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The Role of Wave Action in Producing Storm Surge

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ABSTRACT

Coastal flooding occurs frequently along the New England Coast during winter months sometimes resulting in extensive structural damage and beach erosion. This study discusses all of the primary components of storm surge which are wind forcing, pressure set-up and wave action. An emphasis however is placed on wave action which is often the primary storm surge mechanism along beaches exposed to the open ocean. The influence of bathymetry on wave induced storm surge is also discussed. To demonstrate the importance of wave action a comparison is made between two separate events which occurred along the Down East Maine Coast.

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1. Introduction

Wave action is the ultimate cause of most structural damage and beach erosion from storm surge Fitzgerald et al. (1994) and Dolan and Davis (1992). Due to large ocean waves, water is forced shoreward by the momentum of the waves causing water to pile up along the shore. This effect usually goes unnoticed at tide gauges since they are quite often located in bays and estuaries quite distant from the surf zone. Storm surge generated by wave action is also an extremely localized phenomenon which is governed by bathymetry and exposure to large waves from the open ocean. Sometimes the large waves are not generated locally but originate from fetches hundreds or even thousands of miles offshore. These large waves can raise the water level along the shoreline and drive debris up the beach into structures along the shore.

In order to address the role of wave action in producing coastal flooding, empirical techniques have been developed that incorporate historical data and case studies to develop nomograms that aid forecasters. For example, a nomogram was developed to describe tidal flooding around Boston Harbor (Tancreto 1958). This nomogram was developed from 45 storm surge events and correlated the maximum storm surge in Boston Harbor as a function of offshore wave heights. The author also constructed a conceptual model of synoptic pressure systems most favorable to inundation. In a more recent study on coastal flooding along the Massachusetts shoreline, an empirical forecasting technique was developed from coastal flooding events from 1986 to 2003 (Norcera et al. 2005). The predictors for these techniques were wind speed, tidal cycle and offshore wave heights. Cannon (2007) also developed an empirically derived nomogram in which water levels and waves were correlated with damage along the Northern New England coastline in storm surge events.

Operational storm surge guidance such as the extra-tropical storm surge model has been successful in predicting surge levels generated by wind set-up. More recently the ADCIRC Model which is embedded in larger models such as the Wave Watch III can distinguish elevated water levels generated by wind induced currents which is the primary mechanism for inland tidal flooding. In a study of New York City's vulnerability to coastal flooding, Colle et al. (2008) used the ADCIRC model forced by sea level wind and pressure from the MM5 model along with tidal constitutes. Tidal constitutes are harmonic data derived from measurements at a particular tide site over a period of time. These tidal constitutes are often used in tide prediction. The flooding event described in Colle et al. (2008) was primarily the result of elevated water level from wind driven current (wind set-up) and their approach worked quite well. The SWAN model often is imbedded in the larger Wave Watch III model. When the SWAN model is run at higher resolutions it can resolve the effects of friction, refraction, diffraction, white-capping and shoaling. If run at even higher resolutions it is able to model wave conditions approaching the breaker zone. Parameterizations could eventually be added to extend the model through the breaker and surf zones to the swash zone to handle the effects of set-up and run-up. Nevertheless until such model development occurs it remains necessary for forecasters to understand local effects and compensate for them.

The purpose of this study is to familiarize the forecaster with concepts relating wave action to overall storm surge and provide the tools necessary to forecast the phenomena. It is our opinion that the challenge of forecasting wave driven coastal inundation can best be addressed by first determining the most vulnerable areas hereafter called "hot spots" and then applying dynamic techniques that employ the use of observed and forecasted wave heights, surf zone bathymetry and wave spectral data in the vicinity of hot spots.

We seek to describe how wind, pressure, bathymetry and wave action are all factors in producing storm surge and consequently coastal flooding. In discussing wave action we will describe in details both wave set-up and wave run-up. Wave set-up is the elevation of water from the breaker zone to the beach that are the result of large breaking waves. Wave run-up is the driving of water up the slope of the beach by individual waves. Forecast techniques also will be provided for quantifying the role of wave action. Sufficient detail is provided so that the techniques provided here can easily be incorporated into a spread sheet program for use in real time events.

The role of wave action also will be examined as it relates to storm surge by analyzing coastal flooding along exposed beaches in two separate events. Both events occurred during spring tides with similar tide levels measure at the tide gauges but with different wave conditions in each event. In analyzing these events we will also describe how to determine the most appropriate wave groups from partitioned spectral data so that they can be used in the equations presented in this paper.

Finally, suggestions will be provided for marine focal points and forecasters on incorporating the effects of wave action into the forecast process for coastal flooding. To our knowledge this has never been done before with respect to wave driven storm surge.

2. Methodology

Data from the National Data Buoy Center (NDBC) for the Jonesport buoy (44027, Fig. 1) was collected and used in this study. These data contain the hourly significant wave height; dominant wave period and spectral wave energy density. Tide gauge data from Bar Harbor, Maine supplied by NOAA Center for Operational Oceanographic Products and Services were also used. Archived weather and model data from the Advanced Weather Information Processing System (AWIPS) consisted of analysis products from the Western North Atlantic Wave Watch III which focused on analysis of wave heights only. Accounts of storm surge were taken from information provided by emergency managers, newspaper articles and reports received from harbor masters.

3. Components of Storm Tide

a) Astronomical Tide

In assessing the potential for coastal flooding, the phase of the astronomical tide is of paramount importance. This is particularly important along the Maine coast since there is such a large range of tidal fluctuation. Of particular concern is the concurrence of a spring tide with a storm event. The spring tide occurs when the Sun, Earth and Moon are in line with each other. This alignment will produce a higher astronomical tide.

b) Wind Forcing (Wind Set-up)

The wind forcing or wind set-up component of a storm surge results from wind stress on the water surface causing water to flow towards the coast and pile up along the shore. This effect typically occurs when the wind is blowing perpendicular to the coast (on-shore). However it can also occur when the wind is blowing parallel to the coast. In this case the flow of wind driven water will be turned to the right by the Coriolis force. This phenomenon is part of a larger process known as the Ekman Spiral. Along the Maine coast, a northeast flow will turn the wind driven water flow towards the shore causing the water to pile up along the shore (Fig. 1).

c) Pressure Set-up

Pressure set-up, better known as the inverted barometer effect, is another storm surge component. Water level in the ocean will rise in areas where atmospheric pressure is low compared to surrounding higher pressure. This difference in water level is equal to 1 cm for each change in barometric pressure of 1 mb (Harris 1963). This effect is most prominent where large pressure changes occur over a relatively small area, such as in a hurricane. The pressure component of storm surge can be greatly amplified through resonance should the pressure disturbance move at the same speed as the shallow water wave speed. Incidences of amplification storm surge through resonance are rare.

d) Wave Set-up

Although there is very little lateral transport of water by waves in the deep ocean, the transport of water shoreward by waves becomes very significant in shallow water. When the water depth near the shore is relatively shallow, water transported by waves is forced shoreward by the breaking waves faster than it can flow back to the ocean. This process forces water to pile up along the shore. As waves break, water is forced through the surf zone into the swash zone in the form of bores. The onrushing water represents a flux of momentum or radiation stress directed toward the shore (Lonquet-Higgins and Stewart 1963). The wave momentum flux produces an imbalance of hydrostatic pressure which is then balanced by an elevation in water level along the shore and a depression in water level near the breaker zone known as setdown. This process is referred to as *wave set-up* and it can add 3 feet or more to the total storm surge during an extra-tropical storm event (Figs. 2 and 3).

e) Incident Wave Run-up

This component of storm surge is produced by the large amounts of water transported up the beach by the momentum of successive waves. Wave run-up has a maximum effect when the water depth near the beach is relatively deep (i.e. greater beach slope). Greater beach slope allows waves to break close to shore. This is opposite of wave set-up and wind set-up where gentle slope maximizes these processes. Run-up is a very important component since it is responsible for transporting the destructive force of the waves in the form of water and heavy debris traveling at high velocity into infrastructure along the beach.

f) Infragravity waves and edge waves

Two other components which can provide additional storm surge are infragravity waves and edge waves. Infragravity waves are long period waves with periods in excess of 30 seconds which are generated by radiation stress in wave groups (Holman 1981). Edge waves are also very long period waves which are bound to the shore by refraction. Both infragravity waves and edge waves that significantly affect storm surge are rare occurrences.

4. Computing critical components of storm surge

a) Computing wave set-up

Wave set-up is the increase in mean water level along the shore caused by the action of large breaking waves in the surf zone. This increase in water level is the direct result of water forced shoreward by large breaking waves faster than it can retreat back to the ocean. The process itself is very complex and as a result the actual physics will not be used. As an alternative, various algorithms will be employed as parameterizations of the actual physics. These parameterizations will now be discussed.

Waves undergo a number of transformations as they move from the open ocean and approach the shore. In transition from the deep water buoys to the shoaling area, waves are transformed by bottom friction, refraction, and diffraction and shoaling. The problem is further complicated by the angle at which the waves approach the shore. In addition, waves can break over a reef or sandbar which will result in attenuation of wave energy. After overtopping the obstacle the remaining wave energy will be transmitted to the opposite side and continue on towards the shore as a smaller wave. This study will focus on the wave in the transition from shoaling to the breaker zone onward through the surf zone onto the swash zone where the wave finally runs up to its greatest level on the shore.

Several computations must be completed to compute wave set-up and run-up. In many cases there are alternative methods of computing the same parameter. The method chosen here incorporates bottom slope whereas other methods do not.

It is first necessary to compute the height and depth of breaking waves before proceeding to compute the wave run-up and set-up. We will compute a breaking height by first employing a breaker index by utilizing a relationship derived by Komar and Gaughan (1973).

$$\Omega_b = 0.56\left(\frac{H}{L}\right)^{-\frac{1}{5}} \qquad (1)$$

In this relationship H is the deep water wave height and L is the deep water wave length found from:

$$L = 1.56T^2 \qquad (2),$$

where T is the wave period.

With the breaker index (Ω_b) determined the breaker height H_b can now be determined from USACE (2008),

$$\Omega_b = \frac{H_b}{H_o} \quad \text{or} \quad H_b = \Omega_b H_o \ (3)$$

The term H_o is the deep water wave height.

The next step is to adjust the breaker height base on the bottom slope from the end of the shoaling zone to the beach. We will utilize an expression for breaker depth index from Weggel (1972) for this purpose.

$$\gamma_b = b - a\frac{H_b}{gT^2} \qquad (4)$$

In the expression, γ_b is the breaker depth index, g is the acceleration of gravity equal to 9.8 m s^{-2} and T is the wave period. The value for b is computed by USACE (2008):

$$\mathbf{b} = \frac{1.56}{(1+ e^{-19.5\,tan\beta})} \qquad \textbf{(5)}$$

The value for $\boldsymbol{a}$, is then found by USACE (2008):

$$\mathbf{a} = 43.8(1 - e^{-19tan\beta}) \qquad \textbf{(6)}$$

The value for $\boldsymbol{\beta}$ is the slope extending from the shoaling zone across the breaker and surf zone onto the beach (Fig. 3).

With the breaker depth index determined the breaker depth $\boldsymbol{d_b}$ can now be determined with the expression from USACE (2008):

$$\gamma_b = \frac{H_b}{d_b} \text{ or } d_b = \frac{H_b}{\gamma_b} \qquad \textbf{(7)}$$

The wave set-up and setdown can now be computed. The wave setdown is computed from Longuet-Higgins and Stewart (1963):

$$\eta_b = -\frac{1}{8}\frac{H^{2^{\frac{2\pi}{L}}}}{sinh\left(\frac{4\pi}{L}d_b\right)} \qquad \textbf{(8)}$$

Here $\boldsymbol{H}$ is the deep water wave height, $\boldsymbol{L}$ the deep water wave length and $\boldsymbol{d_b}$ is the depth at breaking.

Finally the wave set-up at the beach can now be computed USACE (2008):

$$\eta_s = \eta_b + \left[\frac{1}{1+\frac{8}{3\gamma_b^2}}\right] h_b \qquad \textbf{(9)}$$

The mean water level slopes upward from the wave setdown to the beach (Fig. 3). To determine the maximum set-up is:

$$\eta_{Max} = \eta_s + \frac{d\eta}{dx}\Delta x \qquad \textbf{(10)}$$

b) Computing wave run-up

Incident Wave run-up is expressed as a function of the Iribarren number or surf similarity parameter derived by Hunt (1959).

$$\xi = \frac{\beta}{\sqrt{\frac{H}{L}}} \qquad \textbf{(11)}$$

Where $\boldsymbol{\beta}$ is the beach slope. Data to find the beach slope is available at

http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html

To compute slope you simply need to calculate the ratio of rise over the run. There are a number of products that can be obtained from the site above such as navigation depth charts or actual bathymetric data that can be downloaded. To compute the bottom slope first measure the distance from the shore through the surf and breaker zones to just beyond the breaker zone. Measure the water depth just beyond the breaker zone and then divide this number by the distance from shore. For example if the water depth was 10 feet and the distance from the beach was a 1000 feet the slope would equal 10÷1000 or .01

The incident wave run-up is normally calculated in terms of two percent exceedance ($\boldsymbol{R_{2\%}}$). This value is the statistical occurrence referring to the probability of being exceeded in a particular storm. Wave run-up is measured from the still water level (SWL).

$$R_{2\%} = H_0\xi \qquad \textbf{(12)}$$

In this expression $\boldsymbol{H_0}$ is the deep water wave height corrected for friction and ξ is the surf similarity parameter.

c) Bathymetry modification

Bathymetry can drastically modify waves as they approach the shore and cause them to vary significantly from wave heights observed at nearby deep water buoys. As waves enter shallower water they interact with the bottom and characteristics of the wave are changed. This process is known as shoaling and causes the wave to increase in height, the wave length to shorten, while the wave period remains constant. If the waves direction of approach to the shore is at an oblique angle it will be refracted which will change both the direction and height of the wave. When a wave encounters a barrier, wave energy is transmitted laterally along the wave crest to the shadow of the barrier. This process is known as diffraction and when it occurs the wave height is reduced and the direction of the wave is changed. Bottom friction is another process that will dissipate a large portion of wave energy as the wave enters shallow water and interact with the bottom. Large waves can also encounter a submerged reef over which the water may be shallow enough for the wave to break. The remaining wave energy is then transmitted over the reef and again into deep water as the wave continues to move toward the shore.

We believe the most effective way to handle the bathymetric effects described above is through the use of the SWAN model. Currently we have access to a version of the SWAN model run at the WFO Taunton (BOX) and another higher resolution experimental version available on the internet. Comparisons with local buoy reports indicate use of a local wave model such as the SWAN provides highly accurate assessment of wave modification due to bathymetry.

Wave refraction imposes another bathymetrically driven issue. The phenomena can concentrate wave energy in headland areas (convergent refraction) thus significantly increasing breaking wave height. On the other hand, in bay and inlet areas the wave energy is spread out (divergent refraction) and the reverse is true. The magnitude of the wave set-up can easily be doubled or cut in half by wave refraction in headland and cove areas as such as those illustrated in Figure 4.

5. Case Studies

a) High Wave Event: Patriot's Day Storm of 2007 (17 April)

On 15 April 2007 a powerful low pressure system developed over the Mid-Atlantic then moved northward along the Eastern Seaboard the next day. A strong high pressure system was in place over the Canadian Maritimes. The juxtaposition of these two system produce a very strong pressure gradient and accompanying southeast wind/wave fetch which extended into the Gulf of Maine from several hundred miles to the southeast. A surface weather chart for this storm is depicted in Figure 5.

The astronomical tide was at the highest level of the month due to the coincidence of a spring tide. Across much of Down East Maine, coastal flooding occurred near the time of high tide along low lying roads and beaches with an exposure to the open ocean. Observations from the coastal buoy 44027 at the time of high tide on 16 April showed significant wave heights of 22 feet and dominate wave periods of 12 to 14 seconds plus sustained wind speeds between 35 and 40 knots. The Bar Harbor tide gauge showed a tidal anomaly of between 1 and 2 feet. Wave height and tide levels from the tide gauge are displayed in the graph in Figure 6. Notice that the largest waves, which reach a maximum of 22 feet, coincide with the high tide cycle on the evening of the 16 April.

Coastal flooding occurred during this high tide cycle. The effects of the storm surge along exposed coastal areas are shown in Figure 7. This image suggests a much higher storm tide level than the 1 to 2 feet observed at the tide gauge. It was suspected that flooding was partially the result of wave action. To explore this possibility a hindcast was performed using techniques described in this paper to compute set-up and run-up for this tidal cycle.

The primary goal of the hindcast was to first partition the existing wave field into separate individual wave groups so they could be utilized in set-up and run-up calculations for specific hot spots. To accomplish this we manually determine the origin of waves groups then determine a connection between the fetch area in which the waves originated and the spectral information observed at the buoys. Determination of wave group source was accomplished by application of a fetch, duration and wind speed monogram to observed wind speed over the ocean fetch areas. Where no wind data was available, short term model wind speed graphics were used. Three separate wave groups were determined by an analysis of the fetch areas associated with this event they are as follows.

Wave group 1: A southeasterly wave group of 17 feet from 165° with a period of 12 to 14 seconds was generated in a long fetch to the east of the storm center. The wave period derived in our hindcast was closer to 10 seconds, however it is possible that a smaller fetch of stronger winds was embedded which would significantly increase the period, especially if angular spreading is factored in.

Wave group 2: A northeasterly wave group with a height of 12 feet, a period of 7 seconds and a direction from 075°, was generated to the west of the low track in the Gulf of Maine.

Wave group 3: This wave group originated in an east-southeast flow in advance of the low center located to the south and east of southern Nova Scotia. This wave group with a height of 10 feet a period of 8.5 seconds and a direction from 120° is partially blocked by the southern tip of Nova Scotia, however due to refraction some of the wave energy does make it into local waters.

Figure 8 shows the 0300 UTC spectral data recorded from buoy 44027. It is wave group 1 that is used for the calculations since it will yield the most significant wave set-up results. This is because the combination of much higher wave height and longer period pack more energy than the other wave groups. The end result of this are higher breaking waves which in turn produces greater radiation stress thus forcing more water shoreward and producing greater wave set-up and run-up.

The data from the buoy located close to the coast was not available during this event. We therefore used an alternative method to estimate the near shore wave height based on previous similar events and runs of the SWAN Model during similar situations. We estimated that half the wave height is lost traversing from the off-shore buoy to the surf zone due to bathymetric effects resulted in an adjusted wave height of 8.5 feet.

The effects of run-up and set-up will now be computed. In performing the calculations a bottom slope for the surf zone of .01 is used along with the 8.5 foot wave height and 13.5 second period determined above.

Setup calculations were performed on the above variables using a spread sheet program and incorporating equations 1 through 9 above. These calculations yield a wave setup of 2.2 feet at the shoreline. Runup calculations are now performed using equations 11 and 12 which yield an additional elevation of 1.3 feet. It should be noted that this value with fluctuate with each individual wave incursion.

The combined surge level is then computed by adding the wind setup, pressure setup, wave setup and wave run-up. During this event the combined wind and pressure setup as determined at the tide gauge is 1.5 feet. The setup level of 2.2 feet and run-up level 1.3 feet, as computed above, is added to this value to produce a total surge level of 5.0 feet.

b) Modest Wave Event: 12 December 2008

During this event low pressure was intensifying over North Carolina during the late afternoon of 11 December 2008. At the same time a strong center of high pressure was exiting the Canadian Maritimes and a second high pressure center was located in the vicinity of Bermuda. There was a stationary front running from the low center northeastward passing south of Nantucket Island and separating the two high centers. A significant southerly fetch developed off the east coast south of the stationary front while at the same time there was as separate northeasterly fetch north of the stationary front in the Gulf of Maine. A surface pressure chart at 1800 UTC on 12 December 2008 is depicted in Figure 9. This storm system was not as intense as the Patriot's Day low pressure system and the developing fetch to the southeast of the Gulf of Maine wasn't nearly as impressive since the pressure gradient between the two systems was not as strong. Similar to the Patriot's Day Event the astronomical tide was also close to the highest levels of the month due to the occurrence of a spring tide. In this event extensive flooding did not occur even though the storm tide level was similar to the first event (14.03 feet) as measured at the Bar Harbor tide gauge (Fig. 10). There was some very minor flooding that occurred in Winter Harbor, across the bay from the Bar Harbor tide gauge. However, there were no other reports of coastal flooding.

Observations from the Jonesport Buoy (44027) indicated that maximum significant wave heights of 14 feet and dominate wave periods of 8 seconds with sustained wind speed of 30 to 35 knots. However, this occurred well after the time of high tide (Fig. 10).

As with the previous case it is important to first consider the spectral data from the buoy and partition the wave groups at high tide before attempting to compute wave set-up and run-up. The spectral data as a function of wave period is presented in Figure 11. We performed a wave group analysis similar to the one completed on the Patriot's Day Storm. This analysis also found three separate wave groups.

Wave Group 1: A southerly wave group was generated in the fetch south of the warm front. The Nantucket Shoals Buoy (44008 not shown) was under light wind conditions during the afternoon of the 11 December and was receiving 10 foot seas with a period of 8 to 9 seconds and a dominate direction from 189˚. This wave group then moved into the Gulf of Maine. After some depletion traversing Georges Banks wave heights were reduced to 8 feet at buoy 44018 near Cape Cod (not shown).

Wave Group 2: As the warm front moved through the Gulf of Maine a southerly fetch of approximately 30 knots developed after 0800 UTC on the morning of 12 December and persisted into the early afternoon when wind shifted into the southwest. From fetch duration analysis this amounted to an 8 foot wave group with a period of 7 seconds from a south southeast direction. It should be noted that this wave group eventually merged with group 1 but not until after the time of high tide.

Wave group 3: From the afternoon of 11 December there was a stationary front extending from the low center over North Carolina and extended northeastward to south of Nantucket Island. North of this front a northeast fetch persisted across the Gulf of Maine from early on the 11 December through 1100 UTC on the 12 December. In this northeast flow a resulting 5 foot wave group with a period of 6 seconds was generated.

Even though wave group 1 is not the highest wave group it has the highest period and contains the most wave energy (Fig. 11). Wave group 1 is used to compute the wave set-up on the beach since it is the most significant wave group. Wave data was available from a near shore buoy which recorded a wave height of 4 feet and period of 8 seconds indicating half the height of wave group 1 is lost due to bottom friction and refraction. Therefore a wave height of 4 feet, a period of 8 seconds and a bottom slope of .01 will be used in the run-up and set-up calculations.

The effects of run-up and setup will now be computed. In performing the calculations a bottom slope for the surf zone of .01 is used along with the 4.0 foot wave height and 8.0 second period determined above.

Setup calculations were performed on the above variables using a spread sheet program and incorporating equations 1 through 9 above. These calculations yield a wave setup of 1.0 foot at the shoreline. Run-up calculations are now performed using equations 11 and 12 which yield an additional elevation of 0.5 feet. It should be noted that this value with fluctuate with each individual incoming then retreating wave.

The combined surge level is then computed by adding the wind setup, pressure setup, wave setup and wave run-up. During this event the combined wind and pressure setup as determined at the tide gauge is 1.0 foot. The setup level of 1.0 foot and run-up level 0.5 feet, as computed above, is added to this to produce a total surge level of 2.5 feet.

It is very possible that due to the direction of the incoming waves from the southwest, larger waves moved into the bay area approaching the entrance to Winter Harbor. This would account for the minor coastal flooding that was observed at that location. Observations from the Harbor master support this hypothesis.

6. Summary and Recommendations

Wave set-up and run-up are important components of storm surge on coastlines exposed to the open ocean. During a storm surge event, the contribution of water level due to wave action may equal or even exceed the components resulting from the combined effects of wind and pressure set-up. In addition it is the contribution of run-up that transmits wave energy up the beaches to produce the most notable destruction of infrastructure caused by storm surge.

Wave set-up and run-up are localized phenomena that can vary greatly over short distances. The techniques in this study provide a way of making estimations of localized storm surge for specific locations exposed to the open ocean (hotspots). Before calculations can be made for these hotspots the slope of the surf zone in these areas must be pre-determined. Specifically the slope from the vicinity of the breaking wave onto the beach where run-up will occur must be calculated from bathymetric information. Also critical values at which flooding begins must also be determined for each of the hotspots.

Wave height and period information is also required for these calculations. Before wave heights can be determined the wave spectra must be partitioned into separate wave groups and the specific wave group with the highest period and largest waves must be calculated and then used in the procedures. It is recommended that spectral information from wave models be used for this purpose. Wave spectral plots available from the Wave Watch III are suitable for this purpose. Useful tools for partitioning wave spectral include the Wave Watch III spectral point data which can be obtained from the National Weather Service Environmental Model Branch (Tolman 2004). Another wave partitioning tool is the Hanson plot (Nicolini 2010). A local wave model such as the SWAN would be even more desirable assuming spectral data is also available for the model.

While the event is ongoing, the spectral forecasts can be validated by using spectral density plots from the detailed wave information section of the individual NOAA Buoys. Some of these buoys also report wave direction. If available, this information can be used to verify the direction of the individual wave groups in the spectral forecasts from the wave models.

If wave forecasts are taken from model spectral points a significant distance off-shore from the surf zone, adjustment must be made to the forecasted wave height. This is because waves can lose 50 percent of their height or more through bottom friction as they approach the coast and enter shallow water. The SWAN Model again is a highly recommend tool for determining the wave height in deep water adjacent to the surf zone. The wave height outside the surf zone will be entered in the surge calculations.

Wave refraction resulting from the shape of the coastline can also greatly modify wave heights in the surf zone. A headland will focus wave energy thus increasing the wave height while a cove area will dissipate wave energy decreasing the height of a wave. A correction must be made for an irregular coastline shape.

One final suggestion is made in order to better refine the technique described here. Forecasts of storm surge can be verified by doing the following procedure. After a storm surge event the high water level mark is usually very prominently marked by sea weed and other debris that has washed up on the beach. The elevation level of this debris above the existing high water level can be measure with a surveyor’s transit to determine the actual storm surge level. We assume here that reference levels on the beach have been noted during similar tide cycles when no storm surge was present. This type of post mortem information will be most valuable in fine tuning the techniques described here and for future study. This same technique can also be used to determine the critical flood levels by measuring the elevation of infrastructure above the highest tide level.

The following operational procedures are recommended to assist the forecaster in the storm surge warning process.

It is recommended that areas chronically susceptible to coastal flooding (hotspots) be predetermined. In these areas the bottom slopes for the surf zone and the critical levels that flooding should also be predetermined.

Longer term focus should be placed on conceptual models. Look for ocean fetch areas of tight pressure gradient in which the wind field is directed towards the coast. The longer the fetch area and duration of the fetch, the greater the potential for large waves.

Longer term evaluation should also focus on the coincidence of a large wave event with the phase of the astronomical tide. A spring tide will provide for greatest potential for coastal flooding.

As an event gets close examine the forecast wave spectral data at the time of high tide. Partition the wave groups and determine the largest waves and highest period to affect the hotspot. These will be the values used to do the calculations suggested in this paper.

Deep water wave height outside the surf zone needs to be determined. This can be accomplished with local studies or a locally run wave model such as the SWAN (Willis et al. 2010).

Once wave height approaching the surf zone and period is determined the information can be directly utilized in spread sheet calculations as described in this paper to compute localized set-up and run-up values. These levels are then added to wind and pressure set-up computed by the extra-tropical storm surge model to determine total surge in these areas.

Currently a tool is being developed based on a USGS technique utilizing a newly developed parameterization to determine wave runup. This tool will incorporate input of wave height, wave period, surge, tide information, beach topography and surf zone slope. Output of estimation of erosion, over-wash and inundation will be given for a particular point. This tool will be undergoing tests at a number of offices in the near future.

Wave model data from off-shore buoys and from ship reports should be compared with the wave model so bias adjustments to the wave model can be made. We have found it useful to plot buoy data directly on graphic wave model output to make comparisons.

When tracking a wave group approaching from a distance and under an existing fetch area traveling at the same speed as the fetch area. Make sure group velocity is used for the speed of the wave group. This wave group will remain under generation as long as it is under the fetch area.

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Figures

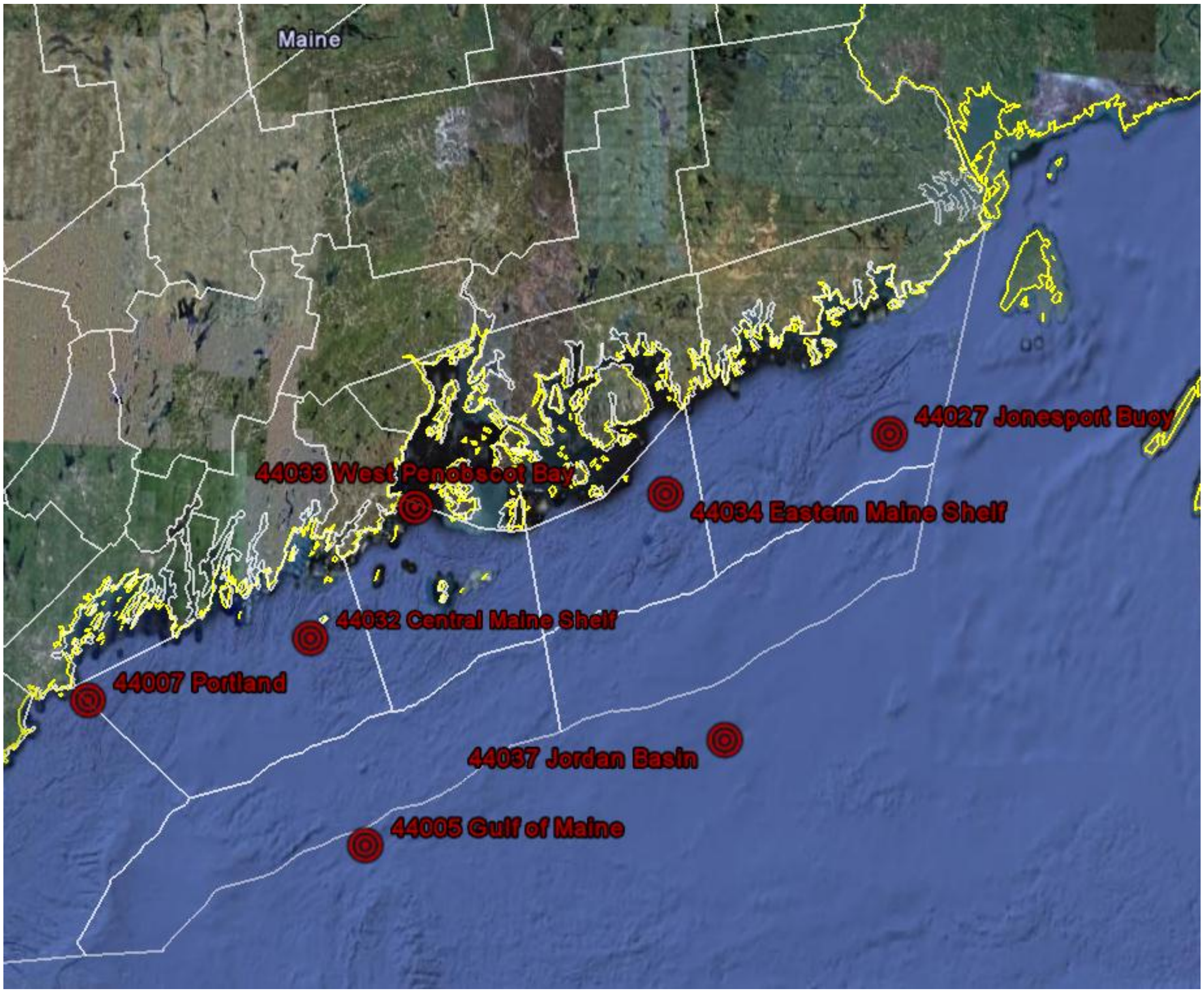

Figure 1. Buoy locations along the Maine Coast.

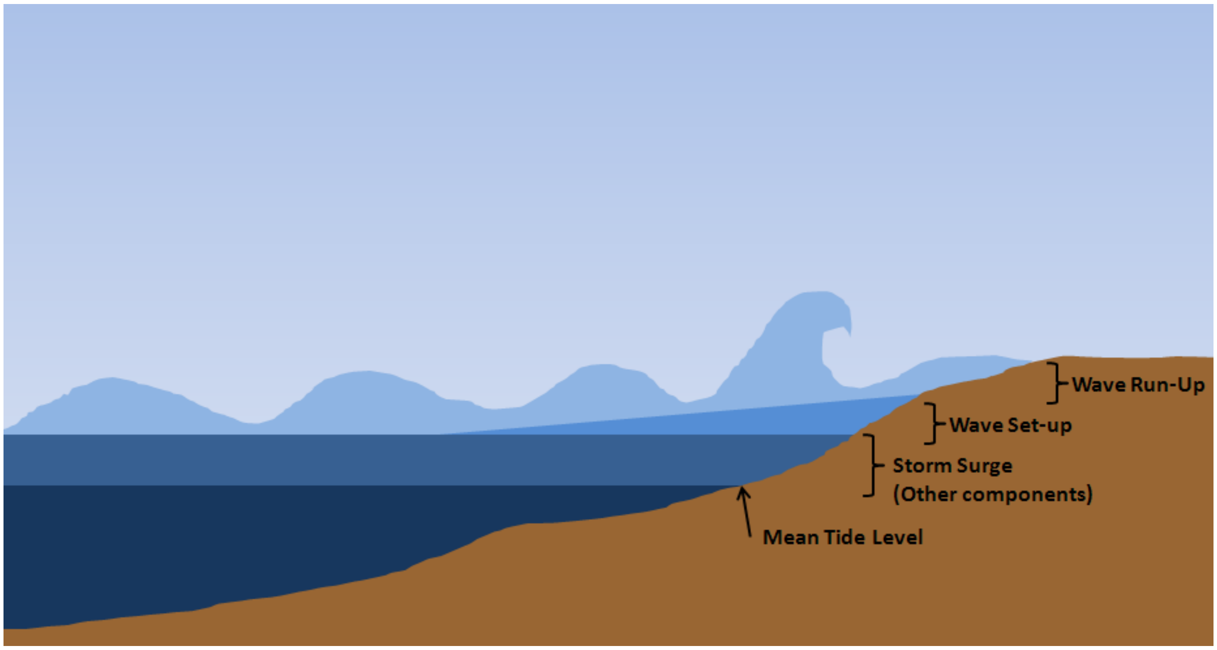

Figure 2. Schematic diagram showing wave set-up and run-up as additional components of storm surge.

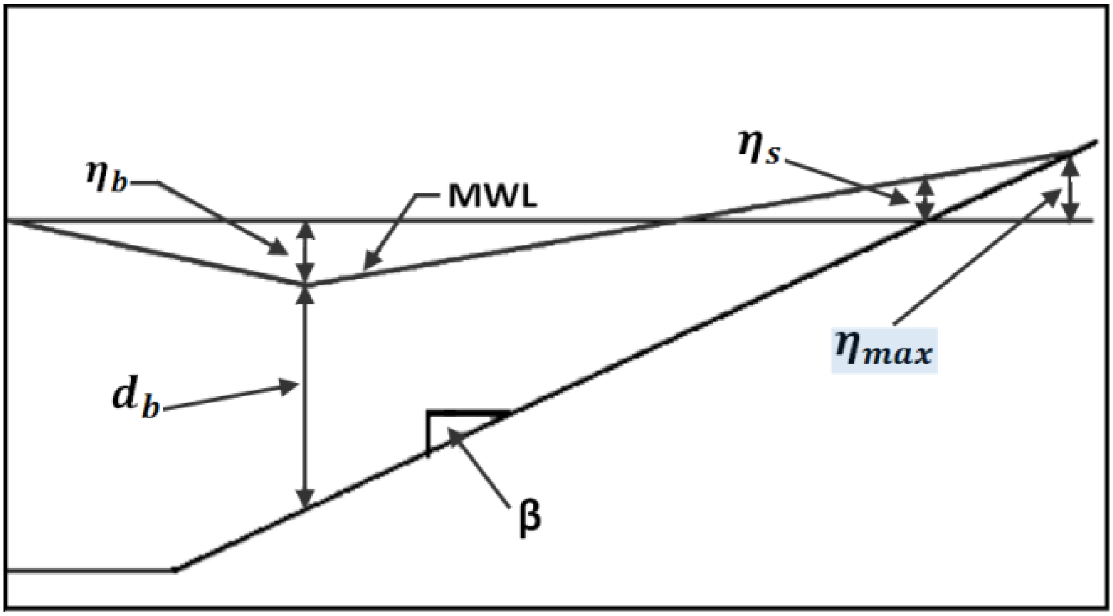

Figure 3. Wave set-up in the surf zone (from USACE 2008). $\boldsymbol{\beta}$ is the slope of the surf zone, $\boldsymbol{\eta_b}$ is the wave set-down, $\boldsymbol{d_b}$ is the depth of the breaking wave, $\boldsymbol{\eta_s}$ is the wave set-up, $\boldsymbol{\eta_{max}}$ is the maximum wave set-up and MWL is the mean water level.

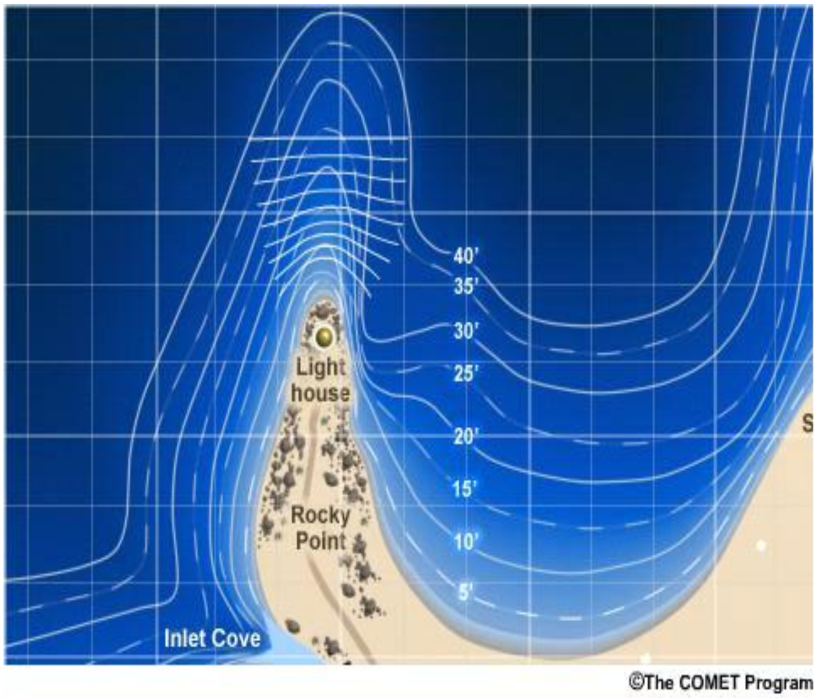

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Figure 4. Wave refraction around a headland and adjacent cove (COMET 2011).

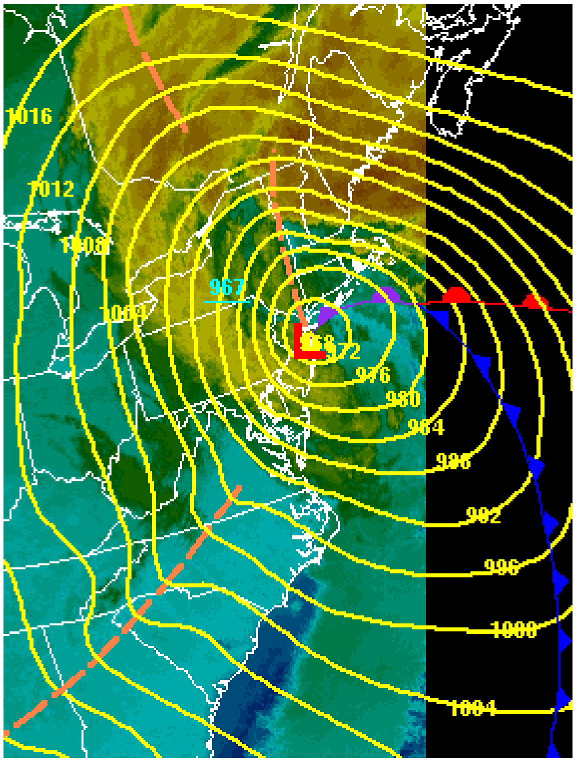

Figure 5. Mean sea level pressure (yellow), frontal position (as labeled) and infrared satellite imagery (image) for 0900 UTC 16 April 2007**.**

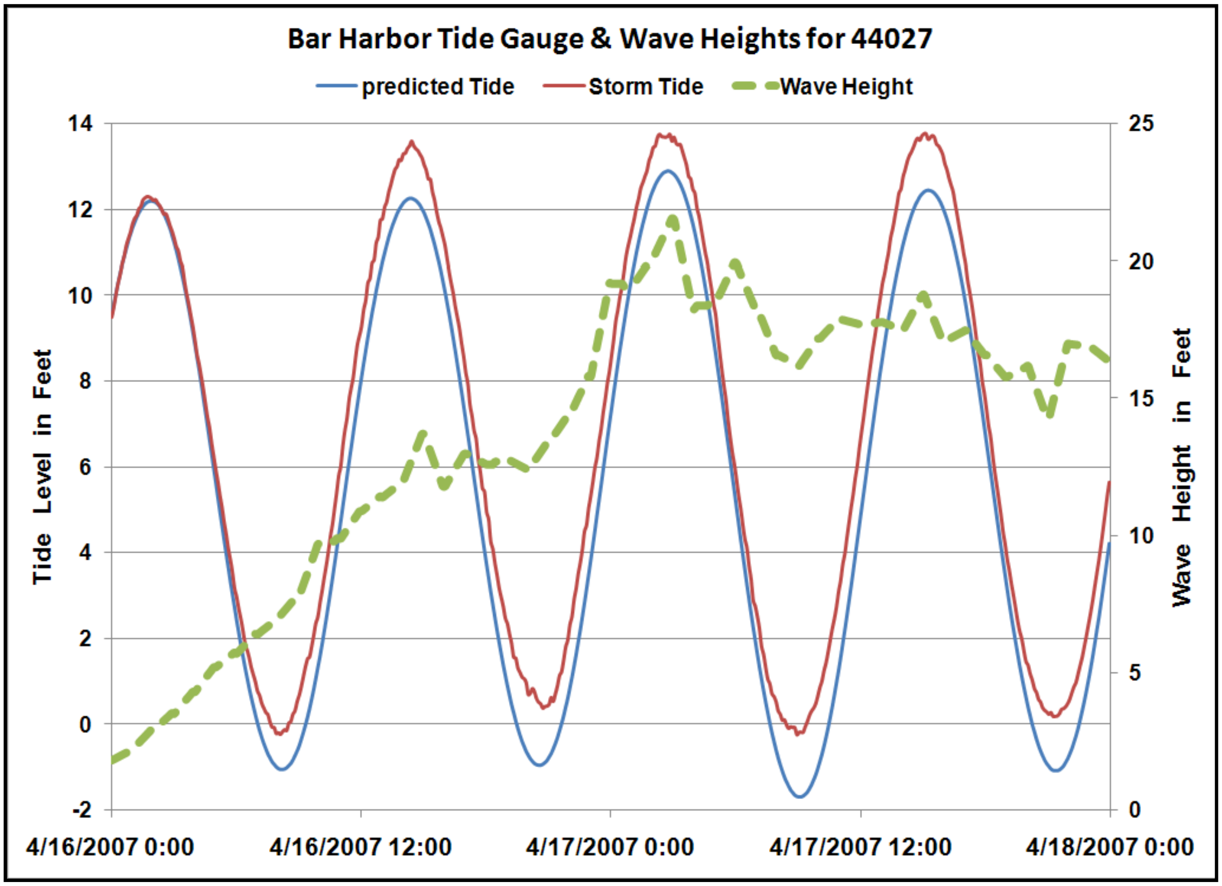

Figure 6. Bar Harbor tide gauge data (as labeled) and wave height observations from 44027 (as labeled) for 16-17 April 2007. Time on x-axis is in GMT.

Figure 7. Southwest Harbor, Maine showing rocks and other debris washed on road (Chapais 2007).

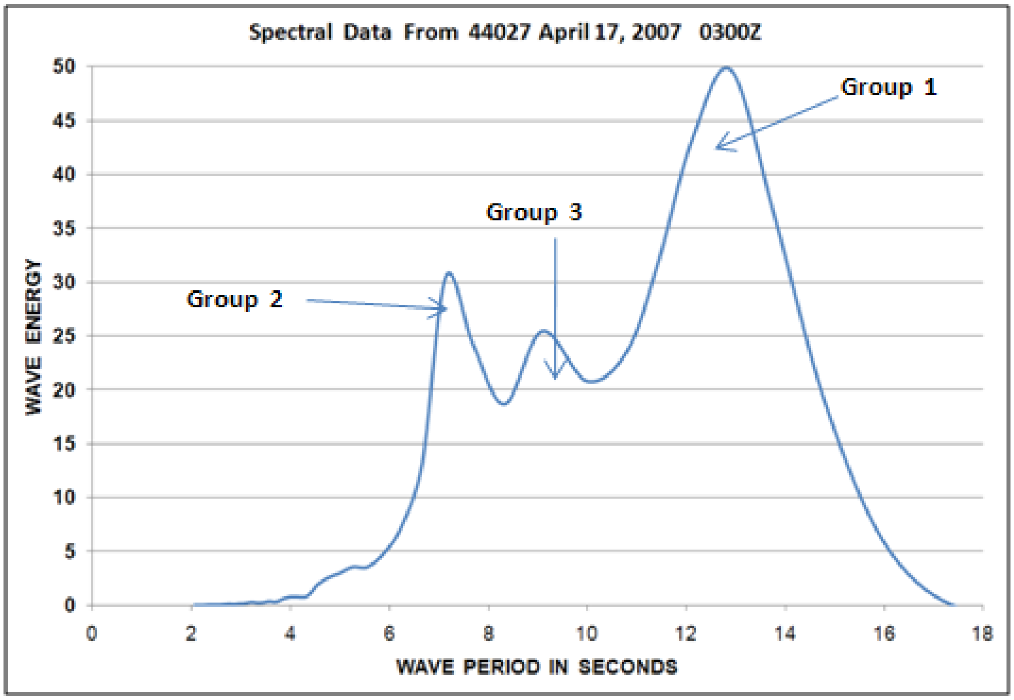

Figure 8. Wave spectral data from buoy 44027 on 17 April 2007 (as labeled). Spectral wave density energy in M^2/Hz.

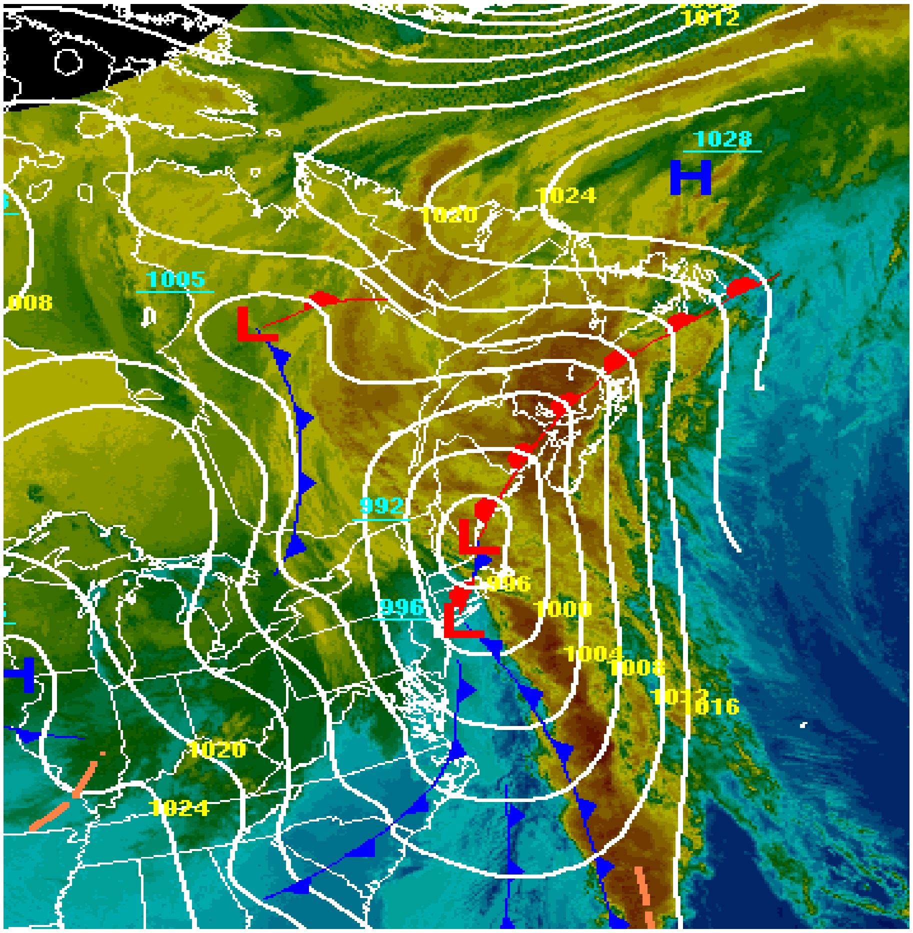

Figure 9. Same as Figure 5 but for 12 December 2008 at 1500 UTC.

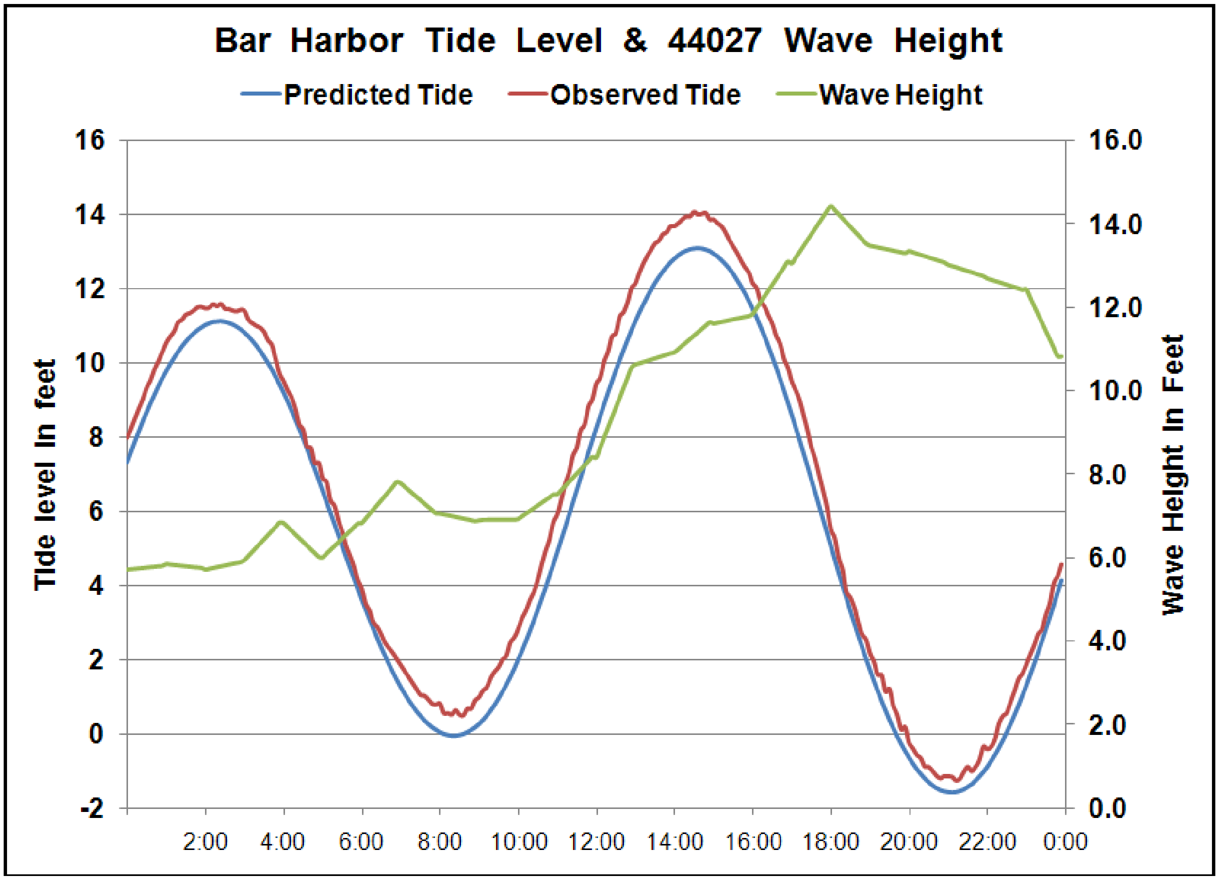

Figure 10. Same as Figure 6 but for 12 December 2008.

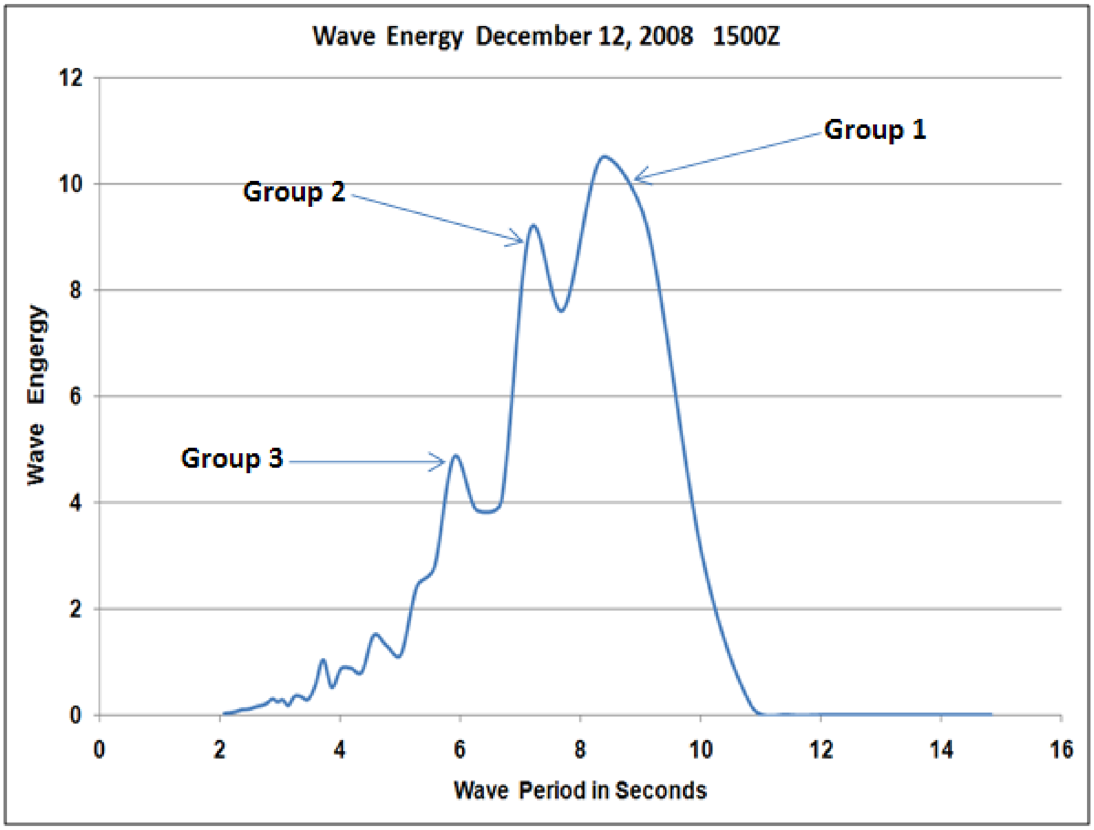

Figure 11. Same as Figure 7 but for 12 December 2008 at 1500 UTC. Spectral wave density energy in M^2/Hz.