Components of Storm-induced Water Level along the Coastal Margin and Related Effects on the Nearshore Wave Environment

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1. INTRODUCTION

Within the contiguous United States, coastal areas comprise less than 20 percent of the Nation's area, yet the coastal zone supports more than half of the U.S. population and more than $1 trillion of coastal infrastructure are deployed in the U.S. alone every year [CMOP 2007]. The situation is similar on a planetary scale. Approximately 40% of the world population lives within 70 miles of the coastline, and this proportion is increasing. Although the coastal margin offers many opportunities for livelihood, commerce, and recreation, there are inherent risks associated within this environment. Wave action and elevated water levels due to maritime storm activity can damage or destroy coastal infrastructure and elevate the hazards for life-safety in a marine or shore edge setting. For shore areas affected by tropical cyclones, the greatest potential for loss of life due to the storm surge. Along the Pacific NW of the US, several people each year succumb to "sneaker waves" associated with transient water levels produced by groups of large waves. This paper investigates how storm wave action can increase the water level along the coastal margin, and describe how the variation of water level may significantly increase the hazards associated with storm waves. The focus of this paper deals with transient nearshore water levels ($\Delta\eta$), related to storm-generated infragravity effects. A hypothesis describing the relationship between transient water levels and storm-related surge is advanced.

Many aspects of maritime and coastal margin activity demand reliable description of the nearshore wave environment, which is contingent upon the accurate representation of wave transformation phenomena and storm-induced water levels along the coastal margin (figure 1). The degree to which storm waves impact a given coastal area is governed by the regional and local wave climate, nearshore bathymetry, currents, and water level. In conditions where waves become depth limited, water level plays a dominant role in controlling the height (destructive power) of waves. A higher water level (which increases the total depth, d) will allow larger depth-limited waves (Hb) to affect a given shallow water location. Processes that increase the total water depth (d) can have a pronounced affect on the wave climate impacting a given nearshore location or coastal structure. Depth-limited wave height (Hb) and the total water depth (d) at a given location may be defined by:

Depth-limited wave height (Hb) = 0.4d to 1.2d, limits for wave breaking due to shoaling (1)

Total water depth (d) = h + total water surface elevation (TWSE) (2)

$$TWSE = PTE + \text{storm surge} + meso + \Delta\eta \quad (3)$$

where,
h = the reference water depth (related to bathymetry elevation)
PTE = predicted tide elevation, tied to bathymetry elevation datum
storm surge =static water level increase due to wind and wave setup
meso = meso-scale effects due to seasonal shifts in water level, el Nino, etc
$\Delta\eta$ = transient effects due to nearshore wave transformation, infragravity motion.

1.1 Relevance of Transient Nearshore Water Levels, Δη

Infragravity motion within the active zone has been well documented within the coastal processes literature. Recently, Ruggiero and List [2007] have recognized the importance of accounting for nearshore infragravity (IG) motion and associated wave run-up when defining a proxy shoreline position, when perform long-term and large-scale shoreline change analyses. However, transient (Δη, IG) effects are rarely considered when defining the "total water depth (d)" or the TWSE needed to design coastal infrastructure, assess coastal hazards, or analyze shoreline evolution. During storm wave conditions, "transient WSE effects, Δη" may become equivalent to the tidal excursion. The consequences of not including "transient effects, Δη" when calculating TWSE (or total water depth) could have serious ramifications when estimating relevant coastal engineering design parameters such as: depth limited wave height, shore face run-up/swash excursion, overtopping on coastal structures, wave force loading, and sediment transport/scour. Other factors which may be relevant to the development of a "design" water level include "mesoscale" effects which area summarized in Part I of this paper. Basic guidance for assessing various processes which affect of coastal water levels, including transient water levels, can be found in the Guidelines and Specifications for Flood Hazard Mapping Partners [FEMA 2004, Technical Appendix D, in revision].

1.2 Paper Outline and Emphasis

This paper is organized into three parts. Part I describes the principal oceanographic processes which may define the components of coastal nearshore water level. Emphasis is directed to the description of transient water level effects, Δη, as motivated by IG energy produced by shoreward propagating storm waves. Part II describes the implications and functional relevance of water level variation upon coastal zone hazards and several coastal engineering performance functions. Long term observations of coastal water levels and short-term observations of transient effects, Δη near the Mouth of the Columbia River are used to develop an estimate of TWSE return periods for the Pacific Coast, along Northern Oregon/South Washington, USA (figure 2 and 6). Part III proposes a hypothesis for relating storm surge to "transient effects, Δη" (as produced by storm waves). The storm surge-Δη hypothesis is developed on the based of eye-witness observation storm surge development, photographic documentation, and water level measurements.

This paper refers to wind generated waves (i.e. short waves, having period = 3-30 seconds) as "waves". Long waves (i.e. waves having period greater than 30 seconds) are considered infra-gravity (IG) waves.

2. PART I: COMPONENTS OF NEARHORE WATER LEVEL

At any point in time, the water level at a given coastal location is a product of many interacting oceanographic processes. These processes can range in spatial scale from micro (10's m) to planetary (>1,000's m). The dominate process driving the water level is dependent upon location and time (Table 1). Very rare and extreme events such as Tsunami can have a spatial impact of 1,000s of km with the devastating impact of a water level elevated by 2-15 m, yet the duration of event impact may persist for only minutes. The perceived risk associated with such unpredictable "high-profile" events is high. A similar situation can occur with Hurricanes (Typhoons) where a storm surge of 1-10 m can persist for several hours, yet these events can be forecast a few hours ahead of event landfall. El Nino can affect regions of 1,000s km at an apparently small degree of water level impact (< 0.5 meter), yet the duration of impact can be months. Astronomical tide occurs perpetually with and effect on elevating coastal water level can range 0.2 - 3.5 meters. The duration of a high tide water level can persist for 2 - 4 hours, each day. The risks due to tide are small, because the process is well understood and predictable. "Low-profile" events such as El Nino, extratropical storm systems (with attendant shore edge effects), or astronomical tide do not motivate a high level of perceived risk, yet the superposition of these low-level risk events can bring about a creeping level of elevated risk.

Table 1. Oceanographic Processes Affecting Coastal Nearshore Water Level (typical values)

Water Level Forcing Process	**Departure from Mean Water Level**	**Temporal Scale of Water Level Effect**	**Spatial Scale of of Water Level Effect**
Mesoscale Events - Infrequent			
-- PDO/Climatic Shift	0.05 – 0.2 m	months - years	Ocean Basin > 1,000s km
-- El Nino/Kelvin-shelf waves	0.1 – 0.3 m	weeks - months	Regional / 1,000s km
-- Seasonal Change	0.05 – 0.2 m	months	Regional / 1,000s km
Tsunami –Very Rare Event	1 – 10's m	minutes - hours	Ocean Basin > 1,000s km
Seich - Rare Event	0.5 – 1.5 m	minutes - hours	Local / 10'skm
Astronomical Tide -Frequent	0.5 – 3.5 m	hours/ perpetual	Regional / 1,000s km
Estuarine/Riverine Effects-Infrequent	0.1 – 1 m	hour - days	Regional / 1,000s km
Large Storm Events - Infrequent			
-- Atmos. Pressure diff.	0.1 – 0.7 m	minutes - hours	Local / 10s km
-- Hurricane/Extr Trop Storm Surge	0.5 – 8 m	minutes - hours	Local / 10s km
-- **Wave Surge-Infragravity**	0.1 – 2 m	seconds - minutes	local / 10s km
-- Wave Set-up (radiation stress)	0.1 – 0.5 m	minutes - hours	Local / 10s km
-- Wave Run-up at Shore's Edge	0.5 – 3 m	seconds	micro / 10s m

= water level components discussed within this paper

2.1 Observed Storm Surge

Figure 1 shows the surge aspects of two distinct types of extreme storms that have made a direct landfall hit along the "open" coastal margin of the US (Pacific North West-Mouth of the Columbia River, OR/WA and Gulf Coast - SW Pass, LA). Figures 7-9 show photographic examples of storm surge. The peak significant wave height for the gulf coast storm was 16.9 m (Tp=14.3 sec); the PacNW storm had peak Hsig=12.8 m and Tp=16.7 sec. Both locations have similar aspects of continental slope; the continental shelf beak (240 m isobath) is about 30 km offshore. These locations are fully exposed to the marine environment and have relatively steep sloping bathymetry out to the shelf break, a morphological attribute which limits the level of storm surge.

The storm surge statistics highlighted in figure 1 are based on the "total observed water elevation" minus "predicted tide elevation" and document the combined effect of mesoscale + storm-related processes. The surge shown in figure 1 does not include transient water levels ($\Delta\eta$, 100-400 sec), due to the 1-hour time increment of the reported data. There are notable differences and similarities between the two storm scenarios featured in figure 1. The level of storm surge and offshore wave height for each location are of similar proportional magnitude. The surge for each location can be said to be approximately 5.5 ft for the events shown. The tide range and frequency along the PacNW coast is significantly greater than the Gulf coast. In a relative sense, the gulf coast storm surge is almost 6X greater than the region's tide amplitude, where as the PacNW storm surge is about 1.5X greater than the regional tide amplitude. In this sense, the surge-related impacts from gulf coast storm would be expected to be greater than for the PacNW storm, even though the surge magnitude for each location was similar. The surge duration for each of the storms shown in figure 1 was about 18 hours, for surge levels exceeding 2 ft. The "open coast" storm surge for each location was similar despite the markedly differing types of weather systems that produced the surge. Both storm scenarios feature in figure 1 have onset of peak surge concurrent with high tide, which seems to be the rule with storms making landfall along any coastal margin.

It must be noted that "open coast" storm surge can become severely enhanced when the storm surge propagates toward a confined coastal embayment or shallow water area which is fully exposed to the coastal ocean (and having relatively flat bathymetry aspect). The level of Katrina storm surge (TWSE) that affected backbay locations of the LA and MS coastal margin was reported to be 20-28 ft [IPET 2007]. The morphology of a region can significantly enhance nearshore circulation, storm surge evolution, and IG motions.

2.2 Example of Superposition of Water Level Components

Consider a coastal location where the high tide level (MHHW) is 1.5 m above mean water level and the occurrence of El Nino further elevates the average water level by 0.2 meters. An extratropical cyclone makes landfall elevating the water level by an additional 1.4 meters (storm surge). Note that an increase in the frequency of intense storm systems is correlated with the presence of El Nino along the west coast of the US. Storm waves offshore are observed to be 10 meters (Hsig) with period of 16 sec (Tp). During the storm's landfall, IG energy associated with shoaling bound waves induces a 1.5 meter transient water level ($\Delta\eta$) along nearshore areas, with periods of 100-400 sec. As short waves advance thru the surf zone, the run-up along the shore's edge elevates the active swash line to 2 meters above the transient nearshore water level.

In the above scenario, the active water surface is elevated above the predicted high tide level by 3.1 meters (0.2+1.4+1.5) making the total water surface elevation (TWSE) = 4.6 meters above the mean water level. Nearshore waves which would have been depth-limited if the water elevation was at mean water level, would now have 4.6 meters of additional water depth during the above El Nino storm event; potentially increasing the nearshore depth-limited wave height by 4.6 meters as compared to wave action that occurred during mean water level. Note that the IG transient component ($\Delta\eta$=1.5 m) accounts for 30% of the TWSE

Areas landward of the shore's edge could be affected by the vertical excursion of wave run-up (2m in elevation) beyond the TWSE. If the shoreface slope was 0.02 (landward of the shore's edge), then wave run-up could affect 100 m of "dry" beach width. Wave run-up could extend to an elevation of 6.6 meters above mean water level. This scenario is based on a modest (static) storm surge of 1.5 meters, yet the combined elements of multiple (dynamic) water level processes act to produce a potentially hazardous condition for the nearshore, shoreface, and infrastructure and people along the coastal margin.

2.3 Concept of Nearshore Infragravity (IG) Energy and Transient Water Levels, $\Delta\eta$

As wind-generated gravity (short) waves (sea and swell) propagate through deep and transitional water depths, individual wave tend to self-organize into wave groups due to the dispersive nature of surface gravity waves. This wave group effect can be accentuated during storm conditions, when waves of many different frequencies interact to saturate the sea state. Wave groups usually propagate in sets of 4-12 waves of similar frequency. The average frequency of the waves within a wave group tends to be closely associated with the peak spectral period (Tp) of the local sea state. The lower frequency waves within a wave group interact non-linearly with the waves having higher frequency, as the lower frequency (faster moving) waves pass the higher frequency (slower moving) waves. Lower frequency short waves act as carrier waves for the higher frequency waves. Group-bounded IG waves are produced by non-linear interactions between waves of different frequencies (as wave groups interact with other waves). These bound waves will cause local a displacement of the mean water level beneath a group of high waves [Longuet-Higgens and Stewart 1964]. The variation of the mean water level within and between wave groups is referred to as a "bound" long wave since it is phase-locked to the carrier short wave group. This is the case when the short waves are in deep or transitional water depth. As short and long waves (and wave groups) propagate toward shore, the non-linear interaction between short waves of different frequencies and short waves and long waves and increases with decreasing depth: The influence of bound waves increases.

When the short waves reach shallow water (d<<L), the bound waves become decoupled from the short waves and the bound waves become "free" long waves and begin to act as the carrier wave for the short waves (opposite of the deep water condition). At this point, the shoaling wave field may still be offshore of the active surf zone, but the long waves may begin to affect IG motion of the water surface and nearshore circulation. As the short/long wave field continues its shoreward advance and related transformation, it enters the active surf zone where the long waves may become a predominate factor affecting water motion. The above non-linear wave interactions are not trivial during storm conditions, and are believed to produce significant infra-gravity (IG) effects, resulting in temporal/spatial variation of in water surface ($\Delta\eta$) along a coastal margin.

The degree to which a storm wave field affects a coastal margin is prescribed by the regional/local wave climate, nearshore bathymetry, and water level. As offshore waves travel shoreward, the waves are modified due to shoaling. Ultimately, the height of the short waves becomes limited by the water depth, regardless of how severe the offshore wave climate. This is the point at which nearshore waves become depth-limited and bound waves may shoal to produce a surf-beat, by allowing larger short waves to ride on the long wave: Effectively increasing the depth of water nearshore by $\Delta\eta$ during the passage of a long wave. In conditions where short waves are depth limited, (a transient) water level plays a significant role in controlling the depth limited wave height. Larger depth-limited short waves can enter the nearshore area and surf zone, if the water level is temporarily surcharged (by the surface expression of transient IG energy, $\Delta\eta$).

2.4 Field Measurements of Nearshore Infragravity Energy Generated by Storms Waves

Storm-wave generated infragravity (IG) transients have been observed offshore the Eel River, CA in water depth of 60 meters, offshore Duck, NC in water depth of 10-20 meters [Write et al 2002], and offshore the Mouth of the Columbia River, OR/WA in water depths of 13-35 meters [Moritz et al 2006]. These observations and subsequent analyses have determined that IG transients are motivated by waves groups. During storm conditions, shoreward propagating wave groups act to produce long waves (bound waves), which become the forcing mechanism for the observed IG transients. The observed IG energy is expressed as a transient in the water surface elevation ($\Delta\eta$) and a corresponding pulsating bottom current bottom (ΔU) exhibiting offshore tendencies.

Offshore the Mouth of the Columbia River (MCR), IG water surface transients ($\Delta\eta$) have been observed to have amplitude of 1-2 meters and period of 100-400 seconds (lower panel of figure 2 and figure 3). These observations are based on field measurements conducted during Oct 1998-Mar 1999 in 35 m water depth and during Sept – Nov 2003 in water depth of 13 m. The IG transients ($\Delta\eta$) became large (>0.5 m) when waves offshore MCR exceed 6 meters (NDBC buoy 46029 in 120 m depth). The corresponding IG effect on bottom current was found to be coherent with the IG surface expression ($\Delta\eta$) and can produce a time varying bottom current transient (Δu) having amplitude of 30 cm/sec. Like the η IG signal, ΔU appears to be modulated by bound waves. ΔU is additionally affected by bottom current forced as a return (offshore) flow to balance the shoreward advancing momentum of the shoaling bound waves. Based on the above observations, the subject IG energy appears to be motivated by storm wave-field processes far outside of the active surf zone.

3. PART II: IMPLICATIONS OF TRANSIENT WATER LEVEL ($\Delta\eta$)

A transient water level ($\Delta\eta$) can be generated along the shore's edge by shoaling wave groups (or bound waves) during moderate to severe storm wave conditions. When a group of larger waves and the attendant IG bound wave encounters the seacoast during storms, the transient water level along the shore's edge can be elevated by 1-2 m within a time-span of 30 seconds and persist for a period of 1 to 4 minutes. A transient water level ($\Delta\eta$) of 1-2 m can have a profound effect on the costal margin, allowing significantly larger waves to affect infrastructure, sediment movement, and people within the nearshore or active shoreface zone. These effects are described below. Table 2 summarizes the relative effect of a transient water level ($\Delta\eta$) in terms of the influence on various infrastructure and coastal hazard performance functions.

3.1 Sneaker Waves – Shoreface Hazards

When the water level along the shore's edge is temporarily "set-up" due to a transient water level, individual waves or waves within a group can ride the transient water level ($\Delta\eta$) further into shore sweeping unsuspecting beach comers into the ocean. The return flow, running down the shoreface, carries the victim away from the shore's edge and into the surf. These waves are known as "sneaker waves". Although sneaker waves are a universal coastal phenomenon, these transients are highly irregular and their approach onto a shoreline is difficult to judge. Sneaker waves can occur anytime on the coast of the Pacific Northwest, and are prevalent when storm waves are affecting the coast. Sneaker waves claim the lives of several people each year along the coasts of Northern California, Oregon, and Washington. The hazard of sneaker waves is not lost on the authors of this paper, who are seasoned beach combers yet were caught by a 1-meter sneaker wave while they were at least 70 meters shoreward of the active swash zone. The authors were tentative to the wave swash zone, during a day of storm wave activity, when a transient water level ($\Delta\eta$) began to move shoreward. We moved shoreward at a deliberate pace, yet we could not outrun the oncoming surge which overtook us before we could make our way past a coastal barrier. The return flow for the sneaker wave was much more difficult to resist than the run–up. We were overcome with surging run-up above our waists at a distance 100 meters from the "nominal swash zone". Figure 5 shows the combined result of storm surge, transient water level, and wave over topping. The affected dune crest would not have been overtopped without the added effect of a transient water surface elevation, estimated to be 1.5 meters in this case (based on visual observations at similar locations).

<u>Sneaker Wave Physics</u>. The physics of a sneaker wave are related to the IG motion of the transient water level ($\Delta\eta$) acting as a carrier wave for short waves. The combined effect of short waves with the transient water level is amplified when the process becomes manifest as a bore rushing up the shoreface. When long waves such as swell (or bound waves forced by a wave group) move into shallow water (wave length, L >> water depth, d), the amplitude increases with the wave crest becoming progressively higher and shorter, while the trough becomes longer and flatter. For long waves, the crest may shorten to 500 ft while the trough extends to 1,000 ft or more. In very shallow water (L>>d), long waves can be approximated as a solitary wave [Munk 1949]. The solitary type wave may have a breaking wave height (Hb) equal to or greater than the local water depth and the celerity (Cs) of the soliton may be expressed as (g(H+d))1/2 [Daily and Stephan 1953]. In this case the resultant bore ($\Delta\eta$) may be 1 to 2 meters high along the shore's edge, capable of translating up the shoreface at 3-5 m/sec, and inundating a 100 meter wide beach in less than 25 seconds. The horizontal excursion of a 1.5 m $\Delta\eta$ running-up a NW PAC coastal beach could range between 40 - 150 meters (when beach slope varies between 0.04-0.01). It's like a quickly developing mini-tide or super-swash, but it is driven by the interaction of bound waves with swells and wind waves and this effect tends to strengthen when large storm-driven waves encounter the coast.

3.2 Transient Water Level – Increased Loading on Coastal Infrastructure

Adding a 1 to 2-meter transient ($\Delta\eta$) to a design water level, can exceed the limit state for many coastal engineering design loading scenarios. This can be of particular concern where depth limited waves are encountered and the design loading scenario is a non-linear function of wave height or total water depth. In the case of a seawall designed to limit wave overtopping or a floodwall/levee designed to resist a prescribed water level (based on tide level + storm surge). Adding 1 meter ($\Delta\eta$) to the design water level (or total water depth, d) of a levee/floodwall will increase the hydrostatic force on the structure by $(d+\Delta\eta)^2$, increase the dynamic loading associated with a larger depth-limited waves, and cause the structure to be overtopped. In either case, the levee or floodwall could fail due to a transient $\Delta\eta$ of 1 meter.

Wave-induced overtopping is a design limit state which is highly sensitive to total water depth and depth-limited wave height (at the toe of the structure). A water level increase of 1 meter can increase wave-induced overtopping by 100% or more. Overtopping of coastal levees and floodwalls can complicate overall flood-control system reliability: By compromising the backside of the overtopped levee or flood wall, and/or by adding flood volume to the protected interior area (via overtopping). During a 3 hour storm-flood, the volume of water that can collect behind 200 ft of flood control barrier being overtopping by 0.01 cu ft/sec/ft is about 22,000 cu ft. If the affected flood control barrier is 2,000 ft, the volume of water introduced to the interior area is 220,000 cu ft....that's just for 0.01 cu ft/sec/ft overtopping rate (very small). Given the uncertainty in overtopping estimation, the interior area could be subjected to a significant volume of unexpected water. The backside of the flood barrier or interior infrastructure such as pump stations can be compromised if the overtopping water volume is higher than expected. Refer to figure 8a for a visual illustration of a severe overtopping condition.

In the case of rubble mound design (armor units sized for breakwaters, revetments, or jetties based on wave height), adding a $\Delta\eta$ of 1 meter to the design water level may produce an increase in depth-limited wave height that exceeds the design limit state by 1 meter. The result could lead to a failed rubble mound structure, since armor unit size is based on incident wave height[3]. A rubble mound structure armor layer designed for a 5 meter wave, but subjected to a 6 meter wave (due to a $\Delta\eta$ of 1 meter) would have its design limit state exceeded by 173%. See table 2 for additional details.

3.3 Transient Bottom Current Δu - Effects on Sediment Transport

As offshore waves travel toward the coastal margin, the waves exert an orbital motion on the seabed which increases with decreasing water depth. As the waves begin to aggressively shoal, a quasi-steady state translational bottom current can be generated by the shoreward progression of the shoaling waves. The alongshore component of the wave-induced bottom current tends to be aligned with the alongshore direction of wave propagation. The cross-shore component of wave-induced bottom current can be in the direction of wave propagation (toward shore), or offshore opposing the direction of wave propagation (rip current). The magnitude and direction of bottom (shear) velocity imparted to the seabed by nearshore wave action are important parameters that govern littoral sediment transport. Estimation of the wave-induce littoral transport is of paramount importance for assessing nearshore morphology change and shoreline response to wave forcing. The presence of a pulsating IG current (ΔU) occurring to 30 meter depth can significantly modify the bottom current regime during storms. This could significantly affect sediment transport along the nearshore and mid-shelf, potentially increasing scour of nearshore infrastructure, and driving the process of localized or regional shoreline recession.

The key to reliably estimating littoral sediment transport is to correctly define the magnitude and direction of wave-induced bottom velocity through out the active nearshore zone. In many coastal engineering applications, it may be assumed that the wave-induced bottom current motivating nearshore sediment transport is constant for a given wave condition (wave burst); by using observed wave data that has been burst-averaged. The burst-averaged (bottom current) data would then be used to verify meso-scale methods/models to simulate bottom current and associated sediment transport. Many coastal engineering applications may assume that most littoral transport occurs inshore of 15 meters water depth. What if there are periods of significant reversals of the bottom current, within a given wave burst observation that are not captured when "averaging" data over a wave-burst record (for 17-32 minutes)? What if there are periods during which wave-induced bottom velocity exceeds 20 cm/sec in water depths greater than 30 meters, when it is assumed that active significant transport does not occur at water depth greater than 15 meters? Implications of these plausible yet incorrect assumptions could be that estimated sediment transport magnitude and direction are severely inaccurate and that a sizable part of the coastal margin is not included in the active littoral sediment budget. There can be considerable IG transients in the bottom current (ΔU) during storms which may significantly skew the flux of sediment along the seabed. To properly estimate the storm-motivated flux of sediment along the mid-shelf and nearshore seabed, the IG component of bottom current must be included in the calculations of sediment, scour potential, and shoreline profile adjustment.

Table 2. Transient Water Level (Δη) and Bottom Current (ΔU) as a hazard to Coastal Zone Infrastructure.

Type of Loading Condition or Hazard Scenario Affected by a Transient Water Level (Δη)	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)	$(\Delta \mathbf{u})^{2.x} + (\Delta\eta)^{1.x}$
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 Δ η)	$2\Delta\eta$

Note: The increase in "coastal infrastructure loading" or "coastal zone hazard" is shown in terms of the increase in nearshore wave height (H) due to the addition of a transient water level (Δη). The assumption is made that before Δη is added to the total nearshore water depth, the nearshore wave height (H) is depth-limited (or H ≈ total depth). ∴ adding Δη to total water depth makes H increase by Δη , or ΔH ≈ Δη . In this case Δη has taken the role of H in the above performance functions

3.4 Estimates of Water Level Components for the Coastal Margin of Pacific Northwest

An analysis was performed to evaluate storm-related processes that affect the "open coast" water level at the Mouth of the Columbia River, an important regional inlet located in the heart of US PacNW coast. The MCR is located at Lat 124 W-45 N, between the states of Oregon and Washington (figure 2). Offshore of MCR, the storm-wave environment can be severe. Although "storm surge" rarely exceeds 2 meters due to the steep continental shelf and speed of storm passage, waves offshore MCR regularly exceed 9 m height (Hmo) and period of 16 sec (Tp).

During October – March, the NW Pacific coast of the US is subjected to eastward moving maritime cyclonic storms that can extend over the ocean for 1000's of km and cover a latitude difference of 25 degrees. When these fast moving maritime low-pressure systems make land fall on the U.S. Pacific Northwest (translation speed=20-40 km/hr), the coast can be subjected to hurricane-like conditions. Offshore wind fields associated with intense winter low-pressure weather systems can create sustained wind speeds greater than 20m/s for fetches greater than 300 km. The resulting wind stress can produce ocean waves (Hmo) greater than 10 m high having wave period (Tp) greater than 16 seconds. The approach and passage of intense maritime storm systems results in a 1 meter (typical) static "surge" of the water surface. The wintertime sea state affecting the coastal margin is characterized by large swell approaching from the northwest to southwest combined with locally generated wind waves from the south to southwest. Astronomical tides are mixed semi-diurnal with a diurnal range of 2.6 m. The continental shelf beak (240 m isobath) is typically 30 km westward from the shore, making the transition from coastal regime to oceanic abrupt.

Storm Waves: The wave environment offshore MCR was analyzed using a 17 year (1990-2007) continuous record of wave conditions (NDBC buoy 46029 and 46050). A Weibull distribution (k=1.4 with correlation=0.9847) was determined to be the optimal distribution for describing the wave data (Hsig) through the entire range of wave events [Moritz 2001 and 2004]. The Weibull distribution was extrapolated to estimate the extreme values for offshore wave height. A 50-year wave (Hsig) was estimated to be 13.0 m. Figure 4 (top) shows the cumulative distribution generated from the above extremal analysis. Similar techniques were applied to develop estimates for astronomical tide (annual percentile exceedence) and storm surge water level. Figure 4 (bottom) illustrates how offshore storm waves are reduced (in height) as waves propagate shoreward.

Storm Surge and Tide: The storm surge was evaluated as "observed water level" minus "predicted water level based astronomical tide". The NOS tide gauge at Toke Pt, WA was used, due to its closer proximity to the open coast as compared to the Astoria tide station, and data capture of recent extreme events during 1996-2007. Water level data was screened such that only values of surge greater than 0.1 meter were used to evaluate the annualized percentile exceedence. Finally, a cumulative distribution for storm surge was calculated using a partial duration frequency analysis. An examination of winter water levels during El Nino of 1997-1998 (excluding significant storm activity) determined that the water level was set-up by 0.2 m due to the regional event. The Astoria NOS tide station was used to estimate astronomical tide attributes for MCR. Results for the estimation of water level components at MCR are shown in figure 6. The hourly astronomical tide level which is exceeded 10% of the time during a given year is 1.04 m NGVD (2.10 m MLLW). The 1% annual high tide is 1.30 m NGVD (2.47 m MLLW). The 10-year (0.9) storm surge was estimated to be 1.43 m. The 10-year (0.9) IG transient water level ($\Delta\eta$) at 50 ft water depth was estimated to be 1.52 m. Note that at MCR, the range between minimum and maximum values for storm surge and transient water level ($\Delta\eta$) is not large. In the PacNW, the level of storm surge (along the open coast) is limited by the relatively uniform and steeply sloped seacoast morphology. Because the annual average storm climate is severe, the annual average surge is near the limit which can be generated within the morphological context of the PacNW seacoast. Hence, there little variation between the average annual storm surge (1.22 m) and the estimated 100-year value of 1.83 m. A similar situation is believed to limit the maximum transient water level (Δη), based on the physics that govern the formation of bound waves and their evolution as they propagate from nearshore waters to the shoreface. Stable bound waves (forcing of the Δη) greater than 1.5-2 m high can not be produced within the PacNW coastal environment. Hence, there is little variation between the 2-year (0.5) transient water level (Δη) of 1.3 m to the 10-year (0.9) level of 1.5 m at a 15 m depth.

4. PART III: The Effect of Infragravity (IG) Transients on Storm Surge

Parts I and II of this paper discussed how nearshore IG energy can be created by groups of large storm waves modulating the water surface to produce bound waves having a period of 100-400 seconds. As these bound waves evolve and travel shoreward, the water level can be temporally elevated by 1-2 meters (formation of IG water level transients, **Δη**). The Δη effect has been observed using insitu measurements of WSE and related water motion kinematics. The shoreward propagation of this type IG energy adds a significant amount of momentum (and advected water volume) to the affect nearshore and shore face. If these IG transients occur in sufficient frequency and duration, there could be an added Δη-effect on the time-averaged WSE along a coastal margin (ie storm surge).

The following hypothesis is proposed: During storm wave conditions, the formation of IG transients in the nearshore water level (Δη) can enhance the development of storm surge affecting the coastal margin. This mechanism would be forced by the superposition of shoreward propagating IG Δη transients during a storm's landfall, such that the nearshore water level would be set-up by the continual addition of IG momentum (and shoreward advected water volume). The time-averaged WSE would be elevated until an equilibrium level is established where the onshore transport of water (due to the shoreward moving IG Δη transients) would be balanced by the offshore return of water, through the formation of rip-current systems. Pulsating offshore flow (bottom rip current) has been shown to be coherent with IG Δη transients during storm wave action [Wright 2002 and Moritz 2006]. Nearshore areas with a steeply sloping bottom would be more efficient at promoting the offshore (return) flow than areas where the nearshore bottom slope is flat. If the proposed "IG Δη - storm surge" relationship holds true, then it is likely a non-linear process: As the water level is increased due to storm surge development, the total water depth increases allowing for more efficient propagation of IG energy into the active coastal margin. This would be the case in back-bay or inshore areas (with unobstructed exposure to the open coast) where the slope of the bottom is very flat.

4.1 Evaluation of Proposed Relationship Between IG Energy (Δη) and Storm Surge

The proposed "IG Δη - storm surge" relationship is evaluated by: A) reviewing visual documentation of storm surge development, and B) applying a 2-D Boussinesq model to assess the interaction of shoreward propagating long and short waves and related effects on WSE.

<u>Photographic Observation</u>. Hurricane Katrina brought much regrettable devastation to the Gulf Coast of AL, MS, and LA and there were many eye-witness accounts of the storm's landfall and attendant storm surge development. Figures 7, 8a, and 9 illustrate the development of Katrina storm surge at Gulfport, MS, from a location within 200 meters from the shore's edge of the Gulf of Mexico. Figure 8 shows storm surge development at Port Hedland, Australia, which was similar to the Katrina effect. The photographs and eyewitness account within figures 7-9 strongly suggest that coastal storm surge has at least some of its development associated with a continual series of long waves propagating onto the shoreface as hydraulic bores. If return flow from the bore is retarded, the following bore will force the transient water surface to build vertically and advance inland. As the long wave bores continue to attack the shoreface, the time-average WSE is elevated by each successive wave. As the WSE is increased, water depth is increased, allowing for unimpeded shoreward long wave propagation which then extends the wave surge effect further inland. As long waves travel inshore over an increasing water depth, short waves (seas) are able to propagate inshore bringing damaging forces to coastal resources, infrastructure, property, and people.

When the storm wave field begins to subside, the spectral forcing mechanism (enhanced bi-modal grouping of seas and swell) driving the bound waves stops. At this point in the storm, the IG transients ($\Delta\eta$) are reduced/ceased such that the mass of water (storm surge) pumped up by the IG transients ($\Delta\eta$) during the storm can return offshore to the ocean, for "open coast" areas. This process appears to be echoed by an eyewitness account of Katrina's passage at Gulfport, MS: "One of the most memorable parts of this experience for me wasn't how fast the surge came up, but how fast it subsided. It was like someone pulled the plug and instantly drained all the water"--*Mike Theiss, UlitmateChase.com.*

Boussinesq Modeling. The numerical model BOUSS-2D [Nwogu and Demirbilek 2001] was applied to evaluate the potential for a storm wave-field to produce IG transients on the water surface and subsequent "surge" along the shore's edge. 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 (see figure 1 and 10). 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 an multi-directional bi-modal spectrum (Ochi-Hubble, Tp1 = 160 sec, Hs1=2 m, nn1=2, Tp2 = 17 sec, Hs1=12.3 m, nn2=3). The model was run for 3,000 s using a 0.4 sec time step. Model output was obtained during t=2,000-3,000 sec. Tp1 was implemented based on the observations of long wave energy at MCR in water depth 35 m [Moritz 2006].

BOUSS-2D results are shown in figures 10 (bottom)-12. Figure 10 (bottom) shows a snapshot of the WSE throughout the model domain at t=2,942 sec. Modulation of the WSE can be clearly seen (due to the interaction of short and long waves). The nearhsore waves-field has been significantly transformed by the time the waves reach within 3 km of the shore's edge. Figure 11 illustrates how the simulated storm wave-field is modified from a point 10 km offshore (depth=23 m) to a point 200 meters offshore (depth=0.7 m), during the simulation time t=2,000-3,000 seconds. The wave field is transformed from a well-defined short wave group-dominated condition to that of a modulated short and long wave mish-mash with IG energy dominating the overall WSE. The period of the IG energy at the inshore location appears to be approximately 500 sec with amplitude of about 0.5 m. Figure 12 shows the time averaged WSE along a cross-shore profile through the model domain. The nearshore area is set-up with a "surge" of 0.85 m. Note that the slope of the model bathymetry matches the prototype condition of MCR (relative steep slope). Given the above results, it appears that the BOUSS-2D model produced wave-wave interactions resulting in the formation of IG energy, affecting the shoreface and generating a storm surge commensurate with PacNW observations.

5. CONCLUSIONS

The storm water level affecting "open" coastal margins can be composed of many processes (components). To better manage coastal zone risks, it is imperative that a basic understanding of these components be attained before initiating significant costal zone planning or implementing the design and construction of coastal infrastructure.

Transient water levels of 1-2 meters and associate rip currents (forced by storm wave infragravity energy) can significantly elevate the risks to life and property within the active coastal margin. More work is needed by the wave science/engineering community to fully parameterize the estimation of transient water level behavior, and use this information to improve our utilization of the coastal zone.

During landfall of severe maritime storms, the production of infragravity WSE transients by storm wave propagation 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.

6. REFERENCES

Center for Coastal Margin Observation and Prediction (CMOP), 2007., http://www.stccmop.org/

Daily, J.W. and Stephan, S.C. (1953). "Characteristics of a Solitary Wave", Transaction of the Society of American Civil Engineers, Vol 118, pp 575-587.

Dean, R.G. and Dalrymple, R.A. (1984). " Water Wave Mechanics for Engineers and Scientists", Prentice-Hall, Inc., Englewood Cliffs, NJ, USA.

FEMA (2004). Guidelines and Specifications for Flood Hazard Mapping Partners. Technical Appendix D

Interagency Performance Evaluation Task Force–IPET. (MAR 2007), Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Final Report: Volume IV – The Storm.

Longuet-Higgins, M.S. and Stewart, R.W. (1964). "Radiation Stresses in Water Waves; A Physical Discussion with Applications." Deep Sea Research. Vol. 11, pp 529-562.

Moritz, H. 2001. Observing Large Waves Using Bottom-Mounted Pressure and Current Meters, Ocean Wave Measurement and Analysis-Proceeding of the 4th International Symposium Waves 2001, ASCE, San Francisco, CA.

Moritz, H. P. and Moritz, H.R. (2004). "Regional Analysis of Extremal Wave Height Variability Oregon Coast, USA". Proceedings 8th International Workshop in Wave Hindcasting and Forecasting, Oahu, HI

Moritz, H.R., Gelfenbaum, G.R., and Kraus N.C. (2006). "Observations Of Cross Shore Infragravity Energy And Related Pulsating Bottom Currents" Proceeding of the 30th International Conference on Coastal Engineering, September 2006, San Diego, CA

Munk, W.H. (1949). "The Solitary Wave Theory and Its Application to Surf Problems", Annals of the New York Academy of Sciences. Vol 51, pp 376-462

Nwogu, O., and Z. Demirbilek. 2001. BOUSS-2D: A Boussinesq wave model for coastal regions and harbors. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-01-25, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Ruggiero, P. and List, J.H. (2007)."Improving Shoreline Position Uncertainty and Shoreline Change Rate Estimates by Accounting for Water Level Fluctuations", in preparation to be submitted to Journal of Coastal Research.

Wright, L.D., Friedrichs, C.T., and Scully, M.E. (2002). "Pulsation Gravity Driven Sediment Transport on Energetic Shelves", Continental Shelf Research, Vol 22 (2002), pages 2443-2460, Elsevier Science, Ltd.

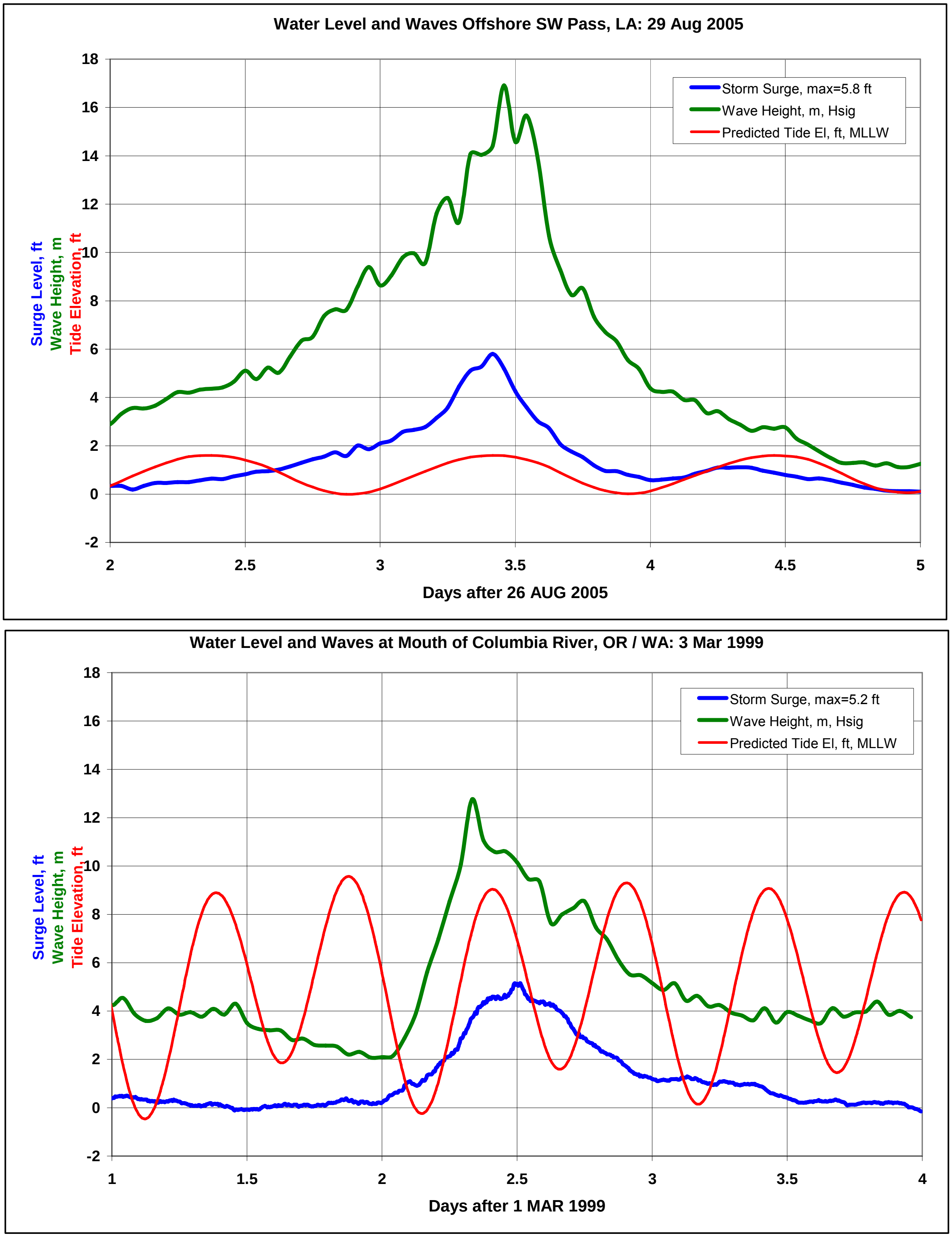


Figure 1. Examples of wave conditions and water levels that affect the coastal margin during extreme storm events. Storm surge = observed water elevation – predicted tide elevation. Top panel is offshore LA: due to Hurricane Katrina (water level is from NOAA gage at SW Pass, waves are from NDBC 46040). Bottom panel is offshore OR / WA: due to an extreme extratropical low pressure system (water level is from NOAA gage at Toke Pt. WA, waves are from NDBC 46029).

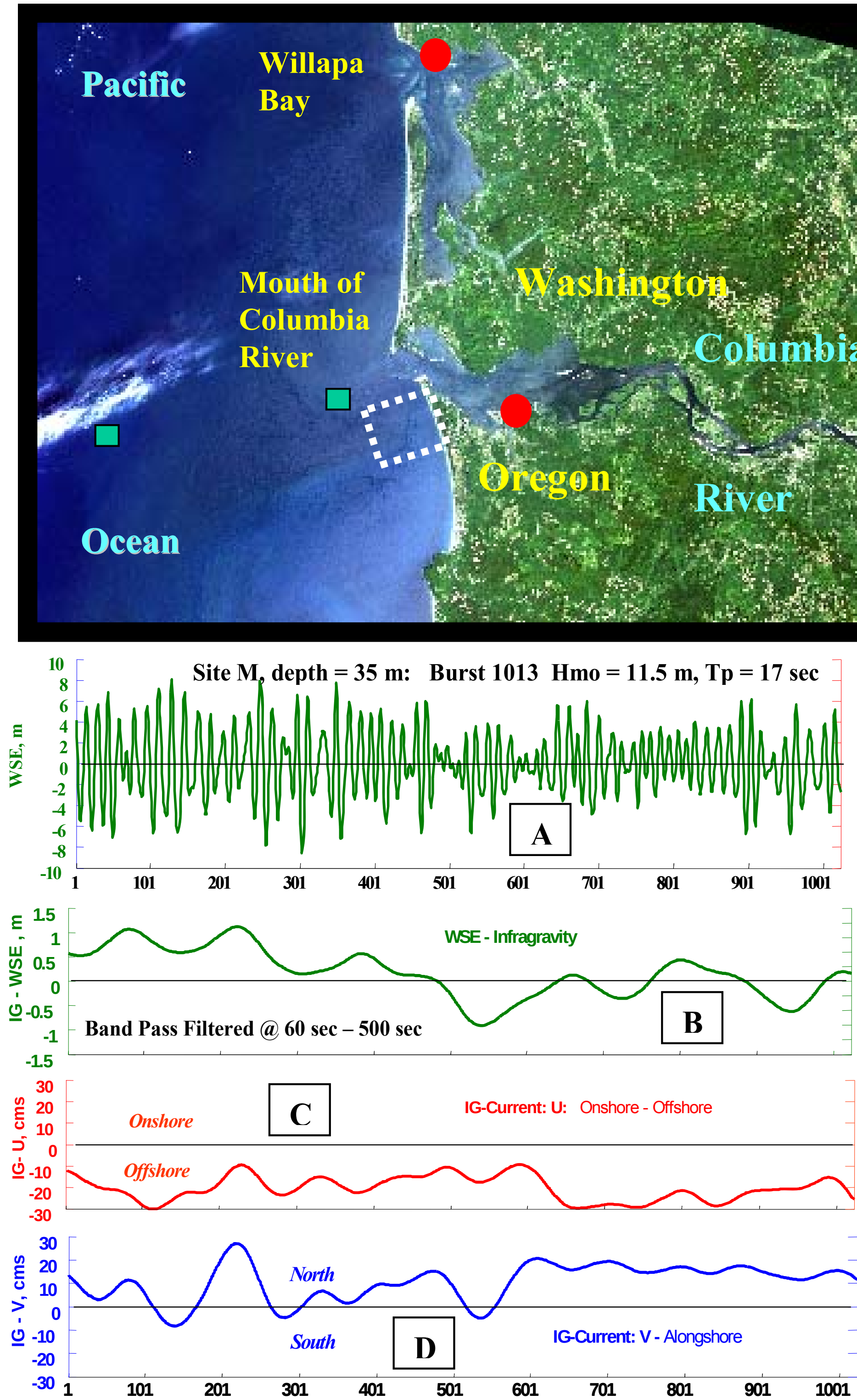


Figure 2 (TOP). Map of OR / WA coast, USA. Mouth of the Columbia River (MCR) is shown with tide stations for Toke Pt (Willapa Bay) and Astoria (Columbia River). Offshore green box is NDBC wave buoy 46029, 18 miles offshore. Inshore green box is monitoring station for infragravity energy (IG) shown in lower panel. White box is model domain for bouss-2d model used to evaluate effects of IG energy and wave-induced surge along the nearshore region. Figure 2-BOTTOM panel (A) shows 1020-sec time series burst for water surface during 3 MAR 1999 storm in 35 m depth. (B) Infragravity (IG) energy within the record, obtained by bandpass filtering. (C-D) IG-pulsing of bottom current for both U and V components. Note that U-IG is directed offshore (west) and V-IG is directed toward the north. Waves and wind were SSW.

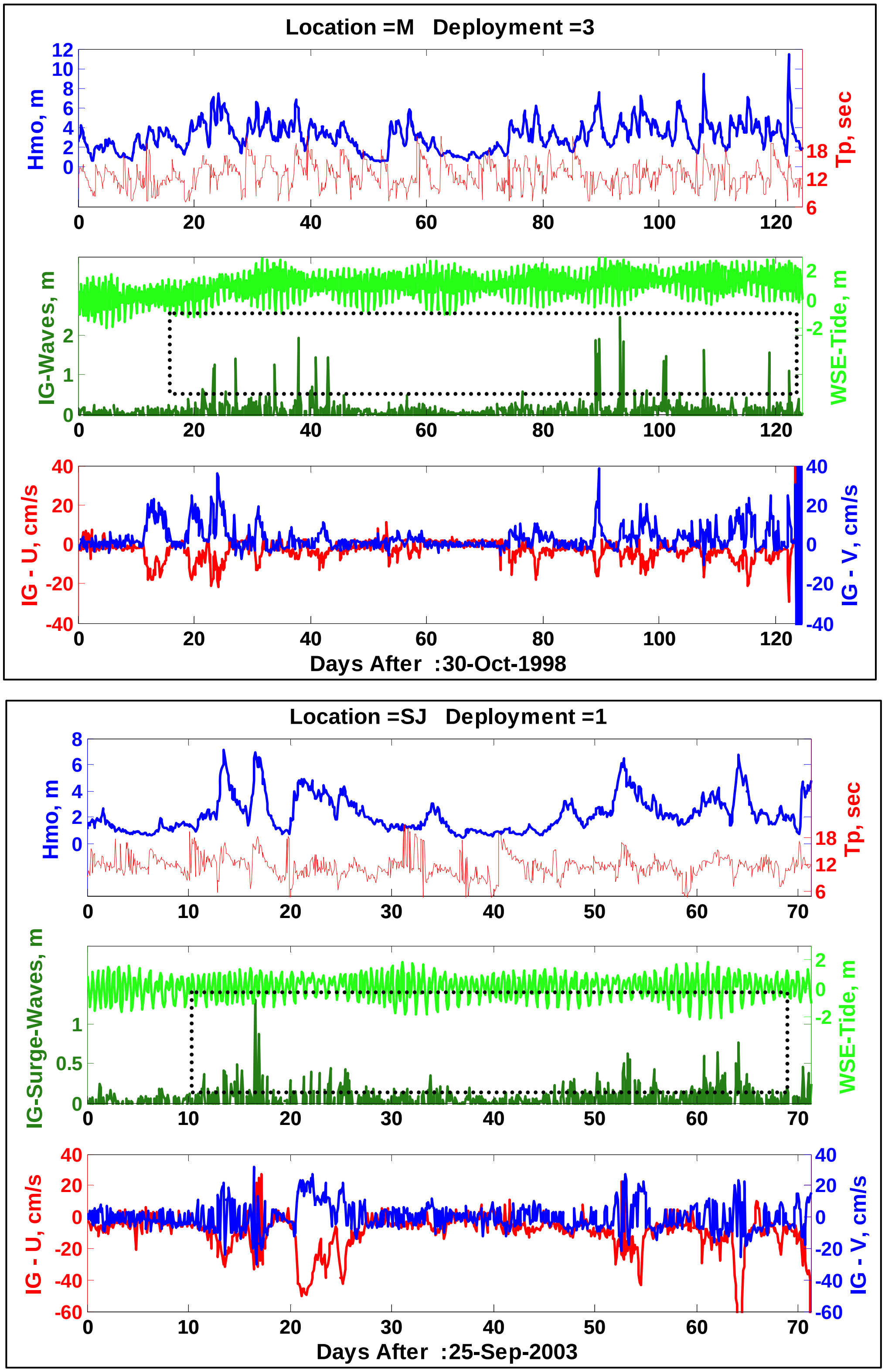
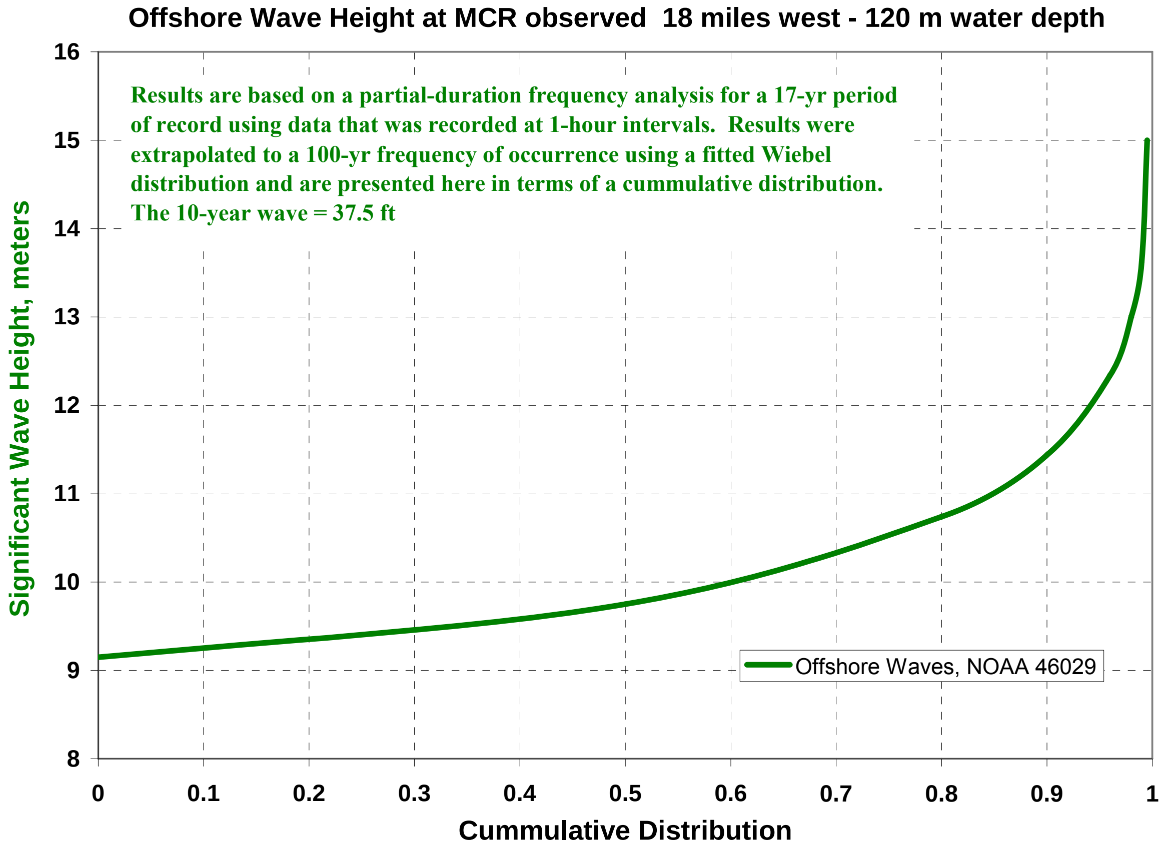


Figure 3. Summary of nearshore oceanographic data collection during NOV 98-MAR 99 (in 35 m water depth) and SEP – DEC 2003 (in 13 m water depth), approximately 2 miles south of MCR (locations shown in figure 2). The top graphs of each panel show burst averaged wave height and period observed at each deployment site. The middle graphs show the computed water surface excursion **(Δη)** due to Infragravity transients . The bottom graphs show the observed bottom current transients **(Δu)** associated with the infragravity enrgy responsible for driving the water surface transients.



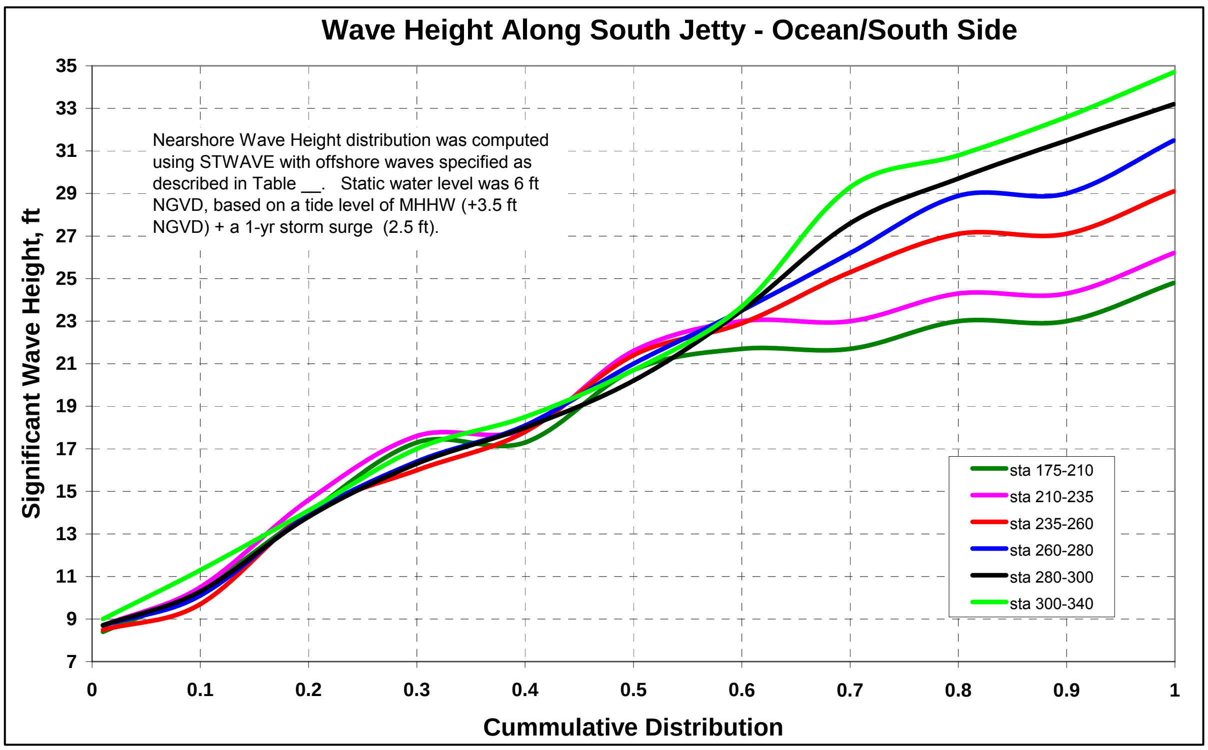
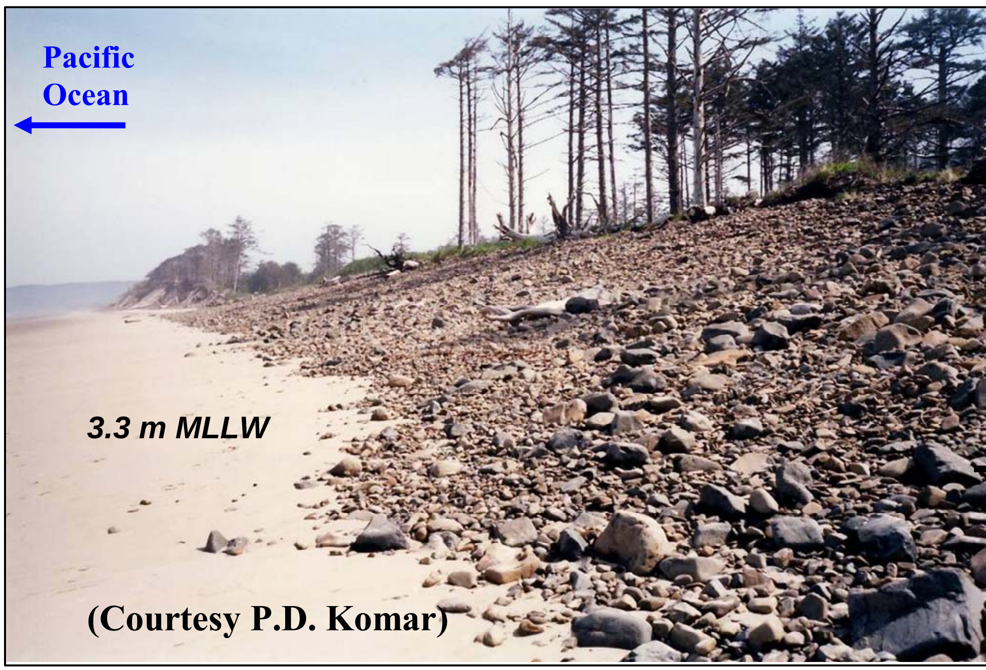


Figure 4. TOP. Cumulative distribution for wave height (Hsig) at MCR. BOTTOM panel. Computed wave height along an offshore transect, (just north of white box in figure) based on variation in morphology and depth (from 25 ft – 70 ft depth). For CDF values > 0.6, much of the wave action become depth limited for inshore areas. A transient change in water level of 2 meters would have considerable effect on the above the nearshore wave environment.

Figure 5. Project site for a dynamic (cobble berm) revetment and artificial dune to stabilize high amenity state park facility, on the Oregon coast. During MAR 1999, the top of dune (7.6 m MLLW) was significantly overtopped. Top photo: note the beach sand and cobbles carried over the dune crest by wave action and run-up. Several of the trees in the backshore area were missing bark due to cobbles abrading the bark off of the trees, suggesting a very high speed of cobble dispersal by the vigorous storm wave action and run-up. Estimates for the various components of water level required to allow this occurrence follow: High tide (2.7 m MLLW), storm surge (1.5 m), Longwave-infragravity transients (1-2 m), and short wave run-up (2-3 m). The total elevation for wave run-up was estimated to be 7.2-9.2 m above MLLW. Photographs provided *by **Dr. Paul Komar, Oregon State University,** through support of **Oregon State Parks and Cape Lookout State Park.** Special Thanks to **Dr. Jonathan Allan, DOGAMI,** project tech lead.*



Top of Dune ≈ +7.6 m MLLW

Static Storm Surge Water Level = +4.3 m MLLW

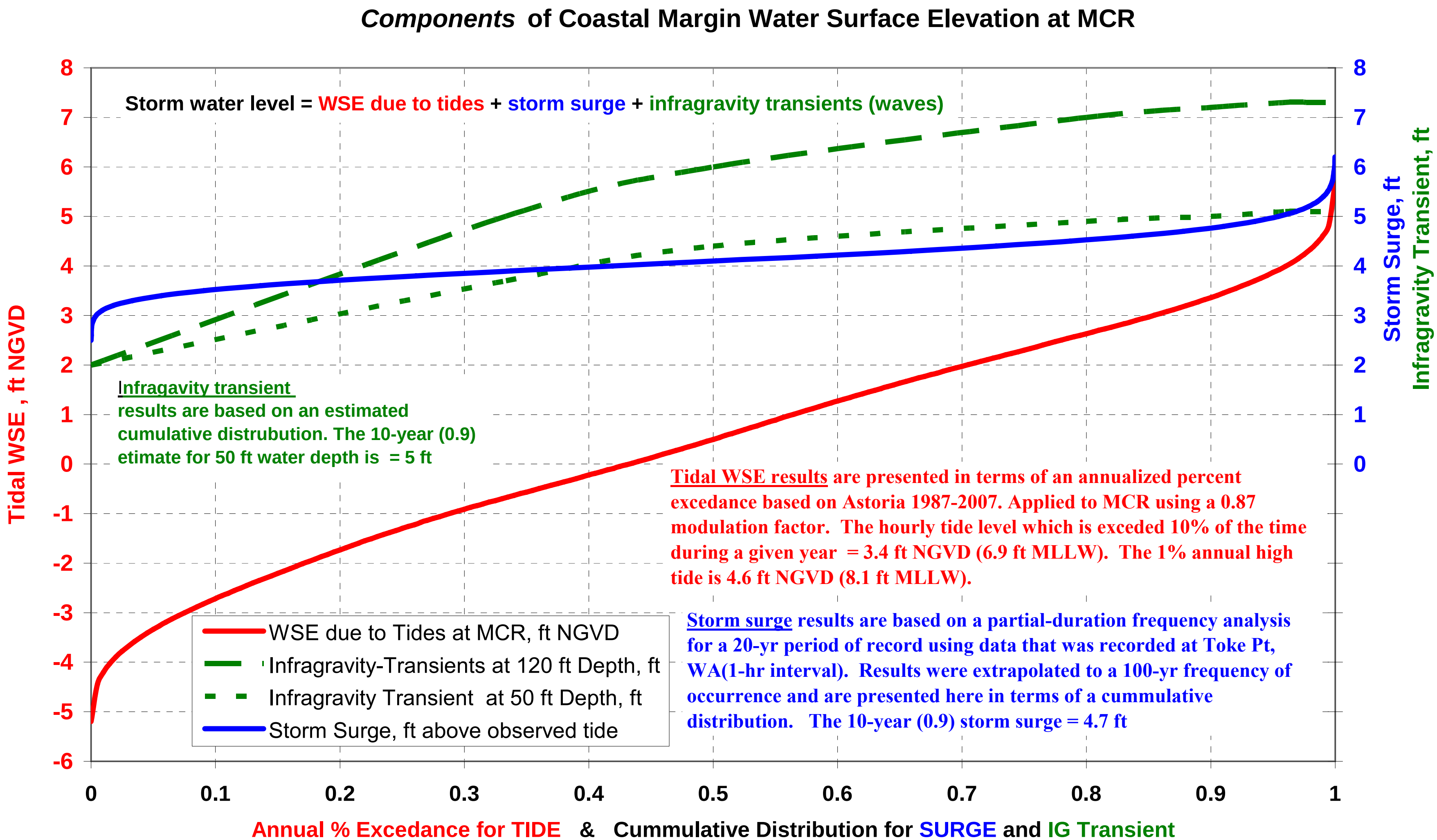


Figure 6. Components of water level along the costal margin at the Mouth of the Columbia River (MCR), OR / WA. The annual % exceedence for predicted tide elevation and cumulative distribution for surge were based on a 20 year period of record. Surge = observed water elevation – predicted elevation. The cumulative distribution for infragravity transient water level ($\Delta\eta$), was based on observation of transient water level during two field data collection campaigns offshore the Mouth of the Columbia River (MCR). Note that the transient component of water level can be larger than the storm surge water component of water level.

Figure 7. Arrival of Hurricane Katrina storm surge, as it came over US Hwy 90 at Gulfport, MS approximately two hours before storm peak made landfall. Time-line of photos proceeds left to right, top down. Note the how the surge is propagating landward in terms of individual bores or long wave transients ($\Delta\eta$). *Photography provided by **Mike Theiss – UlitmateChase.com***

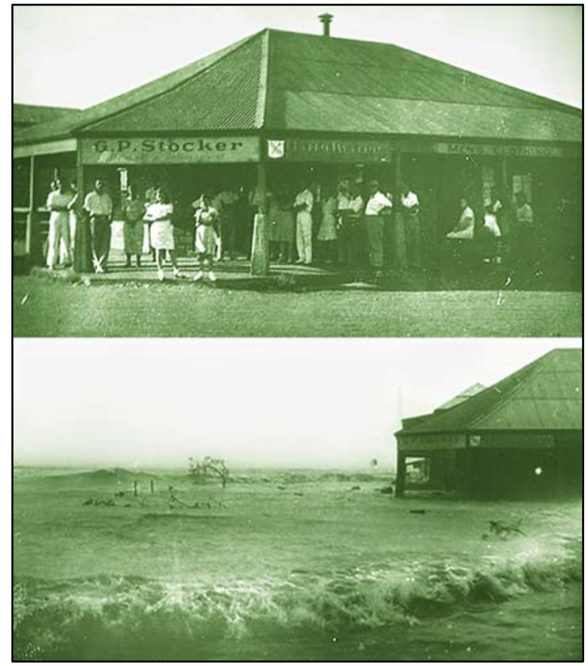


Figure 8. Before and during a storm surge event at Port Hedland, Australia, 1939. Note similarities of surge propagation within this photo and in figure 7. *Photo courtesy of **Australia Bureau of Meteorology***

Figure 8a. Photograph of levee being overtopped by waves propagating on top of storm surge during Hurricane Katrina landfall. The degree of overtopping is considerable. The level crest is shown as a dashed black line. Under such conditions, infrastructure behind the level can be damaged or incapacitated. This level of overtopping can lead to catastrophic failure of coastal flood protection (levee or floodwall).

Figure 9. (TOP) Hurricane Katrina storm surge as it entered Gulfport Beachfront Hotel during storm landfall at Gulfport, MS. Time-line of photos proceeds left to right, top down. The level of the water outside of the hotel (upper photos) is 2-3 ft higher than inside the hotel due to the rapid rise of the storm surge. The surge arrived at the hotel location in terms of long wave pulses, with short waves traveling on top of the long wave transients ($\Delta\eta$). An eyewitness account of the situation: “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. With every surge, the force of the water would bang new objects into my lower legs, threatening to knock me off my feet”. Bottom photos show how the surge entered the hotel thru an exterior entrance. The storm surge evolves as a series of landward propagating longwaves, each successive longwave transient ($\Delta\eta$) is superimposing additional water/momentum on the previous surge transient. As the water level increases, depth limited short waves (storm waves) ride on top of the long waves to add destructive power to the storm surge event. *Eyewitness testimony and photography provided by* ***Mike Theiss – UlitmateChase.com***

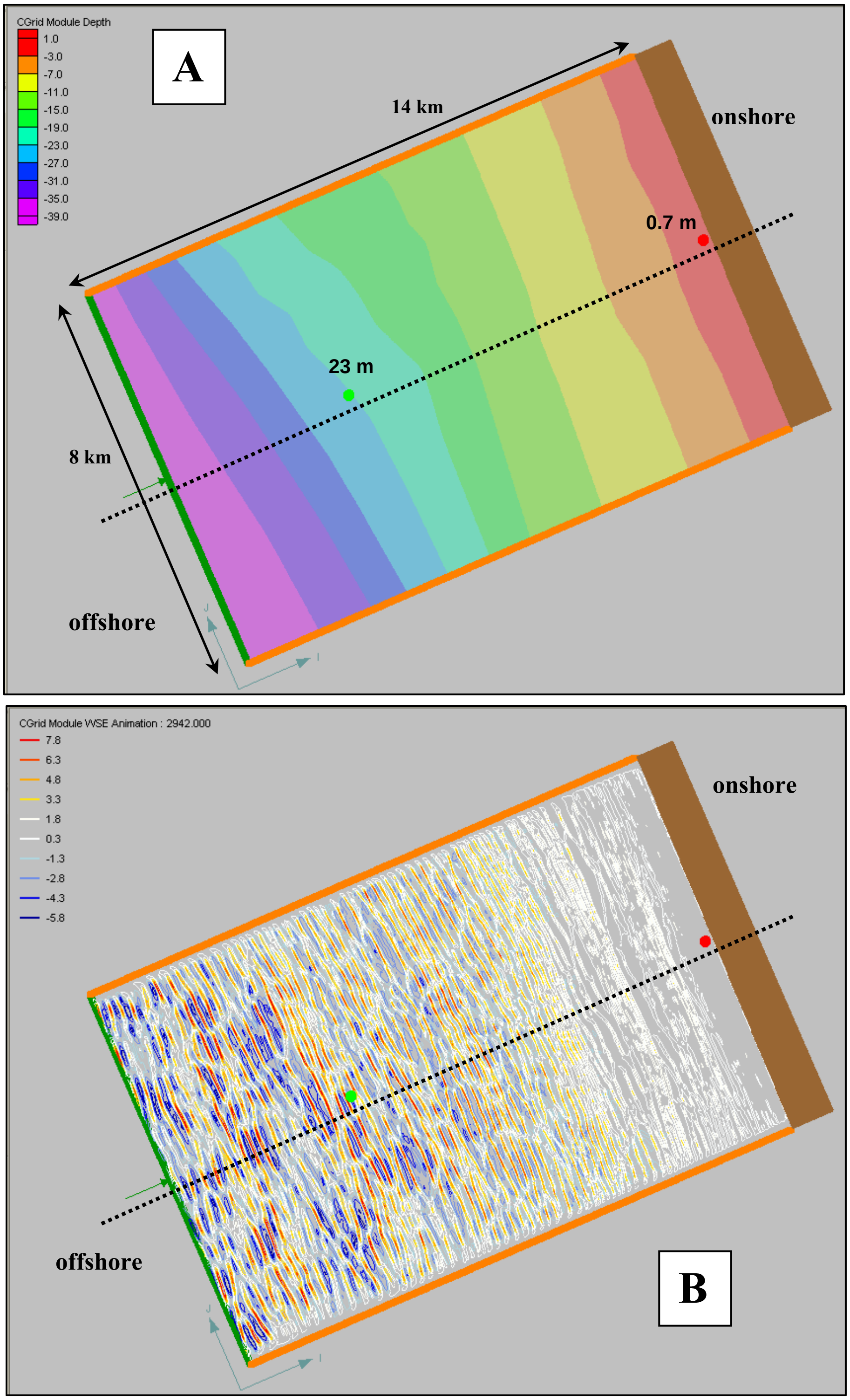
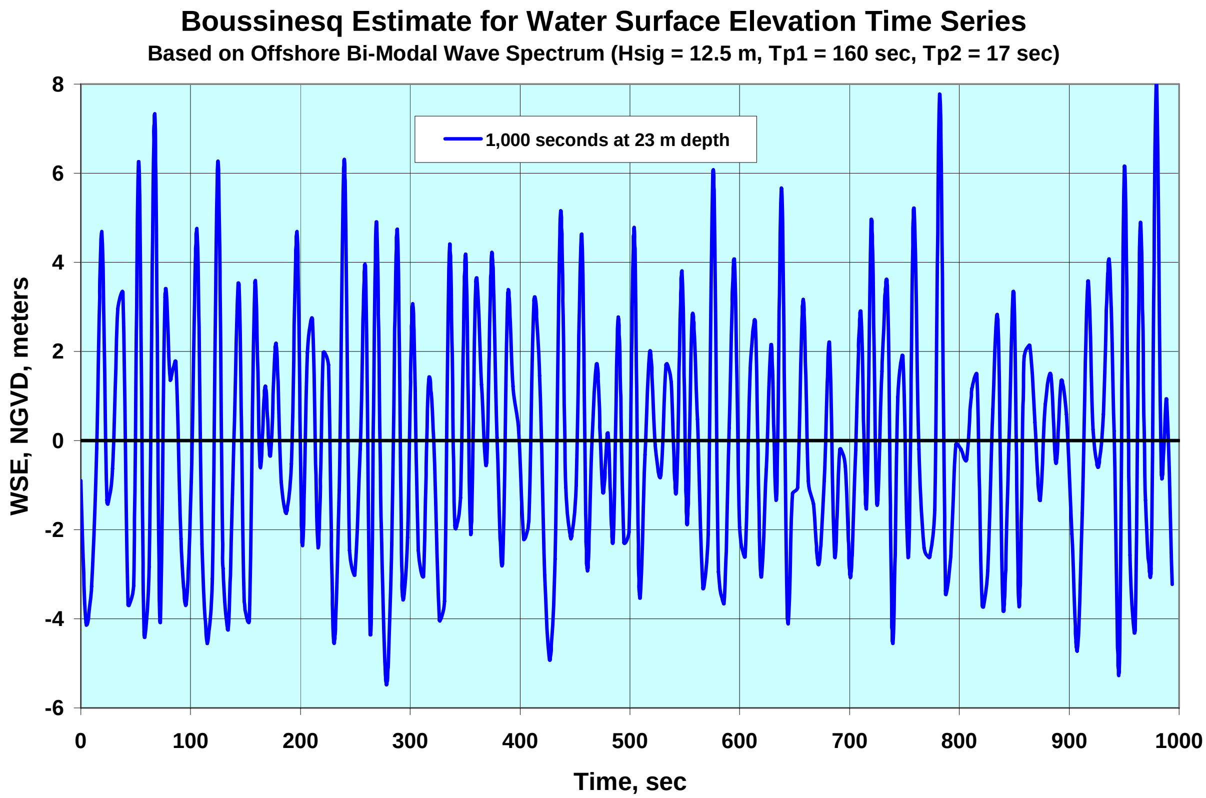


Figure 10. (A) Bouss-2D model domain used to simulate short and long wave propagation (featured area is shown in figure 2, white dashed box), to investigate formation of infragravity transients at the shores edge and "surge" development. Elevation contours are meters below NGVD and range from -38 offshore to +7 onshore. Black dashed-line is a profile alignment used to show variation in seabed elevation and time-averaged water surface elevation, WSE (figure 12). Green and red "dots" are point locations of data extraction for WSE time series (figure 11). (B) Shows the spatial variation of WSE (meters) due to shoreward propagating wave action at t=2,942 seconds into the simulation.



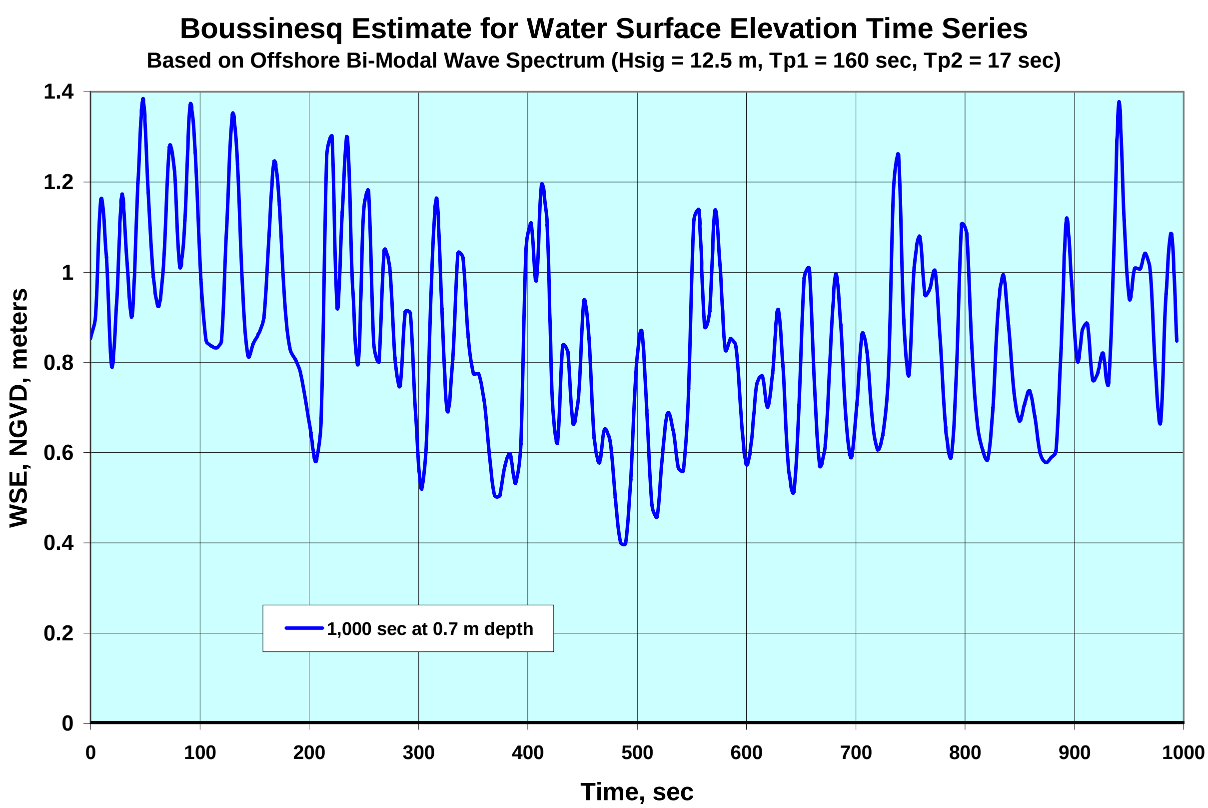
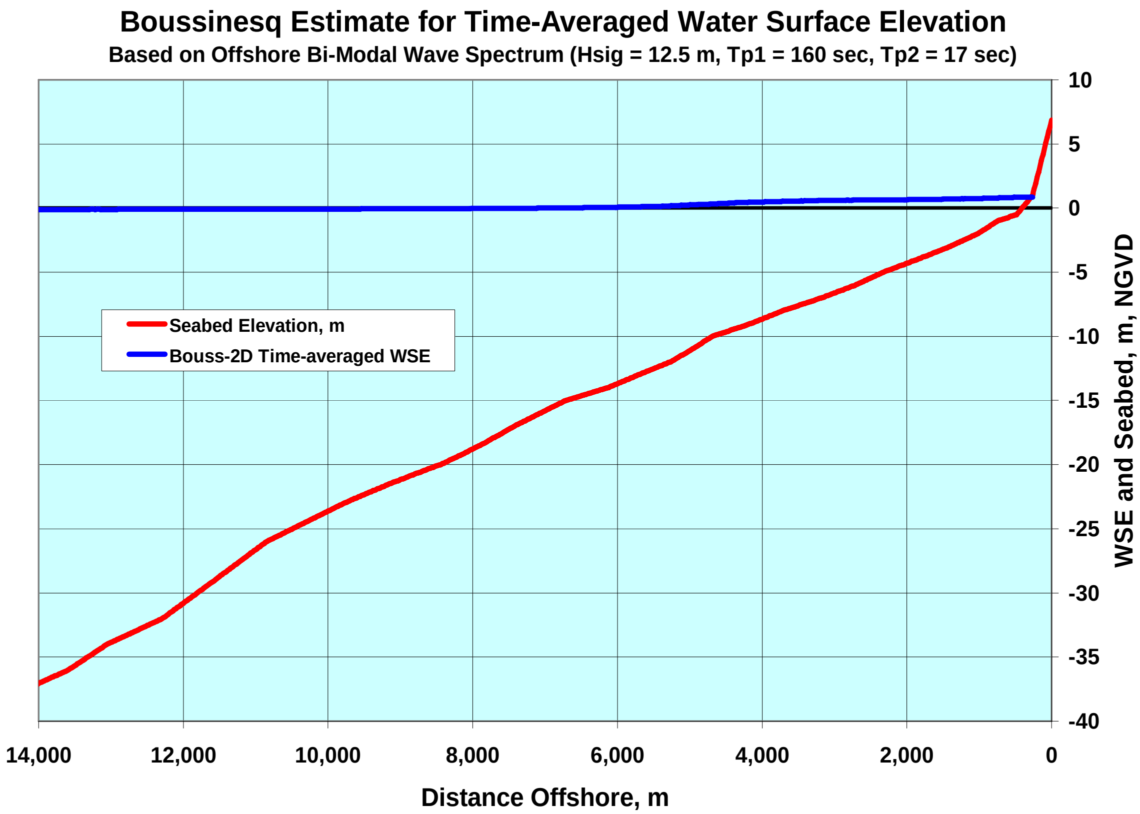


Figure 11. (Top) Time series of WSE at "green dot" (figure 10, depth = 23 m). Offshore waves are forced by bi-model spectrum. Note the modulation of waves into distinct groups (envelope of nodes and antinodes). This effect is manifest due to low frequency component of the wave spectrum. (Bottom) WSE time series at "red dot", depth =0.7 m. Note the transformation of the offshore wave field into long-period crest-dominated wave forms, and the longterm oscillation of water surface elevation. Local waveform amplitude ≈ 0.5-1 m.



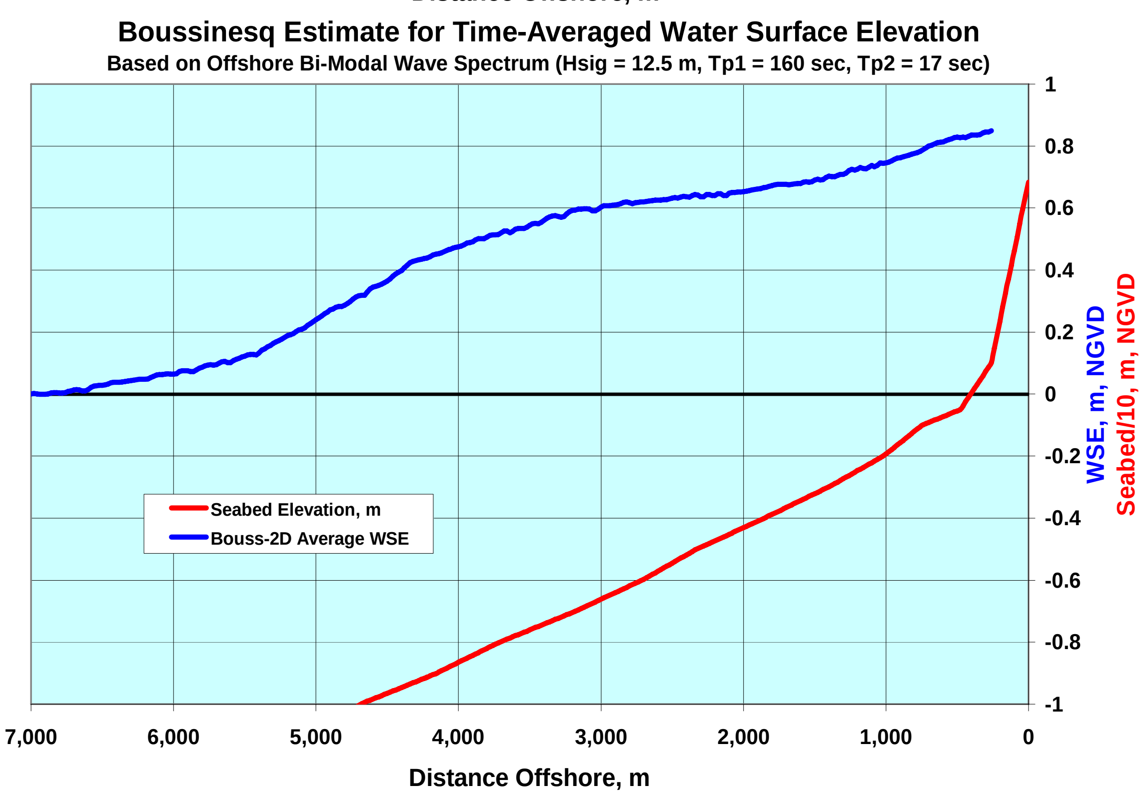


Figure 12. (TOP) Profile of seabed elevation and time-averaged WSE along "black-dashed line" (figure 10) for the entire model domain. The WSE was time-average during the t=2,000-3,000 sec. The average WSE becomes elevated within of 7,000 meters of the active shoreface. (BOTTOM) Detailed view of WSE/seabed profile showing development of wave surge (water level set-up) nearshore. The time-averaged WSE is elevated 0.85 m above the mean water level within 500 m of the shoreface.