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

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1.0 INTRODUCTION

Storm intensity and its effect on coastal infrastructure and shorelines is clearly not just a function of maximum wave height. Recent storm years on the Oregon coast have shown the significant additional effects of storm duration, wave period, storm surge, and wave direction on coastal impacts. In addition, particularly with respect to shorelines, the effects of a series of storms or a series of stormy years can be devastating. In order to better understand the magnitude of the relative forces accompanying each storm and series of storms, storm events need to be described in terms of overall storm power which includes other critical variables.

Dolan and Davis (1994) investigated the relative power of Northeasters along the Atlantic Coast. They developed a classification of northeasters analogous to the Saffir-Simpson Scale for hurricanes. Their analysis evaluated 1564 storms over a 50 year period and developed five classes of storm intensity. Since they were using hindcasted data and generally did not have wave period data, they defined storm power as **(maximum significant wave height)^2 x duration** in hours. Their analysis utilized a storm threshold of 1.5 m.

This investigation utilizes hourly wave data from the National Data Buoy Center's buoy #46029 (Columbia River) making wave period available to provide a more complete calculation of wave power. Storm power is evaluated using two methods: (1) Dolan/Davis method to provide a comparison to that study and (2) storm power calculated using the theoretical wave energy flux calculation, $\mathbf{P_o=½E_oC_o}$. Power is then summed over the storm duration to calculate power of individual storms, storm seasons, and storm years. The variability of storm power with wave direction is presented. The correlation of shoreline erosion and coastal infrastructure damage with historical storm power is identified when possible.

2.0 METHOD

Hourly wave data was obtained for this analysis from the historical record of National Data Buoy Center (NDBC) buoy #46029, Columbia River. This is a 3 m discus buoy located in a water depth of 128 m approximately 20 miles seaward of the Mouth of the Columbia River. Figure 1 illustrates the location of the NDBC buoy. Period of record utilized for the analysis extended from 1984 to 2006. Some data gaps occurred during the period of analysis, the most significant of which extended from 2/87 to 9/91. Directional data was available beginning in the fall of 1995.

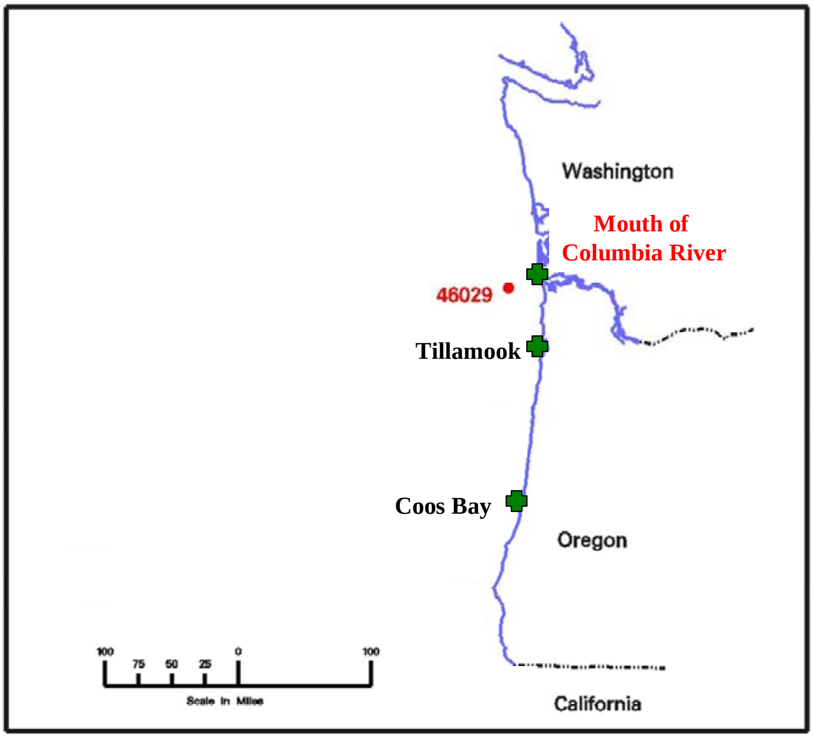


Figure 1. Location of NDBC Wave Data

In order to assess the minimum wave height cutoff defining a storm event, wave height values from October 1 to March 30 (typical storm season) 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 storm threshold for this analysis. The Columbia River buoy showed thresholds around 4.3 m so a value of 4.0 m was used to define a storm event.

Further analysis of the data was conducted in order to identify individual and independent storm events from the record. The peak over threshold method of extremal wave height analysis 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. Figure 2 illustrates results from an earlier analysis of wave data along the Oregon coast (Moritz, 2004). At auto-correlations of 0.3 and 0.5 for typical Oregon coast data, maximum time lags for all but the 1998 data set yield values of 40 to 60 hrs. To ensure independence of events, the time period between local maxima was chosen at 72 hrs.

Wave data was separated into storm years extending from August to June of the following year. Although storm events were identified during this entire time period, the typical storm season for the Columbia River buoy data extends from October through March with the most significant storm

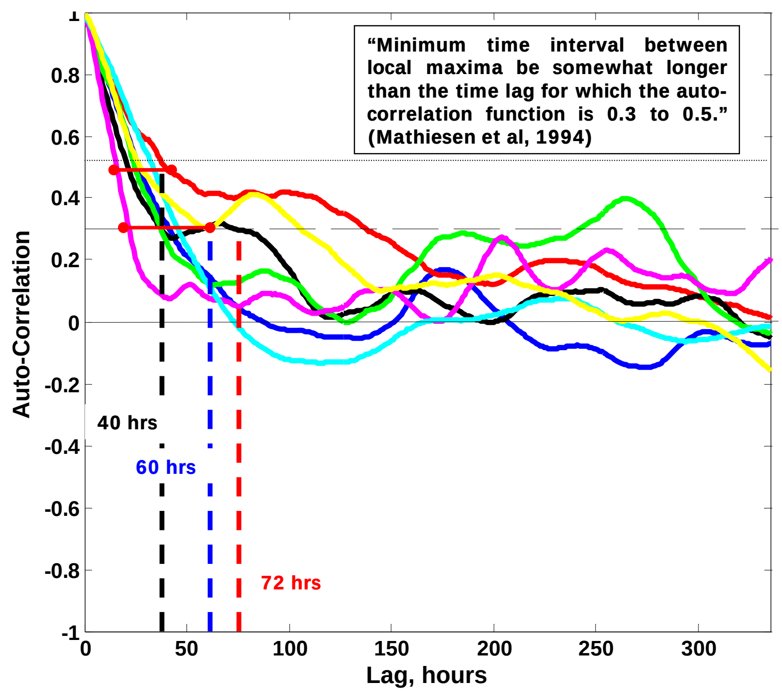


Figure 2. Auto-correlation Values for Oregon Coast Wave Data

months being the five months of November through March. Figure 3 illustrates the storm population and calculated power by month over the period of record. The greatest number of storms occur November through January.

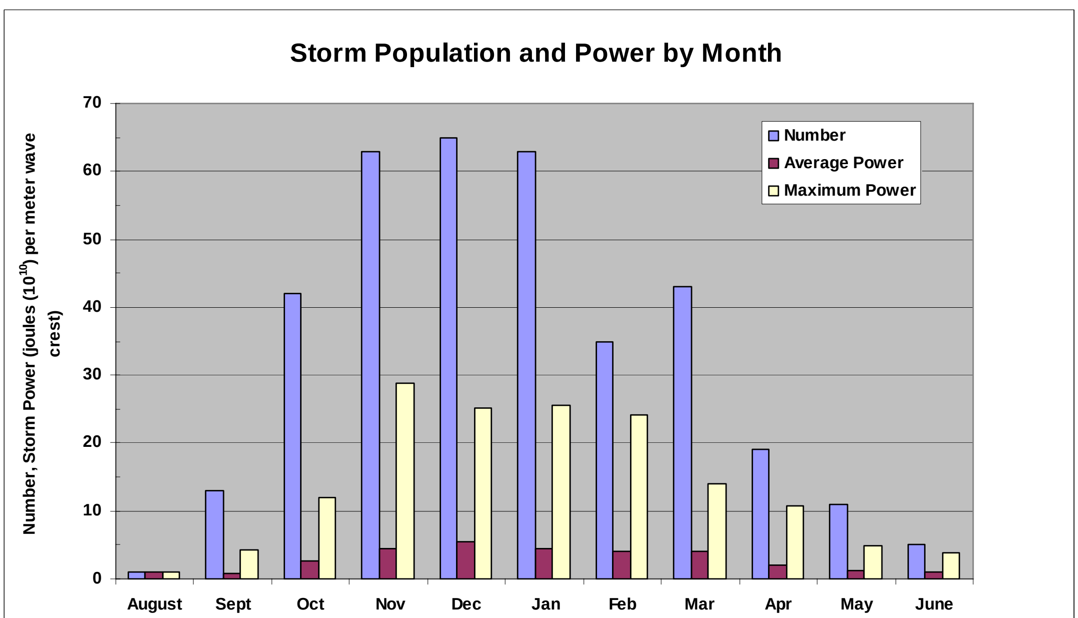


Figure 3.

3.0 STORM POWER ANALYSIS PROCEDURE

Since this analysis utilized wave buoy data, wave period was available for the calculation of wave power. The rate at which energy is transported toward the shore is the wave power or wave energy flux defined by the following equations for deep water: (USACE, 1984)

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

where: P = wave power (N*m/s per meter wave crest)
E_o = energy density (kg/s^2)
C_o = wave celerity (m/s).

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

where: E_o = energy density (kg/s^2)
ρ = density of seawater (kg/m^3)
g = acceleration of gravity (m/s^2)
H = wave height (m).

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

where: C_o = wave celerity (m/s)
g = acceleration of gravity (m/s^2)
T = wave period (s).

$$P/hr = \frac{P*(3600\ s)}{hr}$$

where: total power = joules/hr per meter wave crest.

Wave power was calculated for each hour of storm event and then summed over the duration of the storm. Figure 4 illustrates wave height and period plotted against hourly wave power for the entire data set analyzed. This figure illustrates a strong correlation of wave power to wave height, as expected. It also illustrates that while storm events with periods of 20 to 25 seconds have been measured, the most powerful wave power occurred for wave periods of 16.7 seconds.

4.0 ANALYSIS RESULTS

Final results of storm power were evaluated as individual storms as well as cumulative per storm year. Figure 5 displays the relationship between individual storm power and maximum wave height and duration. Total storm power is strongly controlled by these two variables with the correlation to duration being stronger. Storm power ranges from approximately 1 to 30 joules (10^{10}) per meter wave crest. Based on the distribution of power, 5 storm categories have been identified as illustrated in figure 5 and in table 1. Storm categories range from mild to extreme at 5 joules (10^{10}) increments. For this 18 year analysis (1987 to1990 are not included), 4 extreme events were identified: 24 November 1998, 2 January 2003, 15 December 2002, and 5 February 1999.

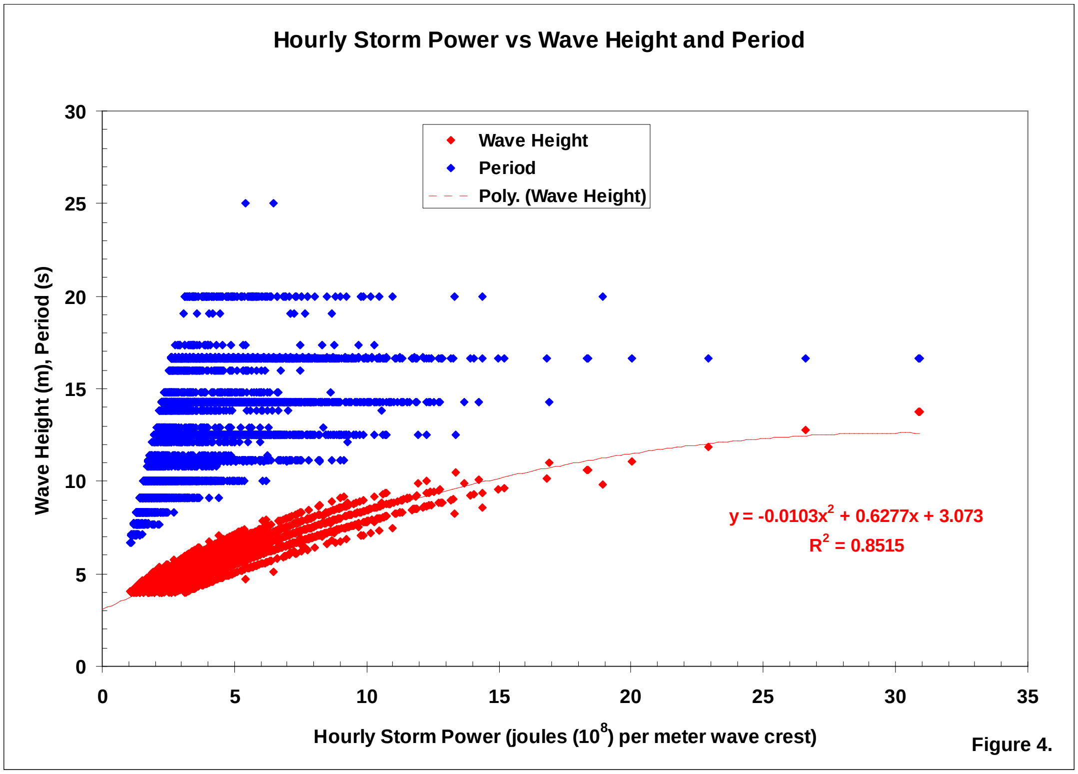


Figure 4.

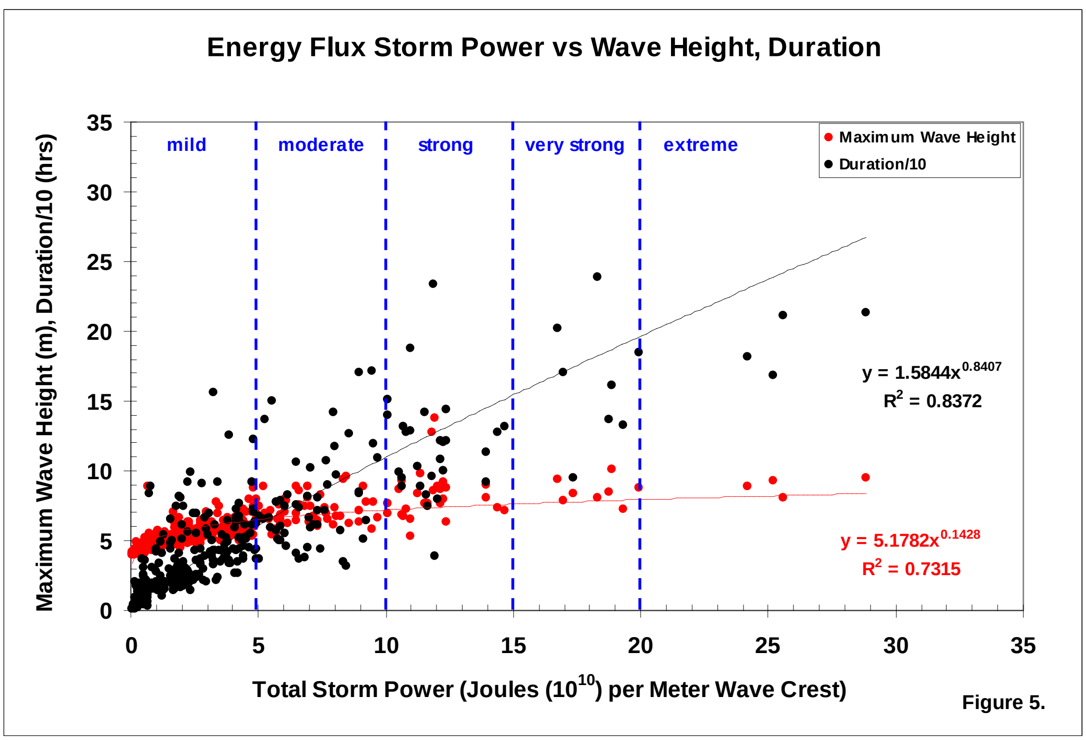


Figure 5.

Table 1. Columbia River Buoy Storm Population by Strength Category

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

In this analysis, 89% of the storm events fell into the mild to moderate range, while 11% fell into the strong to extreme range. Figure 6 displays the relationship between individual storm power and mean wave direction. For the storm categories of strong to extreme, 57% of the storm events were out of the south to southwest, 25% were out of the west, and 18% were out of the northwest. The greatest number of storms, however, were out of the west to northwest.

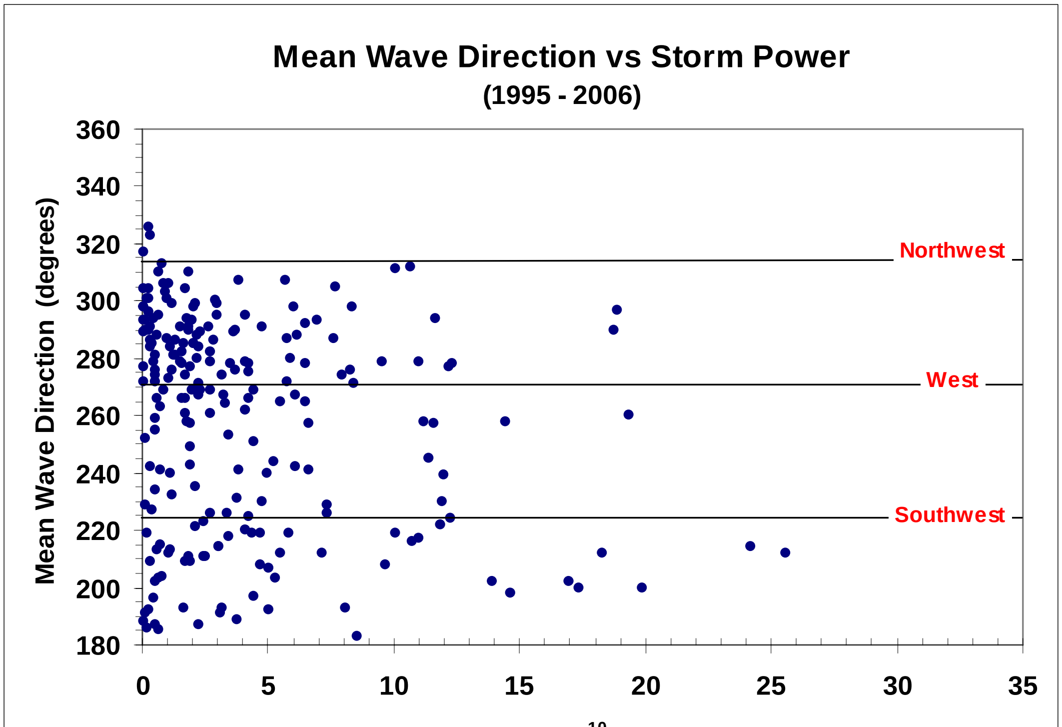


Figure 6.

Figure 7 displays storm duration as a function of maximum wave height. There is a significant amount of scatter in the data. Two storms stand out, however, exhibiting extremely high wave heights but with relatively short duration. These storms seem to be from another storm population different than the rest of the data points. Those two storms occurred 3 March 1999 and 4 February 2006 with maximum wave heights of 12.8 m and 13.4 m, respectively. Due to their short storm durations, neither storm falls within the top 20 most powerful storms.

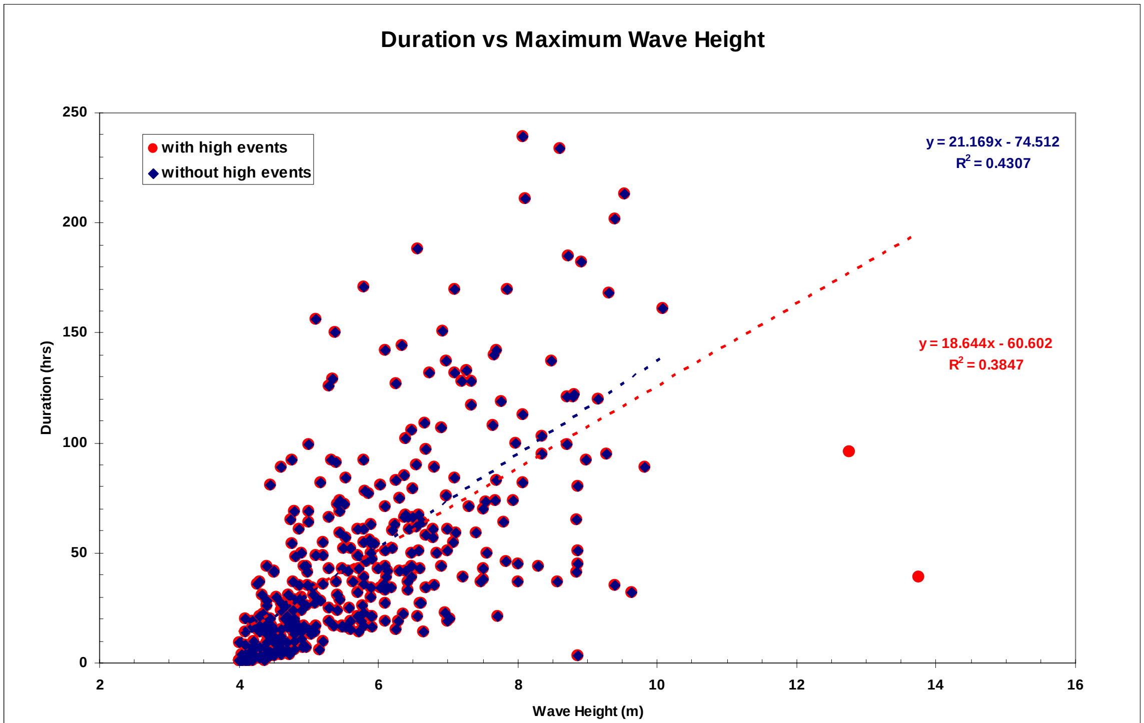


Figure 7.

Tables 2 and 3 summarize the top 20 storm events given both storm power methods. Table 2 lists top 20 storm events using the Dolan/Davis classification method. Table 3 lists the top 20 storm events using the wave energy flux storm power method. Blue shaded lines in both tables indicate storms that occurred in both top 20 lists, however the rank is not necessarily the same. Approximately 60% of the top 20 events occur on both tables.

Both methods resulted in the 24 November 1998 storm being the most powerful storm. That storm is illustrated in figure 8. The primary control for the power of the November '98 storm was its duration of 213 hours. Maximum wave height was 9.53 m. The storm year, 1998/99 had multiple high power storm events. An illustration of the importance of duration is seen in figure 9 which compares the 4th, 5th, and 26th-ranked storms which all occurred in 1999. While the 3 March event had a much larger wave height, its duration placed it at number 26 in the ranking. The horizontal axis is divided up into 72 hour increments. The maximum wave height of individual storm events must be at least 72 hours apart. Segments of wave record which clearly show building wave heights to the maximum wave height are considered part of the total storm record.

Table 2. Dolan / Davis Storm Power Top 20 Storms

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

indicates storm was included in both top 20 storm lists.

Table 3. Wave Energy Flux Top 20 Storms

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

indicates storm was included in both top 20 storm lists.

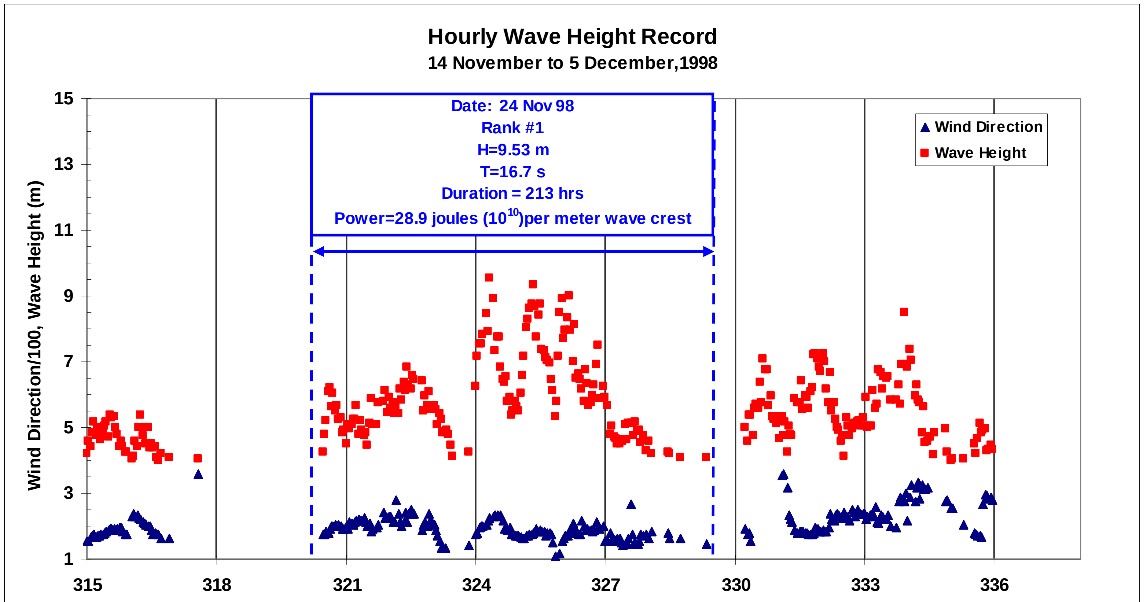


Figure 8.

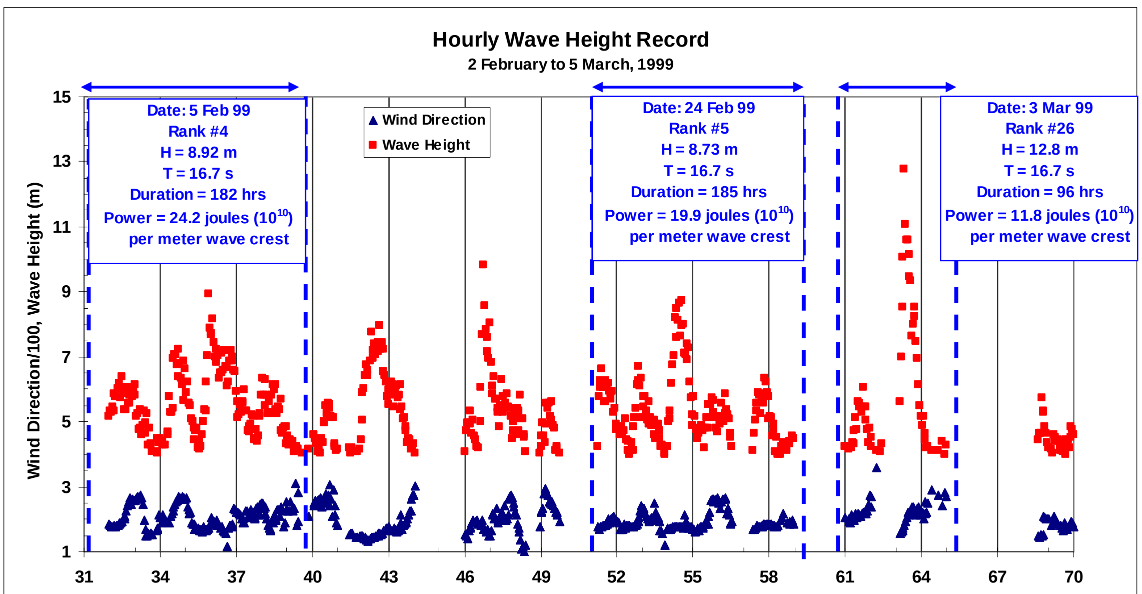


Figure 9.

Table 4 provides a ranking of the storms by maximum wave height alone. The events highlighted by rose shaded background indicate events that also occur on the top 20 energy flux storm power table. Note that neither of the top 2 events with maximum wave heights greater than 12 m made the top 20 wave energy flux storm power table. Those two storm events are categorized as **"Strong"**. Storm ranking is also different between tables.

Table 4. Maximum Wave Height Top 20 Storms

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

indicates storm was included in top 20 energy flux storm list.

Cumulative storm power was calculated for each storm year analyzed. Figure 10 illustrates those results. Cumulative power is given as total power per 100 meters of shoreline. The yellow dotted line at the bottom of the graph indicates the typical daily power output of Bonneville Dam as a reference of relative power of the storm events. Most of the years after 98/99 stand out as high cumulative power years. Figure 11 shows the number of each category storm documented for each storm year evaluated. This figure also shows a higher number of moderate to very strong events occurring after 1998.

There has been much speculation regarding the relative impact of El Nino and La Nina cycles on storm climate. Figure 12 provides one display of El Nino and La Nina cycles which charts sea temperatures as documented by Scripps Institution of Oceanography. Red anomalies in the cycle correlate to El Nino years and blue anomalies in the cycle correlate to La Nina years. Figure 13 illustrates the total power per storm year over the analysis period with respect to El Nino and La Nina years. Red outlines and blue outlines indicate El Nino and La Nina years, respectively. The extreme storm power year 1998/1999 occurred during a La Nina cycle.

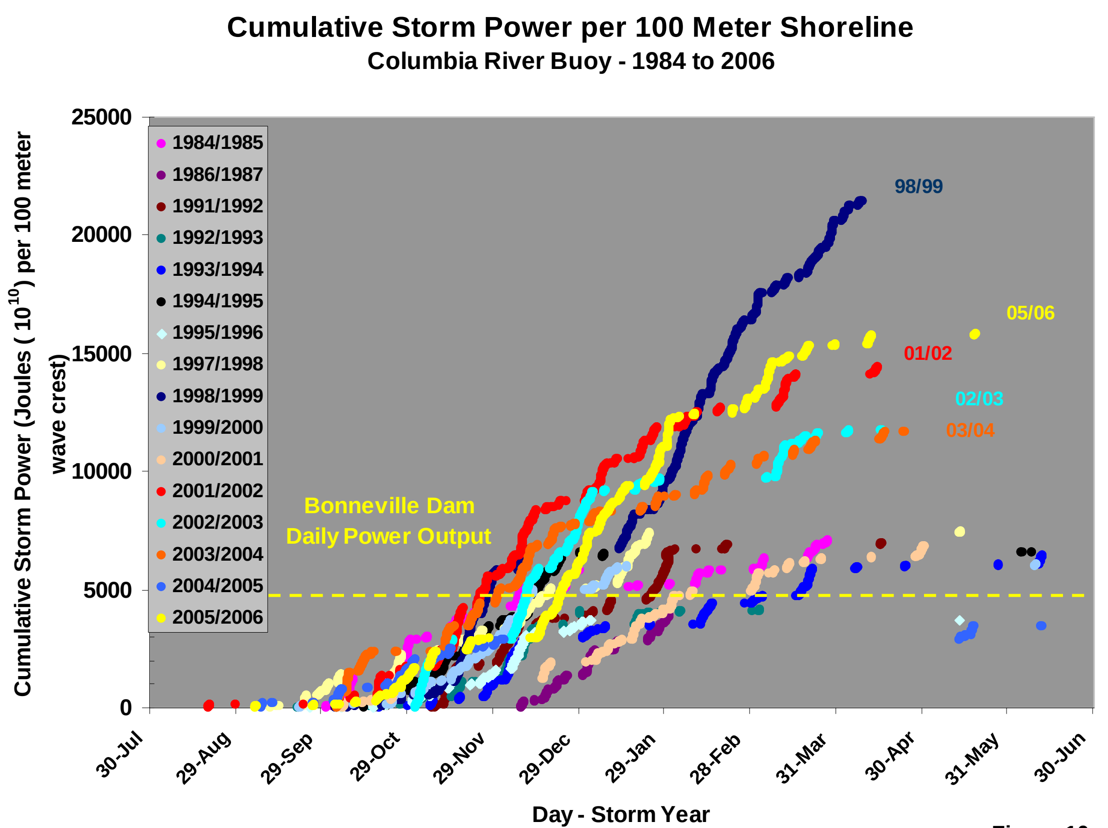


Figure 10.

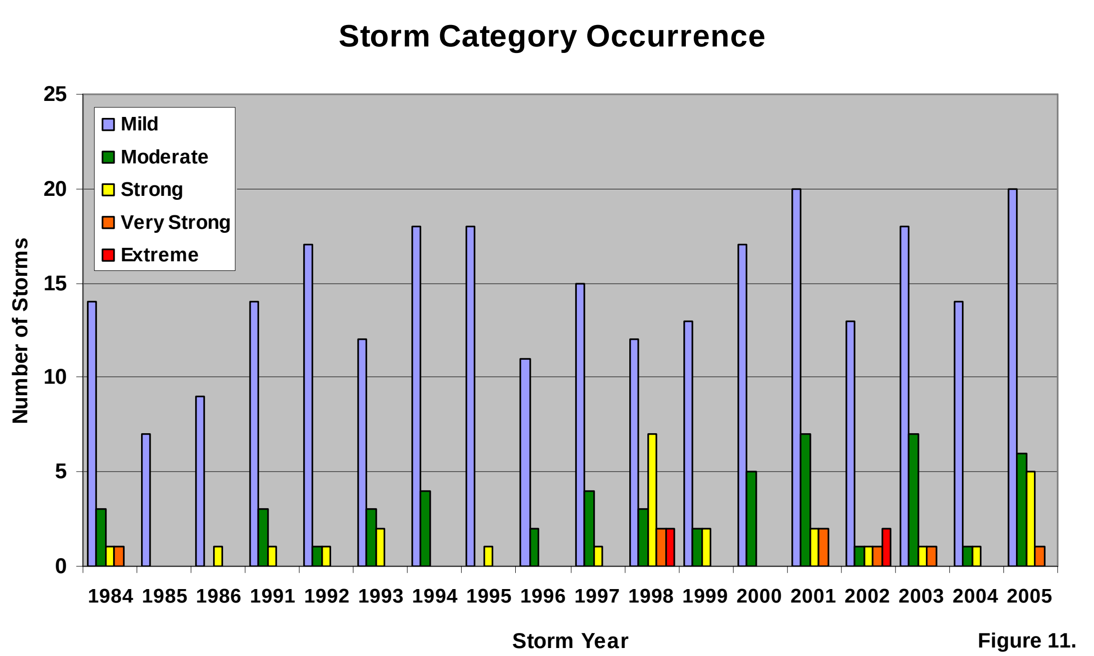
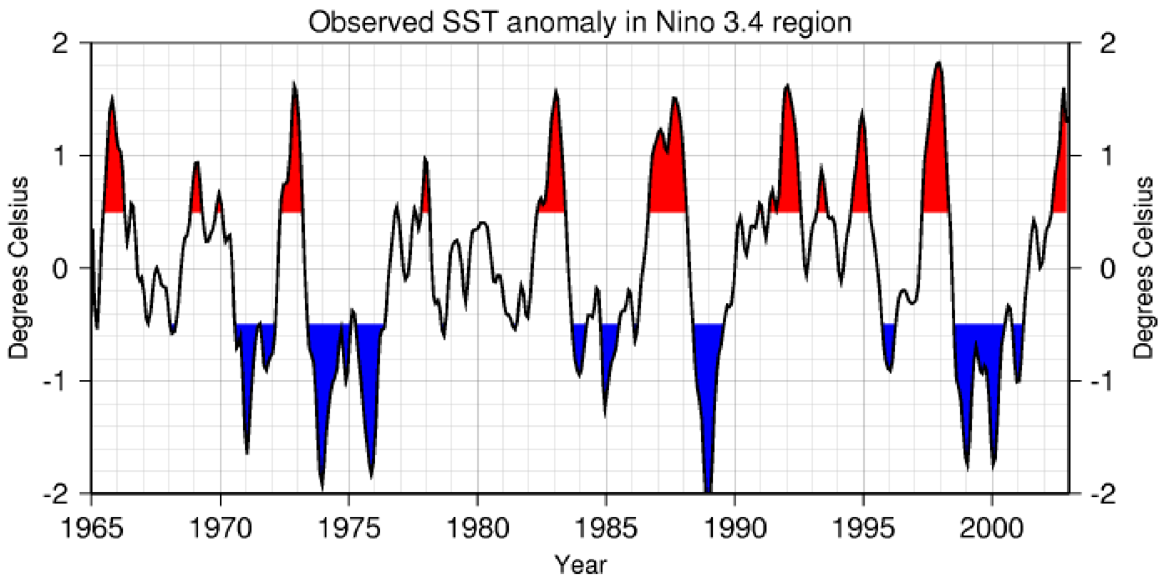
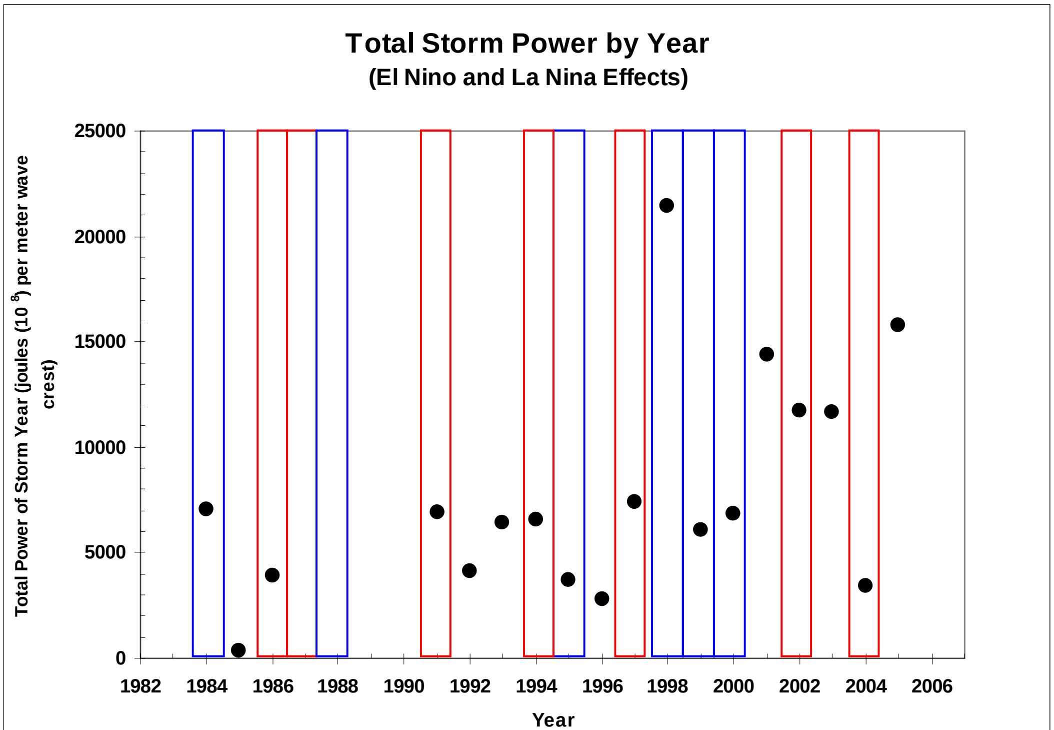


Figure 11.

Figure 12. Illustration of El Nino vs La Nina Cycles



(source: Scripps Institute of Oceanography)



(ref: NOAA, Scripps)

Figure 13.

5.0 STORM POWER RELATIONSHIP TO COASTAL INFRASTRUCTURE DAMAGE

Individual storm power and cumulative storm power per year have been calculated. Establishing a cause and effect relationship with observed coastal structure and shoreline damages is not always straight-forward. Close annual monitoring utilizing photographs of potential problem areas is key to capturing progression of damage and correlation to storms. Budgetary restrictions often limit such close monitoring. In addition, damages to structures, particularly rubblemound structures, and erosion of shorelines can sometimes respond to a series of storms or a series of stormy years prior to visible failure. The preliminary stages can include erosion of foundation or beach/foredune.

Figures 14 through 20 provide some visual responses particularly to the storm years of 1998 through 2006. The location of projects referred to in these photographs (Mouth of the Columbia River, Coos Bay, and Tillamook) are identified on figure 1. Figures 14 through 16 illustrate conditions at the south jetty at the Mouth of the Columbia River. Figure 14 illustrates **"Mild"** storm conditions along the south jetty and identifies an area along the shoreward half of the jetty that has been experiencing increasing damage rates over the past 5 to 8 years. Figure 15 shows a significant notch in the seaward half of the south jetty that has increased in size over the 2005/06 winter storm season. Figure 16 illustrates increased foredune erosion at the root of the south jetty over the same time period.

Figures 17 and 18 illustrate erosional impacts to the shoreline immediately north of the north jetty at Coos Bay, specifically over the time period of 1998 through 2002. Figure 17 shows the shoreline condition for the years 1996, 1999, 2002, and 2006. The width of beach at the jetty root was significantly reduced after the 1998/99 storm season. It appears that subsequent years, 2001/2002 storm season in particular, may have further weakened the area. In November 2002, the root of the North Jetty breached as illustrated in figure 18. Erosion is also illustrated in the log spiral embayment in back of the spit area, also due to storm/wave driven forces.

Figures 19 and 20 illustrate losses to jetty length at the Tillamook Bay project. Both jetties, but particularly the South Jetty, have lost length during the time period of late 1990's to the present. Accelerated erosion also occurred during the same timeframe along the shoreline at the tie-in with the north jetty, necessitating the construction of a protective revetment to stabilize the foredune.

6.0 CONCLUSIONS

The primary intent of this analysis was to develop a more useful and definitive method for describing total power of storms and storm years which incorporates wave period and duration. This method was applied to the NDBC buoy data closest to the Mouth of the Columbia River, NDBC buoy #46029, using a lower storm threshold of 4 m wave height. General categories of storms were identified from mild to extreme. Storm power calculations were compared, in general, to a similar classification using the Dolan/Davis method of storm power calculation. The most powerful storms and the most powerful storm years were identified as well as the parameters which seemed to contribute most to those classifications. The stormiest months were found to be November through March, with November and December having the most powerful storm events. Storm power was closely correlated to both maximum wave height as well as duration. The most powerful storms had dominant wave periods of 16.7 seconds. Fifty-seven percent of the strongest storm events came out of the south to southwest direction band, while a greater number of storm events came out of the west to northwest direction band.

In a comparison of the Dolan/Davis storm power method and the wave energy flux storm power method, 60% of the maximum storm power events occurred in the top 20 storms of both methods. The events with the highest wave height did not come in as the most powerful storms as their duration was significantly less then other storms. La Nina cycles coincide with strong storm event years. The period of record since 1998/1999 stands out as a more powerful time period. It is not known whether this is an indication of an upward trend or just a characteristic of the cycle.

Further investigations into series of storm events and series of stormy years with respect to coastal damages and erosion may lead to a better cause and effect understanding of the larger processes involved. With this information, advanced planning for damaging sequences of events can be applied. An evaluation of other buoys along the Oregon and Washington coasts can also supply more information to the overall storm power and coastal response scenario.

7.0 REFERENCES

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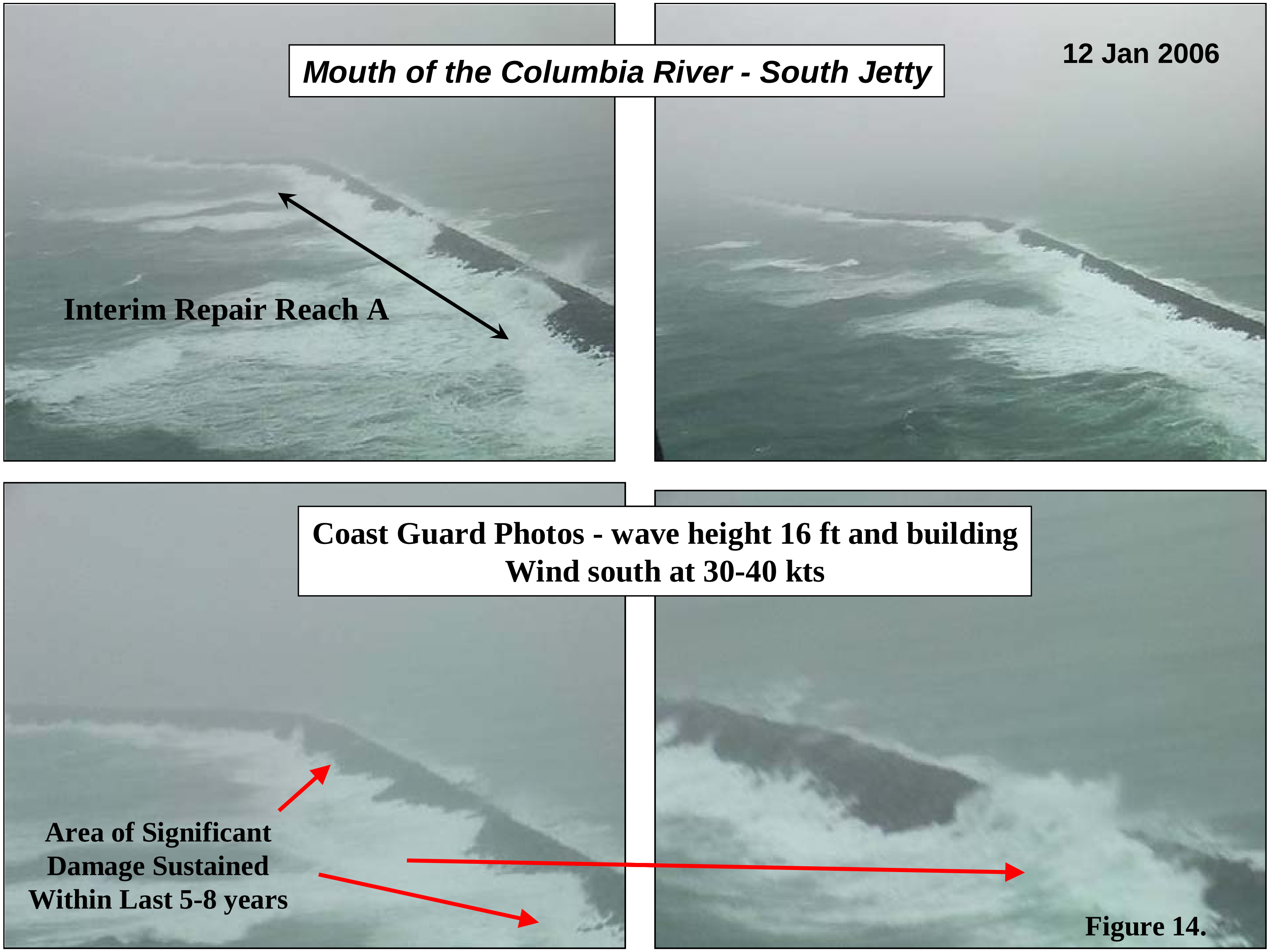
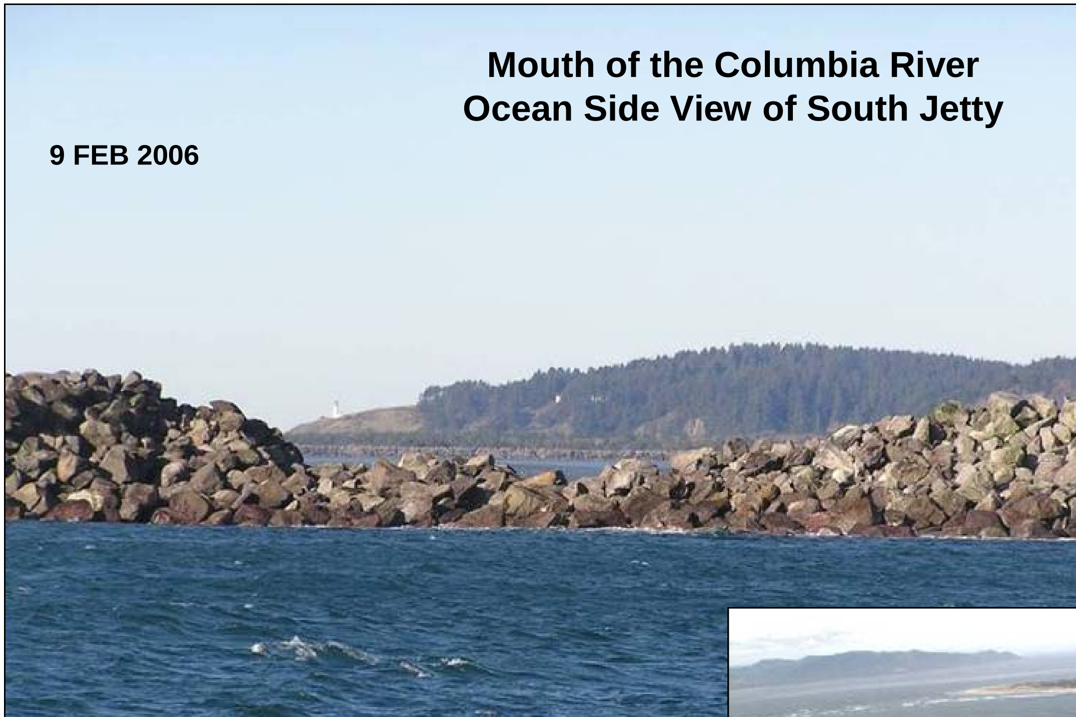

Mouth of the Columbia River - South Jetty
12 Jan 2006
Interim Repair Reach A
Coast Guard Photos - wave height 16 ft and building
Wind south at 30-40 kts
Area of Significant
Damage Sustained
Within Last 5-8 years

Figure 14.

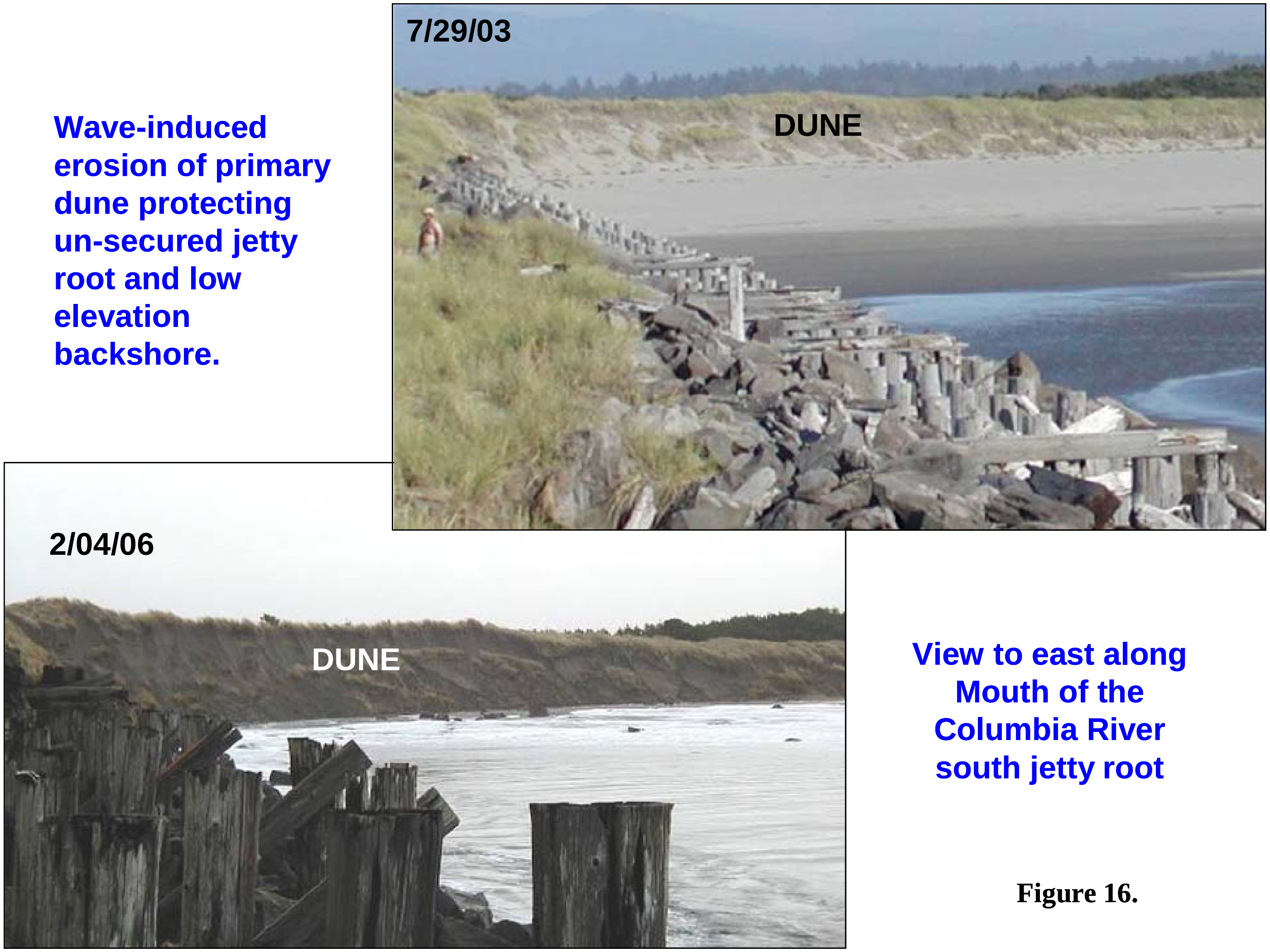


Tide elevation in picture = +3 ft MLLW.
High tide elevation = +8 ft MLLW

"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.

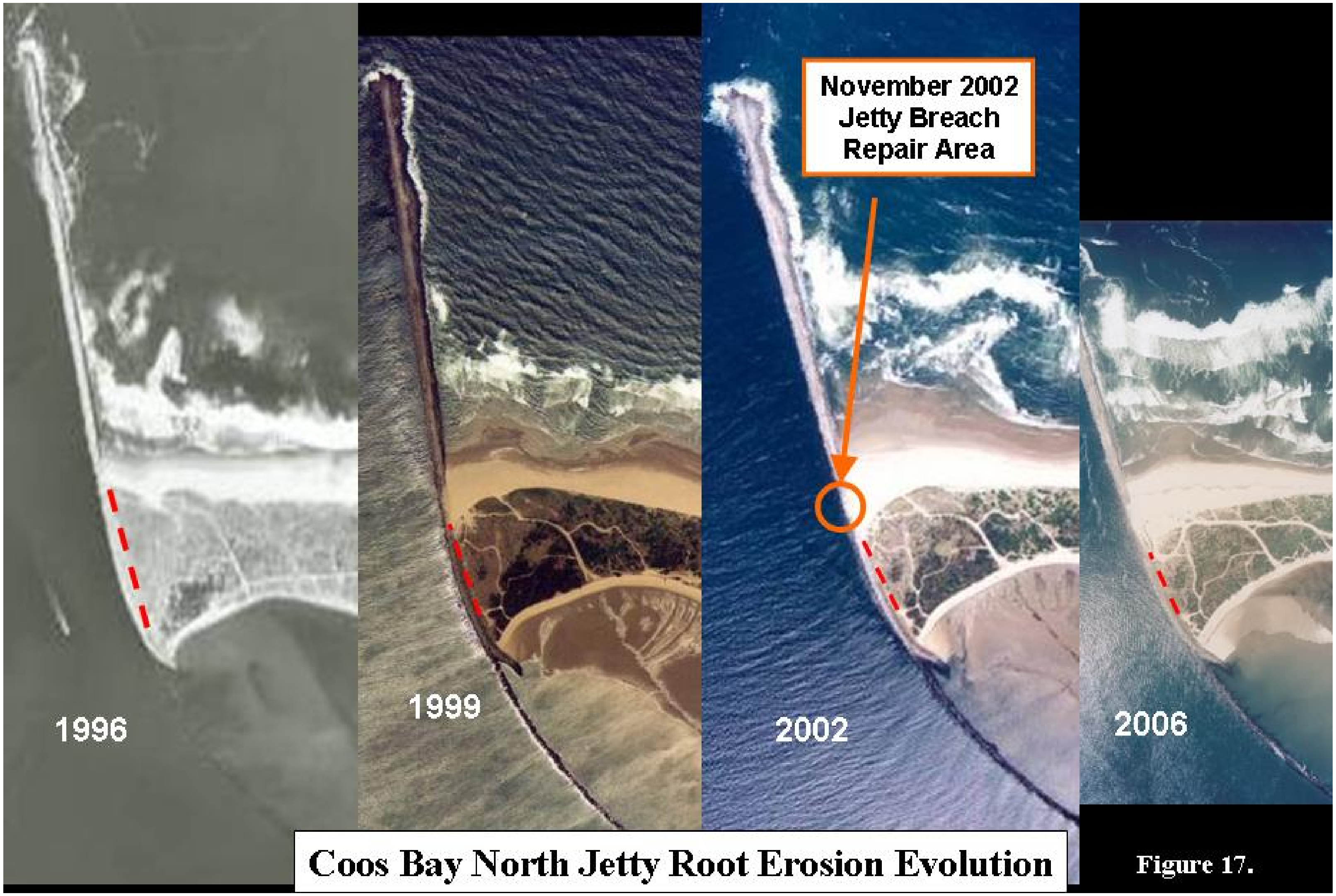
Figure 15.

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

Figure 16.



Coos Bay North Jetty Root Erosion Evolution

Figure 17.

Coos Bay North Jetty

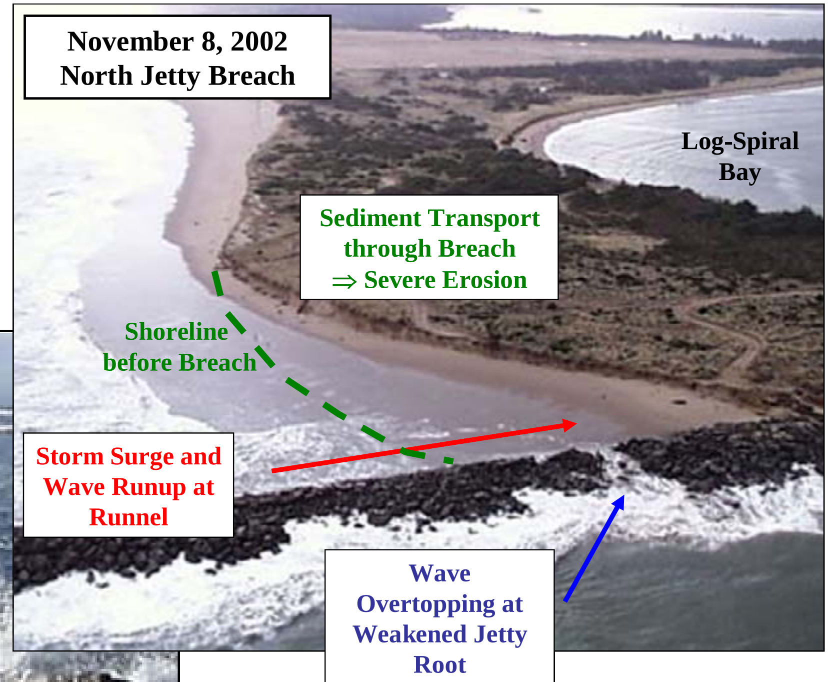


Figure 18.

Tillamook
Jetty Length Impacts

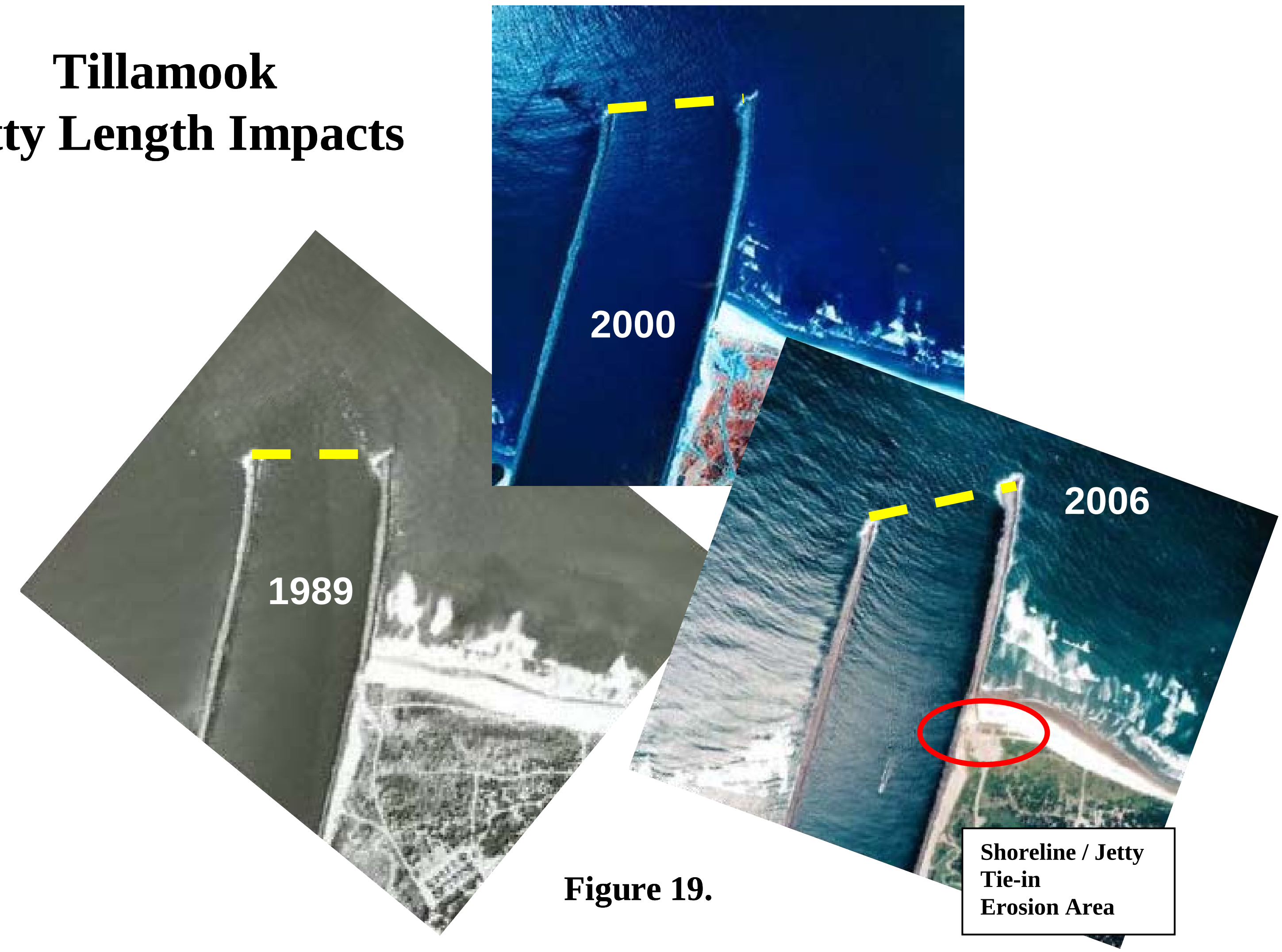
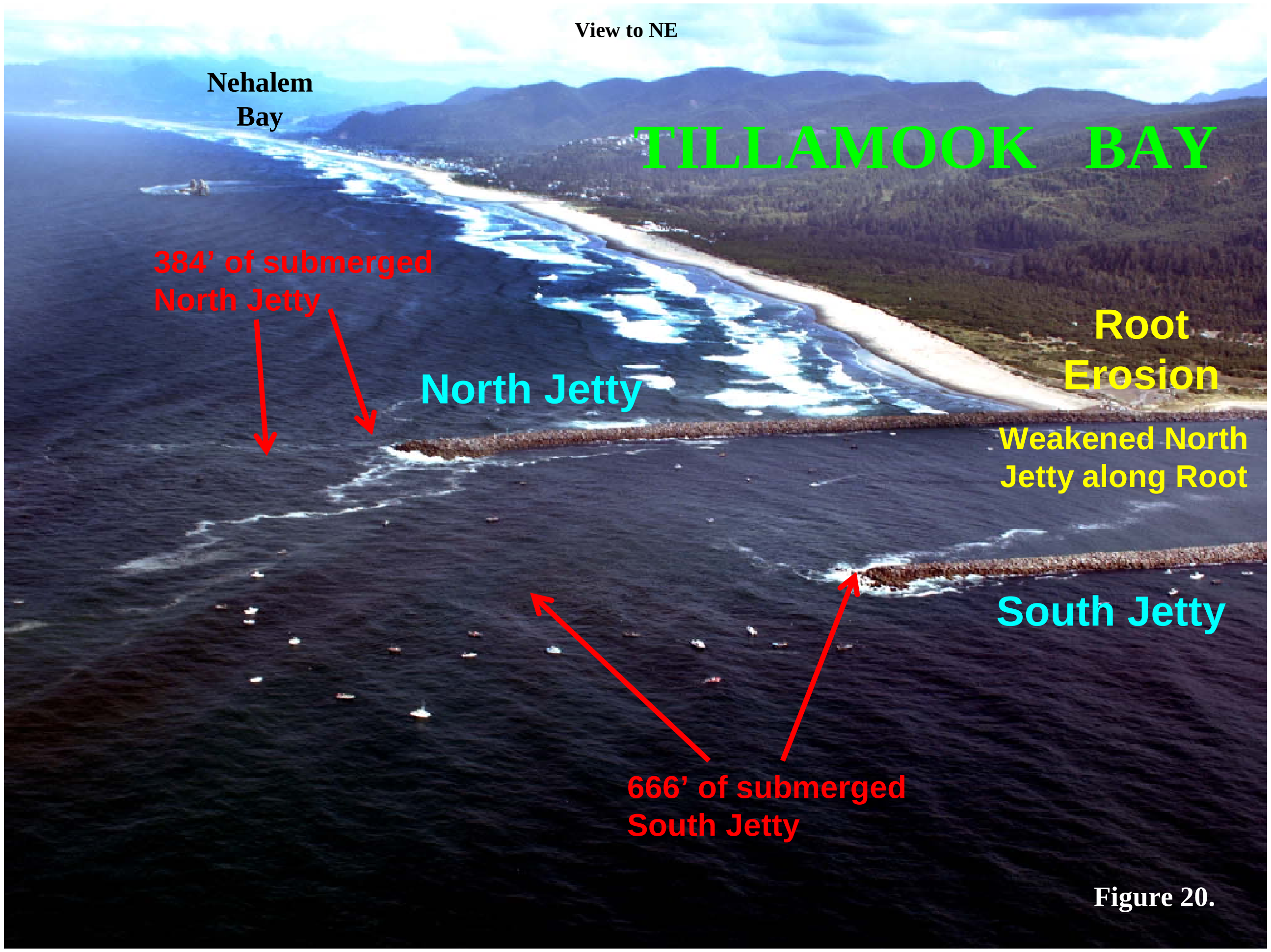


Figure 19.


View to NE
Nehalem
Bay
TILLAMOOK BAY
384' of submerged
North Jetty
North Jetty
Root
Erosion
Weakened North
Jetty along Root
South Jetty
666' of submerged
South Jetty
Figure 20.