The Three Faces of Isabel:
STORM SURGE, STORM TIDE, and SEA LEVEL RISE

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To the thousands of Tidewater residents who encountered this storm on September 18, 2003, Hurricane *Isabel* showed many faces, none of them a welcome sight. I would like to dwell for a moment on three that I saw – three different physical traits that tell us not only what we've just experienced from *Isabel*, in terms of high winds and high water, but what we might expect from other storms like her in the future. Two of these traits –*storm surge* and *storm tide* - are governed by probability. Like rolls of the dice, they have odds but no certainty about them. The third - *sea level rise* - is all too certain and adds slowly but continually to the danger present in the extreme water levels we will experience in our region in coming years.

I'll illustrate my point by comparing *Isabel* with another hurricane that happened 70 years ago. This storm had no name but it is generally known as the August 1933 hurricane – the storm of the century for Chesapeake Bay. Before making the comparison, let's begin with a brief introduction to the three faces.

STORM SURGE

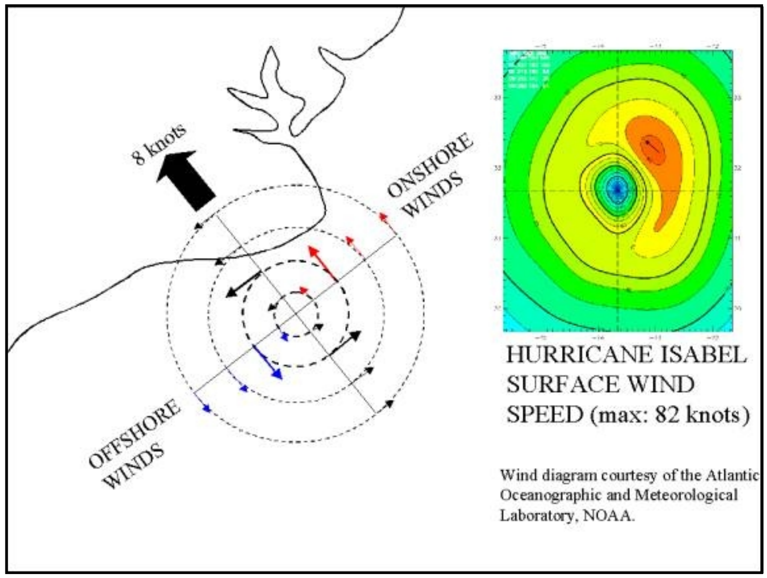
Storm surge is the rise in water level produced by any of several types of organized low-pressure systems that occur in the earth's atmosphere called cyclones. A drop in atmospheric pressure by itself causes water levels to rise but most of the height increase, or surge, comes about as high winds blow across the surface of the water, creating a long wave that eventually piles up against a shoreline. Keep in mind the fact that storm surge is the short-term change in water level due to the effects of the storm – as if the oceans were still, as if tides and long-term sea level changes did not exist.

Cyclones in the northern hemisphere have winds that move counter-clockwise around their central low and consist of two basic types: *tropical* and *extratropical. Extratropical cyclones* or "northeasters" typically originate as lows along frontal systems at mid-latitudes inside the continent. Those that find their way to the U.S. East Coast usually move in a northeasterly direction as huge, sprawling storms whose wind systems span hundreds of miles, often extending over several states at once. A *tropical cyclone* typically originates as a tropical depression in the lower latitudes of the Atlantic Ocean. As the depression becomes better organized around a central low – a low that usually moves to the west - it is called a *tropical storm*. As the low deepens and surface winds exceed 74 miles per hour (64 knots) the tropical storm becomes a *hurricane*.

Unlike extratropical storms, hurricanes pack more of their punch into a relatively small zone – a circular belt or ring of highest winds surrounding the "eye" of the storm as shown below in the satellite image of Hurricane *Andrew* (image produced by the U.S. National Oceanic and Atmospheric Administration – NOAA).

Storm surge experts look at several measures that describe hurricanes and their ability to produce a large surge. Among these are central pressure anomaly, maximum surface winds, radius of maximum winds, forward speed, and direction of movement. All five show considerable variability about their mean value based on past measurements and the combination present in any one storm is a fair example of random chance. Sitting at a particular place along the coast, we could evaluate the probabilities that some of the most dangerous combinations will occur in any given year and take comfort in the fact that they are relatively low. Still, when a major hurricane does develop and comes our way, it's not only the direction that matters, the *side* of the storm we're on – left or right – becomes important as well. This is due to the counter-clockwise wind movement and forward motion of the storm (about 8-9 knots when *Isabel* made landfall). Winds on the right side are augmented by this motion and are blowing water onshore as shown at right.

** note: onshore winds diagram not to scale – for purposes of illustration only!*



Wind diagram courtesy of the Atlantic Oceanographic and Meteorological Laboratory, NOAA.

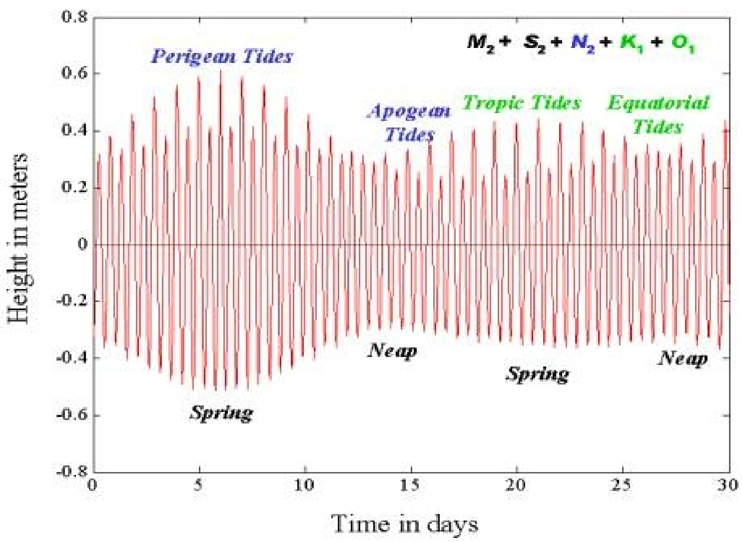
For emergency planning purposes, juggling five sets of numbers isn't workable. Hence a relatively new hurricane classification, the ***Saffir-Simpson Hurricane Scale***, has been devised by the National Hurricane Center at NOAA. Although the five categories that make up the scale are based on wind speed, each has a carefully described set of characteristics, including the height of the storm surge that typically occurs. The wind and surge limits of each category are shown in the table below.

	CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5
WIND	74-95mph 64-82 kt	96-110 mph 83-95 kt	111-130 mph 96-113 kt	131-155 mph 114-135 kt	>155 mph >135 kt
SURGE	4-5 ft 1.2-1.5 m	6-8 ft 1.8-2.4 m	9-12 ft 2.7-3.7 m	13-18 ft 4.0-5.5 m	>18 ft 5.5 m

STORM TIDE

A *storm tide* is the extreme water level that is actually observed at a specific location during a storm. It represents the combination of the storm surge and the *astronomical tide* (the tide caused by the gravitational interactions of the moon and sun with the waters of the earth – see my *Tides and Currents Tutorial* under Research Programs at www.vims.edu/physical/. In addition to the astronomical tide, storm tides also include seasonal and long-term water level changes – up to and including our present trends in yearly mean sea level that show a strong rise relative to the land (check out *The Tidal Datum: Where Sea Meets Land*; you'll find it inside the *Tides and Currents Tutorial*). We'll come back to the topic of sea level rise in a moment. First let's see just what kind of influence the astronomical tides can have on the storm tides we observe in our area.

The astronomical tide gives us the familiar tide cycle, the twice-daily rise and fall of the water's surface with two highs and two lows on most days. Actually there are several cycles going on at once. When we draw a graph of the tide covering more than a single day, we get something that appears pretty complex as shown in the figure on the next page.

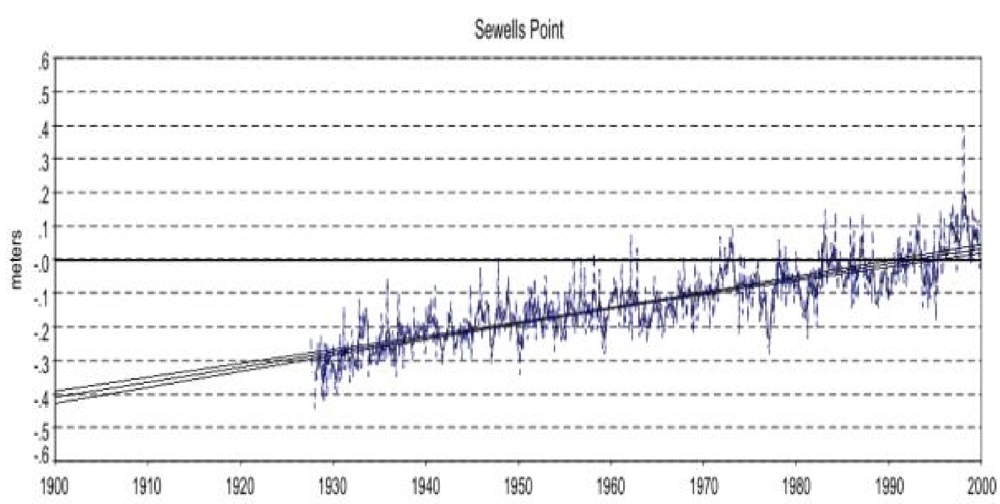


Although this figure has a lot going on within its span of 30 days (spring-neap tides, perigean-apogean tides, tropic-equatorial tides), it's the result of just five simple sine waves added together. Like atoms making up molecules, these simple waves with five different periods make up a large portion of the astronomical tide. Oceanographers identify them with the symbols M_2, S_2, N_2, K_1, and O_1. As M_2 and S_2 interact, for instance, they produce the *spring-neap* cycle, a variation in tidal range (range is the height difference between successive highs and lows). In the same way, M_2 and N_2 produce range variations known as the *perigean-apogean* cycle. K_1, and O_1 produce a cycle that features *daily inequalities* in the tide (successive highs differ in height and/or successive lows differ in height); the inequalities are greatest during *tropic tides* and least or non-existent during *equatorial tides*.

The well-known motions of the earth, moon, and sun determine all of these cycles. As a result, they're predictable years in advance. However, the storm surge and its components are different; not only are they unpredictable before the storm, they are independent of the tide. When the peak of the storm surge finally arrives at some unfortunate spot along the shore, the dice will have already been rolled but before then, it's simply a matter of chance whether it will coincide with a high tide or a low tide (spring tide or neap tide, etc.) or something in between.

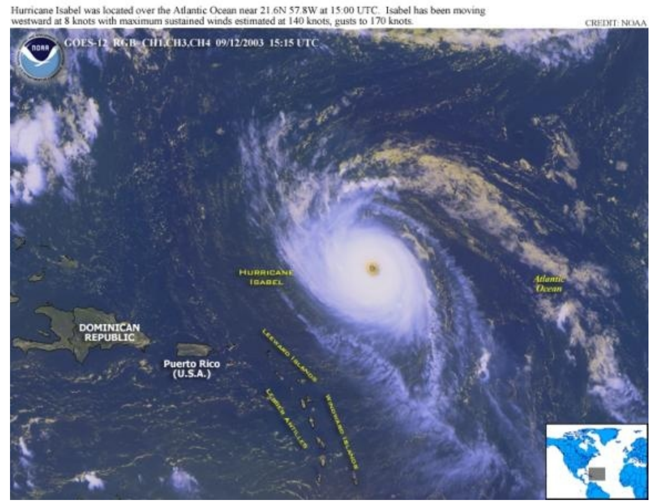
SEA LEVEL RISE

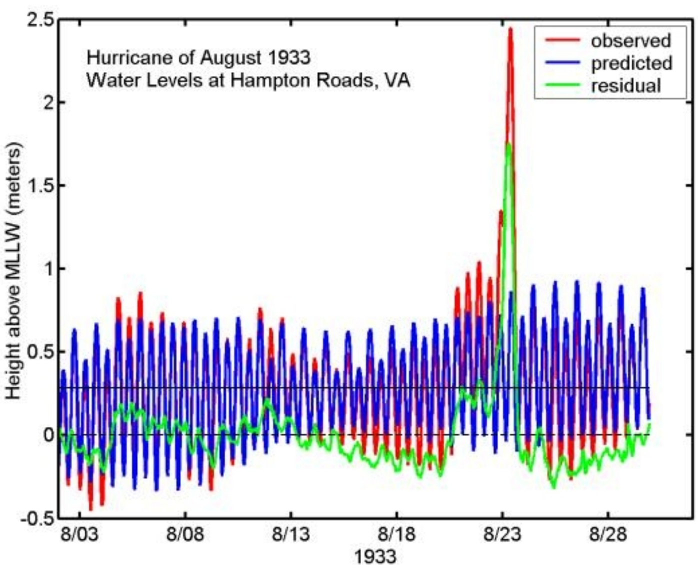
The National Ocean Service, a division of NOAA, keeps track of water levels at primary tide stations in the United States. One of these stations is located at Sewells Point in Hampton Roads, Virginia. Below is a figure that I obtained from their web site (http://co-ops.nos.noaa.gov) showing what the NOS refers to as the mean sea level trend for this station, from 1927 through 1999. They call it a trend rather than a rise because in some parts of the country sea level is actually *falling* relative to the land. The wavy lines are plots of monthly mean sea level with the average seasonal cycle removed. As you can see in the figure, there is a fair amount of 'scatter' from one month to the next but over several years the trend becomes clear. The three fitted lines represent the range in uncertainty of the trend; the middle line or average trend yields an eye-popping 4.42 mm/year or 1.45 feet/century of sea level *rise* relative to the land at Hampton Roads.

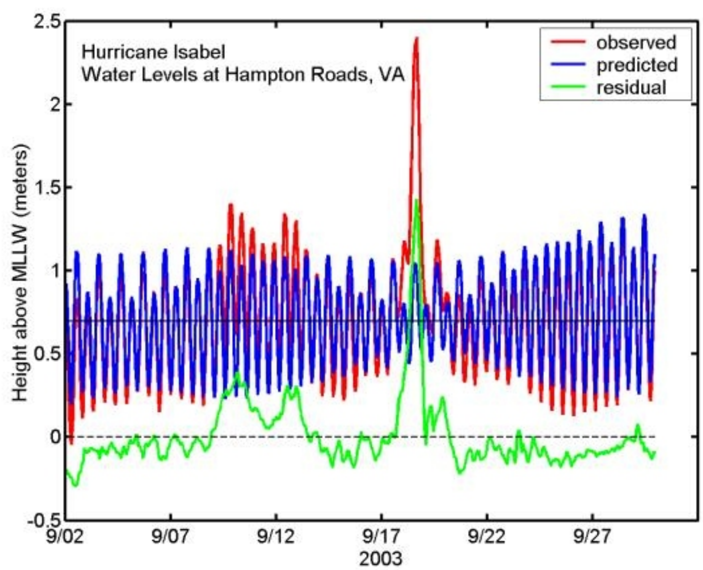


Hurricane Isabel and the Hurricane of August 1933

Tidewater residents who experienced the August 1933 hurricane have stated that the high water marks left by Hurricane *Isabel* approached, or may have exceeded, similar marks witnessed from the 1933 storm. They are probably right. The NOS water level data available for Hampton Roads, VA, (Sewells Point) permit an unusual comparison that answers this question but then raises another. If the high water marks left by the storm tides for these two events are the same or nearly so, how is possible that one had a much greater storm surge than the other and occurred during spring tides while the other occurred during neap tides? The answer appears in the figures below.







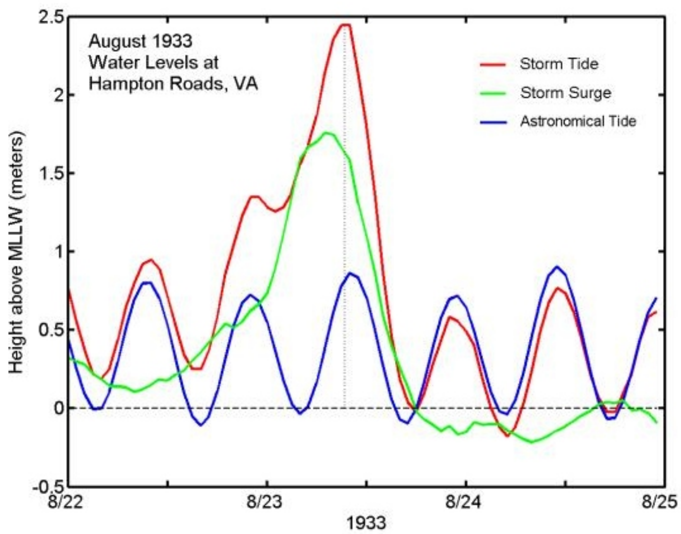
The *green curves* in the above two figures represent the storm surge. As noted in the legend, they are the *residual* or the difference obtained after subtracting the *predicted* or astronomical tide heights (blue curves) from the *observed* water levels (red curves) at Sewells Point. You'll notice that the storm surge during the 1933 storm occurred at the beginning of spring tides (with perhaps some part of a perigean tide added in) while the surge during the 2003 storm occurred in the middle of a neap tide (with strong daily inequalities indicative of tropic tides). At first glance the astronomical tides seem to support a higher storm tide during the 1933 hurricane as opposed to Hurricane *Isabel*.

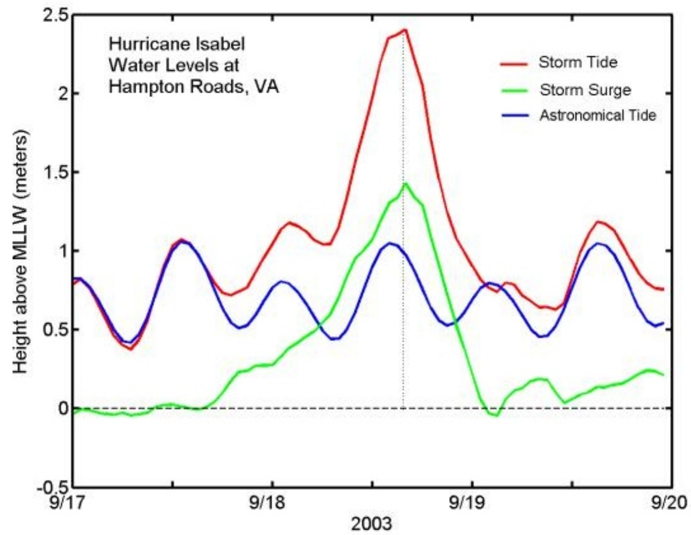
Some numbers – Below is a table summarizing the results of the comparison between *Isabel* and the August 1933 hurricane. The results show that the storm tides from both storms were very similar, the difference being only 4 cm or about an inch and a half. On the other hand, the 1933 storm produced a storm surge that was greater than *Isabel's* by a third of a meter or slightly more than a foot. The 'equalizer' in this case is the difference in monthly mean water level for August 1933 and September 2003 – sea level has risen by 41 cm (1.35 feet) at Hampton Roads in the seventy years between these two months.

Storm	Storm Tide (height above MLLW)	Storm Surge (height above normal)	Mean Water Level (height above MLLW)
Aug 1933	2.444 m (8.018 ft)	1.78 m (5.84 ft)	0.29 m (0.95 ft)
Sep 2003	2.404 m (7.887 ft)	1.45 m (4.76 ft)	0.70 m (2.30 ft)
1933 - 2003	0.040 m (0.131 ft)	0.33 m (1.08 ft)	-0.41 m (-1.35 ft)

Sea level change enters the water level diagrams through the periodic updating of the Mean Lower Low Water (MLLW) tidal datum (see *The Tidal Datum: Where Sea Meets Land* inside the *Tides and Currents Tutorial*). To account for the rise in sea level in our region, tidal datums have been adjusted upwards, by amounts that vary from station to station, during four *National Tidal Datum Epochs (NTDE's): 1924-1942, 1941-1959, 1960-1978*, and most recently, *1983-2001*. That means that the water level diagram for the August 1933 hurricane probably started out looking very much like the present one for Hurricane *Isabe*l. Then, with each new MLLW datum revision, its water level curves moved a step downward. **The inference from the present example is very clear; other things being equal, our present sea level trend will, over time, significantly increase the risk of coastal flooding during hurricanes.**

A Closer Look – A three-day plot of the water level data at Hampton Roads provides more insight into the coupling of storm surge with the astronomical tide:



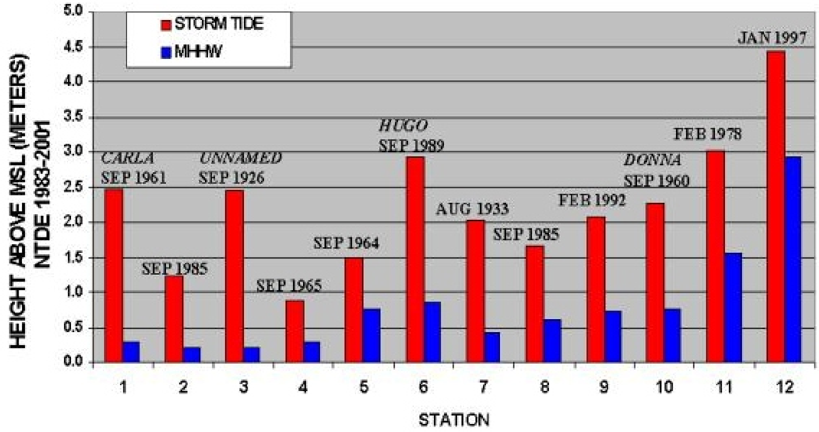


Now it is easier to see that the storm tide peak does not necessarily coincide in time with either the storm surge peak or the astronomical high tide, although both storms in the present example came close to doing so, especially *Isabel*. But the figures also show that the storm tide for either event could have been made larger or smaller with only a slight change in the range of the astronomical tide and/or its phase relationship with the storm surge. In the end, the storm tide for the August 1933 hurricane benefited slightly more from its astronomical tide because of its greater range, all else being equal. This small amount provides closure for the sum of the differences shown in the bottom line of the numbers table above.

Storm Tides Referenced to Mean Higher High Water - Why measure a maximum storm tide height in units (feet or meters) above the tidal datum of Mean Higher High Water (MHHW) rather than, say, MLLW, the reference datum used for soundings on nautical charts - or some other datum? Basically MHHW is a better datum for isolating and evaluating the specific risks associated with storm tides because it removes the effect of tidal range - an independent factor that varies from place to place. Moving along our coastline, we see that there are changes in both tidal type and tidal range that can affect storm tide height referenced to MLLW or Mean Sea Level (MSL), for example.

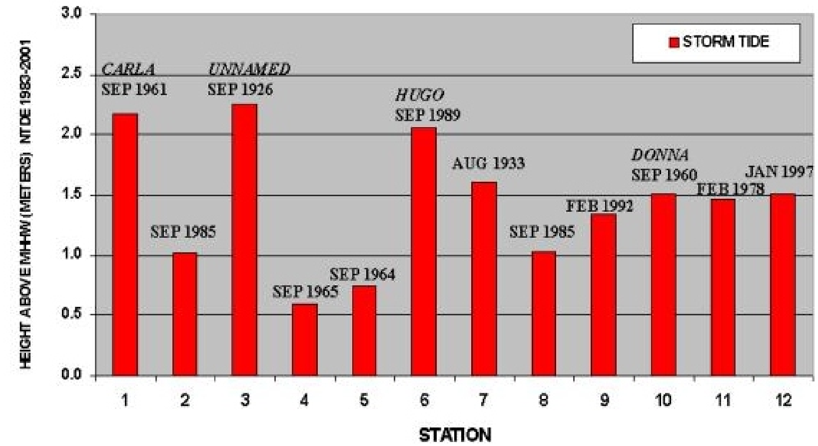
We'll sharpen this point with a histogram combining MHHW elevations and storm tides of record for twelve NOAA reference tide stations along the Gulf and East Coasts of the United States as shown below. Of the twelve stations included, four had record storm tides due to Category 4 hurricanes (*Carla, Donna, Hugo,* and an unnamed storm in 1926). However, water levels referencing MSL (red bars) show that the highest storm tide of record (4.4 meters above MSL at Eastport, ME) was due to a winter storm in January 1997. This storm tide appears overwhelming but is it? Because the New England coast has a large tidal range, the tidal datum of MHHW (blue bars) is much higher there as compared to other stations - the Gulf Coast stations in particular.

The tidal range factor can be removed by referencing the same storm tides to MHHW as shown in the histogram below. Now we see that five stations had greater storm tides than Eastport, ME. All five experienced Category 4 hurricanes except Norfolk, VA (Category 3 in August 1933). It's very likely that Mobile Bay, AL experienced a very large storm tide as well during the September 1926 hurricane but no tide station was in operation there at that time. The same may be true for other storms missed by tide stations in Florida.



1. Galveston TX
2. Mobile AL
3. Pensacola FL
4. Key West FL
5. Mayport FL
6. Charleston SC
7. Norfolk VA
8. Ocean City MD
9. Atlantic City NJ
10. New York NY
11. Boston MA
12. Eastport ME

Final Point - Considering that MHHW comes from a 19-year average of the higher of the two high water levels measured each tidal day during the most recent tidal datum epoch, points that lie just above the MHHW line fall within a zone that appears dry most of the time. Coastal residents therefore tend to take advantage of it, adding infrastructure close by so that the zone becomes a familiar one marked by its enhanced value and frequent use. Yet the hazard remains. Take another look at the histogram above. Sharing the dubious distinction with Charleston, SC (not to mention Pensacola, FL and Galveston, TX) we live in a coastal region with one of the highest storm tide risks relative to the datum that counts: Mean Higher High Water. The next time the forecaster calls for a severe tropical storm or hurricane with possible record storm tides, we have to be especially concerned about any part of our property that lies near MHHW - and the first meter and a half above it.



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WHAT DOES IT ALL MEAN?

As damaging as it was, Hurricane *Isabel* could have been a lot worse. It started out as a Category 5 hurricane and miraculously lost strength all the way down to a category one storm just before its landfall below the Virginia-North Carolina border. We have very little data on Category 5 storms that have reached land but according to NOAA records, one such storm that did - Hurricane *Camille* - produced a storm tide reaching approximately 7.0 m (23 ft) above MHHW at Pass Christian, MS, in August 1969. No tide gauge was left intact anywhere along the Mississippi coast so leveling surveys measuring the height of a series of high water marks left by the storm provide the only evidence of this tremendous storm tide.

When making flood risk assessments, we must be wary of referenced water levels that are not *dynamic* – not capable of adjusting to the most recent sea level trends. Without this step, it makes little sense to speak of a 100-year storm tide or attempt to establish its contours on the ground. Now would be an excellent time for the Federal Emergency Management Agency (FEMA) to revise its risk zone maps in concert with the water level updates recently made by NOAA for the 1983-2001 National Tidal Datum Epoch.