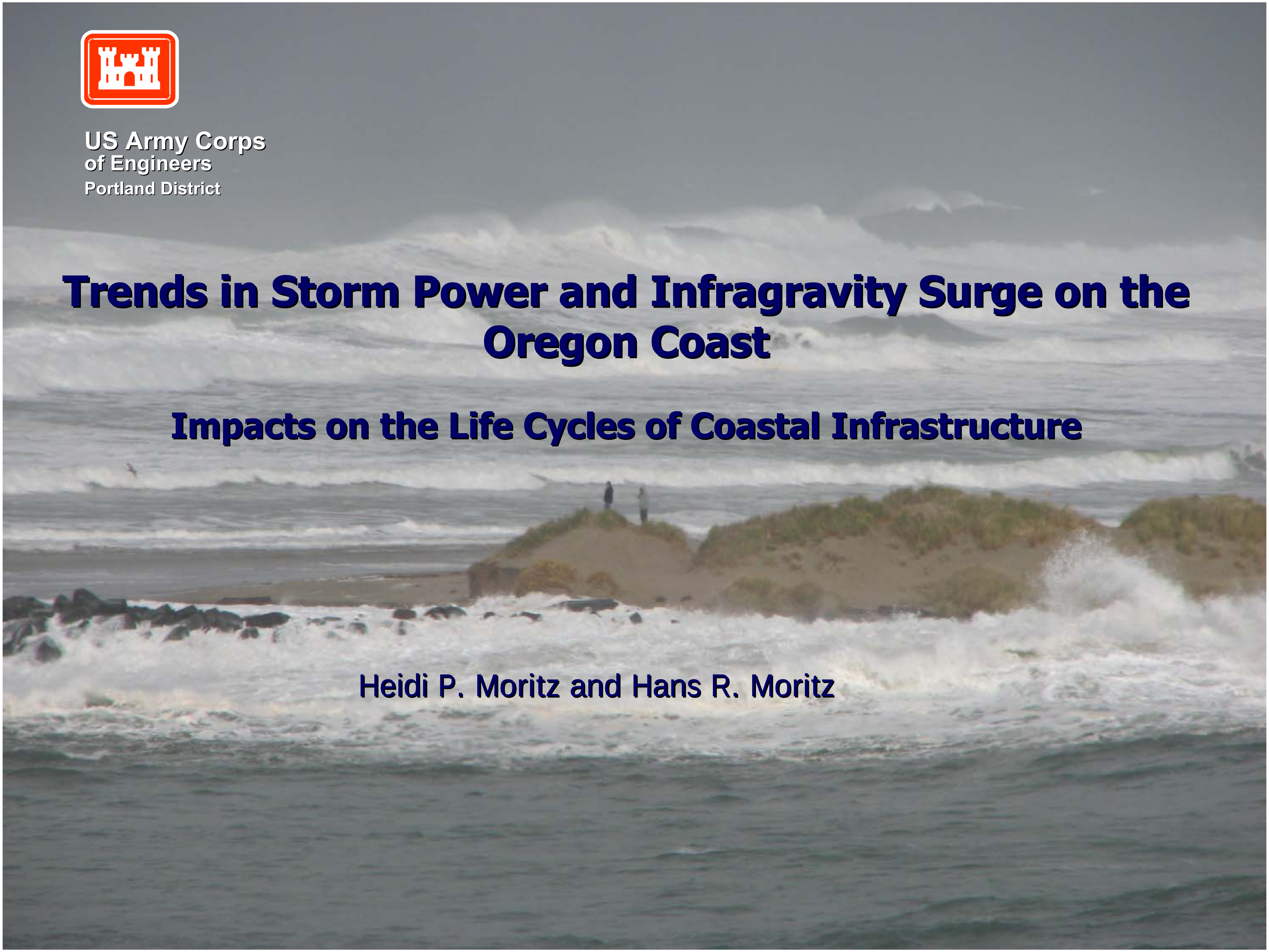

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Trends in Storm Power and Infragravity Surge on the Oregon Coast

Impacts on the Life Cycles of Coastal Infrastructure

Heidi P. Moritz and Hans R. Moritz

Presentation

- Key Points
- Why are we looking at storm power?
- Summary Results
- Some Examples
- Other Studies

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Key Points

- Two new forcing parameters have the potential to advance our ability to understand and manage our projects; storm power and infragravity surge.
- Tracking climate trends and their impacts to our project management is an important USACE-wide goal.
- Preliminary analyses appear to indicate that storm power along the Oregon Coast is experiencing an increasing trend.
- Potential exists to improve design and reliability relationships.
- Increasing our understanding of damage initiation and progression will result in improving our ability to anticipate adverse consequences before they happen.

Why Did We Start Looking at Storm Power?

- We observed that damages to structures and shorelines could not be tied strictly to wave height.
- Events with large wave periods seemed to have additional damaging abilities.
- Series of high energy events or years exhibited impacts on project failure.
- We started having the “100-year wave height” every other year. ????
- Can multiple medium size storms be as / or more damaging than one large storm?

- **Is there a better way to compare individual storms and storm years?**

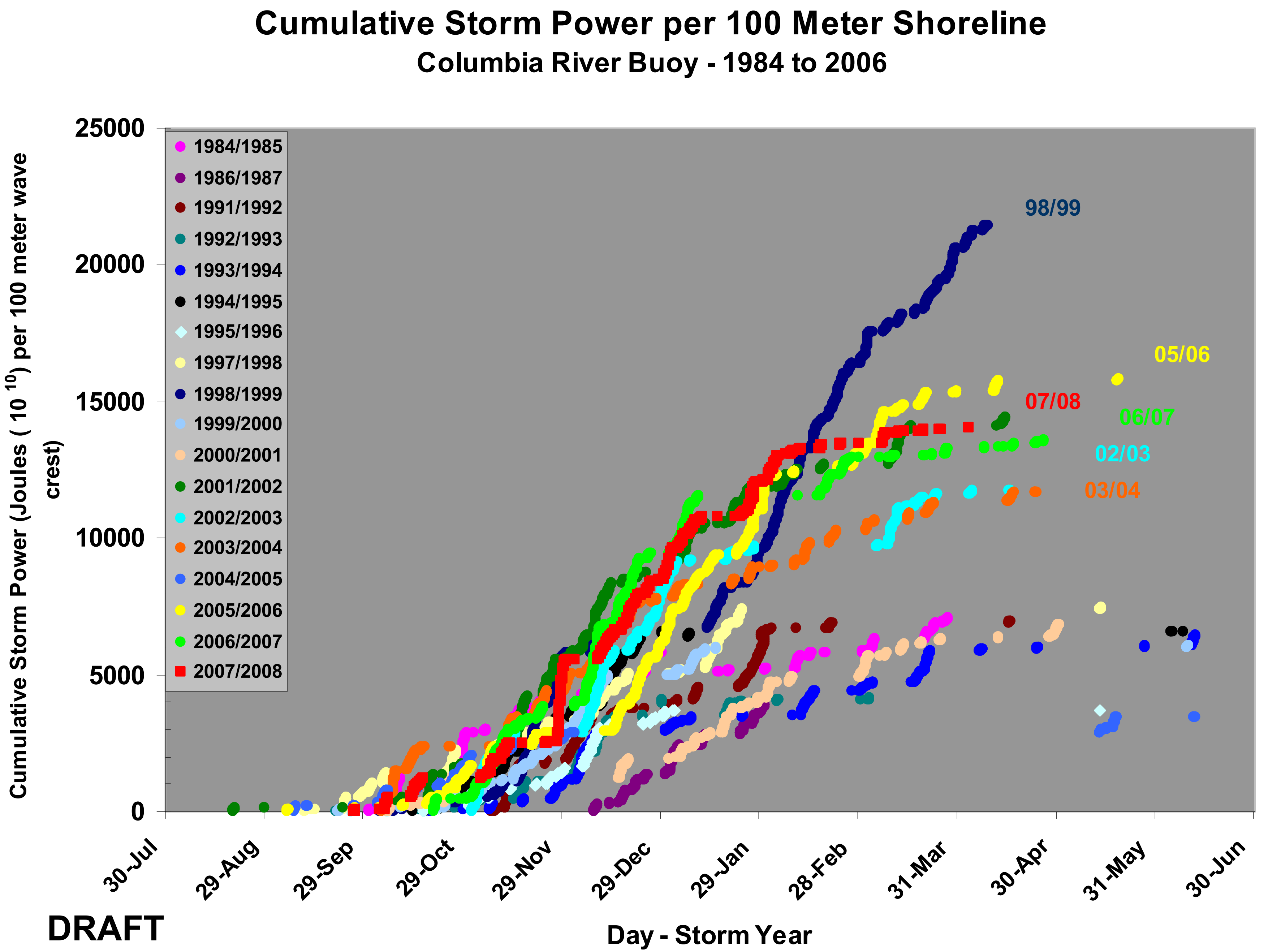
Wave Energy Flux Equations

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

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

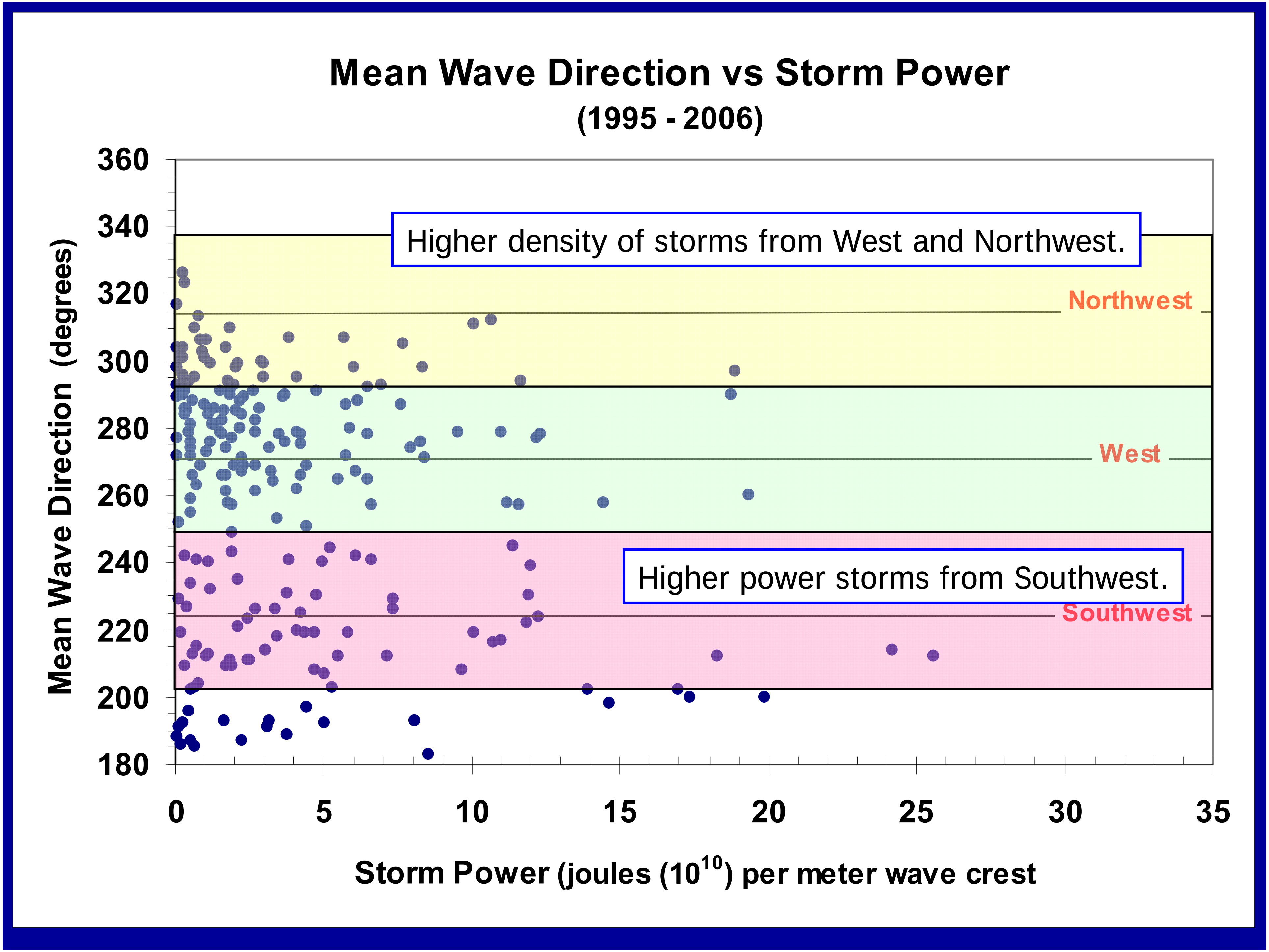
Wave power summed over the storm duration provides the storm power.

This calculation incorporates wave height, wave period, and storm duration.



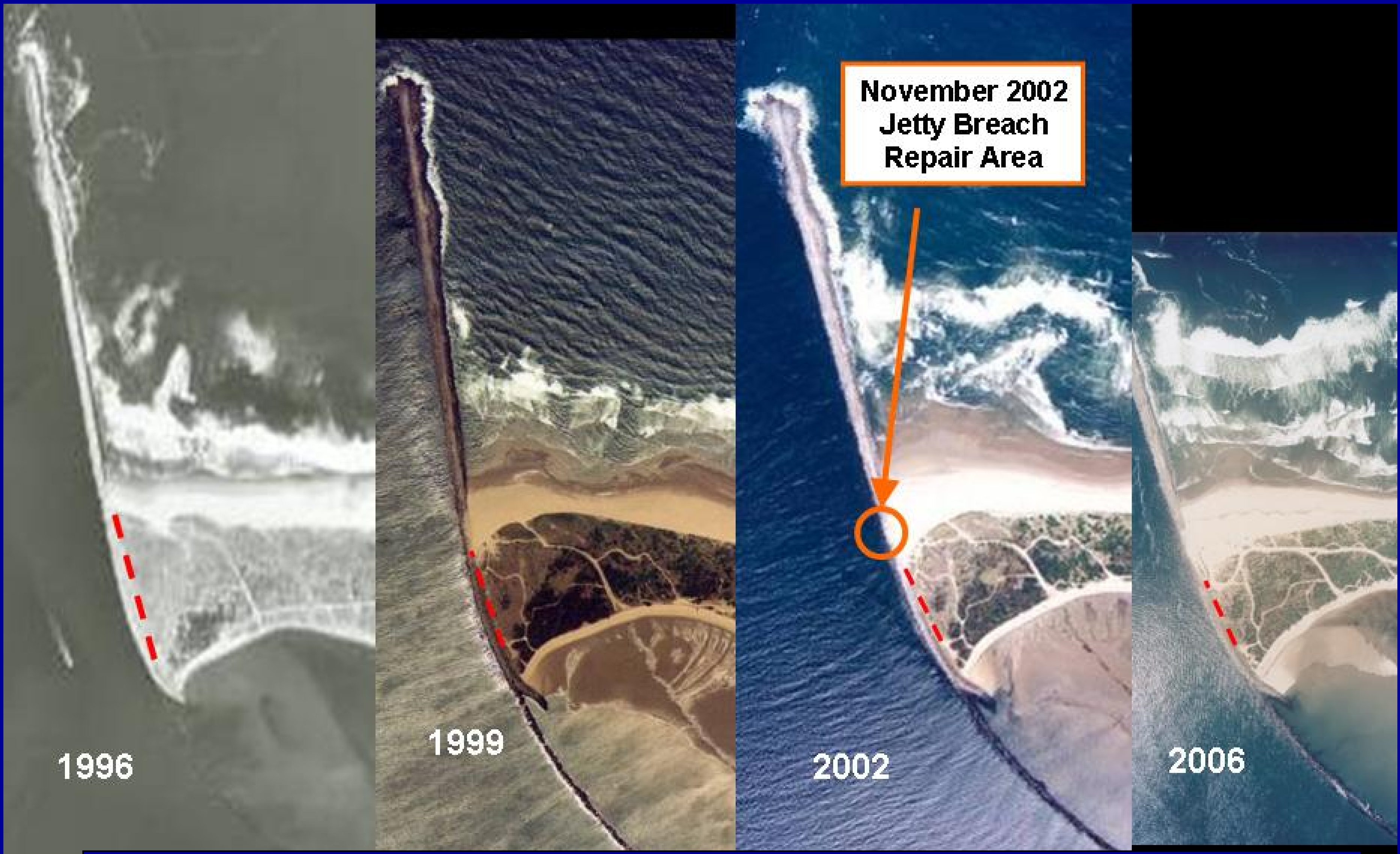
Cumulative Storm Power per 100 Meter Shoreline
Columbia River Buoy - 1984 to 2006
Cumulative Storm Power (Joules (10 10) per 100 meter wave crest)
25000
20000
15000
10000
5000
0
1984/1985
1986/1987
1991/1992
1992/1993
1993/1994
1994/1995
1995/1996
1997/1998
1998/1999
1999/2000
2000/2001
2001/2002
2002/2003
2003/2004
2004/2005
2005/2006
2006/2007
2007/2008
98/99
05/06
07/08
06/07
02/03
03/04
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

DRAFT

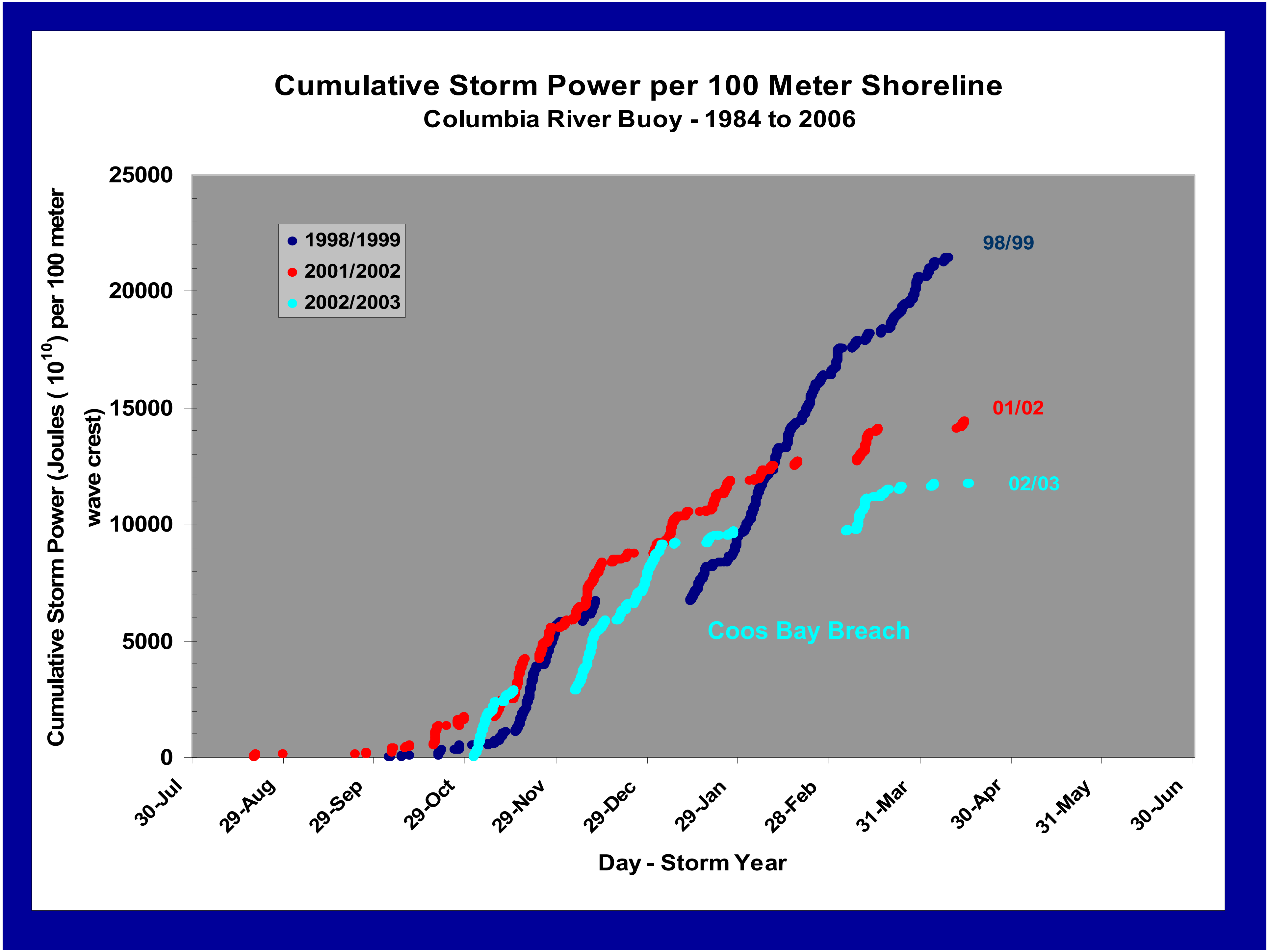


Mean Wave Direction vs Storm Power
(1995 - 2006)
Higher density of storms from West and Northwest.
Northwest
West
Higher power storms from Southwest.
Southwest
Mean Wave Direction (degrees)
360
340
320
300
280
260
240
220
200
180
0
5
10
15
20
25
30
35
Storm Power (joules (10^10) per meter wave crest

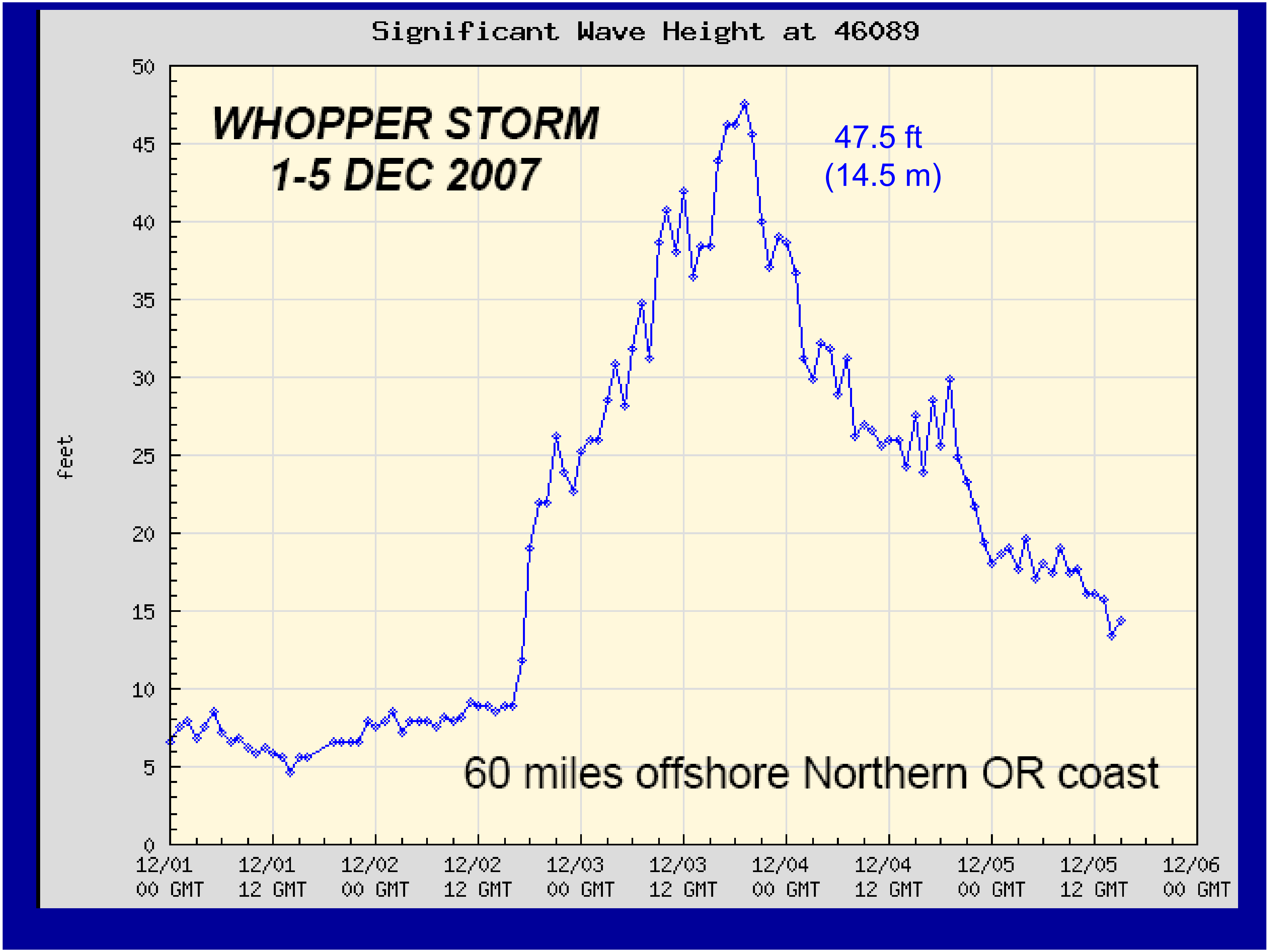
Infrastructure Appears to Respond to a Series of Events / Years



1998 storm season - Significant loss of beach and foredune
2001 – another strong storm year.
8 November 2002 – Very Strong (20 J(10^{10})) storm breaches jetty root.

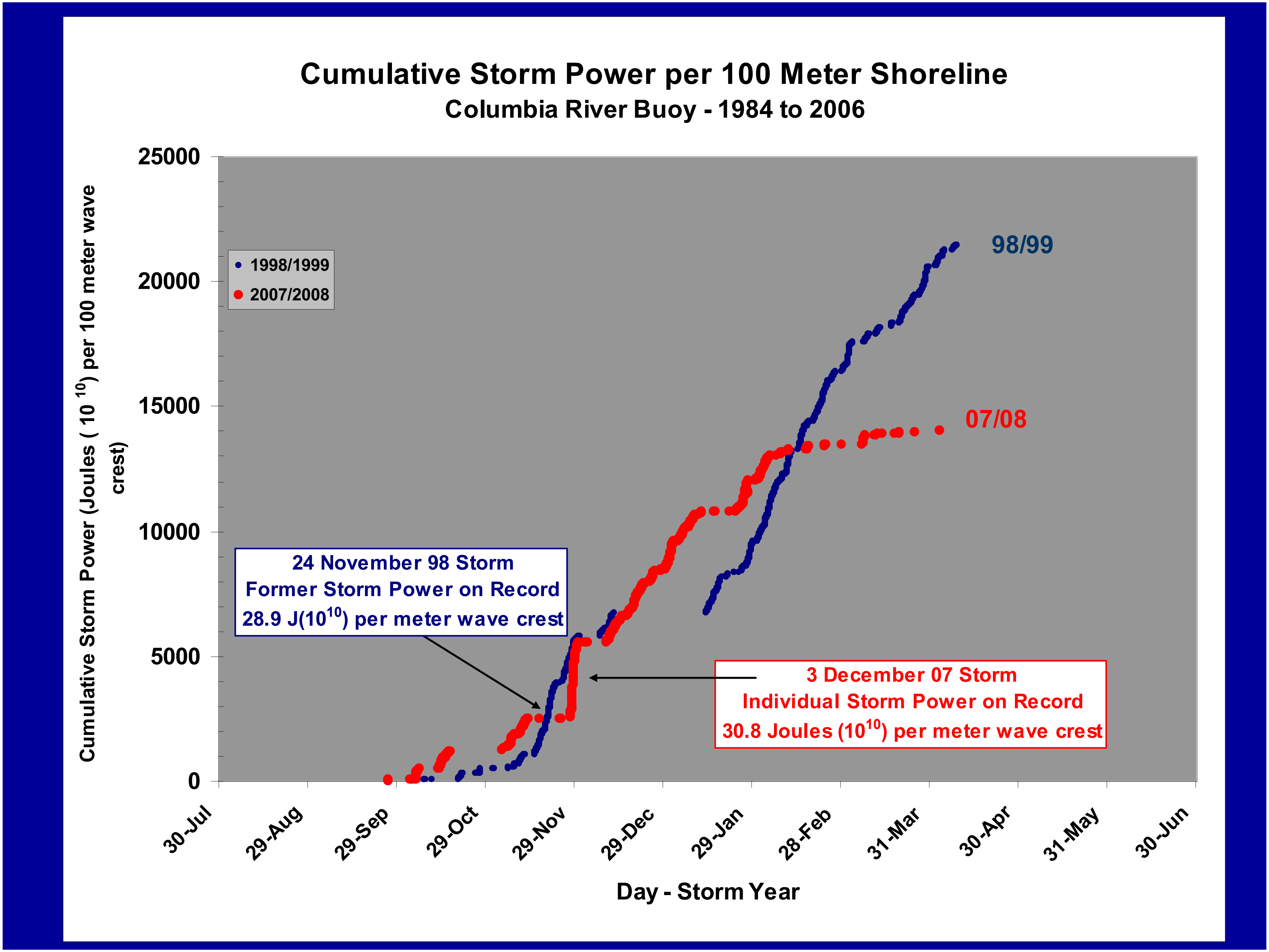


Cumulative Storm Power per 100 Meter Shoreline
Columbia River Buoy - 1984 to 2006
Cumulative Storm Power (Joules (10^{10}) per 100 meter wave crest)
25000
20000
15000
10000
5000
0
1998/1999
2001/2002
2002/2003
98/99
01/02
02/03
Coos Bay Breach
30-Jul
29-Aug
29-Sep
29-Oct
29-Nov
29-Dec
29-Jan
28-Feb
31-Mar
30-Apr
31-May
30-Jun
Day - Storm Year

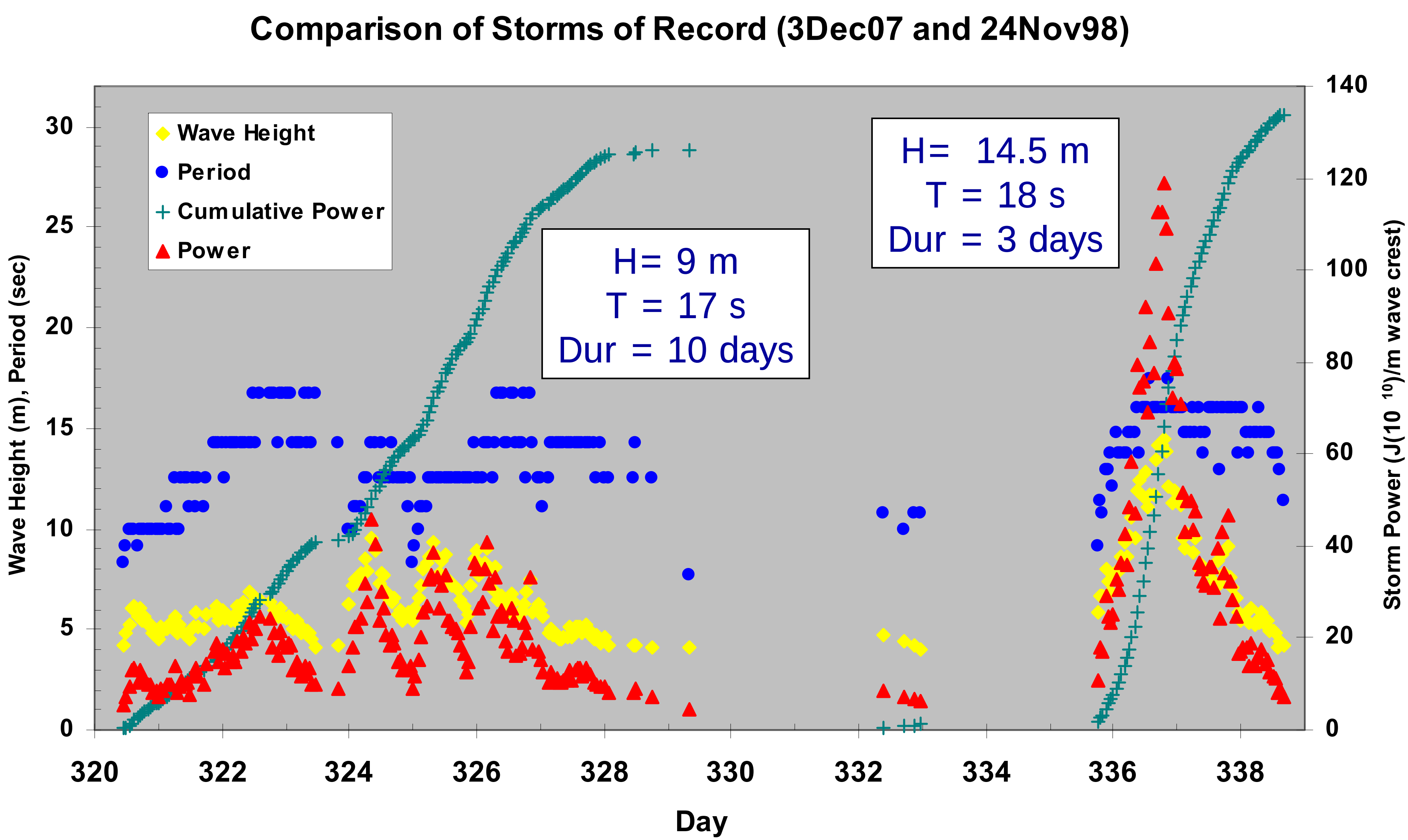

Significant Wave Height at 46089
WHOPPER STORM
1-5 DEC 2007
47.5 ft
(14.5 m)
60 miles offshore Northern OR coast
feet
50
45
40
35
30
25
20
15
10
5
0
12/01 00 GMT
12/01 12 GMT
12/02 00 GMT
12/02 12 GMT
12/03 00 GMT
12/03 12 GMT
12/04 00 GMT
12/04 12 GMT
12/05 00 GMT
12/05 12 GMT
12/06 00 GMT

Shoreline Impacts of 4 December 2007 Storm

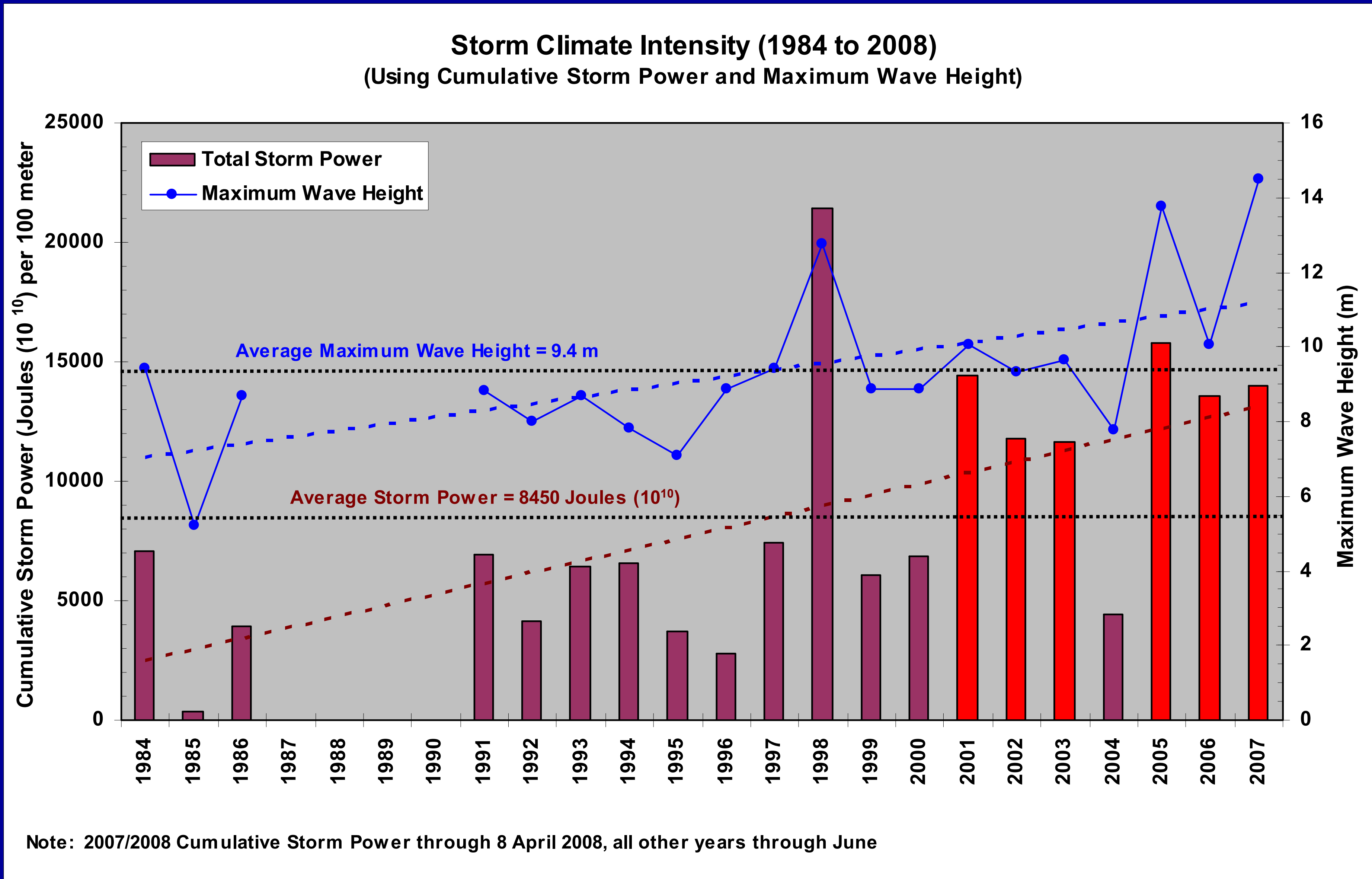
Erosion of shorelines
Exposure of historical artifacts
Jetty head loss.



Cumulative Storm Power per 100 Meter Shoreline
Columbia River Buoy - 1984 to 2006
Cumulative Storm Power (Joules (10 10) per 100 meter wave crest)
25000
20000
15000
10000
5000
0
1998/1999
2007/2008
98/99
07/08
24 November 98 Storm
Former Storm Power on Record
28.9 J(10[10]) per meter wave crest
3 December 07 Storm
Individual Storm Power on Record
30.8 Joules (10[10]) per meter wave crest
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



Contrast medium storm (or storms) of long duration to extreme storm of short duration.

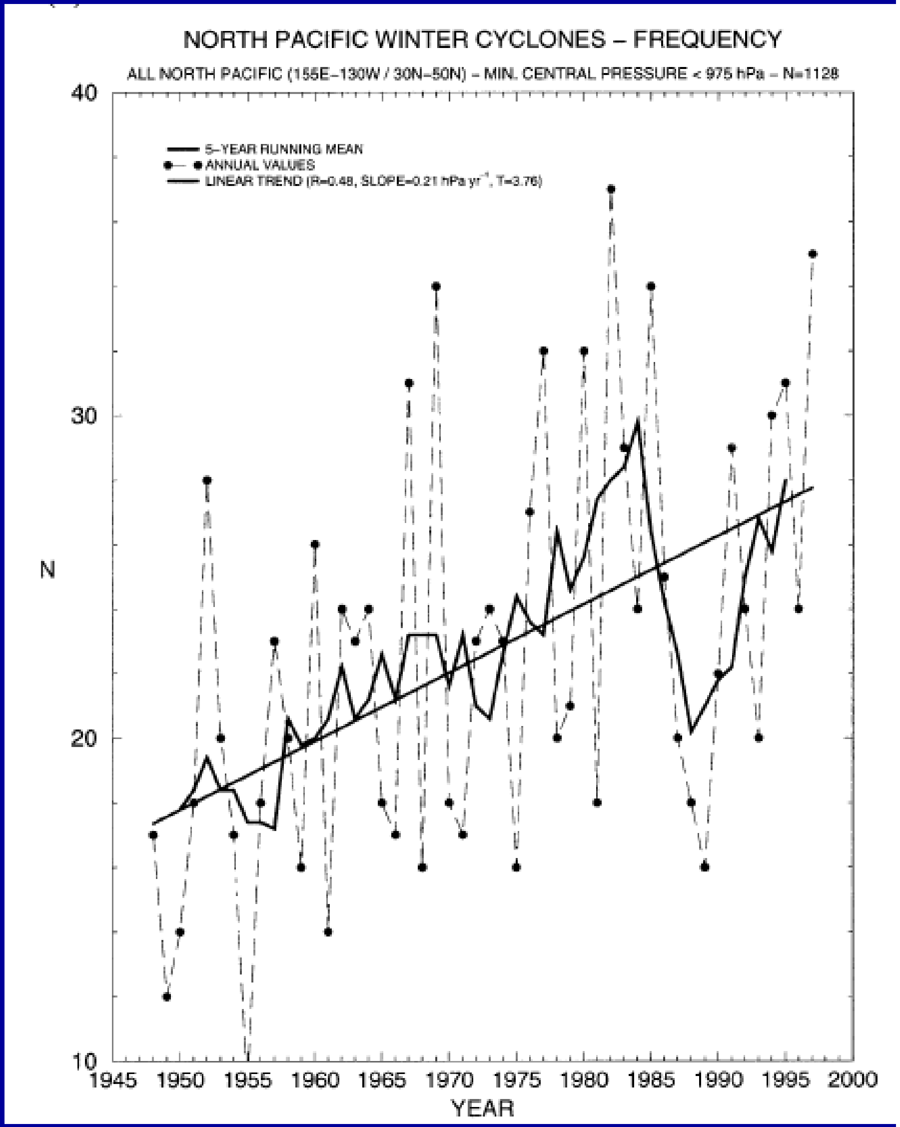


In above graph, storm years bridge two calendar years and are noted by the year of the fall season. (i.e. the fall 2007/winter 2008 storm year is labeled 2007 above.

USACE, Portland District, EC-HY

Evidence for Intensification of North Pacific Winter Cyclones since 1948

- Nicholas Graham and Henry Diaz (Scripps and NOAA)
- Reanalysis of NCEP-NCAR data set (1948 to 1998) (National Centers for Env. Prediction-National Center for Atmospheric Research)
- The results from the cyclone tracking study reveal major changes in winter storm climate over the North Pacific during the past five decades. Showing a clear upward trend in cyclone frequency and intensity.
- The statistical association between cyclone Activity and El Nino indices is modest.
- Hypothesis: Increasing upper-tropospheric zonal winds potentially caused by changes in tropical sea surface temperatures.



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Potential Applications

- Aid in developing and ground-truthing damage relationships for reliability analyses.
- Provide method to track and understand life-cycle damage history of structures and beachfill annual performance.
- Combine with annual aerial photography sets to project future damages.
- Relate to shoreline erosion trends, design relationships, and gradual structure damage.

US Army Corps
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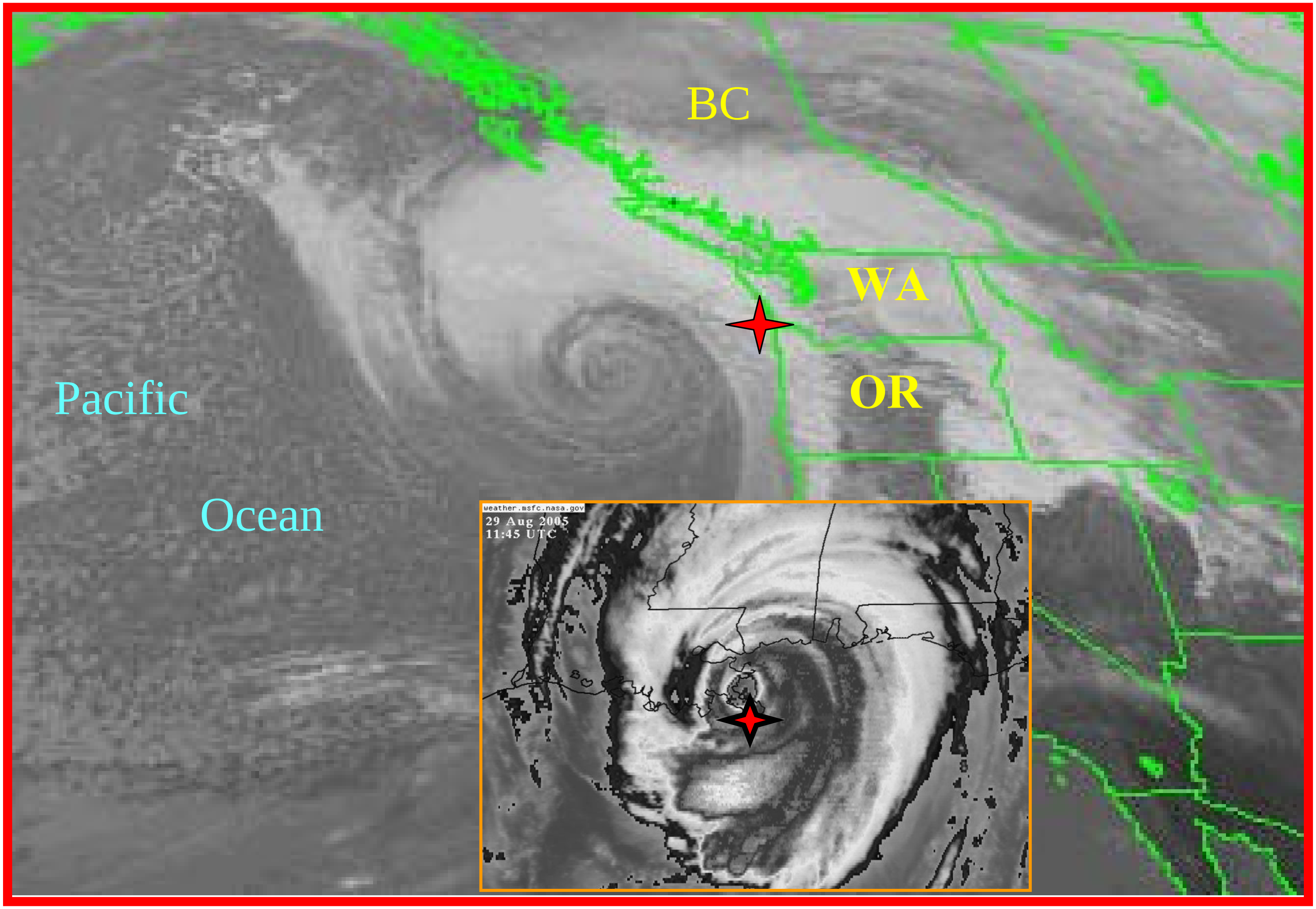
Portland District

Infragravity Surge

1) Compare GOM Hurricane to PAC NW Extra-Tropical Low

2) Observed Infragravity Transients – Produced by Wave-Groups

3) Consider Hypothesis: Storm Surge Enhanced by Infragravity Transients



3 MAR 1999 - Extr Trop Low

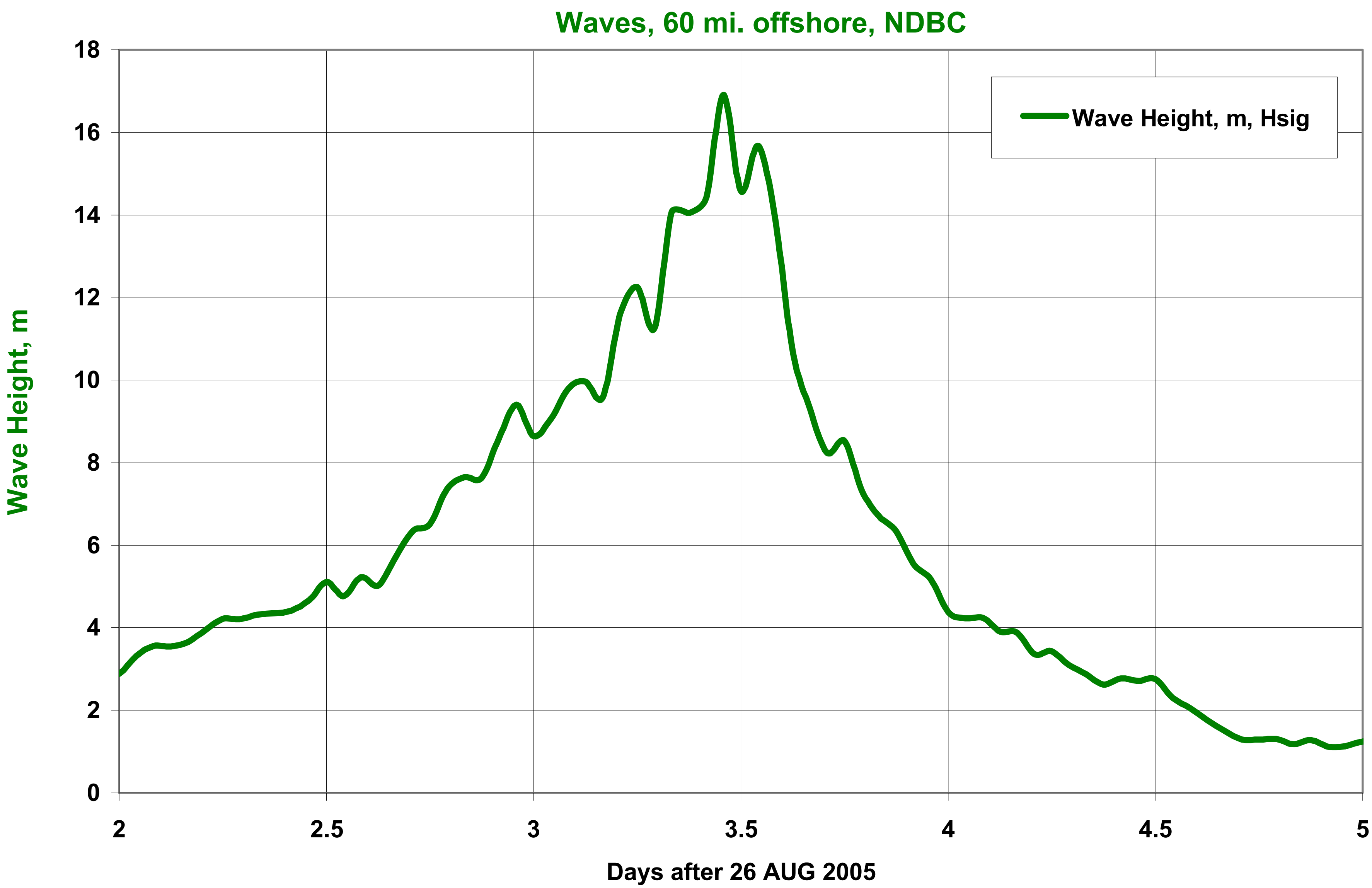
image courtesy of NOAA

29 AUG 2005 - Hurricane

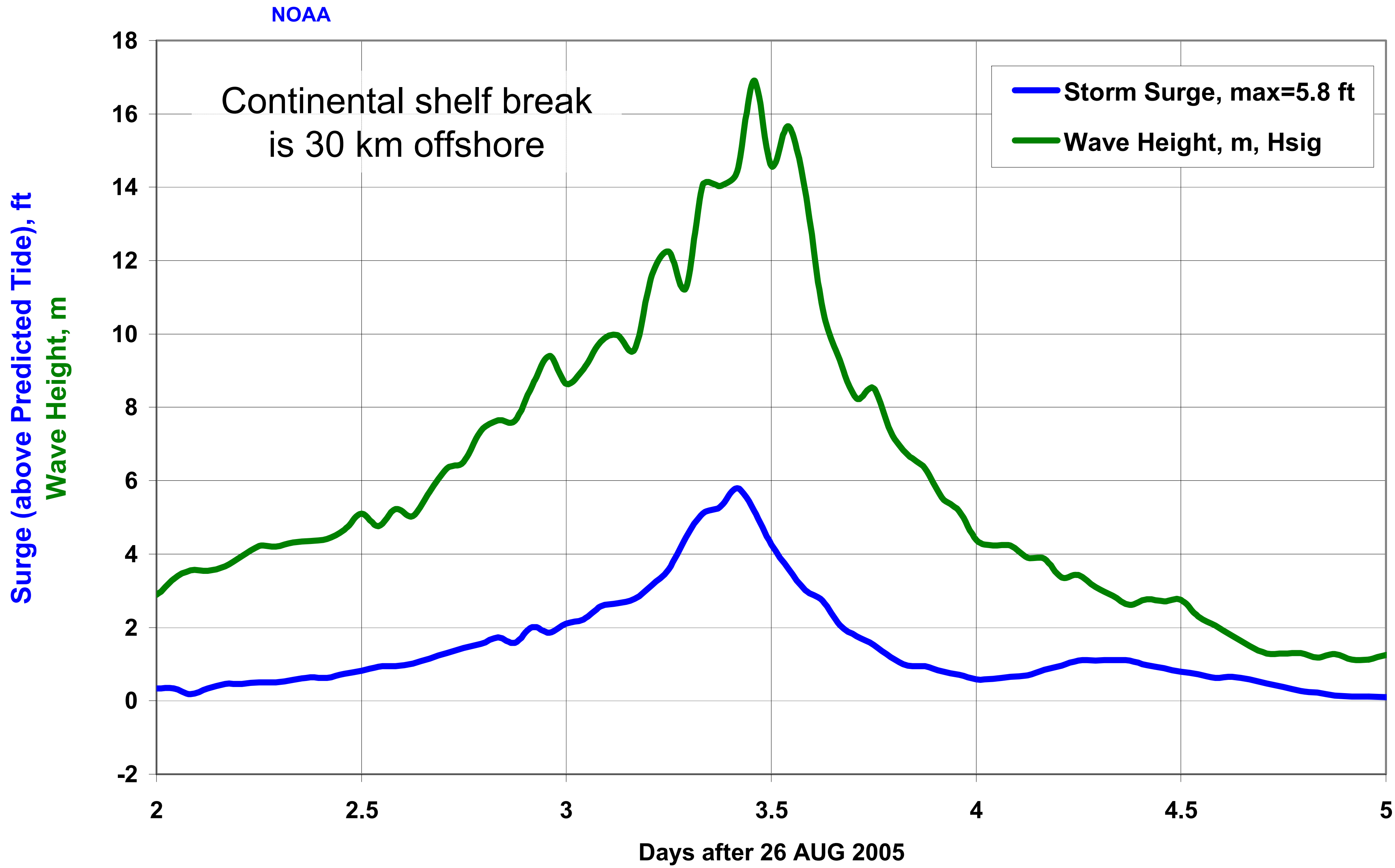
image courtesy of NOAA

Hurricane Katrina

Waves Offshore SW Pass, LA: 26-31 AUG 2005

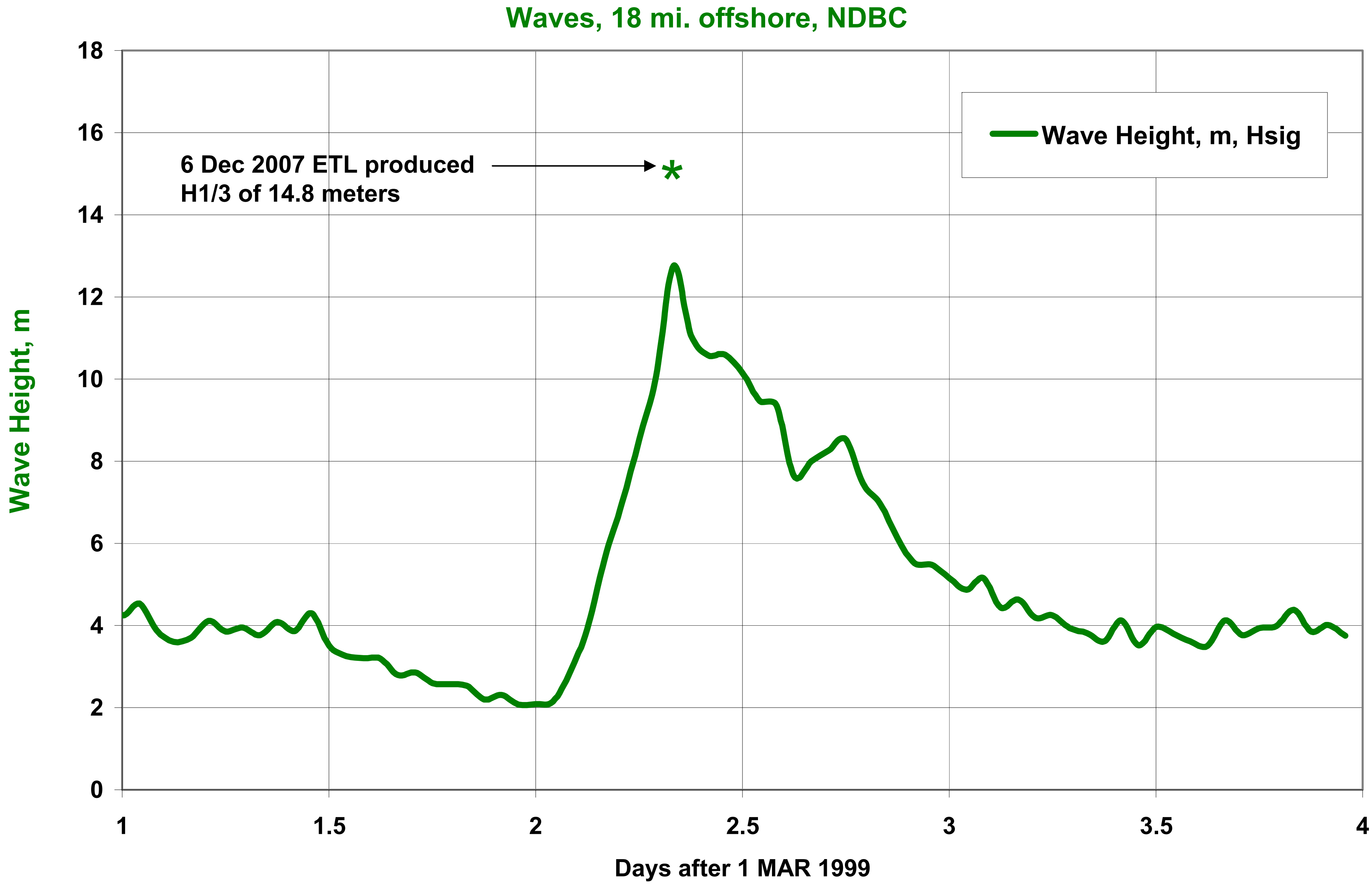


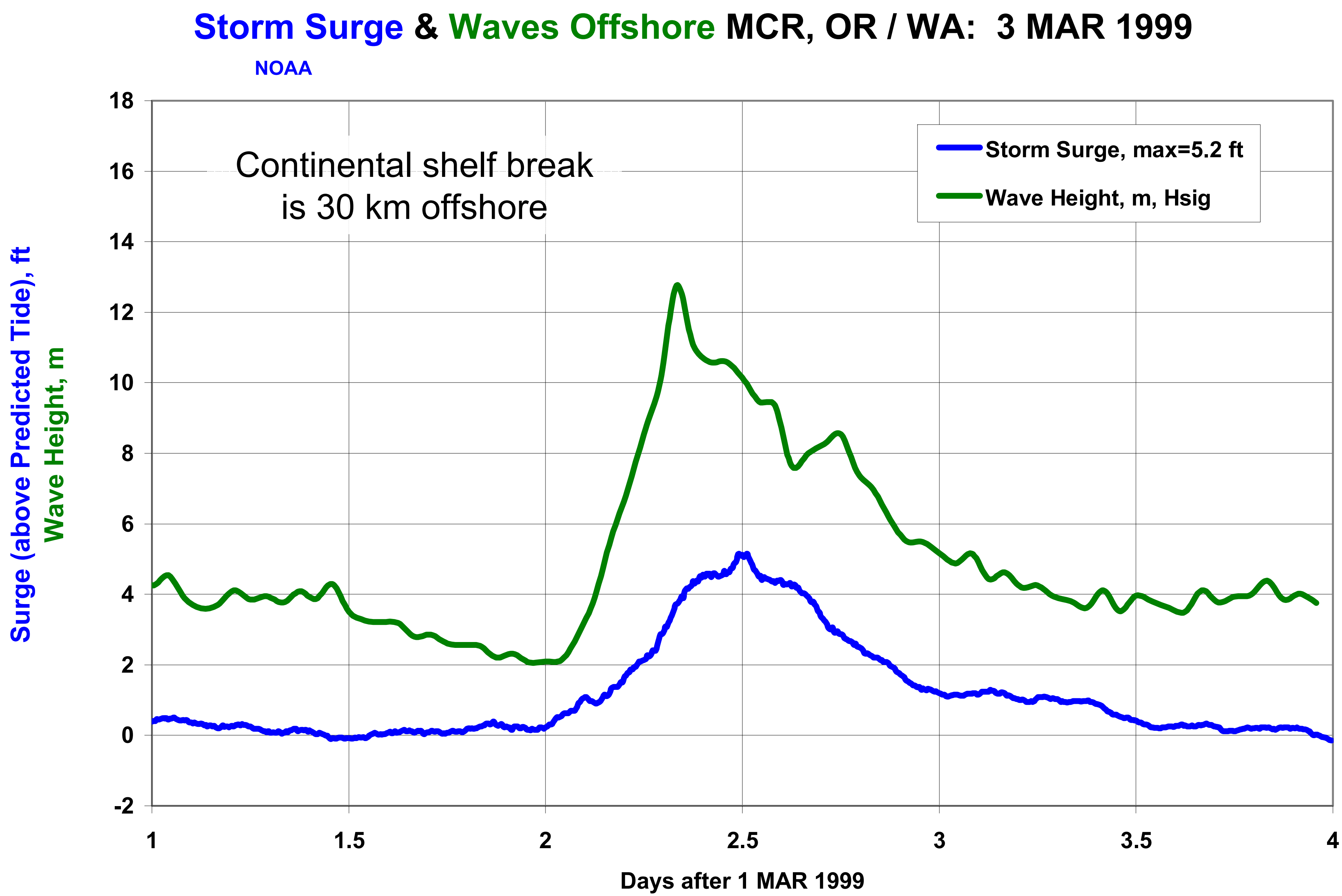
Storm Surge & Waves Offshore SW Pass, LA: 26-31 AUG 2005

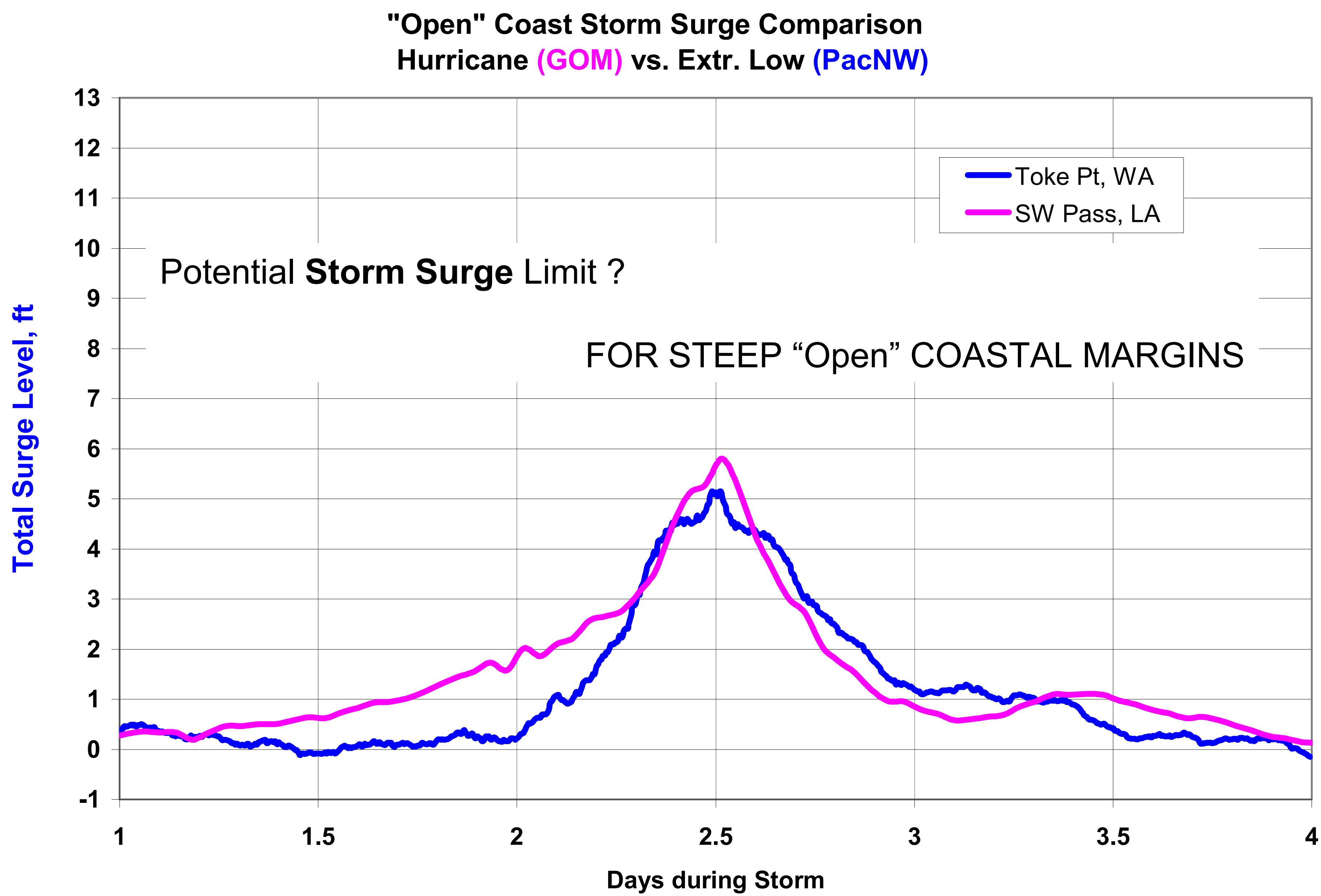


Extra-Tropical Low

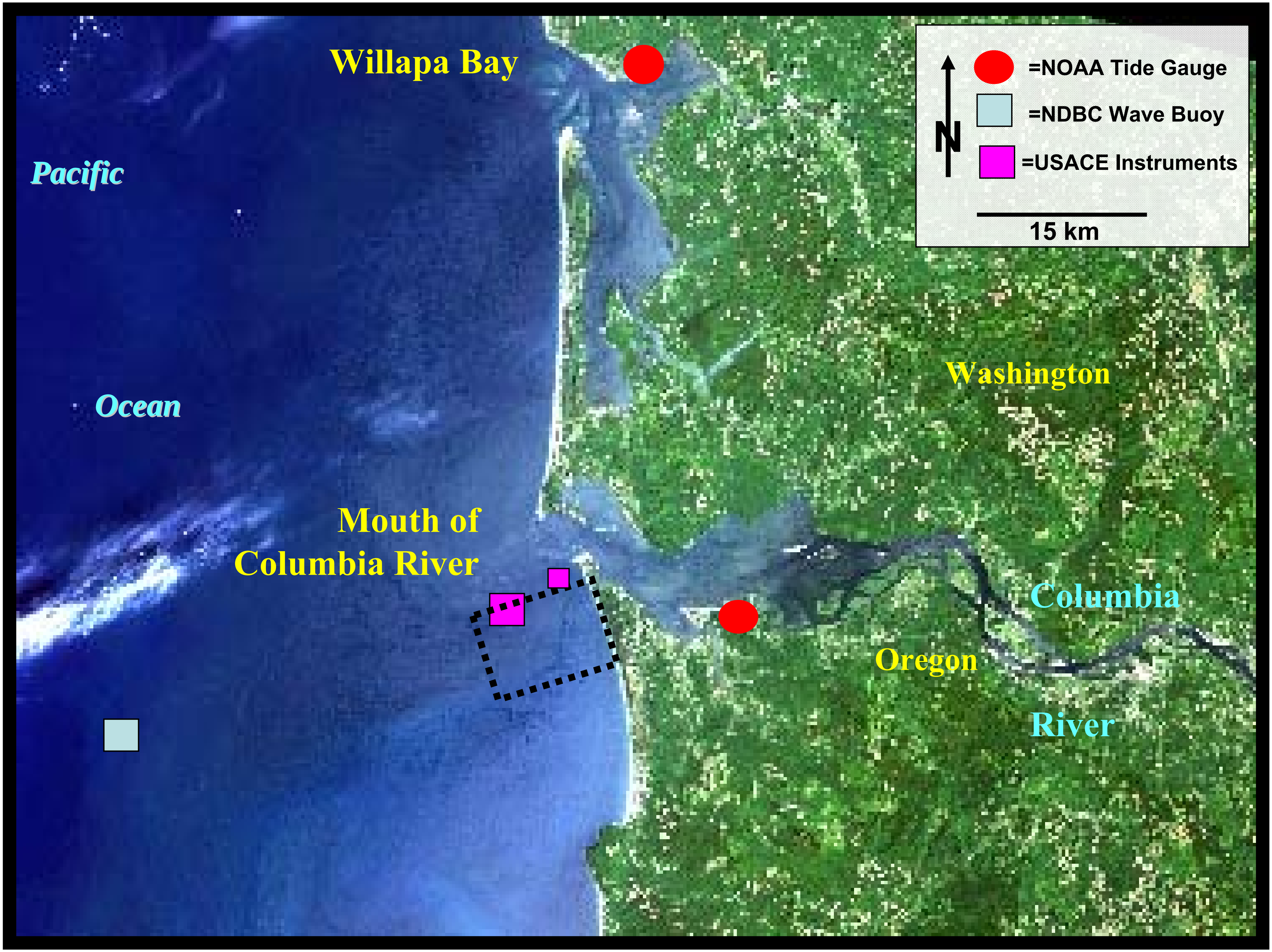
Waves Offshore Mouth of Columbia River, OR / WA: 3 MAR 1999




Storm Surge & Waves Offshore MCR, OR / WA: 3 MAR 1999
NOAA
Continental shelf break
is 30 km offshore
Storm Surge, max=5.2 ft
Wave Height, m, Hsig
Surge (above Predicted Tide), ft
Wave Height, m
Days after 1 MAR 1999
18
16
14
12
10
8
6
4
2
0
-2
1
1.5
2
2.5
3
3.5
4

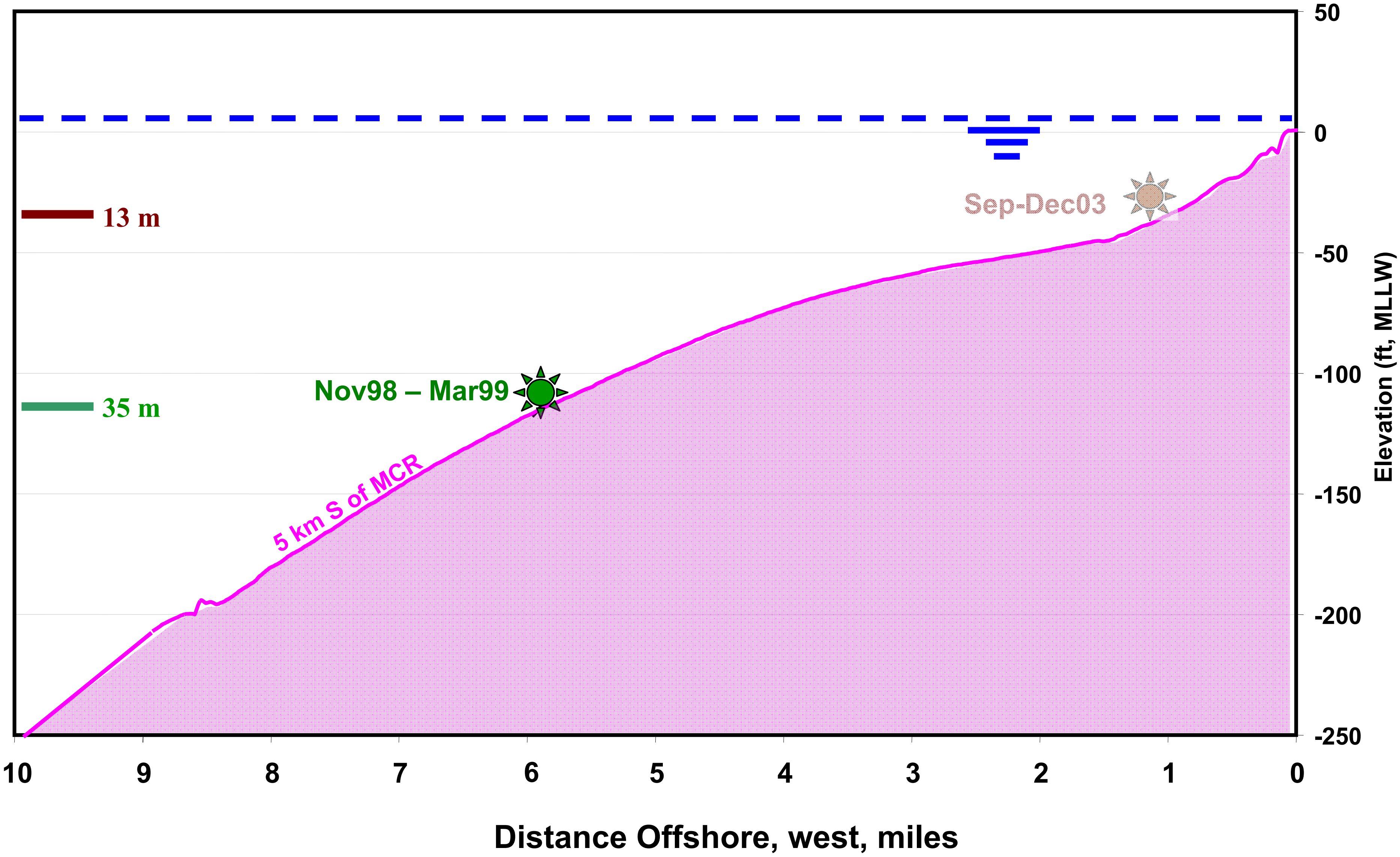


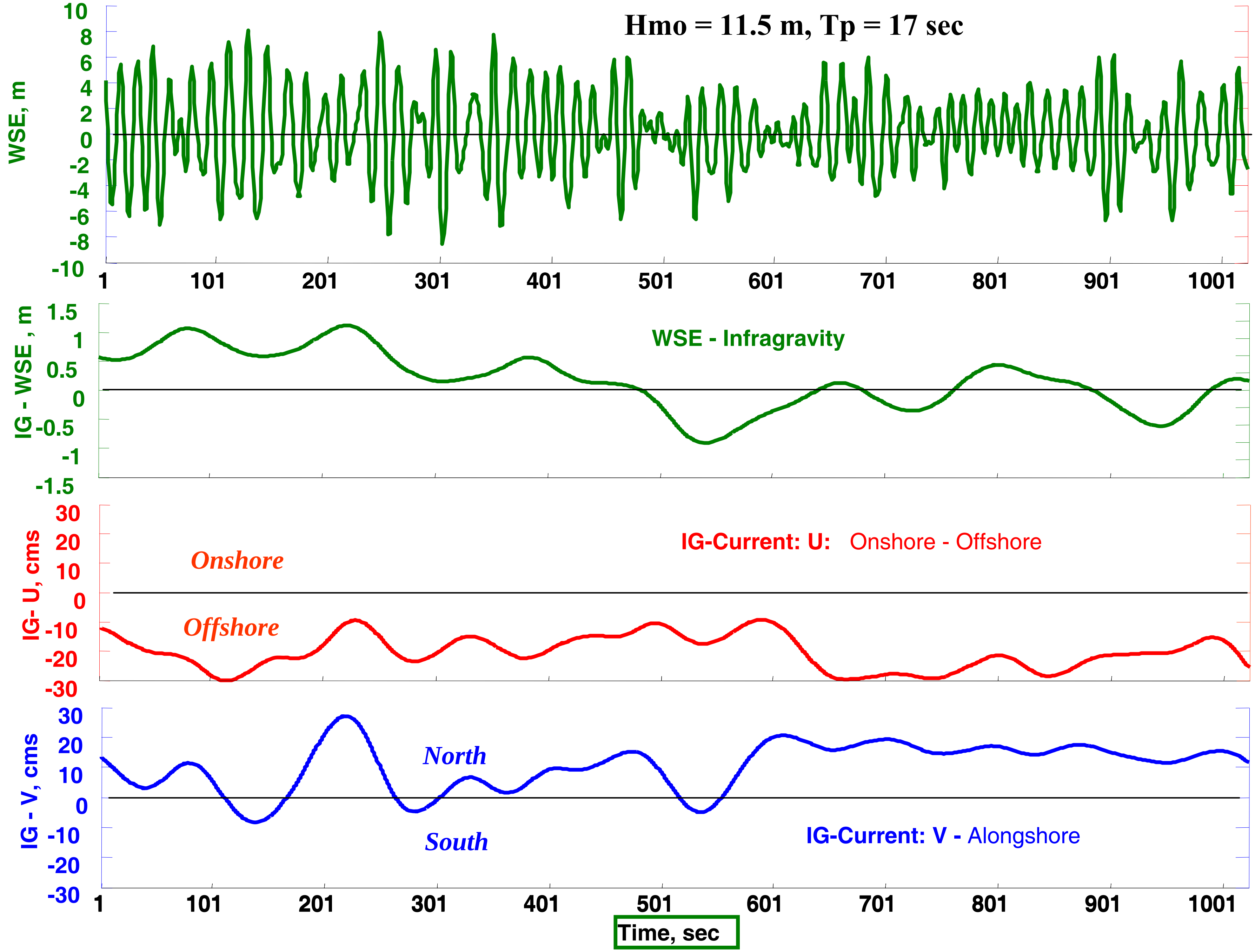
"Open" Coast Storm Surge Comparison
Hurricane (GOM) vs. Extr. Low (PacNW)
Toke Pt, WA
SW Pass, LA
Potential Storm Surge Limit ?
FOR STEEP "Open" COASTAL MARGINS
Total Surge Level, ft
Days during Storm
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
1
1.5
2
2.5
3
3.5
4



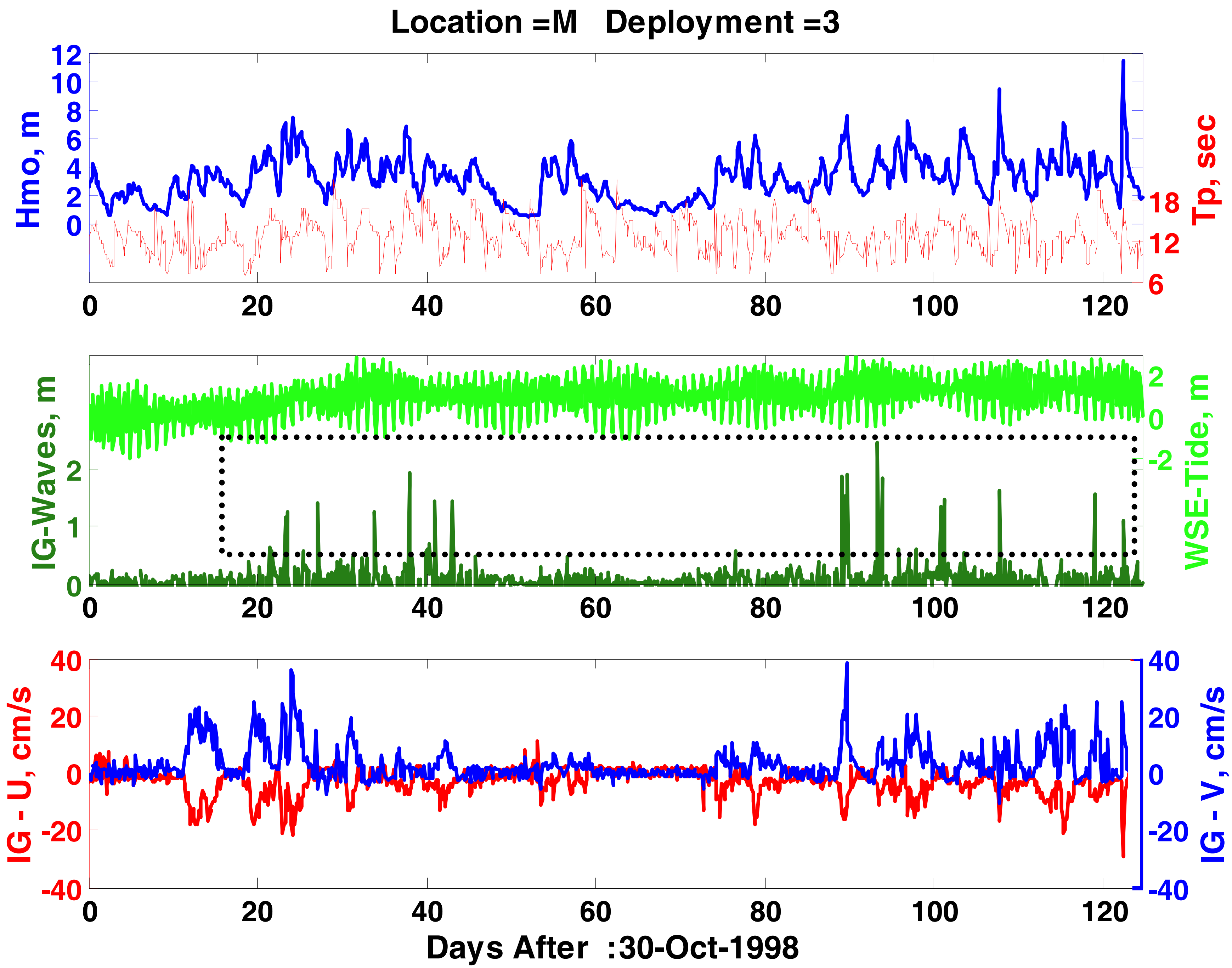
Willapa Bay
Pacific
Ocean
Mouth of
Columbia River
Washington
Oregon
Columbia
River
N
=NOAA Tide Gauge
=NDBC Wave Buoy
=USACE Instruments
15 km

Cross-Shore Profile: 5 km South of Columbia River Mouth



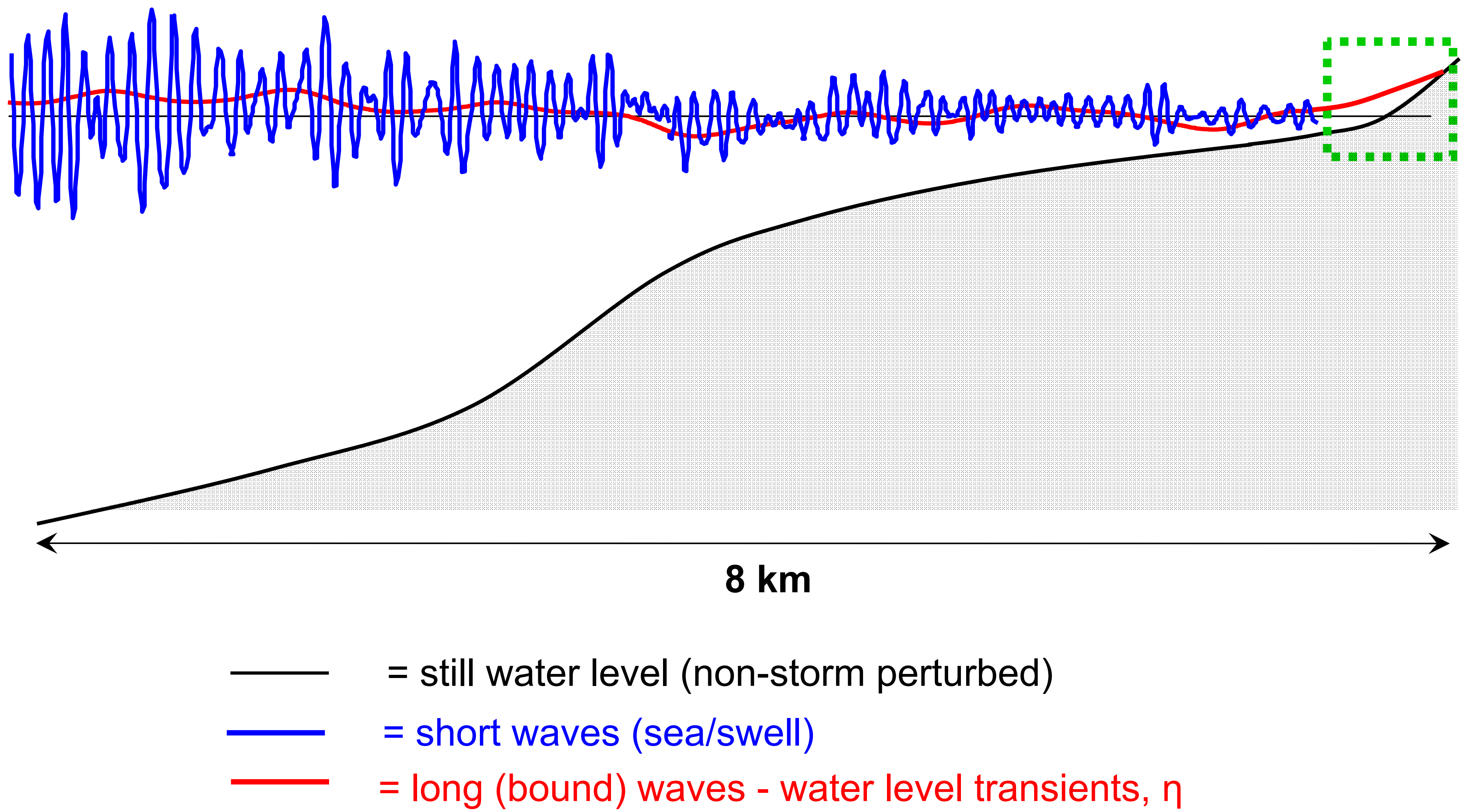


Hmo = 11.5 m, Tp = 17 sec
WSE, m
WSE - Infragravity
IG - WSE , m
IG-Current: U: Onshore - Offshore
Onshore
Offshore
IG- U, cms
North
South
IG-Current: V - Alongshore
IG - V, cms
Time, sec



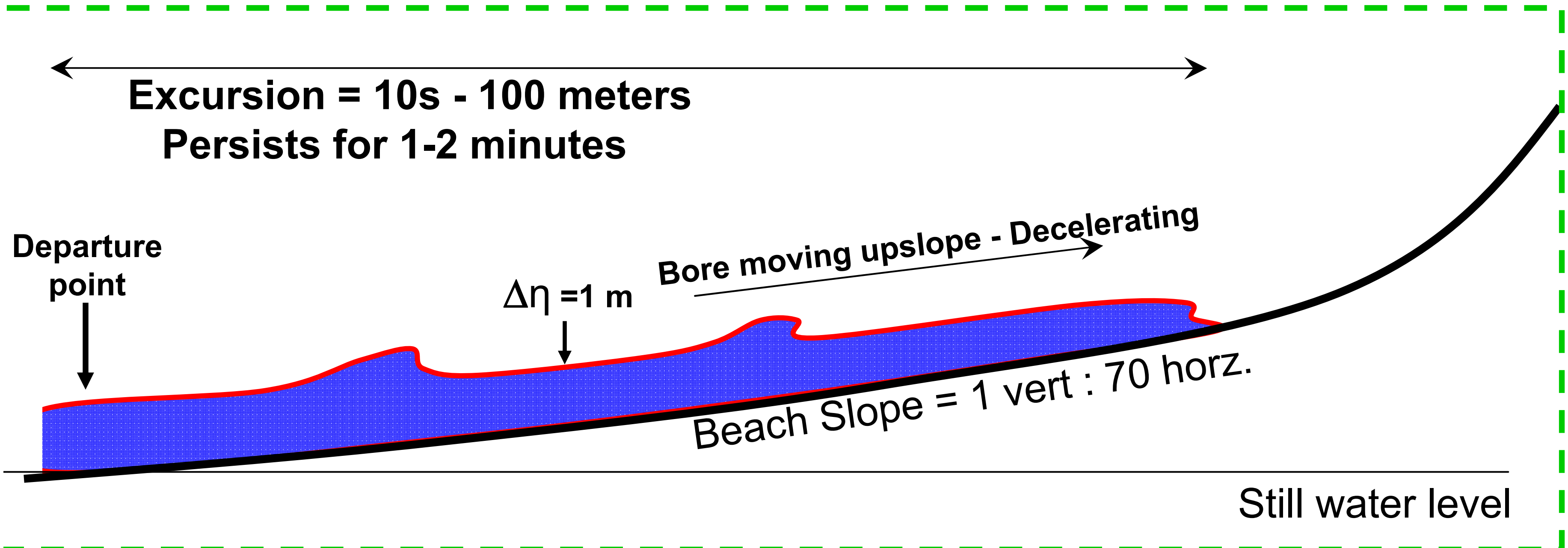
Location =M   Deployment =3
Hmo, m
Tp, sec
IG-Waves, m
WSE-Tide, m
IG - U, cm/s
IG - V, cm/s
Days After :30-Oct-1998

Longwave (IG, η) Propagation in Nearshore and Shoreface



Longwave Propagation, Nearshore, based on Solitary Wave behavior

Depth-limited Translation speed = $\sqrt{g \times (\text{depth} + \text{wave height})}$

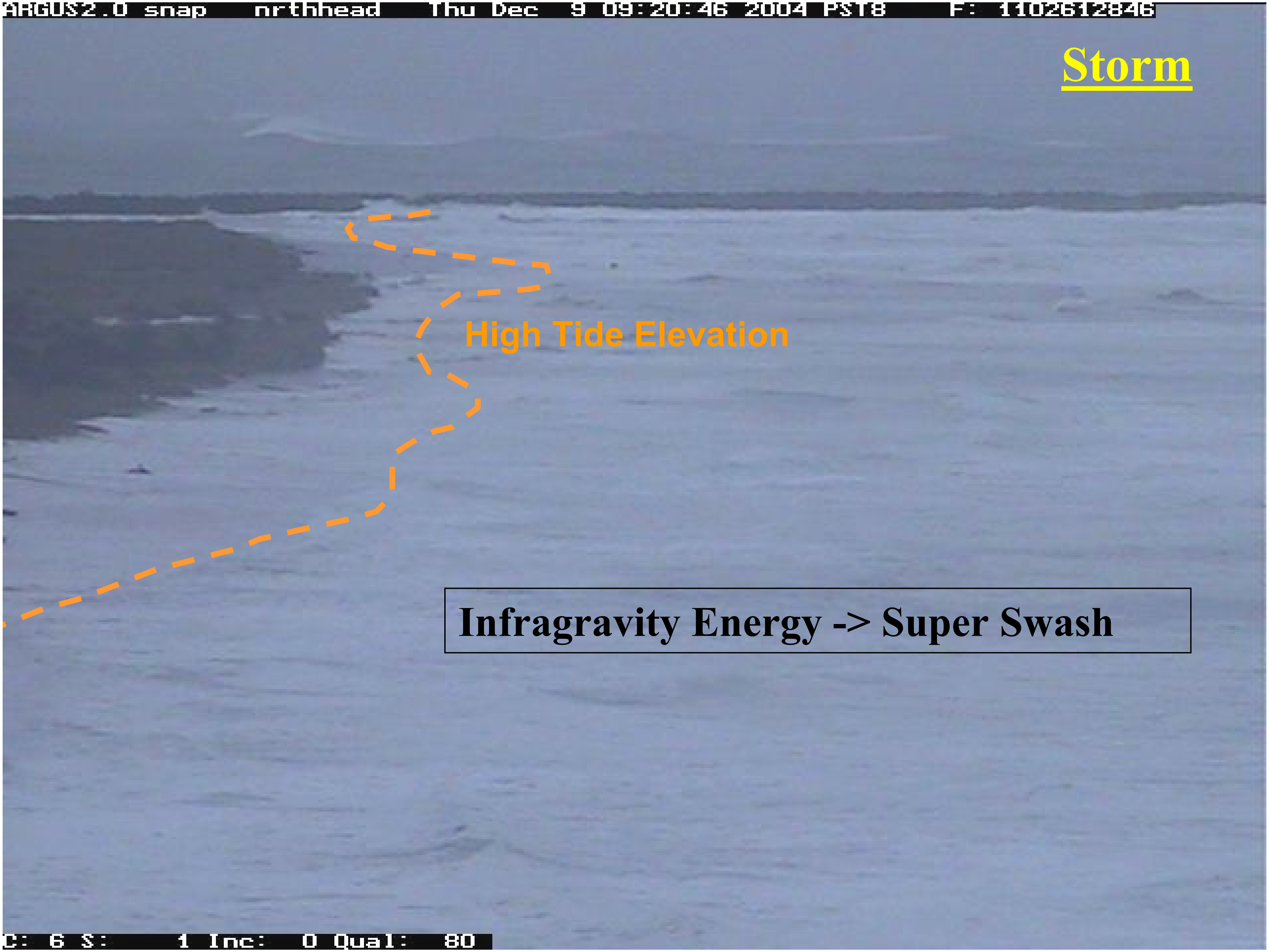


Wave (Bore) Speed at "0" Still Water level – Departure point

Translation speed = $\sqrt{g \times (\text{longwave height}, \Delta \eta)}$

= 3 m/sec…….. for $\Delta\eta$ = 1 m


ARGUS2.0 snap nrthhead Wed Sep 1 08:20:47 2004 PST8 F: 1094055647
North Jetty, 25 ft high
High Tide Elevation
C: 6 S: 1 Inc: 0 Qual: 80


ARGUS2.0 snap nrthhead Thu Dec 9 09:20:46 2004 PST8 F: 1102612846
Storm
High Tide Elevation
Infragravity Energy -> Super Swash
C: 6 S: 1 Inc: 0 Qual: 80

Modulation of Water Surface Elevation ($\Delta\eta$, O-min)

–Can temporarily increase nearshore water depth

Allowing Larger Waves to attack infrastructure

Columbia River Bar Pilots Photo

Effect of Transient Water Level, $\Delta\eta$, <u>when Wave Height (H) is depth-limited</u>

$\Delta\eta$ has taken the role of ΔH in the following performance functions

Type of Loading Condition or Hazard Scenario Affected by a Transient Water Level ($\Delta\eta$)	Performance Function for Coastal Infrastructure (Loading Increase) or Coastal Zone (Hazard)
Conventional Structures (rigid)	
-- Static Loading (hydrostatic)	$(\Delta\eta)^{2}$
-- Dynamic Loading (wave action)	$(\Delta\eta)^{2}$
-- Overtopping/Interior Protection (waves)	$(\Delta\eta)^{1.5} \times \exp^{-(\text{crest elevation} - (\text{TWSE} + \Delta\eta))}$
Compliant Structures (rubblemound)	
-- Direct Wave Action (armor unit stability)	$(\Delta\eta)^{3}$
-- Lee-side Wave Action (armor unit stability)	$(\Delta\eta)^{3} \times \exp^{-(\text{crest elevation} - (\text{TWSE} + \Delta\eta))}$
Nearshore and Structure Foundation Stability	
-- Sediment Transport Potential (seabed erosion)	$(\Delta u)^{2.x} + (\Delta\eta)^{1.x}$
Wave Run – Up on Shoreface	
-- Run-up Distance	$2\,\Delta\eta \times$ beach slope
-- Run-up Speed	$(2\,\Delta\eta)^{1/2}$
-- Run-up Depth (water depth increase before $\Delta\eta$)	$2\,\Delta\eta$

Hypothesis:
Storm Surge Is Affected by Infragravity Transients ($\Delta\eta$)

A component of storm surge evolves as a series of landward propagating longwaves ($\Delta\eta$), which introduce Δ-momentum into the nearshore.

Successive transients ($\Delta\eta$) are adding water/momentum to the previous surge transient.

As the water level increases, depth-limited storm waves ride on top of the long waves to add destructive power to the storm surge event.

If an efficient path (conveyance) for return flow can not be established, the water level (surge) will increase unit conveyance is established such that added shoreward momentum (vol flux) = return flow

Verify: 1) By Review of Surge Event Photography.
2) Apply Bouss-2D Model, forced by Infragravity BC

Arrival of Hurricane Katrina storm surge,
as it came over US Hwy 90 at Gulfport, MS approximately two hours before storm peak made landfall.

Surge propagating landward in terms of individual bores, long wave transients ($\Delta\eta$), with shortwaves traveling on top

Photography provided by Mike Theiss – UlitmateChase.com

Hurricane Katrina storm surge @ Gulfport Beachfront Hotel during storm landfall at Gulfport, MS.



The surge arrived at the hotel location in terms of long wave pulses, with short waves traveling on top of the long wave transients ($\Delta\eta$).

The level of the water outside of the hotel is 2-3 ft higher than inside the hotel due to surge transients, $\Delta\eta$.

An eyewitness account: **"I suddenly envisioned what a tsunami must look like, and realized that I was in a situation similar to that. I watched as the waves were coming in from the Gulf of Mexico.**

They were very long, two-to-three foot tall waves that didn't crash, but just moved in--the classic storm surge".



Eyewitness testimony and photography provided by ***Mike Theiss – UlitmateChase.com***

Bouss-2D Patch Test

BOUSS-2D is a comprehensive numerical model based on time-domain solution of Boussinesq-type equations.

The fully non-linear equations are solved through the surf zone to allow evaluation of wave shoaling-diffraction-bottom friction-breaking, wave-wave interaction, and generation-dissipation of IG motion.

The model was applied using a nearshore domain for an area 5 km south of MCR

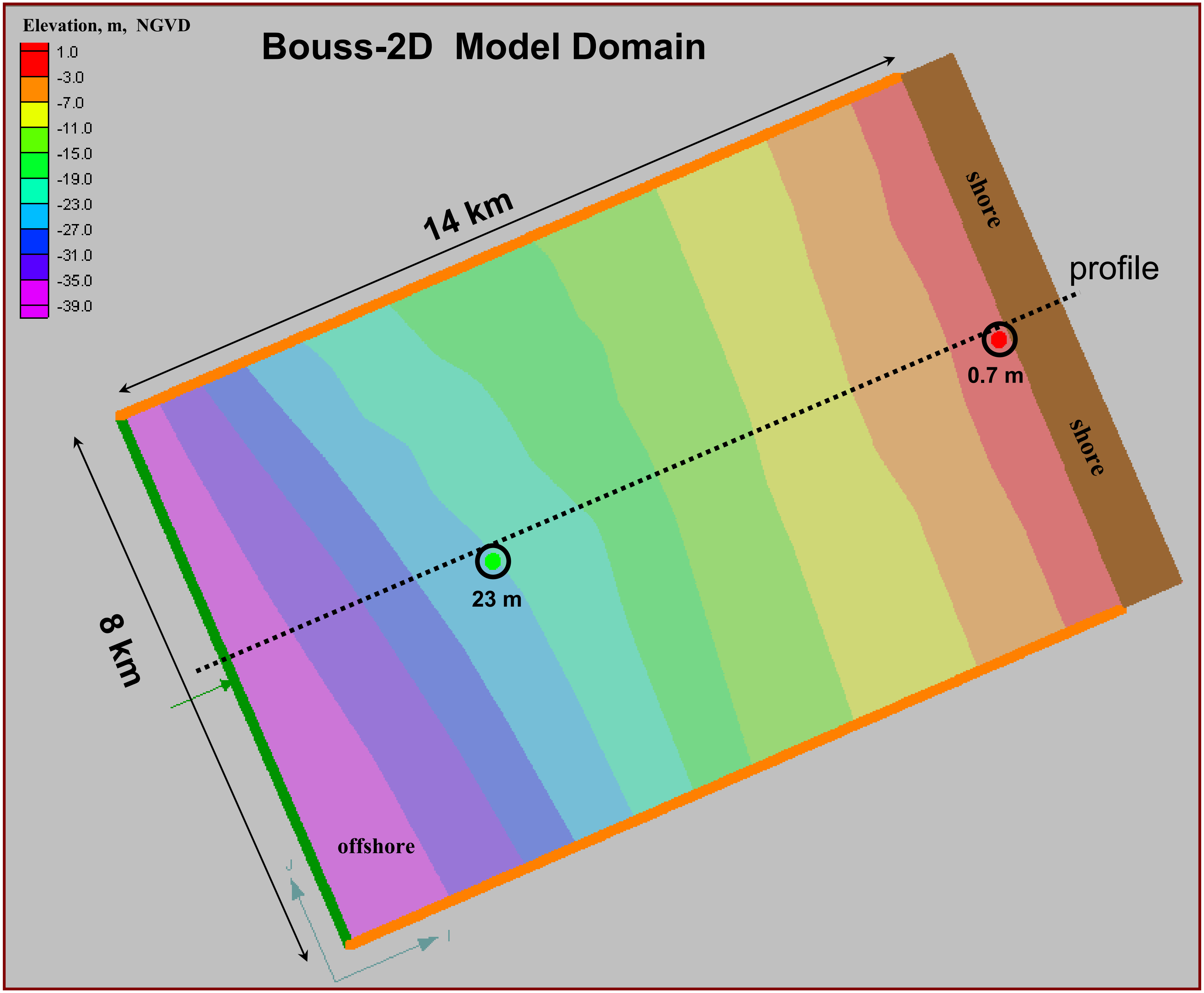
The model domain covered an area of 14 km (onshore-offshore) x 8 km (alongshore).

Water depth within the model domain varied between -38 m (below NGVD) at the offshore boundary to 6 m (above NGVD) at the shore. The domain was descretized using 20x20 m cells.

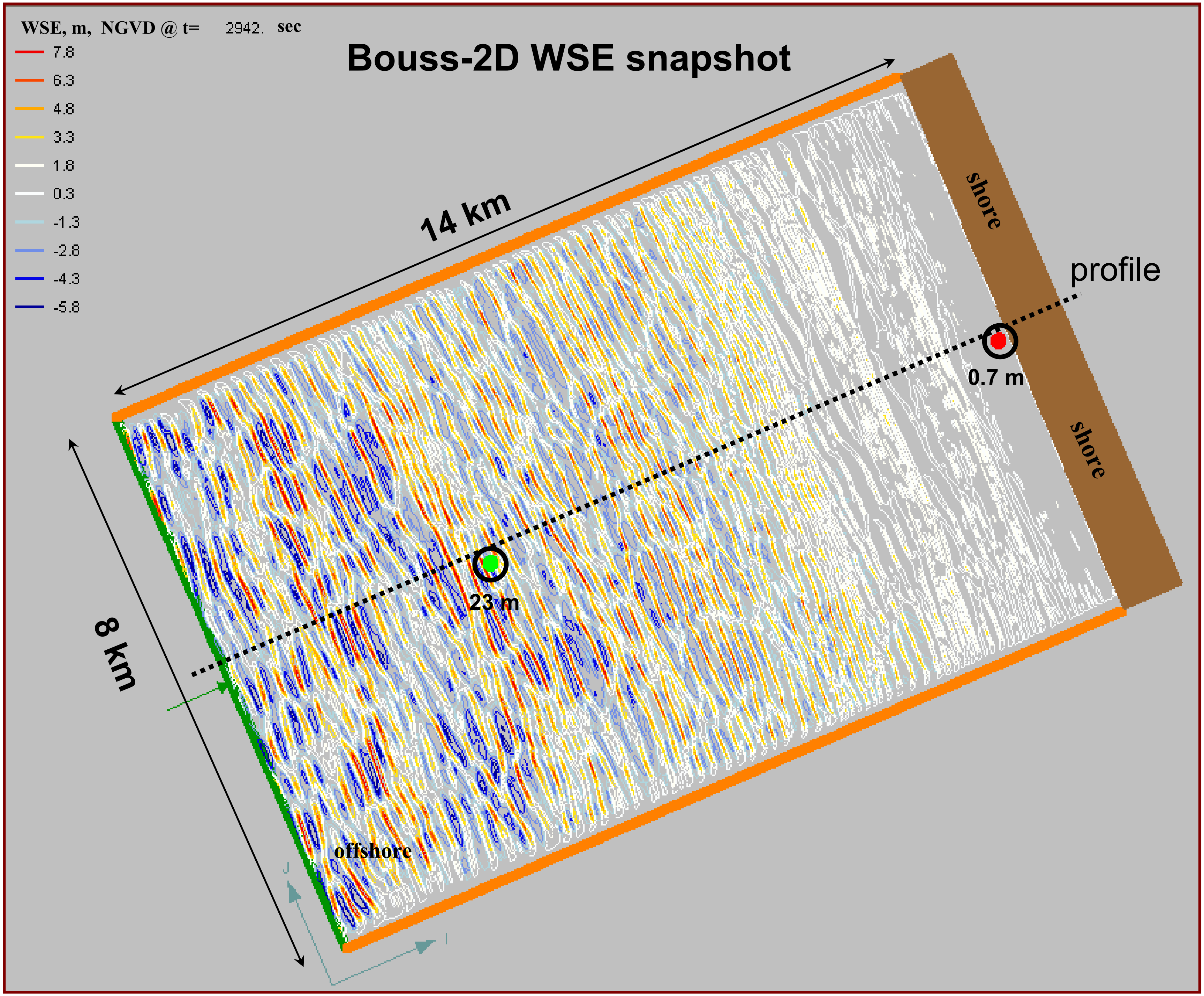
The storm wave-field simulated within the domain was generated using a irregular multi-directional bi-modal spectrum (Ochi-Hubble, Tp1 = 160 sec, Hs1=2 m, nn1=2, Tp2 = 17 sec, Hs1=12.3 m, nn2=3).

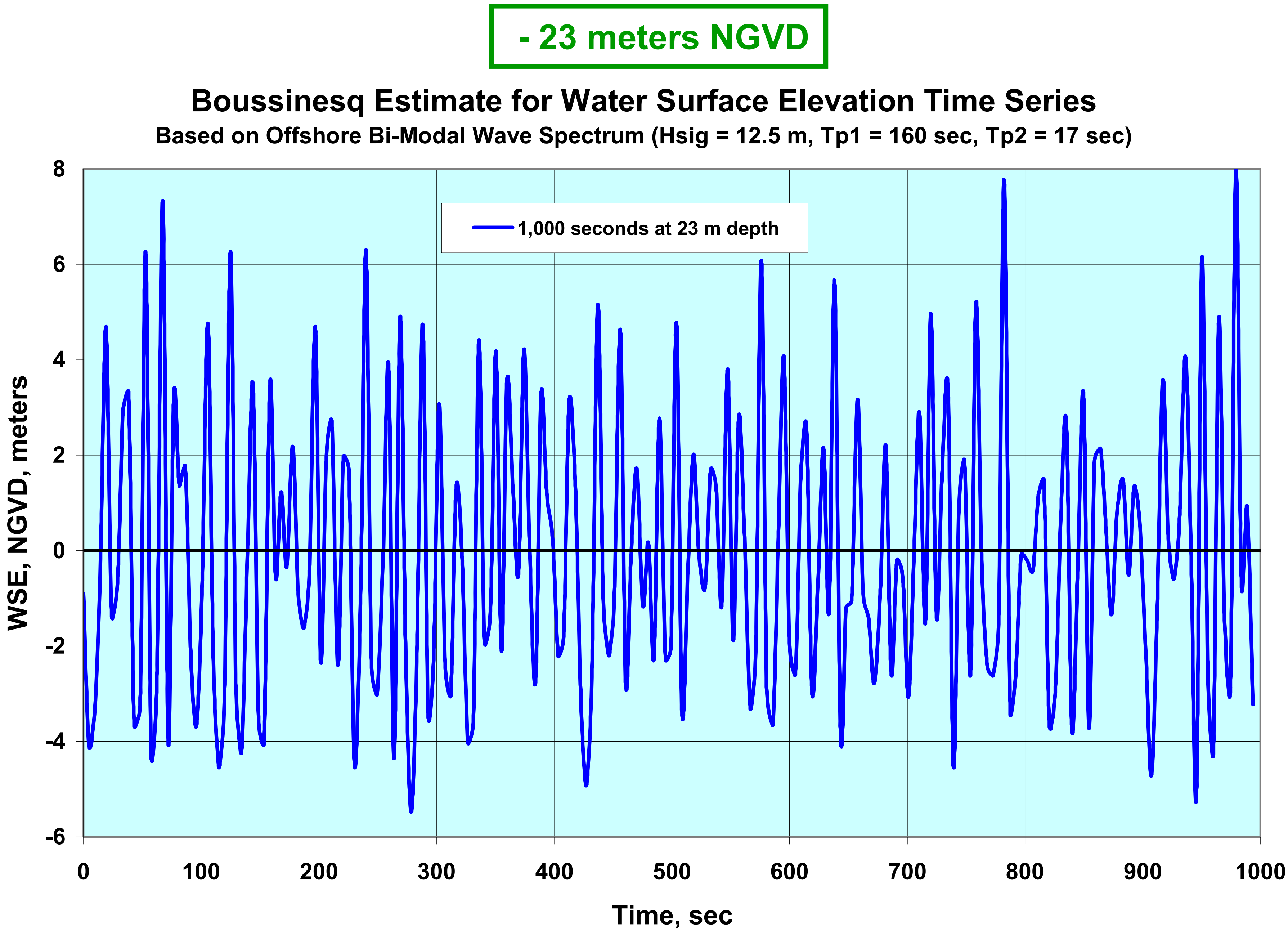
Tp1 was implemented based on the observations of long wave energy at MCR in water depth 35 m

The model was run for 3,000 s using a 0.4 sec time step. Output was obtained during t=2,000-3,000 sec.



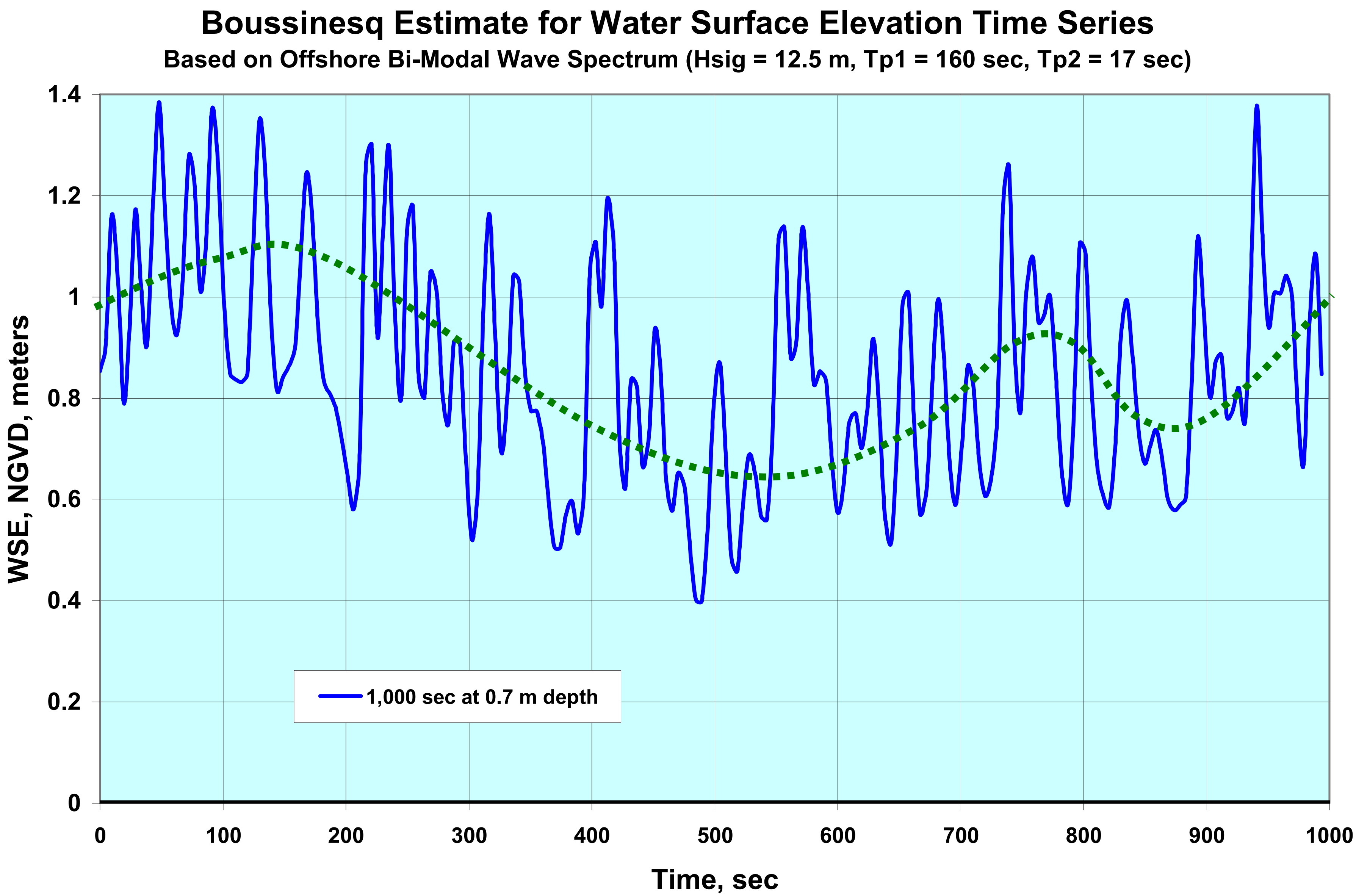
Elevation, m, NGVD
1.0
-3.0
-7.0
-11.0
-15.0
-19.0
-23.0
-27.0
-31.0
-35.0
-39.0
Bouss-2D Model Domain
14 km
8 km
shore
shore
profile
0.7 m
23 m
offshore
J
I

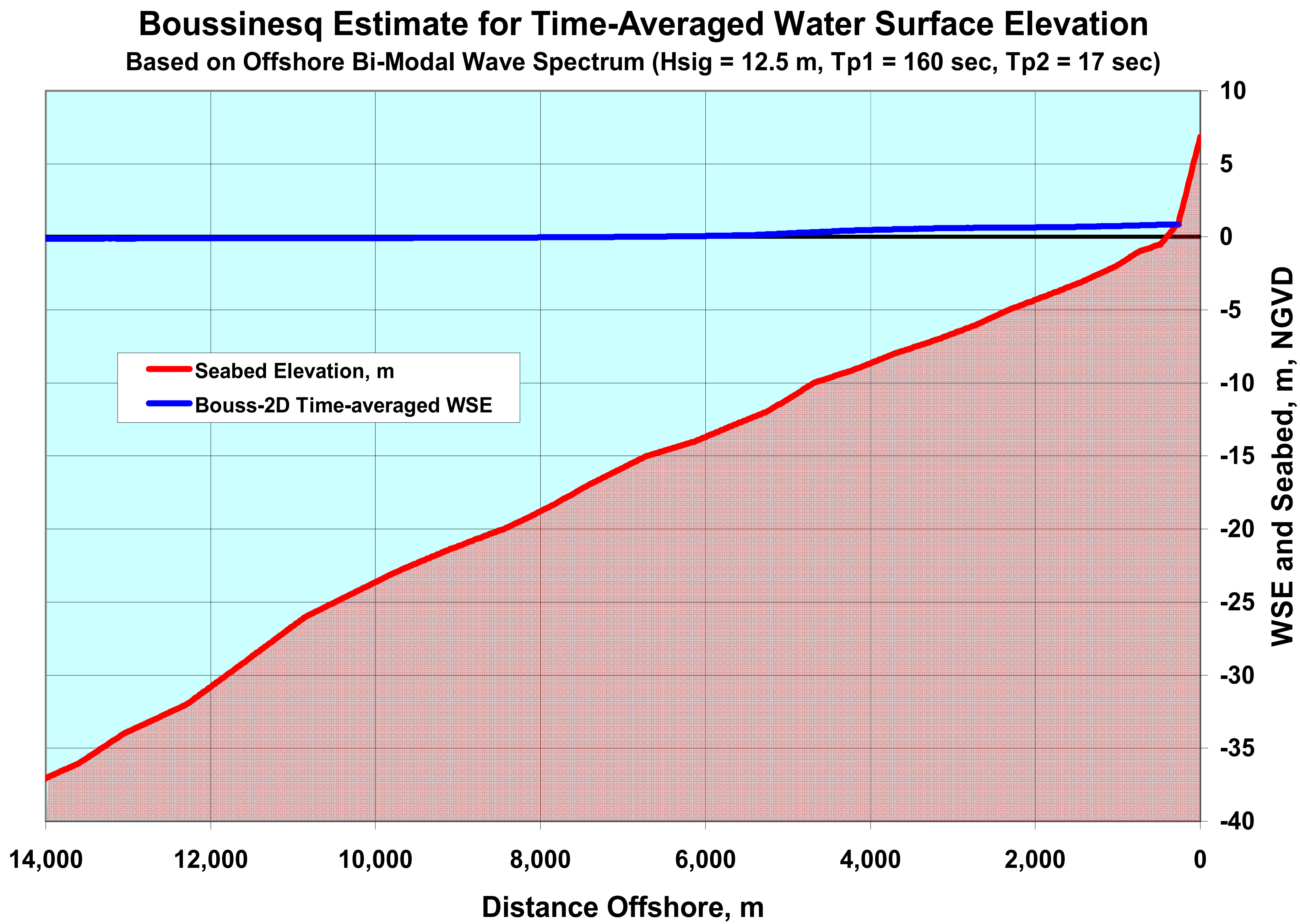

WSE, m, NGVD @ t= 2942. sec
7.8
6.3
4.8
3.3
1.8
0.3
-1.3
-2.8
-4.3
-5.8
Bouss-2D WSE snapshot
14 km
8 km
shore
shore
profile
0.7 m
23 m
offshore
J
I



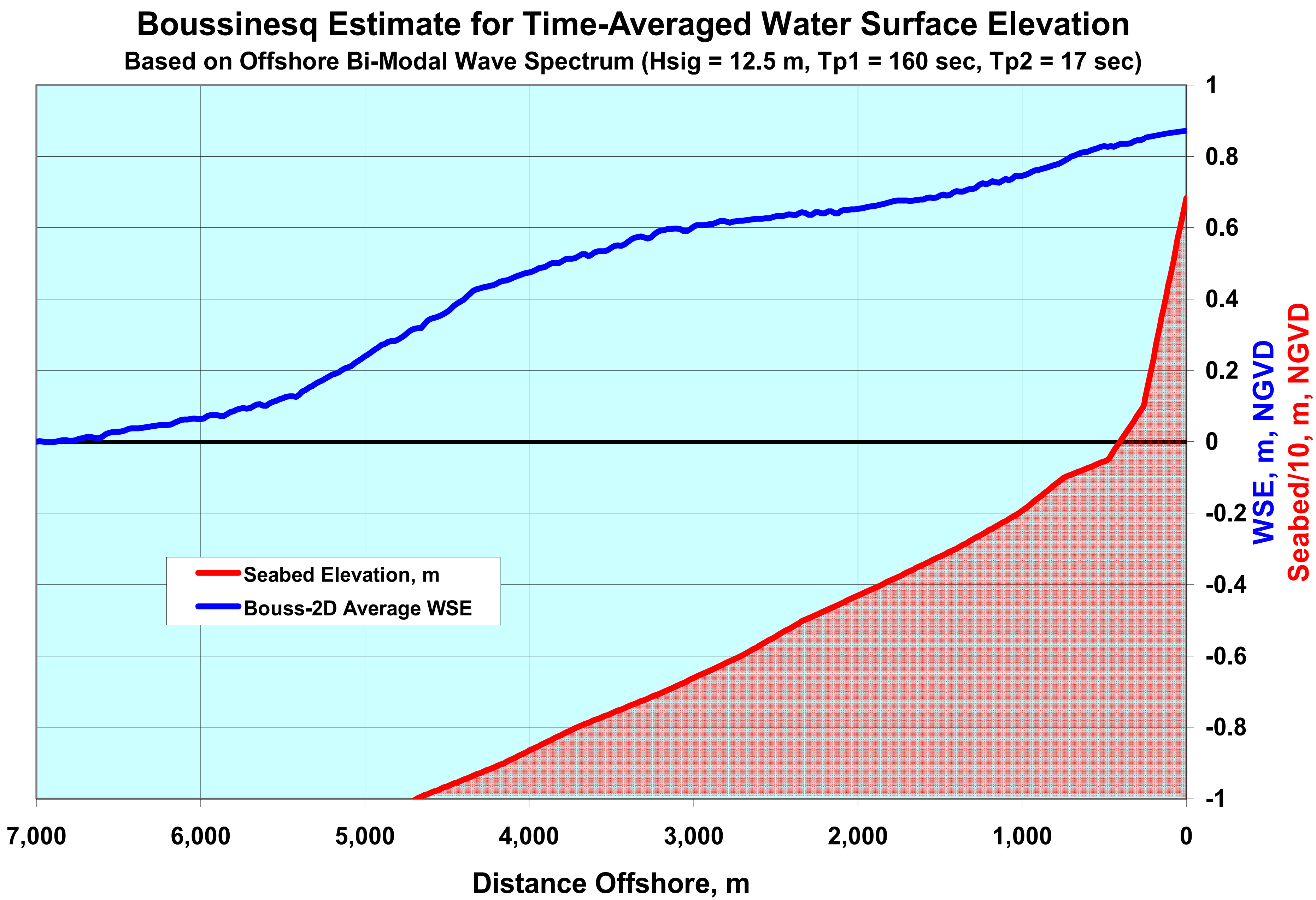
- 23 meters NGVD
Boussinesq Estimate for Water Surface Elevation Time Series
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)
1,000 seconds at 23 m depth
WSE, NGVD, meters
Time, sec
8
6
4
2
0
-2
-4
-6
0
100
200
300
400
500
600
700
800
900
1000

-0.7 ft meters NGVD





Boussinesq Estimate for Time-Averaged Water Surface Elevation
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)
Seabed Elevation, m
Bouss-2D Time-averaged WSE
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
WSE and Seabed, m, NGVD
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Distance Offshore, m



Boussinesq Estimate for Time-Averaged Water Surface Elevation
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)
Seabed Elevation, m
Bouss-2D Average WSE
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
WSE, m, NGVD
Seabed/10, m, NGVD
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Distance Offshore, m

Conclusions

The storm water level that acts upon the coastal margin is a product of many components (processes).

Storm Water Level
= *Storm Surge* + *Infragravity Transients (waves)*

Open Coast Storm Surge for Hurricanes in GOM =~ Etra-tropical Lows in Pac NW

Infragravity Transients (Δη) of 1-2 meters and associated currents elevate the RISKS to life and property within the active coastal margin.

More work is needed to fully parameterize the estimation of Δη, along the coastal zone.

Hypothesis: Δη may be responsible for a considerable fraction of the storm surge which affects coastal margins.

The wave science/engineering community should consider further evaluation of this potentially important storm surge process.

SNEAKER WAVES
An "Unpredictable" Occurrence along the Coastal Margin

Along the Pacific NW coast of the US, several people each year succumb to "sneaker waves"…….

Appear to be associated with transient water levels ($\Delta\ \eta$) produced by groups of large waves.

Landward Speed = 2-4 m/sec

Bore height = 0.3 – 1.5 m

Duration = 1-2 minutes

Excursion Distance = 10-100 meters

Return Flow more dangerous than run-up