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THE DEVELOPMENT OF A COASTAL FLOOD NOMOGRAM FOR SOUTHWEST COASTAL MAINE AND THE SEACOAST OF NEW HAMPSHIRE

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ABSTRACT

Extreme tides and large, battering waves have the potential to cause hazardous conditions along the sandy southwest coasts of Maine and New Hampshire. Increasing storm tides inundate low lying areas, while building waves lead to beach erosion and structural damage. The combined effects of these dynamical forces are complex and not fully understood. According to a recent Northern New England coastal flood climatology (Cannon 2007), damage often occurred during Nor'easters despite tide levels significantly below the Portland Harbor flood stage of 12.0 ft. The empirical relationship between storm tides and large, battering waves demonstrated the need to create a forecast prediction scheme based on impact and not solely on water level. Hourly forecasts of water level and near-shore waves were plotted simultaneously to visually display oceanographic conditions on a single diagram. The East Atlantic Water Level Forecast (ADCIRC) and Wave Watch III models were used to produce the output. The result is a web-based coastal flood nomogram, which is produced twice daily at www.gomoos.org. When animated, users can monitor for critical splash-over and coastal flood benchmarks as thresholds are exceeded. The tool assists meteorologists and emergency managers in the forecast and hazard mitigation process.

1. INTRODUCTION

Forecasts of coastal flooding, splash-over and beach erosion historically have not been visually depicted together. Unfortunately, the environmental conditions which create these phenomena are complex and cross several disciplines, yet each systematically influences the other. As a result, operational meteorologists are challenged to make subjective forecast decisions based on numerous sets of multi-scale parameters.

The synergistic effects of extreme tides and large battering waves often lead to splash-over and coastal flooding. Splash-over can be described as damage driven by large waves "over-topping" obstacles, resulting in significant beach erosion, whereas coastal flooding is the "inundation of land areas adjacent to bodies of salt water" (NWS 2006). Splash-over events are more frequent than coastal inundation and can cause significant damage.

Recently, there have been efforts to improve the visualization of water levels over large geographical areas (GoMOOS 2008). In particular, the East Atlantic Water Level Forecast Model (ADCIRC) employs 10.0 m wind guidance from the North American Mesoscale (NAM) model to produce hourly water level forecasts along the East coast of the United States and the Gulf of Mexico (Westerink 2008) (Fig. 1). However, this model does not explicitly calculate localized sea level rises and beach erosion processes produced by high energy waves.

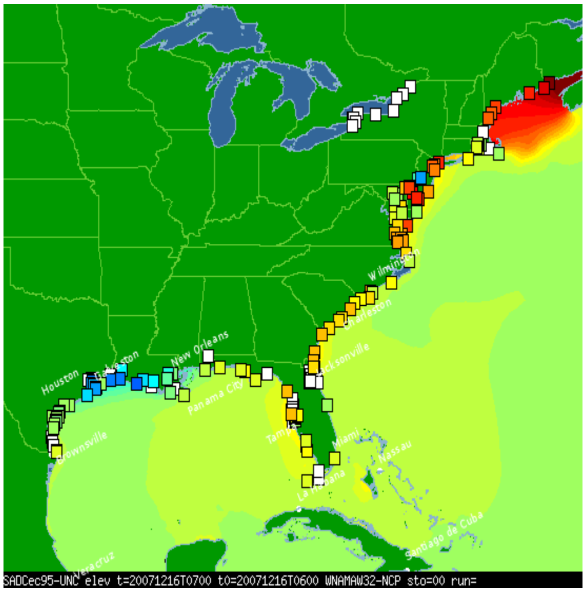

Figure 1. A depiction of forecast water level (m) based on the ADCIRC model output along the East coast and Gulf of Mexico. Warm shading (red and yellow) represents forecast water levels above mean low, low water (MLLW), while cool shading (blue) depicts forecast water levels below MLLW.

In an effort to incorporate the coupling effects of water level and wave action, the ADCIRC and Wave Watch III models have been graphically combined. The result is a web-based, experimental "Coastal Flood Nomogram" which simultaneously plots hourly water levels in Portland Harbor with near-shore wave heights (Fig. 2). The product is available on the Gulf of Maine Ocean Observing System (GoMOOS) website twice daily at *www.gomoos.org*.

Coastal flooding and splash-over benchmarks were then appended to the nomogram. These thresholds were based on empirically derived relationships of water level and waves that correlated with damage found in the Northern New England climatology. When the plot is animated (Fig. 2), a wide variety of users can assess the threat of potential coastal hazards.

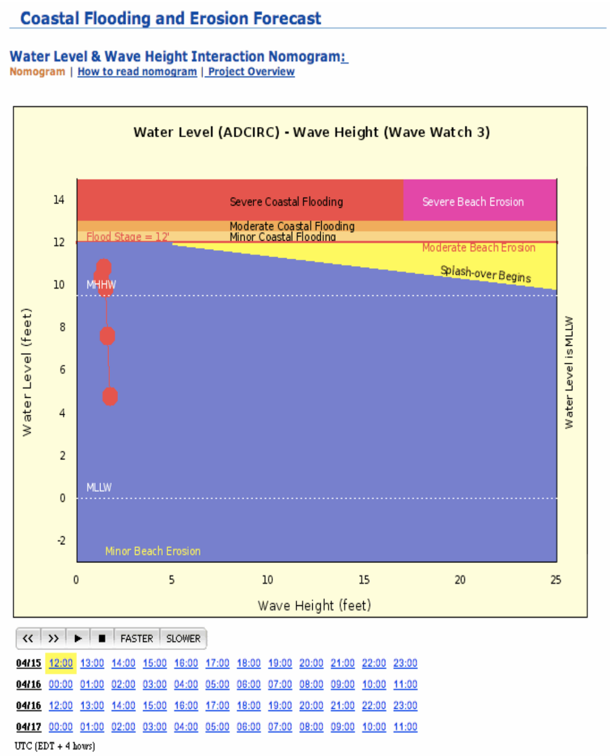

Figure 2. An example of a coastal flood nomogram recreated for the 16 April, 2007 (Patriot's Day) nor'easter. The nomogram animates predicted hourly water levels for Portland Harbor versus forecast wave heights at near-shore buoys. The red line represents the benchmark for coastal flooding, while the yellow shading depicts the onset of splash-over. Click on the image to view animation.

2. THE DEVELOPMENT OF THE COASTAL FLOOD NOMOGRAM

a. The Coastal Flood Benchmark

A red line denoting the magnitude of the storm tide associated with the onset of minor coastal inundation was placed on the nomogram (Fig. 2). This benchmark represents the 12.0 ft (3.77 m) flood stage in Portland Harbor, Maine and was produced by examining a robust catalogue of coastal flood events (1914-2007) along south coastal Maine and the New Hampshire Seacoast (Cannon 2007). In this climatology, the flood stage at the Portland tide gauge showed a consistent and positive correlation with the onset of nearby coastal flooding (NCDC 2007). This is not surprising as the vulnerable sandy region south of Portland, ME exhibits similar characteristics of bathymetry and topographical features and is similarly oriented in a northeast to southwest direction (Fig. 3). The 12.0 ft flood stage did not correlate with coastal flood events along the rugged rocky shoreline northeast of Portland.

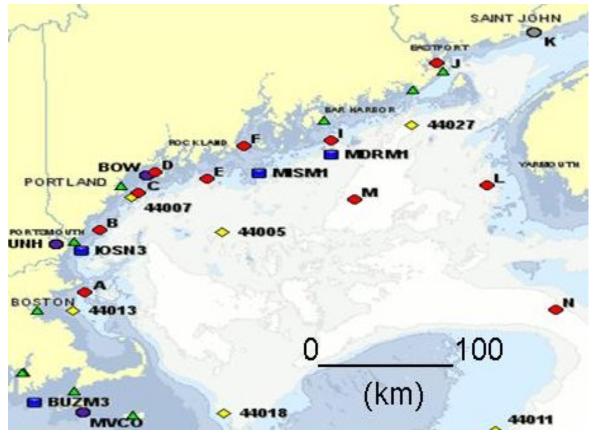

Figure 3. Locations of GoMOOS (red) and NOAA marine reports (yellow and blue) are shown in the Gulf of Maine. The Portland, ME tide gauge site is shown in green.

Benchmarks for minor versus moderate and severe coastal flooding were included on the nomogram. The categories were established based on combined storm impact and the height of the peak storm tide in Portland Harbor of 12.0 ft (3.66 m), 12.5 ft (3.81 m) and 13.0 ft (3.96 m), respectively. However, new collaborative efforts will be undertaken in the future to produce consistent flood severity categories along the entire east coast.

During *minor coastal flood events* (defined as a 12.0 ft storm tide), sea water briefly submerges sections of near-shore roads or low lying properties. Damage and water levels may be locally increased due to the presence of large, battering waves. During these events, sand, rocks and other debris may be tossed onto washed out coastal roads. Low lying areas may become flooded as wave energy is focused in exposed regions. Travel may be briefly limited along vulnerable locations as roads are closed until the tide subsides or snowplows are used to clear debris. Commercial fishing equipment may be damaged or destroyed.

Damage will be magnified during *moderate coastal flood events* (12.5 ft storm tide). At this level, coastal flooding becomes increasingly widespread. Seawalls crumble, jersey barriers are moved by the tide and many piers and wharfs become submerged. Some residents are evacuated by instituting "reverse 911" procedures (Saco EMA 2008). *Severe coastal flooding* (13.0 ft storm tide) events are rare and are limited to the top 15 storm tides ever recorded in Portland (1914-2007). Beachfront homes are lost to the sea and buoys are ripped from their moorings. Coastal flooding spreads inland and may occur for more than an hour either side of high tide. Mammoth waves strike lighthouses. Severe financial strife occurs within the marine community which may prompt a state of emergency.

b. The Splash-over Benchmark: The Influence of "Wave Set-up" and "Wave Run-up"

A yellow line depicting the benchmark for the onset of splash-over was then appended to the coastal flood nomogram (Fig. 2). The empirical relationship between storm tides, large ocean waves and splash-over was derived from the storm data publication database (NCDC 2007) (Fig. 4). As wave heights increased, there was an increased risk of localized splash-over damage or coastal inundation along exposed sandy beaches south of Portland (Fig. 5). This may occur despite tide heights below the 12.0 ft flood stage in Portland Harbor.

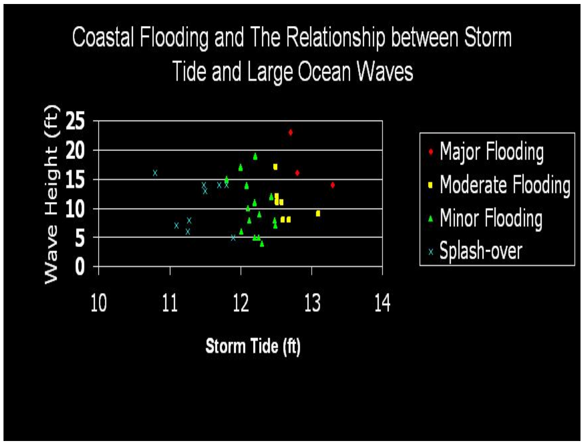

Figure 4. A plot of known coastal flood and splash-over events (1980-2007). Major flooding and significant damage was associated with large ocean waves and significant storm tides (upper right hand portion of the graph), while splash-over events occurred despite the nearby Portland Harbor tide gauge measuring storm tides below flood stage.

Storm data publication traditionally has focused on damage due to coastal inundation. Therefore, splash-over events below the 12.0 ft flood stage in Portland Harbor have historically not been well documented. However, a local archive of ten surveyed storms (1991-2007) along the southwest coast of Maine and the Seacoast of New Hampshire were available for analysis (Table 1).

In this dataset, the onset of splash-over occurred in our domain concurrently with a storm tide as low as 10.7 ft (3.26 m) as recorded in nearby Portland Harbor (Table 1). Localized coastal inundation has also been known to occur below this critical height, mainly due to rare interactions of storm tides with the rapid freshwater runoff associated with extreme rainfall events. These "outliers" were not included in the dataset. Observed waves of as little as 5.0 ft (1.52 m) in height produced splash-over with an associated tide of 11.91 ft (3.63 m).


Figure 5. An example of splash-over damage in Saco, Maine during the Saint Patrick's Day, 2007 storm caused by the battering of ocean waves.

However, the majority of the events featured waves greater than 13.0 ft (3.96 m) measured at buoys nearest the splash-over events (Fig. 3). A best fit analysis utilizing the data (Table 1) was plotted as a yellow benchmark on the nomogram (Fig. 6). The line represents an empirical relationship that approximates the onset of splash-over damage along the southwest coast of Maine and New Hampshire as wave action couples with increasing storm tides. Hourly plots of predicted storm tides (ADCIRC model) and predicted near-shore waves (Wave Watch III model) can be animated. During significant storms, this graphic visually depicts a ball crossing the splash-over or flood stage benchmarks (Fig. 2).

Wave characteristics can also affect coastal damage. Large, long period swells contain a disproportionately greater amount of energy when compared to smaller wind waves. Also, within a wave spectrum, the largest of breaking waves cause significant "wave run-up" along the beaches, thereby increasing the threat of coastal damage.

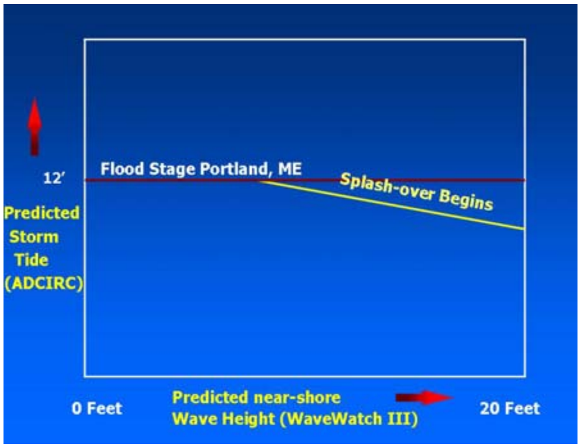

Figure 6. The yellow benchmark on the nomogram depicts a best fit analysis using data from Table 1. This yellow line shows the onset of splash-over for the southwest coast of Maine and the Seacoast of New Hampshire.

In addition, the phenomena of "wave set-up" can allow for splash-over or coastal flooding despite the absence of a wind driven storm surge. Wave set-up is the transfer of potential energy from large breaking waves to the kinetic energy required to maintain a surge of water near the shoreline. This focused energy can increase near-shore water levels by a magnitude of 10 to 15 percent of the shoaling breaker height (COMET 2006). Unfortunately, local increases in waters level due to waves are often not captured by relatively deep water tide gages such as Portland Harbor that are outside the surf zone.

c. Beach Erosion

Beach erosion is one of the most significant impacts of coastal storms because of the vulnerability of beachfront homes (Zhang et al. 2001). Storm tide, wave energy and duration are three major factors determining storm erosion potential. Zhang et al. (2001) found that the erosion potential during severe winter storms (Nor'easters) is more dependent on storm tide than on wave energy and duration. Davis and Dolan (1993) further hypothesized relationships between storm strength (classes) and equivalent beach erosion for the outer banks of North Carolina. However, this study did not explicitly measure beach loss.

In an effort to obtain actual measurements of beach erosion, there have been recent attempts to build a volunteer network of individuals to calculate sand dune loss after significant coastal storm events in northern New England by the Maine Geological Survey. However, at the time of publication, archived information on sand dune loss was not readily available to the National Weather Service (NWS) for examination.

Although net beach loss was not explicitly calculated for the northern New England coastal flood climatology, severe beach erosion has been anecdotally noted in Storm Data Publication (NCDC 2007) to be commonly associated with events which produced large waves and significant storm tides. This is consistent with the findings of Zhang et al. (2001). A place-holder for severe beach erosion was therefore appended to the upper portion of the nomogram (Fig. 2). However, further investigation will be required in future studies to produce quantifiable beach erosion benchmarks.

3. AN EXAMPLE OF A RECENT SEVERE COASTAL FLOOD EVENT: THE 2007 "PATRIOT'S DAY" STORM

An intense (966 hPa) low pressure system became quasi-stationary near Long Island, New York on 16 April, 2007. The storm brought hurricane force winds (up to 75 kts) and 32.0 ft waves (9.75 m), ripping near-shore buoys from their moorings in the Gulf of Maine. Excessive rainfall over 8.0 in (20 cm) combined with rapid snowmelt near the coast to produce widespread fresh water flooding. Five rivers recorded all-time record flows in southern Maine and southeast New Hampshire (USGS 2007). The abundance of fresh water runoff aggravated flooding of marsh roads as it interacted with the incoming storm tide.

The intense winds and large, battering waves produced severe coastal flooding, splash-over and beach erosion. Homes were swept off their foundation and new river inlets were created. The region was declared a disaster area and required assistance from the National Guard. This historical storm produced the seventh highest tide ever recorded of 13.3 ft (4.05 m), since measurements have been kept in Portland Harbor (Cannon 2007), and produced a storm surge of 2.7 ft (0.82 m). This tide was the first of six consecutive high tides above flood stage in Portland Harbor.

Model ensembles and standard atmospheric anomaly data were reviewed for the Patriots Day storm. The ensemble mean sea level pressure fields (1000 hPa) depicted a highly clustered model initialization on 16 April, 2007. Standard sea level pressure anomalies exhibited a rare five standard deviations from the atmospheric mean during the event as the historically deep storm formed off the Mid Atlantic coast (Fig. 7).

During testing phases while creating the nomogram software, the tool accurately predicted 48 hours in advance the extent and timing of the severe coastal damage resulting from the storm. Predicted storm tides versus observed wave heights were available to recreate a coastal flood nomogram for this event (Fig. 2).

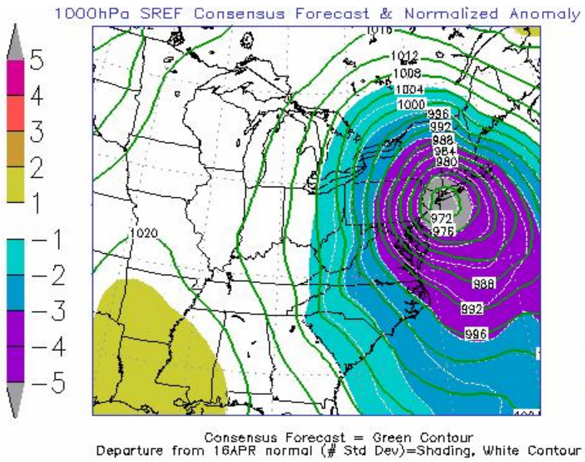

Figure 7. Standard anomaly of mean sea level pressure (hPa, shaded) and ensemble mean sea level pressure for the 16 April, 2007 storm. Shading indicates sea level pressure representing five standard deviations from the atmospheric mean.

4. CONCLUSIONS

Severe coastal inundation is rare, but damage produced by large, battering waves is not. Visualization techniques displayed in the coastal flood nomogram increases meteorologist's confidence during the warning process and assists emergency managers in mitigation preparedness. Ongoing research will allow for the construction of a coastal flood nomogram for other vulnerable locations along the east coast, such as Scituate, Massachusetts.

The coastal flood nomogram showed early success with the Patriot's Day Storm, however, additional verification is needed with the ADCIRC model. Upcoming active storm periods will provide additional opportunities for case by case evaluation.

In the future, information collected from the coastal flood climatology could be interactively retrieved by the users. A mouse roll over feature would allow for "pop-up" windows to display known hazards that comprise the historical database during unique storm tide and wave height combinations. Finally, plans for an interactive nomogram would allow the user to manually adjust the forecasts of storm tides and waves. Recent "predicted" versus "observed" storm surge trends would be plotted to provide a basis for the user to make such adjustments.

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Table 1. Database used to produce splash-over benchmark for the coastal flood nomogram. Damage occurred in association with waves as little as 5 ft., which were coupled with relatively high storm tides. However, all events occurred below the Portland Harbor flood stage of 12 ft.

Date	Near-shore waves (GoMOOS/NOAA Buoys)	Coinciding Storm Tide (Portland Harbor)
3/4/91	7'	11.08'
1/4/94	6'	11.26'
3/6/97	5'	11.91'
10/10/98	8'	11.28'
9/29/03	14'	11.48'
4/3/05	14'	11.68'
5/7/05	13'	11.48'
10/25/05	16'	10.77'
3/13/07	14'	11.80'
12/16/07	16'	11.17'