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THE KURIL ISLANDS TSUNAMI of November 2006.
Part II: Impact at Crescent City by local amplification

(submitted to J. Geoph. Res.)

Crescent City (CC) is particularly susceptible to tsunami attack. The combination of tsunami signal enhancement by both distant bathymetric features and by local nearshore resonance seems to be responsible for this behavior. Application of global tsunami propagation models to the Kuril Islands Tsunami of November 2006 in the first paper delineated the importance of distant bathymetric features for both tsunami wave amplification and for increased duration of the tsunami arriving at CC. These distant features were responsible for delivering the late, high energy signal, which was delayed by two hours from predicted arrival time. Additional local amplification and increased duration are caused by the shelf bathymetry adjacent to CC. As the initial tsunami arrives at CC, the shelf trapping mechanism tends to excite the gravest of the natural modes. This oscillation is slowly shifted towards the natural mode closest to the period of the incident tsunami wave packet. Short duration wave trains tend to influence the tsunami response at CC harbor in such a way that one hour after the first wave arrival, a much stronger wave will be generated due to the tendency of the shelf to initially ring at the frequency of the gravest mode. To investigate the local amplification of tsunami waves at the CC harbor and shelf, the response function and natural modes of oscillations are determined and analyzed by means of shallow water numerical approaches. The major periods found from this analysis are: 15 min, 20 min, 40 min and 67 min. Practical implications of distant and local amplification relate to the potential hazard near CC, highlighting the need for awareness of the tsunami signal duration. In this respect two time scales are important for this event: the 2 hour time delay due to distant bathymetric features and the 1 hour delay due local offshore bathymetry.

1. Introduction

On November 15/2006 at 11:14 UTC an earthquake with moment magnitude 8.3 was recorded 200 km east of the Kuril islands ($46.577^{\circ}N$, $153.247^{\circ}E$, 26.7 km depth - USGS location) which resulted in tsunami waves up to 1.76 m crest-to-trough reaching the California coast (see

West Coast Alaska Tsunami Warning Center webpage <http://wcatwc.arh.noaa.gov/previous.events/11.15.2006/11-15-06.htm>.

The tsunami made its way into the Crescent City (CC) harbor, destroying several docks and damaging at least 10 boats. The total damage in the harbor was estimated at US\$700,000. The first tsunami surge arrived at the CC harbor around 19:45UTC (11:45PST). The first surge caused no damage and it was hardly noticed by local witnesses. Unexpectedly, the destructive wave surge arrived 2 hours later. According to witnesses, the second in the series of larger waves did the most damage, as a strong current was generated in the small basin (Citizen's Dock) shifting boats and floating docks.

As stated in Part I of this study, distant bathymetric features were responsible for delivering efficiently the tsunami energy to this particular location. The prominent bathymetric features Koko Guyot and Hess Rise scattered, delayed and re-routed the tsunami signal. The scattered signal, coming from the west, traveled along the Mendocino Escarpment (i.e. step-like bathymetry change) where it was continuously enhanced and refracted towards CC.

It is well known that the coupling between tsunami forcing and the natural modes of basin oscillation can enhance tsunami signal in a particular location through resonance. Roberts and Kauper (1964) applied a simple formula for the CC harbor, considering it as a channel open at one end. The first natural mode period was 14.45 min and the second mode period was 4.8 min. Keulegan *et al.*(1969) suggested that shelf resonance of the offshore domain was responsible for the high tsunami amplitude at CC harbor. The offshore shelf was approximated as a semi-elliptic body of water for which natural periods can be found analytically. The natural periods of that study were estimated as 89 min, 35 min, 18 min and 15 min.

The interaction of the incident tsunami wave with the shelf geomorphology often results in the trapping and amplification of tsunami energy. Resonant response will depend on the time span of the incident tsunami wave train and whether the wave period arriving from the deep-sea is in proximity to one of the natural periods of the basin (Munk *et al.*, 1956). The longer the tsunami wave train, the stronger the resonance response will be. Sustained resonance is usually related to tsunami energy trapped on a shelf as coastal/shelf trapped edge waves (Fuller and Mysak, 1977; Fujima *et al.*, 2000; Rabinovich *et al.*, 2006)

The purpose of the present study is to determine possible causes of local wave amplification at CC due to the resonant process. In the following sections the tsunami observations along with the analysis of the natural oscillations are discussed briefly.

Two possible causes of local amplification are studied: a) natural

oscillations in the CC harbor, and b) natural oscillation on the shelf adjacent to CC.

2. Observations and Data Analysis

An analysis of the tide gauge record at CC is shown in Figure 1. The recorded sea level and predicted tide are given in Figure 1a. In Figure 1b, the sea level has been de-tided and the mean sea level removed. A wavelet analysis and a power spectra density estimate are given in Figures 1c and 1d.

The leading edge of the tsunami arrived at 19:45UTC, with the wave amplitude growing to an amplitude of 40 cm one hour later, and culminating about 1-1/4 hours after that (22:00UTC/2:00pm PST) in the highest wave of approximately 80 cm amplitude (1.76 m crest to trough). Fortunately, the higher wave surge arrived at low tide as is indicated in Figure 1a. This low sea level condition avoided potential flooding but enhanced the current in the internal dock (Citizen's Dock) entrance as reported by witnesses (http://www.usc.edu/dept/tsunamis/california/Kurile_2006/). Examination of the wavelet analysis indicates that background oscillations in the harbor or shelf exist before and after the tsunami (Figure 1c). The period of these background oscillations ranged from 20 min to 30 min but in general it persisted around 20 min. Similar background oscillation has been observed in a recent study at CC by Rabinovich *et. al* (2006). During the tsunami the range of periods extended from 10 min to 50 min. The largest energy maxima (Figure 1d) are associated with periods of 21 min, 19 min, 30 min and 16 min.

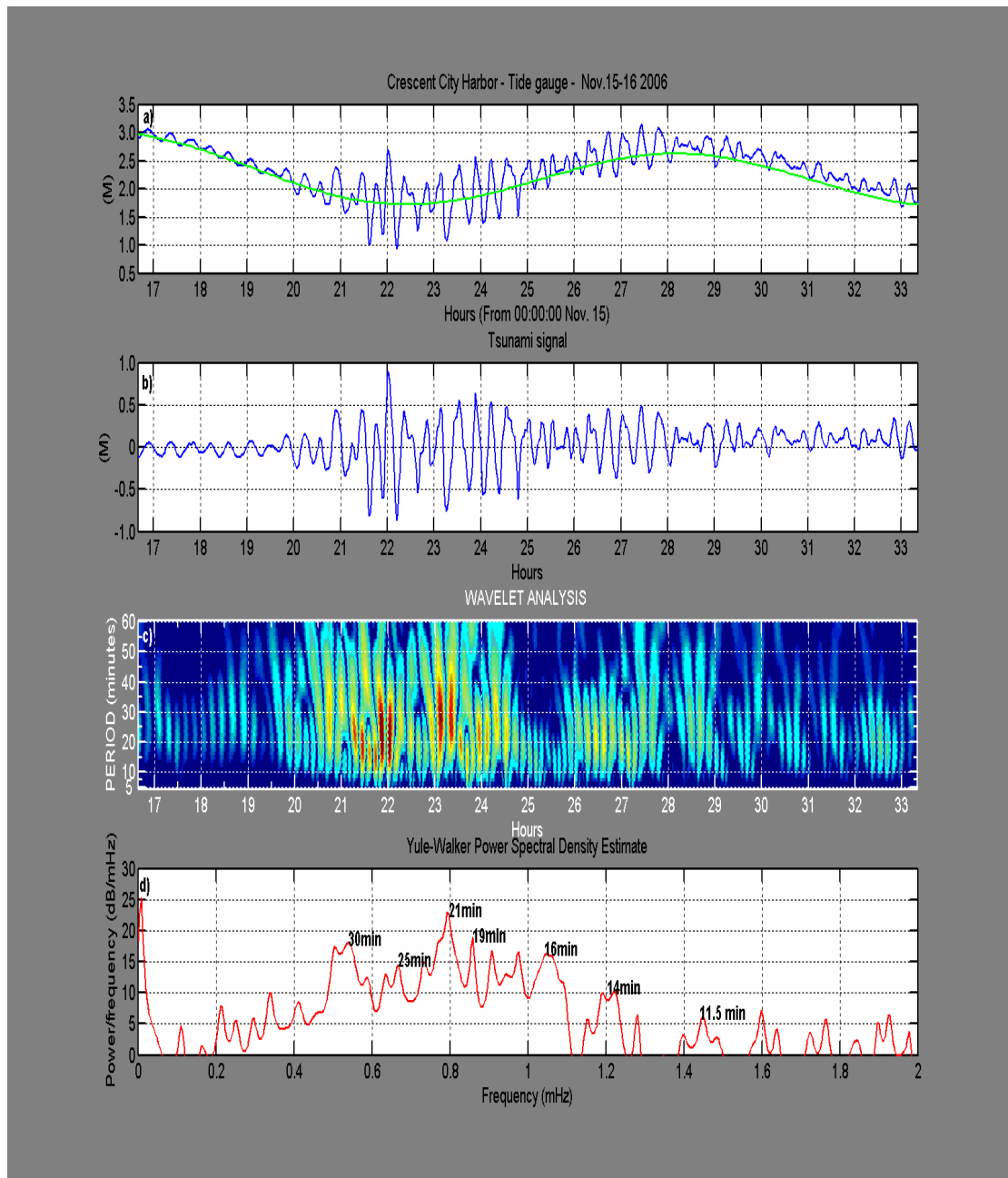


Figure1. Crescent City sea level analysis during Kuril Tsunami of November 15, 2006; a) Blue: recorded sea level; Green: predicted tide; b) tsunami signal (mean sea level and tide removed); c) wavelet analysis using Daubechies wavelet No.3 (normalized values in dB); d) power spectra density estimate using Yule-Walker auto-regressive filter.

In water bodies susceptible to resonance, only the first few recorded tsunami waves can give some indication of the structure of the tsunami arriving from the distant ocean. Thereafter, as pointed out by Munk *et al.* (1956), selective amplification of those particular periods that are in resonance with the basin should dominate the record. The first tsunami wave has a period of 24 min as can be gleaned from Figure 1. This is also consistent with the tsunami signal recorded at the nearest DART buoy

(D411 in Part I).

The gauge record (see Figures 1b and 1c) reveals a late arrival of two wave packets starting at approximately 22:45UTC and 25:40UTC respectively. These wave packets have duration of about 2.5 hours and they have well defined envelopes. The growth and decay of wave amplitudes suggest the arrival of few (2-3) forcing waves with periods close to one of the shelf/harbor's natural modes. It is presumed that bathymetric features other than Koko Guyot and Hess Rise may be responsible for such later arrivals. A distinct behavior is observed in all tsunami packets. A maximum wave amplitude is attained about 1 hour after the first noticeable wave in the packets. This wave behavior is observed in some past CC tsunami records as well.

3. Tsunami Amplification Models

To determine natural modes of oscillation in the CC harbor and nearby shelf, two numerical methods which can deal with arbitrary shape and variable depth were used. First, the nonlinear shallow water numerical model was used to compute wave-height amplification factors (response function) associated with the shelf/harbor's response to incident waves; second, a finite difference numerical model was constructed to calculate the natural (or eigen) periods and corresponding natural (or eigen) modes for CC harbor and shelf. The methodology used to determine the response function and natural modes is briefly explained as follows.

3.1. Response Function

Equations of motion along E-W and N-S directions (Kowalik and Murty, 1993),

$$\rho_o \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - fv \right) = -g\rho_o \frac{\partial \zeta}{\partial x} - \tau_x^b/D \quad (1)$$

$$\rho_o \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + fu \right) = -g\rho_o \frac{\partial \zeta}{\partial y} - \tau_y^b/D \quad (2)$$

and equation of continuity,

$$\frac{\partial}{\partial x} uD + \frac{\partial}{\partial y} vD + \frac{\partial \zeta}{\partial t} = 0 \quad (3)$$

are used to investigate shallow water wave propagation. In the above set of equations, u and v are horizontal components of the velocity vector, directed along E-W and N-S respectively, ζ is the sea level variation around mean-sea level, τ_x^b and τ_y^b are the components of the bottom stress vector, ρ_o is the density of water, f denotes the Coriolis parameter and g is the gravity acceleration. The total depth is $D = H + \zeta - \eta$. Here H is the depth measured from the mean-sea level and η denotes the vertical

component of the bottom deformation due to earthquakes or landslides. This set of equations is used to determine the response function of CC harbor and shelf basins by forcing with a given set of waves introduced at the open ocean boundary.

3.2. Natural Modes (*Eigenmodes*)

In order to investigate oscillation patterns of tsunami in CC harbor and at the adjacent shelf, we start by searching possible resonance amplification by using again the shallow water approach. Natural modes of oscillation of a given ocean basin can be calculated numerically as an eigenvalue problem. For this purpose, the equations of motion and continuity (1, 2 and 3) are linearized and the bottom friction, bottom deformation and Coriolis force are neglected. Assuming dependent variables in the above system change in time as $\exp(i\omega t)$, an equation for the sea level can be obtained (Mei, *et al.*, 2005)

$$gH\nabla^2\zeta + \omega^2\zeta = 0. \quad (4)$$

The boundary conditions satisfy $\frac{\partial\zeta}{\partial n} = 0$ along the coast and $\zeta = 0$ along the open (water) boundary. Here n is normal direction to the shoreline. The symmetrical numerical form of eq. (4) and symmetrical determinant to calculate natural (eigen) periods was constructed by Loomis (1973).

3.3. Natural Modes of Oscillation at Crescent City Harbor

Since the eigenvalues depend on water depth, and because the CC harbor basin is relatively shallow (Figure 2), calculations are sensitive to the tidal fluctuation (~ 2 m at CC). Two scenarios with extreme mean water levels were considered for the calculations: a) mean higher high water level (MHHW) and b) mean lower low water level (MLLW).

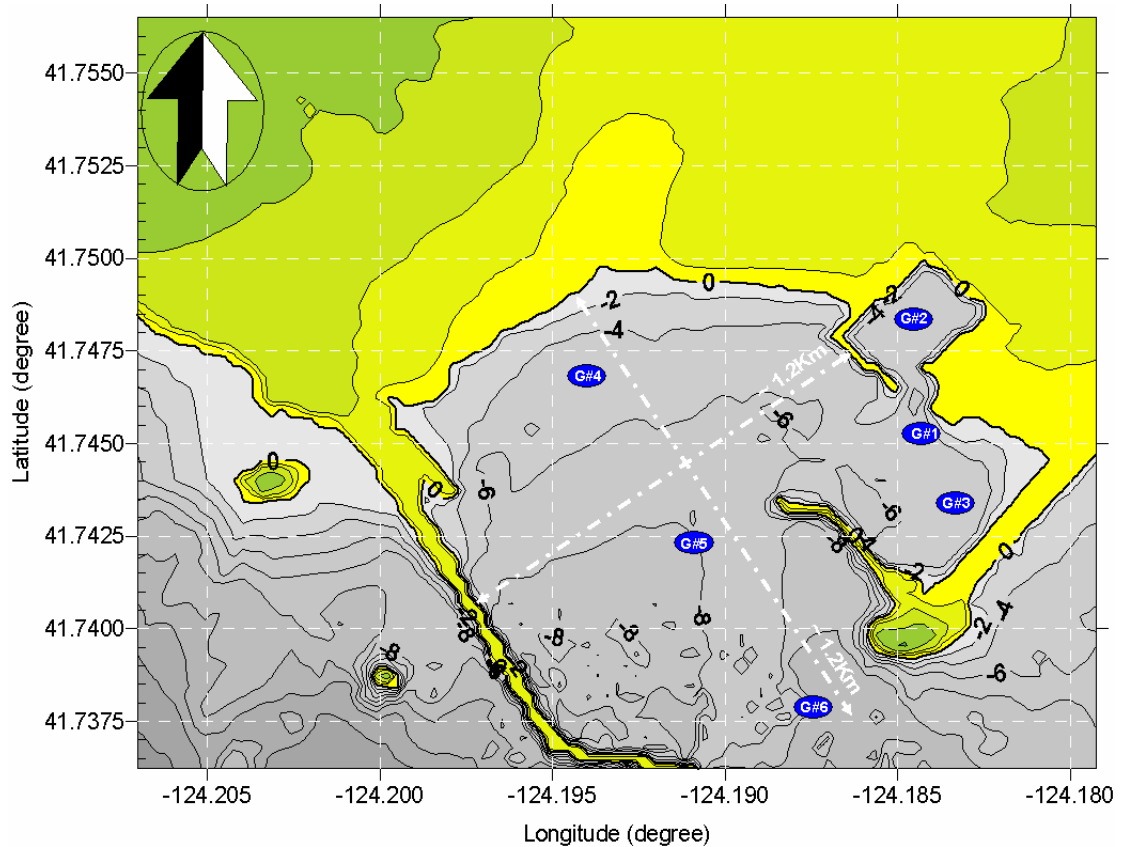


Figure 2. Crescent City harbor bathymetry and location of numerical gauges. Isobaths have units of meters.

Assuming a node at the entrance of the harbor and impermeable walls along the shoreline and seawalls, the following eigenperiods are obtained for each case scenario a) MHHW: 14.45 min, 7.68 min, 7.28 min, 5.68 min and b) MLLW: 15.68 min, 9.01 min, 6.38 min, and 4.71 min. Figures 3 and 4 show the eigenvalues and eigenfunction distributions for first four modes. Although the first four eigenvalues remain quite similar for the low and high mean sea levels, they are related to different distributions, thus underlining the importance of the tides in generating resonance oscillations in very shallow basins.

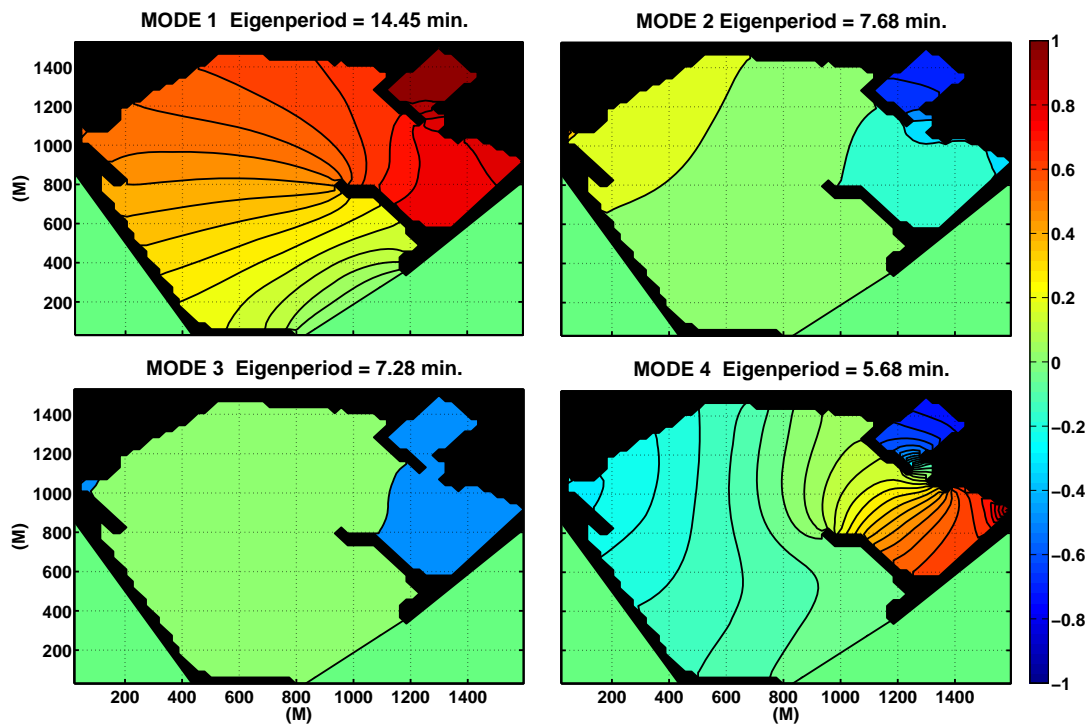


Figure 3. Calculated eigenvalues for the Crescent City harbor. The undisturbed sea level used in the calculations is the MHHW.

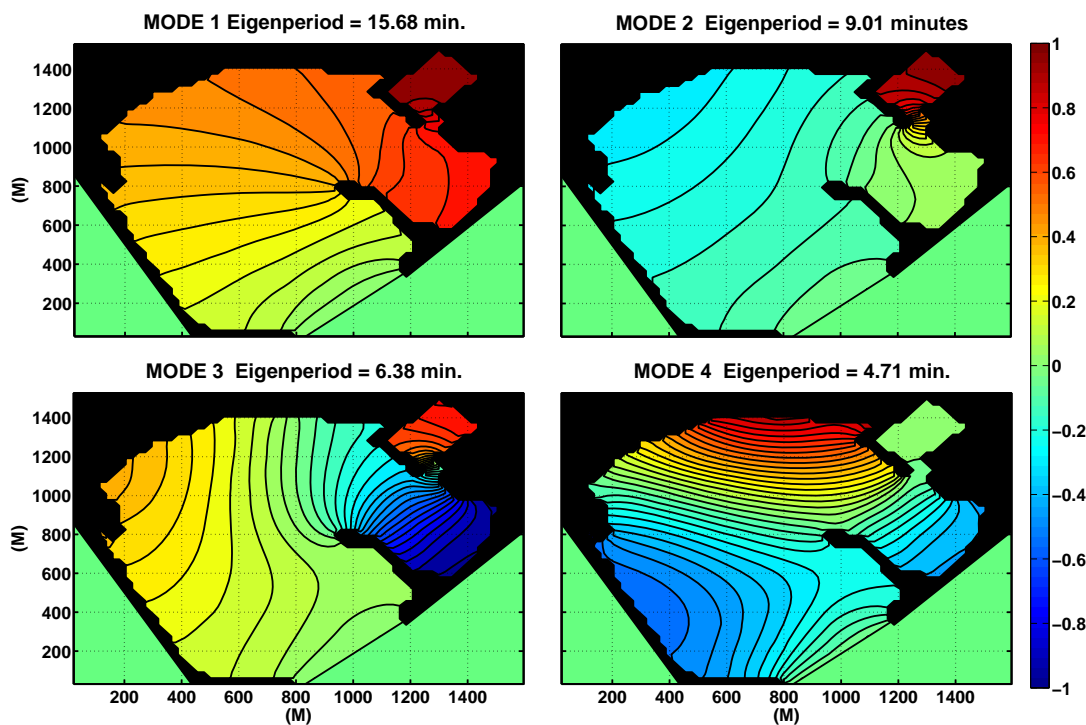


Figure 4. Calculated eigenvalues for the Crescent City harbor. The undisturbed sea level used in the calculations is the MLLW.

Roberts *et al.* (1964) approximated the CC harbor geometry as an elongated channel, using the formula;

$$T_n = \frac{4l}{n\sqrt{gH}} \quad \text{here } n = 1, 3, 5, \dots \quad (5)$$

For a channel of a length $l = 1200$ m, open at one end and of uniform depth $H = 3$ m, a back of the envelope calculation gave a first mode period of 14.45 min and 4.8 min for the second mode. The two-dimensional calculations given above reveal that the second mode period is much longer than 4.8 min because the CC harbor is not a single elongated channel but is instead comprised of three connected subdomains (see Figure 2), resulting in the complicated structure of eigenmodes shown in figs 3 and 4.

The approaches described above suggest that tsunami in the CC harbor can be amplified around eigenperiods through resonance. Since computations were done by assuming that friction and nonlinear terms are negligible, it is important to verify resonance phenomenon around those eigenperiods by including both friction and nonlinear effects in the shallow water numerical method (eqs.1-3).

To force oscillation in the CC harbor using the full system of equations, the domain has been enlarged from Figure 2 to include coastal/offshore bathymetric features and open boundaries. This larger domain has three open boundaries: eastern, western and southern. While at the eastern and western boundaries a regular radiation condition was used, at the southern boundary a continuous periodical sinusoidal wave of 10 cm amplitude was applied. The incident forcing wave is applied together with a radiation condition so that waves reflected from the harbor walls can pass through the southern boundary without reflection. The undisturbed sea level used in this calculation is based on MHHW.

Periods for the incident forcing waves in the range of 5-25 min were used to investigate the response of the CC harbor. Numerical gauges recorded sea level at six locations as indicated in Figure 2. The response function is shown in Figure 5. The period of 14 min dominates response function and the second maximum belongs to 8 min period.

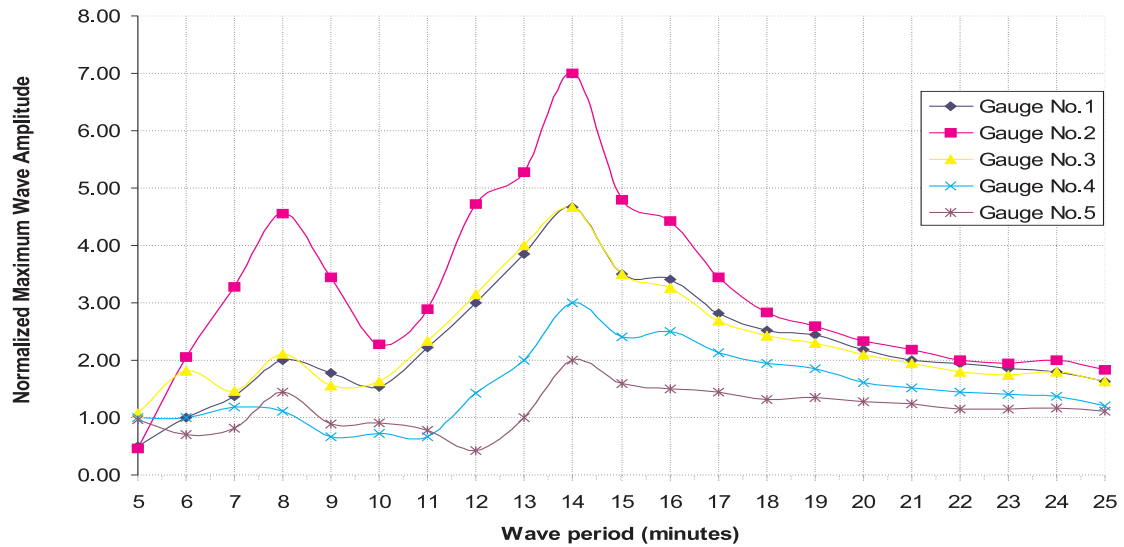


Figure 5. Computed response function for sea level in CC harbor at five locations. Response function is normalized by maximum wave amplitude at harbor entrance (Gauge No.6). Location of numerical gauges is shown in Figure 2.

4. Natural shelf oscillations adjacent to Crescent City

The most energetic period of 21 min obtained in the power spectra estimate (see Figure 1d) appears to be too long to be related to a resonance in the harbor. Therefore, an attempt is made to determine whether or not this period might be related to a natural period of the shelf adjacent to CC. The region within Pt. St. George and Patrick's Pt. was chosen to investigate tsunami amplification due to this resonance process (see Figure 6).

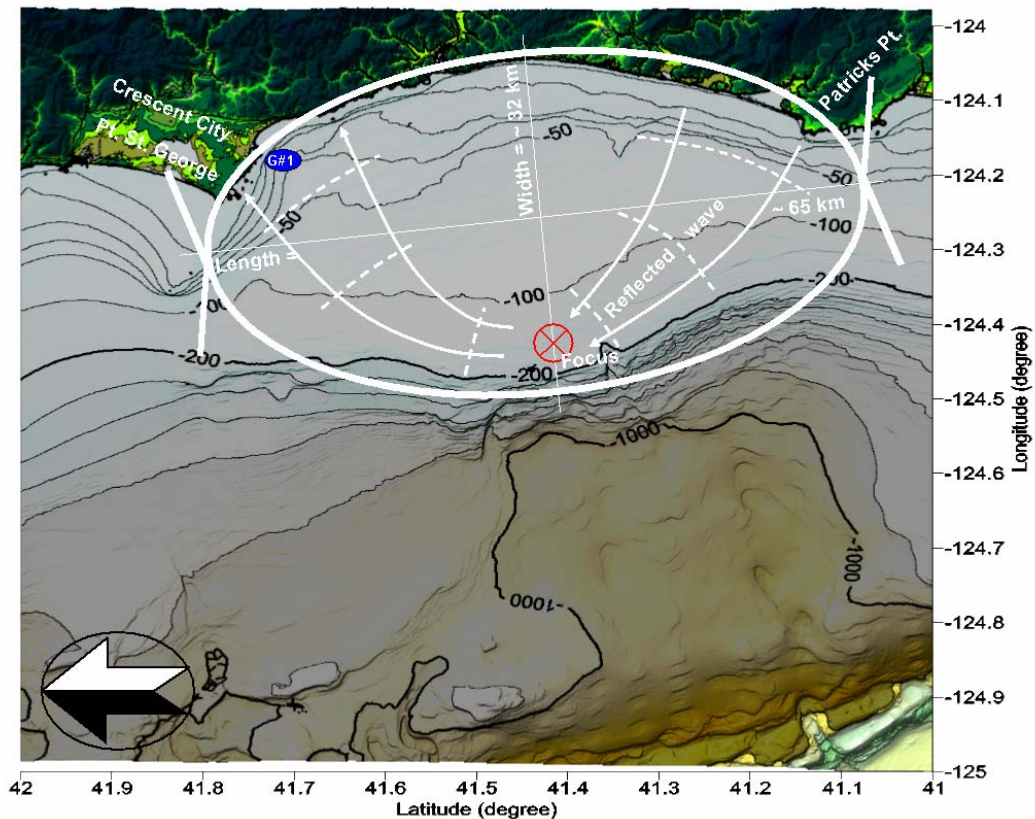


Figure 6. Offshore bathymetry in proximity to Crescent City. Concave and convex curvatures are drawn along shoreline and shelfbreak edge. Wave rays describe the path of a reflected wave from the Southeast to the Northeast concave curvature and the process of refraction, energy focusing and trapping.

This area has a peculiar geomorphology. Its limits resemble a convex and a concave curvature facing each other, one describing the shoreline and the other the shelfbreak edge. Convex/concave curvatures on lenses and mirrors are responsible for interesting optical properties such as the focusing, reflecting and refracting of light. The same can be inferred from this peculiar shape where shoreline, shelfbreak edge, and bottom topography play a similar role in reflecting, refracting, focusing and trapping wave energy. Our line of reasoning presumes that this particular geomorphology likely has strong resonance and focusing properties. This assertion is scrutinized with the same technique as was applied for the CC harbor.

The CC shelf has a width comparable to the wavelength of an incident tsunami wave propagating on the shelf in which the initial refraction/reflection mechanisms can start resonance and therefore amplification of subsequent waves. The CC shelf has an average depth of 77 m with slope of 6:1000 and extending north-south and west-east as shown in Figure 6. It will take approximately 20 min for shallow water

waves to propagate from the shelfbreak edge to the shoreline and about 40 min for the reflected wave to propagate from one side of the concave shoreline to the other side (as is indicated by the wave rays in Figure 6).

A set of numerical experiments was conducted to clarify the refraction/reflection and trapping mechanism, and to show finally the onset of one of the natural modes of shelf oscillation. The experiments considered a propagating wave approaching the shore from the west. As the incident deep-sea wave encountered the convex curvature of the shelfbreak edge (the submerged westward continuation of Pt. George and Patrick's Pt) is refracted, concentrating wave energy on the point marked as focus in Figure 6. The same can be said for the headlands Pt. George and Patricks Pt. where refraction concentrated wave energy on these headlands. The resulting enhanced wave shoaled against the concave coastline and by refraction mechanisms, the wave crest became nearly parallel to the shoreline (wave rays nearly perpendicular to the shoreline). During the period of inward shoaling, part of the wave energy was reflected back by the seabottom and coast. The reflected wave converged again to the focus point due to the focusing property of the coast's concave curvature and shelf bathymetry. During the outward travel to the focusing point, the refraction caused the reflected wave crest to become perpendicular to the shore. After it passed the focus, the wave turned inward to the opposite coastline to be reflected yet again.

The convex curvature and bathymetry of the shelf facilitates wave refraction, turning waves landward and minimizing loss of trapped energy. As the initial incident tsunami arrives at the CC shelf, the trapping mechanism tends to excite the gravest natural mode but this oscillation is slowly shifted towards the natural mode closest to the period of the incident tsunami packet. The resulting wave pattern on the shelf is very complex since trapped waves coexist with not-trapped wave and transient edge waves. The oscillation is sustained or enhanced by the initial wave train or by later intermittent tsunami-packet arrivals generated by prominent bathymetric features, e.g. Koko Guyot and Hess Rise. Note that waves incident from directions other than the west are effectively refracted towards the concave shoreline by the convex curvature of shelf and shelfbreak.

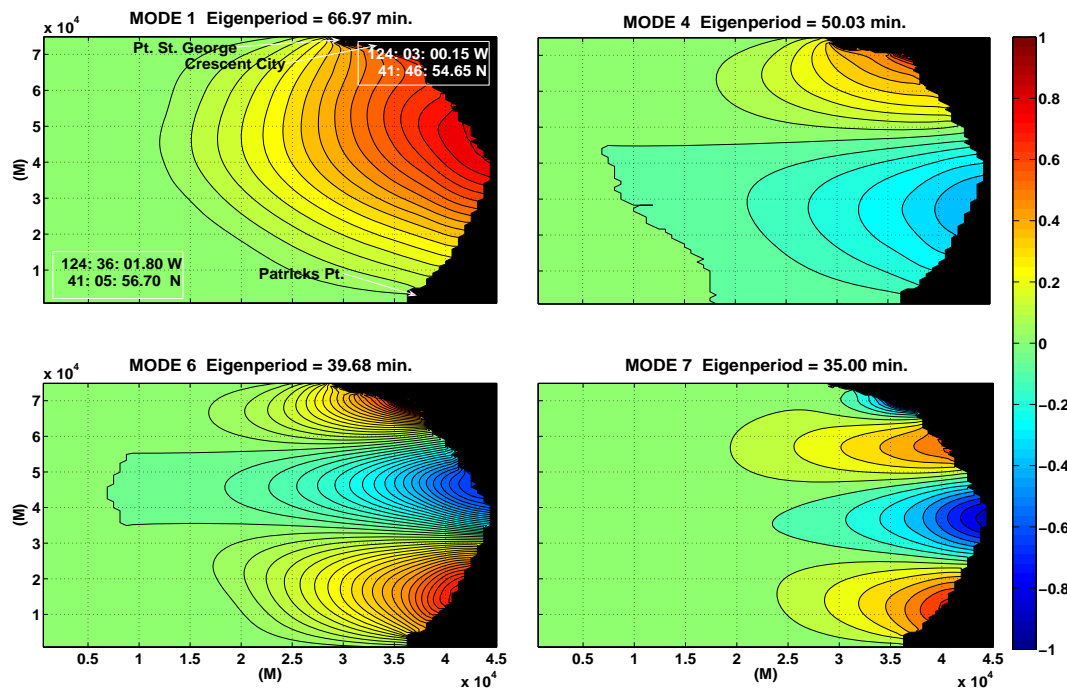


Figure 7. Eigenvalues of the shelf adjacent to Crescent City for modes 1, 4, 6 and 7.

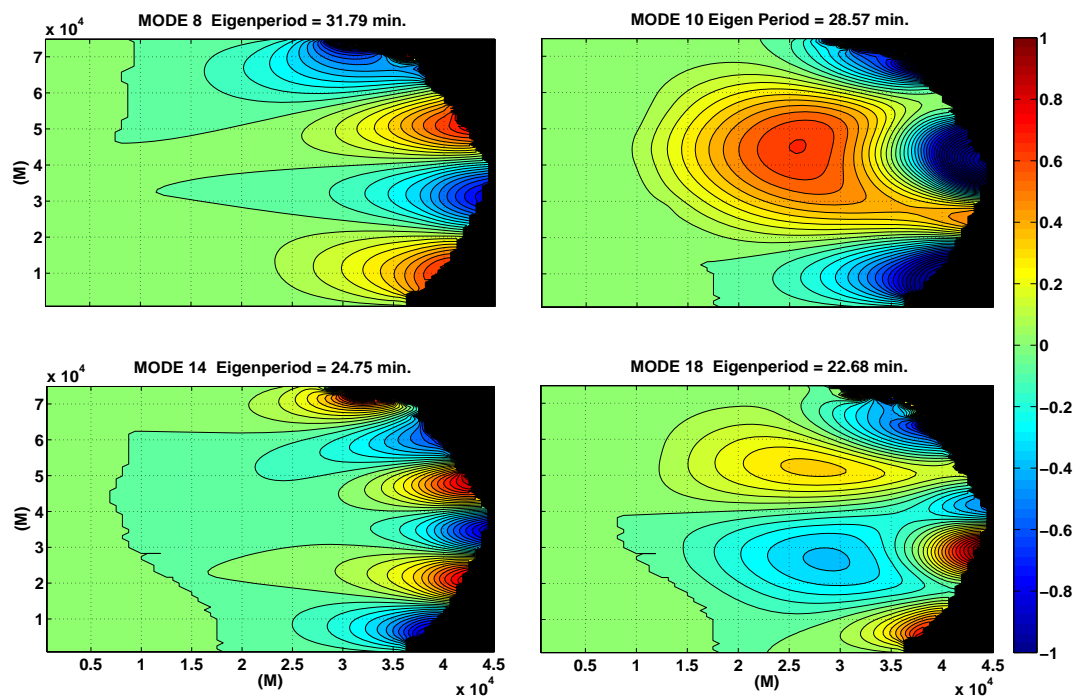


Figure 8. Eigenvalues of the shelf adjacent to Crescent City for modes 8, 10, 14 and 18.

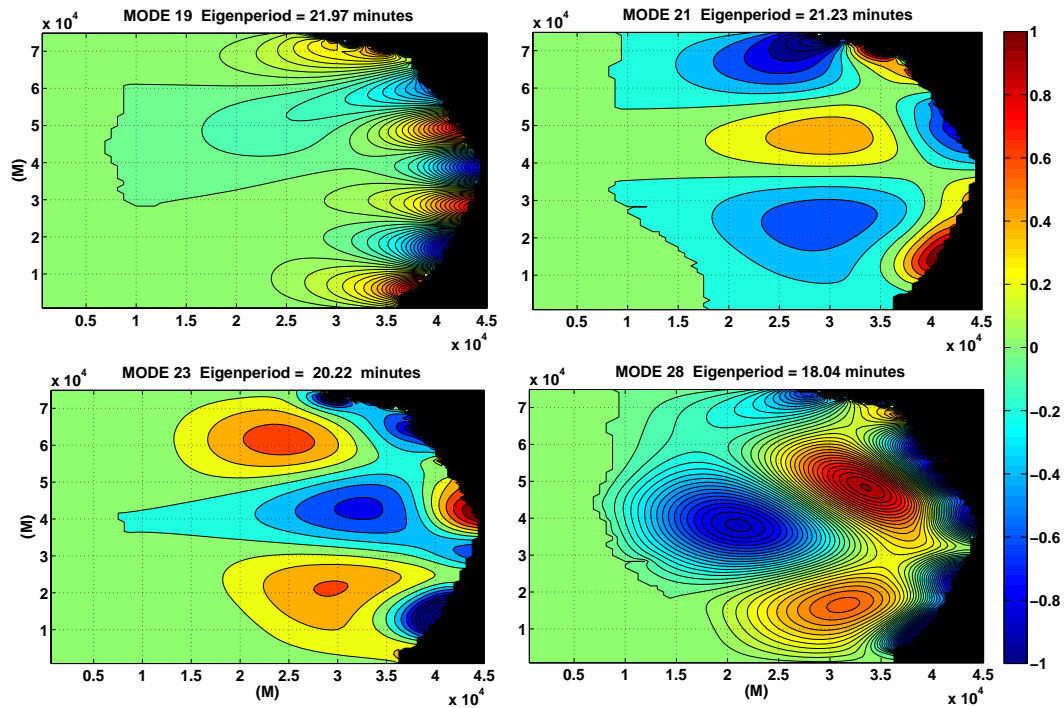


Figure 9. Eigenvalues of the shelf adjacent to Crescent City for modes 19, 21, 23 and 28.

As was done in the previous section for the CC harbor, natural modes of oscillation of the CC shelf are calculated numerically as an eigenvalue problem. Figures.7, 8 and 9 show a selected group of natural modes (eigenvalues) obtained using eq.(4). The calculations assume a node at the shelfbreak isobath of 200 m and walls along the shoreline (see Figure 6). The following eigenperiods are obtained amongst others: 67 min, 50 min 40 min, 35 min, 32 min, 25 min, 23 min, 22 min, 21 min, 20 min and 18 min. These natural modes have been chosen because they present symmetrical nodal line structure. Eigenmodes with eigenperiods 18 min, 20 min, 21 min, 23 min, and 28 min present antinodes on the shelf. These modes are believed to be quite efficient in trapping wave energy faster from outside as pointed out by Murty (1977).

A sea level response function is obtained using the nonlinear shallow water model to uncover efficiency of natural modes in transfer wave energy at a particular location close to CC, Gauge No.1 in Figure 6. Again for this calculation the domain shown in Figure 6 has been enlarged to the north, south and west. The response function shown in Figure 10 delineates basic maxima at the wave periods 40 min, 52 min, 21 min and 15 min. Thus, the 21 min maximum in the spectra from Figure 1 is connected to the response function of the shelf adjacent to CC.

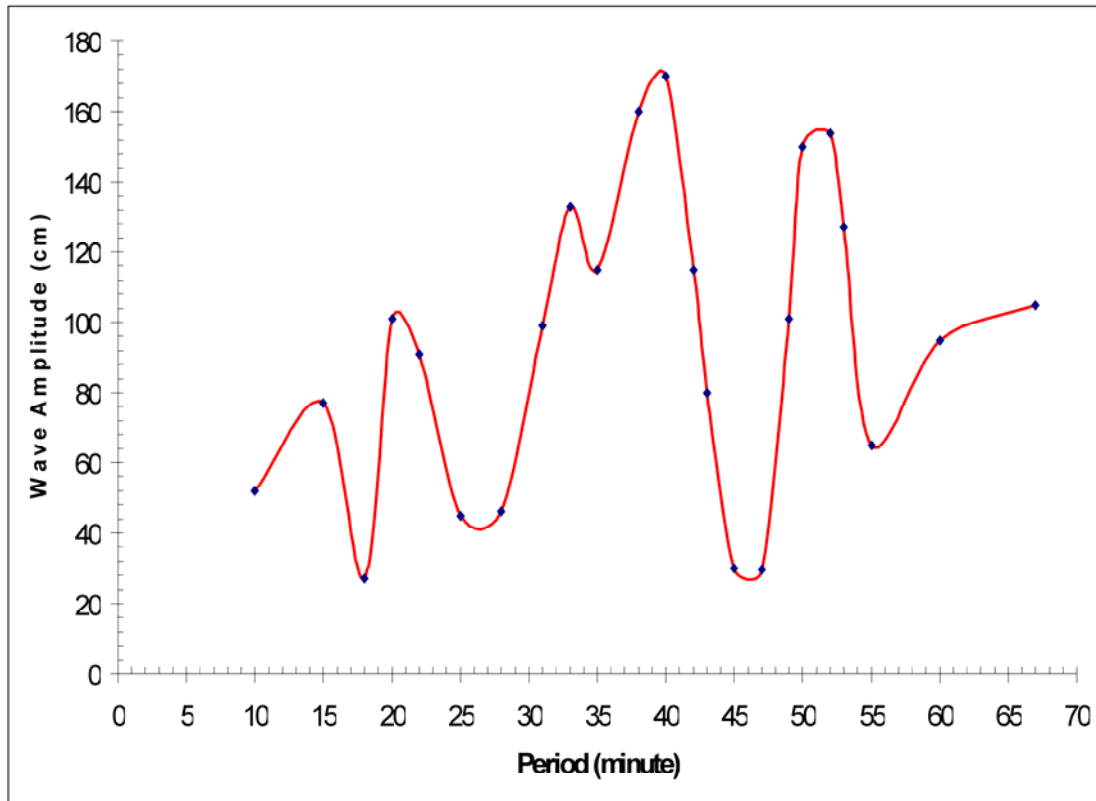


Figure 10. Computed response function for sea level outside CC harbor. Response function is due to periodic signal of 10cm amplitude at the western (open) boundary.

The continuous pumping of energy from the western open boundary into the shelf resulted in a stationary state condition with standing (trapped) waves along the shelf. It is well known that when a tsunami impinges on coastal irregularities it can generate waves which propagate away or along the shore as edge waves, Fuller and Mysak (1977). During numerical experiments it was noticed that some energy was leaking out (non-trapped mode waves) from the computational domain. The energy of oscillatory motion in the coastal domain is concentrated around peninsulas and a small portion of this energy is lost by radiation to the open sea and by generation of transient edge waves which propagate along the coastline, Munk *et. al.* (1956).

To examine the balance of inflowing and outflowing energy from the computational domain during one wave period, a control box from 40.5N to 42.5N and 126.5W to 124W is used. A continuous train of 40 min periodic waves is sent from the western boundary into the control box. After about 20 wave periods a stationary state condition is established and total energy (potential and kinetic) is constant in time.

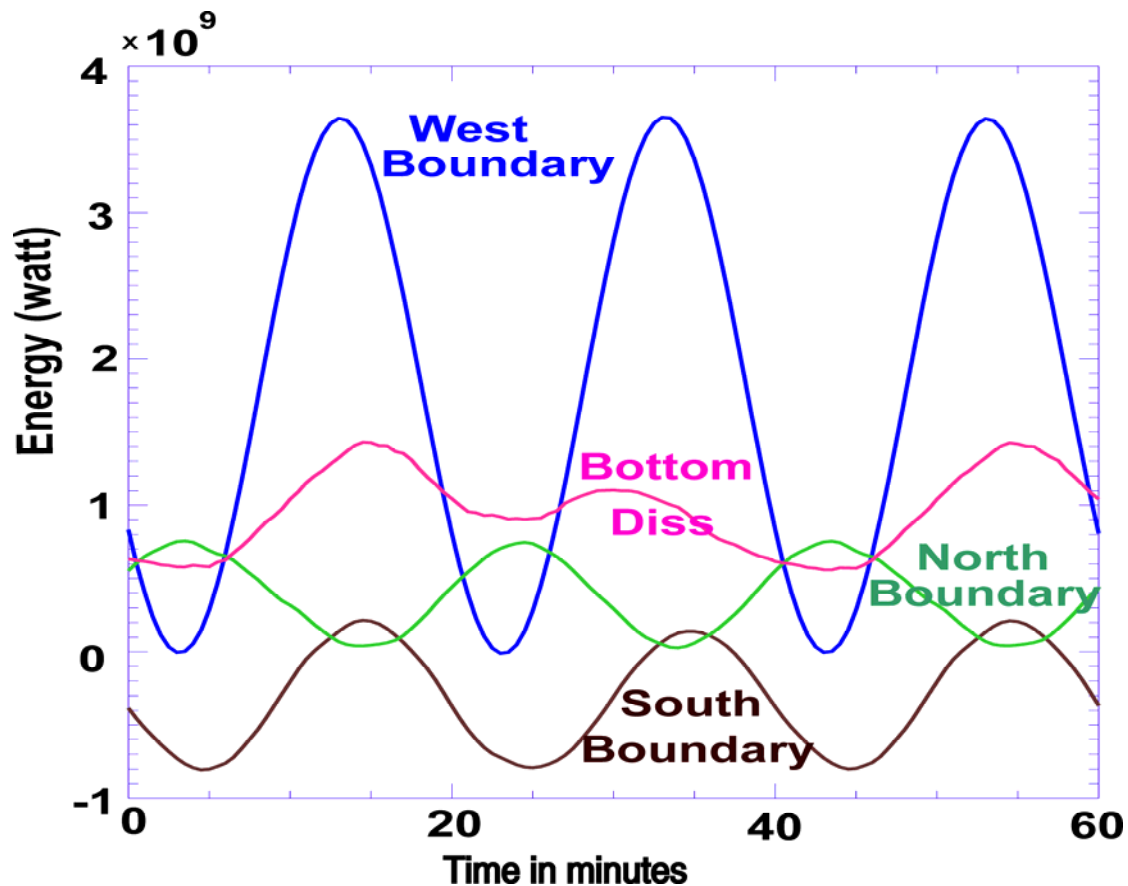


Figure 11. Energy balance for the 40 min period incident wave in the control box surrounding CC shelf. Energy influx through the western boundary is balanced by the outflowing energy from the northern and southern boundaries and the energy dissipated by the bottom friction.

Figure 11 describes the variable portion of energy as it changes in time. It includes fluxes for the stationary state through the western, northern and southern faces together with the energy dissipated by the bottom friction. If the energy is averaged over one wave period, the inflowing energy into the box through the western boundary ought to be balanced by the outflowing energy from the northern and southern boundaries and the energy dissipated inside box by the bottom friction. About 53% of the inflowing energy is dissipated by the bottom friction, 38% outflows through the northern and southern boundaries and 9% is unaccounted for probably due to nonlinear effects such as can be seen in the bottom dissipation term (Fig. 11). For the shorter wave period of 20min, up to 72% inflowing energy was dissipated inside the computational domain. It is also of interest to observe that the energy dissipated by bottom friction shows asymmetrical behavior in time, thus pointing to different current structure during runup and rundown.

Non-trapped wave energy was noticed traveling along the coast toward the northern and southern boundaries. Around peninsulas, higher energy is concentrated which is then radiated away in a transient edge wave

manner towards south and north.

5. Discussion and conclusions

Examination of Crescent City (CC) tide gauge record of Nov. 15, 2006 revealed the major tsunami energy maximum at 21 min period. The same period of oscillation, although less energetic, also occurred before and after the event. The search for natural oscillations inside the CC harbor and at the adjacent shelf revealed that the tsunami signal scattered by distant bathymetric features was further amplified by shelf resonant process. This amplification of the signal was produced by the peculiar shelf and coastal geomorphology adjacent to CC. On this shelf the 21 min period was found by using shallow water approaches, i.e., eigenmodes and response function.

The search for natural oscillations (eigenmodes) and a more practical approach related to the amplitude response function are based on an assumption of stationary oscillations in time. The examination of energy conservation during stationary conditions shows that there is a steady low level inflow of energy which is partly dissipated inside of the coastal domain and partly lost to waves leaking out of the domain. The latter often express the behavior of edge waves generated around coastal irregularities as suggested by Fuller and Mysak (1977).

Although power spectra and response functions help to pinpoint resonance conditions, the tsunami structure is complex and often intermittent in time and space. The short time-series of a tsunami train does not develop the full resonance/response condition for a given basin but can unveil some important resonance/response behaviors. A series of numerical experiments considering only one wave period serves to delineate intermittent behavior. Using the wide range of wave periods it was found that the CC shelf initially responds very similarly to different periods as it always tends to energize the gravest mode of the natural oscillations.

The trigger of this gravest mode of oscillation can be explained in terms of the refraction/reflection of gravity waves by the peculiar geomorphology of CC shelf. As the speed of surface wave propagating towards the coast decreases with water depth, wave-rays traveling toward shallow water are refracted against the concave coastline, the wave crest becomes nearly parallel to the shoreline to be uniformly reflected by bottom bathymetry and coast. The resulting reflected wave travels outward and on its way out, is refracted again, concentrating energy close to the center of the convex curvature of the shelfbreak. It is believed that this initial energy trapping starts the gravest mode of oscillation. The gravest mode is transient due to the selective amplification of incident

waves whose period is close to one of the natural modes of oscillations, Munk *et al.* (1956).

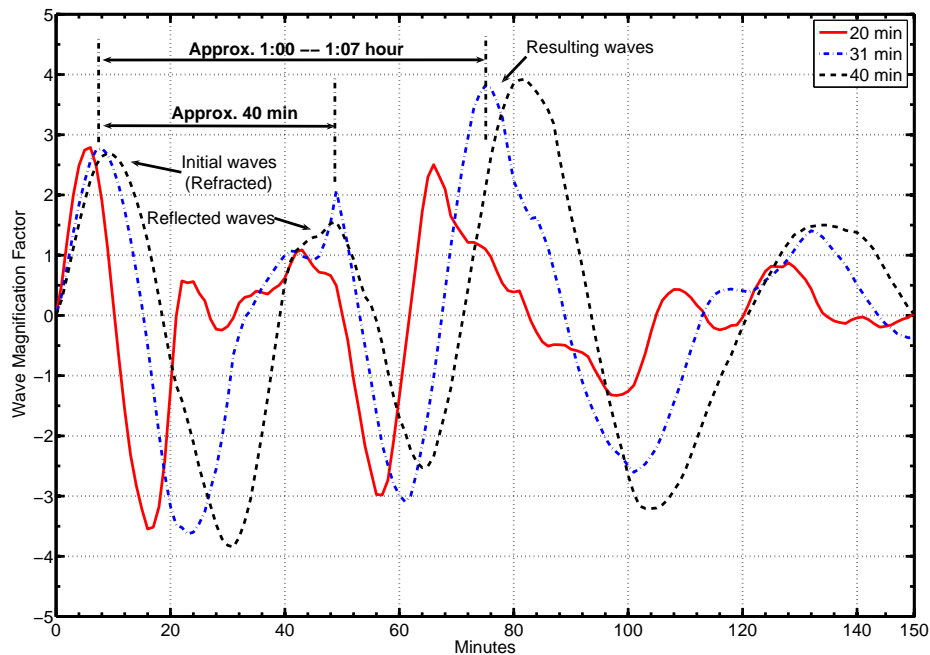


Figure 12. Computed sea level outside Crescent City harbor (gauge No.1 in Figure~6). In this experiment only one sinusoidal incident wave with periods of 20, 31 and 40 minutes is used. The sea level is normalized against incident wave amplitude (10 cm).

Figure 12 shows the sea level response at gauge No.1 indicated in Figure 6. In this experiment only one sinusoidal incident wave with periods of 20 min, 31 min and 40 min is used. As the tendency to organize the gravest mode of oscillations is very strong for all three wave periods, after about 1 hour from the first wave crest the maximum sea level occurs (see also Figure 1). Now, if few more incident waves (2 or 3) are used to simulate a tsunami train, the incident forcing will try to shift the oscillation patterns to a natural mode (Figures.7, 8 and 9) which is in accordance to its energy spectra. This suggest that after approximately one hour from the first wave arrival of the tsunami or tsunami packet, a much stronger wave will be generated due to the tendency of shelf to initially oscillate at the gravest mode.

This persistent behavior of one-wave period amplitude response is related to the simple refraction and reflection from the spindle-like shape described by the coastal shoreline and shelfbreak edge (Murty, 1977; Clarke and Thomas, 1972). Two important time scales for this domain are ~20 min travel time across the shelf towards the shoreline and ~40 min travel time along the reflected/refracted wave rays from the southern to

the northern concave curvature or vice versa.

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References

- [1] Clarke D.J. and N. D. Thomas (1972), The two-dimensional flow oscillations of a fluid in a spindle-shaped basin: application to Port Kembla outer harbor N.S.W. Australia, Aust., *J. Mar. Freshwater Res.* 23 1–9
- [2] Fujima K., R. Dozono & T. Shigemura (2000), Generation and Propagation of Tsunami Accompanying Edge Wave on an Uniform Sloping Shelf, *Coastal Engineering Journal*, Vol.42(2), 211–236
- [3] Fuller J.D. and L.A. Mysak (1977), Edge Waves in the Presence of an Irregular Coastline, *J. of Phys. Oceanography*, Vol.7 No.6, 846–855
- [4] Kowalik Z. & T. S. Murty (1993), *Numerical Modeling of Ocean Dynamics*, World Scientific Publ., 481 pp.
- [5] Keulegan G. H., J. Harrison, and M. J. Mathews (1969), Theoretics in design of the proposed Crescent City harbor tsunami model, *U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.*, Tech. Rept. H-69-9, 1969, 124 pp.
- [6] Loomis H. G. (1973), A new method for determining normal modes of irregular bodies of water with variable depth, *Hawaii Ins. Geop.*, HIG-73-10, NOAA-JTRE-86, 27pp.
- [7] Mei, C. C., M. Stiassnie, and D. K.-P. Yue (2005), *Theory and Applications of Ocean Surface Waves. Part1: Linear Aspects*, Advanced Series on Ocean Engineering, Vol. 23. World Scientific Publ., 506 pp.
- [8] Munk W., F. Snodgrass and G. Carrier (1956), Edge Waves on the Continental Shelf, *Science Vol.123* No. 3187
- [9] Murty T. S. (1977), *Seismic Sea Waves Tsunami*, Department of Fisheries and the Environment Fisheries and Marine Service, Ottawa, Canada.
- [10] Rabinovich A.B., R.E. Thomson and F.E. Stephenson (2006), The Sumatra tsunami of 26 Decembaer 2004 as observed in the North Pacific and North Atalntic oceans, *Surv. Geophys.*, 27 647–677
- [11] Roberts J. and E.K. Kauper (1964), The Effects of Wind and Precipitation on the Modification of South Beach, Crescent City, California. Including An Appendix on the Focusing of Tsunami Energy at Crescent City, prepared by C.-W. Chien, Final Report prepared for Environmental Sciences Div., Dept. of the Army, Contr. No. DA-49-092-ARO-38, 98pp.

