# ISABEL'S SILENT PARTNERS: SEASONAL AND SECULAR SEA LEVEL CHANGE

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## ABSTRACT

Hurricane Isabel made landfall on September 18, 2003, preceded by threats of severe coastal flooding in North Carolina, Virginia and Maryland. As a Category 2 hurricane, 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, VA, in lower Chesapeake Bay. However, *storm tide* high water marks left by Isabel in the lower bay area equaled those of a Category 3 hurricane that produced a surge of about 1.78 m (5.8 ft) on August 23, 1933. Tidal conditions fail to explain the paradox: 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. The answer 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 (1.39 ft/century) predicted an increase of 29.8 cm in 70 years time and 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 at Hampton Roads: 37.0 cm. 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). The 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

Post-storm analysis reveals that the sea level base that existed on September 18, 2003, as hurricane Isabel approached lower Chesapeake Bay, was considerably higher than the base level presented to previous hurricanes including one on August 23, 1933 that produced the largest storm surge on record in Hampton Roads, Virginia. This result explains how Isabel, essentially a Category 1 hurricane by the time of her arrival in Virginia, could produce a maximum storm tide or 'high water mark' on land that may have equaled or even exceeded that of the 1933 hurricane, a Category 3 storm occurring 70 years ago. To understand the result and its future implications *storm tide* and *storm surge* definitions [1] 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 [2]. To separate these from short-term (tidal and sub-tidal) variations, it is convenient to use monthly averages of sea level (monthly mean sea level) tabulated at primary tide stations with long record lengths.

To evaluate the threat of flooding in advance of storms likely to impact the coastal zone long-term (decadal time scale), we must first isolate the long-term sea level change components that, when combined, yield a representative base water level for a given place and time. To this representative level or *vertical datum*, we normally add the *astronomical tide* (water level oscillations resulting from gravitational interactions between sun, moon, and earth) and 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*, their peak sum defining the *storm tide maximum* [1].

Measured storm surge is often derived as the difference between observed and predicted water level, assuming the latter can be provided by an acceptable model of the astronomical tide and 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 tides as well as other tides is customarily an established tidal datum as defined in the next section.

## METHODS

Water level data for Hampton Roads (Sewells Point), VA were obtained from the National Ocean Service (NOS) web site: 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)[1], 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 [3]. 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. More will be said about this datum in the final section of the paper.

Least squares harmonic analysis [4] was applied to a 29-day series of hourly height data to obtain the harmonic constants (amplitude and phase) for nine tidal constituents ($M_2$, $S_2$, $N_2$, $K_1$, $O_1$, $M_4$, $M_6$, $S_4$, $MS_4$). 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 listed 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 *synodic mean sea level* - the equivalent of *monthly mean sea level* (MMSL) conveniently tabulated at most NOS tide stations.

## DATA ANALYSIS AND RESULTS

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[1] A specific 19-year period adopted by NOS for tidal datum averaging; currently the years 1983-2001 are used.

A comparison of storm surge and storm tide for the 1933 hurricane and hurricane Isabel at Hampton Roads is shown in Figures 1 and 2. Both storms produced almost the same storm tide height: 2.44 m MLLW for the 1933 event versus 2.40 m MLLW for Isabel. However, the storm surge for Isabel was estimated to be 1.45 m as compared to 1.78 m for the 1933 hurricane.

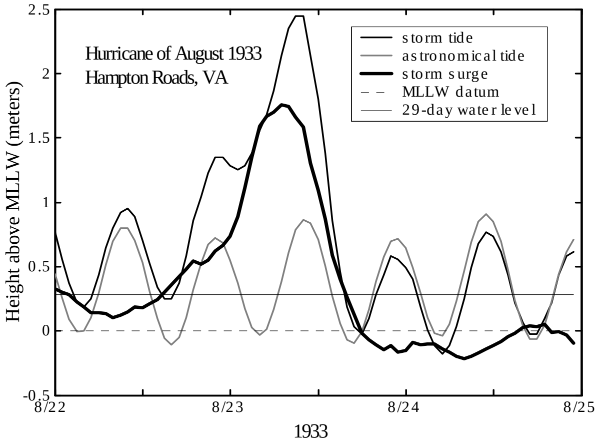

**Figure 1**. Water levels at Hampton Roads, VA during the hurricane of August 1933.

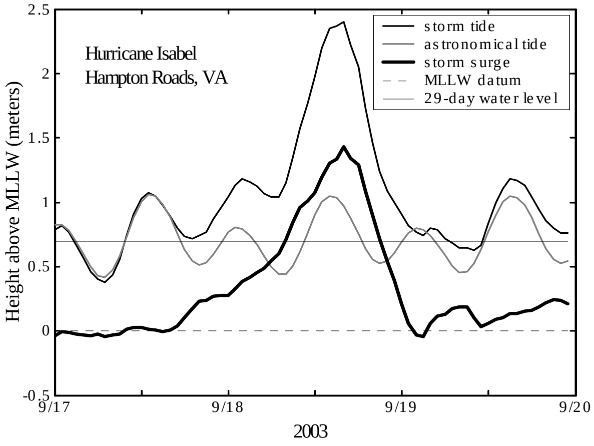

**Figure 2**. Water levels at Hampton Roads, VA during hurricane Isabel, September 2003.

Examining the monthly (29-day) mean water levels for both storms (Figs.1,2), 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 September 18, 2003 compared to a larger (near-spring) range on August 23, 1933. Peak surge occurred approximately two hours after peak astronomical tide during Isabel and approximately three hours before it during the 1933 event. The comparison underscores the importance of sea level change when dealing with large magnitude storm tide events.

It is at this point that the study of monthly mean sea level (MMSL) becomes critically important. 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.

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 mm/yr ± 0.27 mm/yr 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 (Aug33, Sep03, Fig.3). MMSL for other storms of record during this interval, including the 'Ash Wednesday' extratropical storm (Mar62, Fig. 3), show variable but consistently positive deviations from trend - clear evidence that the seasonal variation in water level must be considered along with the secular trend.

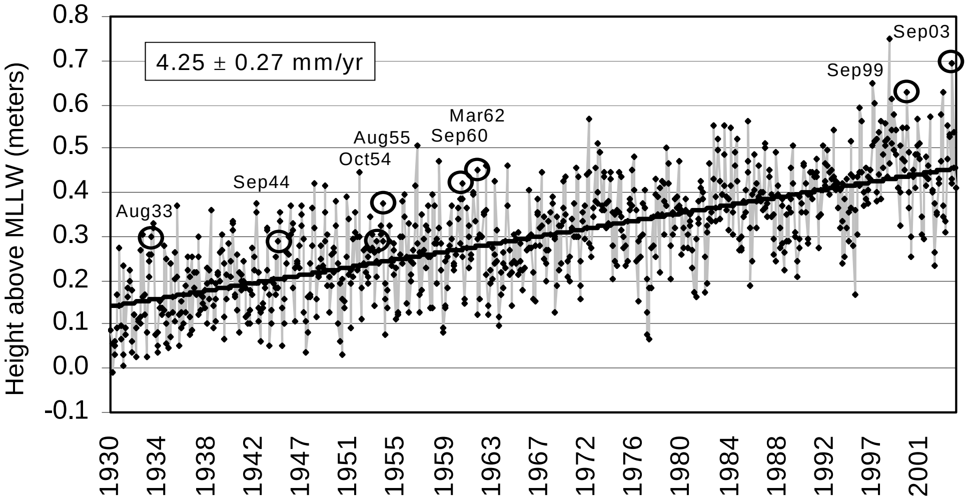

**Figure 3**. Plot of monthly mean sea level (MMSL), 1930-2003, at Hampton Roads, VA. MMSL for September 2003 lies 21.9 cm above annual mean sea level for 2003. Storms of record during this period are circled and indicated by month and year.

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, Fig. 4) occurred then and in February and November as well.

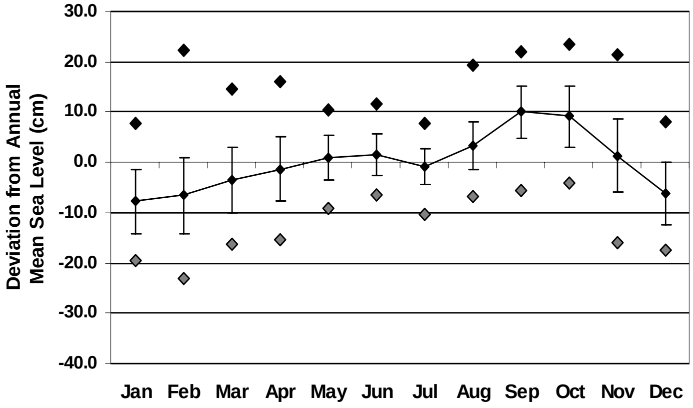

**Figure 4**. MMSL means and extremes at Hampton Roads (Sewells Point), VA 1930-2003. One standard deviation is indicated by the vertical bars about each mean (N=74).

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 being more the result of seasonal heating cycles producing thermal expansion and contraction of the water column and, in some coastal areas, the result of seasonal river discharge [5]. Consequently, unlike other tidal constituents that have a more precise predictive capability, seasonal predictions made specifically with Sa and Ssa are likely to vary substantially from the actual MMSL that occurs 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. 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 arising from Rossby waves in the North Atlantic Ocean – irregular waves characterized by periods between 1 and 10 years or longer. Interestingly, 'broad-band' sea level fluctuations of this type are more commonly seen on western Atlantic shores, a fact consistent with the westward only movement of the Rossby waves in question [2].

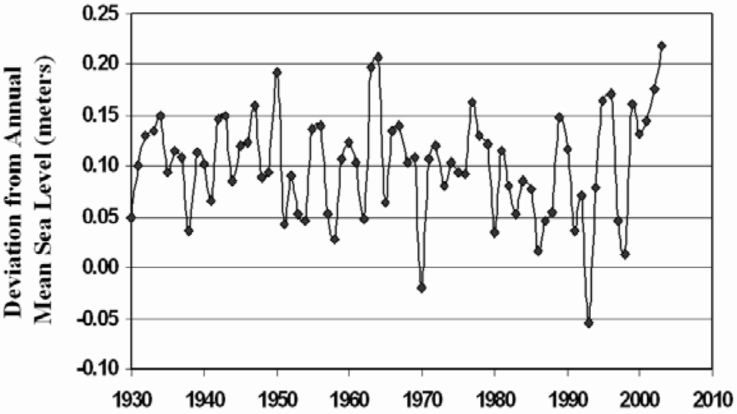

**Figure 5**. September MMSL series at Hampton Roads (Sewells Point), VA 1930-2003. Graph shows decadal variations absent secular trend and seasonal change.

Figure 6 is a histogram displaying the frequency distribution of recorded MMSL values at Hampton Roads for the month of September, fitted by a normal distribution curve. The abscissa values are deviations from annual MSL, the mean (Dm = 10.10 cm) representing the *seasonal change*. Assuming a normal distribution, the average MMSL in September plus two standard deviations is <u>Dm+2s = 20.46 cm, the *projected seasonal change*</u>, a value that is likely to be exceeded in approximately 2% of all instances of September MMSL at Hampton Roads[2]. The September projected seasonal change has in fact been exceeded twice at Hampton Roads in 74 years, once in 1964 (20.7 cm) and again in 2003 (21.9 cm).

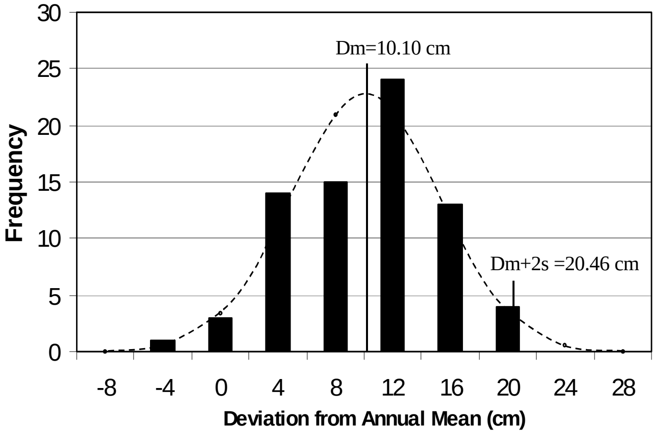

**Figure 6**. September MMSL distribution at Hampton Roads (Sewells Point), VA 1930-2003.

The results for Hampton Roads, VA, are not unique. A 101-year water level record (1903-2003) at Baltimore, MD, yields similar data (Figs. 7, 8). The sea level trend at Baltimore is 3.09 ± 0.20 mm/yr 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

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

for September 2003. The four highest seasonal extremes at Baltimore (black diamonds, Fig. 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.

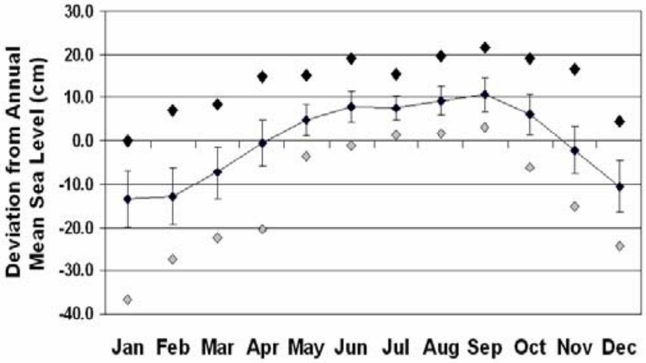

**Figure 7**. MMSL means and extremes at Baltimore (Fort McHenry), MD, 1903-2003. One standard deviation is indicated by the vertical bars about each mean (N=101).

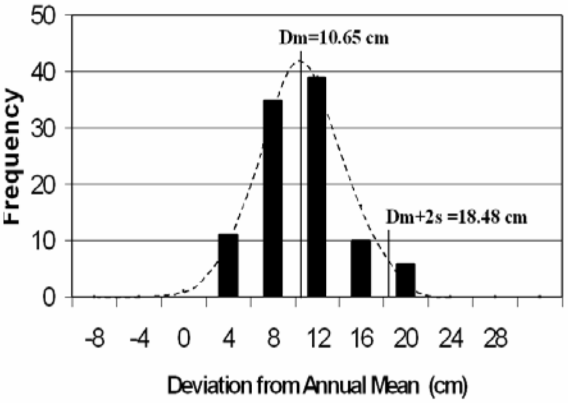

**Figure 8**. September MMSL distribution at Baltimore (Fort McHenry), MD, 1903-2003.

## 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 [6]. 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, 1983-2001) that have 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 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.

**Outlook**: After the disastrous hurricane seasons of 2003 and 2004, few can doubt the immense threat posed by even a Category 1 storm event or the dramatic impact that its 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 seen to be driven by vessel navigation and marine safety issues rather than coastal flooding concerns, nautical charts being the focus item rather than flood maps. In the belief that is time to begin working toward a change in this policy, this paper seeks to make a contribution through the recommendations presented below.

## RECOMMENDATIONS

It is recommended that long-term predictions of storm tide height reference the tidal datum of *mean higher high water* (MHHW). Further, that the *projected secular change* from the midpoint of the current NTDE to a given year of prediction and a *projected seasonal change* (e.g., Dm+2s) for the month of prediction be combined and their sum added to MHHW at a given location to determine the *projected monthly mean sea level* at that location. Finally, 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 MHHW 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 or longer time scales.

Use of MHHW is recommended over the chart datum of MLLW for two reasons: (1) 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. (2) 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.

## REFERENCES

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