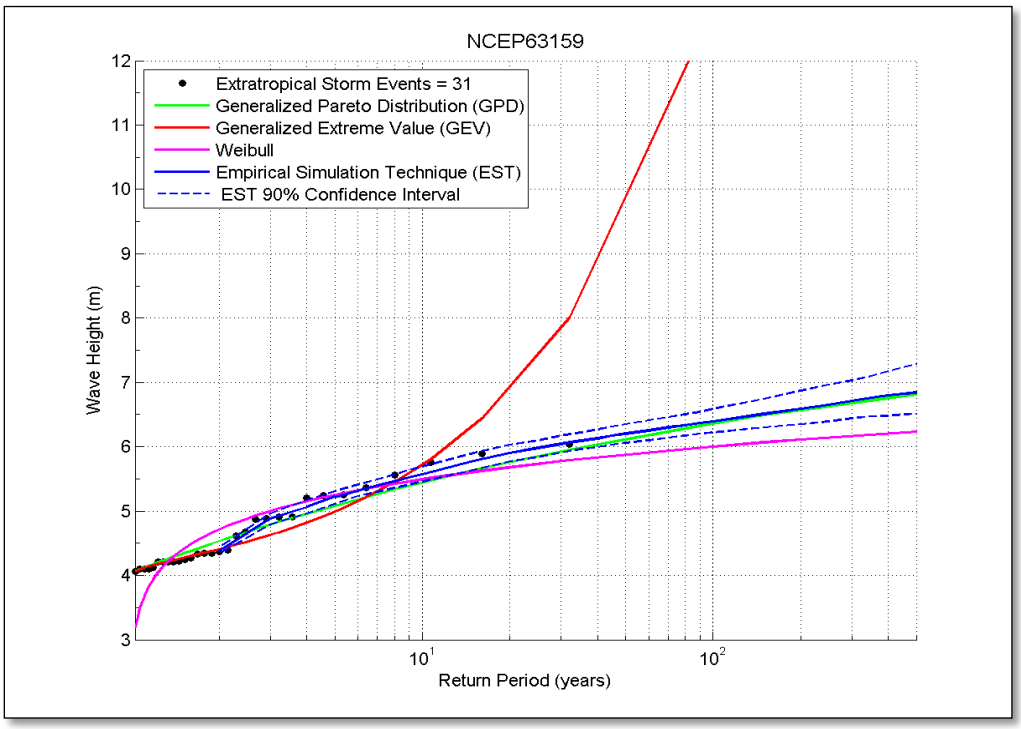

Figure 17. Station 63159 12 miles off the coast of Delaware

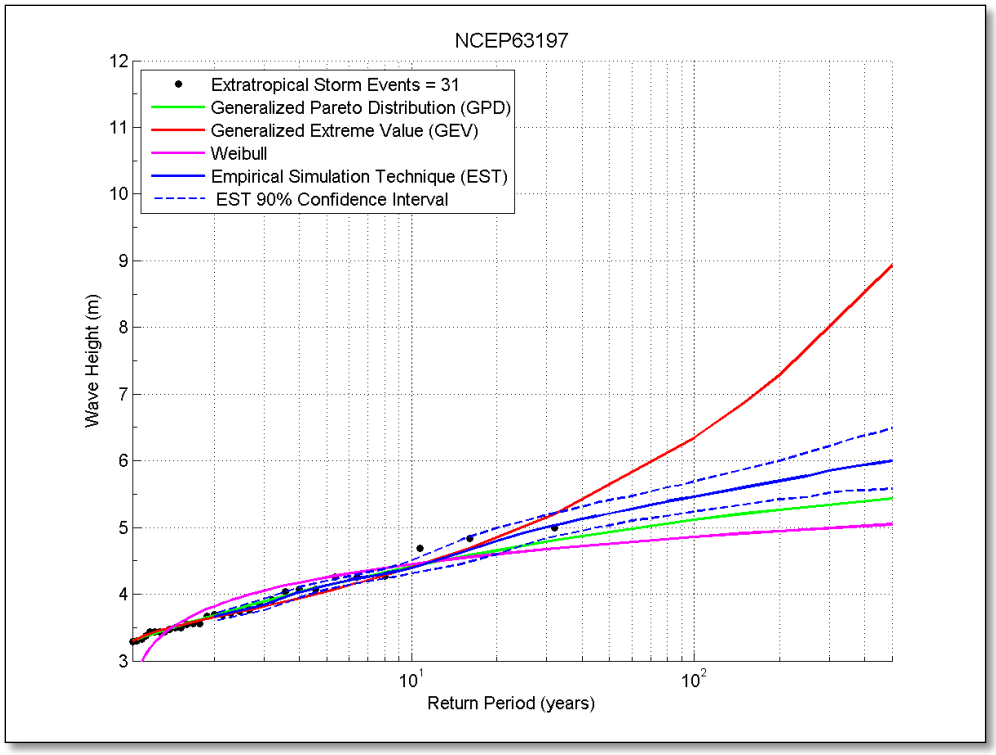

Figure 18. Station 63197 14 miles East of the entrance to Chesapeake Bay

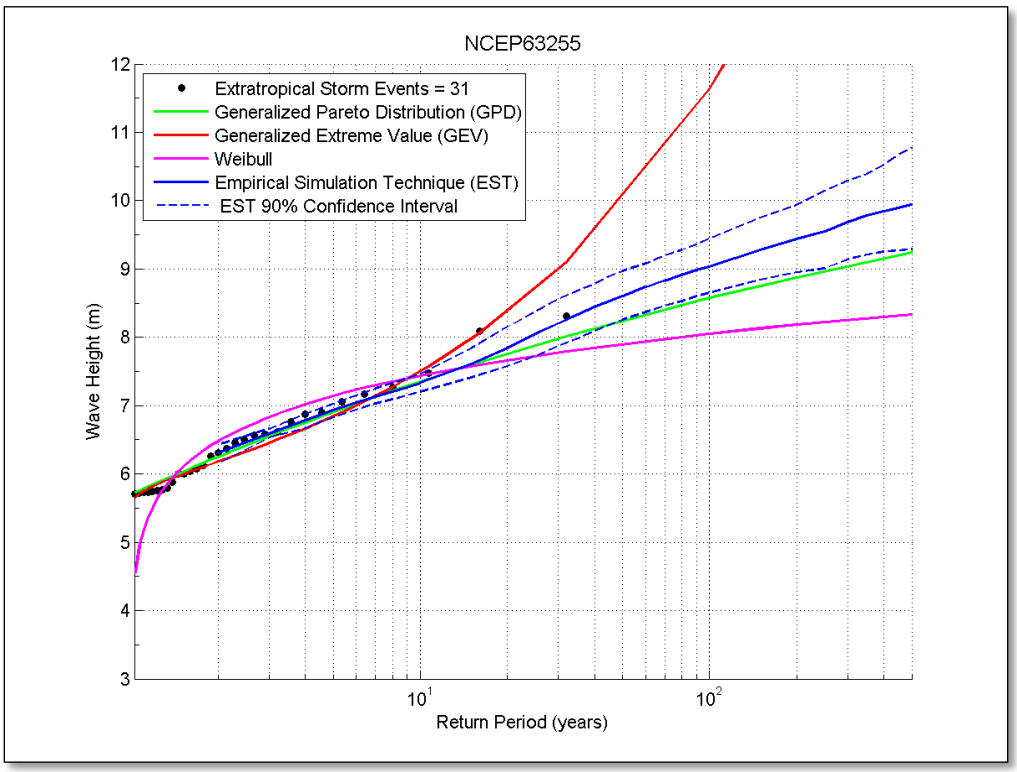

Figure 19. Station 63255 60 miles offshore of NC/VA border.

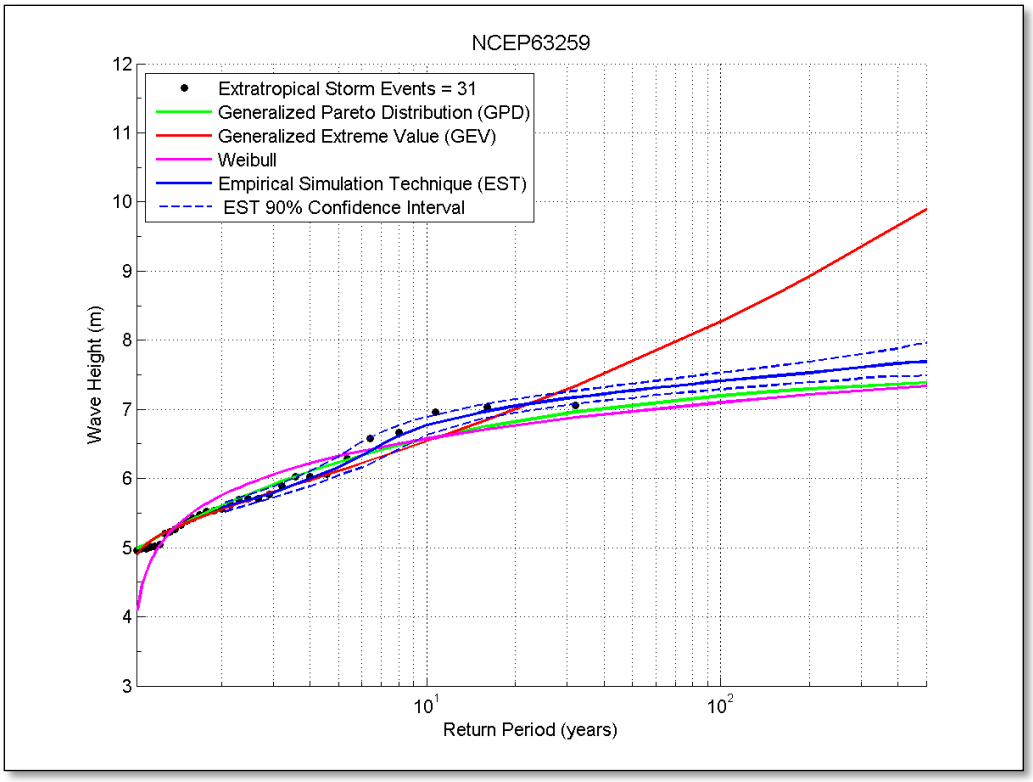

Figure 20. Station 63259 12 miles offshore of Cape Hatteras, NC.

4.2 EST Sensitivity Testing

Storm Population Sensitivity Study

A sensitivity study on storm population and its effect on the EST recurrence intervals was performed using the NCEP 30-yr hindcast at the 5 test locations (blue diamond's) shown in Figure 1. The POT parameters were adjusted to achieve 3 storm populations, high (80-90 storms), mid (30-40 storms), and low (10-20 storms). The inter-event time remained constant at 72 hours. 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 recurrence intervals at 50 and 100-yr were computed. The results are included as Table 1 and indicated that the storm population had little to no impact on the EST computed recurrence interval. Capturing the top 5 most extreme events is paramount when applying the EST technique.

Table 1. Results from Storm Population Sensitivity Study

		Waves			Winds	
	Station	**50yr(m)**	**100yr(m)**		**50yr(m/s)**	**100yr(m/s)**
High	NCEP63126	4.97	5.45		21.92	22.98
	NCEP63159	6.21	6.41		27.06	28
	NCEP63197	5.25	5.49		25.39	25.9
	NCEP63255	8.63	9.07		29.01	30.39
	NCEP63259	7.28	7.41		32.2	33.7
Mid	NCEP63126	4.94	5.43		21.85	22.92
	NCEP63159	6.2	6.39		27.01	27.95
	NCEP63197	5.21	5.46		25.31	25.84
	NCEP63255	8.6	9.04		28.92	30.31
	NCEP63259	7.27	7.41		32.13	33.67
Low	NCEP63126	4.96	5.44		21.86	22.95
	NCEP63159	6.2	6.4		27.03	27.97
	NCEP63197	5.22	5.46		25.33	25.85
	NCEP63255	8.61	9.05		28.94	30.36
	NCEP63259	7.27	7.4		32.14	33.66

4.3 Wind Speed and Wave Height Recurrence Intervals

The EST was applied to winds and waves on all 5 test stations for both the WIS and NCEP hindcast covering the same 20yr period (1980-1999). The 50 and 100-yr recurrence intervals for both wind and waves are compared between NCEP and WIS in Figures 21 and 22 and included in Table 2. The WIS hindcast recurrence intervals were subtracted from the NCEP hindcast recurrence intervals to compute hindcast differences. Winds (NCEP – WIS) have mean differences of 1.13 and 0.76 m/s for the 50 and 100-yr recurrence intervals respectively. Waves have mean differences of -0.98 and -1.37m for the 50 and 100-yr recurrence intervals respectively.

The large difference in the wave height recurrence intervals at station 63259 offshore of Cape Hatteras (Figure 22) is driven by the March 1993 Storm of the Century (Figure 10). As the WIS recurrence interval plot of Figure 23 depicts, this was the most extreme event (rank=1) in the WIS wave height hindcast at this station, with max Hs = 9.5 m. A comparison of the WIS and NCEP significant wave height time series over the course of this event appears in Figure 24. Note that the maximum WIS wave height values are approximately 2.4 m higher than those from the NCEP hindcast. Although there is no ground truth available at this station, hindcast validation results from NDBC station 44014, approximately 70 nautical miles to the north, were previously presented in Figures 11 and 12. At that location, the March 1993 wavefield was most accurately captured by WIS, with a 0.4-m positive bias. The NCEP peak wave heights at that station are biased low by -1.0 m.

This example demonstrates the importance of accurately capturing the most extreme events in a hindcast. At station 63259 a 2.5-m hindcast wave height difference translates into a difference of > 5-m in 100-yr wave height estimates.

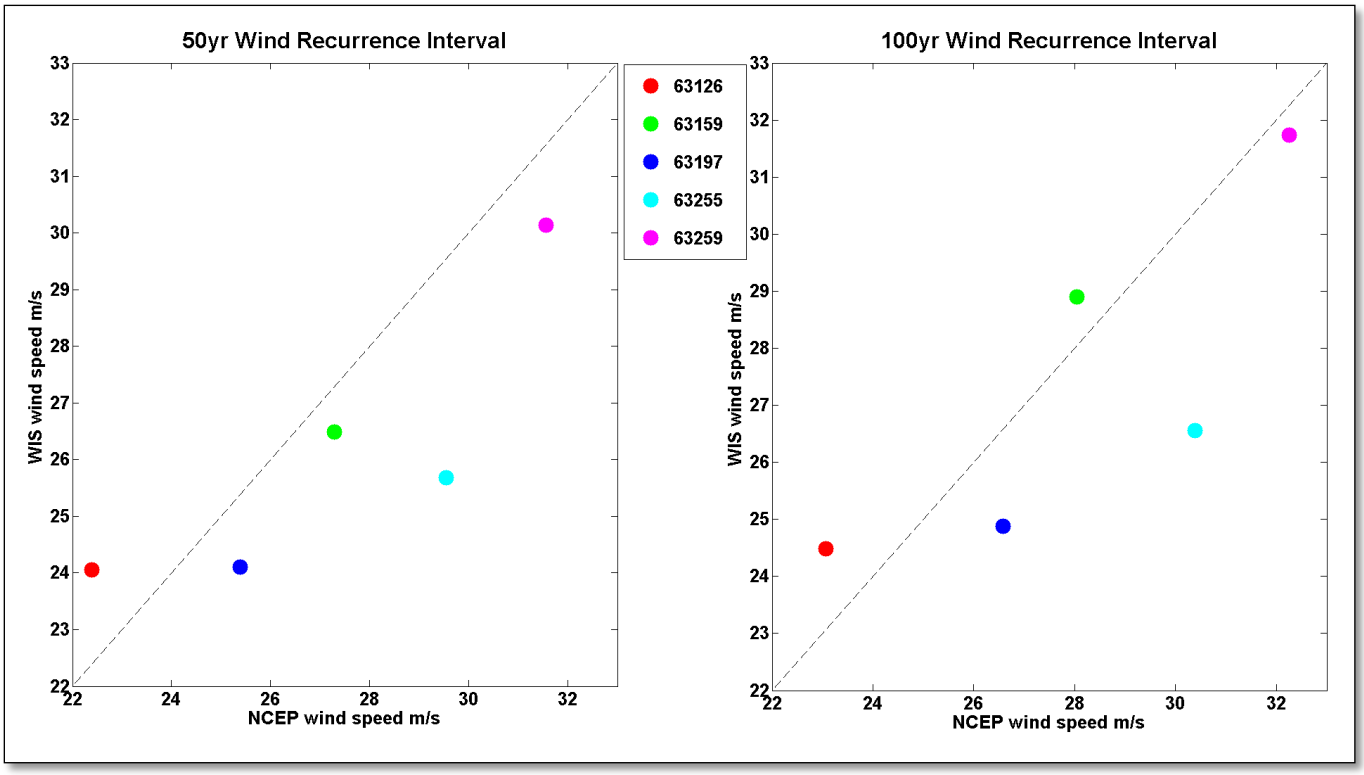

Figure 21. Extratropical wind speed recurrence interval comparison between WIS and NCEP hindcasts (1980-1999)

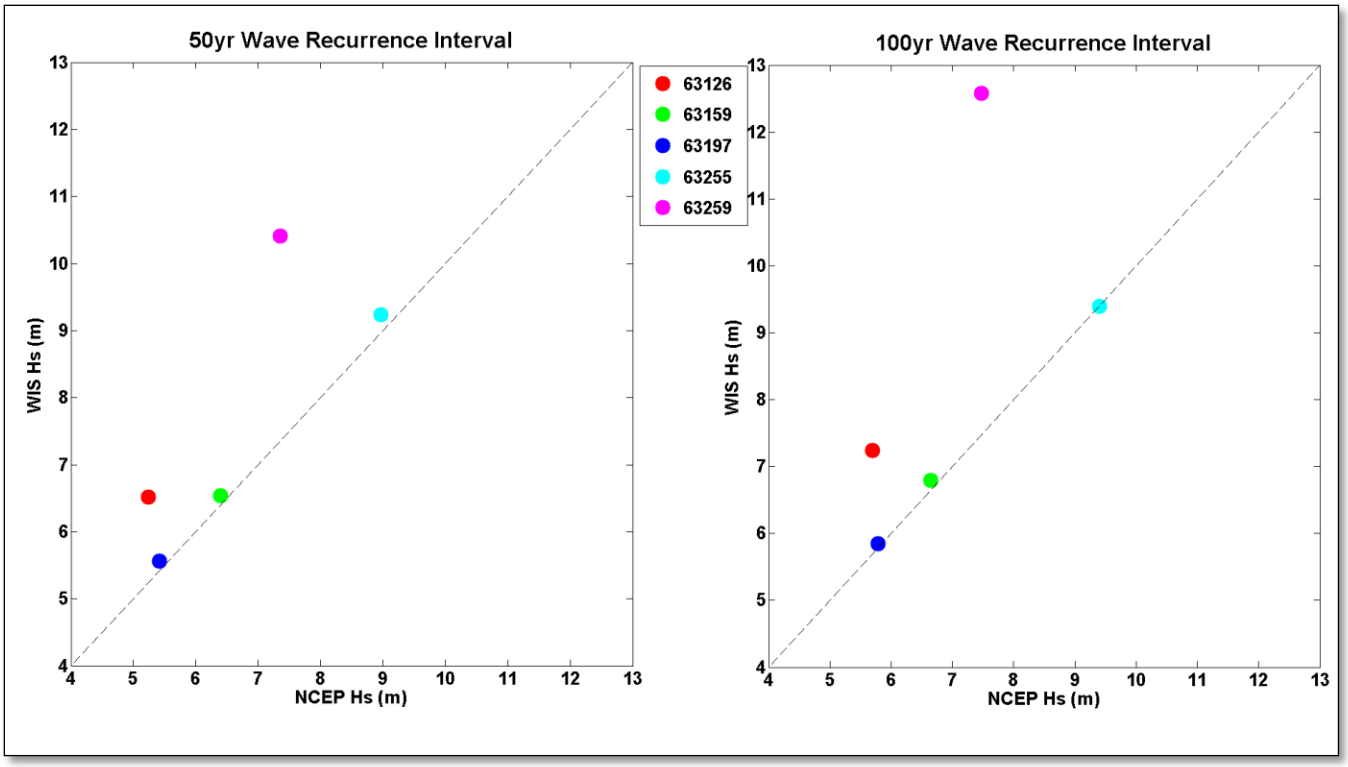

Figure 22. Extratropical wave height recurrence interval comparison between WIS and NCEP hindcasts (1980-1999)

Table 2. Recurrence Interval for Wind and Waves Derived from WIS and NCEP Hindcasts Covering the Period (1980-1999)

Station	NCEP 50 Waves (m)	NCEP 100 Waves (m)	WIS 50 Waves (m)	WIS 100 Waves (m)
63126	5.24	5.69	6.52	7.24
63159	6.4	6.65	6.54	6.79
63197	5.42	5.79	5.56	5.85
63255	8.97	9.4	9.24	9.4
63259	7.35	7.47	10.41	12.58
Station	**NCEP 50 winds m/s**	**NCEP 100 winds m/s**	**WIS 50 winds m/s**	**WIS 100 winds m/s**
63126	22.39	23.07	24.06	24.48
63159	27.28	28.05	26.49	28.9
63197	25.38	26.58	24.1	24.88
63255	29.54	30.38	25.68	26.56
63259	31.56	32.26	30.14	31.73

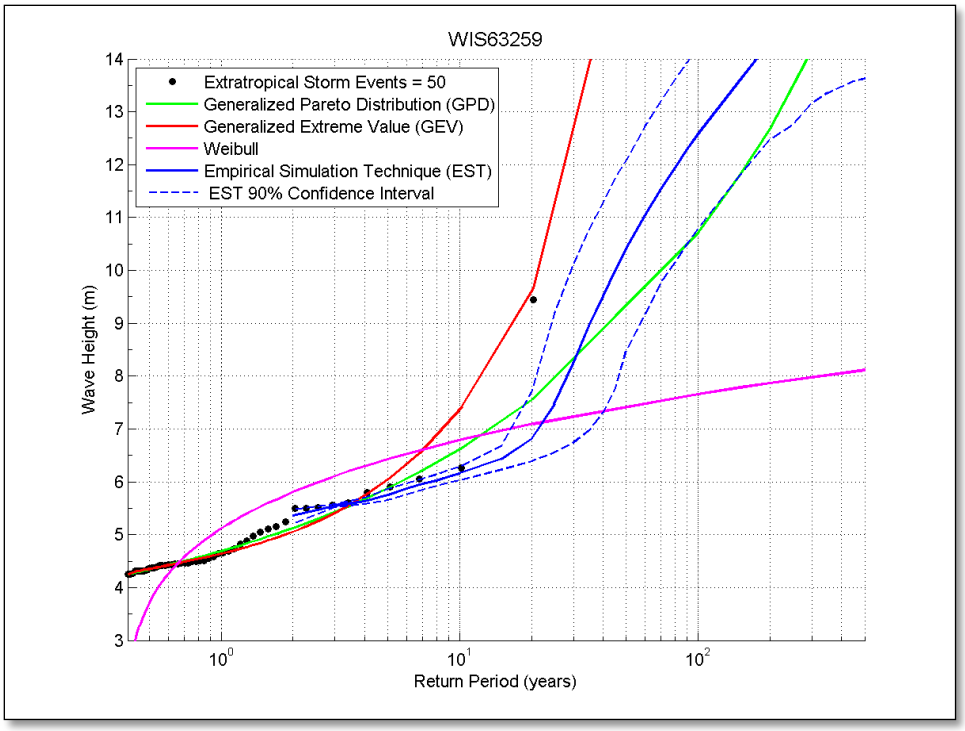

Figure 23. WIS hindcast wave height recurrence intervals from station 63259

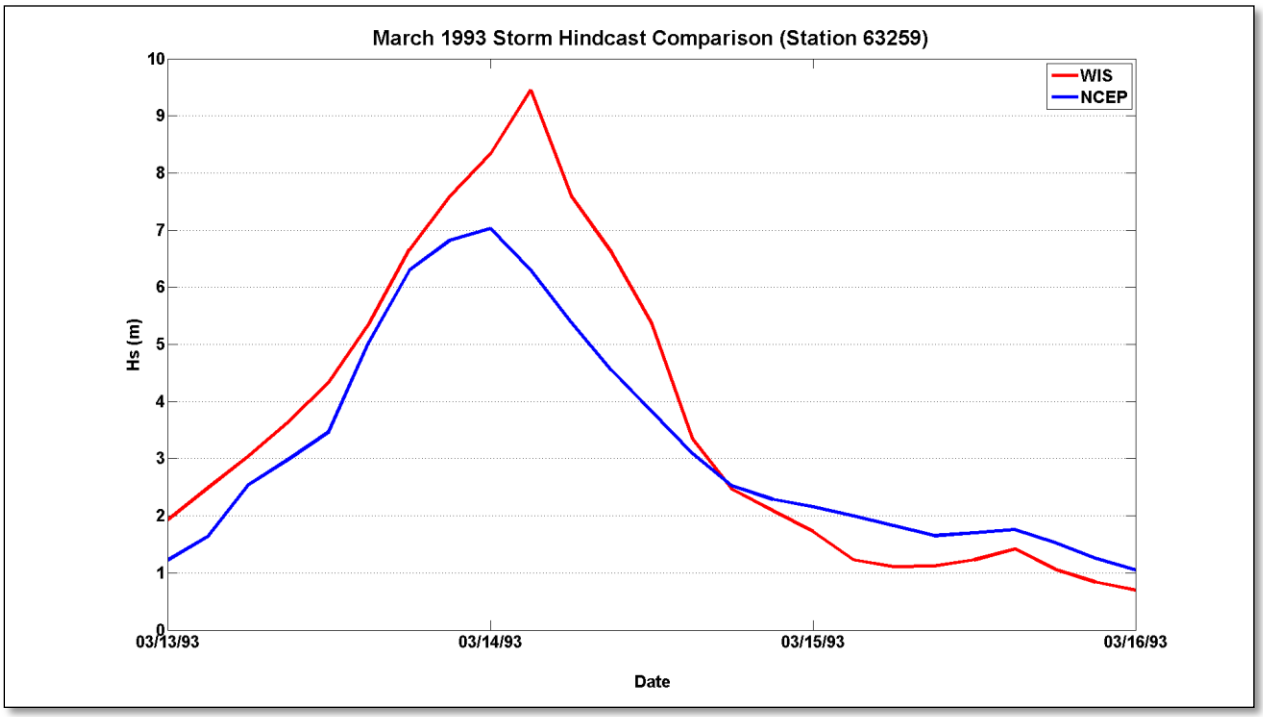

Figure 24. WIS (red) and NCEP (blue) hindcast at station 63259 for the March 1993 storm.

5. Water Level Assessment

To assess the relevance of the FEMA Region III coastal modeling results for this 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.

5.1 FEMA Storm Surge Modeling

The Federal Emergency Management Agency, Region III office (FEMA RIII), 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 US. The end-to-end storm surge modeling system includes the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for simulation of 2-dimensional 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 accessed 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 (Final project report in preparation).

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 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).

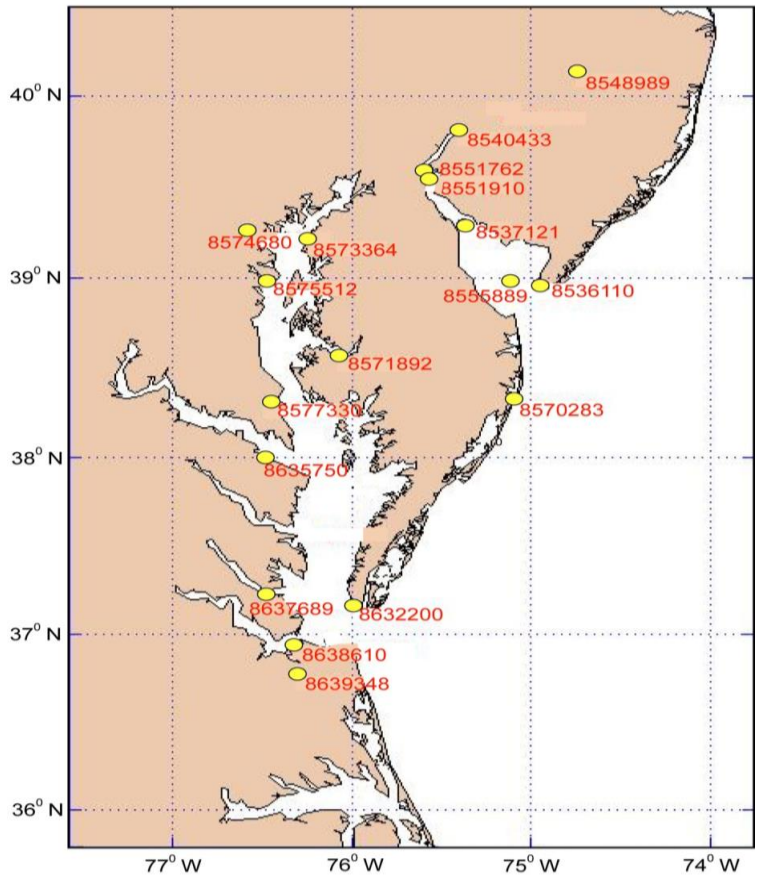

Figure 25. NOS stations used to validate the FEMA Region III coastal water level hindcasts

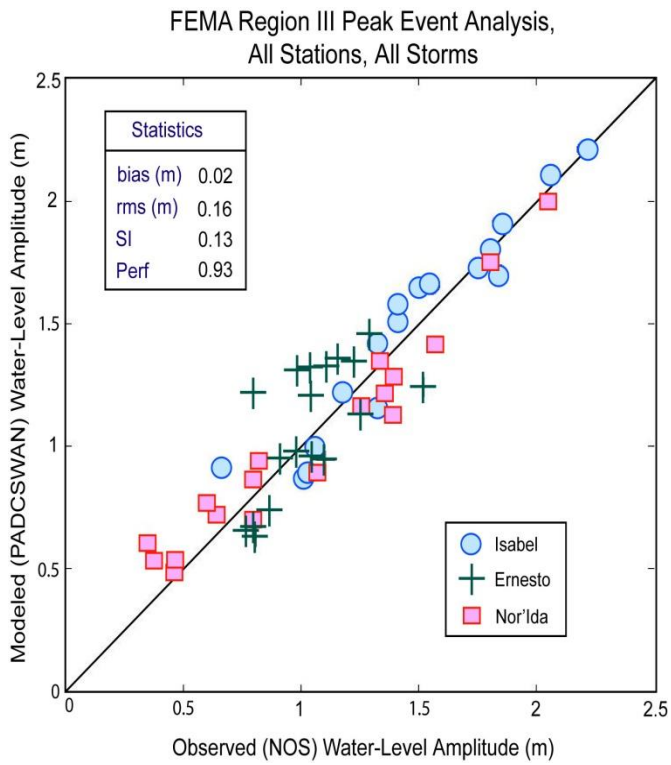

Figure 26. Summary comparison of observed and hindcast peak water levels at the NOS water level stations for all three FEMA RIII validation storms

The FEMA storm surge modeling system was run on a total of 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 recurrence interval water levels. Preliminary 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.

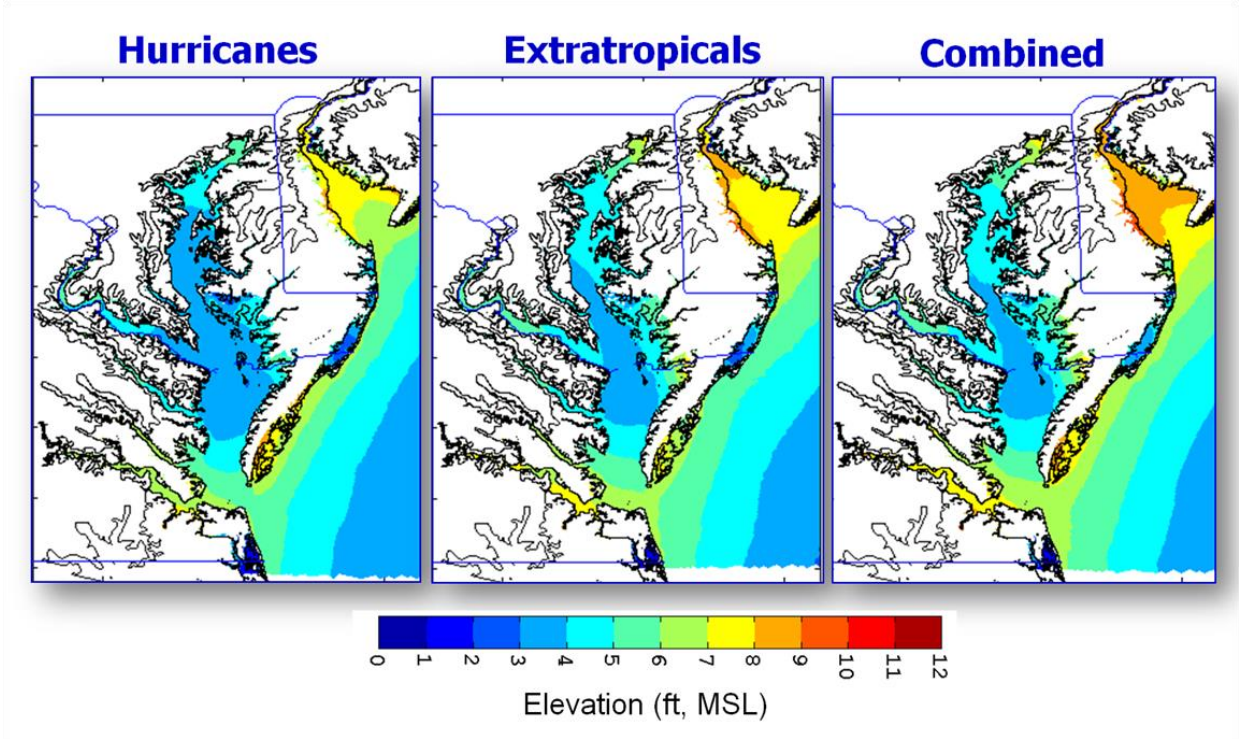

Figure 27. Preliminary FEMA Region III 100-yr water levels (MSL) for hurricanes, extratropical storms, and all events (synthesis). Note: Water elevations are in ft.

5.2 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 furthest offshore. 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 7m. Although this station is south of the FEMA R III study area, the high resolution model domain sufficiently covered this region. This allows us to evaluate FEMA hindcast water levels in an open ocean setting.

Hindcast water levels from each of the FEMA RIII validations storms were extracted for comparison with observed levels at Duck. Results for Extratropical Storm Ida, Hurricane Ernesto, and Hurricane Isabel appear in Figures 29 to 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 26). 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 we conclude that caution should be exercised in using the FEMA RII results outside the primary modeling domain of interest as shown in Figure 27.

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

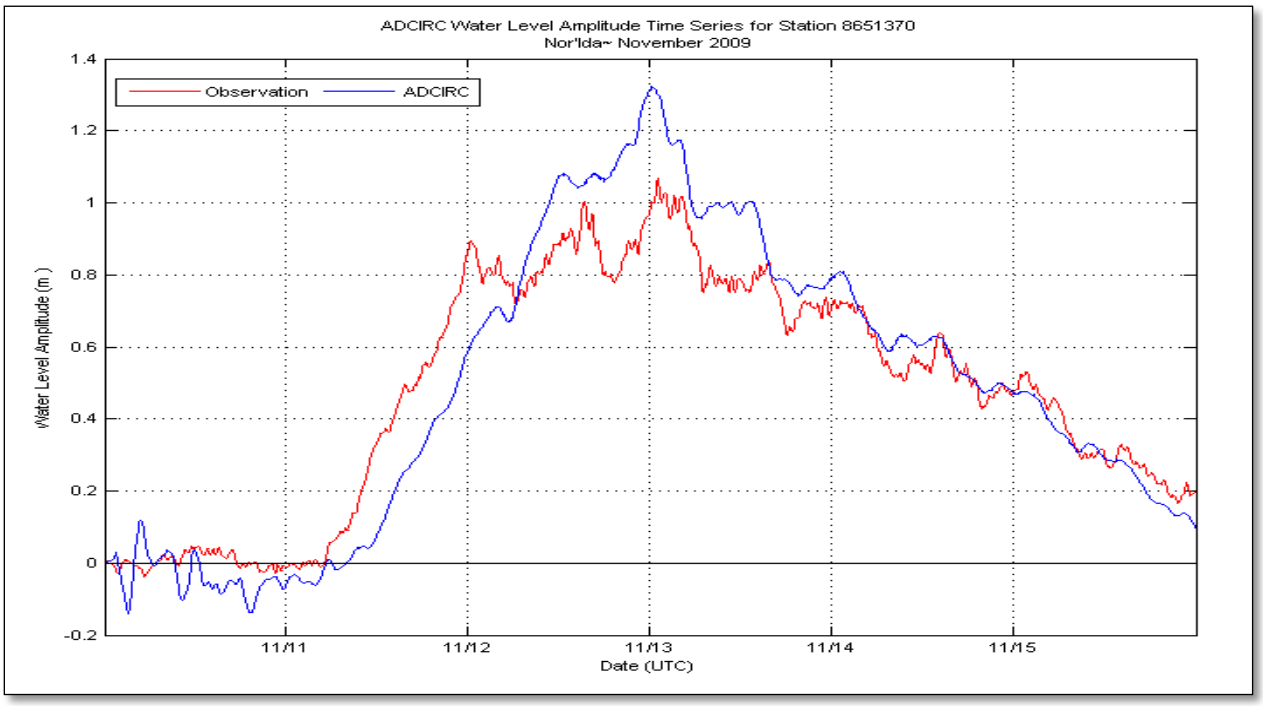

Figure 29. Comparison of FEMA Region III water level hindcast (blue) with observed water levels (red) during Extratropical Storm Ida (November 2009) at Duck.

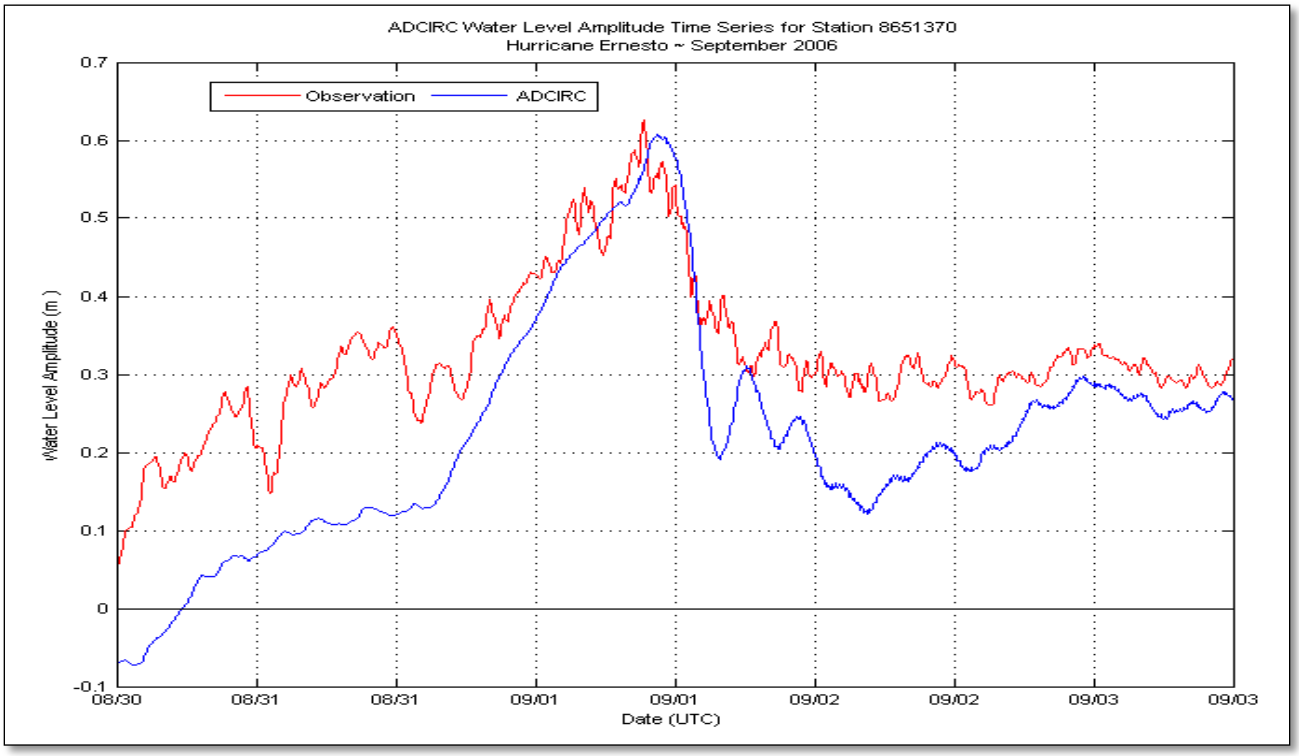

Figure 30. Comparison of FEMA Region III water level hindcast (blue) with observed water levels (red) during Hurricane Ernesto (September 2006) at Duck.

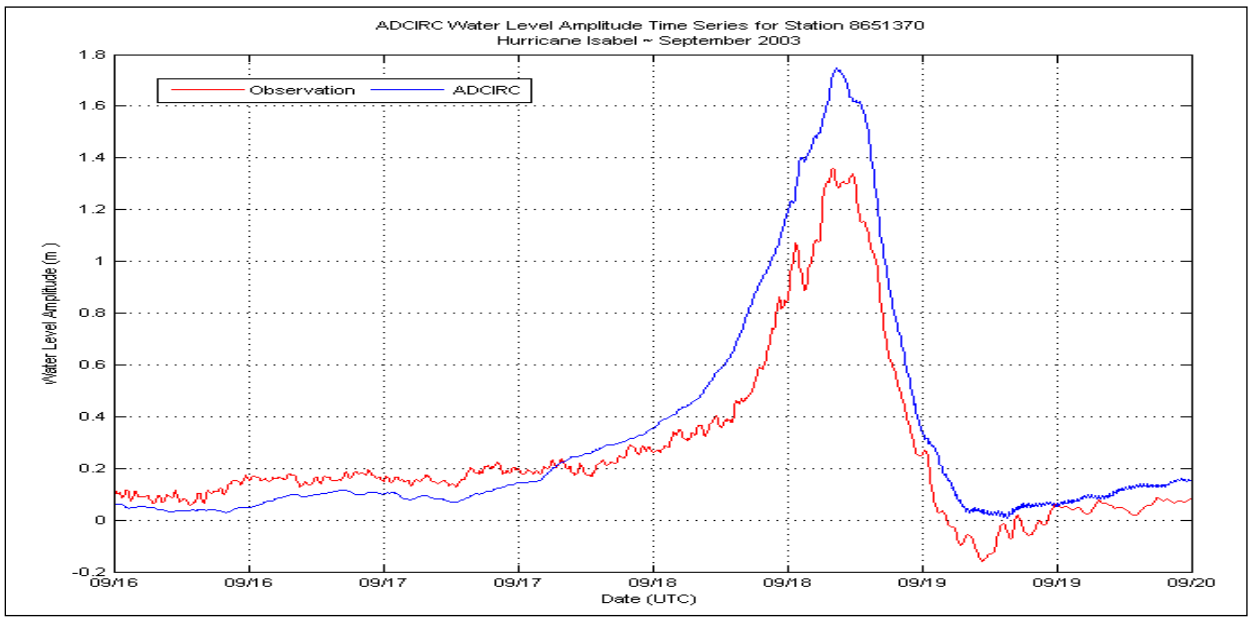

Figure 31. Comparison of FEMA Region III water level hindcast (blue) with observed water levels (red) during Hurricane Isabel (September 2003) at Duck.

6. Conclusions

The primary USACE objectives of the phase I effort 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 Region III storm surge modeling for specifying water level extremes in the mid-Atlantic offshore areas of interest. A summary of our key findings and conclusions in each area appears in the following sections.

6.1 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:

- 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.

As both the WIS and NCEP hindcasts are undergoing improvements in 2012, it is too early to identify a specific hindcast for use in this study. Overall the WIS winds are superior to the CFSR winds; this is likely a result of the IOKA storm enhancements performed by Oceanweather, Inc. In 2012 there are plans to add an additional decade (2000-2009) to the WIS hindcast, using IOKA winds and possibly upgrading to a modern third-generation numerical wave 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 validations in order to ultimately select hindcast archives for producing the extratropical extremal wind and wave statistics required for this study.

6.2 Wind and Wave Extremes

An extremal analysis methodology evaluation for extratropical storm winds and waves was performed at 5 selected locations from the mid-Atlantic region using the NCEP 30-yr hindcast. The EST outperformed the GEV, GPD, and Weibull extremal techniques and thus is the recommended approach for Phase II of the study. 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 recurrence intervals and that the principal driver of the EST recurrence interval was accurately capturing the top 5 most extreme storm events.

Recurrence intervals computed by EST for both WIS and NCEP hindcasts covering the same 20yr period were compared. For the winds, both hindcasts had excellent agreement with average differences (NCEP – WIS) at the 100-yr recurrence interval being 0.76m/s. For the waves, larger average mean differences (NCEP – WIS) on the order of -1.37m at the 100-yr recurrence interval were found. This large difference was primarily the result of the March 1993 Storm of the Century peak wave height differences of 2.4m between hindcasts for the same location, significantly influencing the EST 100-yr recurrence interval wave heights.

6.3 FEMA Region III Water Level Extremes

The FEMA Region III 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 recurrence interval 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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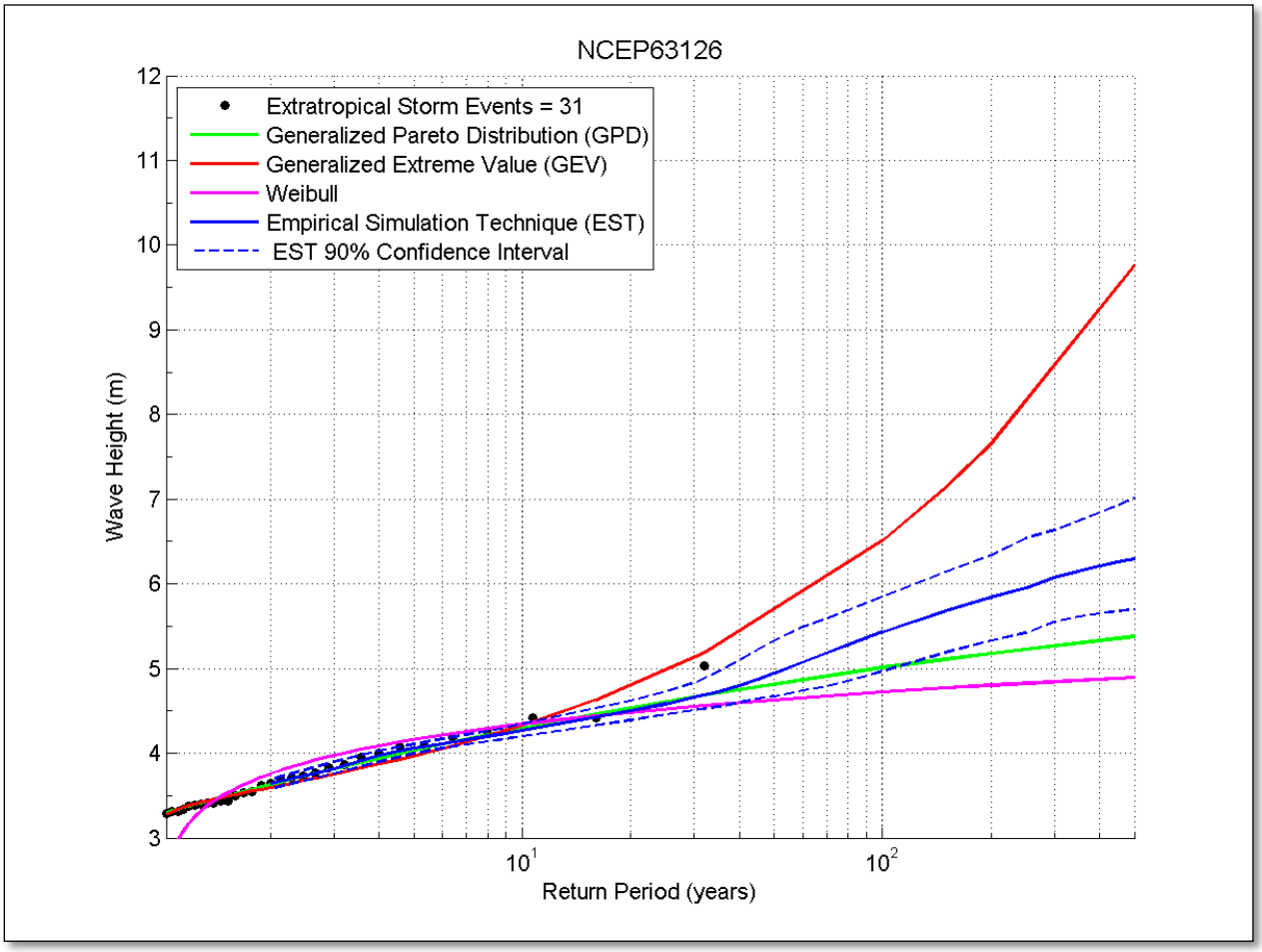
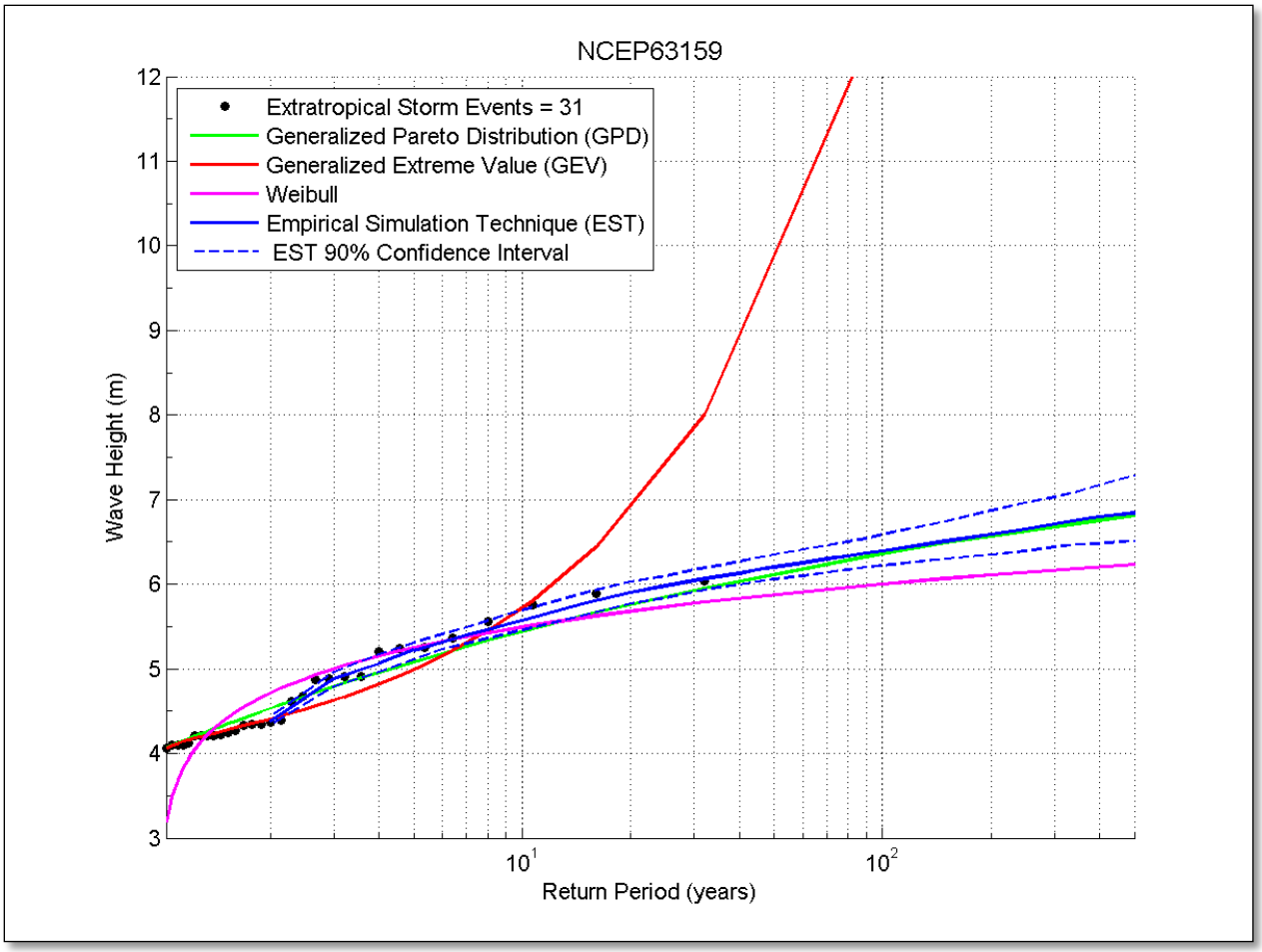
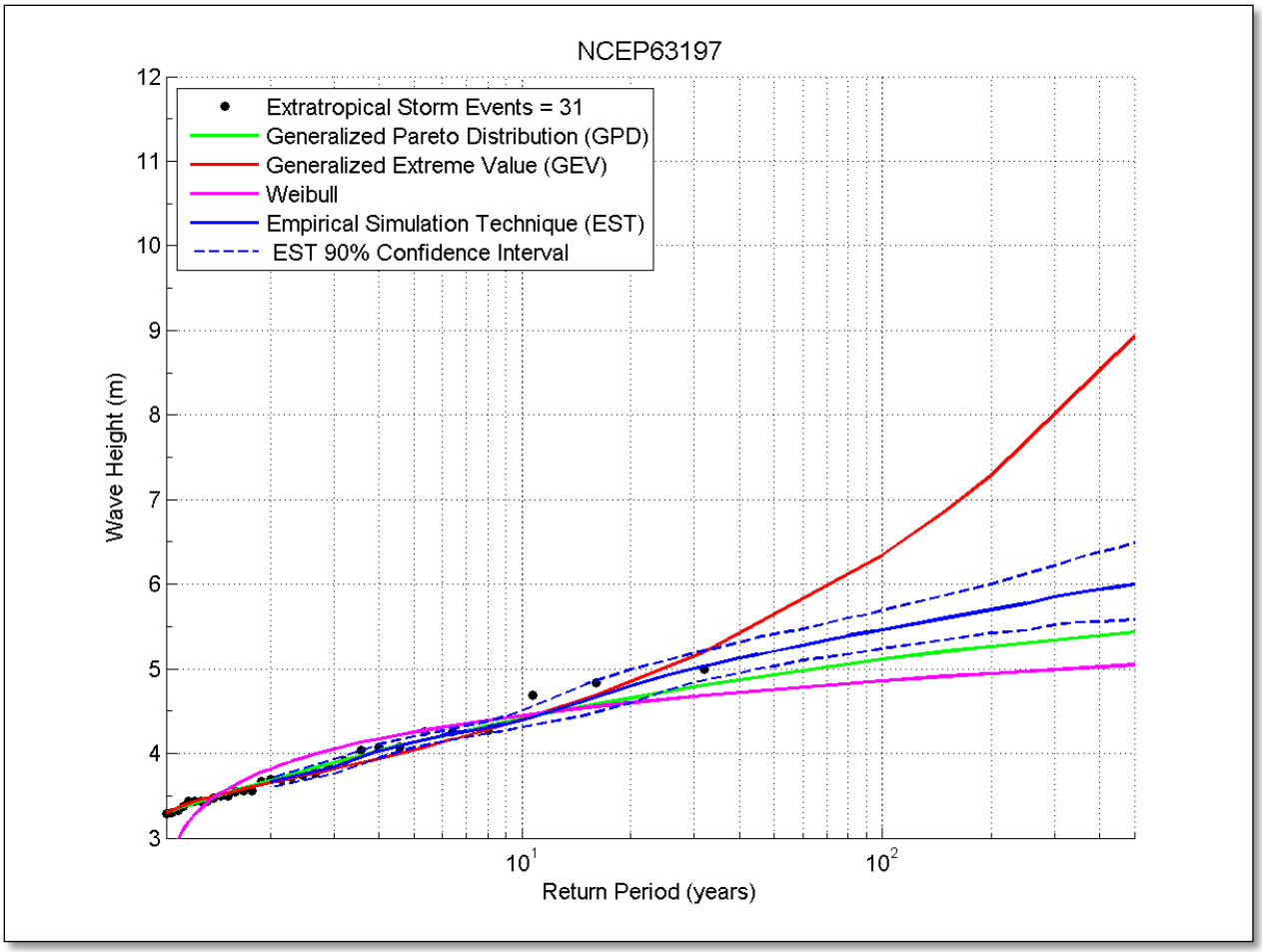
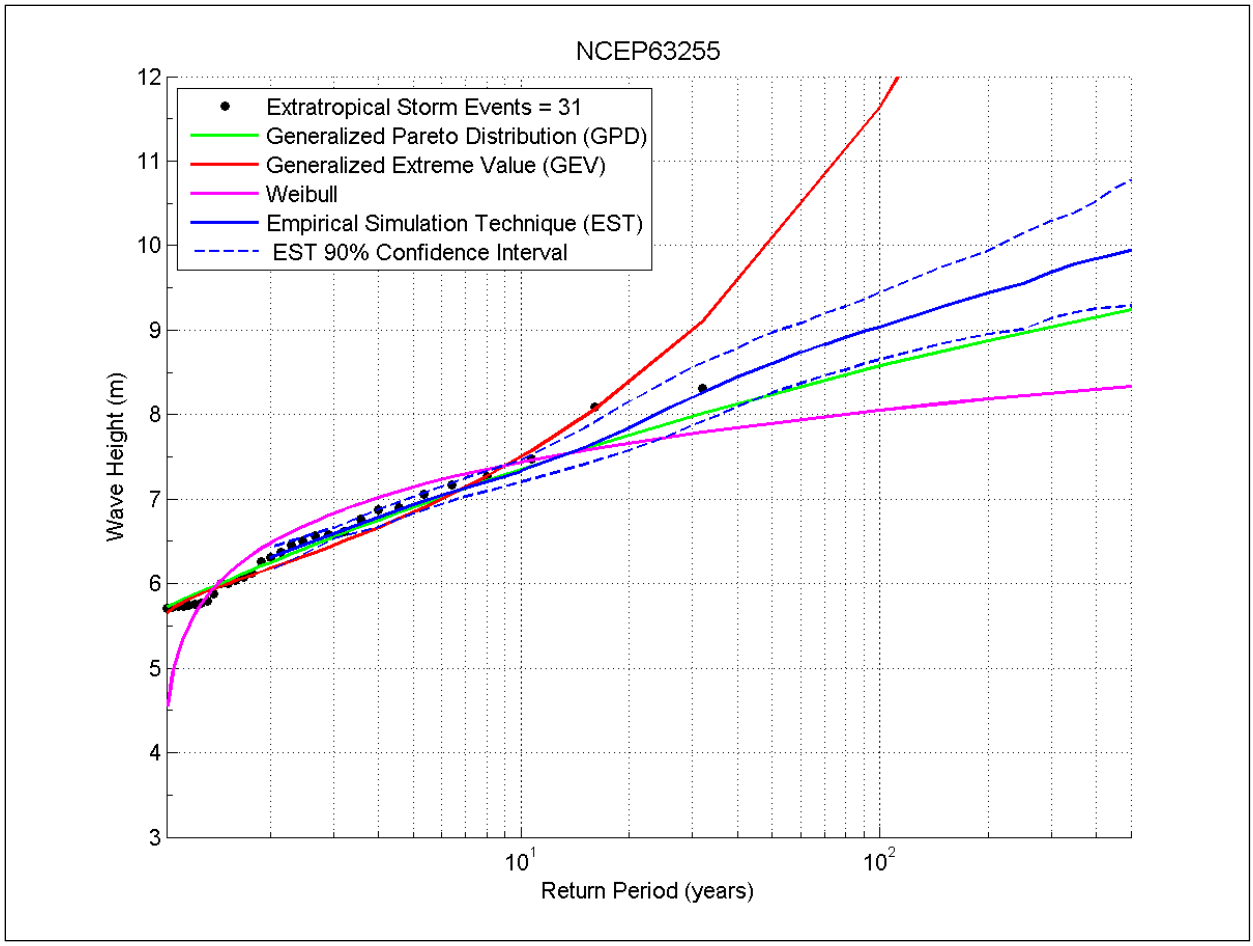
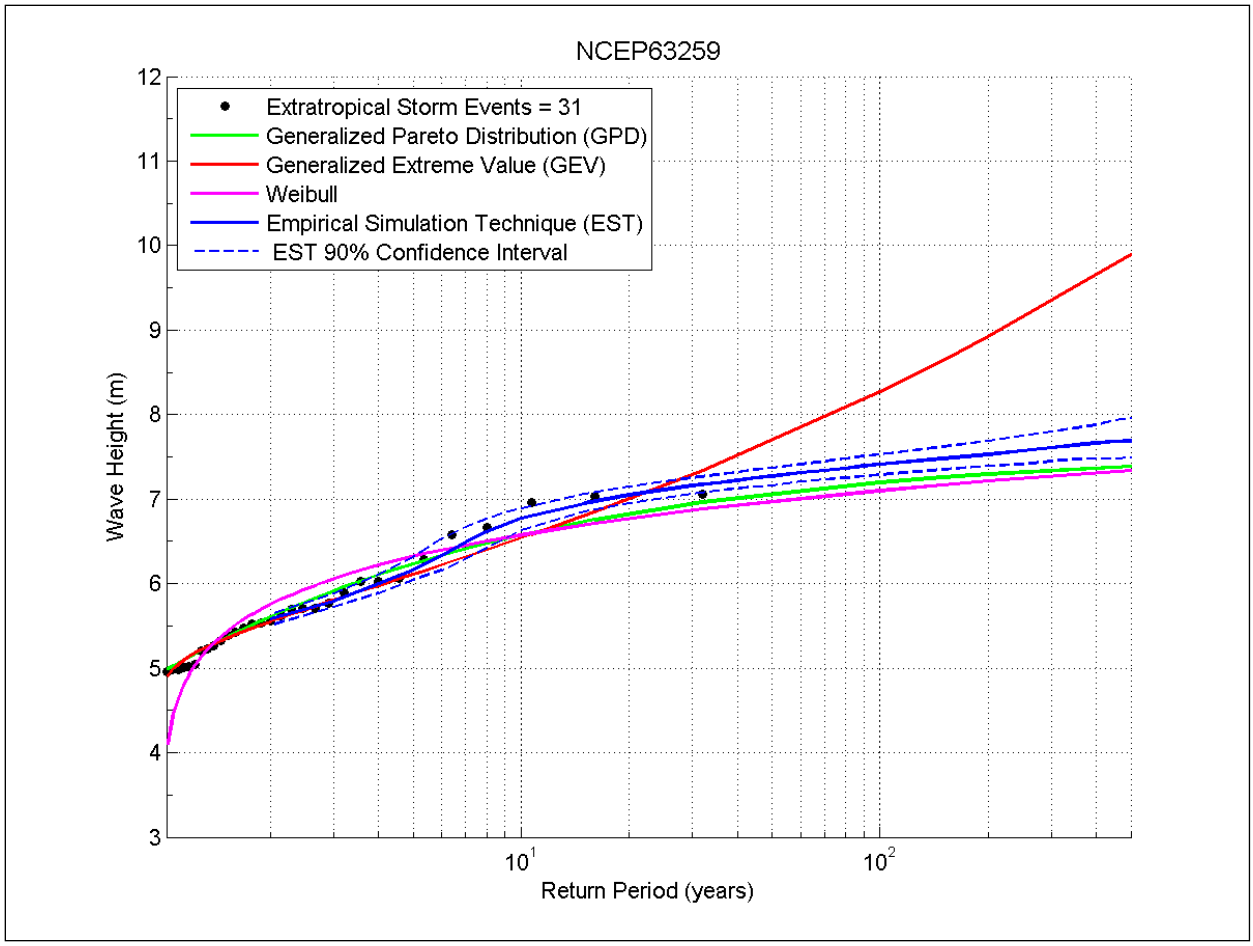
Appendix A. Extratropical Wind Speed Recurrence Intervals From 5 NCEP 30yr (1980-2010) Hindcast Output Stations (Figure 1).



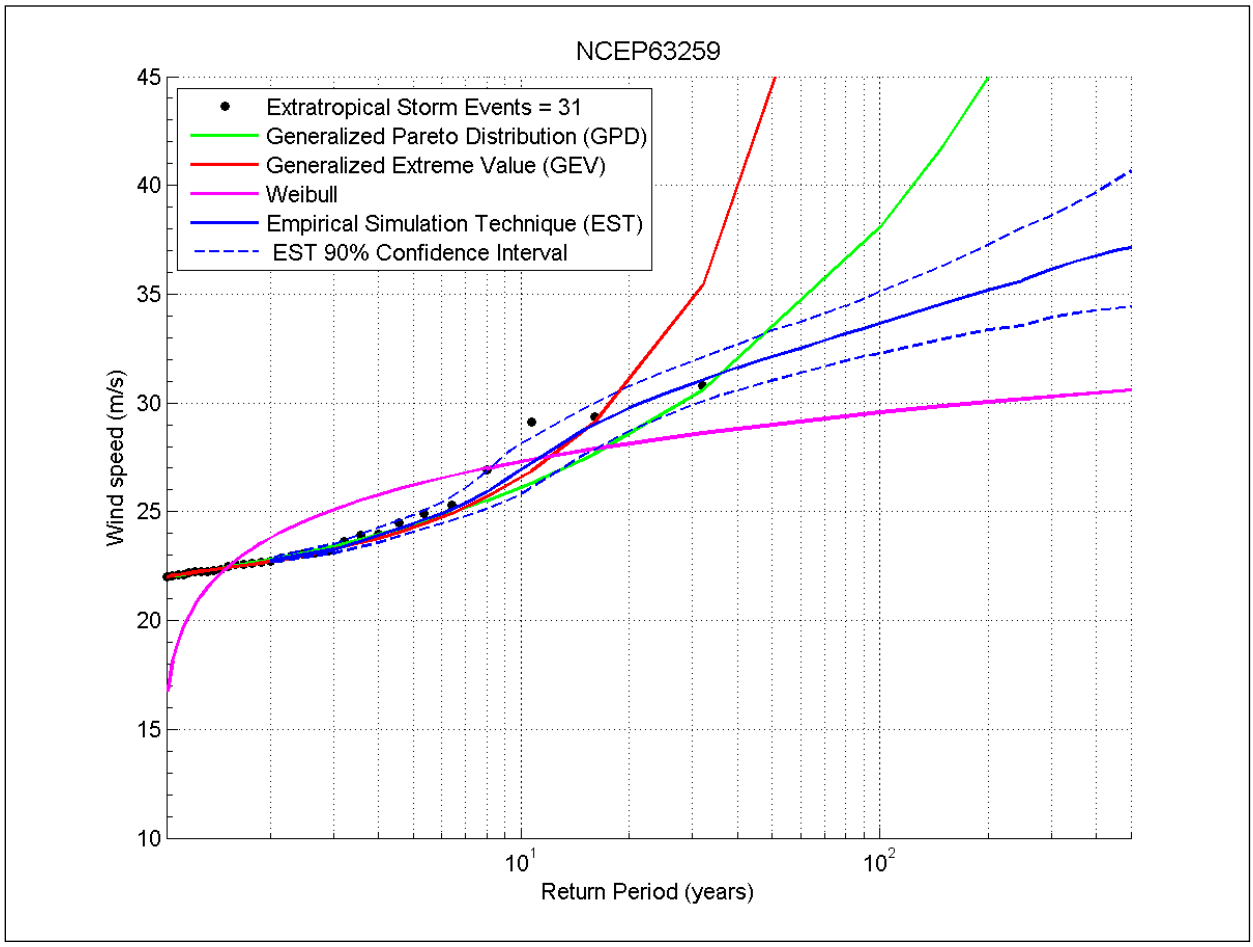

NCEP63159
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wave Height (m)
Return Period (years)
12
11
10
9
8
7
6
5
4
3
10^1
10^2

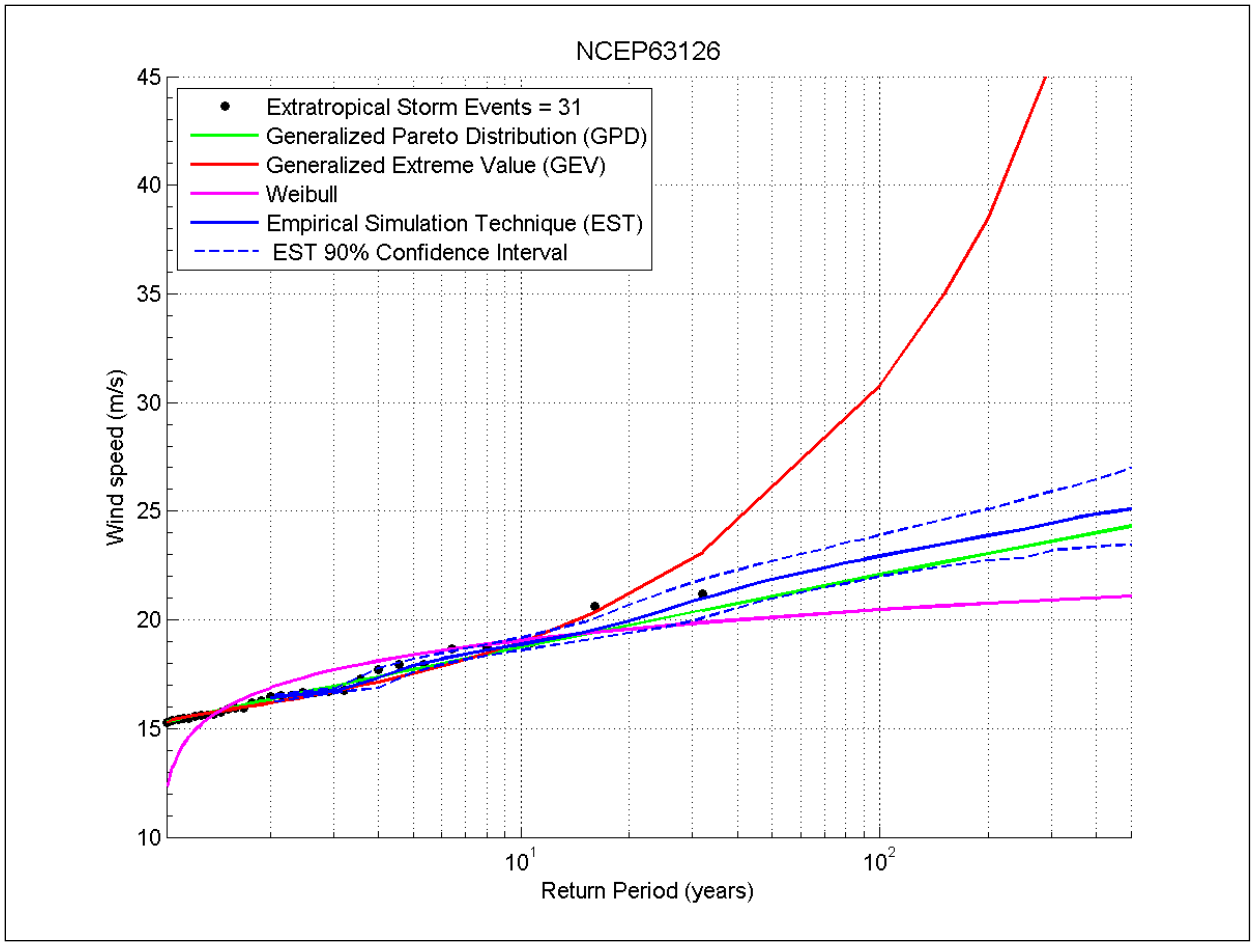

NCEP63197
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wave Height (m)
Return Period (years)
12
11
10
9
8
7
6
5
4
3
10^1
10^2

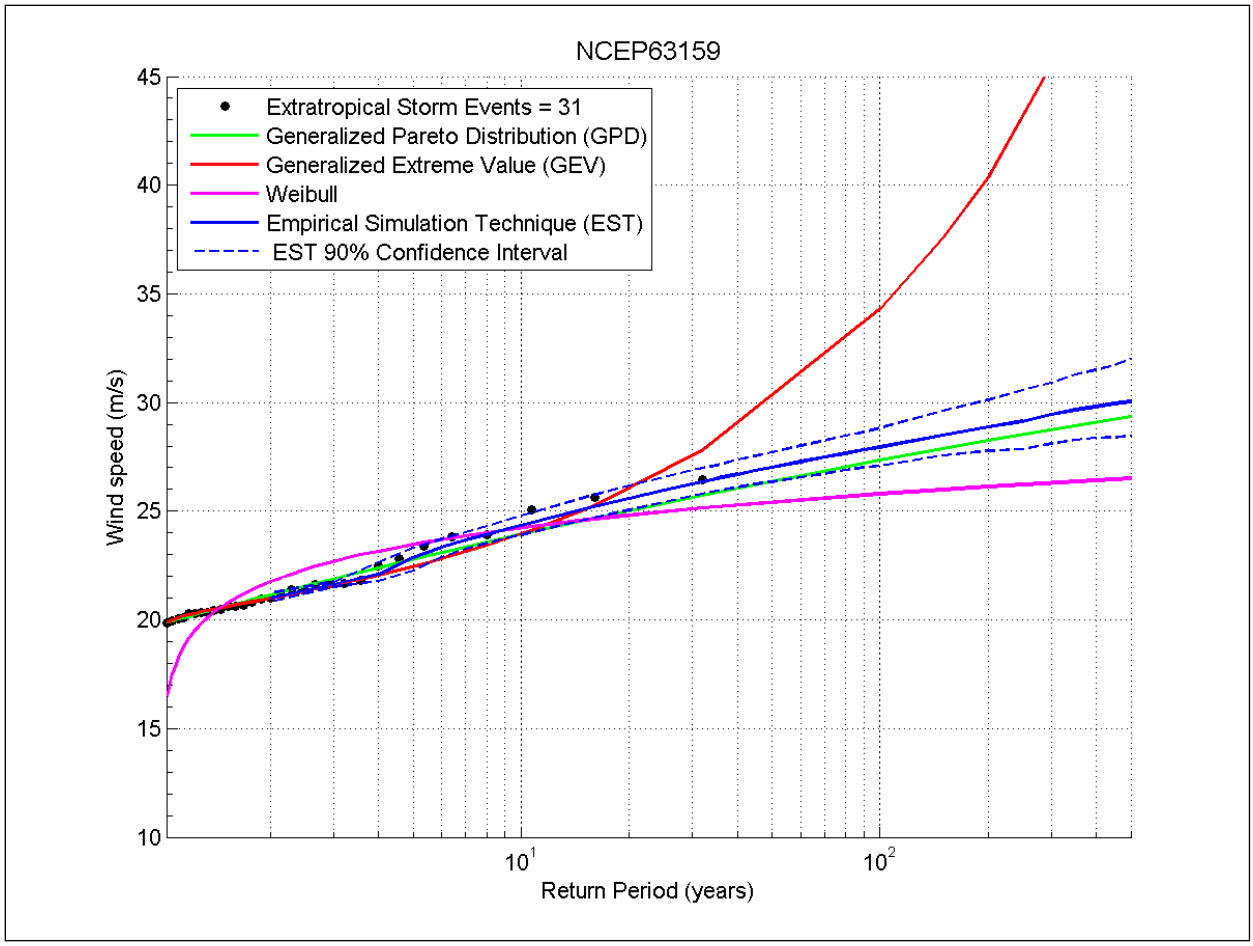

NCEP63255
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wave Height (m)
Return Period (years)
12
11
10
9
8
7
6
5
4
3
10^1
10^2

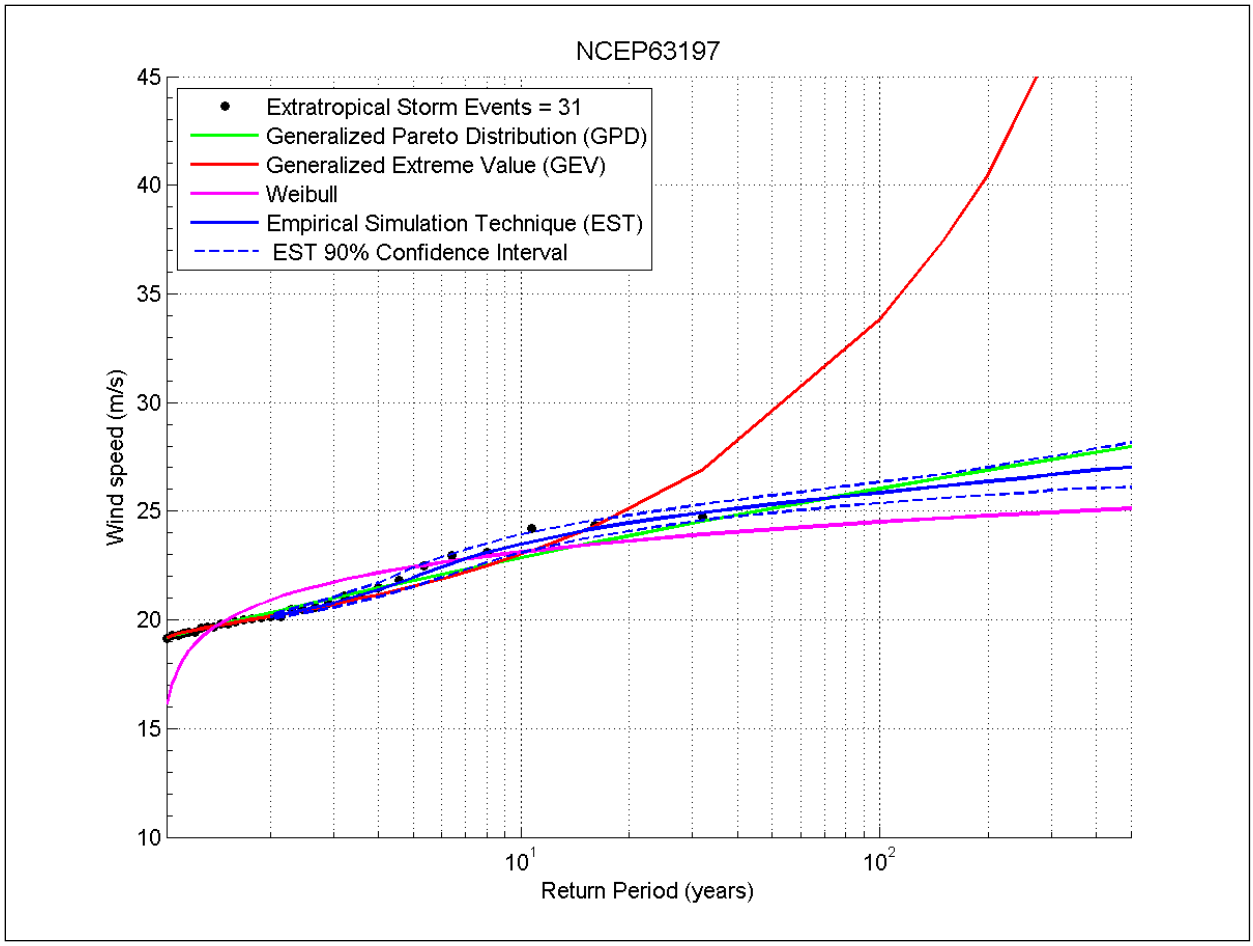

NCEP63259
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wave Height (m)
Return Period (years)
12
11
10
9
8
7
6
5
4
3
10^1
10^2

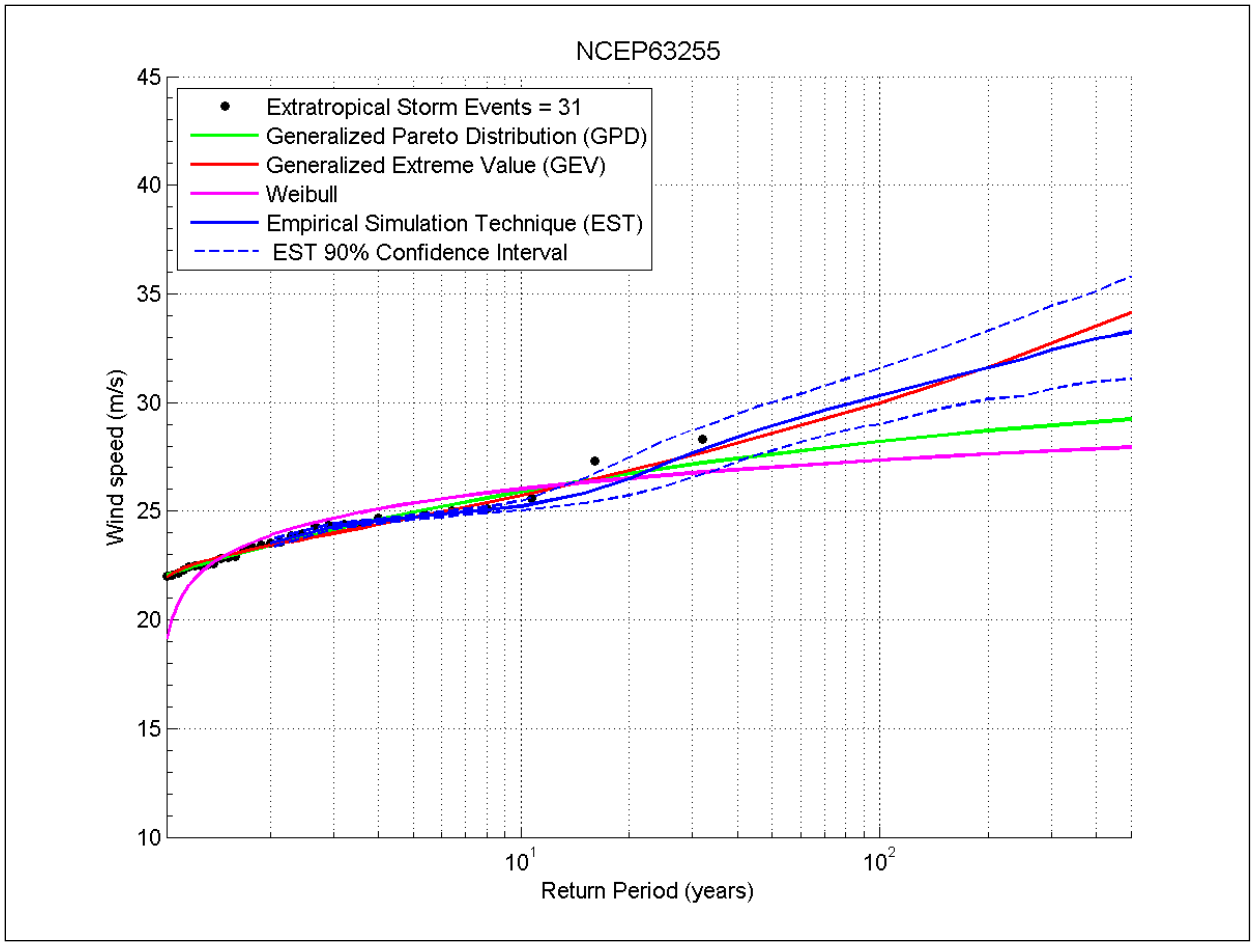
Appendix B. Extratropical Wind Speed Recurrence Intervals From 5 NCEP 30yr (1980-2010) Hindcast Output Stations (Figure 1).




NCEP63126
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wind speed (m/s)
Return Period (years)
45
40
35
30
25
20
15
10
10^1
10^2


NCEP63159
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wind speed (m/s)
Return Period (years)
45
40
35
30
25
20
15
10
10^1
10^2


NCEP63197
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wind speed (m/s)
Return Period (years)
45
40
35
30
25
20
15
10
10^1
10^2


NCEP63255
Extratropical Storm Events = 31
Generalized Pareto Distribution (GPD)
Generalized Extreme Value (GEV)
Weibull
Empirical Simulation Technique (EST)
EST 90% Confidence Interval
Wind speed (m/s)
Return Period (years)
45
40
35
30
25
20
15
10
10^1
10^2