6.4 A STUDY OF MODERATE COASTAL FLOOD EVENTS ALONG THE EASTERN MASSACHUSETTS SHORELINE

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1. INTRODUCTION

Coastal flood events along the eastern Massachusetts shoreline are associated with the combination of storm surge and large wave action associated with the passage of an intensifying extratropical cyclone (nor'easter). The eastern Massachusetts shoreline, historically, has experienced many major coastal flood events (USACE 1981). Major coastal flood events occur when storm tides exceed 14 ft, regardless of accompanying wave action and/or seas. Damage is often widespread, with substantial structural damage to homes and coastal businesses, as well as complete destruction to coastal roadways and bridges. These major events have been generally well forecasted. Examples include the Blizzard of 1978 (NOAA 1978) and the Halloween (Perfect Storm) Nor'Easter of October 1991 (NWS 1992).

Moderate coastal flood events (storm tide 12.0 – 13.5 ft MLLW) have been much more challenging to forecast and warn for due to the fact that they are associated with storm tides which are below flood elevation, and accompanied by large waves produced by strong onshore winds. Moderate coastal flooding results in substantial coastal shore road flooding, enough to have 1 to 2 feet of standing water on roadways, and/or physical damage to roadways and sea walls.

Storm tide is the total observed water elevation including the cyclone induced storm surge (Blier et al. 1997), where as storm surge the arithmetic difference between the observed tide and the predicted astronomical tide. Storms associated with coastal flooding produce an extended period of strong onshore winds, generally from the north through east, which result in tremendous wave action from large seas just offshore. The extended period of onshore winds leads to wave set-up, a process through which ocean water is carried shoreward by the large breaking waves and is unable to flow back out into the open sea. These characteristics present several of the major components for the production of extratropical storm surge (Pore et al. 1974).

The author's past experience with two such moderate events indicate that there was much uncertainty in the forecaster's mind as to whether flooding would occur and if so, on which high tide cycle would that potential be greatest. After intense outreach to the coastal communities and closer examination of the combined storm tides with large seas, it was determined that moderate coastal flooding was occurring during episodes when tides as much as 1.2 feet below the flood elevation were combined with very large seas. This study was launched in an effort to develop thresholds of wind, storm tide and seas required to produce moderate coastal flooding. Onshore winds, storm tides, and wave heights are examined from moderate coastal flood events from 1986 through 2003. The thresholds developed from this research provide an initial warning decision making tool to improve coastal flood watch and warning performance, for moderate events.

2. DATA and METHODOLOGY

Data for this project utilized observed tide elevation observations, at Mean Lower Low Water (MLLW) obtained through the National Ocean Service Tide Reporting Platform located in the inner Boston Harbor.

The established flood warning tide elevation for the Boston Harbor Tide Gage is 13.6 feet MLLW. Wind and wave data was collected from the National Data Buoy Center (NDBC) Buoy located 16 miles east of Boston Harbor (Buoy 44013 at 42.35N, 70.69W), here after referred to as the Boston Buoy (Fig. 1). The period of study, 1986-2003, was defined to utilize Boston Buoy data, which was placed in service in 1986. The Boston Buoy was chosen due to its close proximity to the eastern Massachusetts coastline, the area of focus where coastal flooding occurs. The significant wave height data from this buoy is considered to be representative of the wave heights and behavior which impact the eastern Massachusetts shoreline, from Plymouth northward to Gloucester, based on feedback and observations provided by local emergency managers and NWS Storm Spotters. This portion of the coast is also quite susceptible to large wave action on east and northeast winds. Examination of the Boston Buoy's location allows for the establishment of wind and wave thresholds required to produce moderate coastal flooding along the eastern Massachusetts shoreline when observed storm tides are below flood elevations.

The observed and astronomical tide data were analyzed for a 24 to 48 hour period preceding the high tide upon which flooding occurred. Wave height, sustained wind and peak wind gusts for each hour, from the Boston Buoy were then compared to the observed and astronomical tide data to help determine the significant features associated with the five cases.

There were eight moderate to major coastal flood events during the period of study, associated with the Boston Harbor storm tides exceeding 12.0 feet (MLLW). A monthly distribution of these eight events is provided in Figure 2, which indicates these coastal flood events are confined to the cool season (Oct thru April). Of these eight events, three were classified as major coastal flood events, where storm tides reached or exceeded 14.0 ft (MLLW; Fig. 3). These events were not included, since coastal flood events associated with storm tides (>14 ft) exceeding flood elevations are sufficiently forecasted along with extended lead times. Conversely, coastal flood events associated with storm tides below 13.5 ft (MLLW) are much more difficult to forecast. Hence, the focus of this study is on the 5 moderate coastal flood events associated with storm tides below flood elevation.

3. RESULTS

Each moderate event was associated with the passage of a deepening extratropical cyclone (not shown), producing at least a 12 hour period of onshore (northeast) winds of at least 30 kts resulting in considerable wave set-up. Peak wind gusts near or exceeding 40 kts were observed around the time of astronomical high tide. Table 1 provides a summary of critical parameters associated with the five moderate coastal flood events. These events can be divided into two groups; those associated with storm tides of 13 to 13.5 feet MLLW and those associated with storm tides below 13 feet MLLW. For those events associated with storm tides in excess of 13 feet, seas of 15 to 20 feet produced moderate coastal flooding, while for much lower storm tides of 12 to 13 feet MLLW, seas exceeded 20 feet as measured at the Boston Buoy. Three cases are examined, two of which involve storm tides below 13 feet and one with a storm tide of 13.5 feet. These cases illustrate the importance of increasing wind and seas in the hours leading up to the tide cycle upon which flooding was observed.

The December 6-7, 2003 event produced moderate coastal flooding associated with the lowest storm tide of the 5 moderate events and is representative of the conditions typically observed in the 12 hours prior to the actual flooding. Sustained northeast winds of gale force were observed from 12 UTC on December 6 and continued through the time of high tide at approximately 2 UTC on December 7 (Fig. 4). Note the gradual build up of seas through 21 UTC on December 6, followed by a more rapid build up 3 hours preceding the flood, commensurate with an increase in both sustained wind speeds and gusts maintained from a northeasterly (onshore) direction. Peak wind gusts of 50 kts or greater occurred for three consecutive hours preceding the high tide, and aided in the production of 30 feet seas around the time of high tide. This event produced a storm

surge of 3.4 feet above the astronomical tide, resulting in a storm tide of 12.3 feet (MLLW) on the 2 UTC tide on December 7.

A second example of a moderate event with storm tide below 13 ft MLLW is shown in Figure 5. Similar to the December 6-7, 2003 case, the March 5, 2001 case shows a period of sustained northeast wind in excess of 30 kts and seas greater than 20 feet preceded the arrival of high tide. It is interesting to note that while a period of strong onshore winds sustained at 35 kts with gusts >45 kts occurred near the time of high tide at 1 UTC on March 6, large seas in excess of 20 feet did not develop until 4 UTC on March 6, several hours after the astronomical high tide had occurred. As a result, no moderate coastal flooding was observed on the 1 UTC high tide. Moderate flooding did occur on the 13 UTC tide, which was associated with seas in excess of 20 feet.

The January 4, 2003 event is an example of an event which was associated with a storm tide in the 13 to 13.5 foot range (Fig. 6). This event illustrates that seas do not have to be as high when occurring on a storm tide of 13 to 13.5 feet. Much like Figures 4 and 5, note the period of sustained 30 kt winds and the building seas from 5 UTC on January 4th through the high tide of 17 UTC on January 4th.

4. FORECAST THRESHOLDS FOR MODERATE COASTAL FLOOD EVENTS

The following forecast thresholds have been identified through an analysis of the 5 events listed from Table 1, to assist forecasters in the warning decision making process for the issuance of coastal flood watches and warnings for moderate coastal flood event. The forecaster should determine the potential for large seas, near gale force winds and storm tides in excess of 12 feet (MLLW) associated with an approaching extratropical storm, based on available Numerical Weather Prediction models. The potential for large seas and gale force winds should be present for at least 12 hours prior to the tide cycle upon which a storm tide in excess of 12 feet (MLLW) is expected to occur. The Global Forecast System (GFS) (EMC 2003) provides operational guidance for wind and storm surge. For sea conditions, the Western Atlantic version of the Global Wave Watch Model (WNA; Tolman 1997) provides the highest resolution along the Massachusetts coastline.

4.1 Coastal Flood Watch Threshold

A coastal flood watch is warranted when numerical model and storm surge guidance indicate the potential for the following criteria within 24 to 36 hours of a possible moderate coastal flood event:

a. A period of east or northeast winds in excess of 30 kts preceding the time of high tide by 12 hours or more.
b. For storm tides of 12-12.9 feet - forecast seas of 20 feet or greater, or
c. For storm tides of 13.0 to 13.5 feet - forecast seas of 15 to 20 feet

4.2 Coastal Flood Warning Threshold

A coastal flood warning is warranted when numerical model and storm surge guidance indicate the potential for the following criteria within 24 hours of a possible moderate coastal flood event:

a. A period east or northeast winds in excess of 30 kts preceding the time of high tide by 12 hours or more.
b. For storm tides of 12-12.9 feet - forecast seas of 20 feet or greater, or
c. For storm tides of 13.0 to 13.5 feet - forecast seas of 15 to 20 feet

5. SUMMARY

The eastern Massachusetts shoreline, historically, has experienced many major high impact coastal flood episodes. Moderate coastal flood events, capable of producing structural and property damage along the coast, have been far more difficult to forecast and warn for. Storm tides during moderate events, as measured at the Boston Harbor tide gage, never reached nor exceeded the established flood elevations. These events are associated with the passage of an extratropical cyclone producing strong onshore winds which

induce large wave action atop the sub-flood elevation storm tide. The elevated water levels of the observed storm tide serve as a platform which allows these very large waves to reach and exceed the height of structures and property, thus producing flooding. For the moderate coastal flood events studied, seas in excess of 20 feet produced flooding with a storm tide less than 13 feet MLLW, while seas of 15 to 20 feet produced moderate coastal flooding with storm tides of 13 to 13.5 feet MLLW.

Thresholds have been presented and serve as an initial warning decision making tool, for forecasters in their evaluation of moderate coastal flood potential and for the issuance of coastal flood watches or warnings. While additional moderate coastal flood cases will allow for refinement, it is believed that the application of these initial thresholds will result in increased coastal flood watch and warning lead times, thereby increasing the time for preparedness for people who may be impacted by coastal flooding along the eastern shore of Massachusetts.

6. ACKNOWLEDGEMENTS

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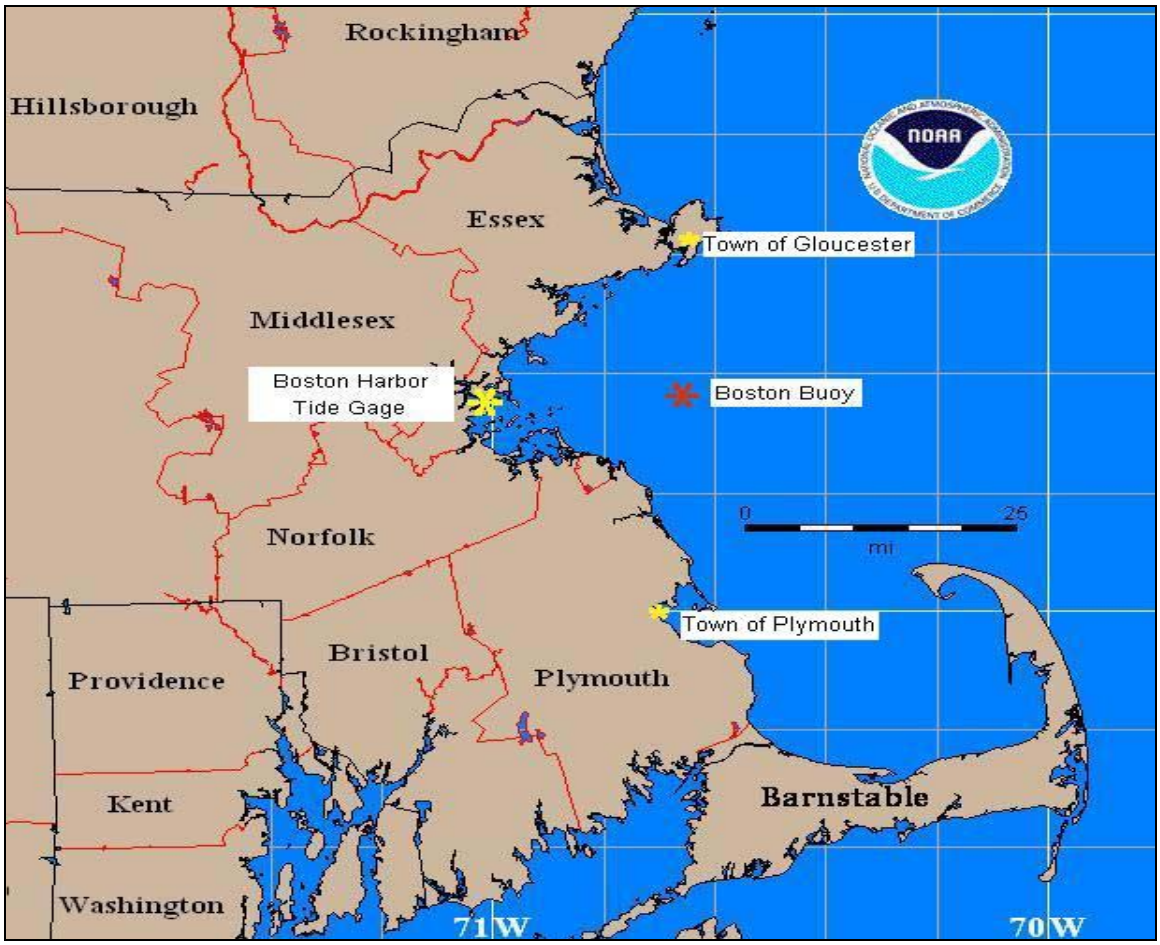

Figure 1. Map depicts the location of the Boston Harbor Tide Gage, located in the inner Boston Harbor, and the NDBC Data Buoy – Boston Buoy (42.35N, 70.69W), located 16 miles east of the entrance to Boston Harbor. State counties are also indicated.

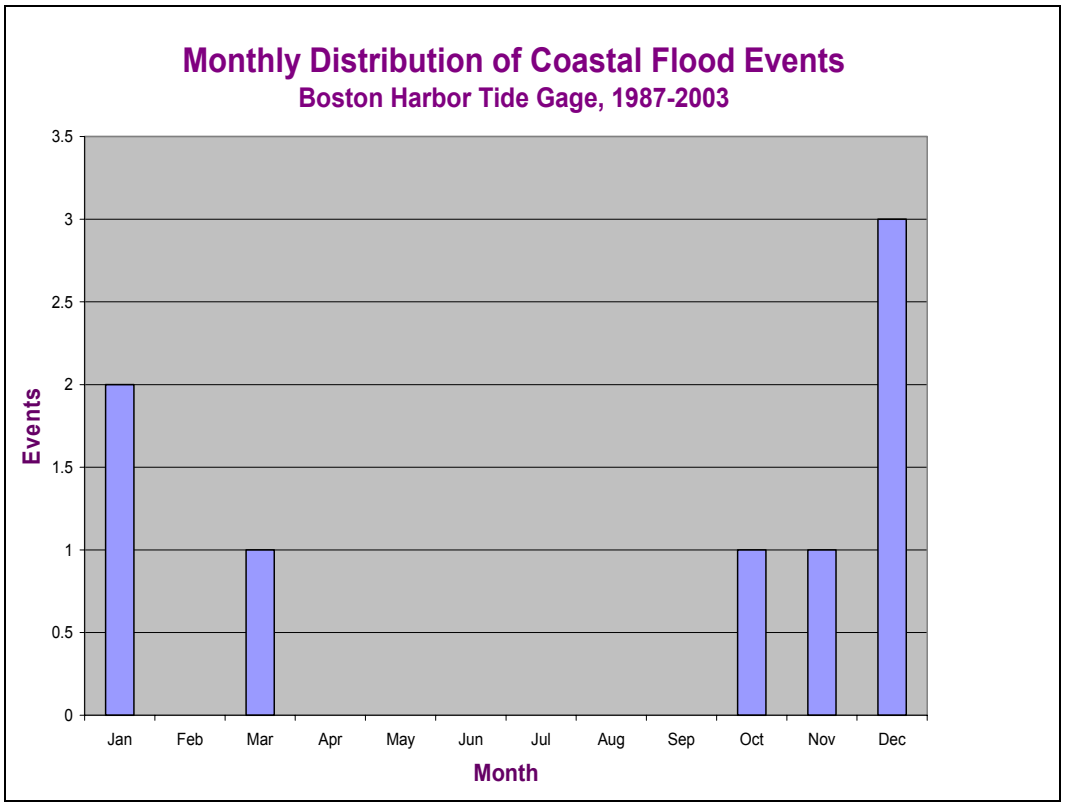

Figure 2. Monthly distribution of coastal flood events for the Boston Harbor tide gage.

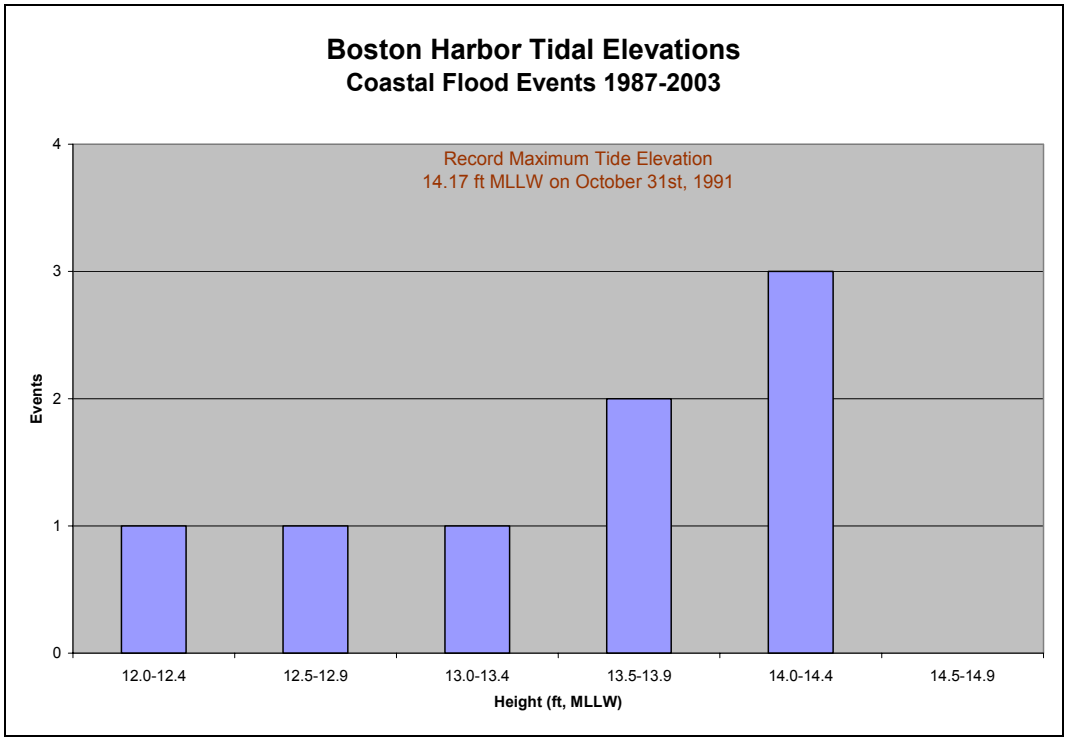

Figure 3. Distribution of coastal flood events for Boston Harbor, as a function of tide elevation.

Table 1. Critical wind, wave and tide data associated with moderate coastal flood events from 1986-2003.

Event Date	Storm Tide (ft, MLLW)	Storm Surge (ft)	Maximum Sustained wind (kts)	Peak Wind Gust (kts)	Highest Seas (feet)
12/6/03	12.3	3.4	42	53	30
3/6/01	12.8	2.3	33	43	23
12/20/95	13.4	1.9	32	37	16
11/6/02	13.5	1.3	32	38	15
1/4/03	13.5	2.4	32	41	20

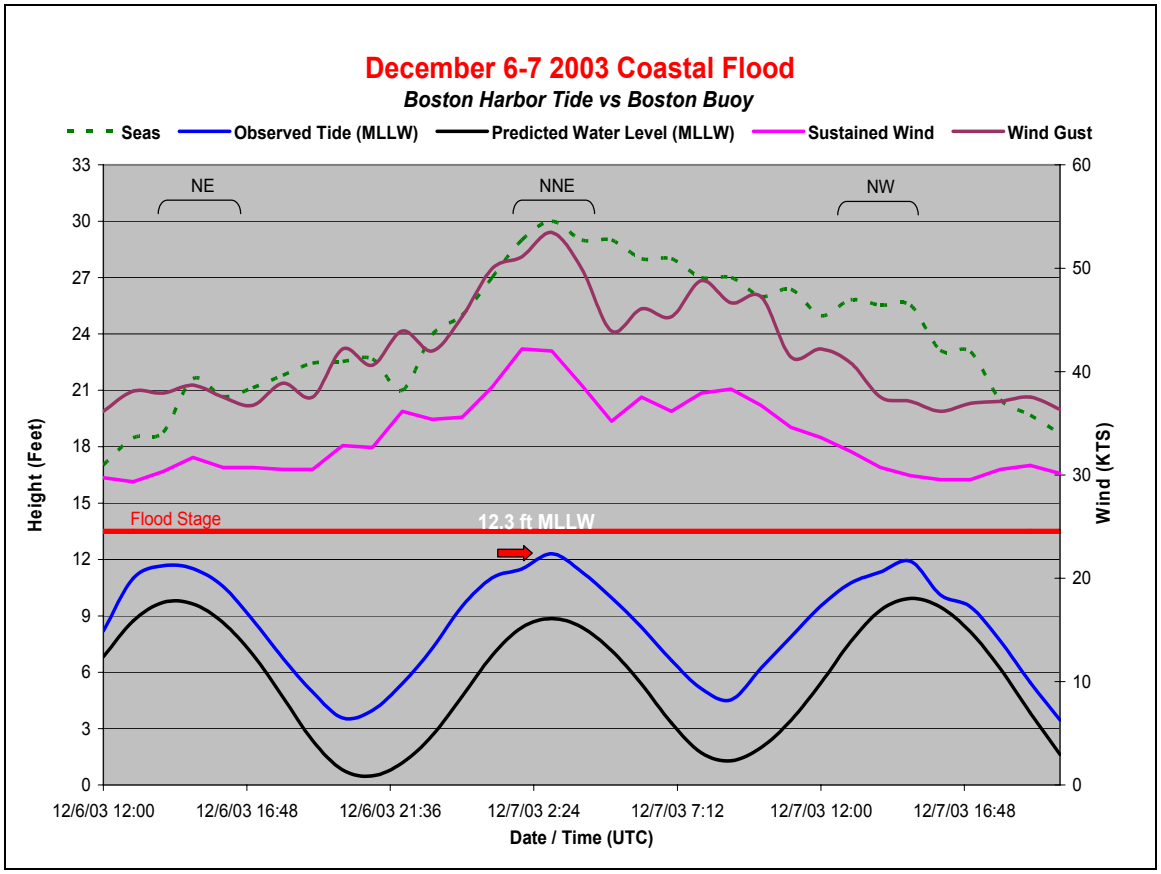

Figure 4. Tide, wind and wave behavior for the moderate coastal flood event of December 6-7,2003. Solid black curve is the predicted astronomical tide (MLLW). Solid blue line is the observed storm tides (MLLW). Pink solid line is sustained winds from the Boston Buoy and the solid brown line represents the observed maximum wind gusts. The dashed green line indicates the observed seas in feet. Brackets along the top represent the observed wind directions, counter clockwise from left to right. Time is referenced in hours and minutes UTC.

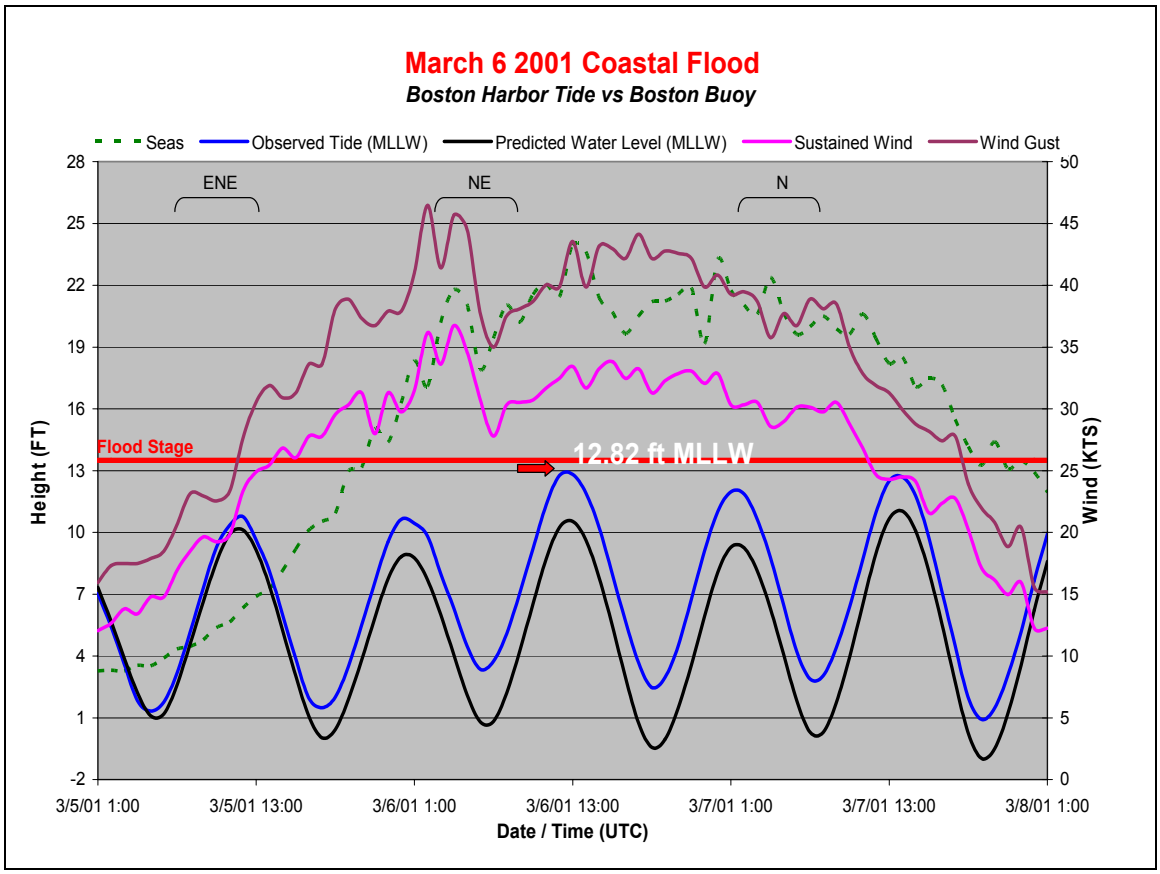

Figure 5. Same as figure 4, except for the moderate coastal flood event of March 6, 2001.

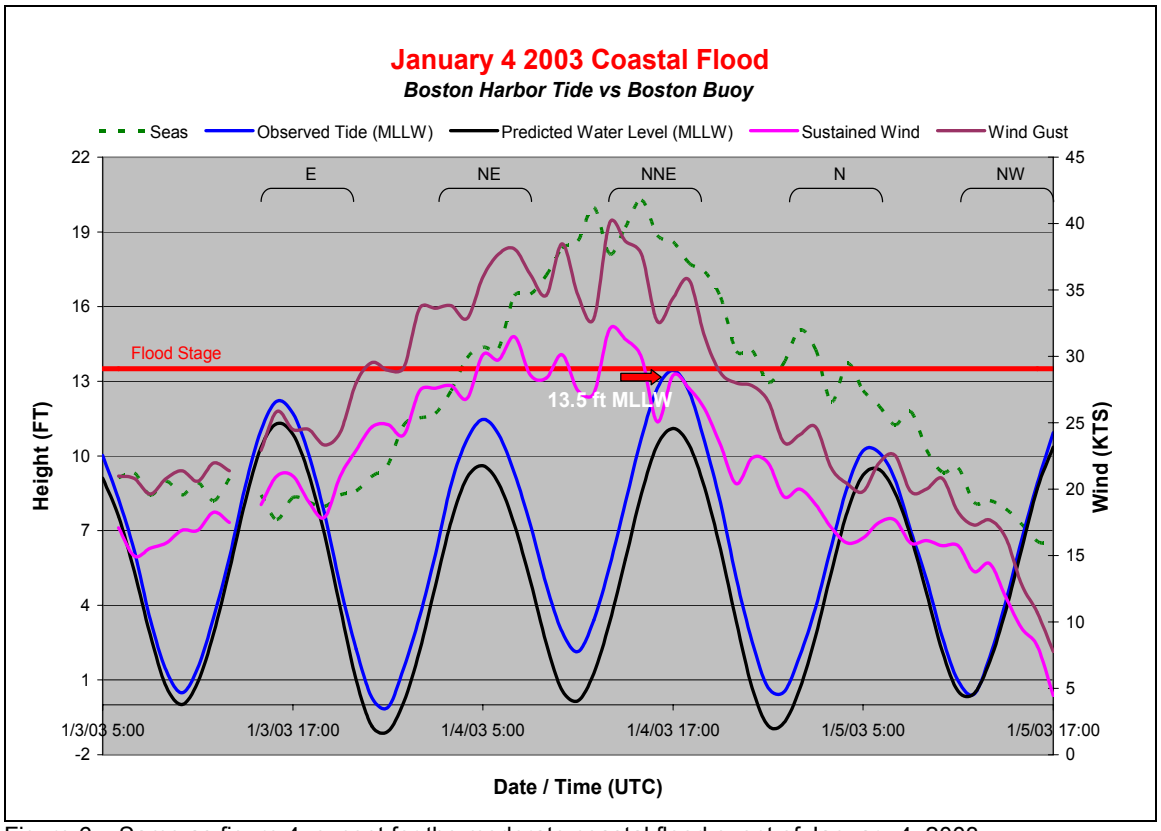

Figure 6. Same as figure 4, except for the moderate coastal flood event of January 4, 2003.