Regional Analysis of Extremal Wave Height Variability
Oregon Coast, USA

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1.0 INTRODUCTION

This extremal wave height study follows up on a 2001 analysis which examined 10 years of concurrent NDBC (National Data Buoy Center) buoy data for four buoys off of the coast of Oregon. (46029, 46050, 46002, 46005) (Moritz, 2001) The purpose of analyzing a smaller set of concurrent data was primarily to isolate key extremal wave and storm differences between the various shelf and deep water buoys as well as to determine the best wave data analysis procedures. Those analysis results were compared to Wave Information Study extremal wave height estimates for the same coastal area. Key analysis results from the 2001 study determined that selection of the storm and significant event thresholds can strongly affect final extremal wave estimates. In addition, the top 2 distributions for the same buoy produced 1 to 2 m differences in 100-yr wave height estimates. It was also found that reliance on deep water buoys to define transitional depth wave climate (even after transformation) may underestimate the extremal wave heights. The NDBC shelf buoy off of Newport (mid-coast) exhibited a 3 m greater 100 year wave height than the Columbia River shelf buoy for the 10 year data set analyzed.

This analysis will expand on the previous analysis both in period of record and in geographical coverage. The complete period of record was used for 4 shelf/nearshore NDBC buoys as shown in figure 1. Extremal analyses were performed for each buoy. The storm threshold to be used in the analysis was re-evaluated. Minimum time period between independent events was also re-assessed at individual buoys and the impact on the extremal distribution was evaluated. Revised results for the buoys were compared to other buoys as well as to the Wave Information Study predicted wave heights. (Corson, 1987)

2.0 WAVE DATA SOURCES

The primary focus of this investigation was to identify the variability in extremal wave height estimates for different locations along the Oregon and Washington coasts, northeastern Pacific Ocean. The NDBC buoys are described in table 1 and shown in figure 1. Nearshore data sources are located 20 to 50 miles offshore of the coasts of Oregon and Washington. NDBC buoys utilized included 46041 (Grays Harbor), 46029 (Columbia River), 46010 (Columbia River), 46050 (Newport), 46040 (Newport) and 46027 (Brookings). Historical NDBC buoys 46010 and 46040 were used to extend the period of record of 46029 (Columbia River) and 46050 (Newport), respectively. Overall water depths ranged from 47.9 m for the Brookings buoy to 132 m for the Grays Harbor buoy. Period of record for the data sources ranges from a minimum of 14 years for the Grays Harbor buoy to a maximum of 18.1 years for the Columbia River buoy.

Table 1. Wave Data Sources

Wave Data Source and Description	Measurement Type	Water Depth (m)	Period of Record	Total Years
NDBC 46041 - Grays Harbor (Cape Elizabeth)	3m discus buoy	132	87 - 04	14
NDBC 46029 - Columbia River Bar	3m discus buoy	128	84 - 04	12.3
NDBC 46010 - Columbia River Bar	3m discus buoy	59.4	84 - 91	5.8
NDBC 46050 - Newport (Stonewall Banks)	3m discus buoy	130	91 - 04	11
NDBC 46040 - Newport (Stonewall Banks)	3m discus buoy	111	87 - 92	4.3
NDBC 46027 - Brookings (St. Georges)	3m discus buoy	47.9	85 - 04	16.6

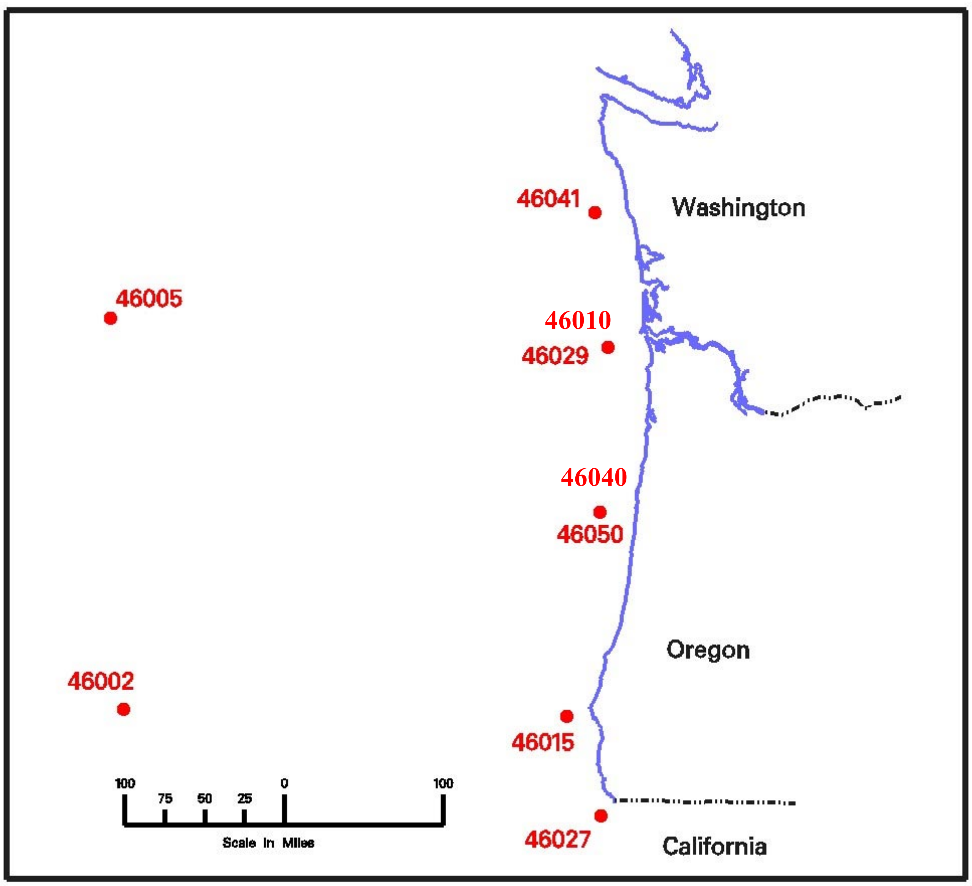

Figure 1. Location of NDBC Wave Data Buoys

3.0 ANALYSIS PROCEDURE

This analysis used the largest period of record available for all of the nearshore buoys beginning in June 1984. This date was selected because of a change in the way the NDBC data is collected and reported before and after that date. Despite that cutoff, only one of the data sources had more than one year of data prior to that date available, so the results would have not been significantly different. An extremal analysis was performed on this data using the following primary references: Mathiesen, et al (1994), Goda (1988), USACE (1996). The data was processed using partial duration series and Peak-Over-Threshold (POT) methods. The analysis period included the 97-98 El Nino and the 98-99 La Nina events.

Additional focus was placed on the selection of the storm event thresholds and the time interval defining separation of independent storm events. Previous analyses had shown that the severity of wave events along this reach of coastline (northern California to Washington) may vary significantly. In order to assess the minimum cutoff defining the total storm population, wave height values from October 1 to March 30 were summarized. Average wave height and average wave height plus one standard deviation were calculated. The average wave height plus one standared deviation was used to define the lower storm threshold. The Columbia River buoy and Newport buoys showed thresholds around 4.3 so a value of 4.5 m was used to define the storm population for those buoys. The Grays Harbor and Brookings buoys showed thresholds slightly less than 4 m so that value was used to define the storm population for those buoys. A 6m threshold was selected to identify the subset of wave heights in the actual extremal plots.

Selection of independent storm events for the extremal analysis is important for a reliable wave height estimate. The peak over threshold method chooses local maxima above a chosen threshold. Mathiesen et al (1994) recommend that the auto-correlation function be computed for different time lags from the sampled wave height time series. They also recommend that the minimum time interval between local maxima be somewhat longer than the time lag for which the auto-correlation function is 0.3 to 0.5. Figures 2 and 3 illustrate auto-correlation plots for NDBC 46050 and 46027. These two buoys were selected as representative of the range of wave height variability along the study reach. Each line plotted represents a continuous time series of data from the total record. It can be seen that the lines vary significantly from year to year. Some years are clearly more stormy than other years. In figure 2, 1998 was a continually storm year. Figure 2 illustrates the range of storm densities for the Newport buoy, typically varying from around 60 hrs to 100 yrs. To evaluate the impact of this time interval selection on the extremal analysis, the Newport buoy data was analyzed for both 60 hrs and 110 hrs separation between events. Figure 4 illustrates a time series comparison at the Newport buoy for a stormy and a relatively mild year (1998 and 2001). To ensure independence of events, 110 hrs was used for all buoys.

Probability distributions analyzed included the Fisher Tippett Type 1 (FT-1) and the Weibull with 4 shape parameters (0.75, 1.0, 1.4, and 2.0). Plotting position formulas utilized included Goda (1988) for the Weibull distribution and Gringorton (1963) for the Fisher Tippett distribution. Equations for the probability distributions and the plotting position formulas are shown below.

Fisher-Tippett Type I (FT-1) Distribution:

$$P(H_s \le \hat{H}_s) = e^{-e^{-\left(\frac{\hat{H}_s - B}{A}\right)}} \quad (1)$$

Weibull Distribution:

$$P(H_s \le \hat{H}_s) = 1 - e^{-\left(\frac{\hat{H}_s - B}{A}\right)^k} \quad (2)$$

$k = 0.75, 1.0, 1.4, 2.0$

$P(H_s \le \hat{H}_s)$	= probability of H_s not being exceeded
H_s	= significant wave height
$\hat{H}_s$	= particular value of significant wave height
B, A, k	= location, scale, shape parameters

Fisher-Tippett I (FT-1) Plotting Formula (Gringorten 1963)

$$P_m = 1 - \frac{m - 0.44}{N_T + 0.12} \quad (3)$$

Weibull Plotting Formula (Goda 1988)

$$P_m = 1 - \frac{m - 0.20 - (0.27/\sqrt{k})}{N_T + 0.20 + (0.23/\sqrt{k})} \quad (4)$$

P_m = probability that the m^{th} highest data value will not be exceeded
m = rank of data value in descending order
N_T = total number of storm events
k = Weibull shape parameter

4.0 ANALYSIS RESULTS

The extremal analysis results for the NDBC buoy data were plotted on the appropriate vertical and horizontal scales such that the data and distributions would plot as a straight line. Distribution parameter estimation was conducted through least squares regression using the USACE Automated Coastal Engineering System (ACES) program. (USACE, 1990) The goodness-of-fit for each distribution was evaluated using several criteria. The primary criteria was the correlation of the estimated distribution value with the actual plotted data. Since the key purpose of most extremal wave height analyses is to project the design wave, fit of the distribution with the upper portion of the data and how that appears to impact any extrapolation of the distribution line is also critical. Another value often calculated is the sum of the squares of the residuals, a value that is desirable to be small. In general, the best fit would be expected to be produced for the distribution with the highest correlation and the lowest sum of the square of the residuals. Other criteria that can aid in the assessment of degree of fit include whether the data appears to plot as a straight line and how well the distribution line fits with the data trend line. Numerous references outline more elaborate and rigorous goodness-of-fit criteria and relationships that should be investigated prior to final acceptance of results.

Figures 5 through 9 illustrate the extremal analysis plots for each of the NDBC buoys with the highest correlation. Data points are illustrated by the blue circles. The blue line is the data trend line and the red line is the probability distribution line. In most of these plots, those two lines closely mirror the other. The two square green data points at the upper end of the plot represent the 30-year and the 100-year return interval estimates given by the probability distribution. Figures 5 and 6 illustrate the results for the Grays Harbor buoy and the Columbia River buoy, respectively. Figures 7 and 8 illustrate two of the distribution plots for the Newport buoy, Fisher-Tippett 1 and Weibull 1.4. These figures show that two relatively good fits to the data result in as much as a meter difference in the 100 year wave height. Figure 9 shows the analysis results for the Brookings buoy.

Figures 10 and 11 display return wave height values for the 4 buoys based on the analysis results. Figure 10 includes the two top distributions for the Newport buoy to illustrate potential range of results. Even using the lower of the two estimates of 14.9 m (Weibull 1.4), the Newport buoy predicted 100 year wave height is 2.4 meters above the next highest buoy of 12.4 meters at the Columbia River. If the Fisher-Tippett result is used, the Newport 100 year wave height is 3.4 meters greater than the next highest buoy result. The Newport buoy comparison raises the question of whether it is reasonable to determine that one of four regional buoys might be better described by a completely different distribution type, i.e. Fisher Tippett rather than a Weibull. Figure 11 illustrates the extremal results of various analysis methods at the Newport buoy. The 72 hr/10 year line illustrates results from the earlier 10 year analysis performed for 91 to 00. Two other lines show a comparison of using a 60 hr versus a 110 hr separation of storms for this 15 year analysis. This comparison shows that there is little difference in results for these 2 time intervals between independent events. This could perhaps be explained if the time interval selection over this range does not significantly affect the highest events which may control the final curve. Also noted in this figure are the two top distribution results for this analysis for Newport, Fisher Tippett I and Weibull, $k = 1.4$. Table 2 summarizes analysis results.

Figures 12 through 14 illustrate comparisons of storm climates for the 4 buoys analyzed. Figures 12, 13, and 14 show the number of storm events per year, the maximum and the average wave heights for the storm data sets, respectively. Comparisons of the NDBC buoy extremal analysis results to the COE Wave Information Study (WIS) results at similar locations are shown in figures 15 through 18. In all cases the WIS Phase II analysis locations are seaward of the NDBC buoy locations. At Grays Harbor, figure 15, the NDBC extremal results fall within the estimates of the WIS Phase II deepwater results. At the Columbia River, figure 16, the NDBC buoy results are higher than the WIS results. At the Newport buoy, figure 17, the NDBC analysis results are significantly higher than the WIS results by as much as 3.8 meters for the 100 year event. At the Brookings buoy, figure 18, the NDBC results fall lower than the WIS predicted results. The Brookings buoy was the one buoy sited in 47.9 meters water depth as compared to an average of 130 m for the other three buoys.

Table 2. NDBC Buoy Analysis Setup and Results

Parameter	Grays Harbor	Col. River	Newport	Brookings
N	93	125	118	71
NT	243	259	215	342
K (yrs)	14	18.1	15.3	16.6
Storms/Yr	17.4	14.3	14	20.6
Max H (m)	10.3	12.8	14.1	13
Max T (sec)	20	20	20	20
Mean H (m)	7.2	7.3	7.4	7.63
Mean T (sec)	13.9	13.8	13.6	14.6
StDev H (m)	1	1	1.5	1.3
Distribution	Weibull	Weibull	FT-1	Weibull
k	2	2	NA	1.4
A	3.435	3.498	1.418	2.024
B	2.604	2.937	5.495	3.125
Correlation	0.9924	0.9866	0.9979	0.9849
Sum sq. residuals	0.0057	0.0193	0.0244	0.0041
100-Yr H (m)	12	12.4	15.8	11.8

It should be noted that both period of record as well as period of analysis may affect the comparison. WIS wave height estimates were obtained from a 20-year hindcast spanning the years of 1956 through 1975. The NDBC buoy analysis was done over a 14 to 18 year period including significant El Nino and La Nina events.

5.0 CONCLUSIONS

The full period of record for 4 NDBC buoys along the Oregon and Washington coasts was used to identify the extremal variability along the coastline. Storm season data from October through March was used to identify the lower storm threshold for each buoy prior to event selection. A 4 m threshold was used for Brookings and Grays Harbor while a 4.5 m threshold was used for the middle two buoys, Newport and Columbia River. The subset of storm events used for the extremal analysis was defined by the 6 m storm threshold for all buoys. It was found that comparison of results using a 60 hr versus a 110 hr separation of storm events did not show significant differences. The two northerly buoys fit the Weibull (2.0) distribution, Newport fit the Fisher Tippett distribution and the Brookings or southerly buoy fit the Weibull (1.4) distribution. Projected 100 year wave heights were similar for all buoys at around 12 m with the exception of the Newport buoy which exhibited a 100 year wave height projection of 3.4 m higher at 15.8 m. The top two probability distributions for the same NDBC buoy produced 1 to 2 m differences in the 100 year wave height estimates. The selection of the best-fitting distribution is critical and not completely straight-forward. Comparison to WIS Phase II projected wave estimates showed similar values with the exception of the Newport buoy which was significantly higher.

6.0 REFERENCES

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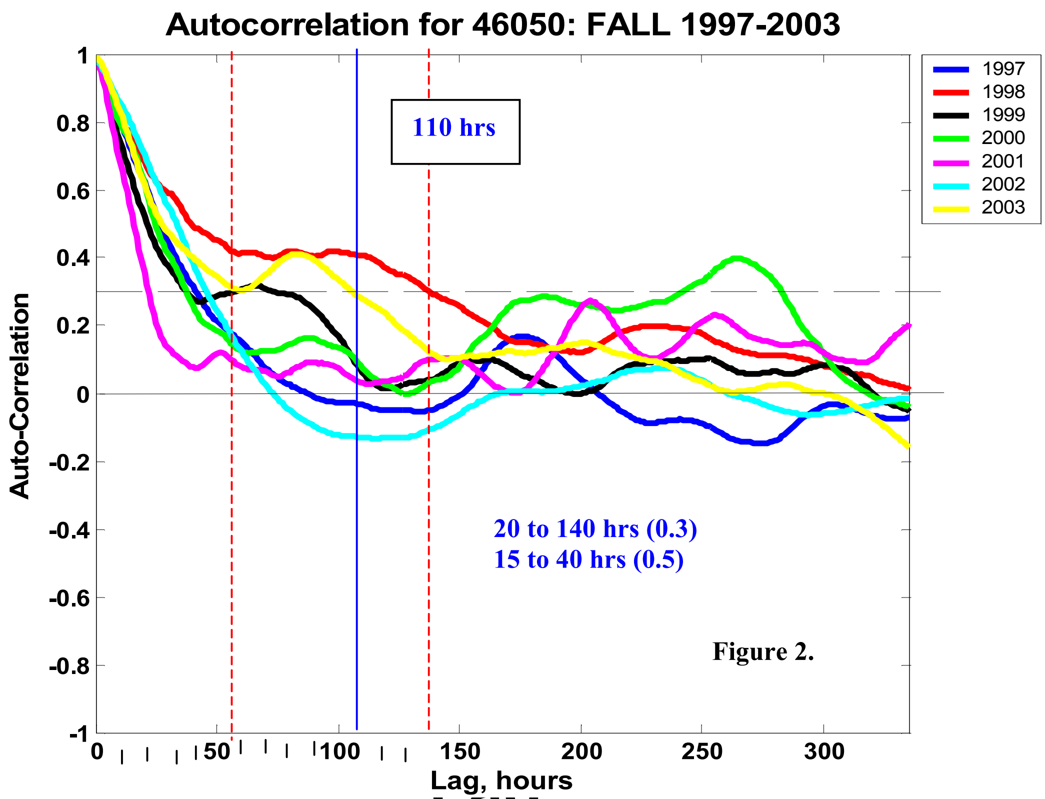
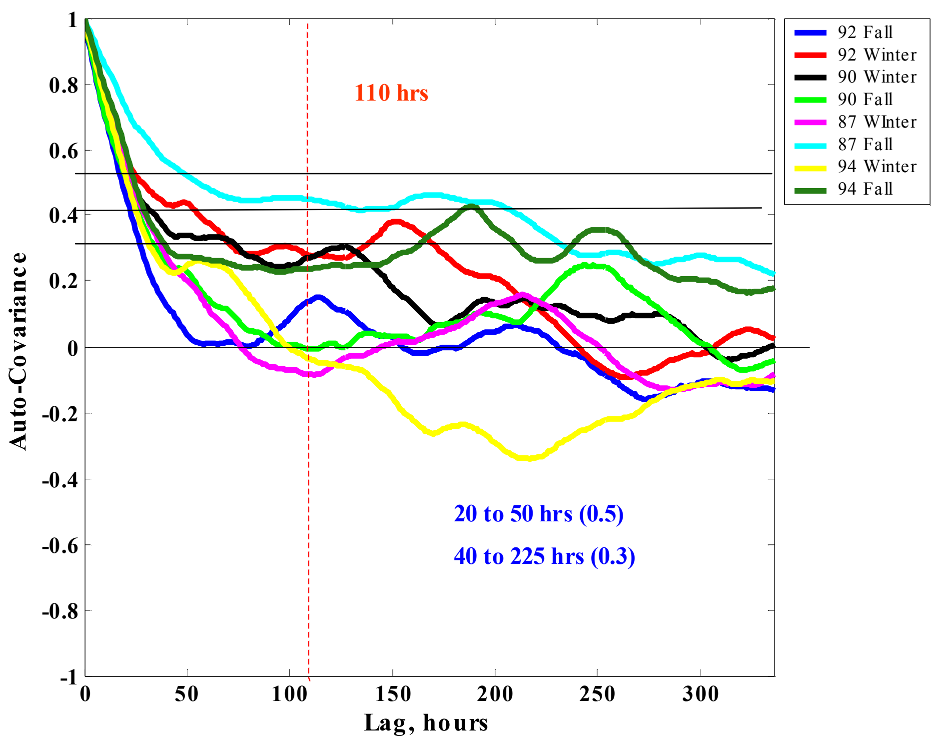


Figure 2.

Figure 3. Autocorrelation for 46027: 1992 to 1994



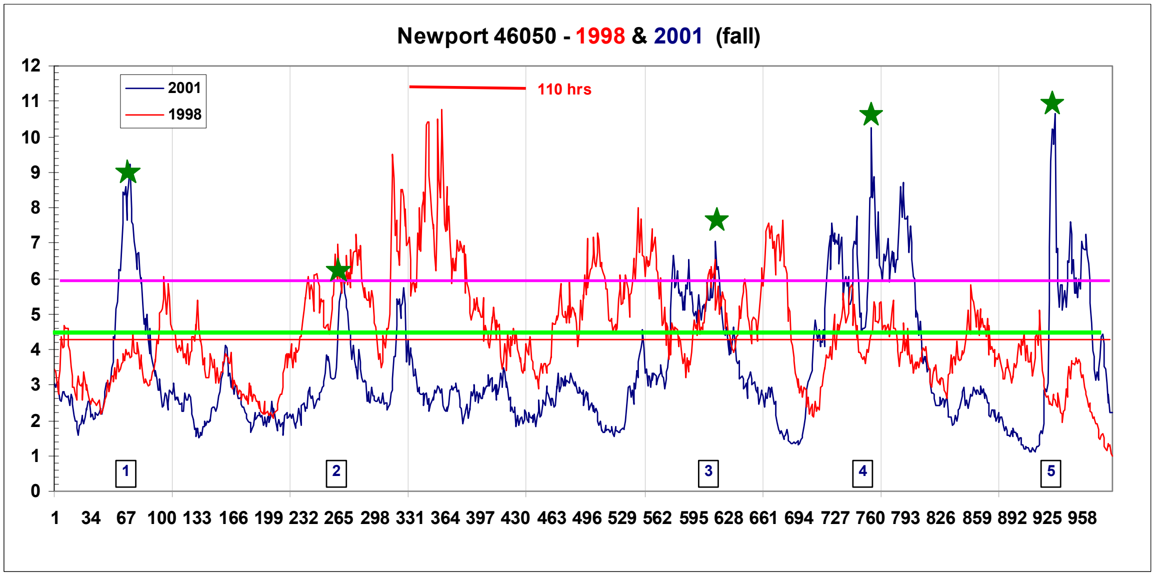


Figure 4. Time Series comparison at 46050

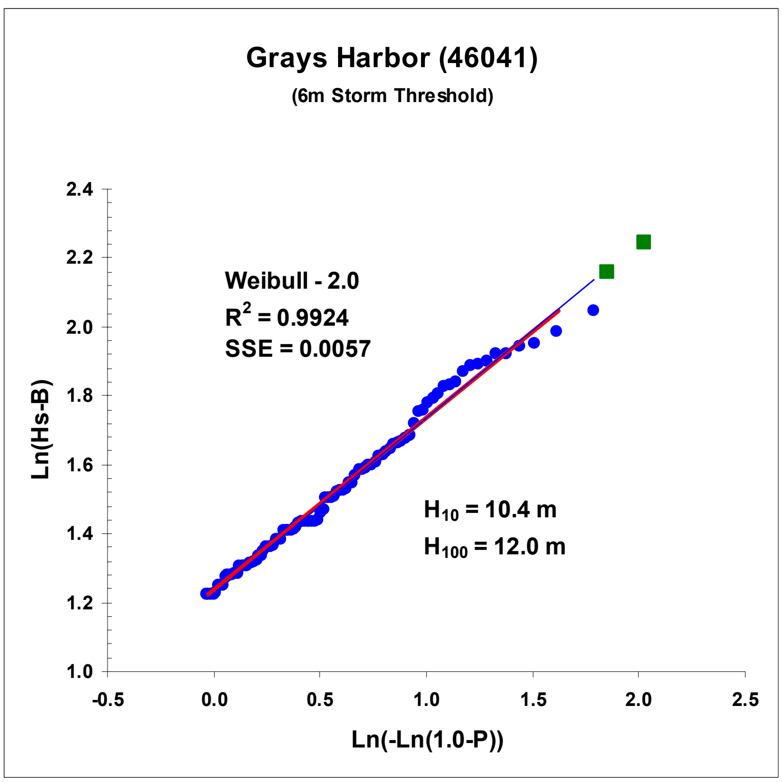


Figure 5. Grays Harbor Extremal Plot

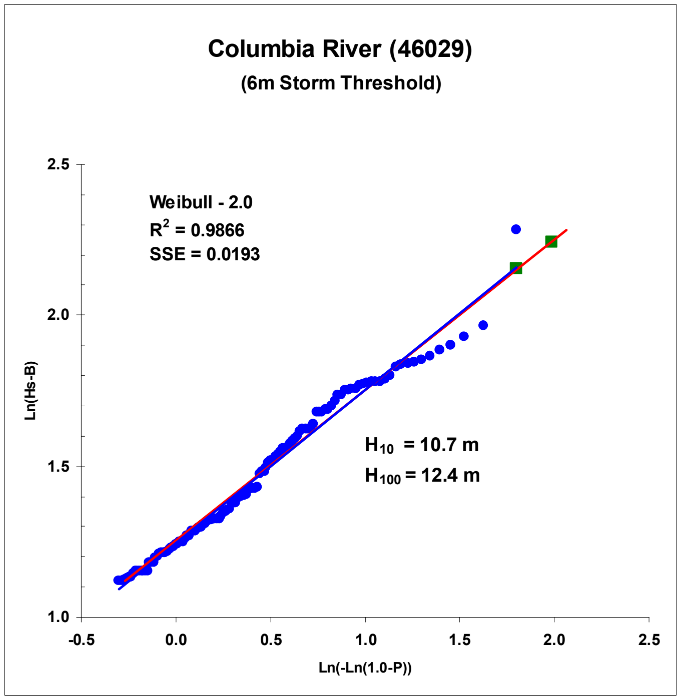


Figure 6. Columbia River Extremal Plot

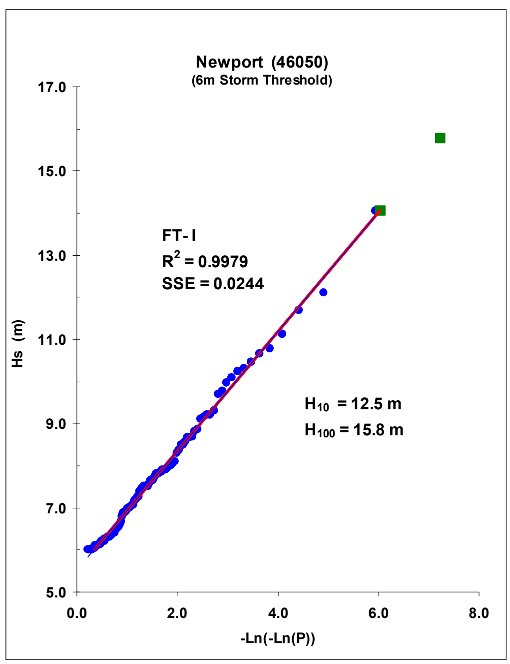


Figure 7. Newport Extremal Plot

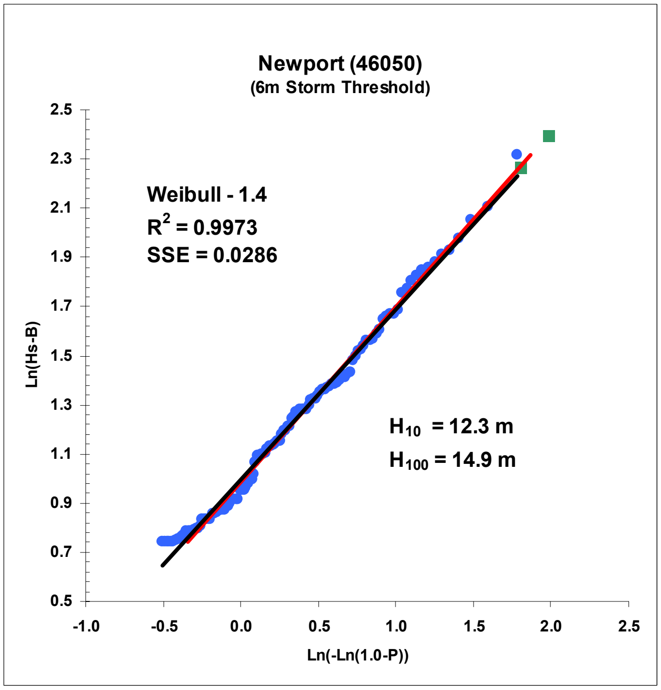


Figure 8. Newport Extremal Plot – Second Distribution

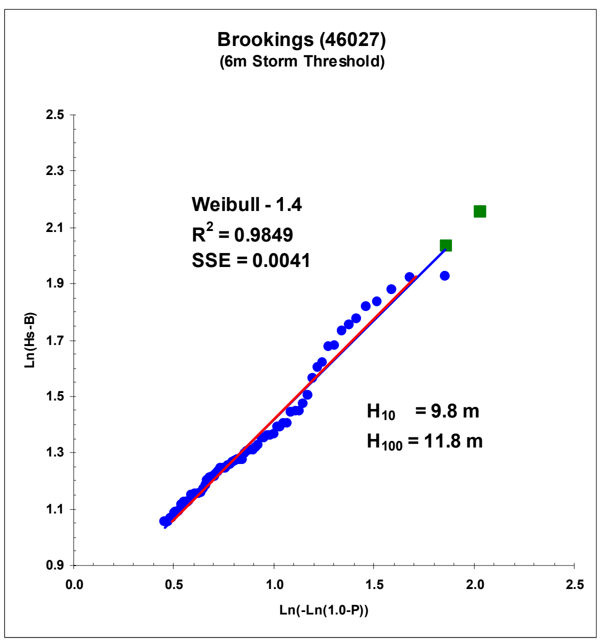


Figure 9. Brookings Extremal Plot

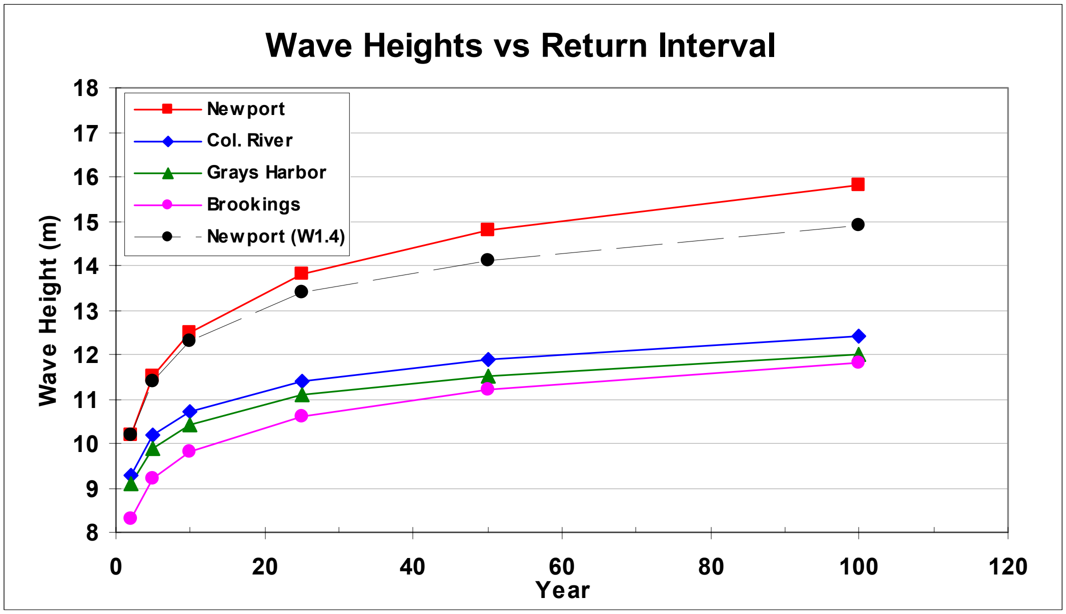


Figure 10. Return Wave Height Results from Extremal Analysis

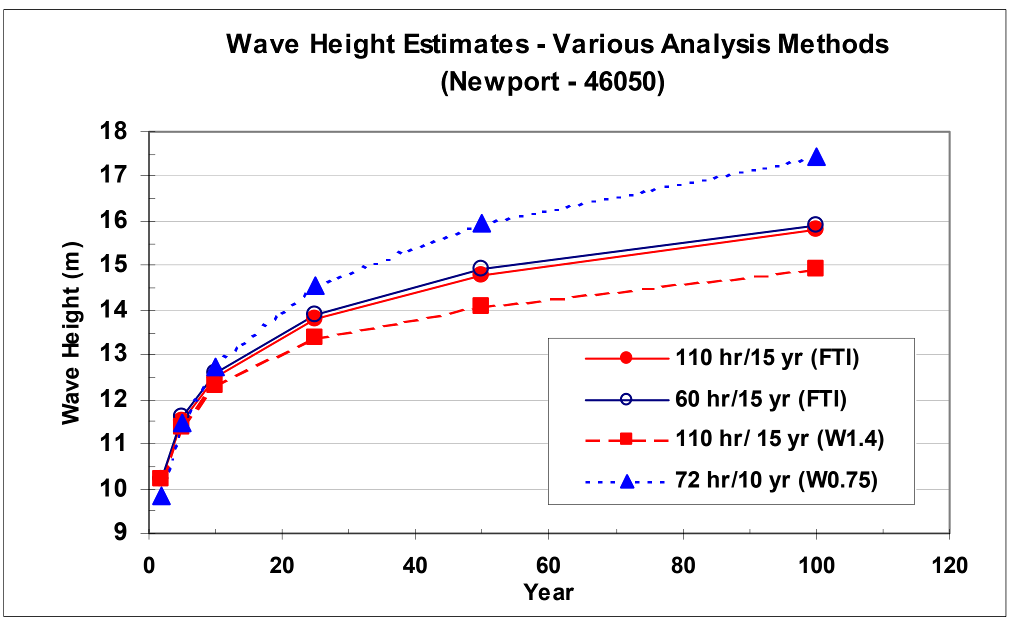
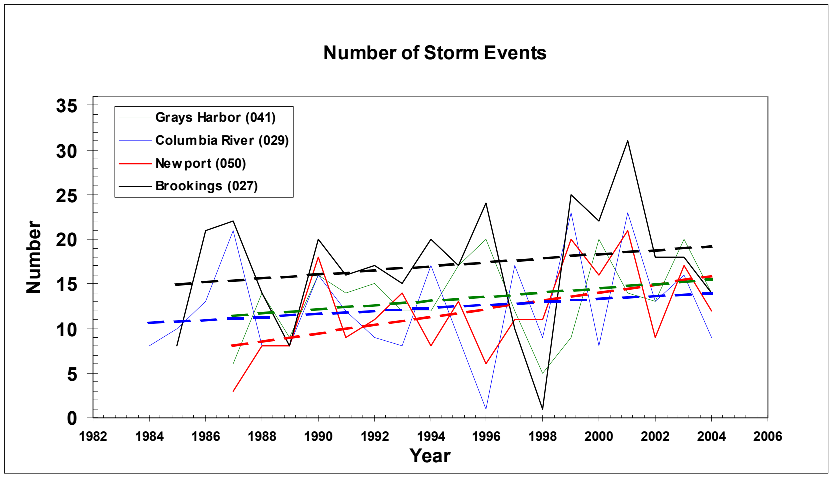
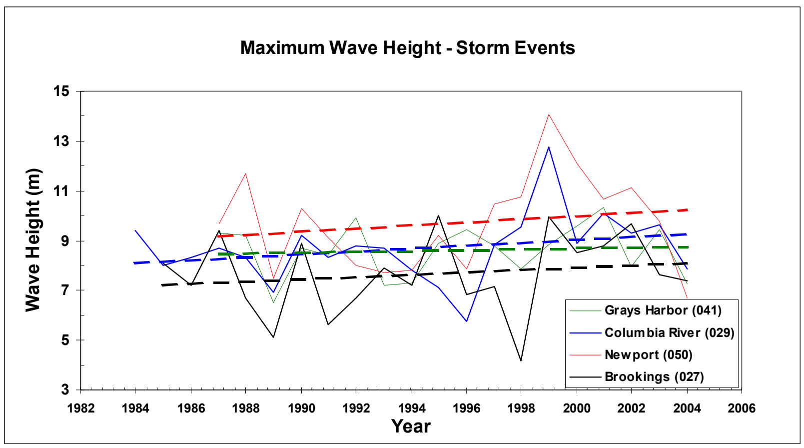
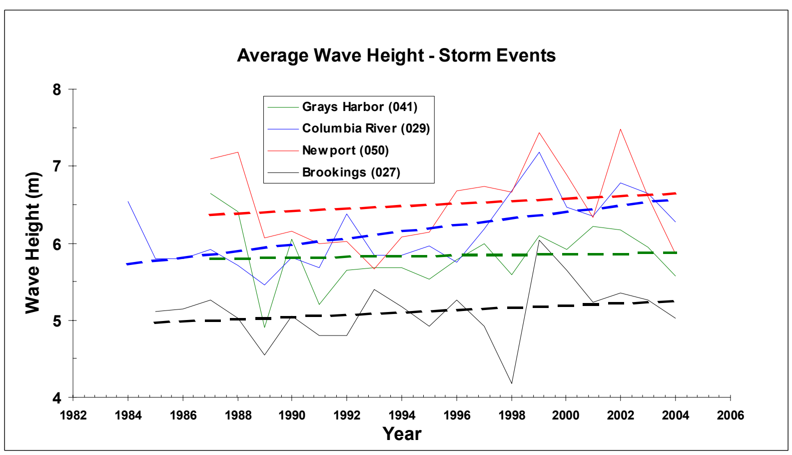


Figure 11. Return Wave Height Comparisons for Different Analysis Methods







Figures 12, 13, 14.. Comparison of Storm Climates, All buoys

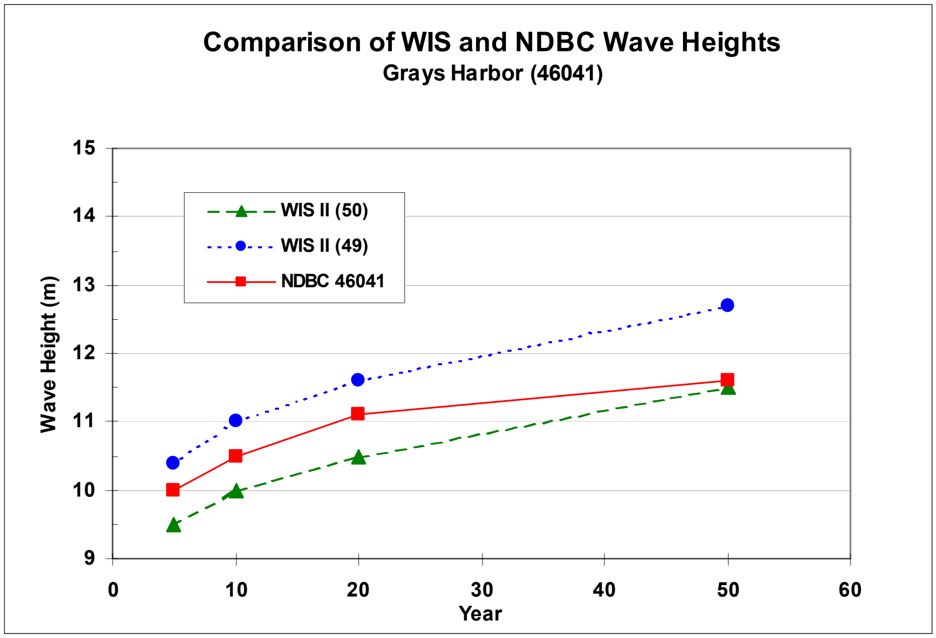


Figure 15. Comparison of WIS Phase II to Analysis Results at Grays Harbor

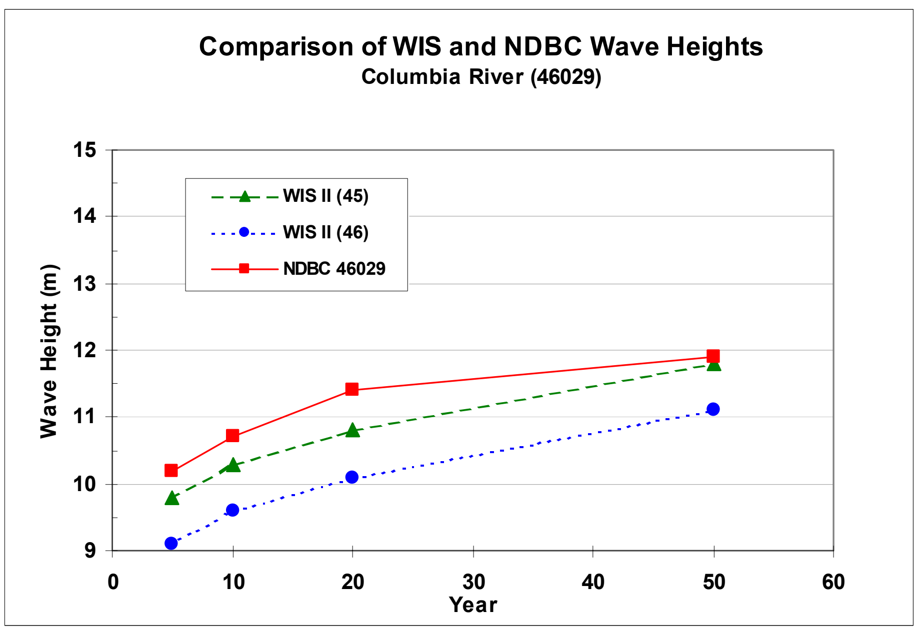


Figure 16. Comparison of WIS Phase II to Analysis Results at Columbia River

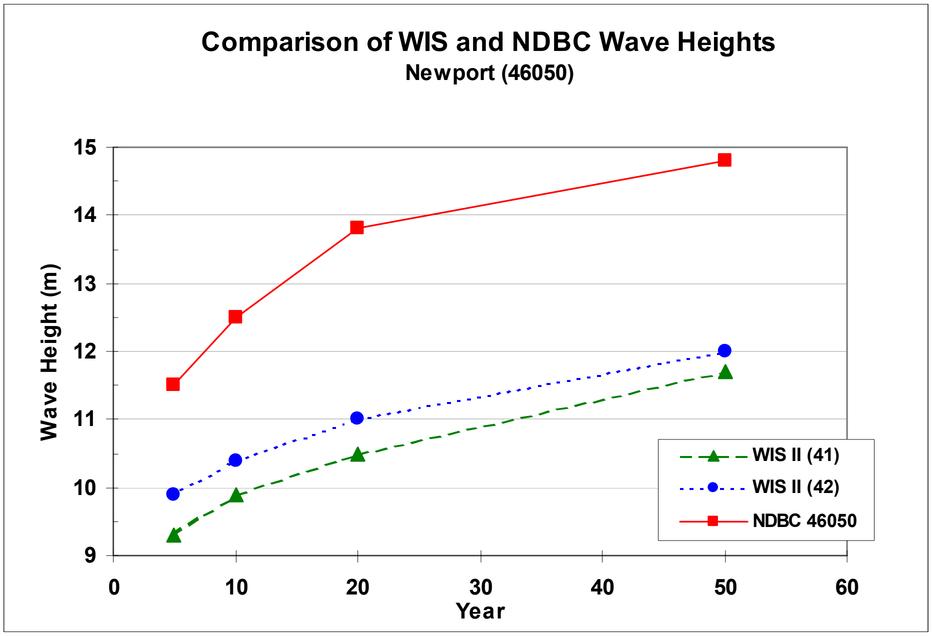


Figure 17. Comparison of WIS Phase II to Analysis Results at Newport

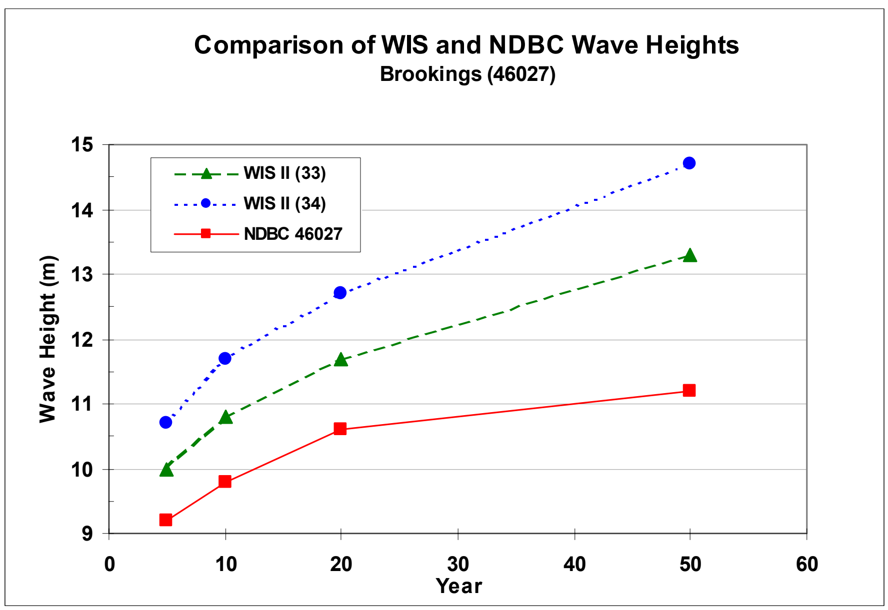


Figure 18. Comparison of WIS Phase II to Analysis Results at Brookings