ISABEL'S SILENT PARTNERS: SEASONAL AND SECULAR SEA LEVEL CHANGE[1]

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ABSTRACT

Tidal conditions fail to explain a paradoxical similarity in water level extremes induced by Hurricane Isabel on 18 September 2003, and the 23 August 1933 storm of record at Hampton Roads, Virginia. Storm surge peaks occurred near astronomical high tide during both storms, but Isabel arrived during neap tides while tides during the 1933 storm were nearer to spring. In addition, Isabel produced a lesser storm surge, yet she yielded a storm tide, or high-water mark, roughly equal to that of the 1933 hurricane. The answer to the paradox lies in observed sea level—water level measured relative to the land—and its movement during the 70 years between these events. Water level analysis shows that the sea level change observed can be divided into three categories at three different time scales: daily (astronomical tides), monthly (seasonal change), and yearly (secular trend in sea level). At Hampton Roads, a secular rise rate of 4.25 mm·yr^{-1} (1.39 ft/century) predicted an increase of 29.8 cm in 70 years; mean sea level for the month of September stood an additional 21.9 cm above the annual mean for 2003. These numbers are comparable to the mean semi-range of tide (37.0 cm) at Hampton Roads. Thus seasonal and secular change are both factors of key importance in evaluating storm tide risk at time scales attributable to major hurricanes (100 years). Adoption of a new vertical reference, *projected monthly mean sea level*, is proposed to facilitate their inclusion in storm tide predictions at decadal time scales.

INTRODUCTION

Hurricane Isabel made landfall on 18 September 2003, preceded by threats of severe coastal flooding in North Carolina, Virginia, and Maryland. A Category 2 hurricane at landfall [1], Isabel could be expected to generate a storm surge of between 1.8 and 2.4 m (6–8 ft) according to the Saffir-Simpson scale. Instead, the storm produced a lesser surge of approximately 1.45 m (4.8 ft) at Hampton Roads, Virginia in the lower Chesapeake Bay. However, Isabel created a storm tide equal to that of the Category 3 hurricane on 23 August 1933, which produced a surge of about 1.78 m (5.8 ft) at Hampton Roads. Post-storm analysis reveals that the sea level base that existed on 18 September 2003, as Hurricane Isabel approached the lower Bay, was considerably higher than the base level presented to the 1933 hurricane that produced the largest storm surge on record in Hampton Roads. This result explains how Isabel, reduced to a Category 1 hurricane by the time of her arrival in Virginia [1], could produce a maximum storm tide that may have equaled or even exceeded in places the high water marks left by the 1933 hurricane 70 years ago.

To understand the result and its future implications, storm tide and storm surge definitions [2] must be revisited in the context of sea level dynamics, a goal that leads to the study of both deterministic variations in water level (secular trends, seasonal cycles) as well as random (stochastic) variations that occur at decadal time scales [3]. To separate these variations from short-term (tidal and sub-tidal) variations, it is convenient to use monthly averages of sea level (monthly mean

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[1] *Contribution No. 2639, Virginia Institute of Marine Science and School of Marine Science*

K.G. Sellner (ed.). 2005. Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.

sea level) tabulated at primary tide stations with long record lengths. These averages will be used "as-is" in the analyses that follow (i.e., no attempt is made to adjust the means for the effects of individual storms).

To evaluate the threat of flooding in advance of storms likely to impact the coastal zone in the long term (decadal time scale), the long-term sea level change components that yield a representative base water level for a given place and time when combined must be isolated. To this representative level or vertical datum, the astronomical tide (water level oscillations resulting from gravitational interactions between sun, moon, and earth) is normally added to the storm surge (water level change resulting from the storm). Adding astronomical tide and storm surge superposed to the datum elevation yields the observed water level at tide stations or the storm tide history with their peak sum defining the storm tide maximum [2].

Measured storm surge is often derived as the difference between observed and predicted water level histories. Both histories must refer to corresponding time intervals and the same vertical datum; it is assumed that predictions can be made with an acceptable model of the astronomical tide allowing for its interaction, if any, with the surge. Since it is derived as the difference between two referenced water levels, storm surge is a relative measure and has no inherent reference of its own. A storm tide, on the other hand, is dependent on its elevation above a specified vertical datum. The vertical reference used in the United States and its territories for storm and other tides is customarily an established tidal datum as defined in the next section.

METHODS

Water level data for Hampton Roads (Sewells Point), Virginia were obtained from the National Ocean Service (NOS) website (*http://co-ops.nos.noaa.gov/*). Several reference datums may be selected on this site, including mean lower low water (MLLW), the average of the lower low water height of each tidal day over the National Tidal Datum Epoch (NTDE)[2], mean sea level (MSL), the average of all hourly heights over the NTDE, and the station datum (STND). Station datum is the zero point of the vertical measurement scale fixed in position when a tide station is first established. Although STND does not change thereafter, MLLW, MSL, and other tidal datums are periodically revised in relation to it whenever the NTDE is updated in response to observed sea level change [4]. Another datum not commonly used to reference tidal heights is mean higher high water (MHHW), the average of the higher high water height of each tidal day over the current NTDE. The final section of the paper contains additional information about this datum.

Least squares harmonic analysis [5] was applied to a 29-day series of hourly height data to obtain the harmonic constants (amplitude and phase) for nine tidal constituents (M_2, S_2, N_2, K_1, O_1, M_4, M_6, S_4, and MS_4). The resulting time-local model of the astronomical tide subsequently accounts for the maximum possible variance (in the least squares sense) present in the data at these tidal frequencies. Although the nine constituents above are only a subset of the 26 tidal constituents used in NOS predictions for Hampton Roads, many of the latter represent "perturbations" on the major constituents (e.g., K_2 on S_2). These perturbations are unimportant in a time-local model of the tide. The 29-day analysis also provides the equivalent of monthly mean sea level (MMSL) conveniently tabulated at most NOS tide stations. Although MMSL can be referenced to other tidal datums or to the station datum STND, 1983–2001 MLLW will be used in all of the sea level evaluations and comparisons that follow.

DATA ANALYSIS AND RESULTS

Figures 1 and 2 show a comparison of storm surge and storm tide for the 1933 hurricane and Hurricane Isabel at Hampton Roads. Both storms produced almost the same storm tide height: 2.44

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[2] *A specific 19-year period adopted by NOS for tidal datum averaging. Currently the years 1983–2001 are used.*

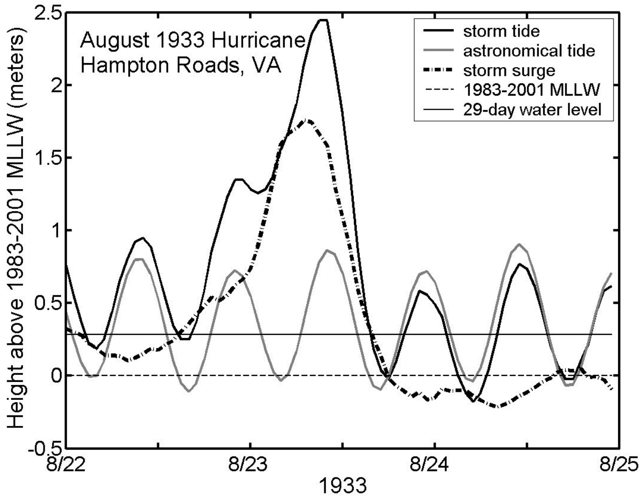

Figure 1. Water levels at Hampton Roads, Virginia during the hurricane of August 1933.

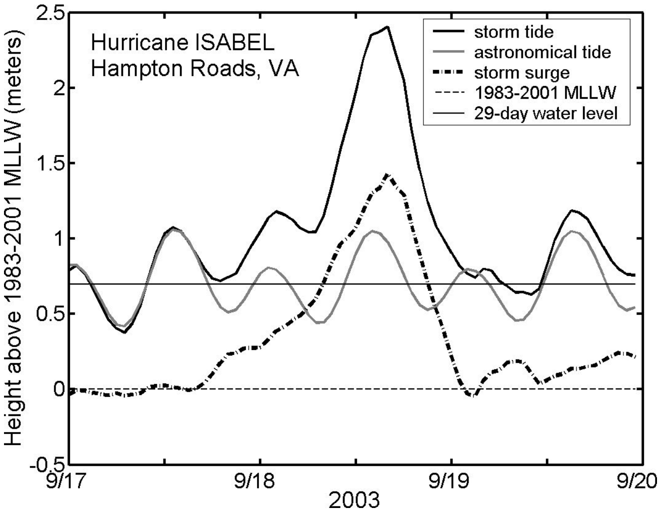

Figure 2. Water levels at Hampton Roads, Virginia during Hurricane Isabel in September 2003.

m (8.0 ft) MLLW for the 1933 event versus 2.40 m (7.9 ft) MLLW for Isabel. However, the storm surge for Isabel was estimated to be 1.45 m (5.8 ft) as compared to 1.78 m (4.8 ft) for the 1933 hurricane.

Examining the monthly (29-day) mean water levels for both storms (Figures 1 and 2), it is immediately clear that Isabel's smaller storm surge capitalized on the higher water level average for September 2003, a level about 40 cm higher than the average for August 1933 (water levels on both occasions refer to MLLW for the 1983–2001 NTDE). Other factors had secondary influence on storm tide outcome: Isabel's 40-cm "boost" in mean water level was slightly offset by a smaller (neap) tidal range on 18 September 2003 compared to a larger (near-spring) range on 23 August 1933 (mean range of 74 cm). Peak surge occurred about two hours after peak astronomical tide during Isabel and about three hours before it during the 1933 event. The comparison underscores the importance of sea level change when dealing with major storm tide events.

Long-term sea level change is easily evaluated by MMSL plots of the type shown in Figure 3. The sea level trend indicated by the slope of the linear regression line in this figure (4.25 ± 0.27 mm·yr^{-1} at the 95% level of confidence) is based on 74 years of record at Hampton Roads. It projects a sea level rise of 29.8 cm over a 70-year interval, about 10 cm less than the 40-cm change seen in Figures 1 and 2. The 10 cm difference appears in the MMSL deviation from trend for the months in question (August 1933, September 2003, Figure 3). The MMSL for other storms of record during this interval, including the Ash Wednesday extratropical storm (March 1962, Figure 3), show variable but consistently positive deviations from trend. Although the MMSL values shown are unadjusted, tests were run that indicate some means may have increased by 2 to 3 cm because of major individual storms.

Combinations of meteorological and hydrological factors are responsible for the MMSL deviation from regression in Figure 3. One set produces the seasonal cycle depicted by the curve in Figure 4; it shows that average MMSL is higher than annual MSL (12-month MMSL average) during the months of August, September, and October. Highest extremes (black diamonds in Figure 4) occurred then and in February and November as well.

The seasonal tide cycle in Figure 4 is approximated in tidal predictions by the seasonal tide constituents, Sa and Ssa. Most of the water level variance attributed to these "tidal" constituents with annual and semiannual periods is, in fact, non-tidal in origin. This variance results largely from seasonal heating cycles producing thermal

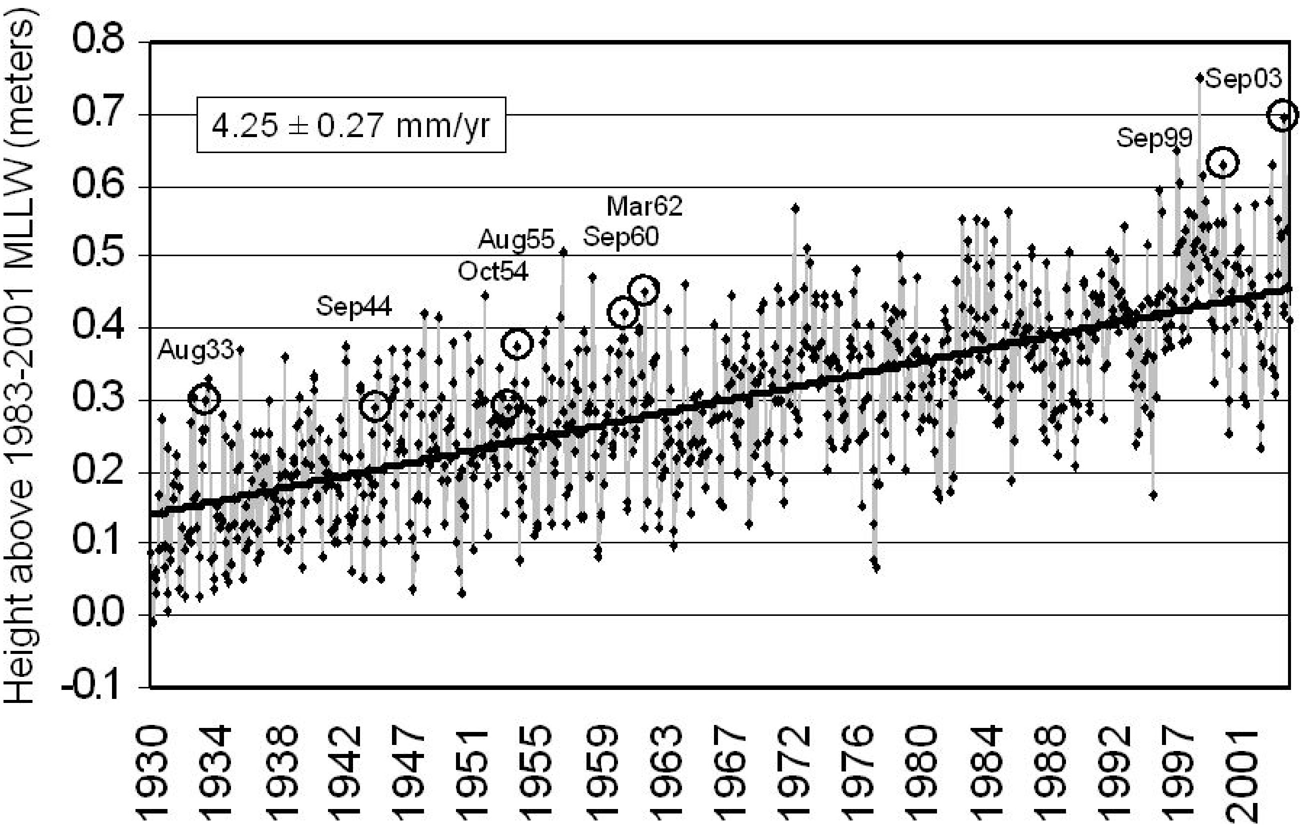

Figure 3. Plot of monthly mean sea level (MMSL), 1930–2003, at Hampton Roads, Virginia. The MMSL for September 2003 lies 21.9 cm above annual mean sea level for 2003. Storms of record during this period are circled and indicated by month and year.

expansion and contraction of the water column and, in some coastal areas, is due to seasonal river discharge [6]. Consequently, unlike other tidal constituents with more precise predictive capabilities, seasonal predictions made specifically with Sa and Ssa are likely to vary substantially from the actual MMSL in any given month and year.

The last assertion is substantiated by the large spread in the distribution of MMSL values about each monthly mean plotted in Figure 4. One standard deviation above and below the mean is indicated by vertical bars, assuming the 74 data points comprising each mean are normally distributed. Equally important, the MMSL distribution about each mean represents a time series with its deterministic components (seasonal variation and secular trend) removed. For example, the September MMSL series shown in Figure 5 approximates a stationary stochastic process with constant mean and variance over time.

Source of Variation

While surges caused by major storms are included in MMSL determinations, they are not the primary reason for high MMSL values. The MMSL values for September 2003 and August 1933 increased by only 2% of the surge maximum (2 and 3 cm, respectively) due to the hurricane and its effects over a 24-hour period. Probably the major source of sea level variation in this case is the interannual or decadal variability believed to arise from Rossby waves in the North Atlantic Ocean—irregular waves characterized by periods between 1 and 10 years or longer. Interestingly, "broadband" sea level fluctuations of this type are more commonly seen on western Atlantic shores, a fact consistent with westward-only movement of the Rossby waves [3].

Figure 6 is a histogram displaying the frequency distribution of recorded MMSL values at Hampton Roads for the month of September,

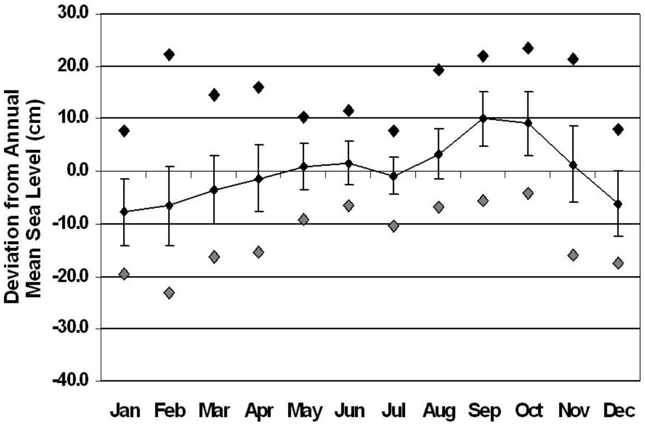

Figure 4. MMSL means and extremes at Hampton Roads (Sewells Point), Virginia (1930–2003). One standard deviation is indicated by the vertical bars about each mean (N=74).

fitted by a normal distribution curve. The abscissa values are deviations from annual MSL with the mean (Dm = 10.10 cm) representing the seasonal change. Assuming a normal distribution, the average MMSL in September plus two standard deviations is Dm+2s = 20.46 cm (the projected seasonal change), a value that is likely to be exceeded in approximately 2% of all instances of September MMSL at Hampton Roads.[3] The September projected seasonal change has, in fact, been exceeded twice at Hampton Roads in 74 years—in 1964 (20.7 cm) and again in 2003 (21.9 cm).

The results for Hampton Roads, Virginia are not unique. A 101-year water level record (1903–2003) at Baltimore, Maryland yields similar data (Figures 7 and 8). The sea level trend at Baltimore is 3.09 ± 0.20 mm·yr^{-1} and for the month of September, Dm = 10.65 cm, and Dm+2s = 18.48 cm, a value exceeded six times in 101 years including a 21.1 cm seasonal change for September 2003. The four highest seasonal extremes at Baltimore (black diamonds in Figure 7) occurred in June, August, September, and October, the latter three being the most common months in which major tropical storms and hurricanes have impacted the Chesapeake Bay.

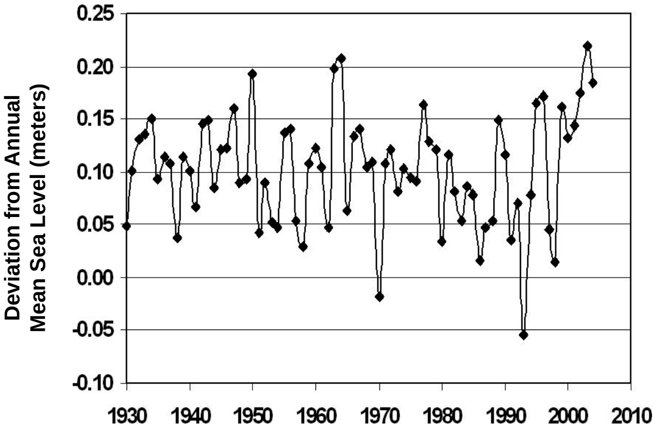

Figure 5. September MMSL series at Hampton Roads (Sewells Point), Virginia (1930–2004). Graph shows decadal variations absent secular trend and seasonal change.

CONCLUSIONS

Comparative evaluation leaves little doubt that ongoing seasonal and secular changes in sea level become increasingly important to flood risk assessments at time scales approaching 100 years. Authorities charged with determining that risk in the past have largely ignored long-term sea level change while seeking to define the 100-year flood as a level with 0.01 annual probability of occurrence irrespective of time [7]. Only the NOS has recognized sea level as dynamic by responding to it with a series of four NTDE updates (1924–1942, 1941–1959, 1960–1978, and 1983–2001) that have

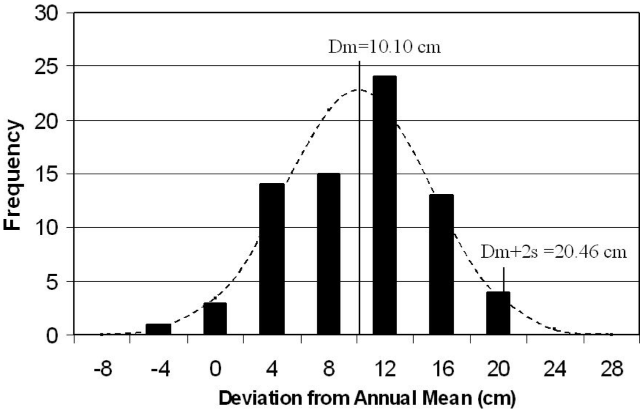

Figure 6. September MMSL distribution at Hampton Roads (Sewells Point), Virginia (1930–2003).

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[3] *The probability for a normally distributed value to fall more than two standard deviations above the mean is 0.0227.*

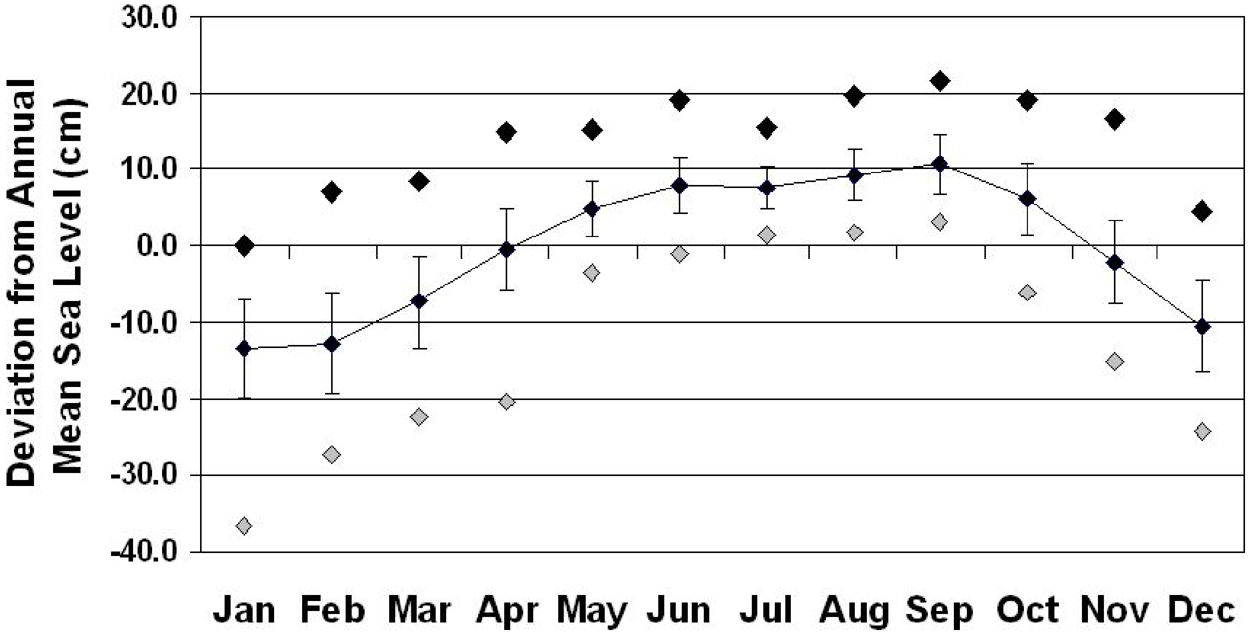

Figure 7. MMSL means and extremes at Baltimore (Fort McHenry), Maryland (1903–2003). One standard deviation is indicated by the vertical bars about each mean (N=101).

revised tidal datum elevations at intervals ranging from 17 to 23 years. Although a specific interval for updating has not been prescribed, the NTDE and resulting tidal datums remain an indispensable component of storm tide forecasts that actively consider sea level change. The extremes of projected sea level change described above were, in fact, realized during Hurricane Isabel. Although there is no certainty that a similar combination will reoccur in the future (even sea level rise, to a degree, is uncertain), the evidence strongly suggests that it will if past trends continue in conjunction with seasonal and decadal variations in sea level.

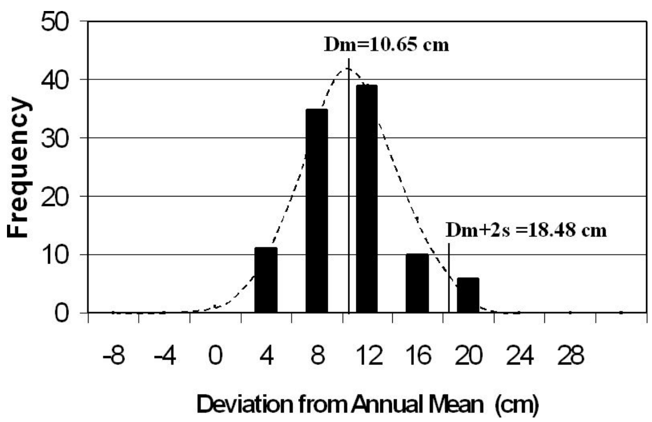

Figure 8. September MMSL distribution at Baltimore (Fort McHenry), Maryland (1903–2003).

Outlook

After the disastrous hurricane seasons of 2003 and 2004, few can doubt the immense threat posed by even a Category 1 storm or the dramatic impact that extreme winds and high tides can have on coastal communities. Although sea level change has clearly played a role in shaping that impact over time, the threat it poses is not perceived as an imminent one and has received little attention as a result. Historically, NTDE updates are driven by vessel navigation and marine safety issues rather than coastal flooding concerns, with nautical charts being the focus rather than flood maps. In the belief that it is time to change this policy, this paper makes a contribution through the recommendations presented below.

RECOMMENDATIONS AND RATIONALE

It is recommended that the projected secular change from the midpoint of the current NTDE to a given year of prediction and the projected seasonal change (e.g., Dm+2s) for the month of

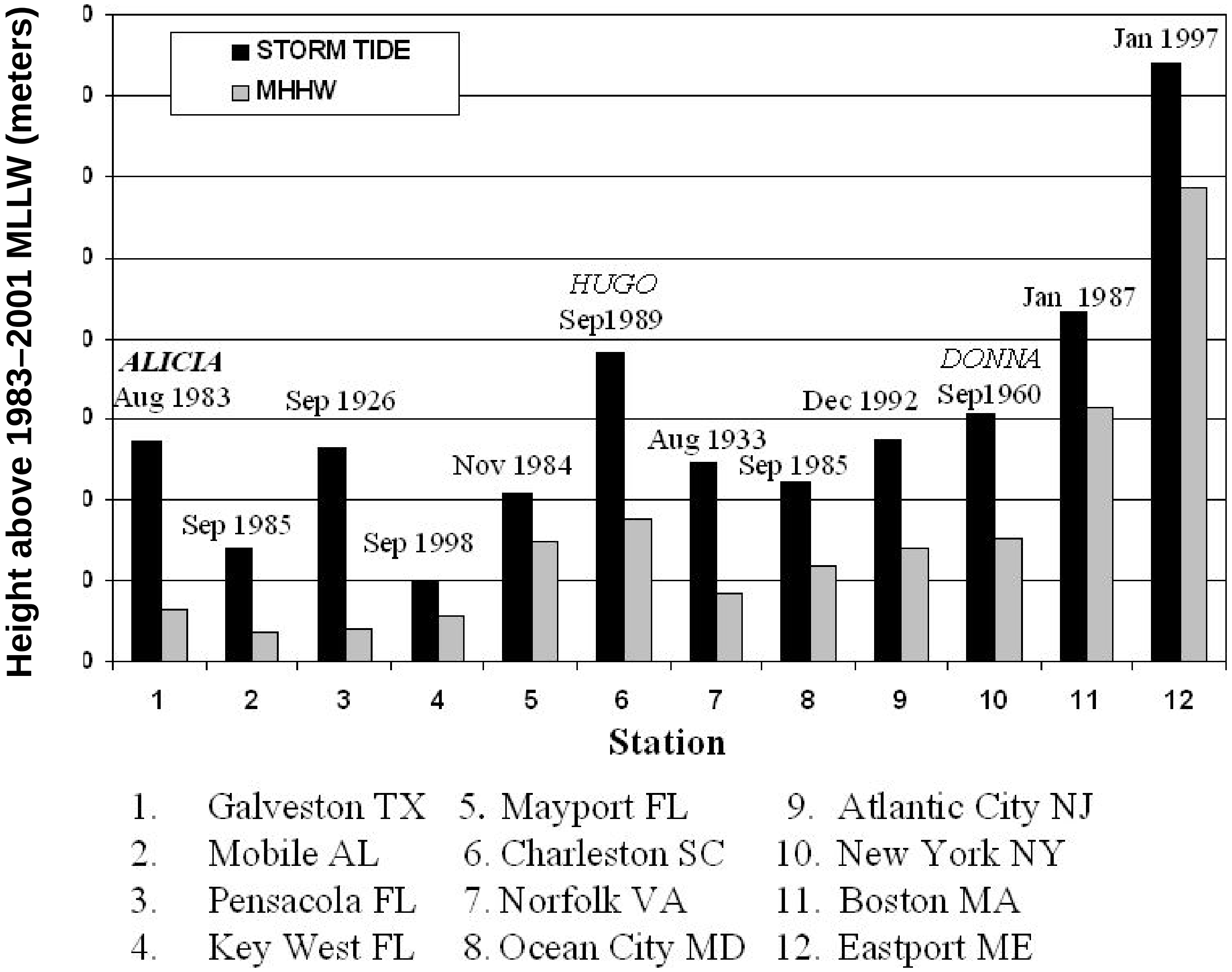

Figure 9. Record storm tides measured above 1983–2001 MLLW at 12 NOS tide stations along the U.S. Gulf and Atlantic coasts.

prediction be combined, with the total change determining the projected monthly mean sea level at that location when referenced to a suitable tidal datum. It is proposed that the predicted storm surge from any source, such as a hydrodynamic model, be added to the projected monthly mean sea level to obtain the predicted storm tide height above datum for any specified event (e.g., the 10-year or 100-year storm). Emergency management planning—for example, determining whether to raise the first-floor elevation of homes flooded during Isabel (and by how much)—requires this or a similar approach to be effective at decadal time scales.

It is further recommended that long-term observations and predictions of storm tide height reference the tidal datum of mean higher high water (MHHW) rather than the chart datum of MLLW. Figure 9 shows the relationship between these datums and record storm tides at 12 NOS tide stations from Galveston, Texas to Eastport, Maine. In this figure, Eastport appears to have the largest storm tide of any station but this is a rather biased view, directly resulting from the greater tidal range (MHHW-MLLW) at this location. If the storm tides are referenced to MHHW, the range effect is removed. Stations located in hurricane zones, such as Galveston, Pensacola, or Charleston, then receive their proper recognition as stations with the highest risk from storm tides, noting that MHHW itself is likely to be exceeded several times by astronomical tides alone in the course of a year.

The possibility of confusing similar sounding terms could also lead one to mistakenly report a 7.5-m storm surge at Eastport due to the way the information is presented in Figure 9.

The MHHW accounts conservatively for the astronomical tide contribution to storm tide heights during all but the spring astronomical extremes. Just as the mariner may rely on charted depths below MLLW even at the lowest levels of the tide, the property owner may rely on storm tide heights forecast above MHHW even at the highest levels of the tide. The MHHW line is arguably a more recognizable contour on land and lies nearer to coastal infrastructure most likely to be impacted by storm tides.

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