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Evidence of Sea Level Acceleration at U.S. and Canadian Tide Stations, Atlantic Coast, North America

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ABSTRACT

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Evidence of statistically significant acceleration in sea level rise relative to land is found in a recent analysis of monthly mean sea level (mmsl) at tide stations on the Atlantic coast of North America. Serial trend analysis was used at 11 U.S. Atlantic coast stations and 1 Canadian station (Halifax, Nova Scotia) with record lengths exceeding 75 years to examine change in the linear trend rate of rise over time. Deriving trend estimates that apply in the median year of fixed-length mmsl series, reversals in rate direction (increasing or decreasing) were observed around 1939–40 and again in the mid-1960s except at the northeasternmost stations in the latter period. What has not been observed until recently is a sharp reversal (in 1987) followed by a uniform, near-linear change in rise rate that infers constant acceleration at eight mid- to NE Atlantic tide stations, change not seen at SE U.S. Atlantic stations. Quadratic regression and analysis of variance applied to mmsl series over the last 43 years (1969–2011) confirms that addition of a quadratic term representing acceleration is statistically significant at 16 tide stations from Virginia to Nova Scotia. Previous quadratic model studies have focused on sea level series of longer spanning periods with variable serial trends undermining quadratic expression of either accelerating or decelerating sea level. Although the present 43-year analysis offers no proof that acceleration will be long lived, the rapidity of the nascent serial trend increase within the region of interest is unusual. Assuming constant acceleration exists and continues, the regression model projects mmsl by 2050 varying between 0.2 and 0.9 m above mean sea level (MSL) in the NE region and between –0.3 and 0.4 m above MSL in the SE region.

ADDITIONAL INDEX WORDS: *Sea level rise, serial trend analysis, sea level acceleration.*

INTRODUCTION

Much attention has been given to the question of global sea level rise, including acceleration in the rate of rise, in the last two centuries. Seminal papers discussing evidence for acceleration from tide gauge records include Woodworth (1990), Douglas (1992), Holgate and Woodworth (2004), Church and White (2006), Jevrejeva *et al*. (2006), and a critical review by Woodworth *et al*. (2009). These works generally addressed perceived accelerations over several decades rather than short-term (decadal) variations in sea level of the type discussed by Holgate (2007). Spatial dependencies among sea level histories at individual tide stations—stations nonuniform in their distribution around the world—were investigated through synthesized global time series obtained using empirical orthogonal function analysis (Church and White, 2006, 2011; Church *et al.,* 2004; Grinsted, Moore, and Jevrejeva, 2010). Other studies projecting global mean sea level (GMSL), its rate of rise, and future acceleration include a semiempirical relationship between historical means in global surface temperature and sea level time series (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009).

In their synthesis and further inspection of tide gauge records primarily from Europe and North America, Woodworth *et al*. (2009) found evidence of a positive acceleration or "inflexion" in monthly sea level data around 1920–30 and a negative acceleration (deceleration) around 1960 but noted the occasional absence of these features locally. From the analyses of Church and White (2006), accelerations determined by quadratic regression for the period 1870–2004 produced a global average of 0.013 ± 0.006 mm/y^2 but with wide variations regionally (± 0.04 mm/y^2; Figure 4 in Woodworth *et al.,* 2009). Analyzing 25 U.S. tide gauge records over the 80-year period 1930–2009, Houston and Dean (2011) reported a mean deceleration of -0.0138 ± 0.0148 mm/y^2 (95%) for the Atlantic and Gulf coast regions and -0.0091 ± 0.0096 mm/y^2 (95%) averaged for the Pacific coast. Clearly, these are very small decelerations and, on the basis of the 95% confidence intervals given, not statistically different from zero.

In a discussion of Houston and Dean (2011), Rahmstorf and Vermeer (2011) criticized the 1930 starting date as uniquely chosen—the quadratic curve fitting involved being sensitive to choice of time origin—and posed the following question: "Why would tide gauge data of the twentieth century show the

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acceleration in the twenty-first century?" This is an especially important question to ask if there is reason to believe that a specific aspect of climate change influencing sea level dynamics may have begun late in the 20th century and that its effects now apply to a specific coastal region. Such questions shift attention from a global to a regional interest and, if the resultant sea level acceleration presents in an unmistakable way, may alter the conclusion by Douglas (1992) that record lengths approaching 50 years are needed to determine global sea level acceleration from tide gauge data.

This paper addresses sea level relative to the land (RSL)—its rise and new evidence of "hot spot" accelerations in RSL found at tide stations along the NE Atlantic coastal region of the United States and Canada (Sallenger, Doran, and Howd, 2012). Climate-based model projections by Yin, Schlesinger, and Stouffer (2009) highlight a dynamic adjustment of sea level in the NE region in response to a reduction in the Atlantic meridional overturning circulation (AMOC). The adjustment would take the form of a progressive change in existing coast-normal geostrophic gradients in sea level maintained by western boundary currents (*e.g.,* Florida Current and Gulf Stream), in addition to steric change that would accompany a slowdown (or shutdown) of the AMOC and the formation of North Atlantic Deep Water. Fluctuations in coastal sea level at interannual and decadal timescales have been linked by numerous authors to variations in the strength of these currents (Blaha, 1984; Maul, Mayer, and Bushnell, 1990; Sweet, Zervas, and Gill, 2009) and their relationship to wind stress curl in the open Atlantic (DiNezio *et al.,* 2009; Hong, Sturges, and Clarke, 2000).

LINEAR TRENDS

Sea level data at tide stations in the United States and its territories are collected and distributed by the Center for Operational Oceanographic Products and Services (CO-OPS) of the National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA). Sea level trends determined by CO-OPS scientists at stations with sufficient record length (minimum of 30 y) may be found online (CO-OPS, 2012). Monthly mean sea level (mmsl) data referenced to a tidal datum controlled by tidal benchmarks are used to determine the RSL trend at each station through a linear regression model after first removing the average seasonal cycle (Zervas, 2009). The model takes the form

$$Y = b_0 + b_1 X + \varepsilon \tag{1}$$

where the error term ε is minimized through least-squares regression of a time series of Y (RSL in meters) on X (serial time in years) to obtain coefficients b_0 and b_1 and the dependent variable estimate

$$\hat{Y} = b_0 + b_1 X \tag{2}$$

The residual errors for a series of length $i = 1,n$ are then

$$\varepsilon_i = Y_i - \hat{Y}_i \tag{3}$$

Reducing the data series to deviations from mean,

$$y_i = Y_i - \bar{Y}, \quad x_i = X_i - \bar{X}$$

the regression coefficient estimating the RSL trend is

$$b_1 = \sum_{i=1}^{n} x_i y_i \Big/ \sum_{i=1}^{n} x_i^2 \tag{4}$$

and the estimated standard error of the trend is

$$s_e = s_{y \cdot x} \Big/ \sqrt{\sum x_i^2} \tag{5}$$

where $s_{y \cdot x} = \sqrt{\sum \varepsilon_i^2 / (n-2)}$ is the sample standard deviation from regression. The 95% confidence interval about the RSL trend estimate can then be derived as

$$b_1 \pm s_e t_{.05} \tag{6}$$

where $t_{.05}$ is the t-statistic with $n - 2$ degrees of freedom and 5% probability of a larger value.

The preceding derivations assume that the residual errors are independent and random-normally distributed; alternatively, the residuals may be serially correlated in time, leading to an underestimate of the standard error in Equation (5). Testing for serial correlation can be done using the Durbin-Watson statistic (Draper and Smith, 1998; von Storch and Zwiers, 1999). In the case of mmsl series from tide stations, serial correlation is usually significant, even after removal of the seasonal cycle represented in tide predictions by the solar-annual and solar-semiannual tidal harmonic constituents (Zervas, 2009). Boon, Brubaker, and Forrest (2010) tested mmsl series, with the seasonal cycle removed, from 10 Chesapeake Bay tide stations and found serial correlation to be significant at all 10 stations. However, repeating the tests after using numerical filtering to isolate and remove the decadal signal in each series gave satisfactory (nonsignificant) results, a consequence of removing a highly coherent oscillation present at each station, an example of the decadal signal (Sturges and Hong, 2001). Still, while the filtering procedure gave reasonable RSL trends and reduced trend confidence intervals, the required filter width shortened the original series by 2 years at either end. A correction to the standard error in Equation (5) can also be used based on an autoregression coefficient representing the part of the Y series predictable from the previous (lag 1) residual (Zervas, 2009). However, the correction has no effect on the trend estimate; instead, it simply increases the stated uncertainty about the estimate in Equation (6).

A key point in trend analysis is that both the RSL trend and the confidence interval about the trend (Equation (6)) apply at the midpoint of the time series used in the regression: neither of these estimates is a projection of future RSL trend values or the uncertainty that may exist about those values. However, the RSL height at a specified time X_0 can be predicted with

$$\hat{Y}_0 = \bar{Y} + b_1 (X_0 - \bar{X}) \tag{7}$$

where, for individual observations, the standard deviation (standard error) about $\hat{Y}_0$ at X_0 is

$$s_Y = s_{y \cdot x} \sqrt{1 + \frac{1}{n} + \frac{(X_0 - \bar{X})^2}{\sum (X_i - \bar{X})^2}} \tag{8}$$

Equation (8) can be used to compute confidence bands around the regression line by applying the t-statistic as in Equation (6). The band width is minimal at the midpoint of the series $(X_0 = \bar{X})$.

ACCELERATION (DECELERATION) IN SEA LEVEL RISE

Equation (2) estimates RSL rising or falling at a constant rate—the trend b_1 expressed in millimeters per year. An equation of the same form can be written to estimate $\hat{V}$, the time-variable rate of rise or fall assuming it is changing at a constant rate b_2 (in millimeters per years squared), where

$$\hat{V} = b_1 + b_2 X \quad (9)$$

Integrating Equation (9) over a series of years,

$$\hat{Y} = b_0 + b_1 X + \frac{1}{2} b_2 X^2 \quad (10)$$

The polynomial represented by Equation (10) has frequently been fitted using a quadratic regression model to search for acceleration in sea level rise, *i.e.,* by obtaining the quadratic coefficient 1/2 b_2 that is half the acceleration. But in using this model, the investigator accepts the premise of constant acceleration or, if $b_2 = 0$, no acceleration over the fitted interval made explicit by Equation (9). If the fitted interval includes tide station data collected over the 80 years from 1930 through 2009 (Houston and Dean, 2011), the assumption of constant acceleration would not seem to be a particularly good one given the observations by Woodworth *et al*. (2009) and others cited in the introduction. The question then becomes, over what interval, if any, does constant acceleration or constant deceleration apply? This question can be explored more effectively using Equations (9) and (10) in a complementary way. To answer the objection of Rahmstorf and Vermeer (2011) to an arbitrary starting time when applying Equation (10), it is reasonable to look for evidence that the starting and ending times cover a period of constant acceleration, large or small. This may be done using serial trends.

SERIAL TRENDS

As previously noted, a linear trend derived by least-squares regression provides an estimate of the sea level rise rate in millimeters per year, a rate that applies at the midpoint of the fitted series where it represents an estimate of $\hat{V}$ in Equation (9). If N years of mmsl time series data are available at a tide station, I can derive

$$p = N - n + 1 \quad (11)$$

estimates of $\hat{V}$ by applying Equation (2) to all RSL time series of fixed length n, where $n \leq N$. Ordering the estimates in time yields a serial trend series$\{\hat{V}\}$ of length p at that station, and a plot of $\hat{V}$ on X using Equation (9) results in a straight line over any interval wherein acceleration or deceleration is constant. Choosing a small value of n clearly provides a longer series of $\hat{V}$ values but at the cost of greater variability among the p estimates; choosing $n = N$, produces a single value that represents the trend estimate using all available data. Useful information can be found between these extremes. Taking a specific value of n and expanding the analysis to include adjacent coastal tide stations introduces a spatial dimension that, along with the temporal one, resembles a topographic development, where n might represent the number of nearest-neighbor points used to smooth the data plotted on a grid.

I have computed serial trends at 12 U.S. and Canadian tide stations along the East Coast of North America (Figure 1) with at least 76 years of near-continuous mmsl data, from which I removed the average seasonal cycle but not the decadal signal, through December 2011. These were 11 U.S. stations from the U.S. National Water Level Observation Network and 1 Canadian station (Halifax, Nova Scotia), listed in Table 1 along with the year series selected for analysis. Data for Halifax and another Canadian station not part of the serial trend analysis but used elsewhere (St. John's, Newfoundland) were obtained through 2010 from the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003) based at the National Oceanography Centre in Liverpool, U.K. (data available at PSMSL, 2012), and from the Canadian Ministry of Fisheries and Oceans for 2011. Both mmsl data sets were adjusted to equivalent heights above U.S. mean sea level (MSL), a tidal datum defined at CO-OPS tide stations as the average of the hourly heights over the U.S. National Tidal Datum Epoch, which currently includes 1983–2001 (median year 1992).

Analyzed serial trends are presented in two contrasting groups centered on Norfolk (Sewells Point), Virginia (Figure 1): a NE group including eight stations from Norfolk to Halifax and a SE group including four stations from Charleston to Key West, as listed in Table 1. Figure 2 shows 36-year serial trends $(n = 36)$ for the NE group plotted against the trend median year. Linearly increasing RSL trend values are seen at Baltimore, New York, and Portland until 1942, when there is a reversal and general decline—with considerable variability across stations—that continues until 1987, when a second reversal occurs marked by rapidly increasing linear trend rates rising in unison at all eight stations. A weak rate increase appeared briefly following a 1989–90 reversal at the four stations in the SE group $(n = 36$, figure not shown).

Principal Components

Figure 2 illustrates, but does not define, the relationship between RSL serial trends at different locations; trend patterns can differ substantially depending on the choice of n, the series length determining the trend. Given fixed values of n and N in Equation (11), a set of p serial trends can be found common to all stations in a group, enabling a principal components analysis (PCA) to be performed.

Let $[S]$ represent a $p \times m$ matrix of serial trend data, where p is the number of serial trend rates and m is the number of tide stations. After reducing the serial trend rates in each station column to zero-mean value, the $m \times m$ variance–covariance matrix is obtained as the minor product matrix divided by $p - 1$:

$$[VCV] = [S]'[S]/(p - 1) \quad (12)$$

from which $[U]$, an $m \times m$ matrix of eigenvectors, was derived—along with $[\lambda]$, an $m \times m$ diagonal matrix of eigenvalues—using

Figure 1. Location of tide stations on the Atlantic coast of North America.

the MATLAB *eig* function. Principal components were then found in the $p \times m$ matrix [SR], computed as

$$[SR] = [S][U] \tag{13}$$

The principal components obtained with Equation (13) for the eight stations in the NE group (Table 1) take the same form as the plot in Figure 2, showing the RSL trend rate as a function of time, except that the component series mean rate is zero because of the zero-mean data reduction in [S]. PCAs of this type were run for different values of n. The eigenvalues obtained for the NE group with n varying between 10 and 55 years show that the first two principal components (PC1 and PC2) consistently account for more than 95% of the total variance in [VCV]. PC1 derived with $n = 10$ years (figure not shown) contained heightened variability resembling the decadal signal of Holgate (2007) with altimeter data added (*e.g.,* Figure 6 in Houston and Dean, 2011), only with higher trend maxima and minima in millimeters per year, consistent with a western ocean boundary (Church *et al.,* 2004; Sturges and Hong, 2001; Woodworth *et al.,* 2009). Of particular interest here is the change in variance found for the first principal component (PC1) relative to the second (PC2) as n varies. Figure 3 shows that the percent variance accounted for by PC1 and PC2 for the NE group is nearly equal (PC1 reaches a minimum as PC2 reaches a maximum) when $n = 36$ years. The components then represent two principal modes balanced in terms of variance accounted for. As shown in Figure 4, PC1 evidences the weak 1960–70 reversal apparent in Figure 2 at the southernmost stations (Norfolk to New York) of the NE group, PC2 reflecting its absence at the northernmost stations (Boston to Halifax). Both PC1 and PC2 in Figure 4 show the sharp 1987 reversal and subsequent RSL rise rates increasing in near-linear mode at all eight stations in the NE group. A similar PCA for the four stations in the SE group (results not shown) gave no clear indication of a late reversal in trend.

SERIAL TRENDS – A GUIDE TO CONSTANT ACCELERATION?

A Guide to Constant Acceleration?

If serial trends are a guide to periods of constant acceleration in sea level rise, the clearest indication of it may well be the abrupt transition to linearly increasing trend values that appears in PC1 and PC2 in median year 1987 (Figure 4). This feature is unprecedented in the water level records now spanning more than three-quarters of a century at tide stations on the U.S.–Canadian Atlantic coast. A linear increase in trend values has previously appeared at the three of these stations with the longest record length, beginning as early as 100 years ago (in 1911) and continuing until 1942 (Figure 2). Acceleration in sea level rise during that period, as well as again starting in 1987 and continuing to the present, thus seems plausible, but the search for it using quadratic regression now points to shorter, as well as longer, records. Linear regression analysis of

Table 1. *Tide stations and mmsl series used in serial trend analysis of the U.S. and Canadian Atlantic coast region. Data from NOAA/NOS CO-OPS (7-digit identifier) and the PSMSL are divided into NE and SE groups.*

Station Name	Group	Acronym	Station ID	Years Analyzed
Halifax, NS	NE	HFAX	PSMSL 96	1920–2011
Portland, ME	NE	PORT	8418150	1912–2011
Boston, MA	NE	BOST	8443970	1921–2011
The Battery, NY	NE	NYTB	8518750	1893–2011
Sandy Hook, NJ	NE	SDHK	8531680	1933–2011
Atlantic City, NJ	NE	ATLC	8534720	1923–2011
Baltimore, MD	NE	BALT	8574680	1903–2011
Sewells Point, VA	NE	SWPT	8638610	1928–2011
Charleston, SC	SE	CHAR	8665530	1922–2011
Fort Pulaski, GA	SE	FTPL	8670870	1936–2011
Mayport, FL*	—	—	8720220	1929–2000
Mayport, FL†	SE	MYPR	8720218	2001–2011
Key West, FL	SE	KYWS	8724580	1913–2011

* Ferry Depot.
† Bar Pilots Dock.

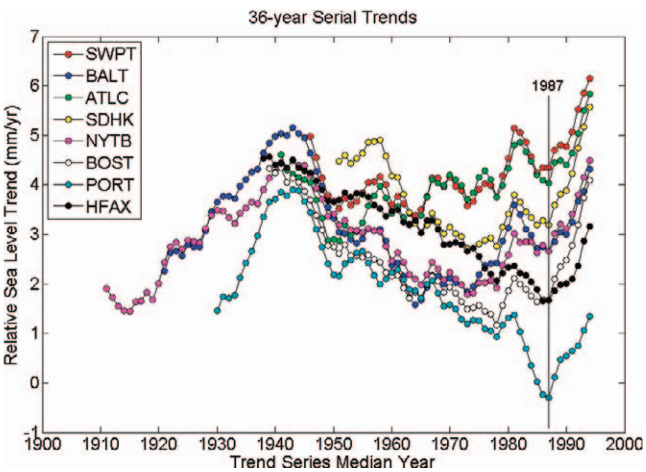

Figure 2. Serial trends at tide stations, NE group ($n = 36$ y).

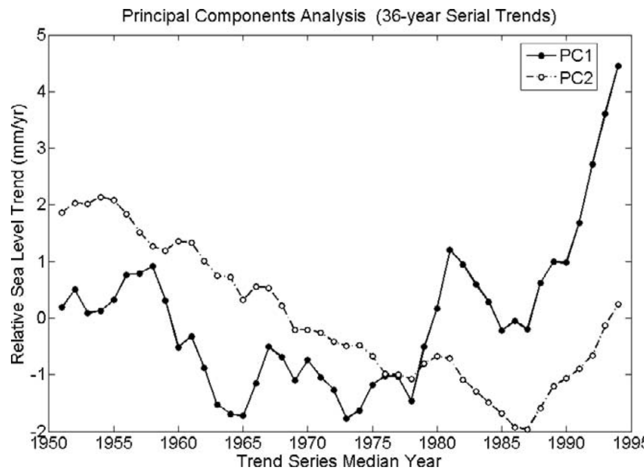

Figure 4. PC1 and PC2, NE group ($n = 36$ y).

short (32 y) mmsl series in Chesapeake Bay was conducted by Boon, Brubaker, and Forrest (2010) after addressing serial correlation using a numerical filter. However, quadratic regression over the most recent years searching for nascent acceleration is affected by filter width requirements; thus, filtering is not applied in this study. Other corrections (widening confidence intervals about the regression coefficients) were not relevant to quadratic model uncertainty as presented here; thus, they were also not applied. Aspects of the uncertainty impacting flood risk as a consequence of sea level rise are discussed in a later section.

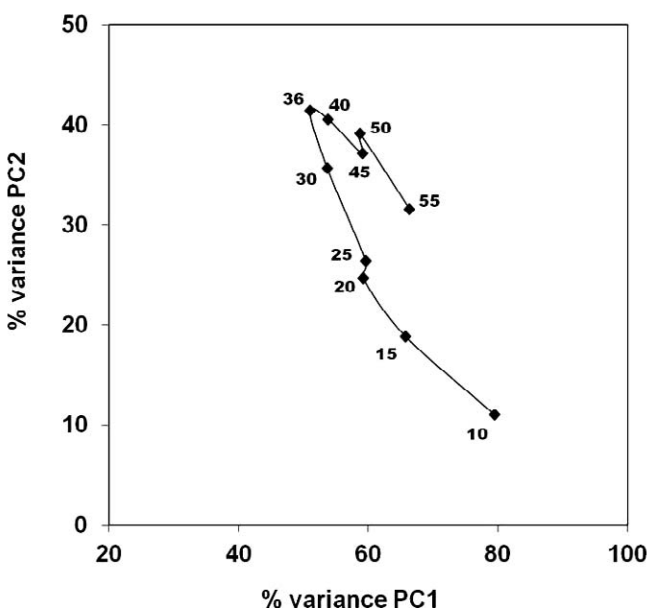

Figure 3. Percent of total variance accounted for by PC1 and PC2 for variable trend series lengths ($n = 10$ to 55 y), NE group.

To look for evidence of acceleration, quadratic regression based on Equation (10) was applied over the period 1969–2011, recalling that, for an even series of length $n = 36$ years and median year 1987 marking the transition to linearly increasing trend rates (Figure 4), the starting year is 1969. Likewise, for 1994, the latest median year in Figure 4, the series ending year is 2011. The MATLAB *polyfit* and *polyval* functions were used with independent variable centering and scaling transformation to fit the mmsl data in this series. Confidence intervals about the linear and quadratic regression coefficients were not computed; instead, an analysis of variance was performed using an F test to determine (1) the significance of the regression model, including both linear and quadratic terms, and (2) the significance of the added quadratic term in Equation (10) (Draper and Smith, 1998). If the quadratic term contribution to regression is found to be nonsignificant, the null hypothesis of zero acceleration is not rejected.

Tests at both the 95% and the 99% levels of confidence were performed for 23 East Coast tide stations with near-complete records over the 1969–2011 period (Table 2). Combined (linear plus quadratic term) regression was highly significant (99%) at all 23 stations as expected due to the strength of the linear term. After testing the contribution of the quadratic term to regression, statistically significant acceleration was found for 1 station in the extended NE group of Table 2 at the 95% level of confidence (Kiptopeke, Virginia) and for 15 others in this group at the 99% level of confidence. In contrast, acceleration was nonsignificant for St. John's, Newfoundland (top of Table 2), and for all six stations in the extended SE group (bottom, Table 2).

LOOKING FORWARD

RSL Height Anomaly

Regression analysis and the F test results given in Table 2 provide important information concerning expected RSL height distributions locally, in addition to evidence of RSL acceleration. To obtain confidence estimates on individual

Table 2. *Linear and quadratic regression coefficients* b_1 *and* $b_2/2$ *derived from 1969–2011 fitted mmsl series with 2050 sea level rise projections above 1983–2001 MSL and 95% confidence intervals at U.S. and Canadian Atlantic coast tide stations. Significance of the coefficient contribution in analysis of variance F-tests is indicated at the 95% (*) or the 99% (**) confidence level; ns indicates contribution is non-significant.*

Station Name	Station ID	Continuous Year Series	Linear (b_1) (mm/y)	Quadratic ($b_2/2$) (mm/y^2)	Rise by 2050 Projection (m)
St John's, NL	PSMSL 393	1961–2011	2.799 **	0.011 ns	0.21 ± 0.22
Halifax, NS	PSMSL 96	1920–2011	2.423 **	0.100 **	0.49 ± 0.14
Eastport, ME	8410140	1929–2011	1.489 **	0.150 **	0.62 ± 0.12
Portland, ME	8418150	1912–2011	0.937 **	0.134 **	0.54 ± 0.14
Boston, MA	8443970	1921–2011	2.882 **	0.150 **	0.71 ± 0.15
Nantucket, MA	8449130	1965–2011	3.485 **	0.090 **	0.52 ± 0.14
New London, CN	8461490	1939–2011	3.532 **	0.138 **	0.69 ± 0.15
The Battery, NY	8518750	1893–2011	3.465 **	0.103 **	0.57 ± 0.18
Sandy Hook, NJ	8531680	1933–2011	4.189 **	0.132 **	0.71 ± 0.18
Atlantic City, NJ	8534720	1923–2011	4.632 **	0.087 **	0.57 ± 0.20
Baltimore, MD	8574680	1903–2011	3.286 **	0.083 **	0.48 ± 0.19
Annapolis, MD	8575512	1929–2011	3.272 **	0.086 **	0.49 ± 0.19
Washington, DC	8594900	1932–2011	3.078 **	0.086 **	0.49 ± 0.27
Solomons Island, MD	8577330	1938–2011	4.537 **	0.114 **	0.66 ± 0.18
Gloucester Point/Yorktown, VA	8637624/689	1951–2011	4.664 **	0.121 **	0.70 ± 0.21
Sewells Point, VA	8638610	1928–2011	4.996 **	0.093 **	0.62 ± 0.22
Kiptopeke, VA	8632200	1952–2011	3.670 **	0.048 *	0.38 ± 0.20
Wilmington, NC	8658120	1966–2011	1.473 **	0.007 ns	0.10 ± 0.23
Charleston, SC	8665530	1922–2011	2.504 **	0.003 ns	0.15 ± 0.21
Fort Pulaski, GA	8670870	1936–2011	2.853 **	−0.009 ns	0.13 ± 0.22
Fernandina Beach, FL	8720030	1939–2011	1.889 **	−0.045 ns	−0.06 ± 0.25
Mayport, FL	8720220/218	1929–2011	2.565 **	0.015 ns	0.19 ± 0.24
Key West, FL	8724580	1913–2011	2.295 **	−0.008 ns	0.11 ± 0.15

mmsl heights that may be expected in any given year, Equation (8) is used after adding another term for the quadratic component and applying the t-statistic, as in Equation (6). As illustrated in Figure 5 for Boston, Massachusetts, the fraction of all mmsl heights observed over 1969–2011 that fall within the resulting 95% confidence bands ($Ne = 0.947$) is in close agreement with the number expected. This relationship points to an essential concept regarding coastal inundation in response to sea level rise: A base level of mmsl variability will exist *in situ* at any point in future, as well as at the present time—a pseudo-random anomaly characteristic of the location and an inherent part of the flood risk potential. After projecting the average sea level forward to some future year by quadratic regression or other means, uncertainty remains for the mmsl value expected in any particular month, including one in which a tropical or extratropical storm occurs. For Boston, the monthly uncertainty evidenced by the 95% bands is now about ±10 cm (Figure 5), which may increase to ±15 cm by 2050 (Table 2). Based on past observations, it can be inferred that the present anomaly is unlikely to decrease regardless of whether sea level trends increase, decrease, or stay the same over the next few decades.

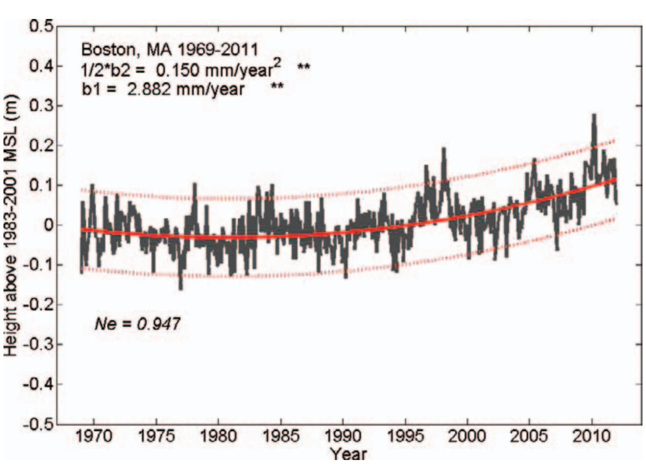

Figure 5. Quadratic model (solid line) fitted to 1969–2011 mmsl series, Boston, Massachusetts. Both linear and quadratic terms ($b_1 = 2.882$ mm/y, $1/2b_2 = 0.150$ mm/y^2) are statistically significant (99%). Ne = fraction of observed mmsl within 95% confidence bands (dotted lines). (Color for this figure is only available in the online version of this paper.)

To show the limits of the anomaly at the level it is likely to present to coastal communities in the near term (*e.g.,* first half of the 21st century), I have not made adjustments to the mmsl data for atmospheric pressure. Although pressure variations contribute between 15 and 20% of the total variance in regional mmsl time series, the magnitude of the reduction in variance found at Boston was small (~1 mm^2) and had minimal effect on the regression coefficients.

21st Century Outlook

Given the regression coefficients presented in Table 2, projections beyond the series of mmsl observations can be made in the context of statistical inference—an inference that becomes progressively weaker as projection time increases. It is useful to make limited projections, based on the assumption that acceleration remains constant (still a large assumption requiring more data for verification), with the clear understanding that such projections have no physical basis, unlike climate model projections; *e.g.,* those of Yin, Schlesinger, and

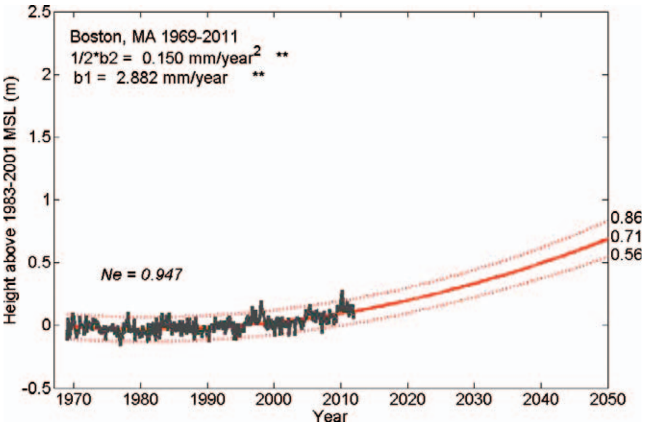

Figure 6. Quadratic model (solid line) fitted to 1969–2011 mmsl series, Boston, Massachusetts. RSL is projected to rise 0.71 ± 0.15 m above 1983–2001 MSL by 2050. Linear and quadratic terms are statistically significant (99%). *Ne* = fraction of observed mmsl within 95% confidence bands (dotted lines). (Color for this figure is only available in the online version of this paper.)

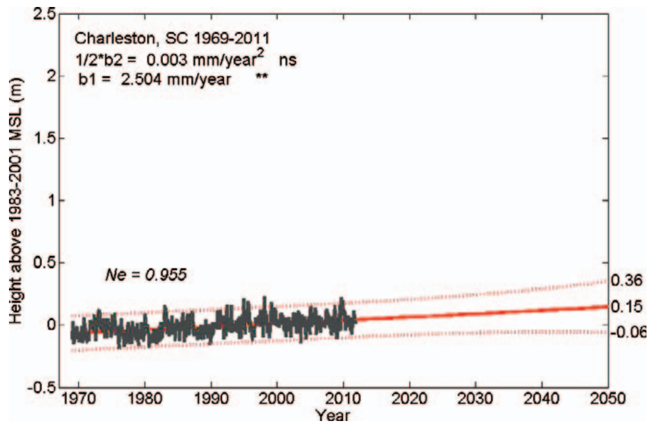

Figure 8. Quadratic model (solid line) fitted to 1969–2011 mmsl series, Charleston, South Carolina. RSL is projected to rise 0.15 ± 0.21 m above 1983–2001 MSL by 2050. Quadratic term is statistically nonsignificant. *Ne* = fraction of observed mmsl within 95% confidence bands (dotted lines). (Color for this figure is only available in the online version of this paper.)

Stouffer (2009) for the North Atlantic region. Moreover, it may be useful to compare RSL projections at coastal tide stations with GMSL projections that increasingly rely on satellite altimetry, as in the most recent work by Church and White (2011). While the satellite record since its start in 1993 has largely overcome the sparseness issue of tide gauge records in determining GMSL, there remains the question of land interference with the satellite radar footprint where the tide gauges are located; *i.e.,* along the coast, the region of interest in this work. Specifically, projections based on local mmsl observations are needed to guide regional sea level planning and adaptation measures being pursued with increased urgency in many coastal localities. An example of a planning measure to which this applies is addressed in "Discussion."

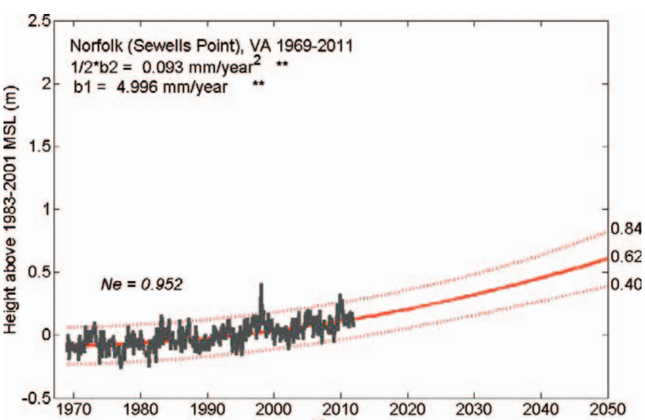

Figure 7. Quadratic model (solid line) fitted to 1969–2011 mmsl series, Norfolk (Sewells Point), Virginia. RSL is projected to rise 0.62 ± 0.22 m above 1983–2001 MSL by 2050. Linear and quadratic terms are statistically significant (99%). *Ne* = fraction of observed mmsl within 95% confidence bands (dotted lines). (Color for this figure is only available in the online version of this paper.)

With the preceding precautions in mind, limited projections are made here in accordance with the length and level of variance (the anomaly) in the observed mmsl series. Confidence bands provide additional guidance by widening perceptibly when projections are overly long or the observed series length is short in comparison to the series variance. Observing these limitations, projections of mmsl above 1983–2001 MSL by 2050 were obtained and are presented in Table 2. A graphical representation of midcentury projections for two stations in the NE group (Boston, Massachusetts, and Norfolk, Virginia) and one station in the SE group (Charleston, South Carolina) are given in Figures 6 to 8, accompanied by 95% confidence bands.

End-of-century sea level rise projections were made for different scenarios in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (Bindoff *et al.,* 2007). The AR4 reported on global-average sea level rise and global factors contributing to it, including globally averaged surface warming but omitting land-based ice melt amounts as unresolved and uncertain. It gave sea level rise projections of 0.18 to 0.59 m from 1990 to the end of the 21st century (Table SPM-2 in Bindoff *et al.,* 2007). In contrast to AR4, the present study is regional and observation based, and it addresses only RSL rise. My RSL rise estimates in meters above 1983–2001 MSL (Table 2) extend only to 2050, a 58-year projection of sea level reckoned from 1992 at the midpoint of the current U.S. National Tidal Datum Epoch. Given the limited number and size of records available for testing the hypothesis that constant acceleration informs serial trends, it is not yet known whether a linear rate of rise increase (constant acceleration) will persist over an extended period going forward. But at the time of writing, 20 years have passed since 1992, with 38 years remaining until 2050.

Comparing acceleration estimates (b_2, Table 2) for Boston (Figure 6) and Norfolk (Figure 7), the estimate at Boston is more than 1.6 times that at Norfolk (0.300 *vs*. 0.186 mm/y^2), a finding broadly consistent with dynamically forced sea level rise in the NE region and certain hot spot locations identified by Sallenger, Doran, and Howd (2012). However, a smaller linear rise rate (b_1, Table 2) is found at Boston compared to that at Norfolk (2.88 *vs*. 5.00 mm/y), consistent with an anomalously high linear subsidence rate previously reported for Norfolk (Boon, Brubaker, and Forrest, 2010). It is therefore not surprising that 2050 average rise projections at these two cities are similar (0.71 *vs*. 0.62 m) and that the highest mmsl values expected within the 95% bands are almost the same (0.86 *vs*. 0.84 m) due to a greater anomaly (wider bands) at Norfolk (Figure 7).

Perhaps more surprising are the minimal RSL rise projections at tide stations in the SE group (Wilmington, North Carolina, to Key West, Florida, Table 2). As seen in the RSL projection and 95% confidence bands for Charleston (Figure 8), the inferred rise by 2050 is 0.15 m—roughly a third of the expected anomaly there. At Boston and Norfolk, the inferred 2050 rise is 2.4 and 1.4 times their respective anomalies. Again, when future storms occur, storm surge will add to the mmsl present at the time but not necessarily to the projected RSL (solid line in Figures 6–8).

DISCUSSION

In their review of the evidence for sea level acceleration, Woodworth *et al*. (2009) placed particular emphasis on studies with timescales of several decades or more. Church *et al*. (2004), for example, had earlier combined satellite altimetry data with tide gauge data to reconstruct both global and regional sea level histories over the period 1950–2000, but they were unable to detect a significant increase in the rate of sea level rise. Reasons given for the uncertainty in this instance include decadal variation and the need to correct tide gauge records for ongoing glacial isostatic adjustment and tectonic movements—the latter being required to separate land movement from RSL to obtain eustatic or absolute sea level change (steric change in ocean volume, addition or redistribution of ocean water mass, *etc*.).

A consideration of the preceding factors is central to the recent U.S. Army Corps of Engineers (USACE) *Climate Change Adaptation* evaluation, which includes sea level change curves developed for engineering guidance (USACE, 2012). Three USACE curves designated low, intermediate, and high are available through an online calculator (USACE, 2012) based on Equation (10) in this paper, with $b_0 = 0$ at 1992, $b_1 =$ 20th century eustatic change (1.7 mm/y) + vertical land movement (variable), and b_2 as assigned to follow three climate scenarios originally developed by the U.S. National Research Council. Curve shape thus varies only slightly among locations on the U.S. East Coast in response to locally varying estimates of vertical land movement. At New York, for example, the USACE high curve projects a sea level rise of 0.55 m above MSL by 2050, which compares well with 0.57 m given for New York (Table 2, this paper). However, the USACE high curve projects the same height, 0.55 m by 2050, at Charleston, South Carolina, whereas the present study projects only 0.15 m of rise at that city by 2050, accompanied by a large uncertainty estimate (±0.21 m, Table 2). Adopting the USACE low curve at Charleston gives a more likely projection, 0.17 m by 2050, but leaves open the question of how to obtain the appropriate guidance (which curve) to follow. The correct choice clearly must weight mmsl observations made locally, in addition to—or in some cases, in place of—global change scenarios.

CONCLUSIONS

Analysis of serial trends in RSL along the U.S. and Canadian Atlantic coast has identified variable rise rates during the 20th century and the first 11 years of the 21st century. In agreement with previous work summarized in Woodworth *et al*. (2009), a period of increasing sea level rise rates was detected in the first decade of the 20th century at three active tide stations with 100 years or more of near-continuous monthly data, continuing until a reversal occurred around 1941–42 that initiated decreasing but more variable rates at eight stations with more than 79 years of record from Norfolk (Sewells Point), Virginia, to Halifax, Nova Scotia. The variability in serial trend patterns appears to have changed abruptly with a second reversal in 1987, followed by uniform and rapidly increasing rise rates at all eight stations. Linearly increasing rates of sea level rise infer a constant acceleration (in millimeters per years squared) over the interval in which it occurs, the prerequisite for quadratic regression of sea level height on time in years. For the NE U.S. and Canadian region, the 43-year period 1969–2011 has been identified as one such interval with the aid of a PCA.

Applying quadratic regression analysis to the 1969–2011 mmsl series, I found quadratic contributions to regression to be significant for 16 mid- to NE U.S. Atlantic coast tide stations at locations consistent with the pattern of modeled projections by Yin, Schlesinger, and Stouffer (2009) and a recent observational analysis by Sallenger, Doran, and Howd (2012). The observational data support the claim that sea level rise is now accelerating at locations from Norfolk, Virginia, to Halifax, Nova Scotia, at rates as high as 0.30 mm/y^2, rates that justify concern over this region of the U.S. East Coast. By contrast, projected RSL rise by 2050 along the SE U.S. coast is minimal; serial trend analysis provides no clear evidence of acceleration, although the number of tide stations in this region with continuous mmsl series of sufficient length for analysis is limited. What remains unknown at this point is the duration of the constant acceleration epoch that now seems evident in the mid- to NE Atlantic region. Should it depend on Atlantic Ocean dynamics, it must be recognized that the timescales associated with a "slowdown," or even a "shutdown" of the AMOC are not well known but are likely to be more episodic or cyclic than other climatic change mechanisms with a timescale of centuries or millennia. Under these circumstances, with the region of concern positively identified, it seems prudent to take a heuristic approach and carefully examine each additional year of mmsl data as it becomes available at existing tide stations.

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LITERATURE CITED

Bindoff, N.L.; Willebrand, J.; Artale, V.; Cazenave, A.; Gregory, J.; Gulev, S.; Hanawa, K.; Le Quéré, C.; Levitus, S.; Noijiri, Y.; Shum, C.K.; Talley, L.D., and Unnikrishnan, A., 2007. Observations: oceanic climate change and sea level. *In:* Solomon, S., *et al*. (eds.), *Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change*. http://www/ipcc.ch.

Blaha, J.P., 1984. Fluctuations of monthly sea level as related to the intensity of the Gulf Stream from Key West to Norfolk. *Journal of Geophysical Research*, 89, 8033–8042.

Boon, J.D.; Brubaker, J.M., and Forrest, D.R., 2010. *Chesapeake Bay Land Subsidence and Sea Level Change: An Evaluation of Past and Present Trends and Future Outlook*. Special Report No. 425 in Applied Marine Science and Ocean Engineering. Gloucester Point, Virginia: Virginia Institute of Marine Science, 42p, Appendices *A, B*.

CO-OPS (Center for Operational Oceanographic Products and Services), (2012). Turning Operational Oceanographic Data into Meaningful Information for the Nation. http://www.tidesandcurrents.noaa.gov/ (accessed January 15, 2012).

Church, J.A. and White, N.J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, 33, L01602, doi: 10.1029/2005GL024826.

Church, J.A. and White, N.J., 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, 32, 587–602, doi: 10.1007/s10712-011-9119-1.

Church, J.A.; White, N.J.; Coleman, R.; Lambeck, K., and Mitrovica, J.X., 2004. Estimates of the regional distribution of sea level rise over the 1950–2000 period. *Journal of Climate*, 17, 2609–2625.

DiNezio, P.N.; Gramer, L.J.; Johns, W.E.; Meinen, C.S., and Baringer, M.O., 2009. Observed interannual variability of the Florida current: wind forcing and the North Atlantic Oscillation. *Journal of Physical Oceanography*, 39, 721–736.

Douglas, B.C., 1992. Global sea level acceleration. *Journal of Geophysical Research*, 97(C8), 12699–12706, doi: 10.1029/92JC01133.

Draper, N.R. and Smith, H., 1998. *Applied Regression Analysis*, 3rd edition. New York: Wiley, 706p.

Grinsted, A.; Moore, J.C., and Jevrejeva, S., 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100. *Climate Dynamics*, 34, 461–472, doi: 10.1007/s00382-008-0507-2.

Holgate, S.J., 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters*, 34, L01602, doi: 10.1029/2006GL028492.

Holgate, S.J. and Woodworth, P.L., 2004. Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters*, 31, L07305, doi: 10.1029/2004GL019626.

Hong, B.G.; Sturges, W., and Clarke, A.J., 2000. Sea level on the U.S. East Coast: decadal variability caused by open ocean wind-curl forcing. *Journal of Physical Oceanography*, 30, 2088–2098.

Houston, J.R. and Dean, R.G., 2011. Sea-level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses. *Journal of Coastal Research*, 27(3), 409–417.

Jevrejeva, S.; Grinsted, A.; Moore, J.C., and Holgate, S., 2006. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research*, 111, C09012, doi: 10.1029/2005JC003229.

Maul, G.A.; Mayer, D.A., and Bushnell, M., 1990. Statistical relationships between local sea level and weather with Florida–Bahamas cable and Pegasus measurements of Florida current volume transport. *Journal of Geophysical Research*, 95, 3287–3296.

PSMSL (Permanent Service for Mean Sea Level), 2012. Welcome to the Permanent Service for Mean Sea Level (PSMSL). http://www.psmsl.org (accessed January 14, 2012).

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, 315, 368–370, doi: 10.1126/science.1135456.

Rahmstorf, S. and Vermeer, M., 2011. Discussion of: Houston, J.R. and Dean, R.G., 2011: sea level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses. *Journal of Coastal Research*, 27(4), 784–787.

Sallenger, A.H; Doran, K.S., and Howd, P.A., 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change* (published online 24 June 2012), doi: 10.1038/NCLIMATE1597.

Sturges, W. and Hong, B.G., 2001. Decadal variability of sea level. *In:* Douglas, B.C.; Kearney, M.S., and Leatherman, S.P. (eds.), *Sea Level Rise: History and Consequences*. San Diego, California: Academic Press, pp. 165–180.

Sweet, W; Zervas, C., and Gill, S., 2009. Elevated East Coast Sea Levels Anomaly: June–July 2009. *NOAA Technical Report NOS CO-OPS 051*, 28p.

USACE (U.S. Army Corps of Engineers), 2012. Responses to Climate Change: Climate Change Adaptation: Comprehensive Evaluation of Projects with Respect to Sea-Level Change. http://corpsclimate.us/ccaceslcurves.cfm (accessed May 11, 2012).

Vermeer, M. and Rahmstorf, S., 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, 106(51), 21527–21532, doi: 10.1073, pnas.0907765106.

von Storch, H. and Zwiers, F.W., 1999. *Statistical Analysis in Climate Research*. Cambridge, United Kingdom: Cambridge University Press, 484p.

Woodworth, P.L., 1990. A search for accelerations in records of European mean sea level. *International Journal of Climatology*, 10, 129–143.

Woodworth, P.L. and Player, R., 2003. The Permanent Service for Mean Sea Level: an update to the 21st century. *Journal of Coastal Research*, 19(2), 287–295.

Woodworth, P.L.; White, N.J.; Jevrejeva, S.; Holgate, S.J.; Church, J.A., and Gehrels, W.R., 2009. Review: evidence for the accelerations of sea level on multi-decade and century timescales. *International Journal of Climatology*, 29, 777–789.

Yin, J.; Schlesinger, M.E., and Stouffer, R.J., 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, 2, 262–266, doi: 10.1038/NGGEO462.

Zervas, C., 2009. Sea Level Variations of the United States 1854–2006. *NOAA Technical Report NOS CO-OPS 053*, 75p, Appendices A–E.