Regional Analysis
Extremal Wave Height Variability
Oregon Coast, USA

Heidi P. Moritz and Hans R. Moritz

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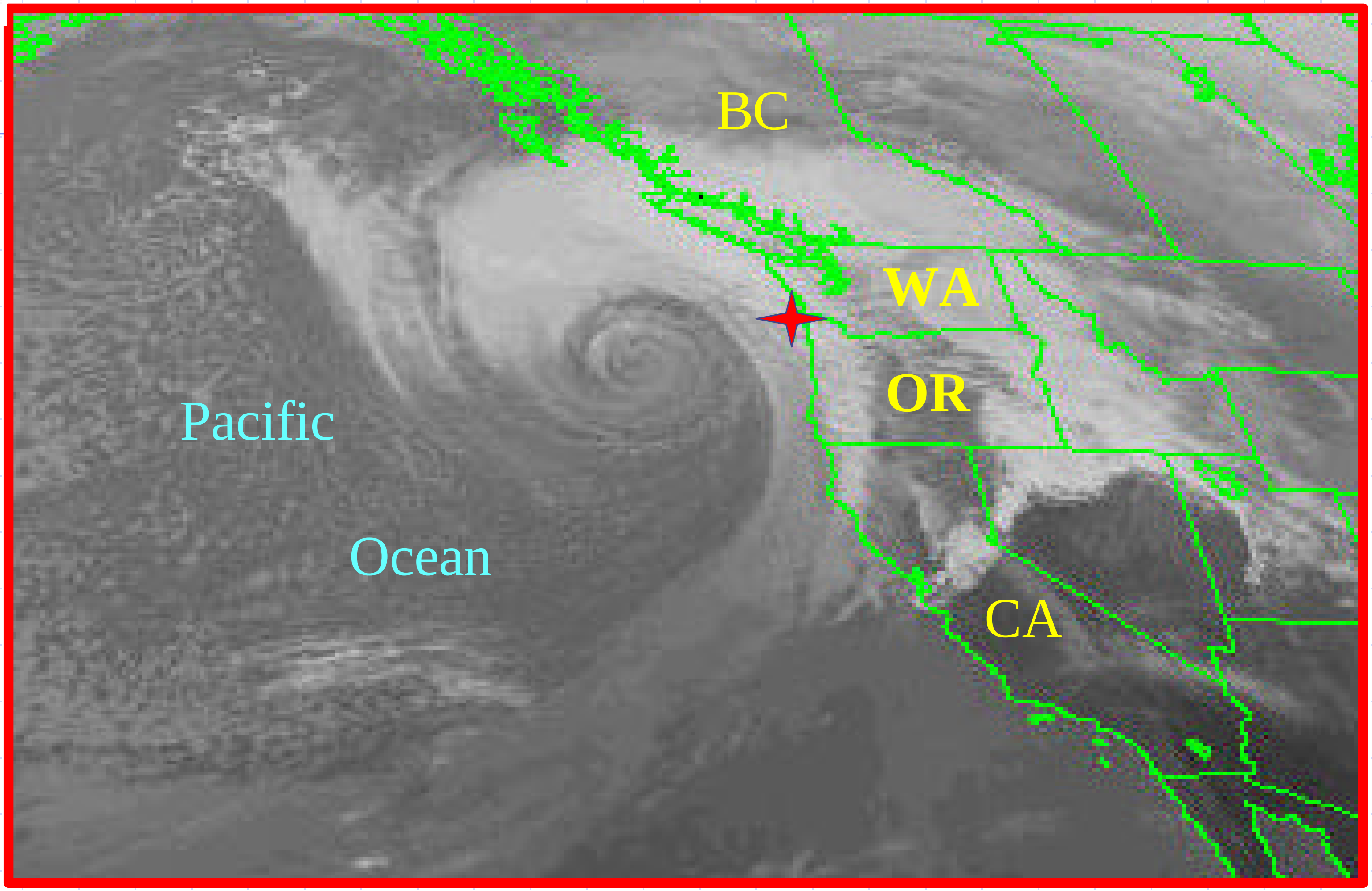

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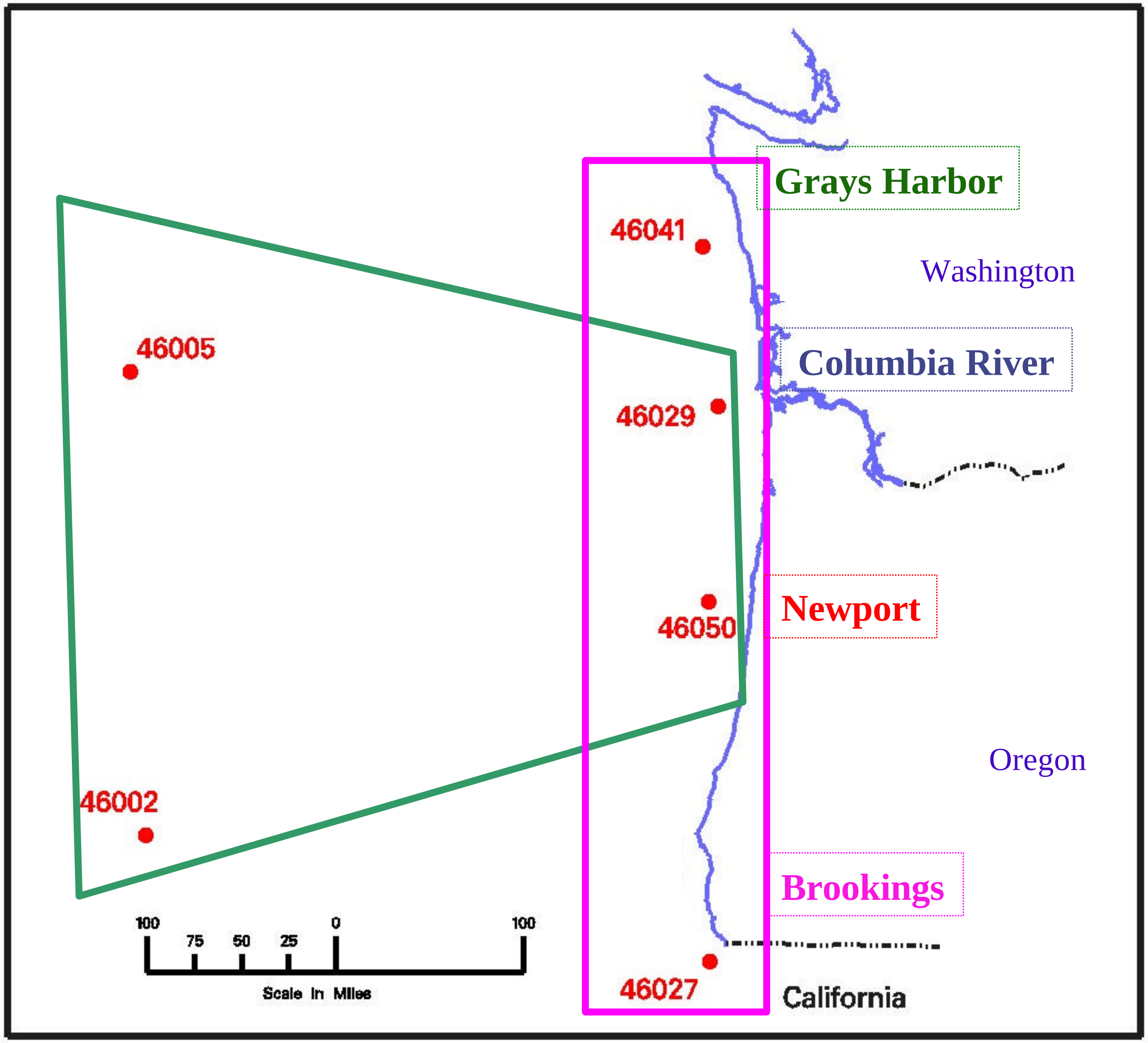
Grays Harbor
46041
Washington
46005
Columbia River
46029
Newport
46050
Oregon
46002
Brookings
100
75
50
25
0
100
Scale In Miles
46027
California

NDBC Buoys Used in Analysis

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

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Key Analysis Questions

- How does the nearshore wave climate vary along the Oregon coast?
- What are the impacts of varying distribution fitting and analysis procedures on extreme wave height estimation?
- How does increasing the period of record affect the extremal wave height estimates?
- Do the updated results for the Newport buoy still indicate a significant difference from the other buoys?

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Key Analysis Questions

- Can data gaps in buoy records be filled from adjacent buoys?
- How does the wave climate defined by the Wave Information Study (WIS) compare to the wave climate defined by the NDBC buoys?

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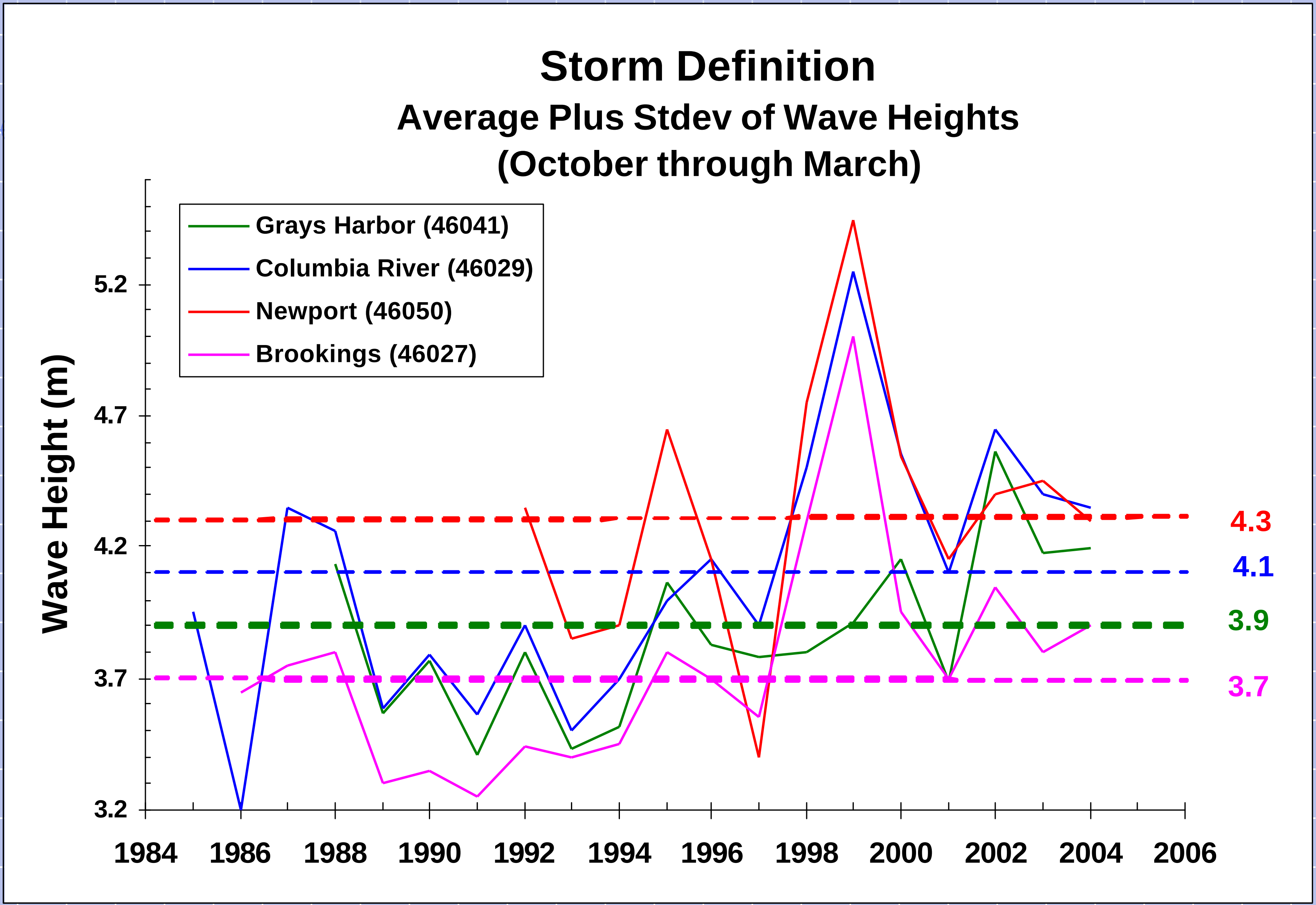
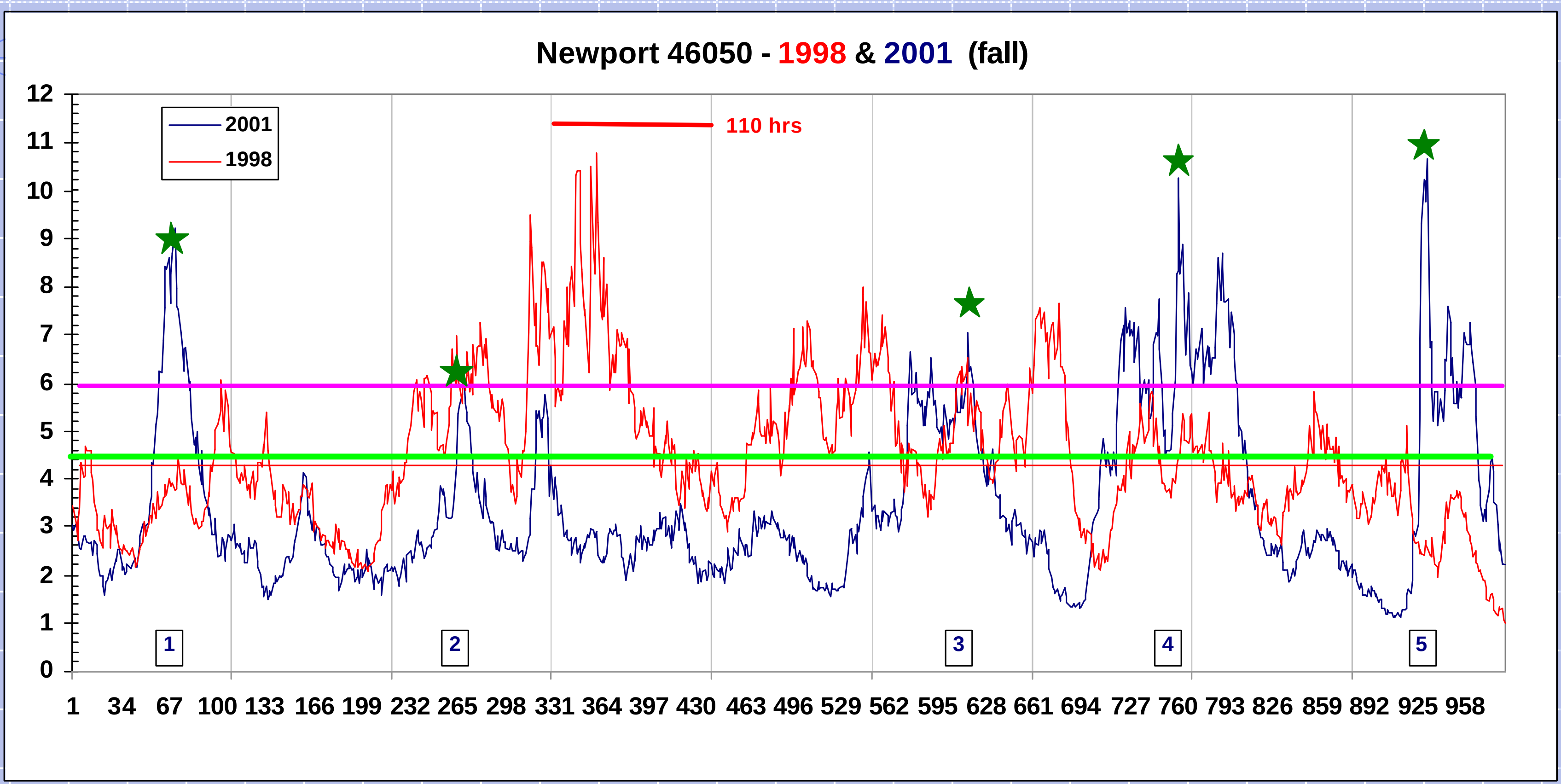
Previous Studies/Analyses

- **Goda** - *Extremal/Design Wave Height Analyses* (1988, 1990)
- **Van Vledder, et al** - *Case Studies of Extreme Wave Analysis* (1997)
- **Mathiesen, et al** - *Recommended Practice for Extreme Wave Analysis* (1994)
- **USACE -** Coastal Engineering Manual (1996)
- **Teng, et al** - *Northeastern Pacific NDBC buoy analyses* (1993, 1996)
- **Rossouw** - *Design Waves and Their Probability Density Functions* (1988)

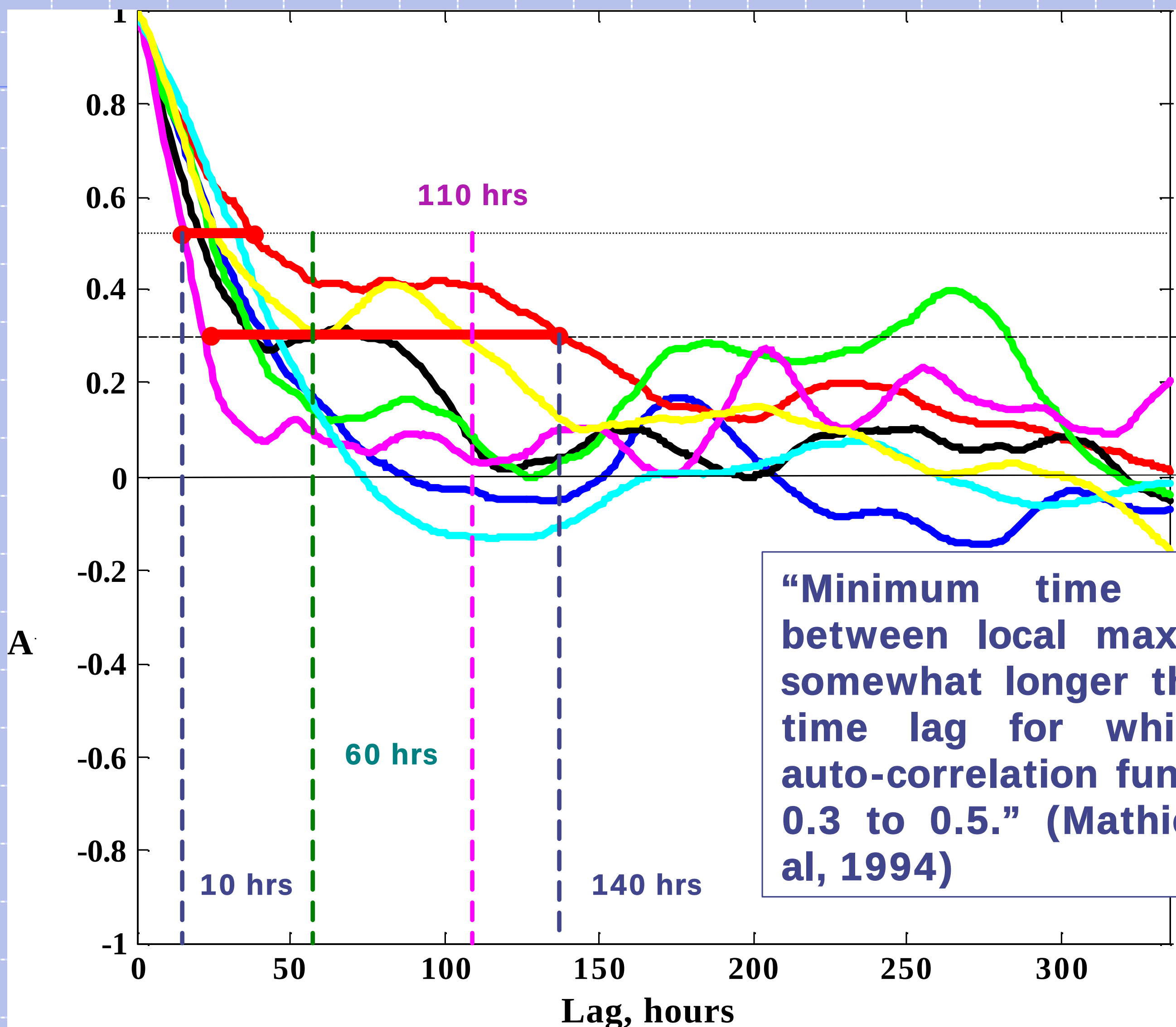


Storm Definition
Average Plus Stdev of Wave Heights
(October through March)
Grays Harbor (46041)
Columbia River (46029)
Newport (46050)
Brookings (46027)
Wave Height (m)
5.2
4.7
4.2
3.7
3.2
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
4.3
4.1
3.9
3.7



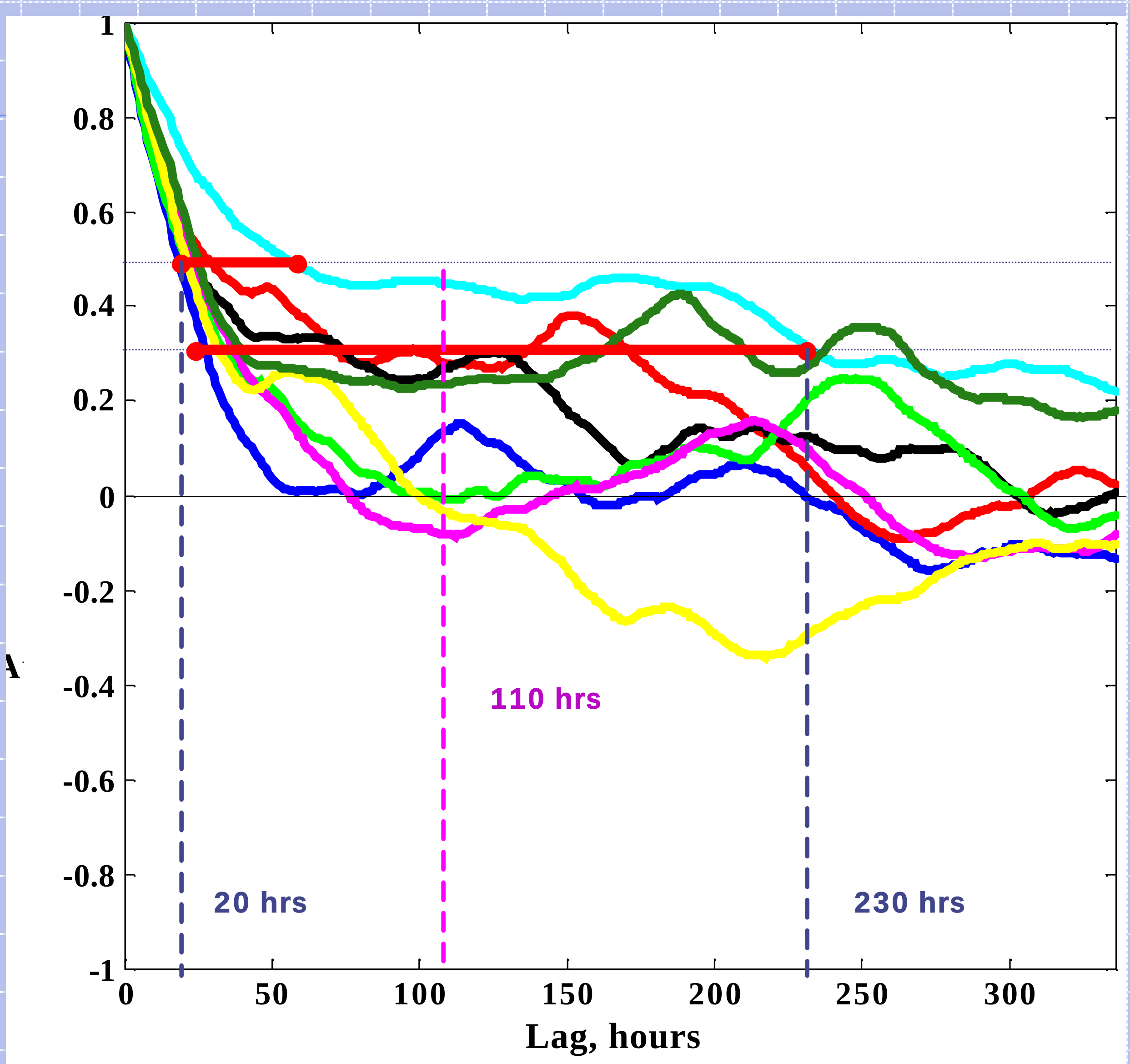
Newport 46050 - 1998 & 2001 (fall)
2001
1998
110 hrs
12
11
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
1 34 67 100 133 166 199 232 265 298 331 364 397 430 463 496 529 562 595 628 661 694 727 760 793 826 859 892 925 958

Auto-Correlation - NDBC 46050 - Newport



"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." (Mathiesen et al, 1994)

Auto-Correlation - NDBC 46027 - Brookings



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Analysis Procedure

- **Period of Record**: June '84 to April '04 (14 to 18.1 years)
- **Partial Duration Series**
- **Peak-Over-Threshold Method (POT)**
- **Separation of storm events:** 60 to 110 hrs
- **Storm Threshold** - Average + 1 stdev (Oct - Mar)
- **Storm definition** (N_T)= 4 m/4.5 m threshold
- **Threshold** for significant storms (N) = **6 m**
- **Distributions** analyzed: FT-1, Weibull (k=0.75, 1.0, 1.4, 2.0)

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

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

Weibull Distribution:

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

$k = 0.75, 1.0, 1.4, 2.0$

$F(H_s \le \hat{H}_s)$ = 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

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Plotting Procedure

- **Plotting position formulas**: FT-1 (Gringorton, 1963), Weibull (Goda, 1988)
- Data reduction to **straight line plot**.
- **Parameter estimation** using Least Squares Regression.
- USACE ACES analysis of **distribution parameters**.
- **Goodness-of-fit** evaluation using several criteria.

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

$$\hat{F}_m = 1 - \frac{m - 0.44}{N + 0.12}$$

Weibull Plotting Formula (Goda 1988)

$$\hat{F}_m = 1 - \frac{m - 0.20 - (0.27/\text{Ö}k)}{N + 0.20 + (0.23/\text{Ö}k)}$$

$\hat{F}_m$ = probability that the m^{th} highest data value will not be exceeded

m = rank of data value in descending order

N = total number of storm events

k = Weibull shape parameter

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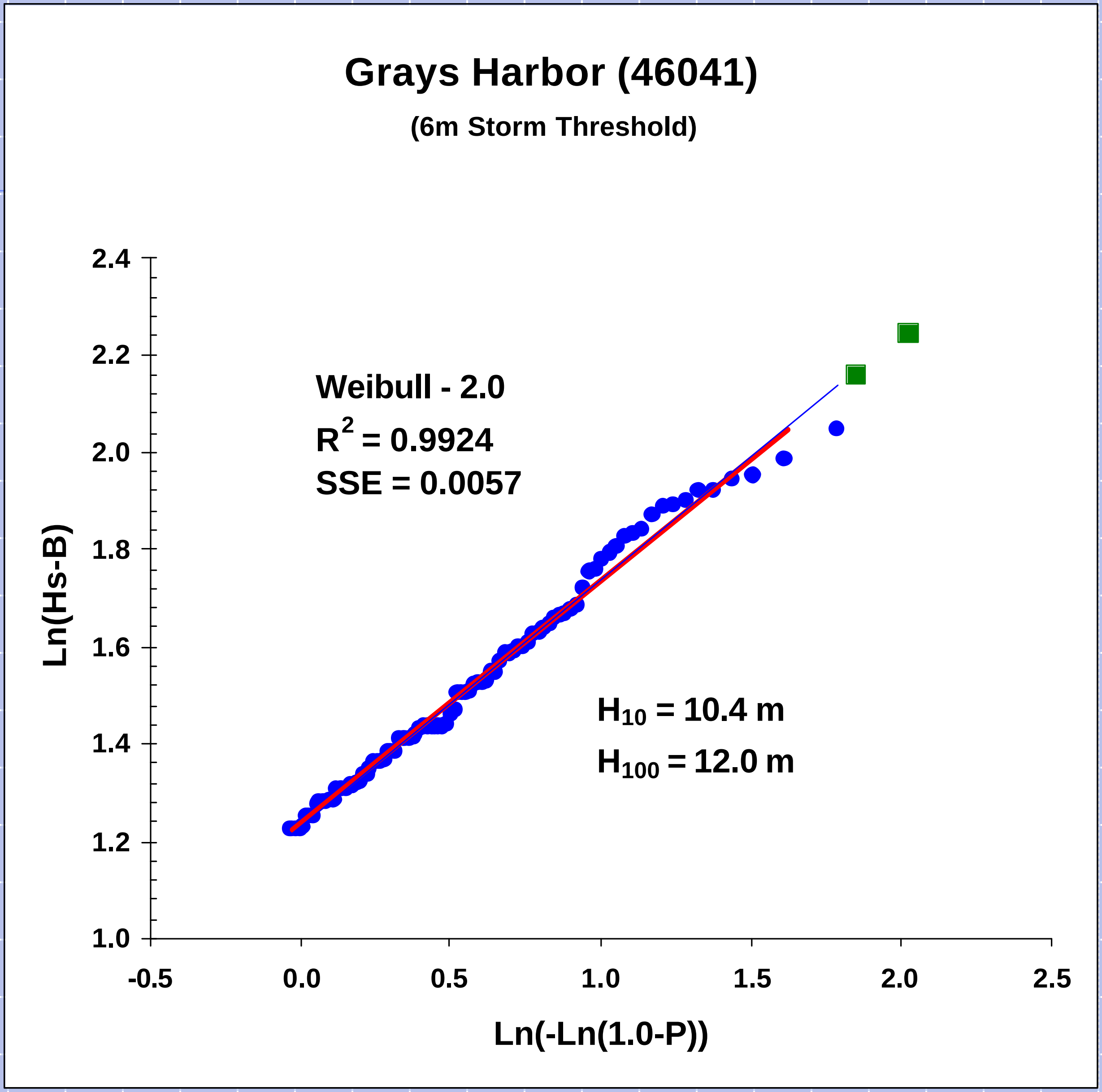
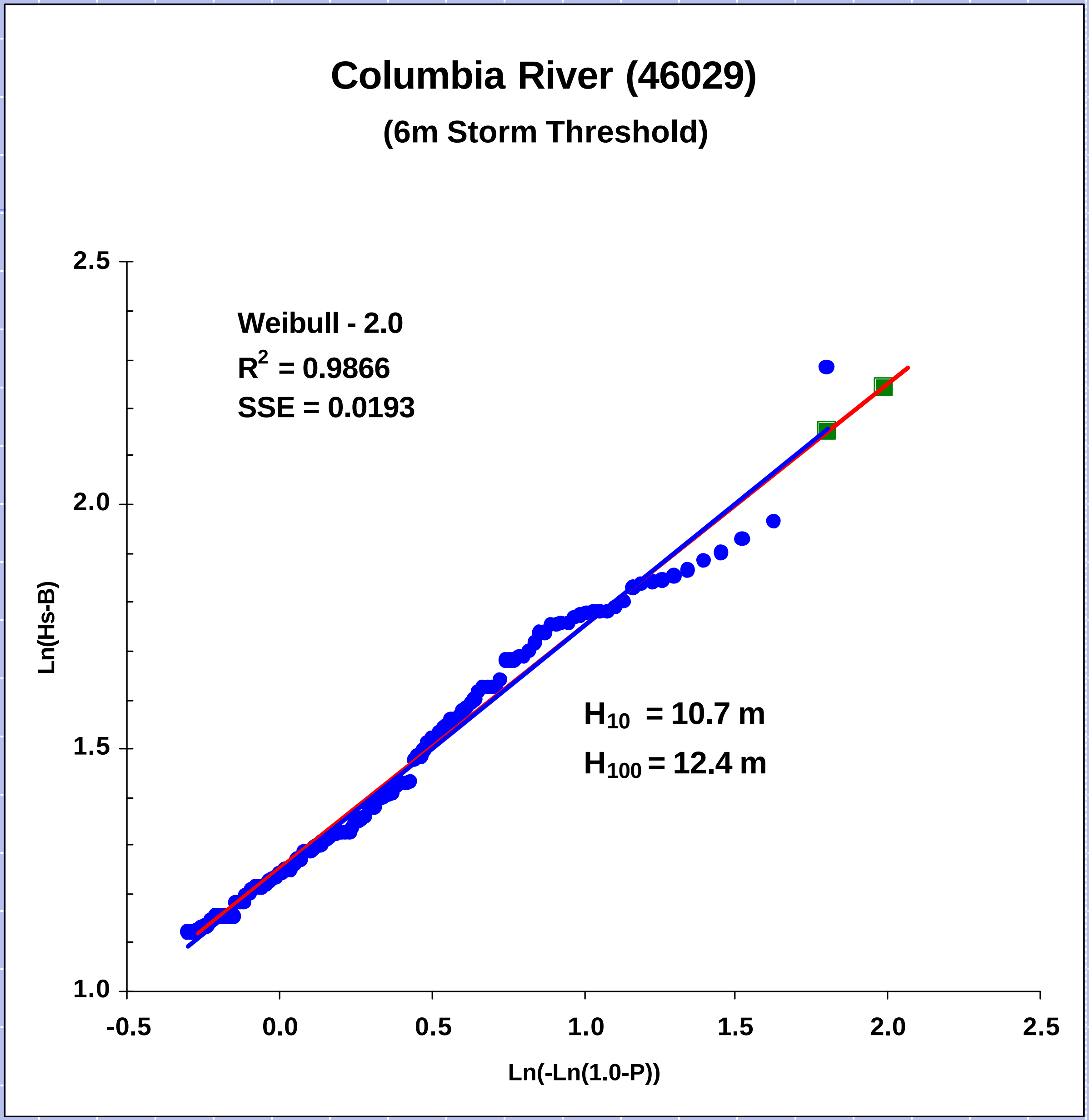
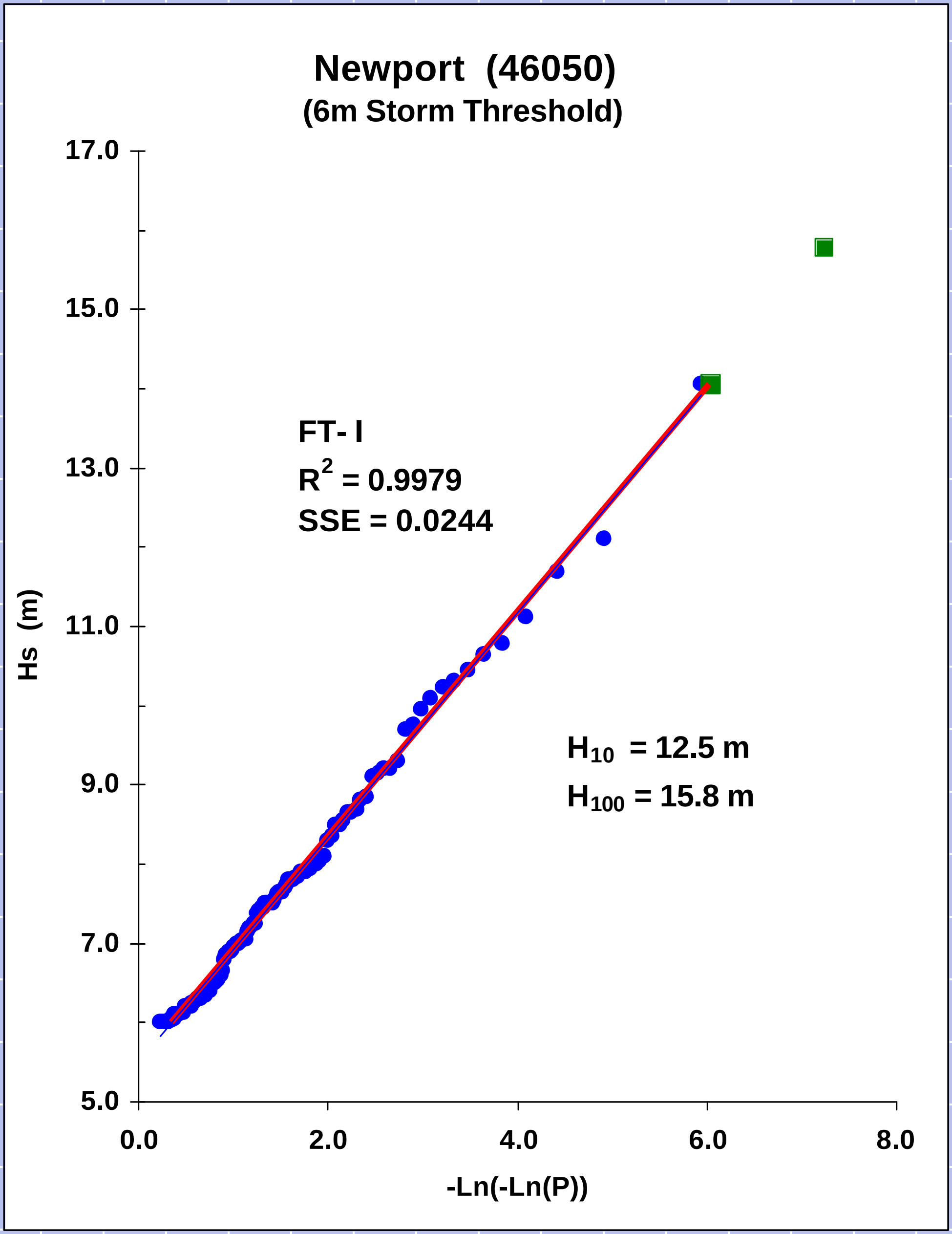
Goodness-of-Fit Criteria

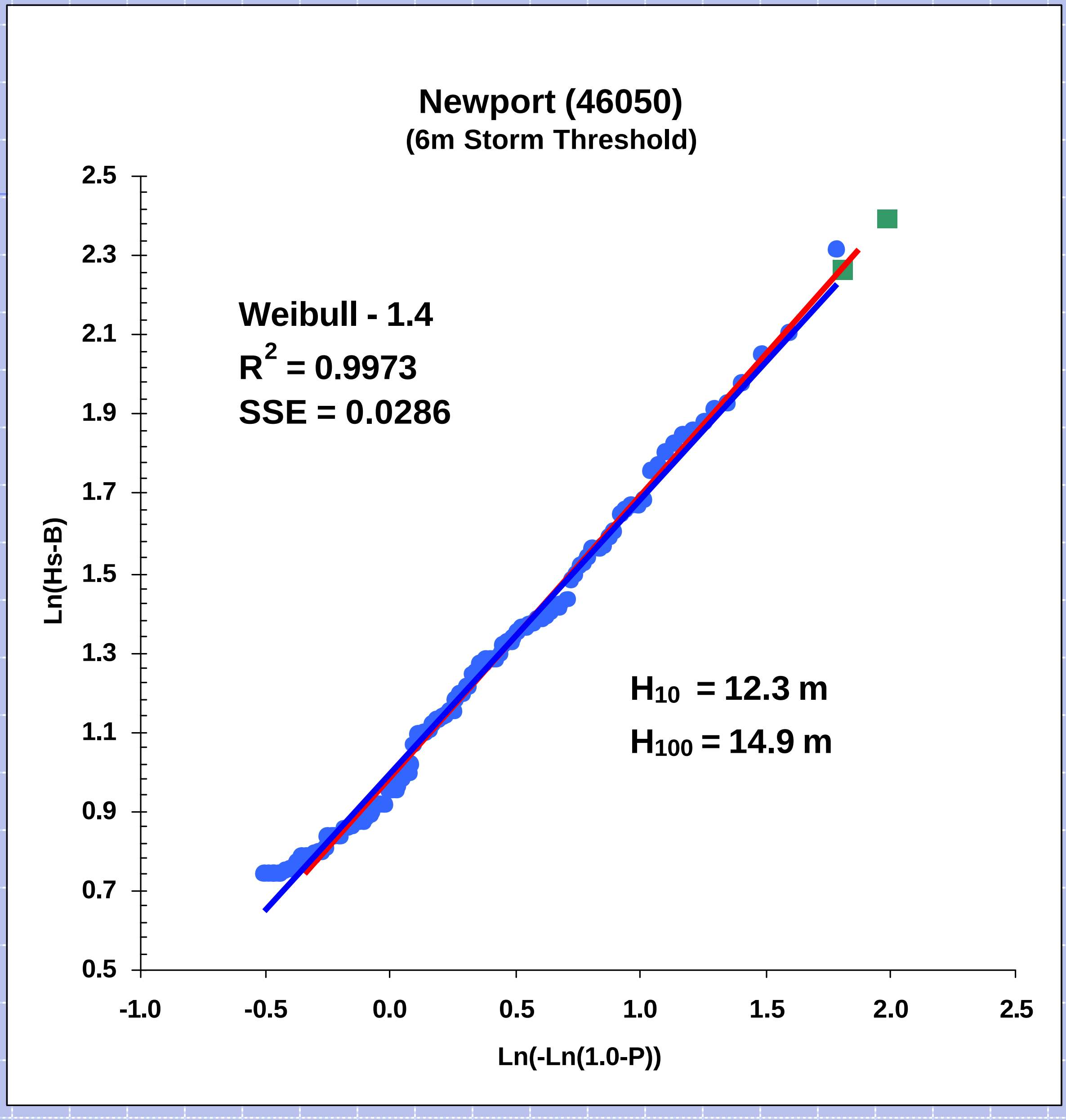
- Correlation
- Distribution Fit with Upper Portion of Data
- Straight Line Plot of Data
- Sum Square of Residuals
- Distribution Line Extrapolation
- Distribution Line Fit with Data Trend Line



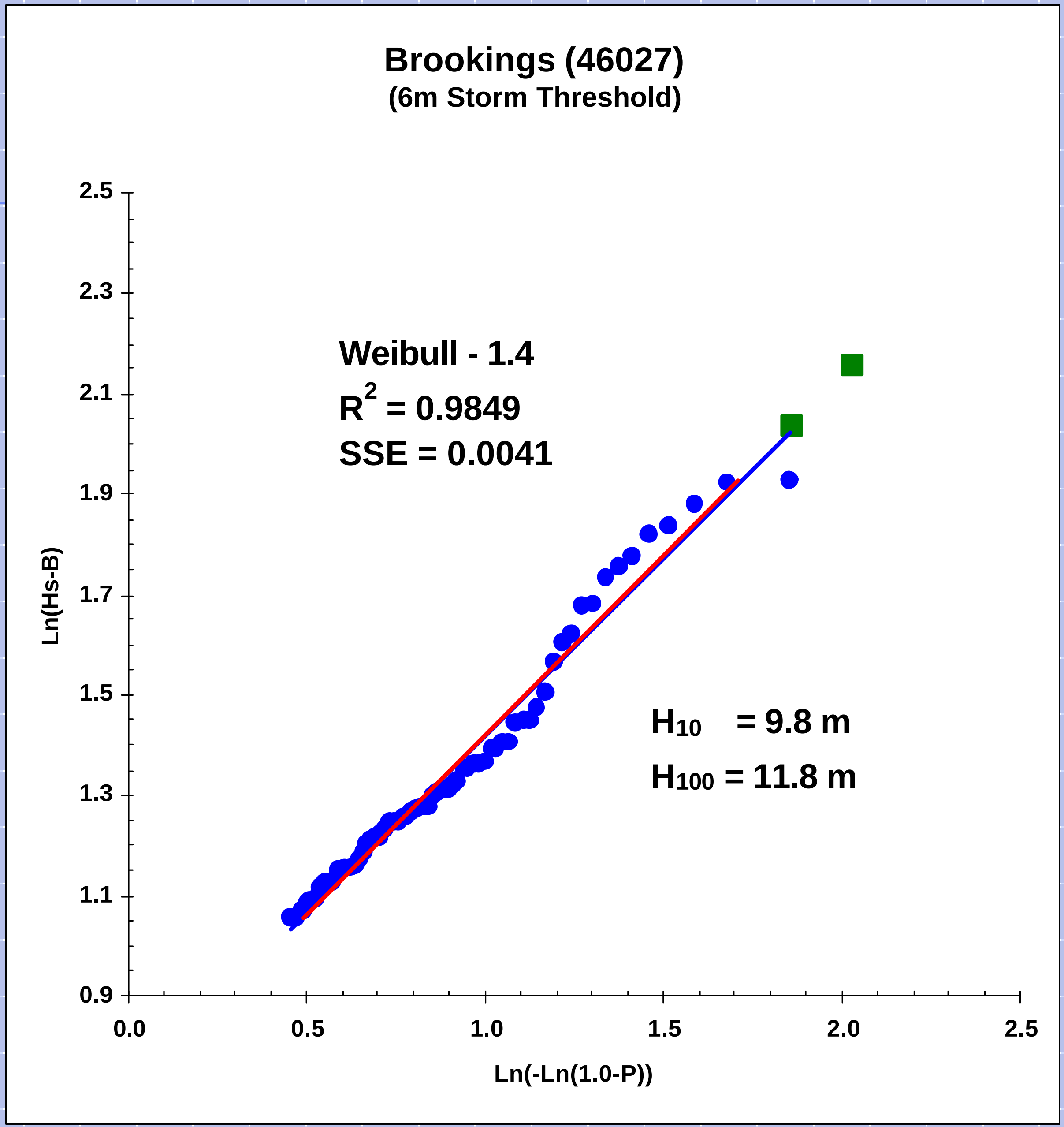
Grays Harbor (46041)
(6m Storm Threshold)
Weibull - 2.0
R2 = 0.9924
SSE = 0.0057
H10 = 10.4 m
H100 = 12.0 m
Ln(Hs-B)
Ln(-Ln(1.0-P))
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5


Columbia River (46029)
(6m Storm Threshold)
Weibull - 2.0
R2 = 0.9866
SSE = 0.0193
H10 = 10.7 m
H100 = 12.4 m
Ln(Hs-B)
Ln(-Ln(1.0-P))
2.5
2.0
1.5
1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5


Newport (46050)
(6m Storm Threshold)
17.0
15.0
13.0
11.0
9.0
7.0
5.0
Hs (m)
0.0
2.0
4.0
6.0
8.0
-Ln(-Ln(P))
FT- I
R2 = 0.9979
SSE = 0.0244
H10 = 12.5 m
H100 = 15.8 m



Newport (46050)
(6m Storm Threshold)
Weibull - 1.4
R2 = 0.9973
SSE = 0.0286
H10 = 12.3 m
H100 = 14.9 m
Ln(Hs-B)
Ln(-Ln(1.0-P))
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5



Brookings (46027)
(6m Storm Threshold)
Weibull - 1.4
R2 = 0.9849
SSE = 0.0041
H10 = 9.8 m
H100 = 11.8 m
Ln(Hs-B)
Ln(-Ln(1.0-P))
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.0
0.5
1.0
1.5
2.0
2.5

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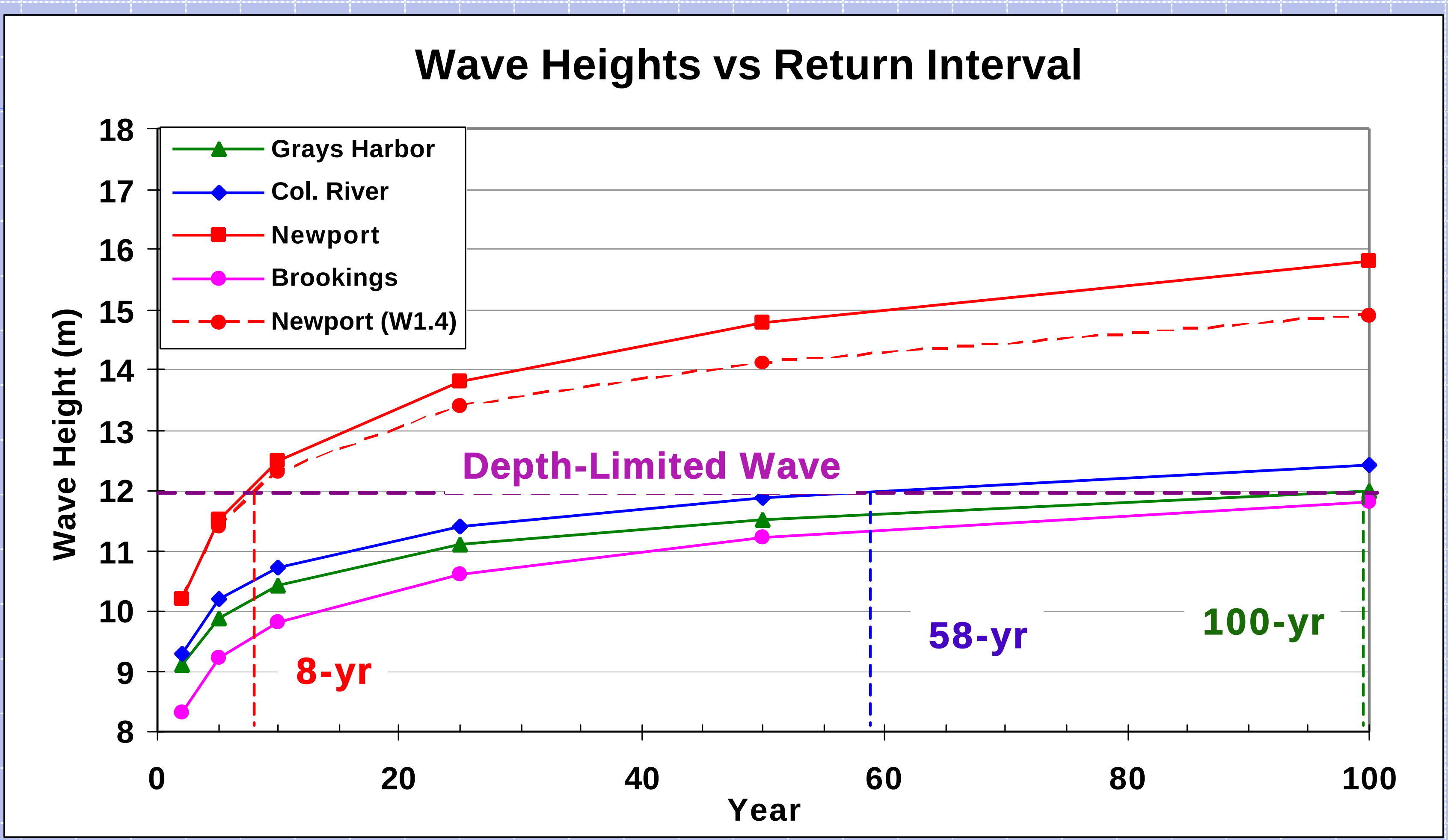
Lessons Learned - Analysis and Distribution Fitting

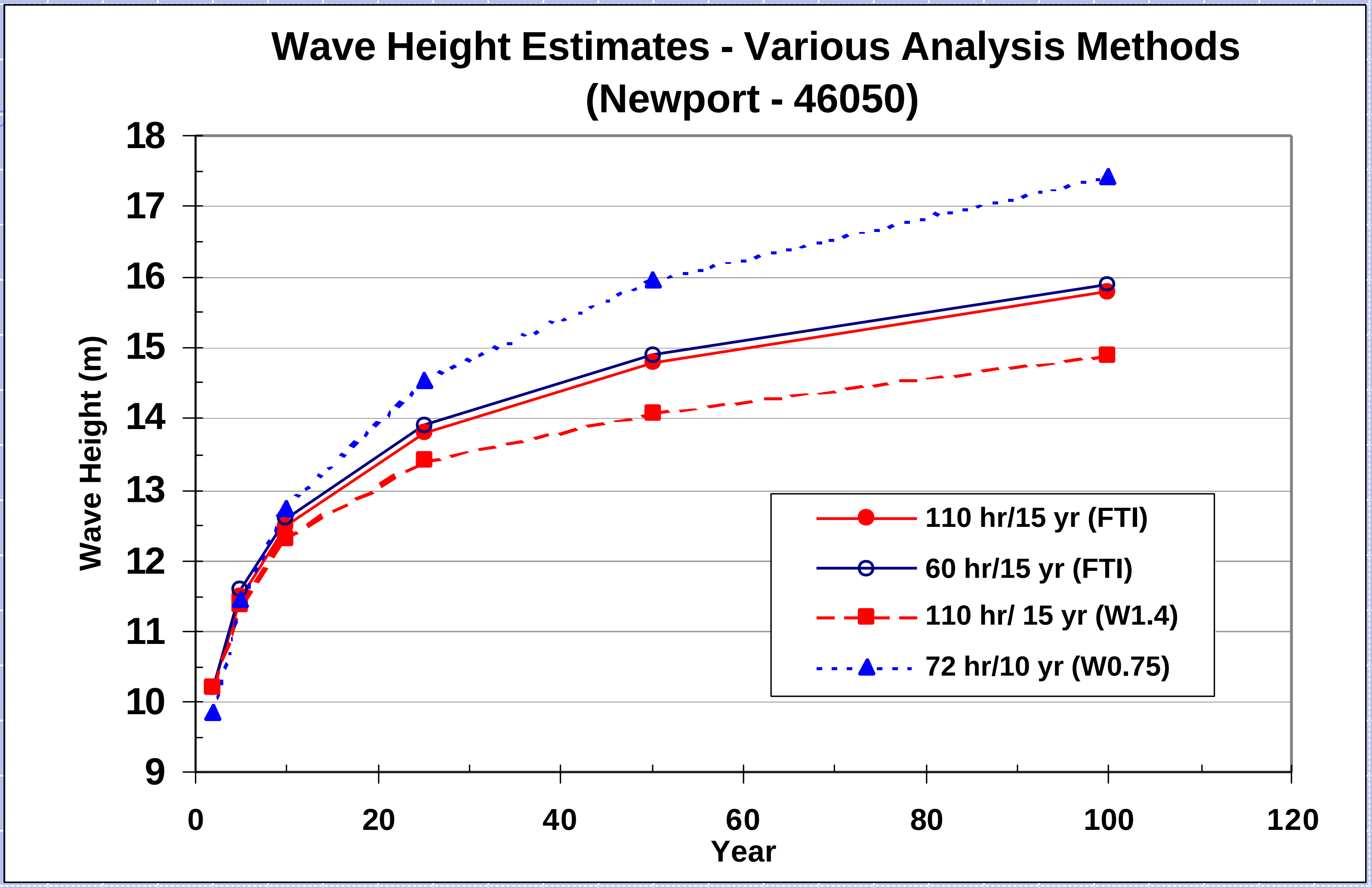
- Selection of significant **storm threshold** can influence results.
- Essential to **plot data points** for selection of distribution.
- **Straight line plot** of distribution/data points aids in best fit selection.
- **Highest correlation** does not always provide best fit of upper portion of plot.

Extremal Analysis Results

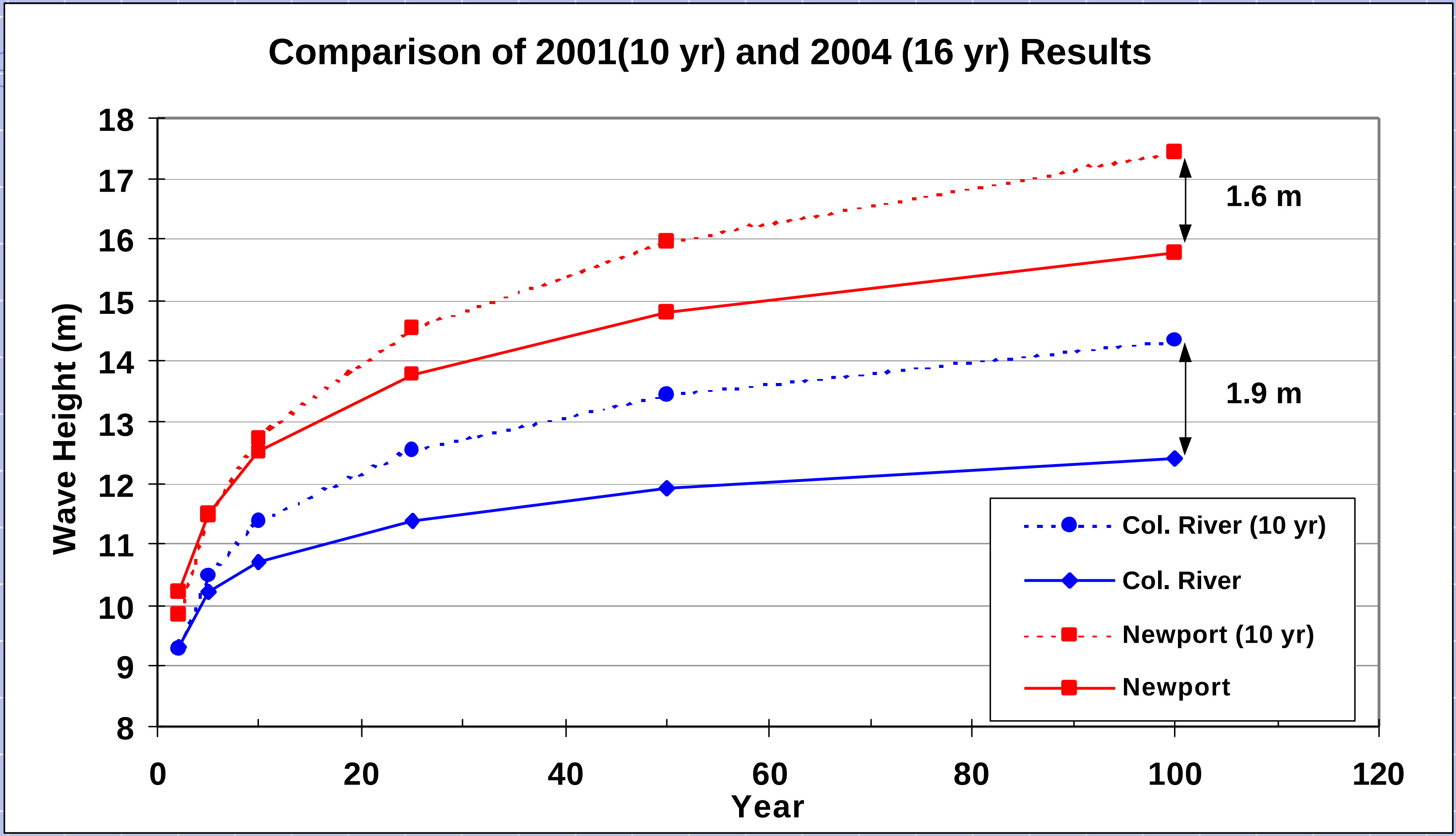
Parameter	Grays Harbor	Col. River	Newport	Brookings
N	93	**124**	118	71
NT	243	259	215	**342**
K (yrs)	14	**18.1**	15.3	16.6
Storms/Yr	17.4	14.3	14	**20.6**
Max H (m)	10.3	12.8	**14.1**	10
Max T (sec)	20	20	20	**25**
Mean H (m)	7.3	7.4	**7.5**	7.0
Mean T (sec)	14	13.8	13.7	**15.9**
StDev H (m)	1.1	1.2	**1.5**	1
Distribution	Weibull	Weibull	FT-1	Weibull
k	2	2	NA	1.4
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

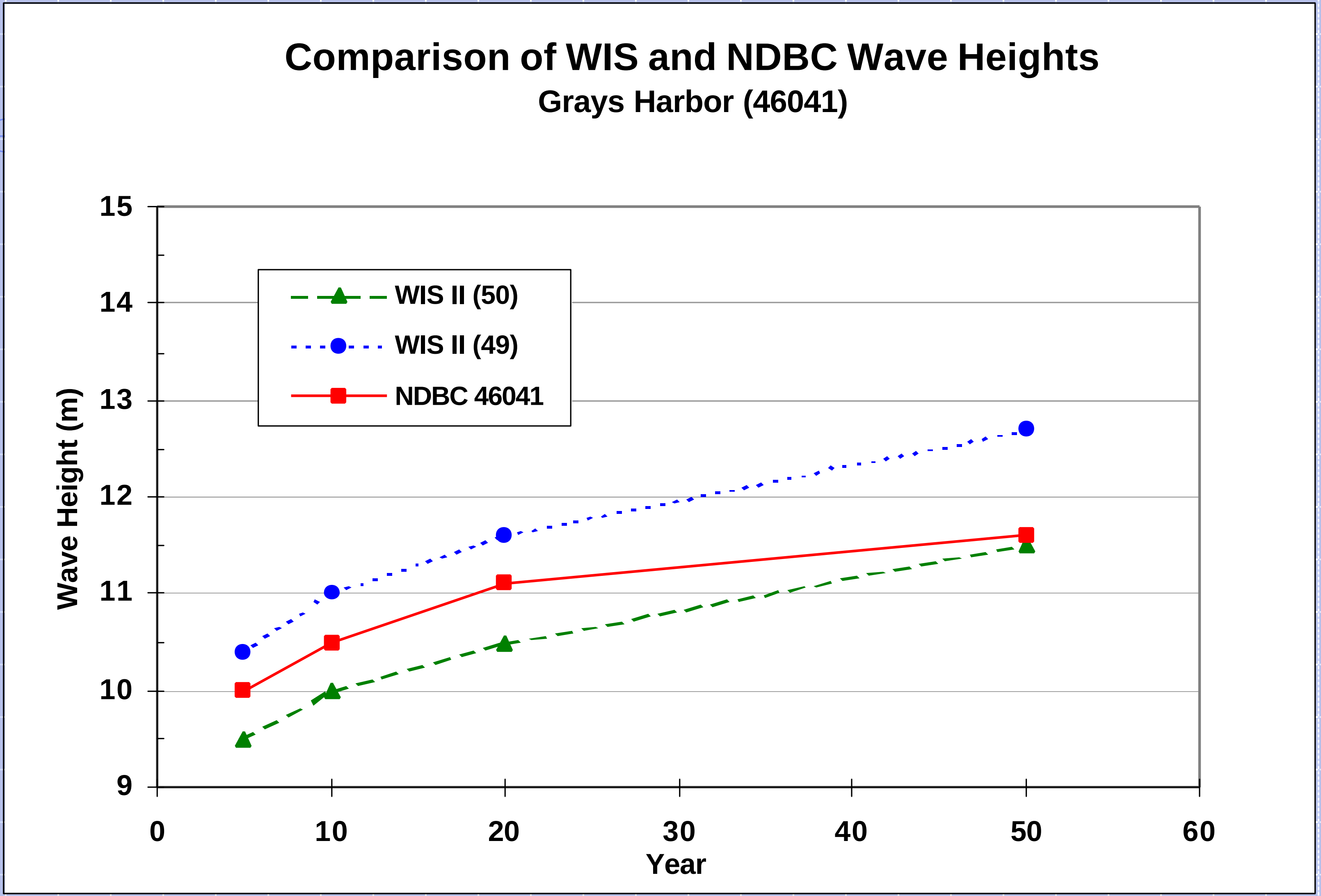


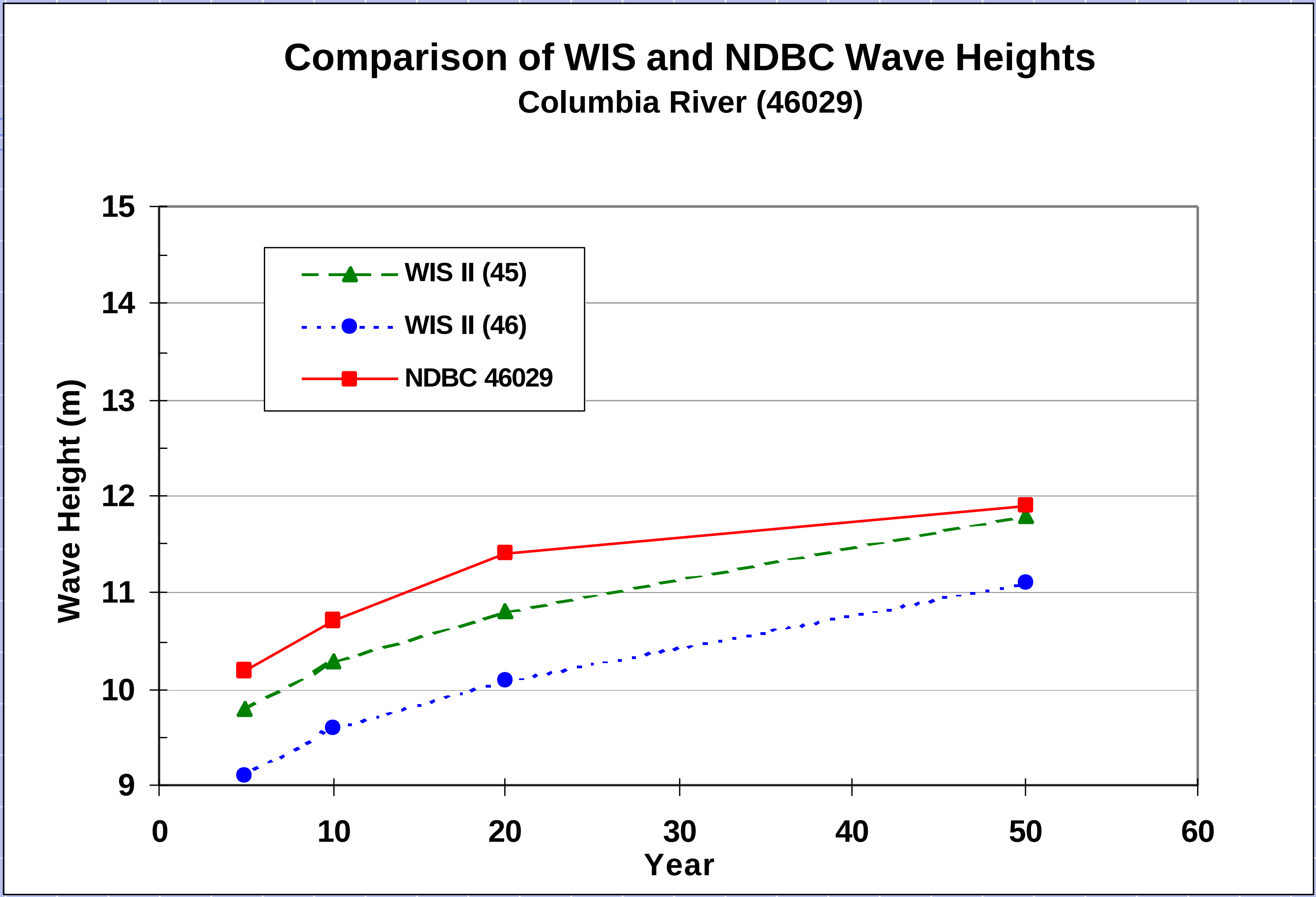
Wave Heights vs Return Interval
Grays Harbor
Col. River
Newport
Brookings
Newport (W1.4)
Depth-Limited Wave
8-yr
58-yr
100-yr
Wave Height (m)
Year
18
17
16
15
14
13
12
11
10
9
8
0
20
40
60
80
100



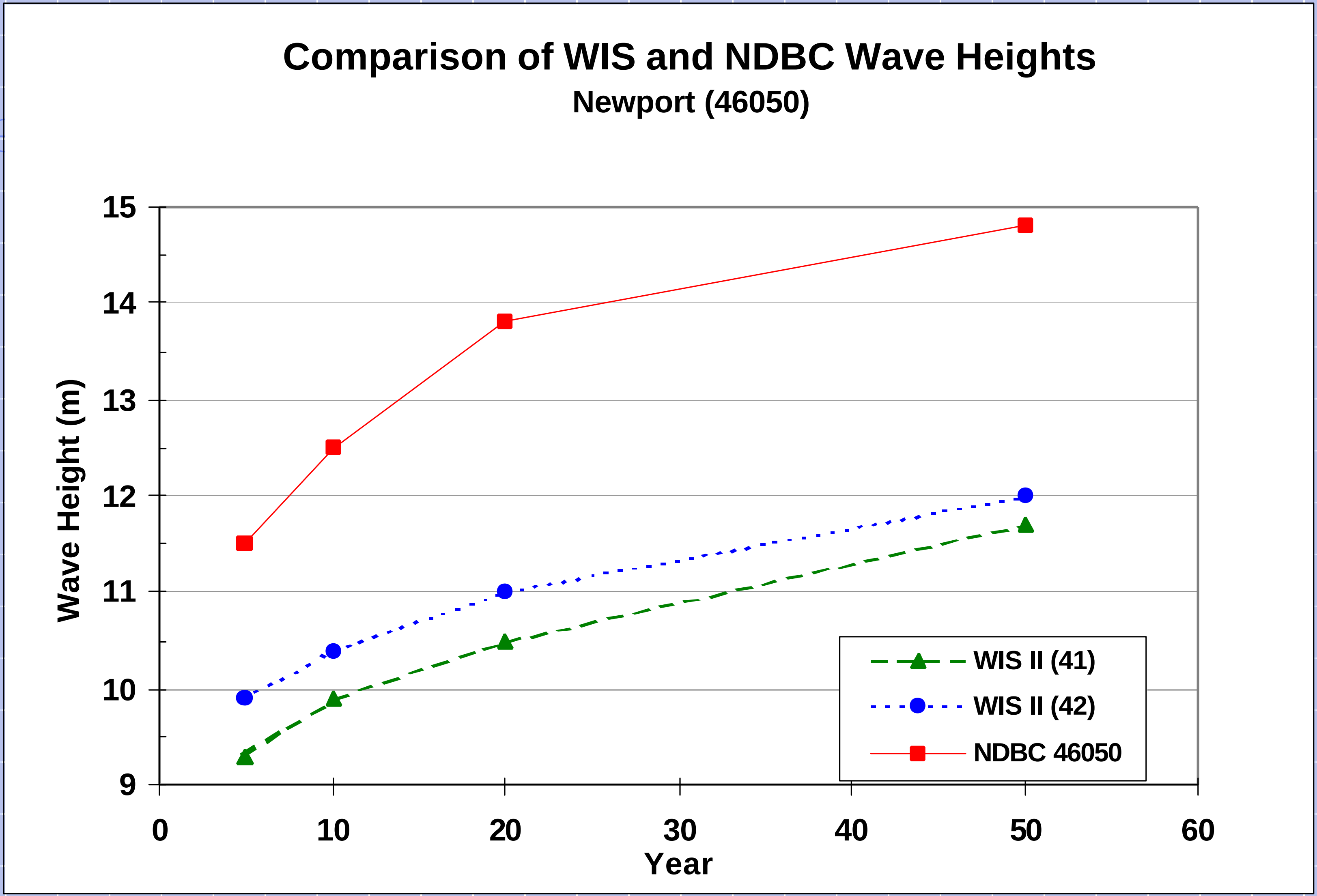
Wave Height Estimates - Various Analysis Methods
(Newport - 46050)
Wave Height (m)
18
17
16
15
14
13
12
11
10
9
0
20
40
60
80
100
120
Year
110 hr/15 yr (FTI)
60 hr/15 yr (FTI)
110 hr/ 15 yr (W1.4)
72 hr/10 yr (W0.75)


Comparison of 2001(10 yr) and 2004 (16 yr) Results
Wave Height (m)
18
17
16
15
14
13
12
11
10
9
8
0
20
40
60
80
100
120
Year
1.6 m
1.9 m
Col. River (10 yr)
Col. River
Newport (10 yr)
Newport

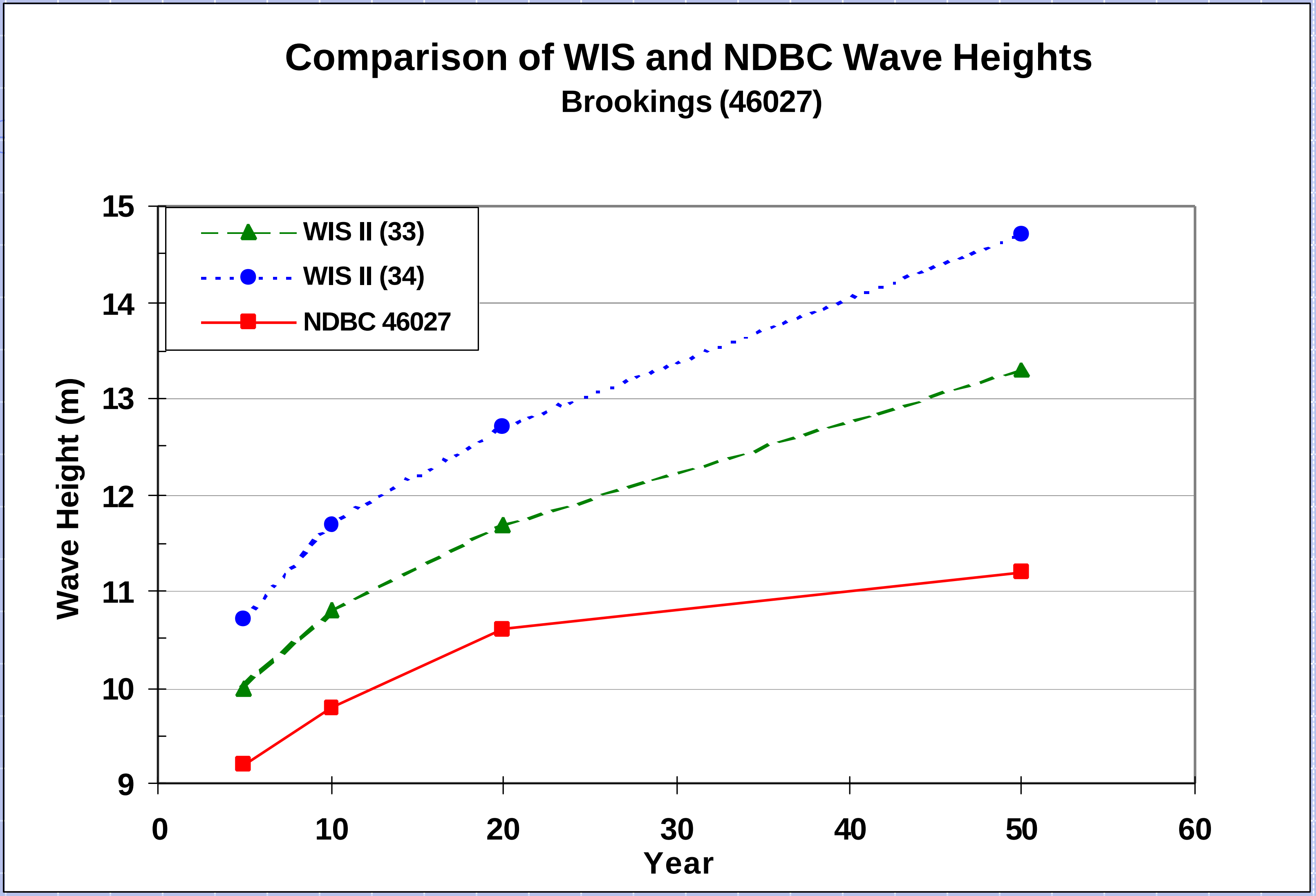

Comparison of WIS and NDBC Wave Heights
Grays Harbor (46041)
WIS II (50)
WIS II (49)
NDBC 46041
Wave Height (m)
Year
15
14
13
12
11
10
9
0
10
20
30
40
50
60



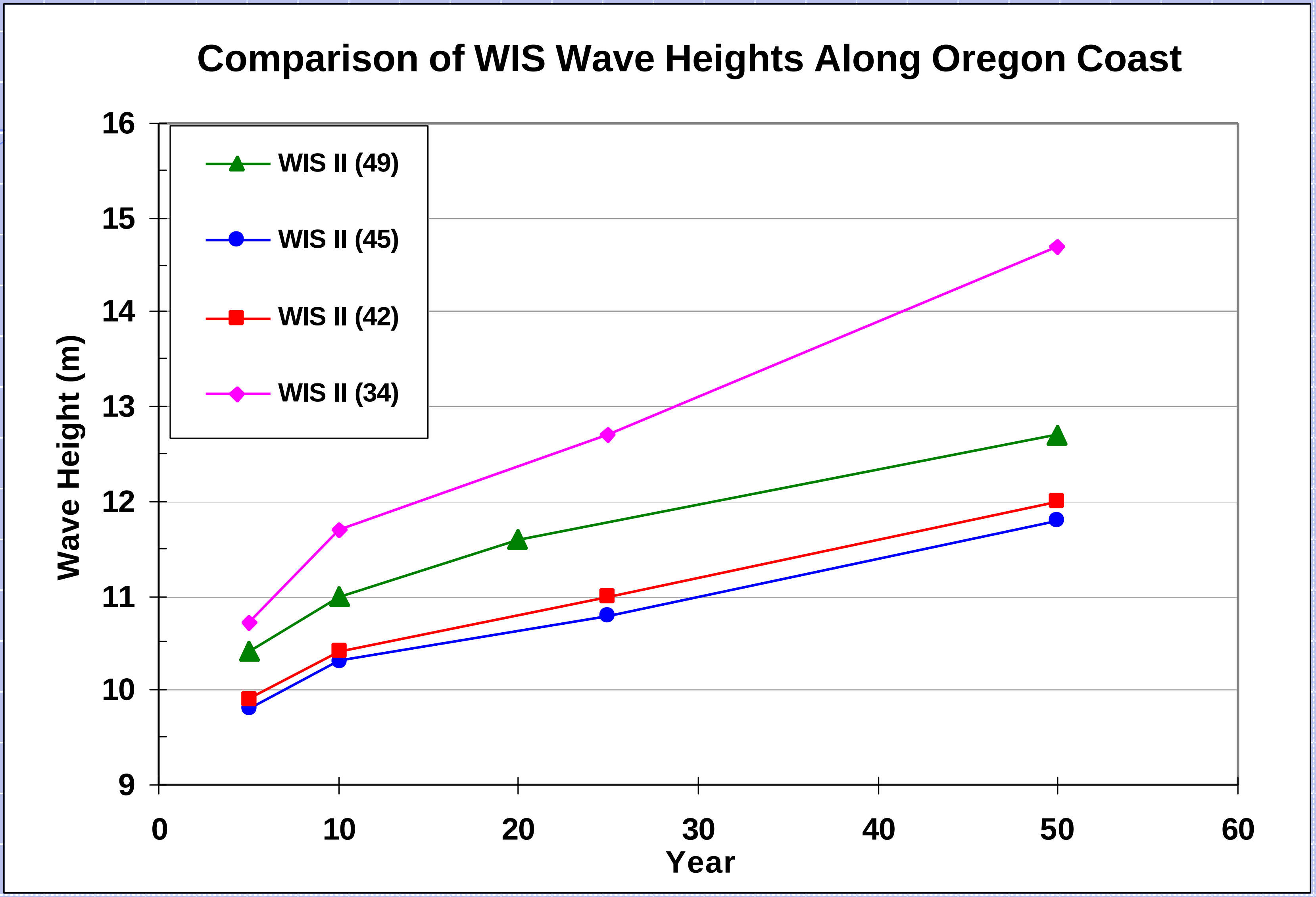
Comparison of WIS and NDBC Wave Heights
Columbia River (46029)
WIS II (45)
WIS II (46)
NDBC 46029
Wave Height (m)
15
14
13
12
11
10
9
0
10
20
30
40
50
60
Year



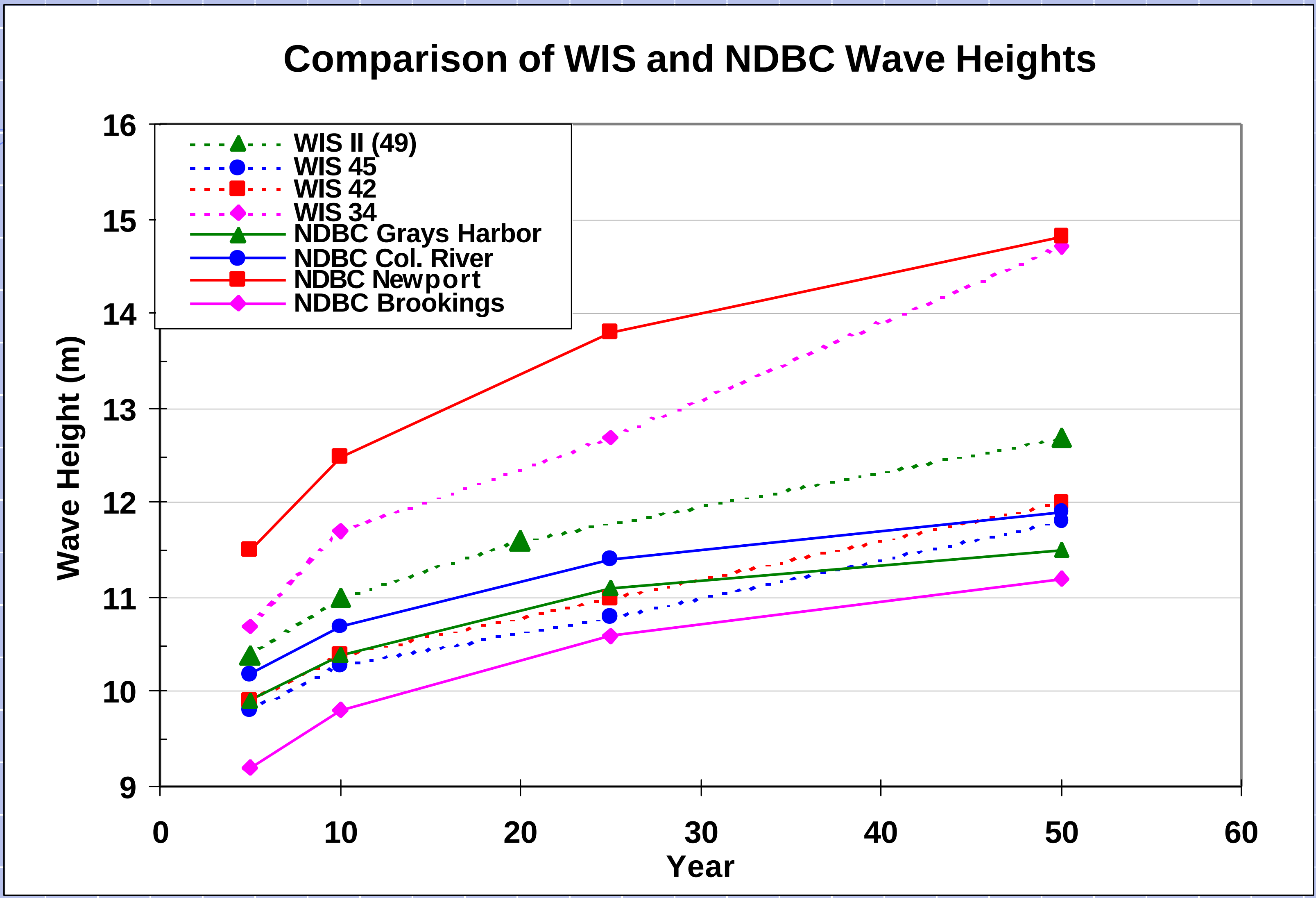
Comparison of WIS and NDBC Wave Heights
Newport (46050)
Wave Height (m)
15
14
13
12
11
10
9
0
10
20
30
40
50
60
Year
WIS II (41)
WIS II (42)
NDBC 46050



Comparison of WIS and NDBC Wave Heights
Brookings (46027)
WIS II (33)
WIS II (34)
NDBC 46027
Wave Height (m)
15
14
13
12
11
10
9
0
10
20
30
40
50
60
Year



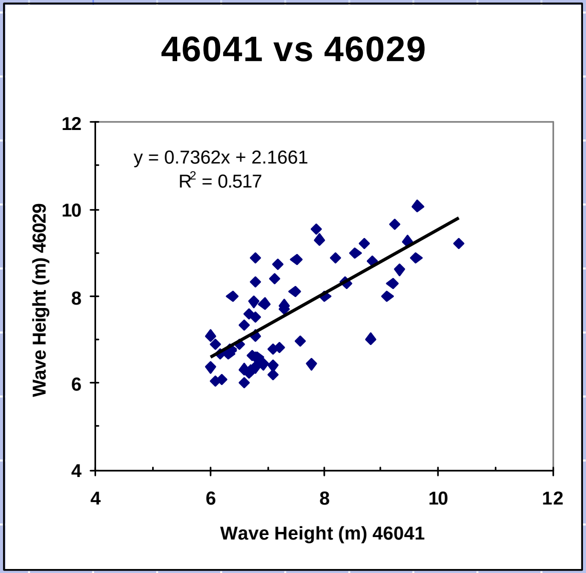
Comparison of WIS Wave Heights Along Oregon Coast
WIS II (49)
WIS II (45)
WIS II (42)
WIS II (34)
Wave Height (m)
16
15
14
13
12
11
10
9
0
10
20
30
40
50
60
Year

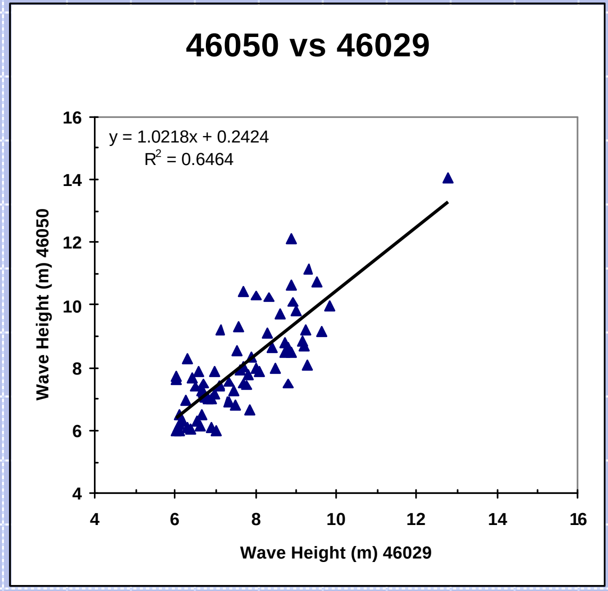


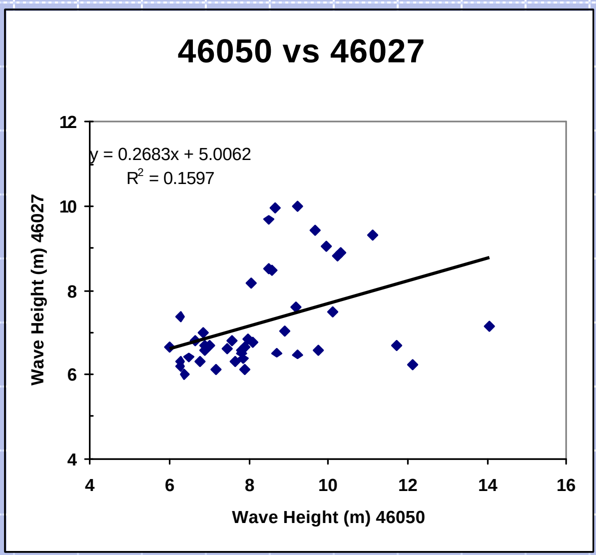
Comparison of WIS and NDBC Wave Heights
WIS II (49)
WIS 45
WIS 42
WIS 34
NDBC Grays Harbor
NDBC Col. River
NDBC Newport
NDBC Brookings
Wave Height (m)
16
15
14
13
12
11
10
9
0
10
20
30
40
50
60
Year

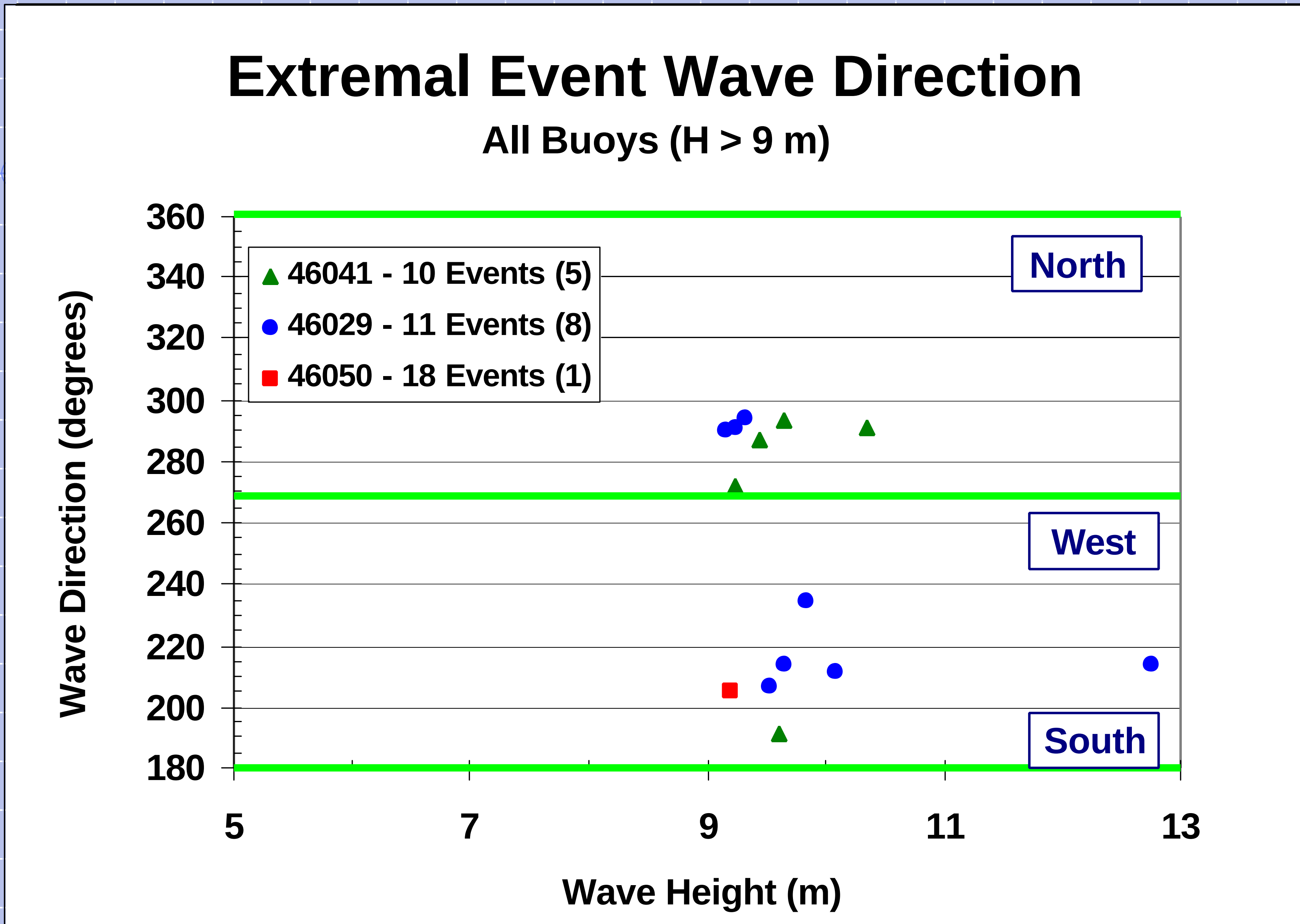
Correlation Function - Adjacent Buoys

	Grays Harbor	Columbia River	Newport	Brookings
Total storms > 6 m	93	105	118	62
# Storms w/ buoy to north	N/A	60	73	44
% Coincidence		57	62	71
Correlation		0.52	0.65	0.16








Extremal Event Wave Direction
All Buoys (H > 9 m)
46041 - 10 Events (5)
46029 - 11 Events (8)
46050 - 18 Events (1)
North
West
South
Wave Direction (degrees)
360
340
320
300
280
260
240
220
200
180
5
7
9
11
13
Wave Height (m)

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Conclusions

- Grays Harbor, Columbia River, Brookings buoys all predict similar extremal climates for this time period.
- Shelf wave climate at Newport exhibits significantly higher (3.4 m) 100-yr wave estimates compared to other buoys.
- Increasing the period of record from 10 to 16 years reduced the 100-year wave height by 1.5 to 2.0 m.
- Top 2 distributions for same buoy produced 1 to 2 m differences in 100 yr wave height estimates.
- Weibull distribution with higher k (2.0) fits northern buoy data, k (1.4) fits southern buoy data. (FT-1 fits Newport best.)
- The comparison of 60 hr and 110 time interval between storms illustrated little impact on final extremal result.

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Conclusions

- Correlated storm events from adjacent buoys indicates that on average 60% of the storm events are experienced at adjacent buoys.
- Correlation for the northern buoys (Grays Harbor to Columbia River) and (Columbia River to Newport) appear fairly high around 0.6 while the correlation of southern buoys (Newport to Brookings) is relatively low.
- Directional results indicate that extreme events at all buoys are centered around the western quadrant (225 to 315 degrees).
- Comparison to WIS II waves shows a good match with northern two buoys (Grays Harbor and Columbia River). Southern two buoys (Newport and Brookings) appear to be switched in comparing to WIS wave heights.

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Questions/Comments

- Why is the Newport (mid-Oregon coast) so much higher than lower and upper coasts?
- Can the mis-match with the WIS data along the mid- to southern Oregon coast be explained?
- Directional information is of much more limited geographical and time coverage.
- Regarding both shoreline recovery as well as structural damages, sequences/durations of extreme storms can be of greater importance than magnitude.
- Direction, wave period, and water level experienced during extreme storms also significantly impact resultant damages.

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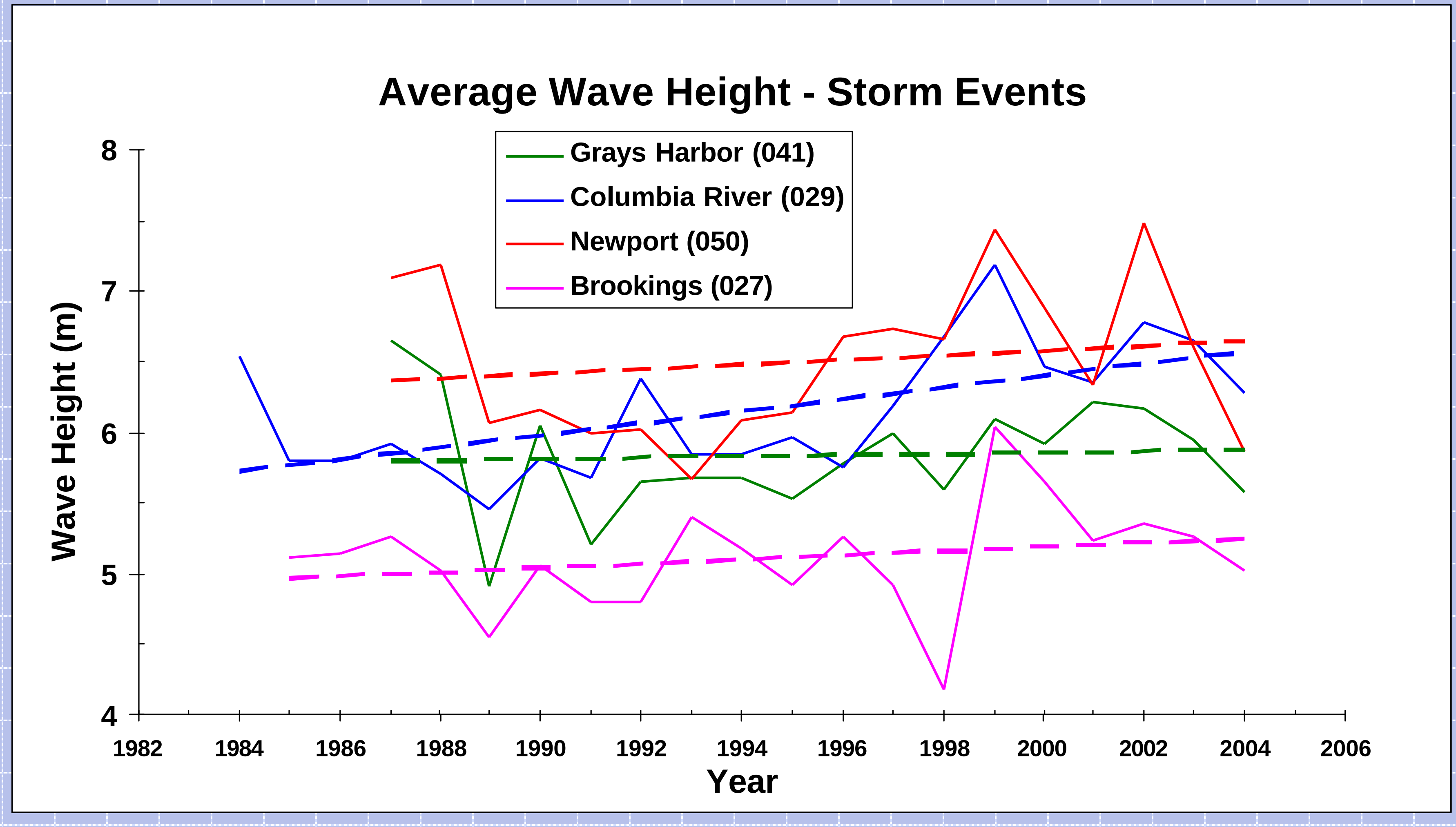
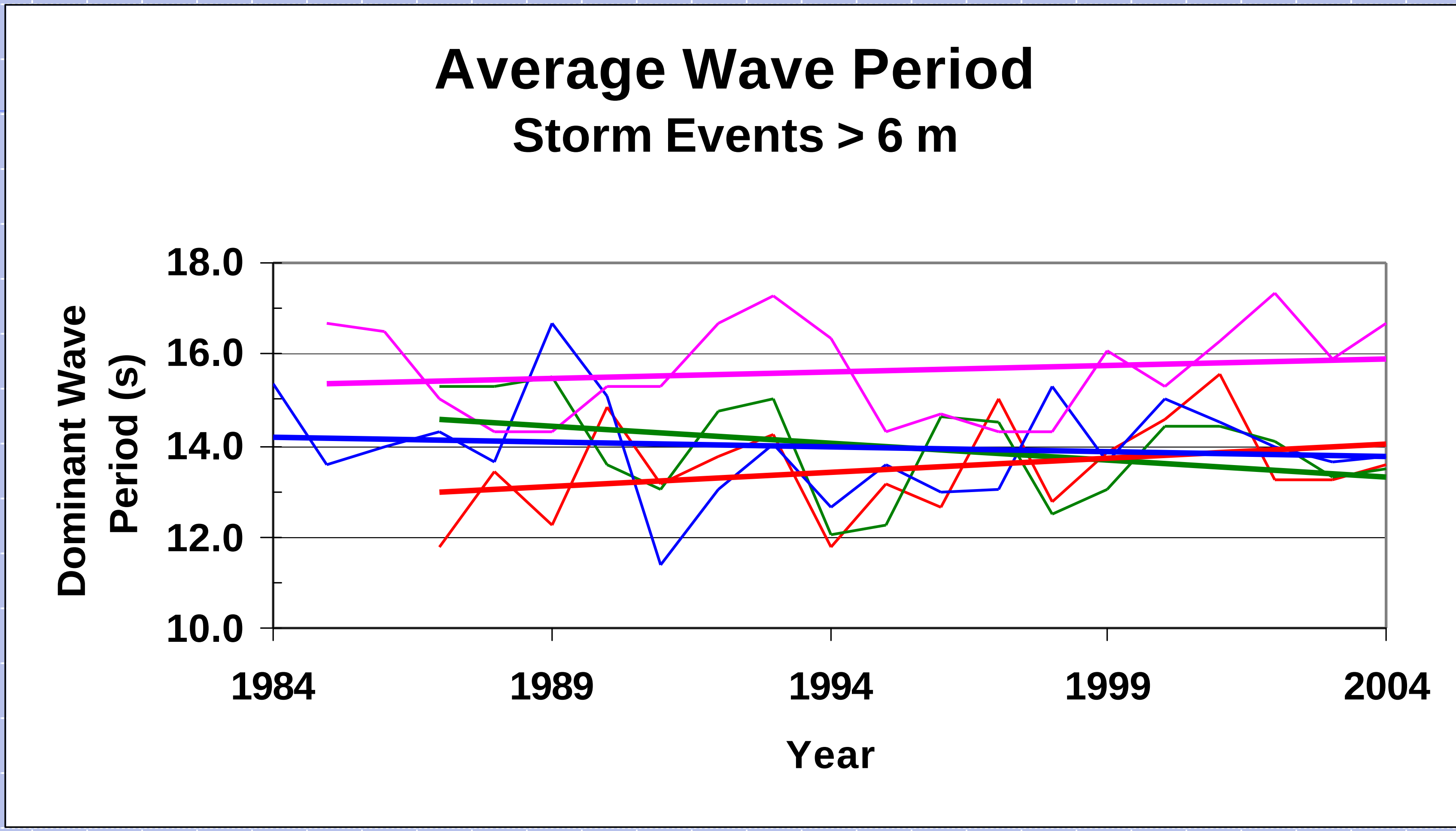
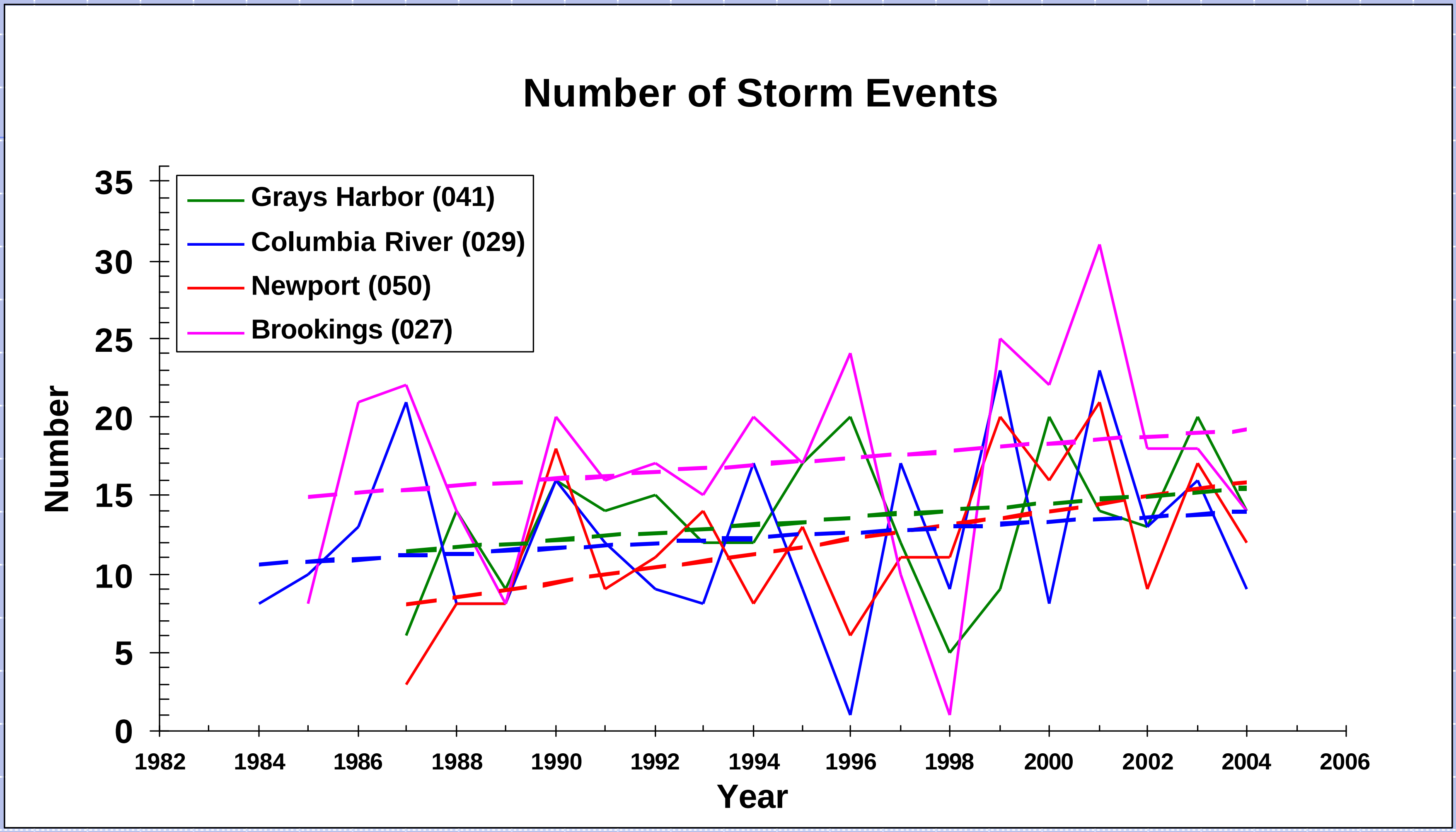
Conclusions – 2001 Analysis

- Varying storm histories (deep/shelf) were the result of offshore events combining for nearshore, events not propagating to shore, data gaps.
- For 91-00 analysis, Newport buoy predicts 100-yr wave height 3 m higher than other buoys.
- Washington, Oregon, Columbia River buoys all predict similar extremal climates for this time period.
- Weibull distribution with lower k (.75 – 1.0) fits shelf buoy data, higher k (1.4) fits deep water buoy data.
- Reliance on deep water buoys to define transitional depth wave climate (even after transformation) may underestimate extreme wave heights.

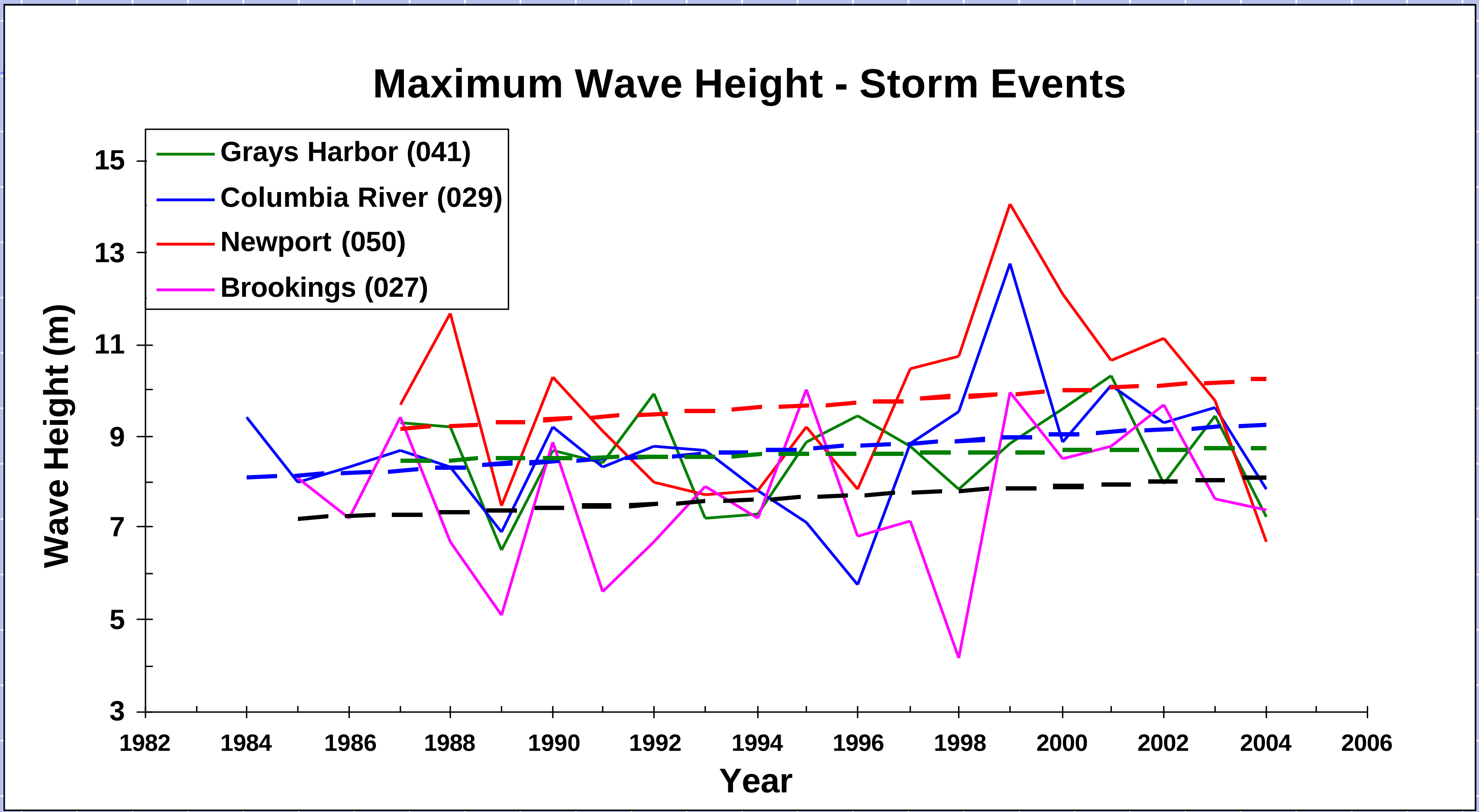


Average Wave Height - Storm Events
Grays Harbor (041)
Columbia River (029)
Newport (050)
Brookings (027)
Wave Height (m)
8
7
6
5
4
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Year


Average Wave Period
Storm Events > 6 m
Dominant Wave Period (s)
18.0
16.0
14.0
12.0
10.0
1984
1989
1994
1999
2004
Year



Number of Storm Events
Grays Harbor (041)
Columbia River (029)
Newport (050)
Brookings (027)
Number
35
30
25
20
15
10
5
0
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Year



Maximum Wave Height - Storm Events
Grays Harbor (041)
Columbia River (029)
Newport (050)
Brookings (027)
Wave Height (m)
15
13
11
9
7
5
3
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Year