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Analysis of relative sea level variations and trends in the Chesapeake Bay: Is there evidence for acceleration in sea level rise?

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Abstract*— Over the past few decades the pace of relative sea level rise (SLR) in the Chesapeake Bay (CB) has been 2-3 times faster than that of the globally mean absolute sea level. Our study is part of ongoing research that tries to determine if this SLR trend is continuing at the same pace, slowing down (SLR deceleration) or speeding up (SLR acceleration). We introduce a new analysis method for sea level data that is based on Empirical Mode Decomposition (EMD) and Hilbert-Huang Transform (HHT); the analysis separates the SLR trend from other oscillating modes of different scales. Bootstrap calculations using thousands of iterations were used to test the robustness of the method and obtain confidence levels. The analysis shows that most sea level records in the CB have significant positive SLR acceleration, so the SLR rates today are about twice the SLR rates of 60 years ago. The acceleration rates of our calculations are larger than some past studies, but comparable to recent results [1] who show accelerated SLR “hotspots” in the coastal areas between Cape Hatteras and Cape Cod. The results have implications for projections of future SLR and the impact on flooding risks in the Hampton Roads area. The contributions to SLR from land subsidence and climate-related changes in ocean circulation need further research.

***Index Terms*—Chesapeake Bay, sea level rise, coastal inundation, tide gauge data, climate change.**

I. INTRODUCTION

Water level measurements in the Chesapeake Bay (CB), obtained from tide gauge data, show that over the past few decades the relative sea level has been rising in the Bay faster than the globally mean absolute sea level trend [2]. The combined impact of sea level rise and land subsidence results in frequent flooding in communities along the shores of the CB. For example, cities such as Norfolk, VA, experience more severe flooding during high tides and during storm surges than in years past [2, 3, 4]. The relative sea level rise (SLR) includes impacts from local land subsidence and long-term post glacial rebound [5]. Additional impacts on sea level along the Atlantic coast of North America may result from interannual and decadal variations in the intensity of the thermohaline overturning circulation and the Gulf Stream dynamics [1, 6-8]. Those long-term variations are imbedded in shorter-term variations such as the seasonal cycle, tides, river flows and coastal dynamics. Therefore, there are considerable spatial variations in SLR rise globally, and in particular, along the North Atlantic coast north of Cape Hatteras, where a recent study found evidence for “hotspots” of accelerated SLR [1]. The acceleration rates in this latest study are significantly higher than global acceleration rates reported in previous studies [9-12]. Therefore, it is important to understand the spatial variations because future sea level rise projections [13, 14] may impact each coastal location differently.

The rise of sea level in the CB area is faster than the global mean, but the exact value of RSL trends and whether the sea level rise rate is increasing with time (positive acceleration) or decreasing with time (negative acceleration) are essential for future projections, mitigations and planning [3]. Methods for calculating sea level trends vary. For example, NOAA calculates linear trends from 50-year data increments (http://tidesandcurrents.noaa.gov/), but the method can only apply to few tide gauge records that are very long and the method does not provide trends for recent decades, so using their method it is not possible to show a statistically significant SLR acceleration. Other methods filter out seasonal and decadal variability and then use least-square linear curve-fit methods to calculate the trends [2], or quadratic fit to calculate acceleration [10]. While global observations indicate an increase in ASL trend from 1.8 mm/y for 1961-2003 to 3.1 mm/y for 1993-2003 [13], analyses of tide gauge records [2] could not find statistically significant sea level rise acceleration in the CB. The difficulty of finding statistically significant acceleration using regression methods is that most sea level records are not long enough; for example, at least 60-year record is needed for obtaining accuracy in trends of ±0.5 mm/y with a 95% confidence level. Moreover, the way in which seasonal and decadal oscillations are filtered may affect the trends, and calculating trends within subset windows (say, 1950-1980 versus 1980-2010) shorten the record available for each trend calculation, thus reduces the statistical significance. All the above difficulties in calculating accurate SLR rates and possible SLR acceleration led us to try a new method that to our knowledge has not been implemented before to SLR trend calculations; our method reduces the contamination of the SLR by other sea level variability.

II. Methods and Sea Level Data

The analysis method is based on Empirical Mode Decomposition (EMD) and Hilbert-Huang Transform, known as HHT [15], together with bootstrap simulations [16] to find confidence intervals. The EMD/HHT method is especially useful for non stationary and nonlinear time series, and has been used for different geophysical applications, such as the dynamics of earthquakes [17], analysis of hydrological and atmospheric data [18], and the dynamics of oceanic internal waves [19]. Any time series data is divided into a finite number (~10) of intrinsic mode functions with time-dependent amplitudes and frequencies. Compared with Fourier transform or harmonic analysis methods, EMD/HHT is a more general technique and a non-parametric analysis (e.g., no specific frequencies are targeted and no particular function is assumed for each mode). In the applications mentioned above the method has been mostly applied to study the EMD modes with the highest frequency [19], but here we suggest a new (to our knowledge) application for sea level trend, using the remaining residual after all the oscillatory modes have been extracted as a representative of the SLR trend. The HHT analysis can separate the SLR trend from long-term oscillations with periods that are longer than the record itself, thus limiting the contamination of the SLR trend with decadal and multi-decadal variations.

Monthly mean sea level records from 8 tide gauge stations in the CB were obtained from NOAA's "verified data" (http://tidesandcurrents.noaa.gov/). The stations are located in the CB, from the Chesapeake Bay Bridge Tunnel (CBBT) at the mouth of the bay in the southeast to the city of Baltimere in the north (Table 1), with record length ranges from 37 years (CBBT) to 110 years (Baltimore) . Most of these stations have been used in previous studies of SLR [1-4], allowing us to compare our results with previous analyses that used different methods.

Table 1. Sea Level Tide Gauges Used in the Study, Their Duration and Location.

Station	Years	Location (°W, °N)
Baltimore, MD	1902-2011	76.5783, 39.2667
Annapolis, MD	1928-2011	76.4800, 38.9833
Solomons Island, MD	1937-2011	76.4517, 38.3167
Lewisetta, VA	1974-2011	76.4633, 37.9950
Gloucester Point, VA	1950-2003	76.5000, 37.2467
Kiptopeke, VA	1951-2011	75.9883, 37.1650
Sewells Point, VA	1948-2011	76.3300, 36.9467
CBBT, VA	1975-2011	76.1133, 36.9667

III. Results

To understand how the HHT analysis works, Fig. 1 demonstrates the analysis for Sewells Point, which is located near the high flood risk area of Norfolk, VA. For this station, the analysis divides the original record (mode-0 in Fig. 1) into 9 modes, the first 8 of which are oscillating modes with periods ranging from a few months (mode-1) to a multi-decadal long-term mode with a period of about 40 years (mode-8); the last mode (mode-9) is the remaining trend. The trend in this case does not seem linear, but instead resembles a quadratic or an exponential function with a slope that increases with time. While the oscillatory modes can be used to study various impacts on SLR, for example, the impact of variations in ocean circulation [6], in the study reported here, our focus is on the SLR trend. While the trend for this station shows SLR acceleration, one needs to show that the method is robust and accurate within an acceptable statistical confidence level. To check the robustness of the analysis, we use a bootstrap re-sampling technique, which is often used for analysis of climate data [16]. The method is demonstrated in Fig. 2.

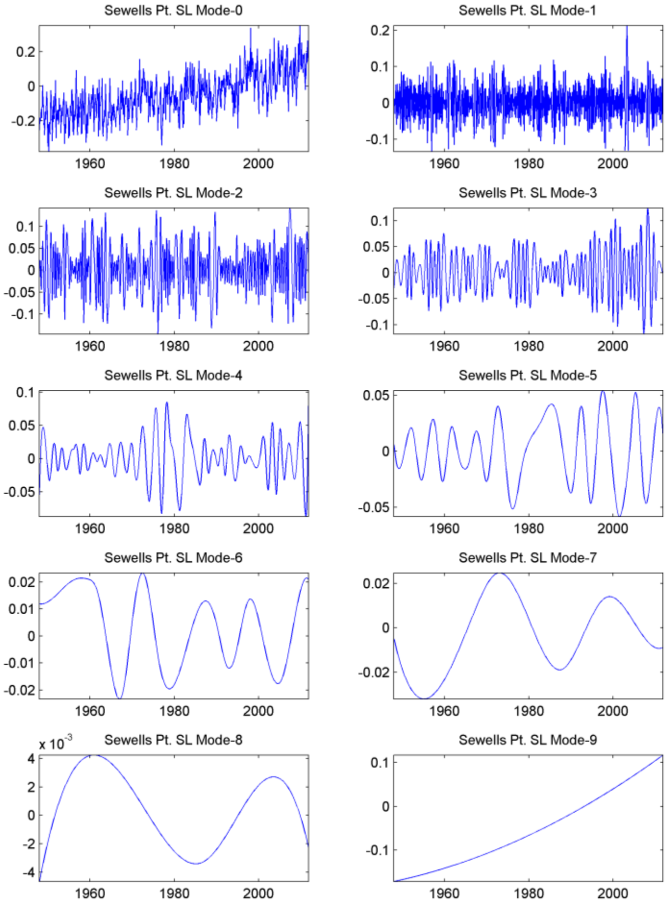

Fig. 1. An example of the HHT modes obtained for the sea level data of Swells Point. Mode-0 is the original monthly data, modes 1-8 are oscillating modes and mode-9 is the SLR trend. The sum of modes 1-9 is equal to the original data. The x-axis is time in years and the y-axis is sea level in meter.

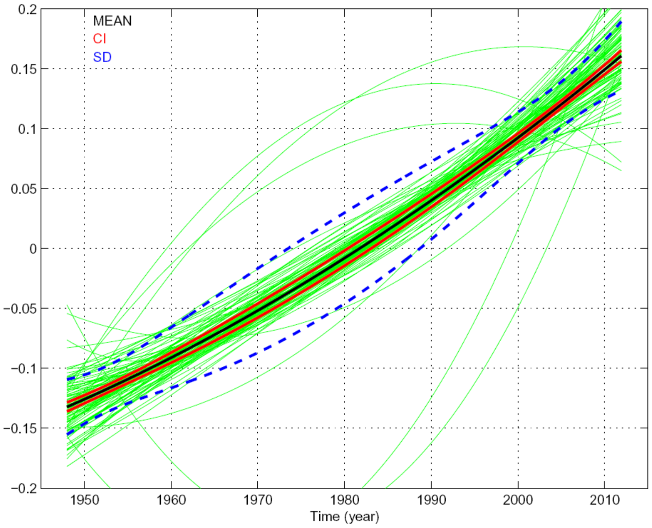

Fig. 2. The bootstrap simulations of sea level trend at Sewells Point (last HHT mode) using 100 iterations; the green lines are individual simulations, the black line is the ensemble mean, the blue and red lines are the standard deviation and 95% confidence interval (CI), respectively.

The idea behind the bootstrap calculation is to resample the data itself so that the real variability of the data is represented. An artificial time series is generated by replacing the real residuals (mode-0 minus mode-9 in Fig. 1) with randomly selected residuals. Then, the trend is calculated from the HHT (e.g., one of the green lines in Fig. 2). The process is repeated many times, and if the analysis is robust, the mean of all the simulations (black line in Fig. 2) will converge toward the real SLR trend (mode-9 in Fig. 1). It was found that about 5000 simulations are required in order to achieve CI of ±0.5 mm/y around the mean trend at 95% statistical significance, and the analysis is consistent and converges for all the stations.

When the trend is calculated for all the CB stations, almost all of them show very similar trend as seen in mode-9 of Fig. 1, indicating a consistent bay-wide impact on sea level from the same source; there are however, some spatial differences in SLR that may relate to land subsidence, similar to previous findings [2]. To summarize the results, the decadal averages of sea level (relative to mean sea level in Baltimore in 1900), SLR rates and SLR acceleration rates are shown in Fig. 3; they are calculated from the full continuous trend line, not from fitting to subset sections of the data as previously done by others. All the stations clearly show a SLR (Fig. 1a) of ~350 mm (more than 1 foot) over the past century (an average SLR of ~3.5 mm/y). However, the SLR rates have increased with time from ~1-3 mm/y in the 1930s to ~4-9 mm/y today (Fig. 3b). Since the 1970s the spatial pattern of SLR remains almost unchanged, with higher rates in the north of the Bay (Baltimore, Annapolis and Solomons Island) and in the south of the Bay (Sewells Point and CBBT), but somewhat lower rates in Gloucester Point and Kiptopeke. An exception is Lewisetta, where the increase in SLR was unusually high, from ~2 mm/y in the 1970s to ~9 mm/y in the 2000s, but its record is relatively short, only 38 years. The SLR acceleration is surprisingly almost identical for 5 of the 8 stations, 0.05-0.1 mm/y^2, (Fig. 3c). These acceleration rates are very similar to recent findings of accelerated "hotspots" in the region [1], though both, our study and [1] found higher acceleration rates than previous studies. At 3 locations the SLR acceleration is different than that found in the rest of the Bay. At Lewisetta the acceleration is about 2.5 times larger than that at the other stations. While the calculations may be less accurate for this relatively shorter record, it is also possible that there is a real increased acceleration rates in recent years due to slowdown of the Atlantic circulation- the acceleration rates since the 1970s may be much higher than before [1]. At Gloucester Point the SLR acceleration is positive, but smaller than the other locations; this station stopped recording in 2003, so recent increased in SLR acceleration, if exist, may be missing from the data. The tide gauge at CBBT is the only one showing small negative acceleration (deceleration). However, the gauge is located on a man-made island to support bridge infrastructure, so the local land motion there is expected to be different than the other coastal stations.

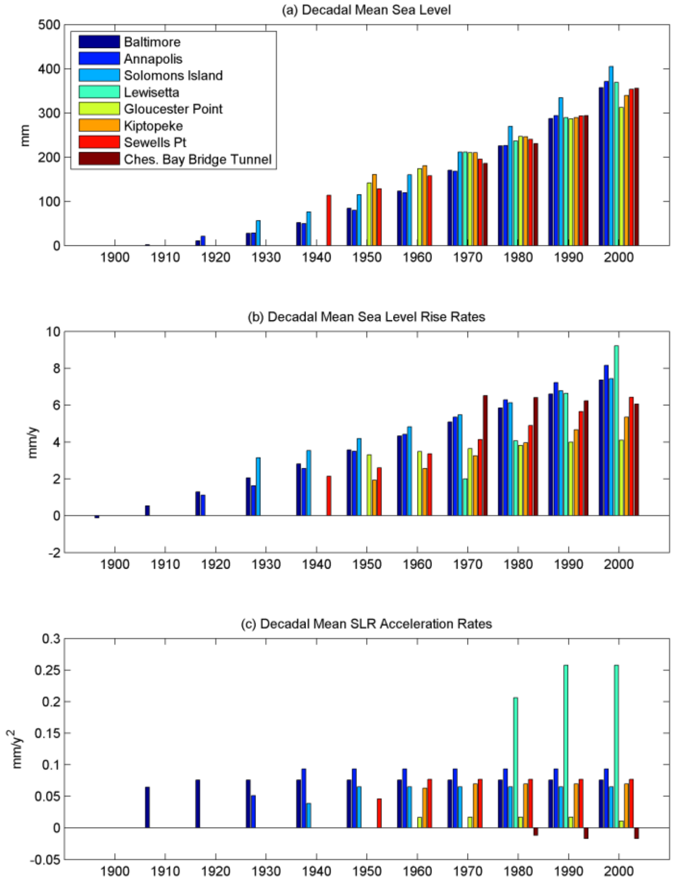

Fig. 3. Decadal averages of sea level changes calculated from the trend of each station (indicated by different colors). The year represents the beginning of the decade, i.e., "2000" represents the average of 2000-2010. (a) The sea level (in mm) relative to the mean sea level of Baltimore in 1900. (b) The SLR rates (in mm/y) calculated from the decadal changes of (a). (c) The SLR acceleration (in mm/y^2) calculated from the decadal changes of (b).

In any case, the similarity in SLR acceleration rates across the length of the CB suggests that the Bay is affected by similar processes, potentially from Atlantic Ocean dynamics [1, 4, 6, 8]. Note also that land subsidence from glacier rebound [5] is a very slow process with a much longer time scale than the sea level records, thus it can affect the SLR rates (Fig. 3b) but it cannot affect the acceleration of recent years (Fig. 3c).

IV. SUMMARY AND FUTURE PROJECTIONS OF SLR

The new analysis method presented here is based on EMD/HHT and shows promising results; it allows the separation of the SLR trend from long-term oscillations, overcoming difficulties with curve fitting methods. The average SLR rates obtained here and the spatial differences within the CB are consistent with previous studies [2]. Moreover, the SLR acceleration is consistent with recent calculations based on different methods [1] which shows the CB as part of accelerated SLR "hotspots". The results suggest that high rates of SLR in the bay may not be just due to land subsidence, but potentially additional contribution to SLR acceleration may come from climate-related changes in ocean dynamics. For example, previous studies show that a slowdown of the Atlantic circulation and weakening of the Gulf Stream may increase coastal sea level along the US east coast [4, 6, 7]. The ~1m sea level difference across the Gulf Stream is large compared with global SLR rates of a few mm/y, so small changes in the intensity of the Gulf Stream may be felt along the coast. However, further research is needed to fully understand the impact of large-scale ocean circulation on coastal sea level.

The practical importance of this and similar studies is to help future planning and risk assessment, in particular for flood-prone regions such as Norfolk, VA [2, 3, 4]. Future projections of SLR depend on estimates of past SLR rates and potential SLR acceleration. For example, the U.S. Army Corps of Engineers introduces 3 SLR scenarios based on assessment of the National Research Council (NRC), they include SLR of 0.5m (NRC-I scenario), 1.0m (NRC-II) and 1.5m (NRC-III) between 1986 and 2100. In Fig. 4, we compare various SLR projection scenarios for 4 CB locations with long records, Baltimore and Annapolis in the northern CB and Kiptopeke and Sewells Point in the southern CB. In black lines are the SLR trends calculated from the HHT analysis for 1950-2011. In addition to the 3 NRC scenarios, 4 different SLR projections are calculated for 2011-2100 and shown in Fig. 4:

- Global SLR (orange line). The most conservative estimate assumes that SLR will continue at a constant rate of the global ocean over the 20th century (~1.7 mm/y). This projection clearly underestimates the SLR rates in the CB.
- Local average SLR (blue lines). The SLR is assumed to be the average SLR rate of the past 60 years for each station. In this case the projected sea level in 2100 is slightly higher than the NRC-I scenario.
- Local recent SLR (green lines). The SLR is assumed to be the SLR rate of 2011 for each station. In this case the projected sea level in 2100 is between NRC-I and NRC-II scenarios.
- Local SLR acceleration (red lines). The sea level projection is calculated as $SL= a + bT + 0.5cT^2$; b and c are the 2011 SLR rate and acceleration, respectively, for each station, a is a constant to match the beginning of the record in 2011, and T is time in years. In this case the projected sea level in 2100 is between slightly below NRC-II scenario to the middle between NRC-II and NRC-III scenarios. This case is the best fit to the trend function at the end of the observations in 2011.

Note the differences in the projected sea level in 2100 for the different stations. For example, the difference between the 2100 projection of sea level at Annapolis and Sewells Point is ~0.2m for the local average SLR scenario (blue), but is ~0.4m for the SLR acceleration scenario (red), so higher SLR rates or including acceleration may reduce the accuracy of the projections.

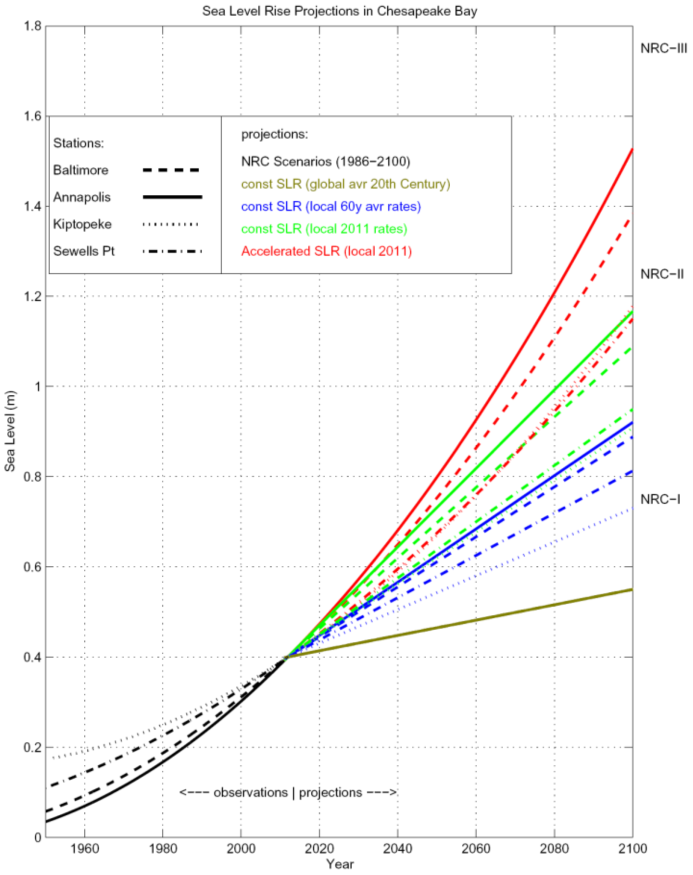

Fig. 4. Sea level projections for Baltimore (dashed line), Annapolis (solid line), Kiptopeke (dotted line) and Sewells point (dash-dot line). Black lines are the trends for 1950-2011 calculated from the last HHT mode of each station; color lines are various SLR scenarios (see text for details). Also shown on the right are the 3 NRC scenarios based on 0.5, 1.0 and 1.5m SLR between 1986 and 2100.

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