# Evaluating Extreme Storm Power and Potential Implications to Coastal Damage Oregon Coast, USA

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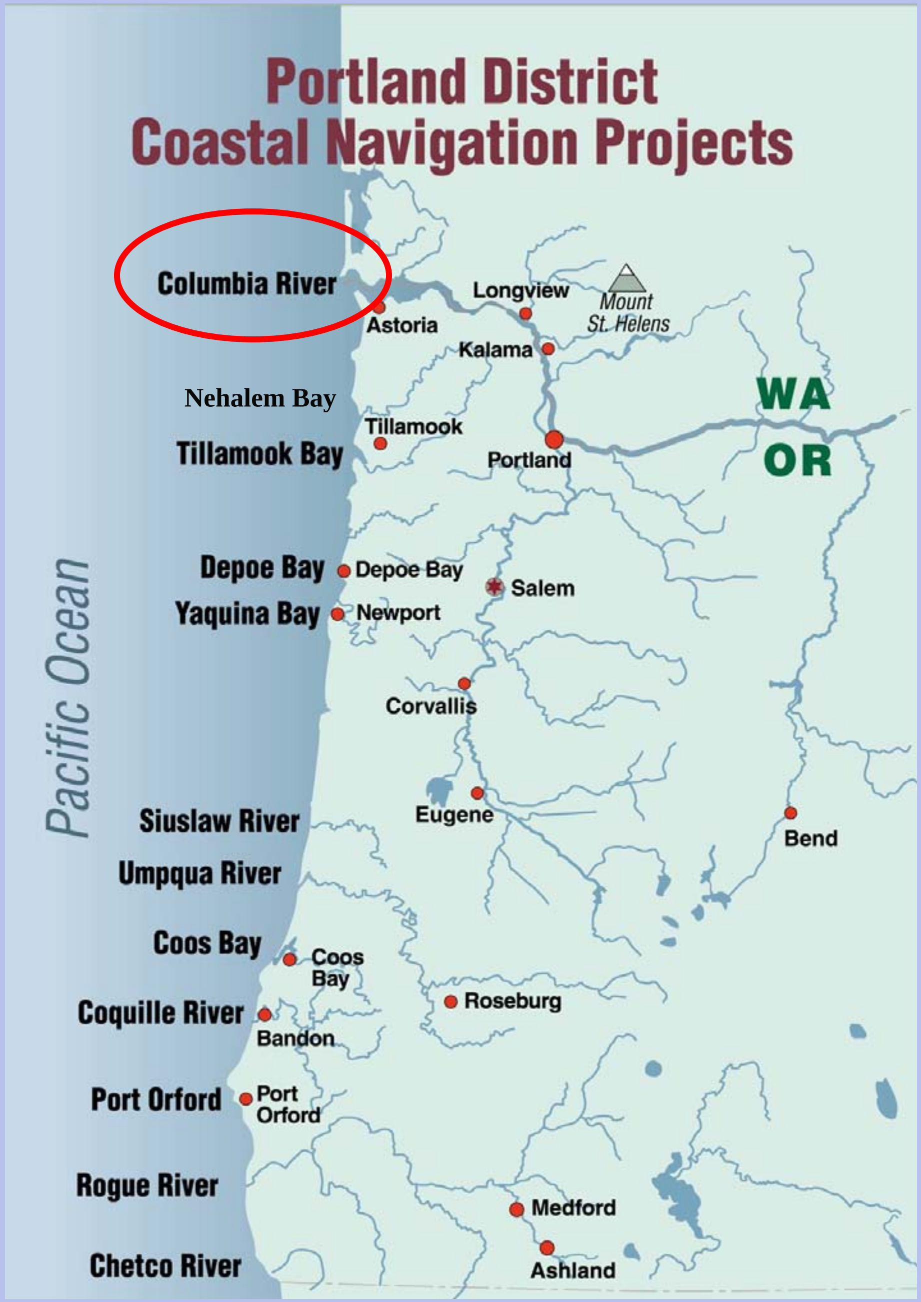
# Presentation Outline

- Scope of investigation
- Explanation of method of analysis
- Presentation of storm power results and comparison to other storm power ranking methods.
- Translation of individual storm power to cumulative storm power measurement
- Comparison to coastal damages
- Conclusions; areas needing further study




**11 Jettied Entrances**

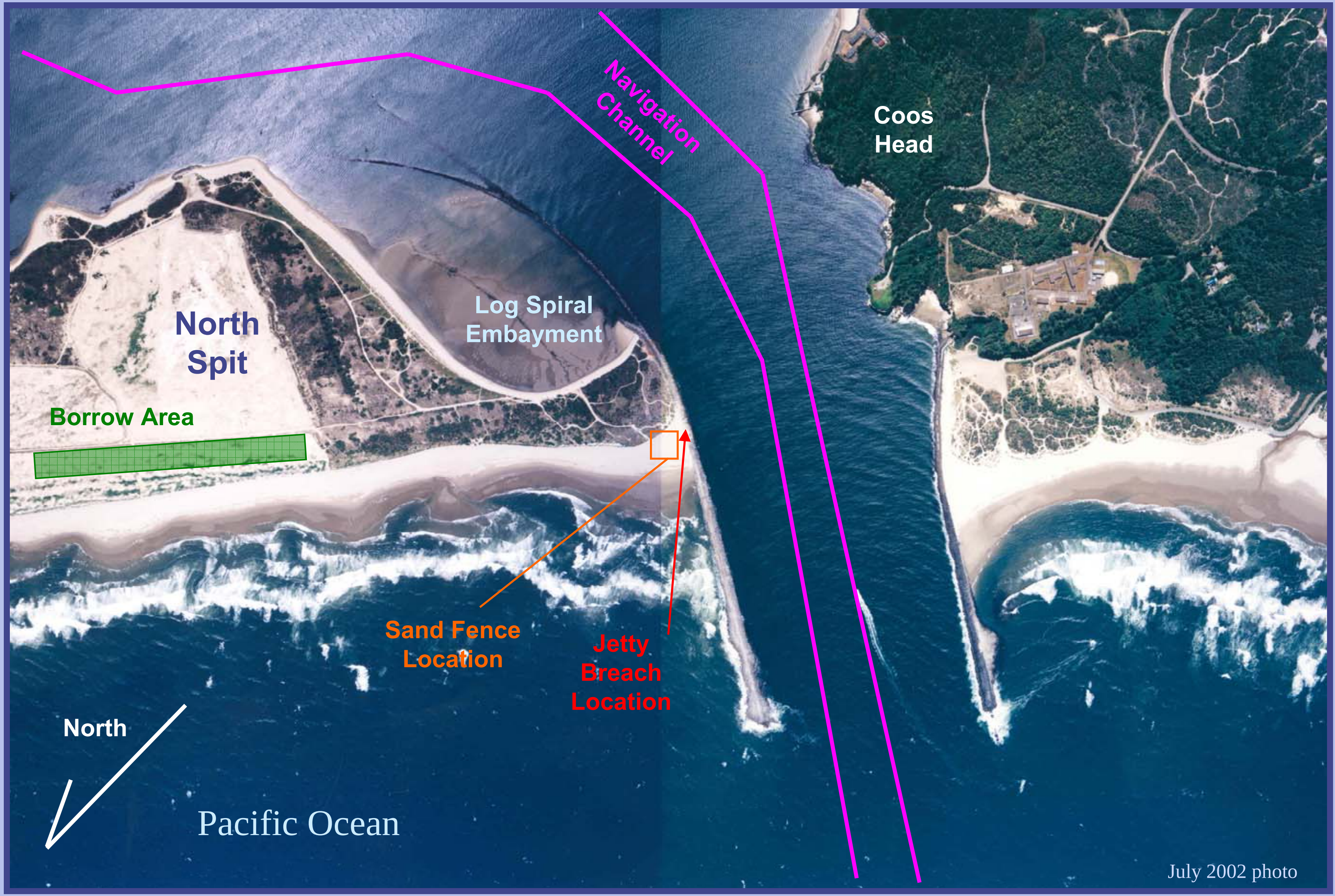
**(Including Mouth of Columbia River)**

**30 Miles – Rubble mound Structure**

**Construction / Repair - $2.0 Billion**
**(1880 – 2006)**

**Armor Size – 20 to 50 ton**

# Coos Bay Navigation Project

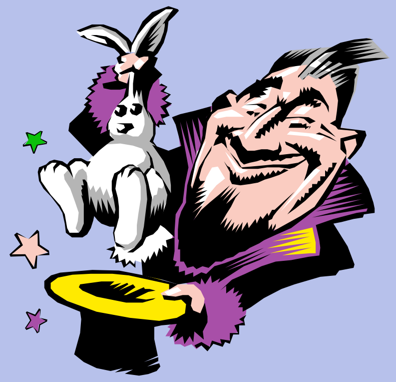



**Yaquina Bay**

# Why Do We Care About Storm Power?

- 100-year old coastal projects compete within the region for scarce infrastructure repair dollars.

- Every year we are asked to project risk of failure for critical coastal projects for the budget 2 years out.



- Projects can be impacted by loss of function/safety.

## Key Questions:

- What drives damage initiation and damage progression?
- Can we predict critical project failure by tracking individual and cumulative storm power?

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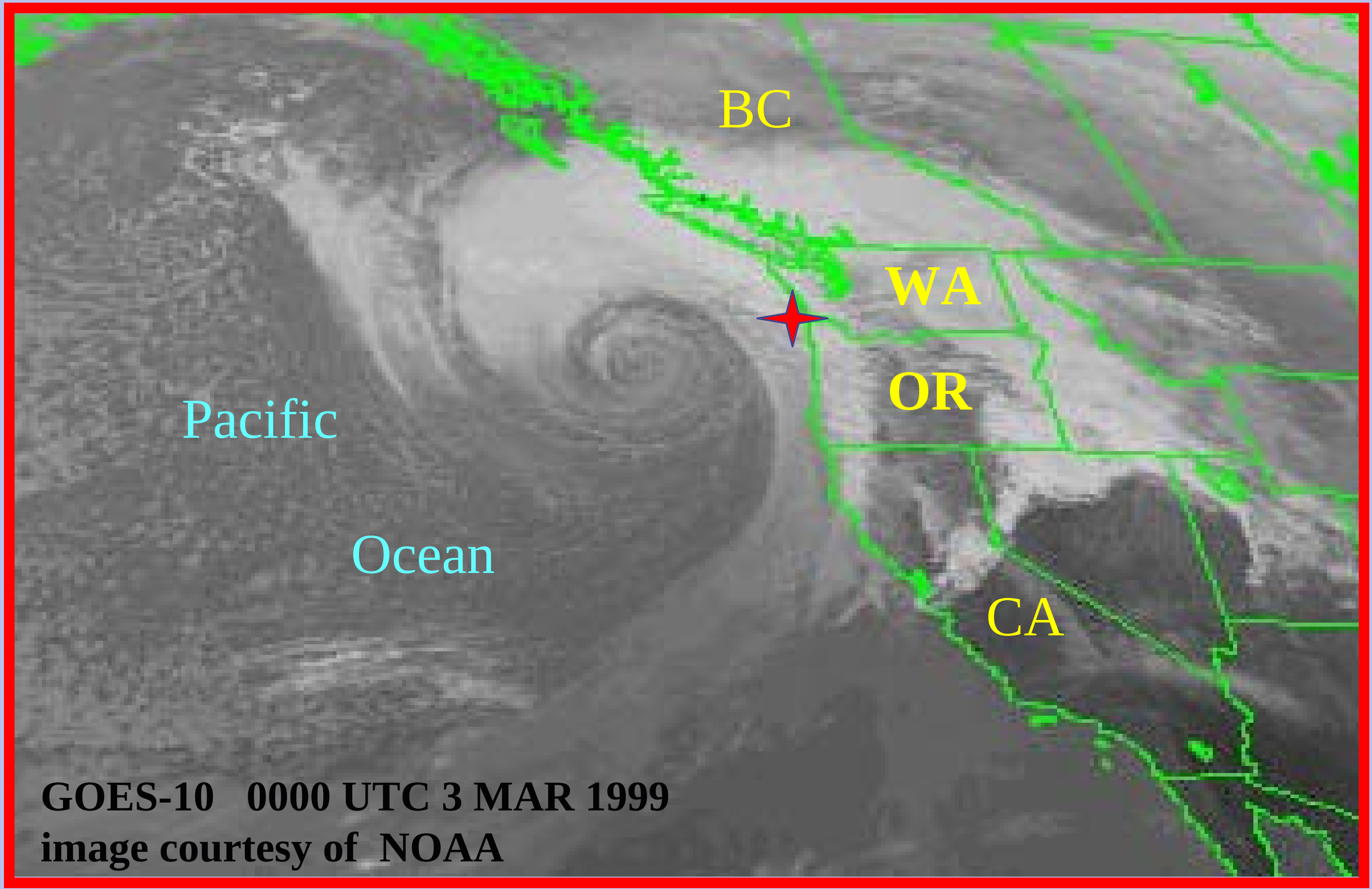
# Dolan / Davis Investigation (1994)

- **Relative power of Northeasters – U.S. Atlantic coast**
- **Developed a classification analogous to the Saffir-Simpson scale for hurricanes.**
- **1564 storms – 50 year period (hindcasted data)**
- **Developed 5 classes of storm intensity**
- **Defined storm power = $(H_s(max)^2)(duration)$**
- **Storm threshold = 1.5 m**

# 3 March 1999 - The Perfect Storm? - Hs=12.8m




## How Do We Measure Storm Power?

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# Scope of Investigation

- Develop a method to quantify and compare the power of individual storms.
- Include wave period and storm duration in addition to wave height in calculation.
- Identify relative importance of key variables.
- Propose Oregon coast storm power categories.
- Sum storm power over seasons and years.

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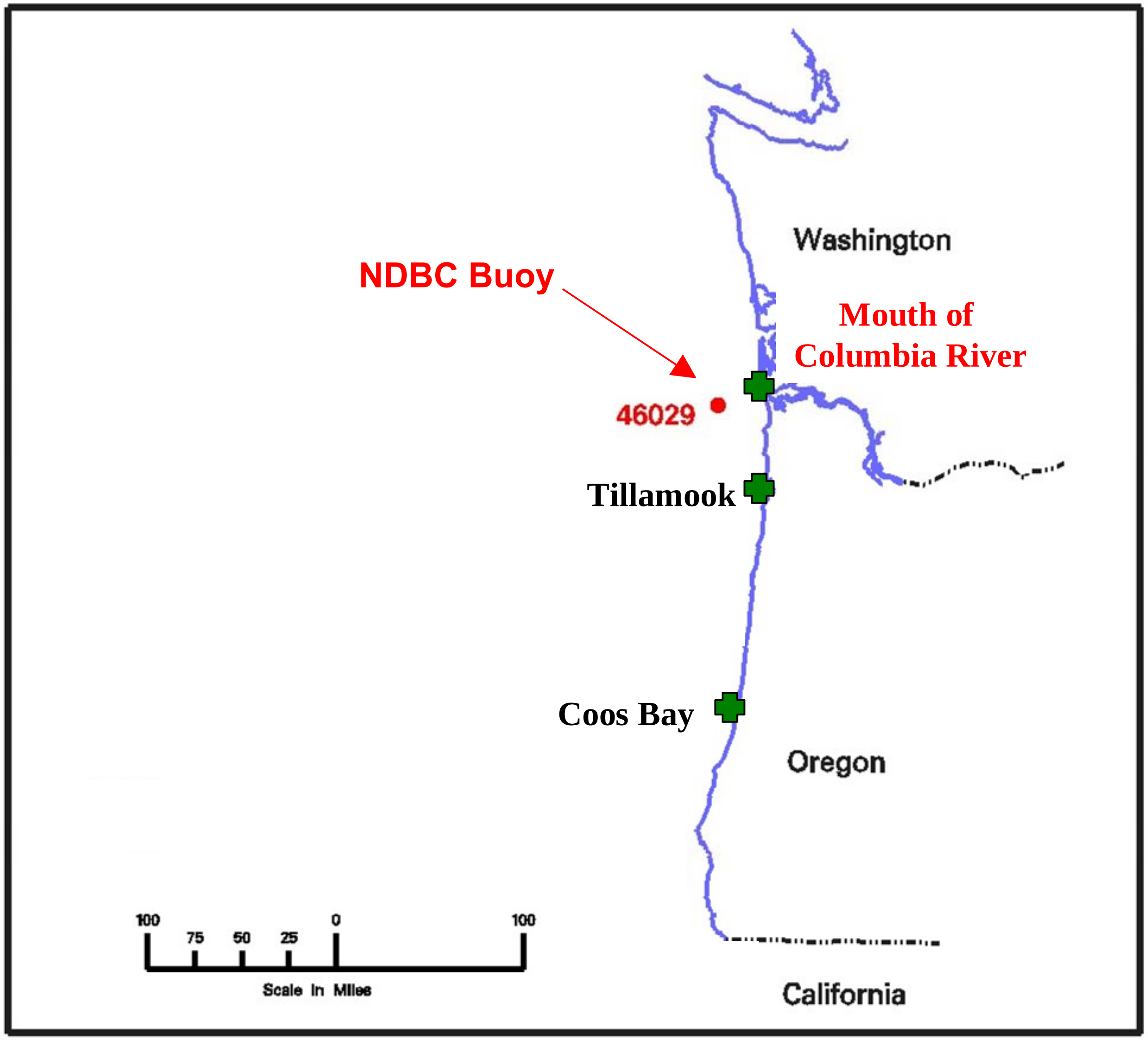

# NDBC Buoy #46029 – Columbia River
# Period of Record (1984 to 2006)

**Owned/maintained by National Data Buoy Center**
**3-meter discus buoy**
**DACT payload**
**46.12 N 124.51 W (46°07'00" N 124°30'36" W)**

**Site elevation:** sea level
**Anemometer height:** 5 m above site elevation
**Water depth:** 128.0 m
**Watch circle radius:** 130 yards

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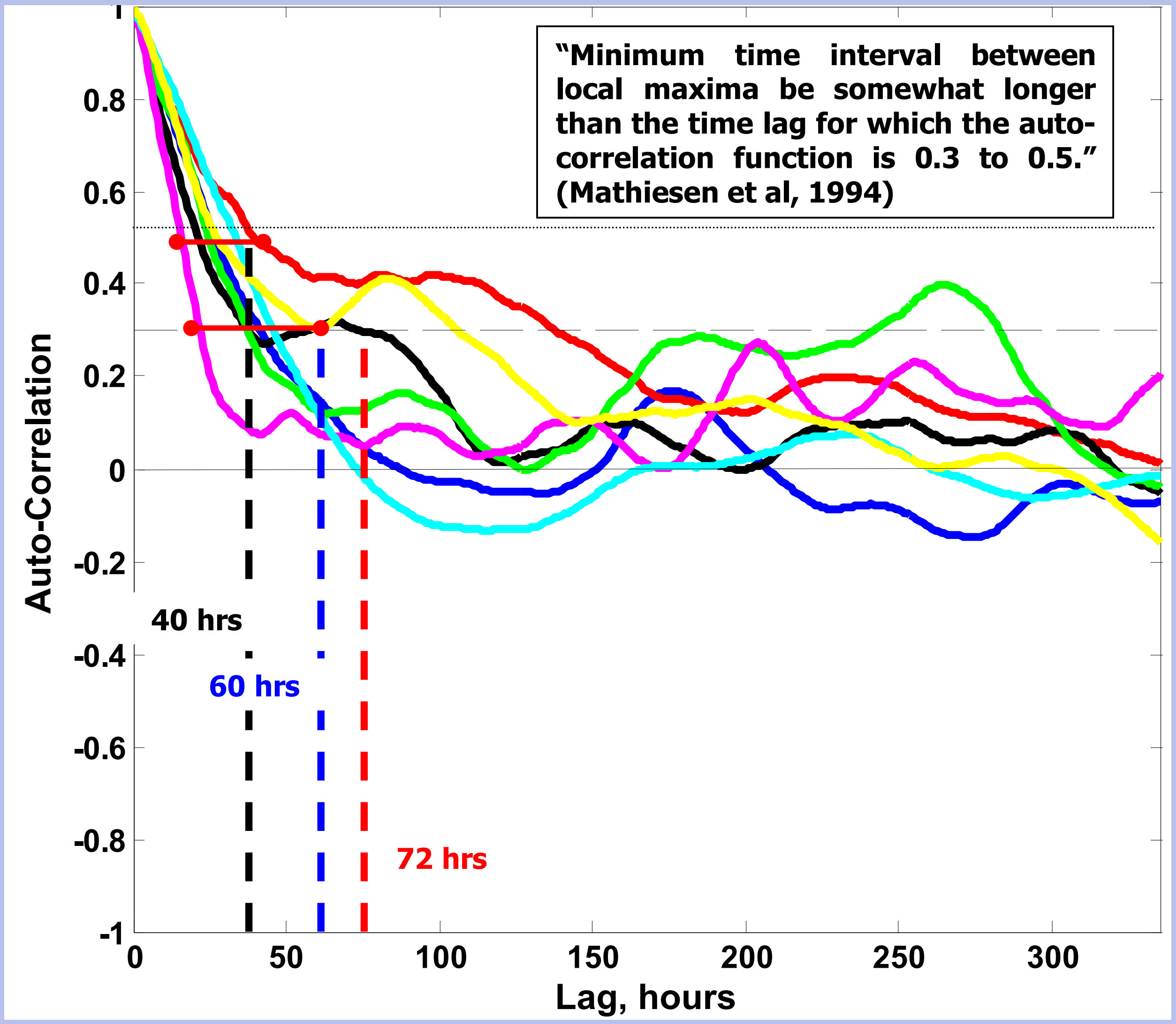
# Method

- Determine storm threshold: mean + 1 std. dev.
  storm season (Oct. through March) = 4.0 m
- Define independent storm events
- Select individual storms
- Calculate deepwater wave energy flux / hr

  = ½ (energy density)(wave celerity)
- Sum power over storm duration

# Independence of Storm Events



# Wave Energy Flux Equations

The rate at which energy is transported toward the shore is the wave power or wave energy flux.

$$P = \tfrac{1}{2} E_o C_o$$

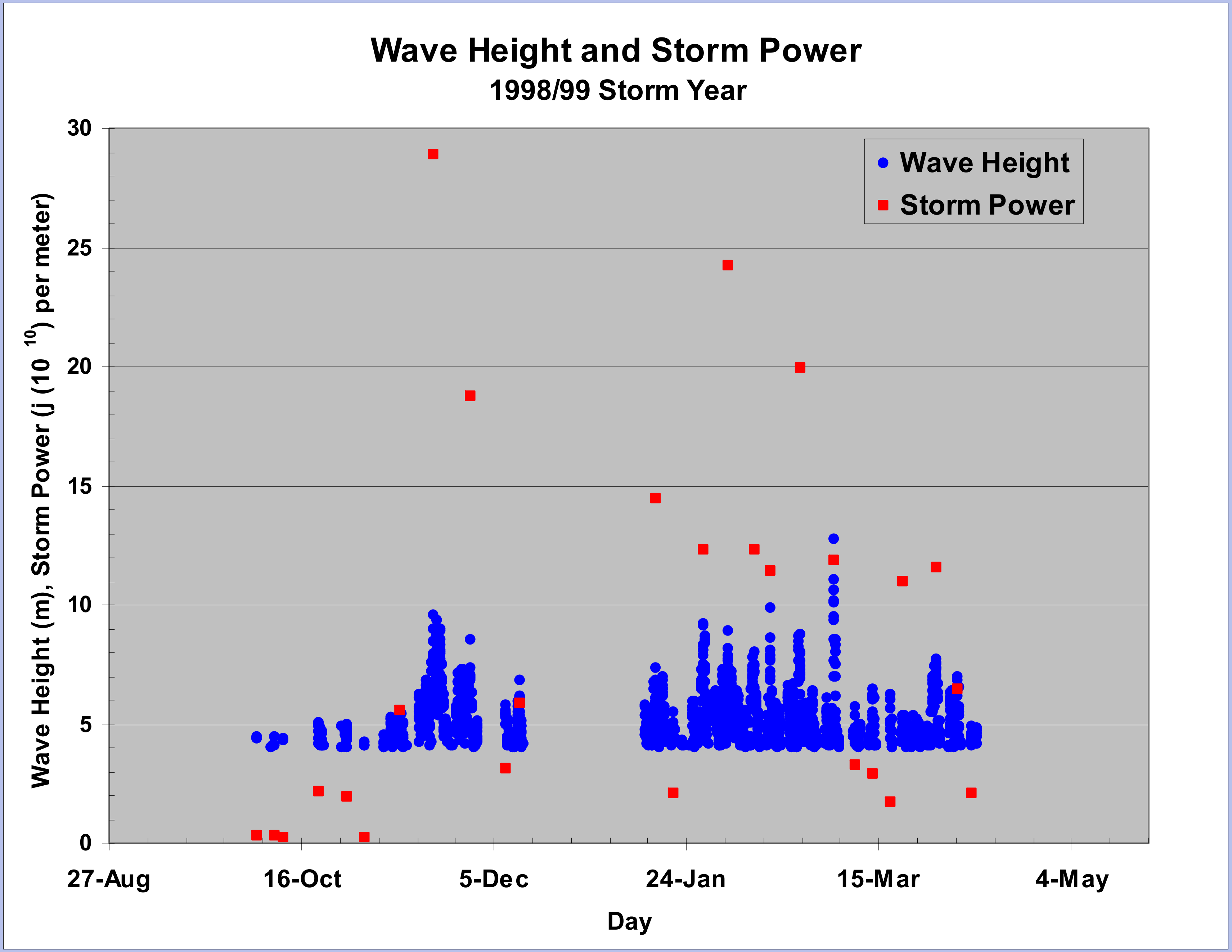
**P = wave power (N*m/s per meter wave crest)**
**$E_o$ = energy density (kg/s2)**
**$C_o$ = wave celerity (m/s).**

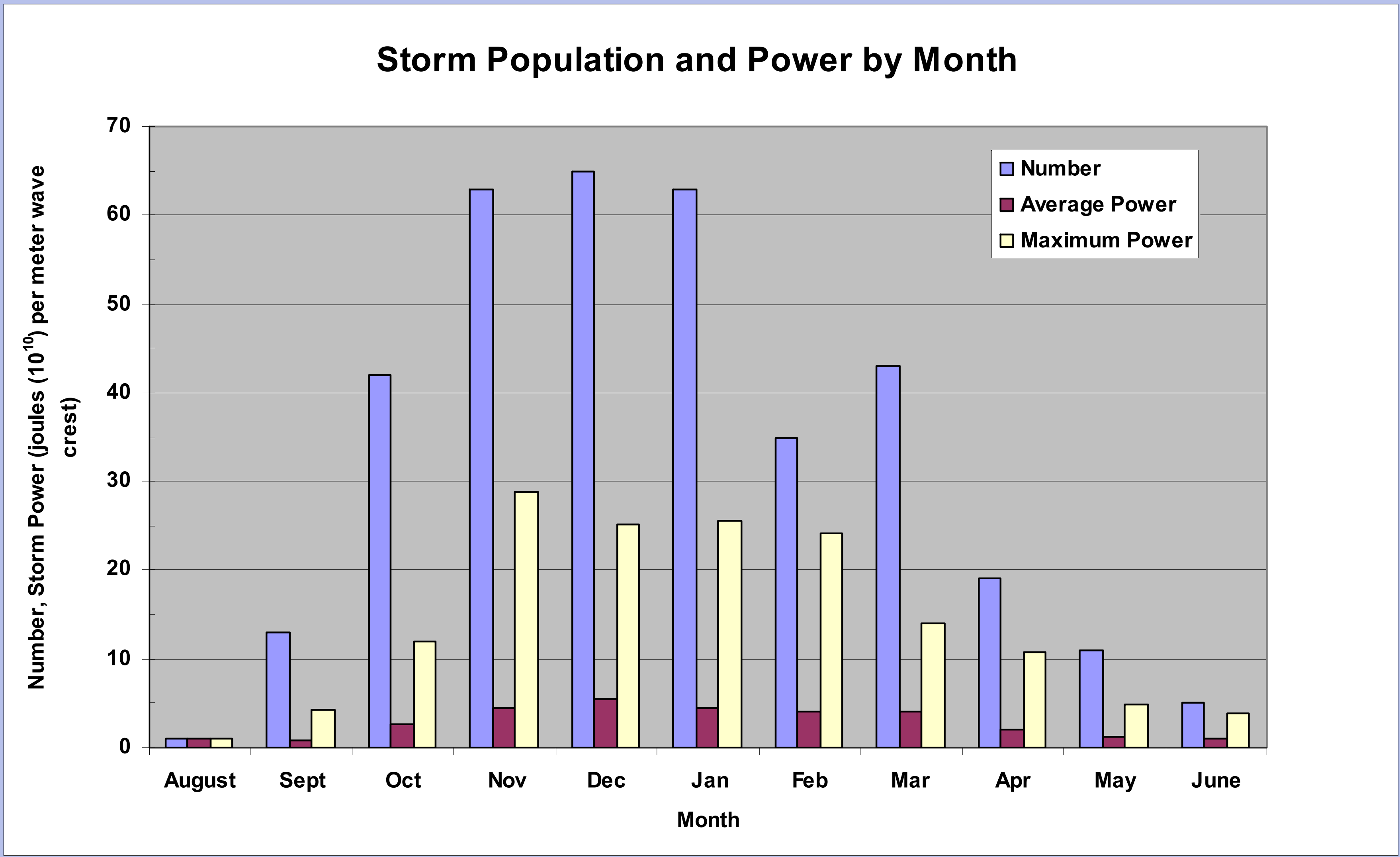
$$E_o = \frac{\rho g H^2}{8}$$

**$E_o$= energy density (kg/s2)**
**ρ = density of seawater (kg/m3)**
**g = acceleration of gravity (m/s2)**
**H = wave height (m).**

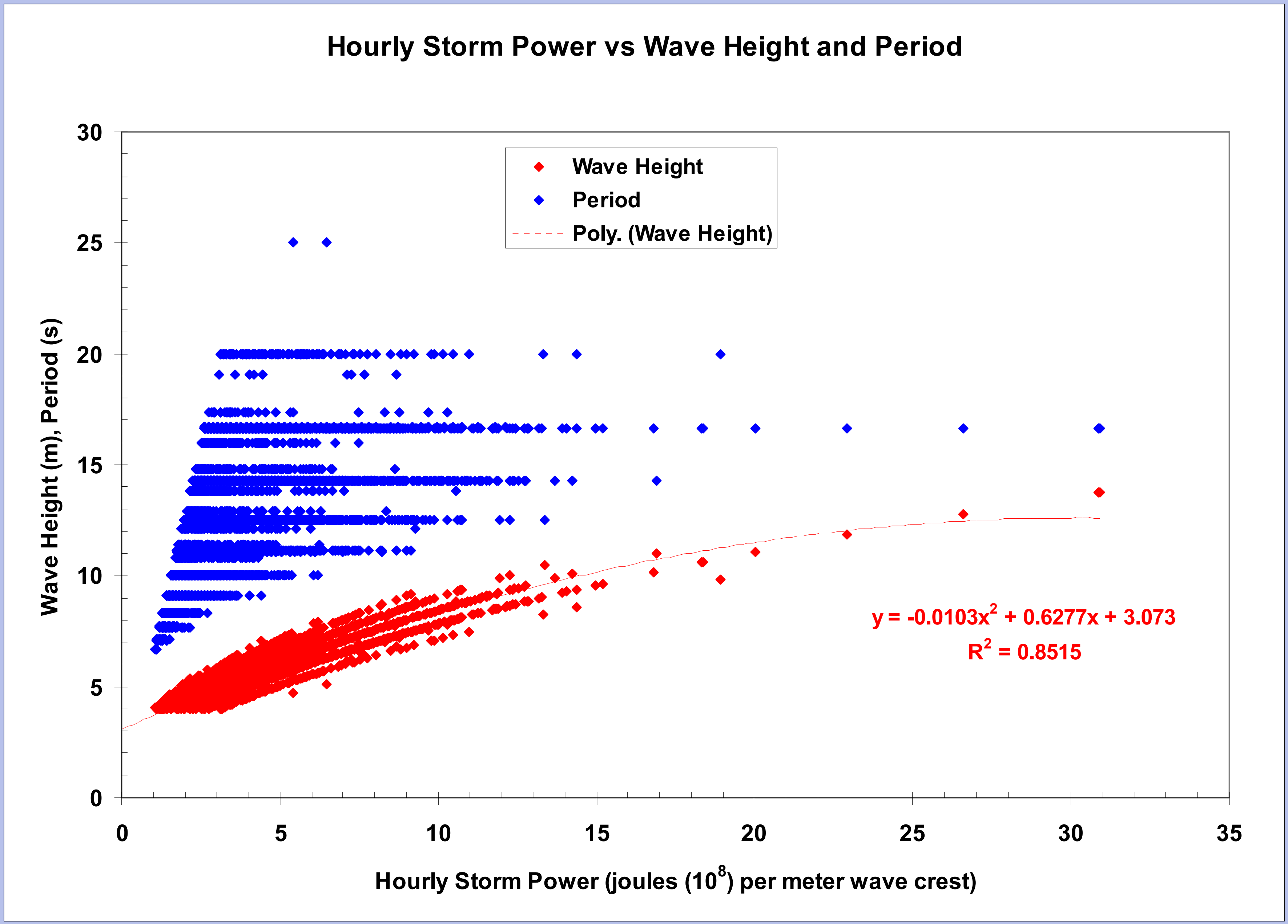
$$C_o = \frac{gT}{2\pi}$$

**$C_o$ = wave celerity (m/s)**
**g = acceleration of gravity (m/s2)**
**T = wave period (s).**


Wave Height and Storm Power
1998/99 Storm Year
Wave Height
Storm Power
Wave Height (m), Storm Power (j (10 10) per meter)
Day
27-Aug
16-Oct
5-Dec
24-Jan
15-Mar
4-May
0
5
10
15
20
25
30



Storm Population and Power by Month
Number
Average Power
Maximum Power
Number, Storm Power (joules (10^10) per meter wave crest)
70
60
50
40
30
20
10
0
August
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
June
Month

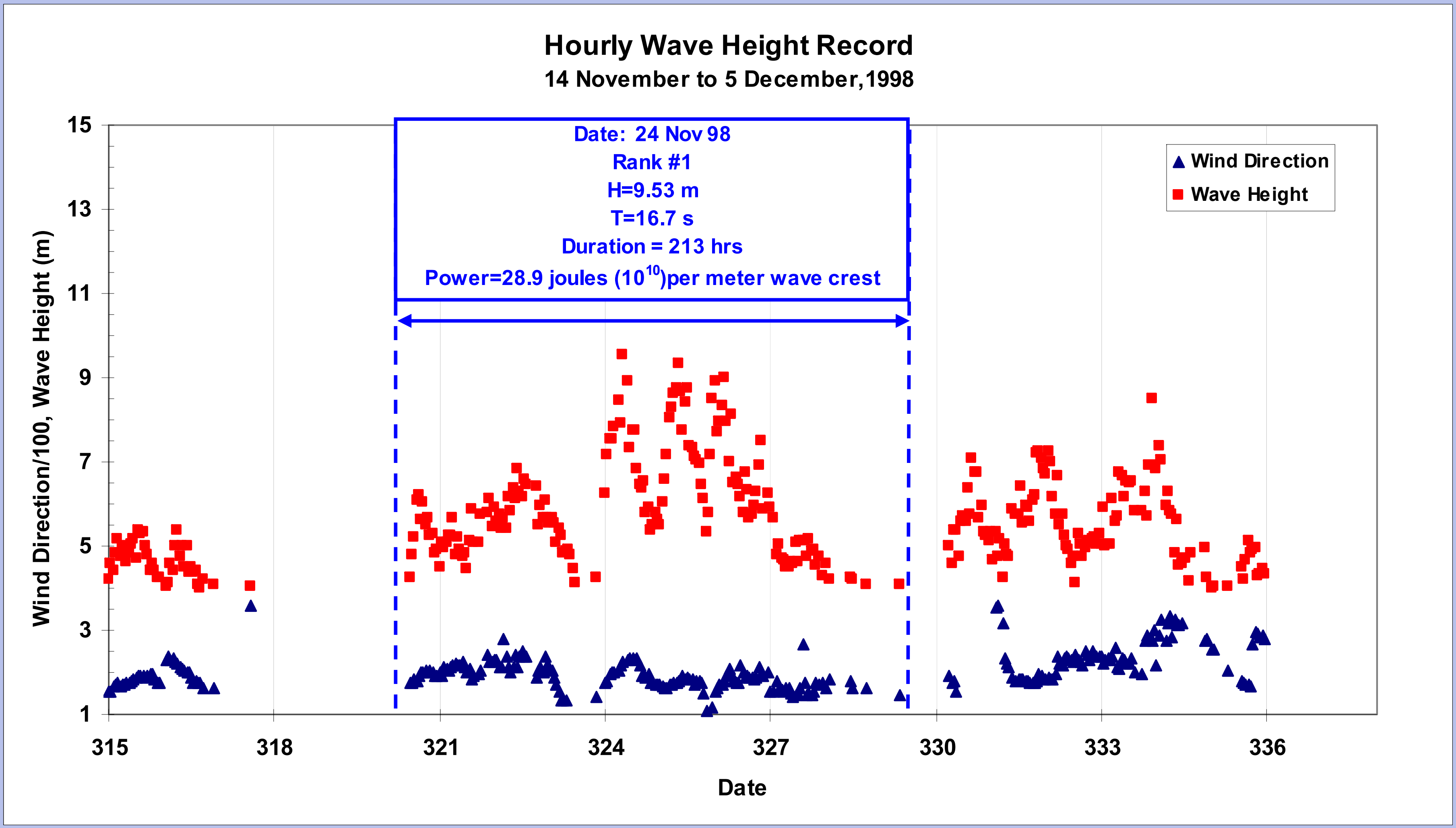

Hourly Storm Power vs Wave Height and Period
Wave Height (m), Period (s)
30
25
20
15
10
5
0
Wave Height
Period
Poly. (Wave Height)
y = -0.0103x2 + 0.6277x + 3.073
R2 = 0.8515
0
5
10
15
20
25
30
35
Hourly Storm Power (joules (10^8) per meter wave crest)

# Top 20 Storm Events – Dolan/Davis Method

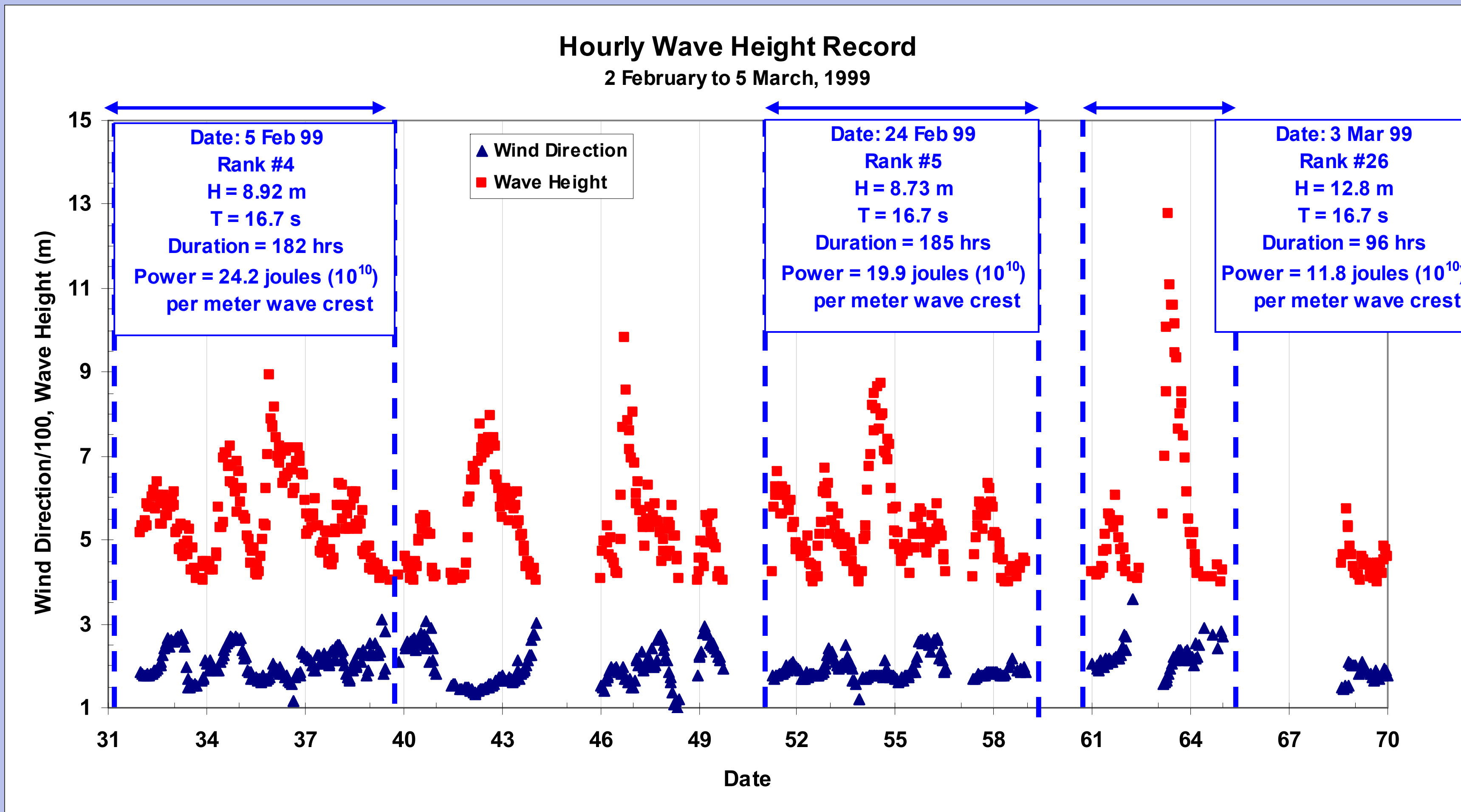
| Date | Maximum Wave Height (m) | Average Wave Height (m) | Maximum Wave Period (s) | Average Wave Period (s) | Mean Wave Direction (degrees) | Duration (hrs) | Storm Power ($m^2$ - hrs) |
|---|---|---|---|---|---|---|---|
| 24-Nov-98 | 9.53 | 6.02 | 16.7 | 13.1 | N/A | 213 | 19.3 |
| 3-Nov-84 | 9.4 | 6.04 | 20.0 | 13.8 | N/A | 202 | 17.8 |
| 13-Oct-84 | 8.6 | 4.89 | 16.7 | 13.0 | N/A | 234 | 17.3 |
| 14-Dec-01 | 10.08 | 5.73 | 14.3 | 11.4 | 297 | 161 | 16.4 |
| 3-Mar-99 | 12.76 | 5.96 | 16.7 | 13.4 | 222 | 96 | 15.6 |
| 16-Dec-03 | 8.08 | 5.14 | 20.0 | 13.5 | 212 | 239 | 15.6 |
| 15-Dec-02 | 9.31 | 5.71 | 16.7 | 12.7 | N/A | 168 | 14.6 |
| 5-Feb-99 | 8.92 | 5.53 | 16.7 | 12.3 | 214 | 182 | 14.5 |
| 24-Feb-99 | 8.73 | 5.36 | 16.7 | 12.1 | 200 | 185 | 14.1 |
| 2-Jan-03 | 8.11 | 5.34 | 20.0 | 13.5 | 212 | 211 | 13.9 |
| 30-Dec-05 | 7.85 | 5.00 | 25.0 | 13.6 | 202 | 170 | 10.5 |
| 29-Jan-99 | 9.16 | 5.78 | 16.7 | 12.0 | N/A | 120 | 10.1 |
| 3-Dec-98 | 8.49 | 5.54 | 20.0 | 14.3 | 290 | 137 | 9.9 |
| 28-Oct-99 | 8.81 | 6.20 | 16.7 | 13.4 | 230 | 122 | 9.5 |
| 31-Jan-92 | 8.8 | 5.24 | 16.7 | 13.0 | N/A | 121 | 9.4 |
| 10-Dec-93 | 8.7 | 5.46 | 16.7 | 12.7 | N/A | 121 | 9.2 |
| 16-Feb-99 | 9.83 | 5.38 | 16.7 | 13.5 | 245 | 89 | 8.6 |
| 13-Feb-94 | 7.1 | 4.76 | 14.3 | 11.2 | N/A | 170 | 8.6 |
| 21-Mar-94 | 7.7 | 5.00 | 16.7 | 12.8 | N/A | 142 | 8.4 |
| 21-Dec-05 | 7.66 | 5.03 | 16.7 | 13.0 | 219 | 140 | 8.2 |

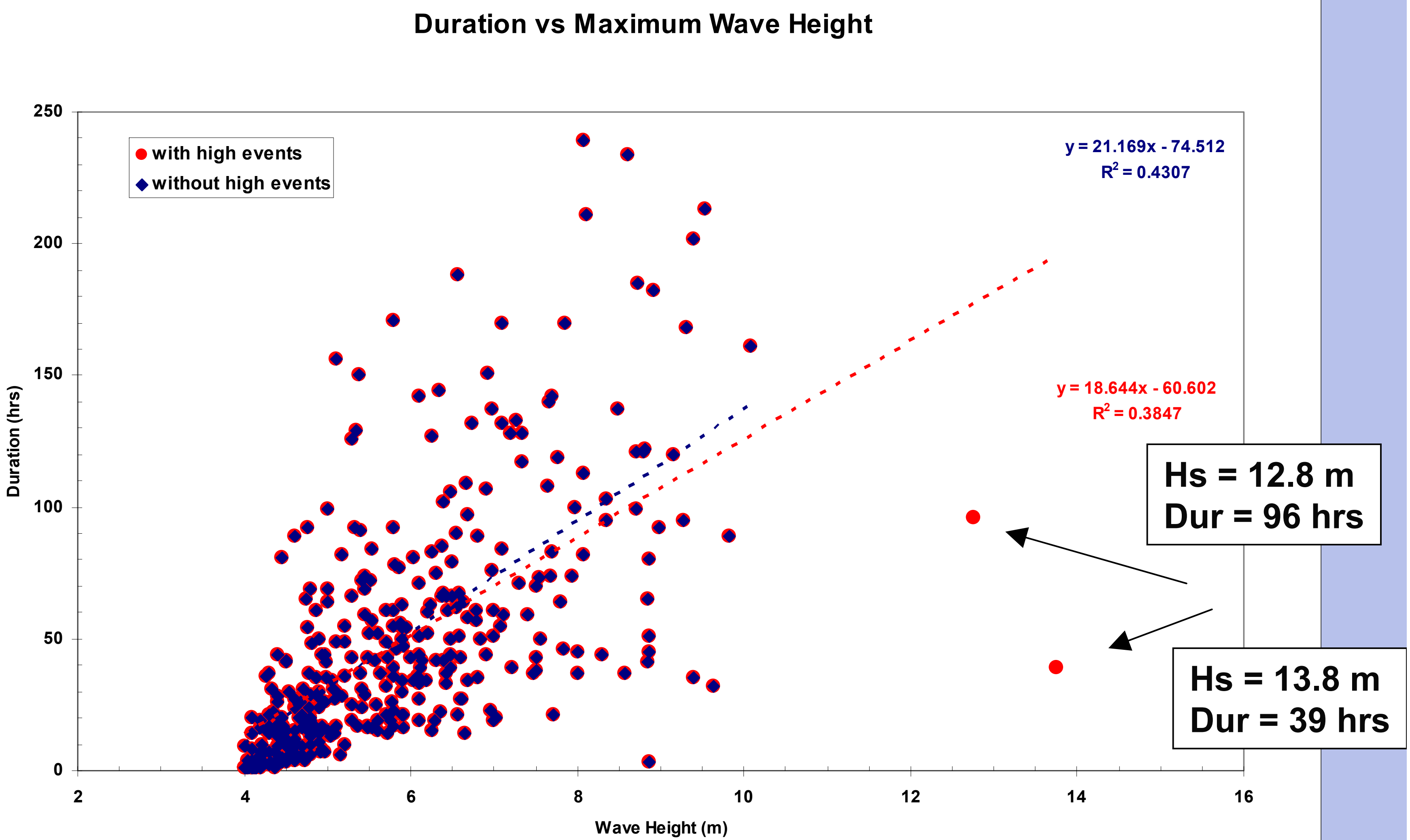
# Top 20 Storm Events – Wave Energy Flux Method

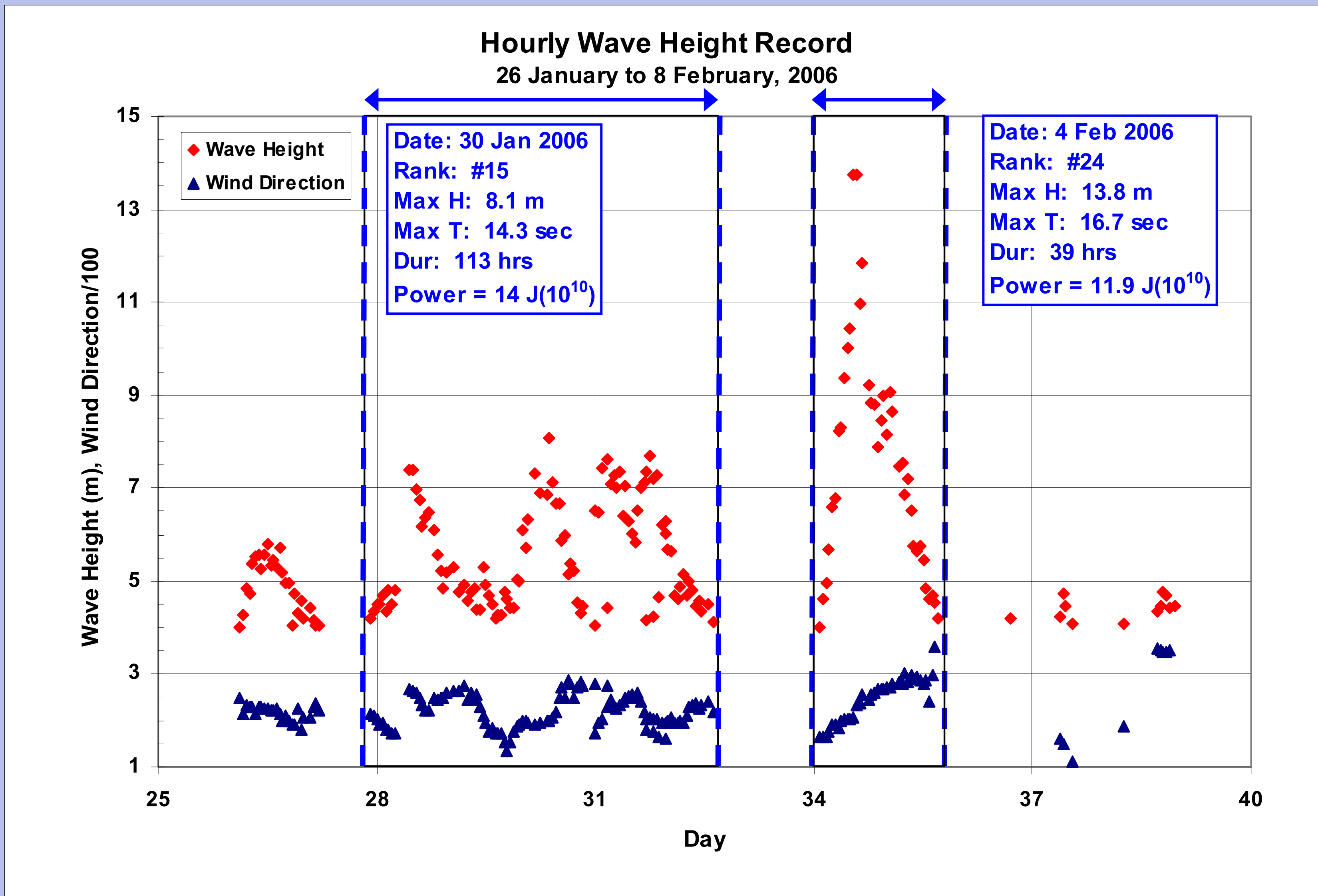
| Date | Maximum Wave Height (m) | Average Wave Height (m) | Maximum Wave Period (s) | Average Wave Period (s) | Mean Wave Direction (degrees) | Duration (hrs) | Storm Power (Joules ($10^{10}$) per m wave crest) |
|---|---|---|---|---|---|---|---|
| 24-Nov-98 | 9.53 | 6.02 | 16.7 | 13.1 | N/A | 213 | 28.9 |
| 2-Jan-03 | 8.11 | 5.34 | 20.0 | 13.5 | 212 | 211 | 25.6 |
| 15-Dec-02 | 9.31 | 5.71 | 16.7 | 12.7 | N/A | 168 | 25.2 |
| 5-Feb-99 | 8.92 | 5.53 | 16.7 | 12.3 | 214 | 182 | 24.2 |
| 24-Feb-99 | 8.73 | 5.36 | 16.7 | 12.1 | 200 | 185 | 19.9 |
| 8-Nov-02 | 7.27 | 5.24 | 20.0 | 14.1 | 260 | 133 | 19.3 |
| 14-Dec-01 | 10.08 | 5.73 | 14.3 | 11.4 | 297 | 161 | 18.9 |
| 3-Dec-98 | 8.49 | 5.54 | 20.0 | 14.3 | 290 | 137 | 18.7 |
| 16-Dec-03 | 8.08 | 5.14 | 20.0 | 13.5 | 212 | 239 | 18.3 |
| 20-Nov-01 | 8.34 | 5.99 | 20.0 | 13.7 | 200 | 95 | 17.4 |
| 30-Dec-05 | 7.85 | 5.00 | 25.0 | 13.6 | 202 | 170 | 17.0 |
| 3-Nov-84 | 9.40 | 6.04 | 20.0 | 13.8 | N/A | 202 | 16.8 |
| 11-Dec-95 | 7.10 | 5.27 | 14.3 | 12.6 | 198 | 132 | 14.7 |
| 16-Jan-99 | 7.34 | 5.05 | 16.7 | 13.0 | 258 | 128 | 14.4 |
| 30-Jan-06 | 8.08 | 5.57 | 14.3 | 12.1 | 202 | 113 | 14.0 |
| 13-Mar-03 | 8.98 | 5.97 | 16.7 | 12.5 | N/A | 92 | 13.9 |
| 31-Jan-92 | 8.80 | 5.24 | 16.7 | 13.0 | N/A | 121 | 12.4 |
| 14-Dec-99 | 6.34 | 4.89 | 16.7 | 11.8 | 278 | 144 | 12.4 |
| 29-Jan-99 | 9.16 | 5.78 | 16.7 | 12.0 | N/A | 120 | 12.3 |
| 12-Feb-99 | 7.97 | 5.43 | 16.7 | 13.4 | 224 | 100 | 12.3 |



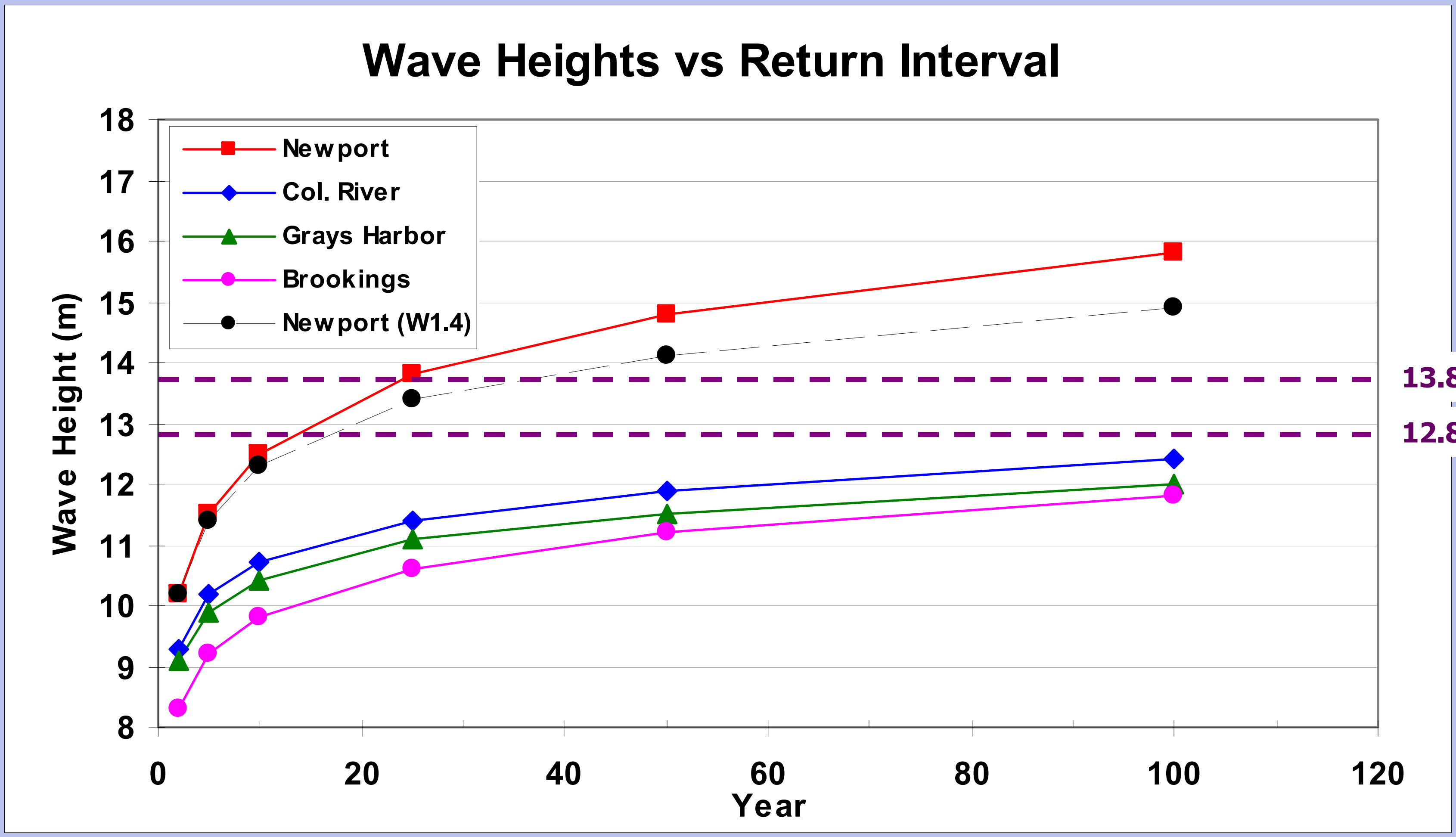
Hourly Wave Height Record
14 November to 5 December,1998
Date: 24 Nov 98
Rank #1
H=9.53 m
T=16.7 s
Duration = 213 hrs
Power=28.9 joules ($10^{10}$)per meter wave crest
Wind Direction
Wave Height
Wind Direction/100, Wave Height (m)
15
13
11
9
7
5
3
1
315
318
321
324
327
330
333
336
Date


Hourly Wave Height Record
2 February to 5 March, 1999
Date: 5 Feb 99
Rank #4
H = 8.92 m
T = 16.7 s
Duration = 182 hrs
Power = 24.2 joules (10^10)
per meter wave crest
Wind Direction
Wave Height
Date: 24 Feb 99
Rank #5
H = 8.73 m
T = 16.7 s
Duration = 185 hrs
Power = 19.9 joules (10^10)
per meter wave crest
Date: 3 Mar 99
Rank #26
H = 12.8 m
T = 16.7 s
Duration = 96 hrs
Power = 11.8 joules (10^10)
per meter wave crest
Wind Direction/100, Wave Height (m)
15
13
11
9
7
5
3
1
31
34
37
40
43
46
49
52
55
58
61
64
67
70
Date

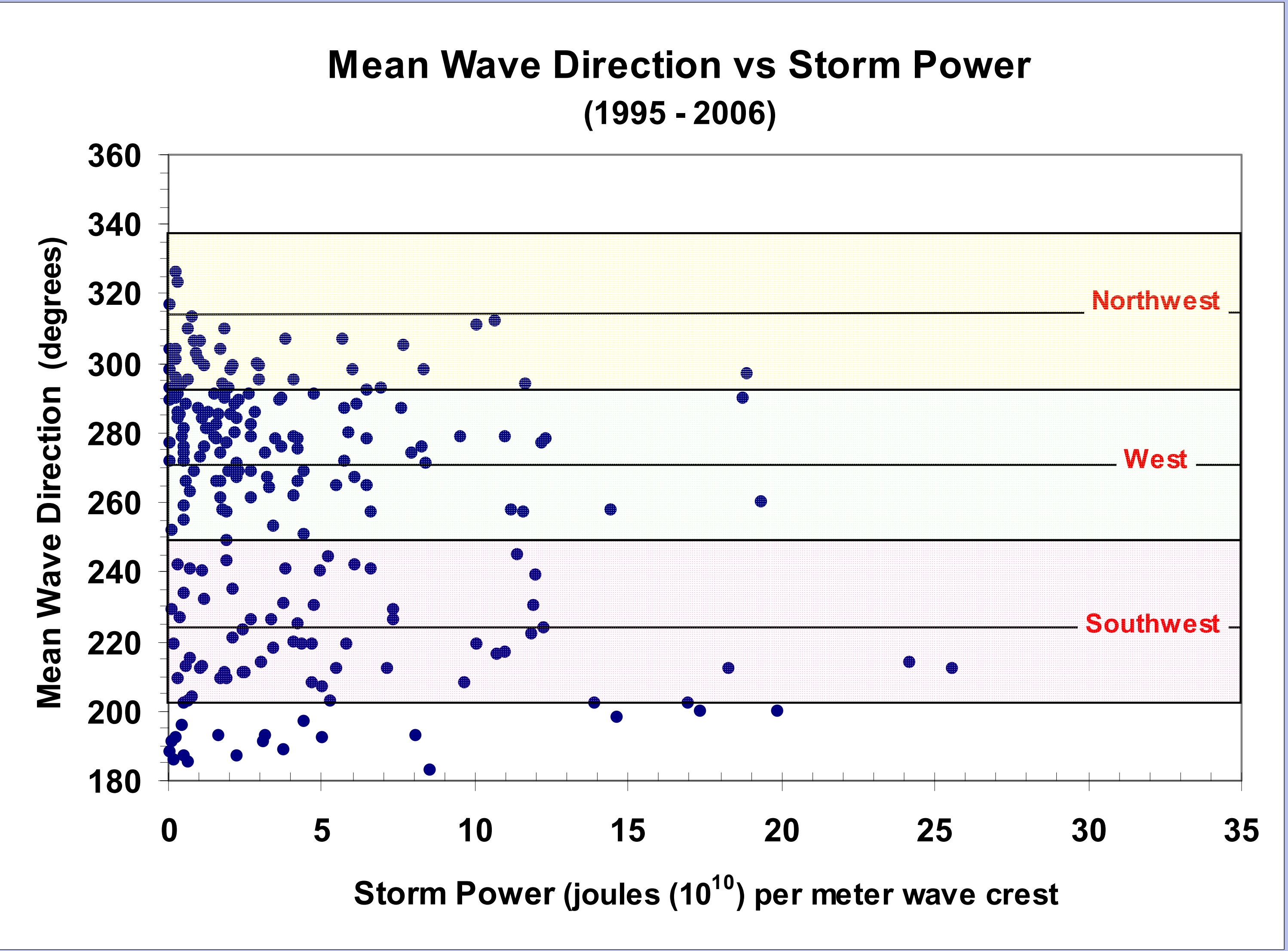

Duration vs Maximum Wave Height
Duration (hrs)
Wave Height (m)
with high events
without high events
y = 21.169x - 74.512
R2 = 0.4307
y = 18.644x - 60.602
R2 = 0.3847
Hs = 12.8 m
Dur = 96 hrs
Hs = 13.8 m
Dur = 39 hrs
0
50
100
150
200
250
2
4
6
8
10
12
14
16



Hourly Wave Height Record
26 January to 8 February, 2006
Wave Height
Wind Direction
Date: 30 Jan 2006
Rank: #15
Max H: 8.1 m
Max T: 14.3 sec
Dur: 113 hrs
Power = 14 J(10^10)
Date: 4 Feb 2006
Rank: #24
Max H: 13.8 m
Max T: 16.7 sec
Dur: 39 hrs
Power = 11.9 J(10^10)
Wave Height (m), Wind Direction/100
15
13
11
9
7
5
3
1
25
28
31
34
37
40
Day

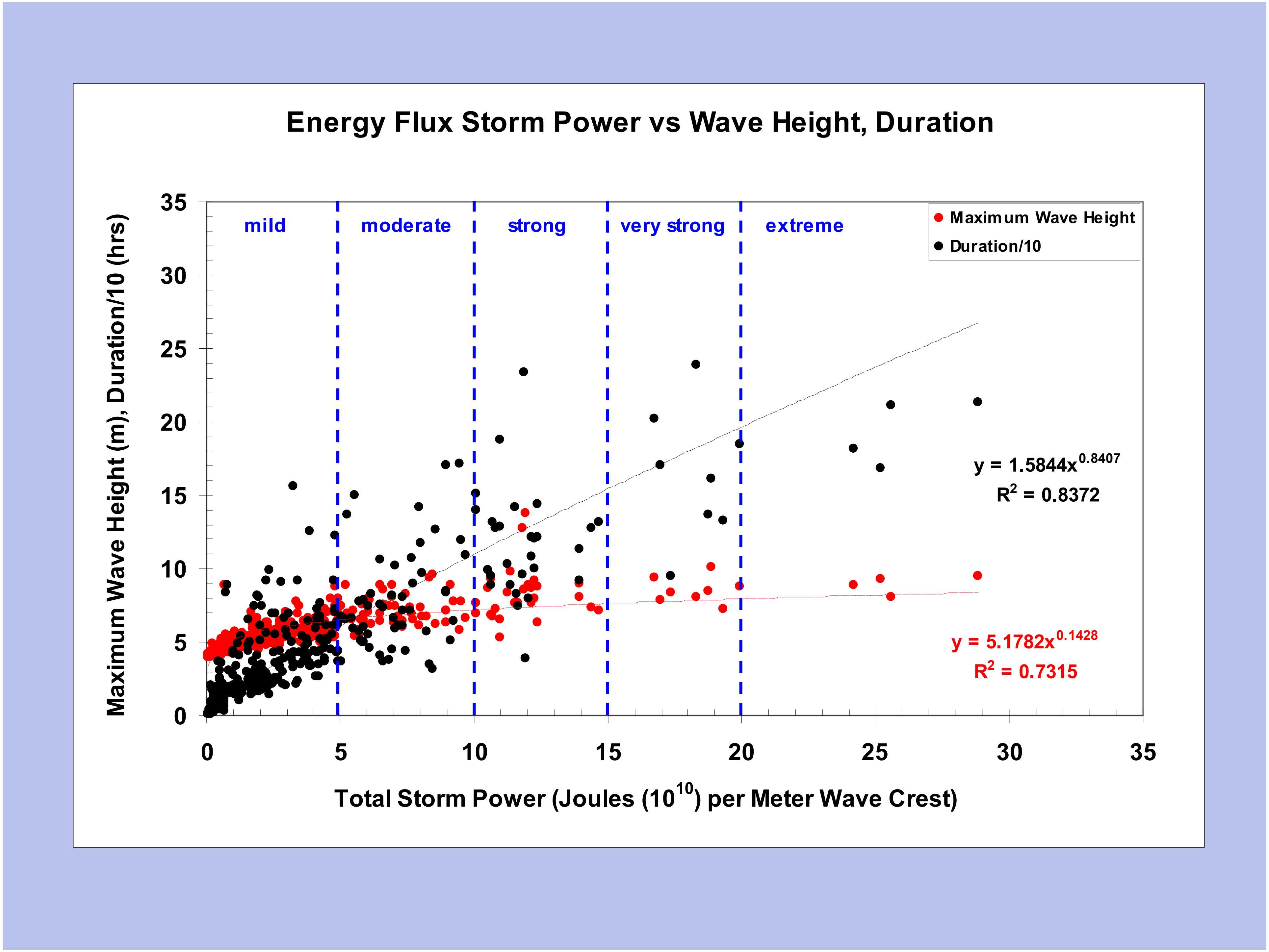


Wave Heights vs Return Interval
Wave Height (m)
Year
Newport
Col. River
Grays Harbor
Brookings
Newport (W1.4)
13.8 m
12.8 m
18
17
16
15
14
13
12
11
10
9
8
0
20
40
60
80
100
120


Mean Wave Direction vs Storm Power
(1995 - 2006)
360
340
320
300
280
260
240
220
200
180
Mean Wave Direction (degrees)
Northwest
West
Southwest
0
5
10
15
20
25
30
35
Storm Power (joules (10^10) per meter wave crest

# Top 20 Storm Events – Maximum Wave Height

| Date | Maximum Wave Height (m) | Average Wave Height (m) | Maximum Wave Period (s) | Average Wave Period (s) | Mean Wave Direction (degrees) | Duration (hrs) | Storm Power (joules ($10^{10}$) per m wave crest) |
|---|---|---|---|---|---|---|---|
| 4-Feb-06 | 13.75 | 7.59 | 16.7 | 13.0 | 230 | 39 | 11.9 |
| 3-Mar-99 | 12.76 | 5.96 | 16.7 | 13.4 | 222 | 96 | 11.8 |
| 14-Dec-01 | 10.08 | 5.73 | 14.3 | 11.4 | 297 | 161 | 18.9 |
| 16-Feb-99 | 9.83 | 5.38 | 16.7 | 13.5 | 245 | 89 | 11.4 |
| 12-Oct-03 | 9.64 | 6.87 | 16.7 | 15.2 | 271 | 32 | 8.5 |
| 24-Nov-98 | 9.53 | 6.02 | 16.7 | 13.1 | N/A | 213 | 28.9 |
| 3-Nov-84 | 9.40 | 6.04 | 20.0 | 13.8 | N/A | 202 | 16.8 |
| 23-Oct-01 | 9.39 | 6.49 | 16.7 | 14.0 | 298 | 35 | 8.4 |
| 15-Dec-02 | 9.31 | 5.71 | 16.7 | 12.7 | N/A | 168 | 25.2 |
| 17-Nov-03 | 9.27 | 5.42 | 16.7 | 11.8 | 312 | 95 | 10.6 |
| 29-Jan-99 | 9.16 | 5.78 | 16.7 | 12.0 | N/A | 120 | 12.3 |
| 13-Mar-03 | 8.98 | 5.97 | 16.7 | 12.5 | N/A | 92 | 13.9 |
| 5-Feb-99 | 8.92 | 5.53 | 16.7 | 12.3 | 214 | 182 | 24.2 |
| 28-Oct-00 | 8.87 | 5.94 | 16.7 | 13.4 | 123 | 51 | 9.1 |
| 5-Jan-06 | 8.86 | 5.58 | 20.0 | 14.2 | 239 | 80 | 12.0 |
| 28-Nov-01 | 8.86 | 5.94 | 14.3 | 12.3 | N/A | 45 | 6.9 |
| 16-Jan-00 | 8.86 | 6.59 | 12.5 | 10.0 | N/A | 3 | 0.7 |
| 9-Oct-03 | 8.85 | 5.88 | 16.7 | 13.7 | 278 | 41 | 6.5 |
| 31-Mar-97 | 8.85 | 5.16 | 17.4 | 13.5 | 244 | 65 | 5.2 |
| 28-Oct-99 | 8.81 | 6.20 | 16.7 | 13.4 | 230 | 122 | 4.8 |



Energy Flux Storm Power vs Wave Height, Duration
Maximum Wave Height (m), Duration/10 (hrs)
Total Storm Power (Joules (10^10) per Meter Wave Crest)
mild
moderate
strong
very strong
extreme
Maximum Wave Height
Duration/10
y = 1.5844x^0.8407
R^2 = 0.8372
y = 5.1782x^0.1428
R^2 = 0.7315
0
5
10
15
20
25
30
35

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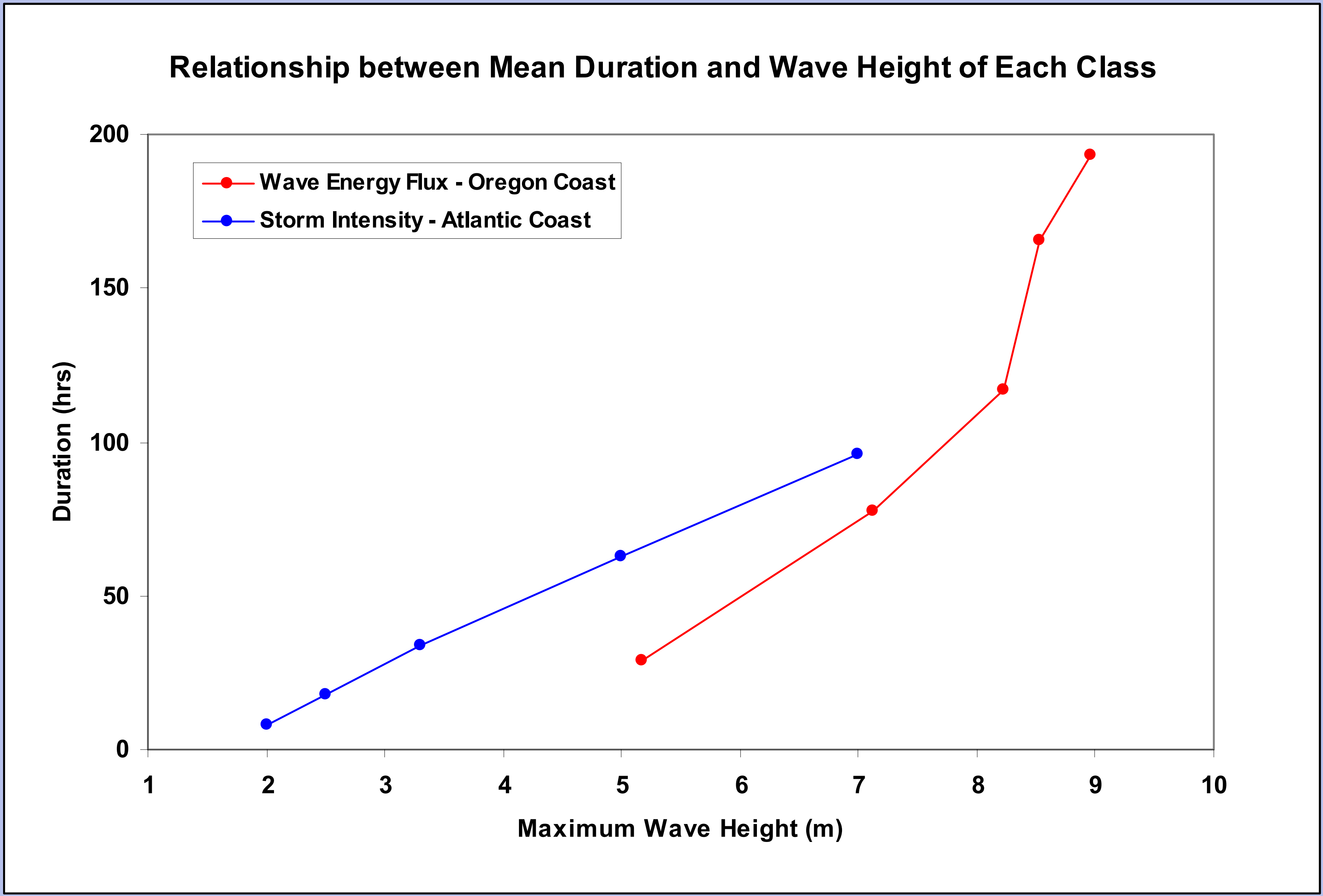
# Summary of Storms Analyzed
# 1984 to 2006

| Storm Category | Power (J($10^{10}$)per m wave crest) | Total Number | Percent Population |
|---|---|---|---|
| Mild | 0 < P < 5 | 268 | 75 |
| Moderate | 5 < P < 10 | 52 | 14 |
| Strong | 10 < P < 15 | 28 | 8 |
| Very Strong | 15 < P < 20 | 8 | 2 |
| Extreme | P > 20 | 4 | 1 |

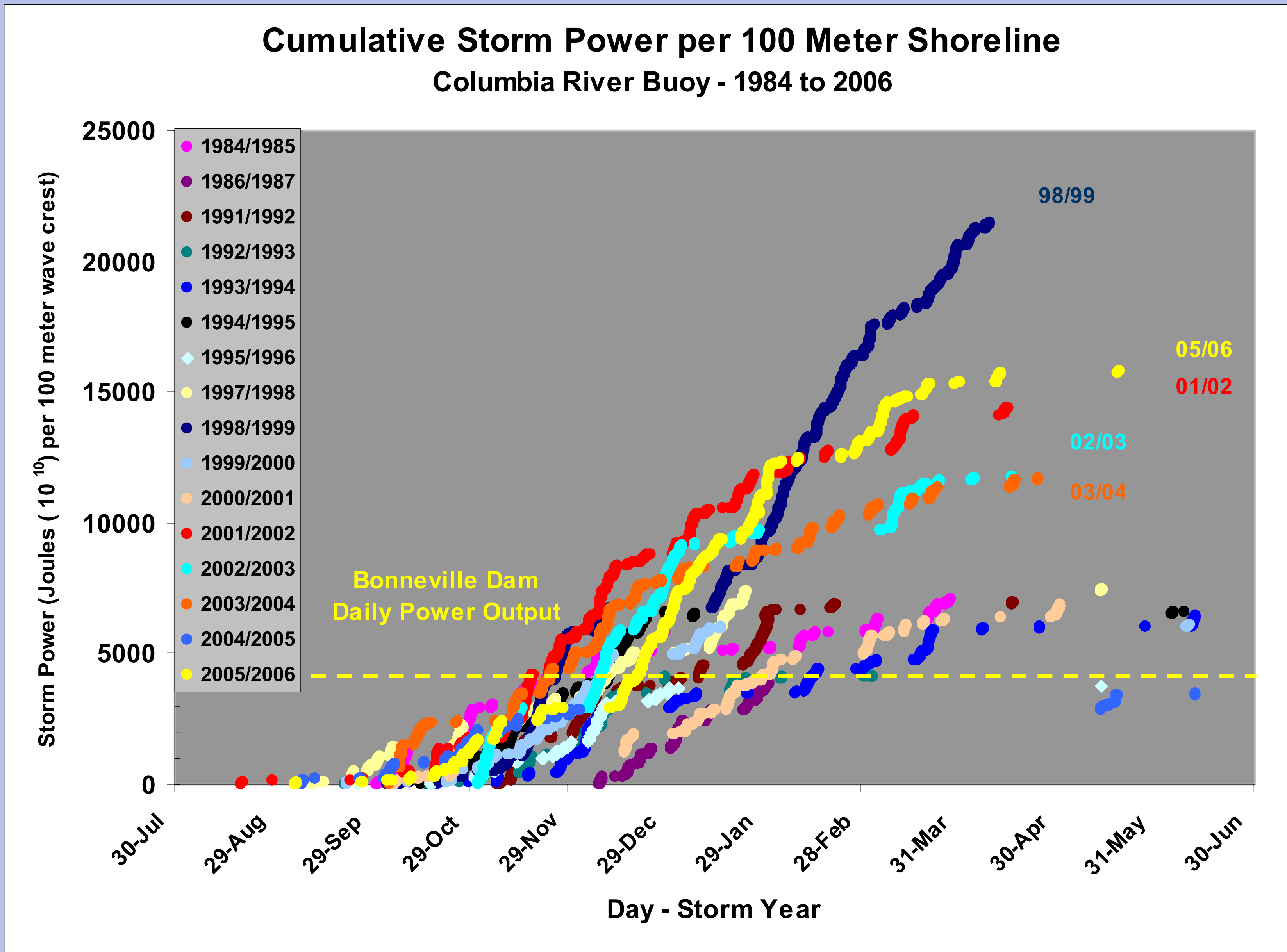
# Five Storm Classes – Dolan / Davis Scale

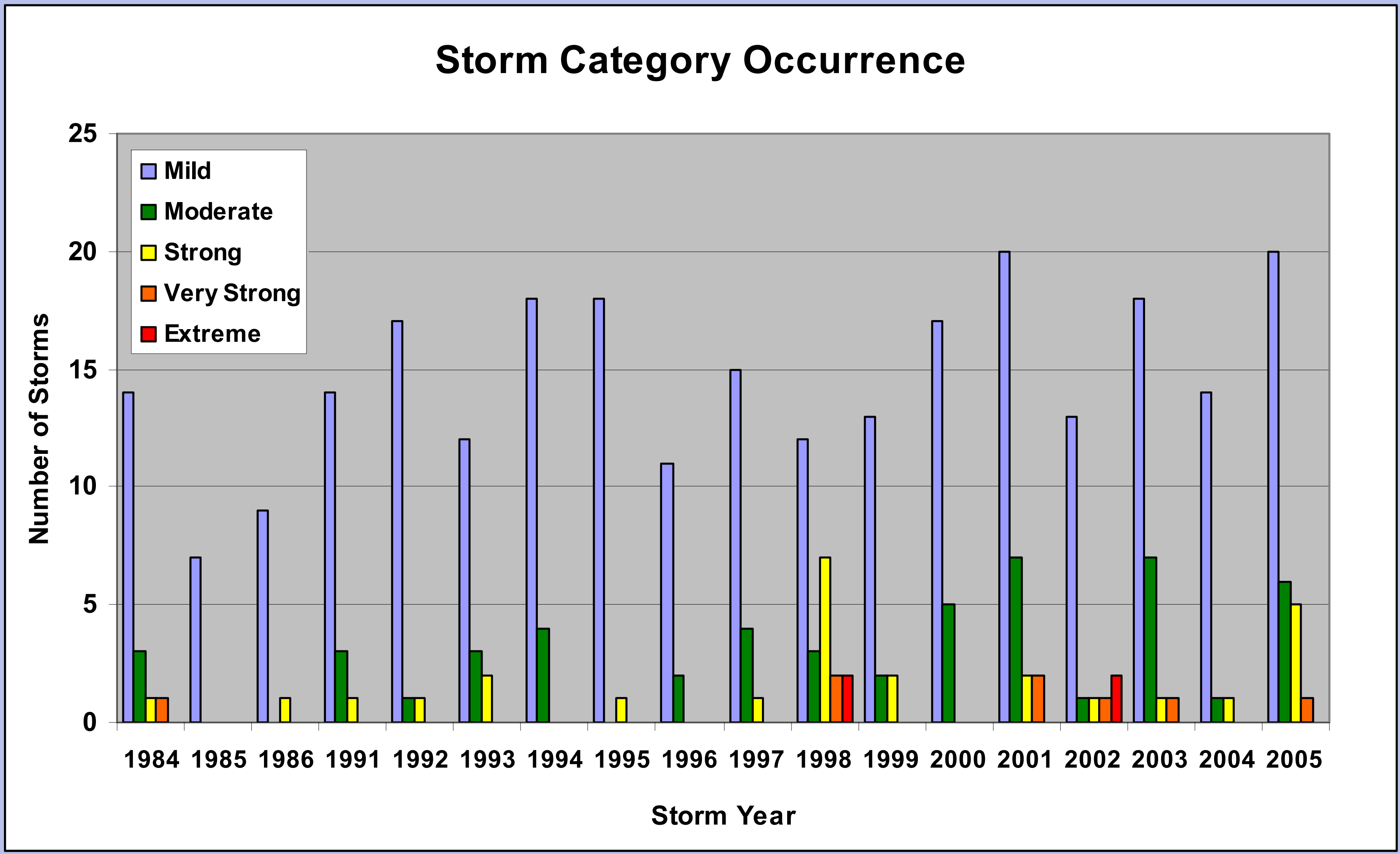
| Storm Class | Frequency | | Significant Wave Height (m) | | Duration (hr) | |
|---|---|---|---|---|---|---|
| | N | % | $\bar{x}$ | s | $\bar{x}$ | s |
| 1 Weak | 670 | 49.7 | 2.0 | 0.3 | 8 | 4.3 |
| 2 Moderate | 340 | 25.2 | 2.5 | 0.5 | 18 | 7.0 |
| 3 Significant | 298 | 22.1 | 3.3 | 0.7 | 34 | 17 |
| 4 Severe | 32 | 2.4 | 5.0 | 0.9 | 63 | 26 |
| 5 Extreme | 7 | 0.1 | 7.0 | 1.3 | 96 | 47 |

| Storm Class | Power ($m^2hr$) | | Range ($m^2hr$) | Range ($ft^2hr$) |
|---|---|---|---|---|
| | $\bar{x}$ | s | | |
| 1 Weak | 32 | 20 | power ≦ 71.63 | power ≦ 771 |
| 2 Moderate | 107 | 25 | 71.63 < power ≦ 163.51 | 771 ≤ power ≦ 1760 |
| 3 Significant | 353 | 178 | 163.51 < power ≦ 929.03 | 1,760 < power ≦ 10,000 |
| 4 Severe | 1,455 | 378 | 929.03 < power ≦ 2,322.58 | 10,000 < power ≦ 25,000 |
| 5 Extreme | 4,548 | 2,370 | power > 2322.58 | power > 25,000 |



Relationship between Mean Duration and Wave Height of Each Class
Wave Energy Flux - Oregon Coast
Storm Intensity - Atlantic Coast
Duration (hrs)
0
50
100
150
200
1
2
3
4
5
6
7
8
9
10
Maximum Wave Height (m)


Cumulative Storm Power per 100 Meter Shoreline
Columbia River Buoy - 1984 to 2006
Storm Power (Joules ( 10 10) per 100 meter wave crest)
25000
20000
15000
10000
5000
0
1984/1985
1986/1987
1991/1992
1992/1993
1993/1994
1994/1995
1995/1996
1997/1998
1998/1999
1999/2000
2000/2001
2001/2002
2002/2003
2003/2004
2004/2005
2005/2006
98/99
05/06
01/02
02/03
03/04
Bonneville Dam
Daily Power Output
30-Jul
29-Aug
29-Sep
29-Oct
29-Nov
29-Dec
29-Jan
28-Feb
31-Mar
30-Apr
31-May
30-Jun
Day - Storm Year

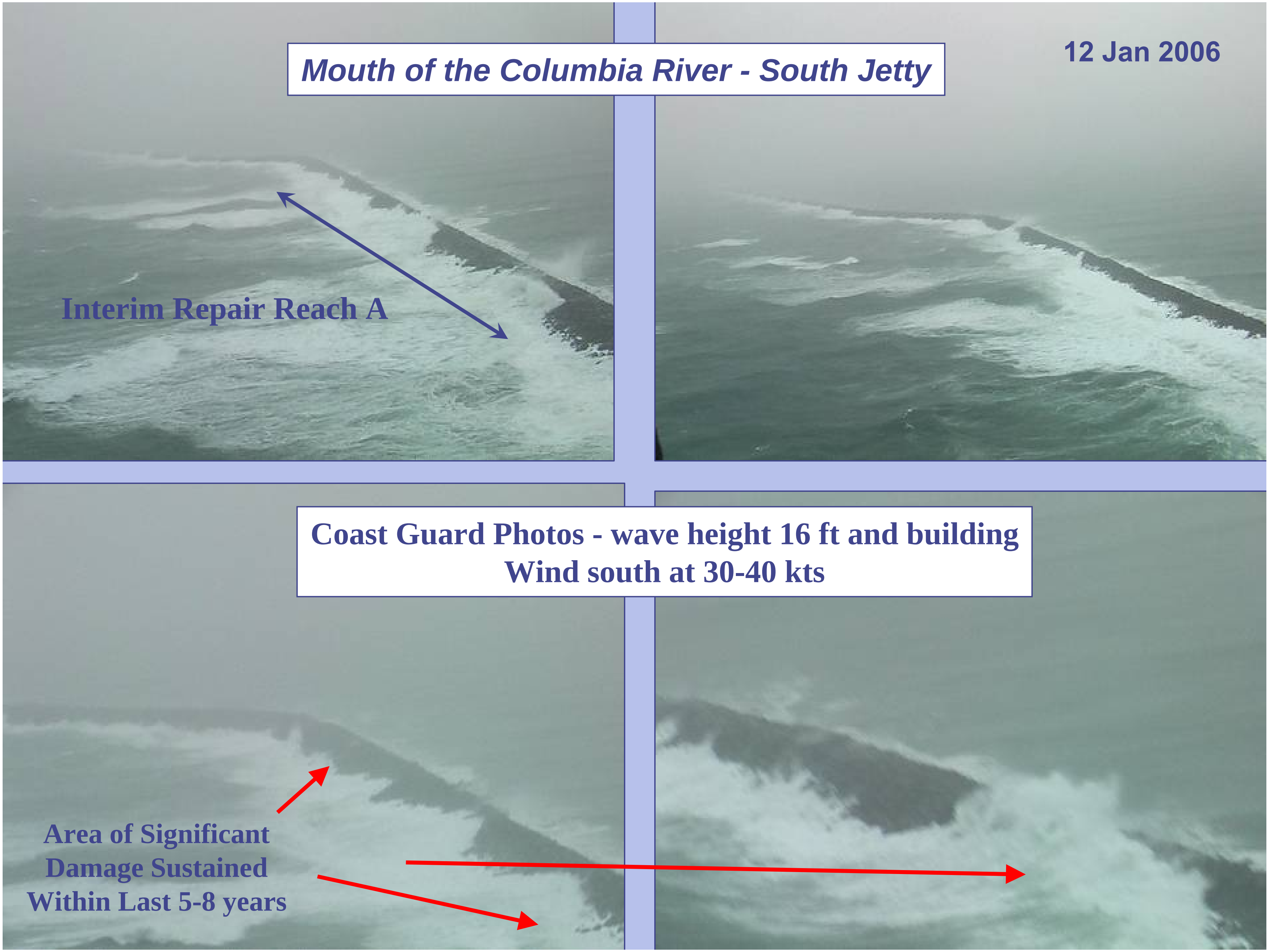


Storm Category Occurrence
25
20
15
10
5
0
Number of Storms
Mild
Moderate
Strong
Very Strong
Extreme
1984 1985 1986 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005
Storm Year

# Hypothesized Relationships between Dolan-Davis Northeaster Storm Class and Coastal Damage

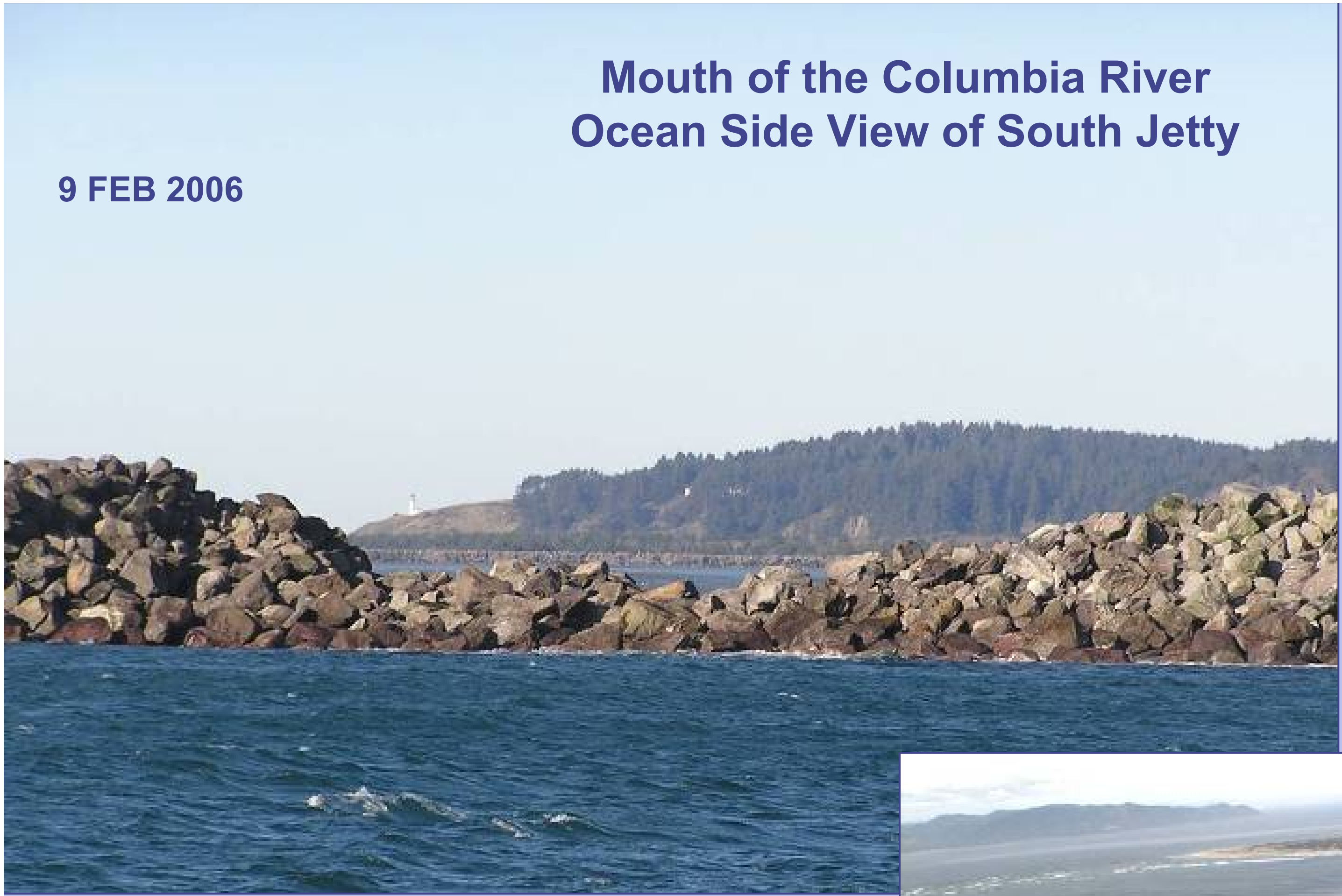
| Storm Class | Beach Erosion | Dune Erosion | Overwash Damage | Property Damage | Mean Wave Ht. (m) | Mean Duration (hr) |
|---|---|---|---|---|---|---|
| Class I (weak) | Minor | None | None | None | 2.0 | 8 |
| Class II (moderate) | Moderate | Minor | None | None | 2.5 | 18 |
| Class III (significant) | Extends across beach | Significant | None | Moderate | 3.2 | 35 |
| Class IV (severe) | Severe with recession | Severe or localized destruction | On low-profile beaches | Loss of structures at community scale | 5.0 | 62 |
| Class V (extreme) | Extreme | Dunes destroyed over extensive areas | Massive in sheets and channels | Extensive regional scale losses in millions of dollars | 6.8 | 97 |

(Dolan/Davis, 1994)


Mouth of the Columbia River - South Jetty
12 Jan 2006
Interim Repair Reach A
Coast Guard Photos - wave height 16 ft and building
Wind south at 30-40 kts
Area of Significant
Damage Sustained
Within Last 5-8 years

# Mouth of the Columbia River
# Ocean Side View of South Jetty

**9 FEB 2006**



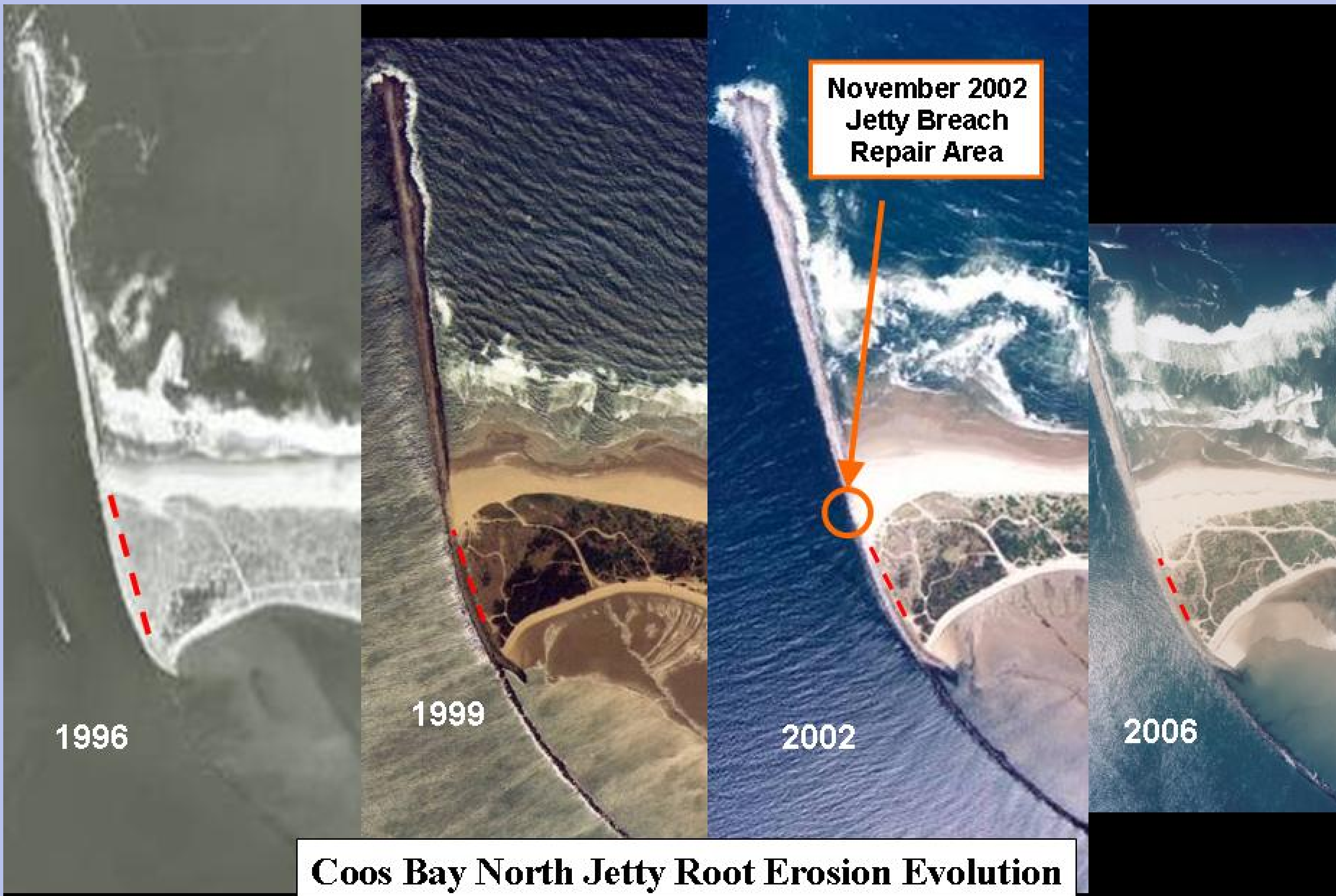
**Tide elevation in picture = +3 ft MLLW.**
**High tide elevation = +8 ft MLLW**

**"Notch" in south jetty due to Winter 06 storm waves.**
**A notch was present prior to Feb 06.**
**Recent damage lowered notch by 10-12 ft.**
**Lowest point of notch is at + 8 ft MLLW.**

Wave-induced erosion of primary dune protecting un-secured jetty root and low elevation backshore.



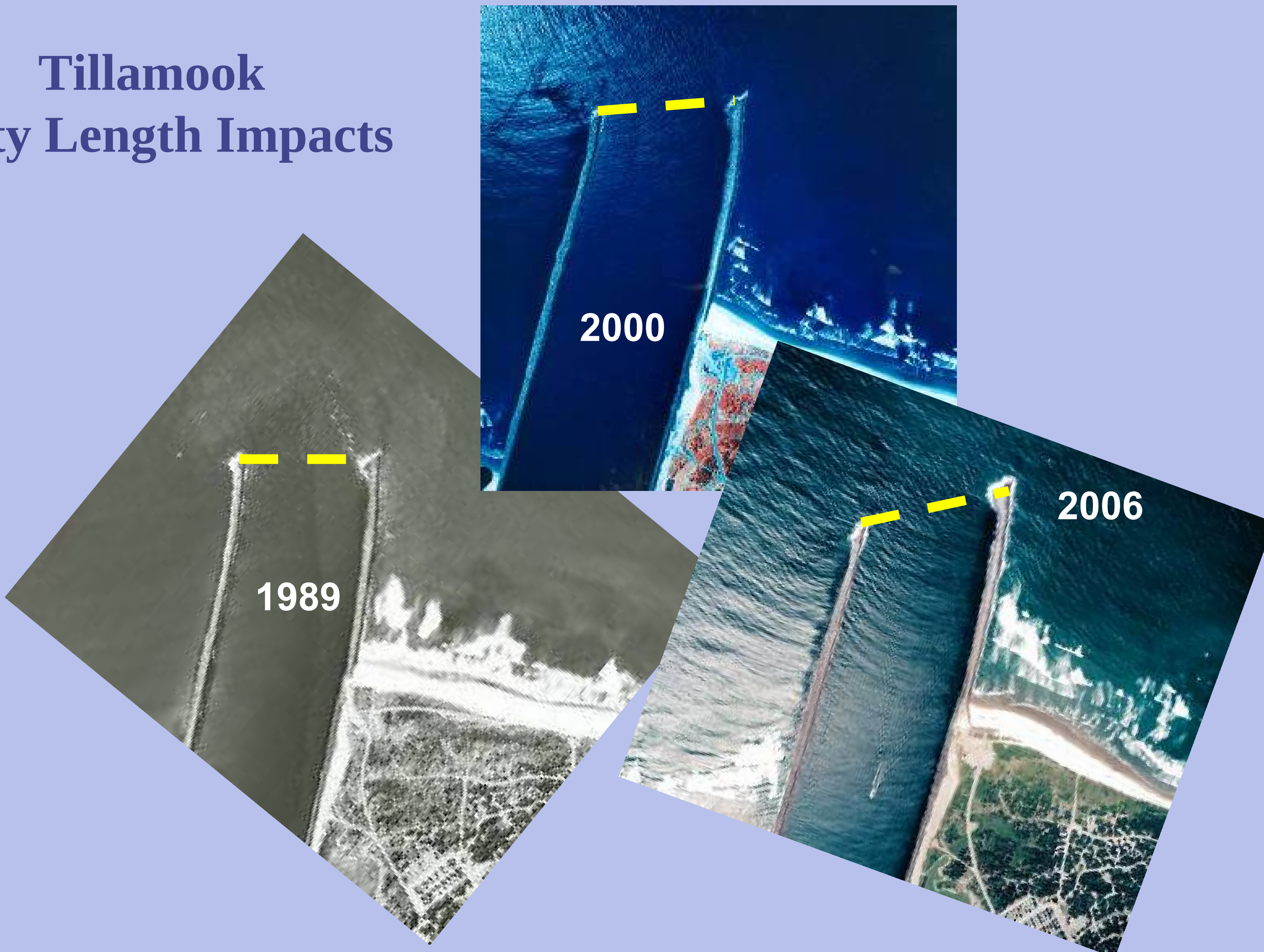
View to east along Mouth of the Columbia River south jetty root

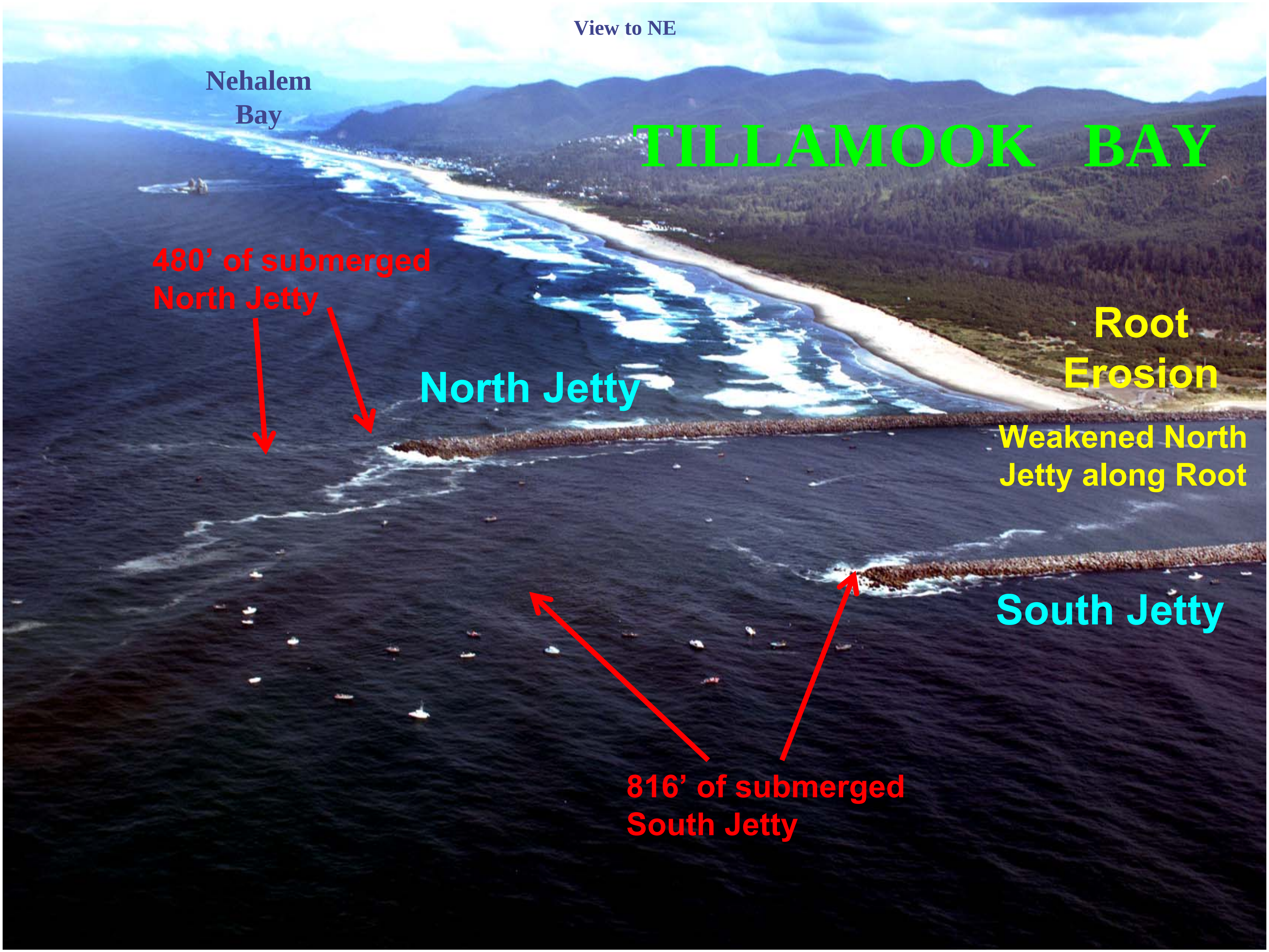



Coos Bay North Jetty Root Erosion Evolution

# Coos Bay
# North Jetty


# Tillamook
# Jetty Length Impacts




View to NE
Nehalem Bay
TILLAMOOK BAY
480’ of submerged North Jetty
North Jetty
Root Erosion
Weakened North Jetty along Root
South Jetty
816’ of submerged South Jetty

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# Conclusions

- Dominant wave periods of 17 to 25 seconds represent the most powerful events.
- Total storm power is strongly controlled by maximum wave height and storm duration.
- 5 storm categories from mild to extreme (5 J($10^{10}$) increments) have been identified.
- 18 year analysis of Columbia River buoy yielded 4 extreme storm events.
- Cumulative storm power identified 98/99 and 05/06 as most powerful storm years.
- 60% of top 20 storm events were identified using both methods.
- Events with the highest wave heights did not always represent the strongest storms. A second storm population may explain larger maximum wave heights.
- The period of record since 1998 stands out as a more powerful time period.

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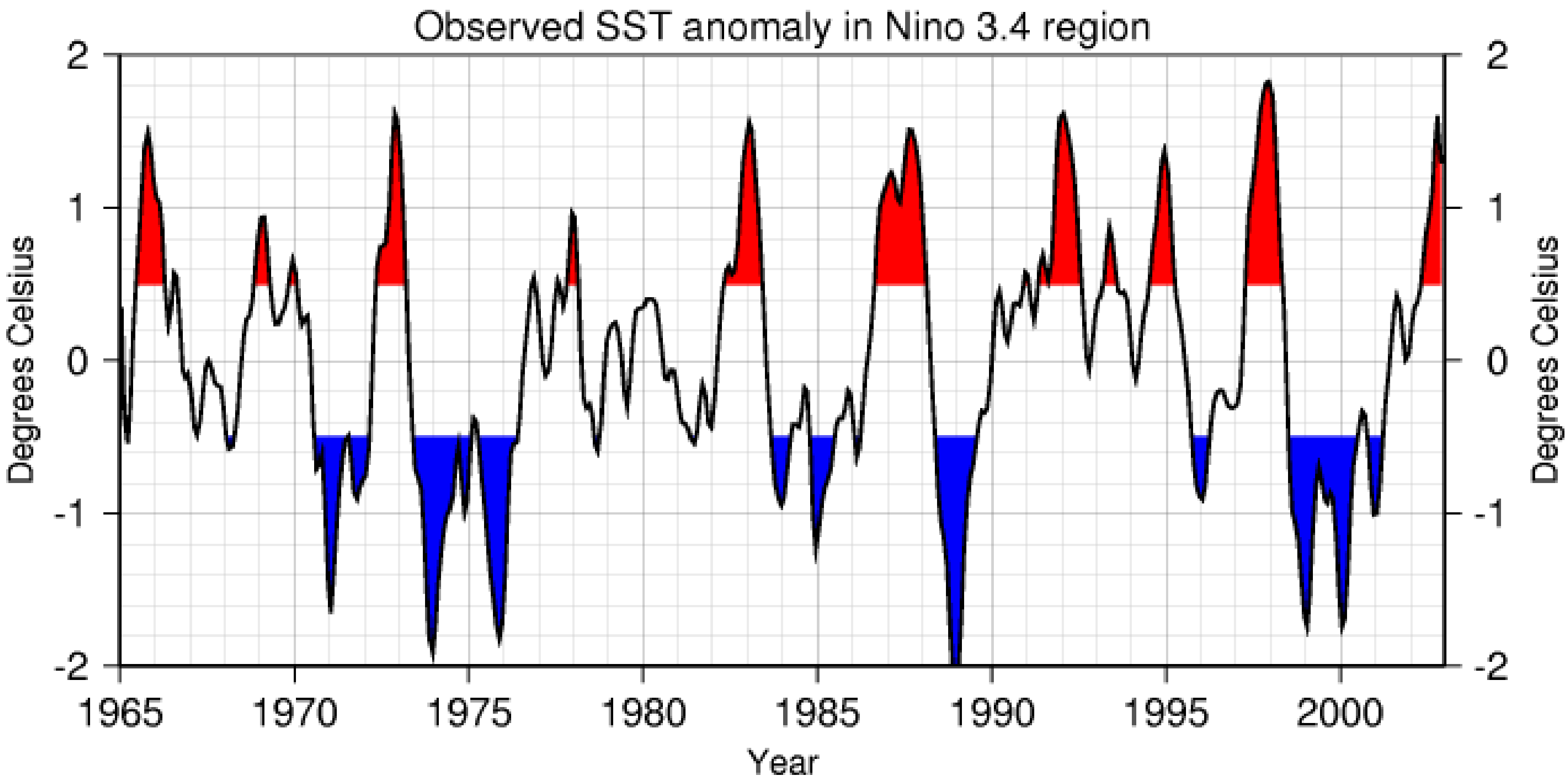
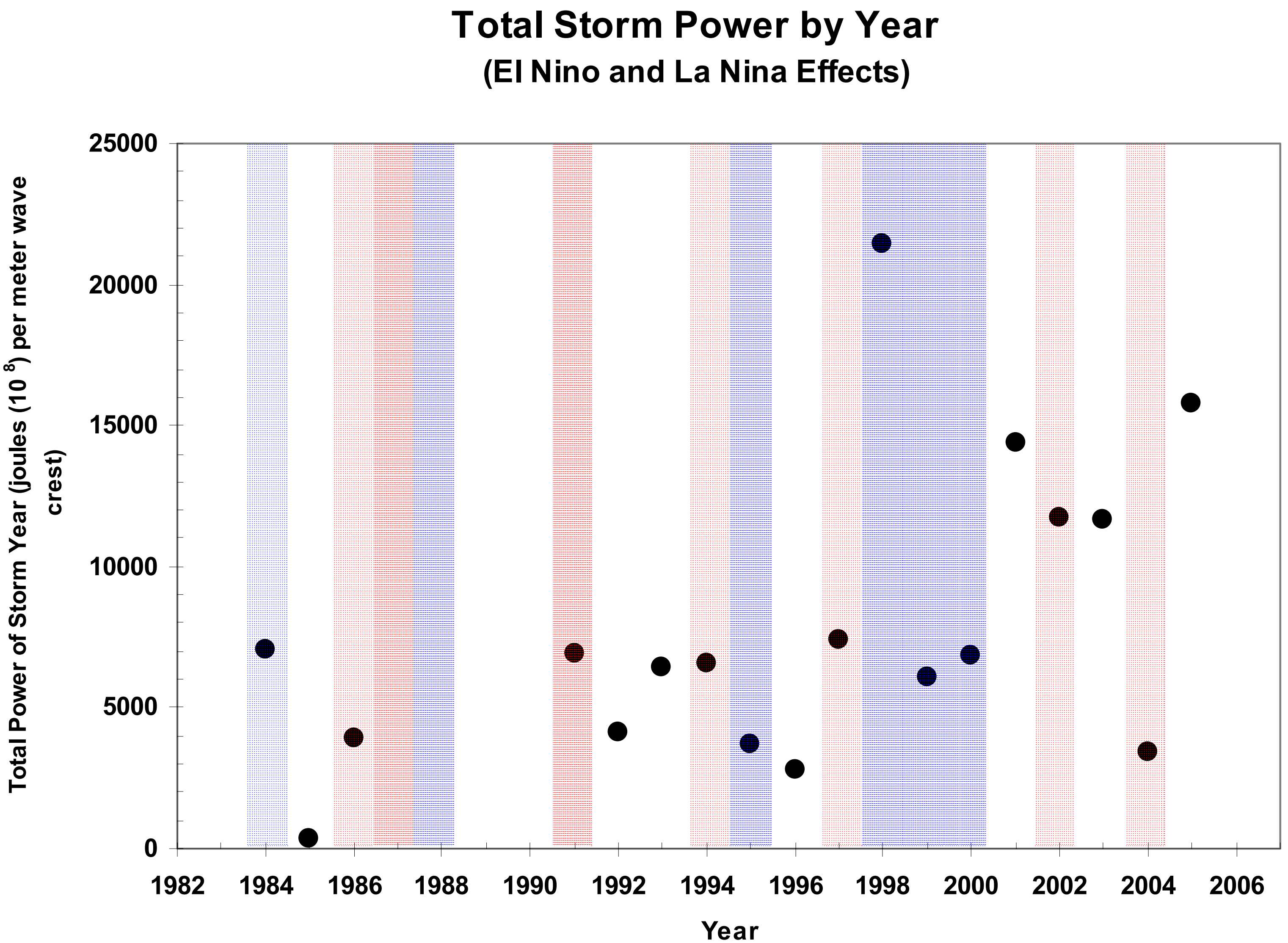
# Areas Needing Further Study

- Analysis of additional buoys (46050, 46027, 46041).
- Addition of storm surge as a key variable.
- Evaluate shallow water equations.
- More study of weather patterns and origin of storms.
- Better tracking and correlation of storms/series of storms with coastal damage.
- Explore if greater power as measured by wave energy flux really means greater coastal damage.
- Further investigation into response to a series of stormy years may lead to a better understanding of the larger processes involved.
- Understanding of storm power effects may lead to improvements in coastal structure design.




(ref: NOAA, Scripps)

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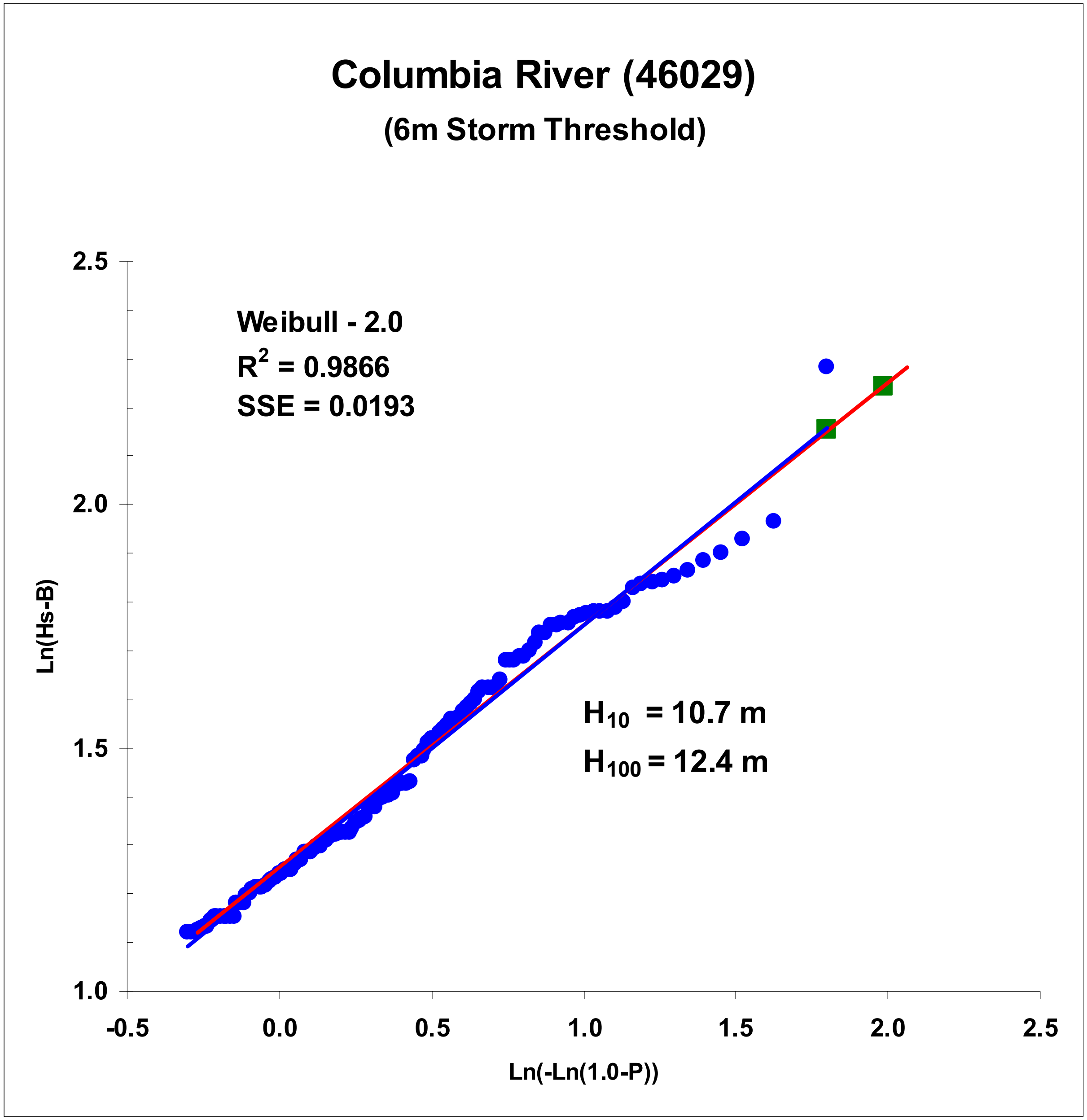
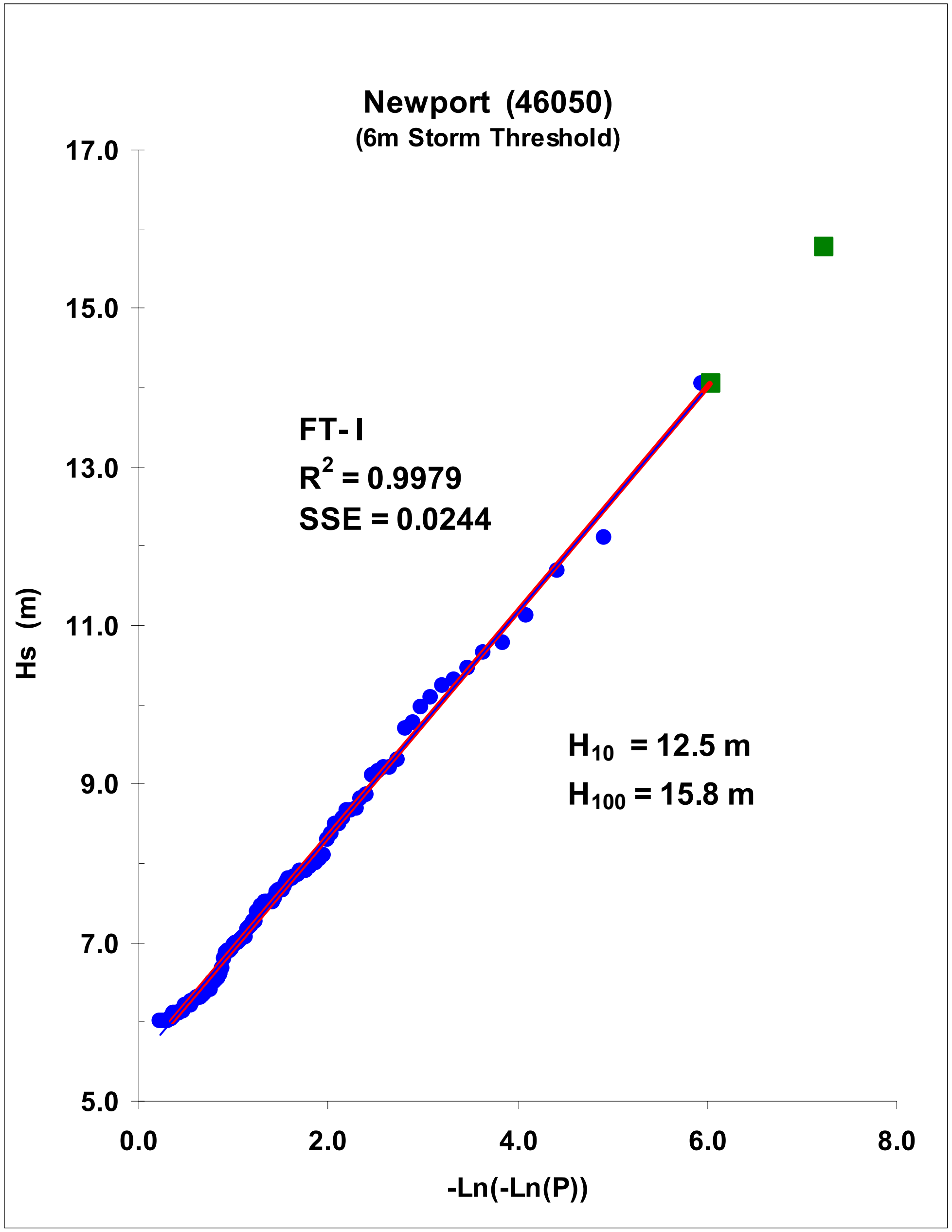
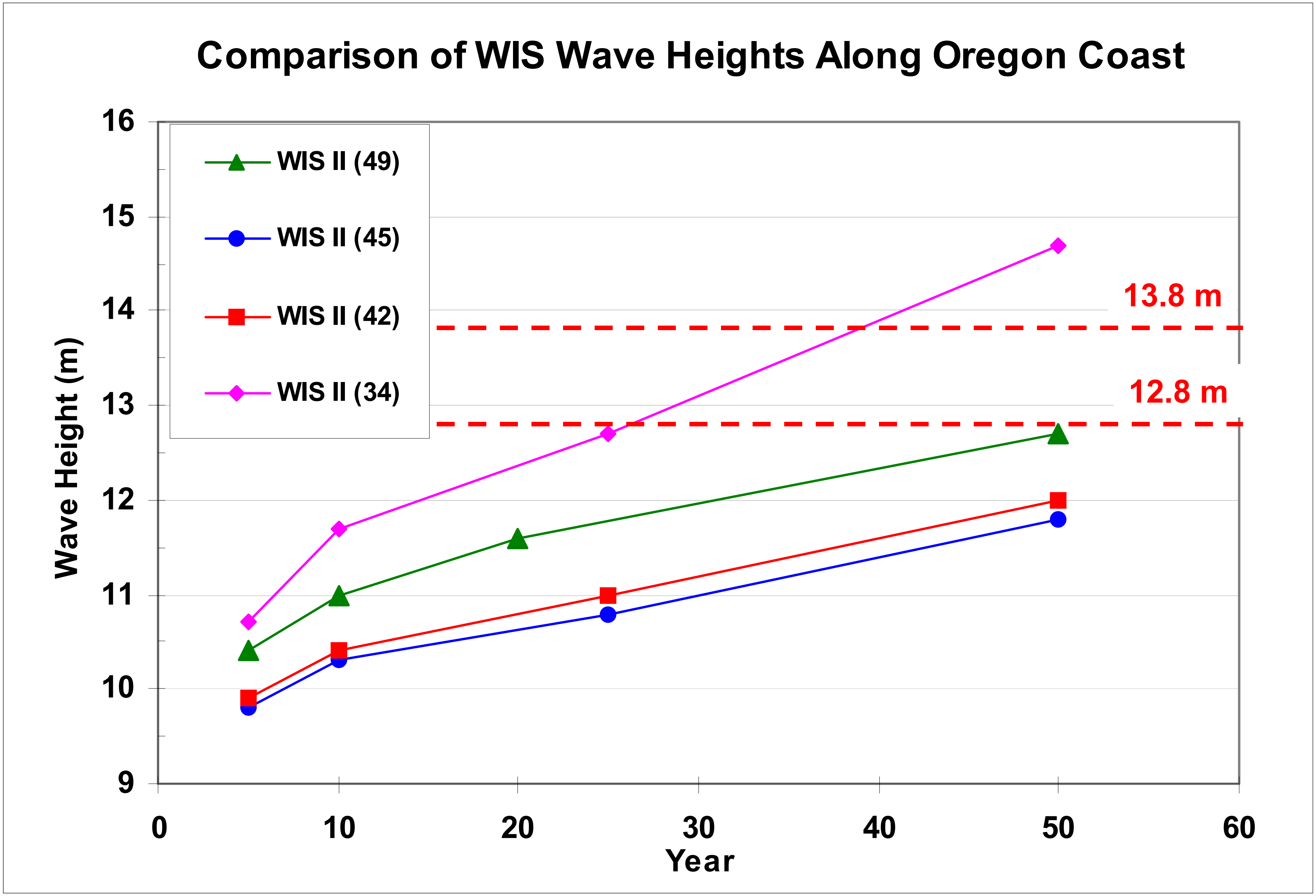


Columbia River (46029)
(6m Storm Threshold)
Weibull - 2.0
R2 = 0.9866
SSE = 0.0193
H10 = 10.7 m
H100 = 12.4 m
Ln(Hs-B)
Ln(-Ln(1.0-P))
2.5
2.0
1.5
1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5



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



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