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REPLY

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INTRODUCTION

Objections raised by J.R. Houston to relative mean sea level (RMSL) projections made by Boon and Mitchell (2015) stem from his previous work published with the late professor R.G. Dean. Houston and Dean (2011) stated that "Without sea-level acceleration, the 20th-century sea-level trend of 1.7 mm/y would produce a rise of only approximately 0.15 m from 2010 to 2100; therefore, sea-level acceleration is a critical component of projected sea-level rise" (p. 409). After applying quadratic regression to records from 57 tide stations across the United States and its territories, these authors cast considerable doubt on that same component by finding, on average, a slight deceleration. Citing work by Douglas (1992), they computed an error about their group average from the 57 residuals, rather than using the error estimates of the individual station records. Six stations that showed more than a slight acceleration were termed *outliers* on the basis of their "short" records of between 62 and 70 years (Houston and Dean, 2011, p. 411). Houston and Dean (2013) further asserted that decadal variations (*e.g.,* Sturges and Hong, 2001) would obscure underlying accelerations if record lengths for individual gauges were not greater than at least 75 years. These findings, if correct, place severe limitations on estimates of temporal and spatial variation in the rate of sea-level change as measured by tide gauges. In retrospect, it is not surprising that the underlying acceleration of -0.0014 ± 0.0161 mm/y^2 they found by smoothing across 57 locations using records lengths varying between 62 and 156 years is not statistically different from zero. We are among those who have questioned their deterministic assertions in favor of a data-driven probabilistic approach that seeks to understand trends in recent sea-level acceleration looking forward rather than backward in time. The purpose of our research is not the derivation of a globally averaged, worldwide estimate of sea-level change throughout the 21st century; we wish to know what recent observations now suggest at individual locations within the coastal zone of North America over the next few decades.

Measuring Sea-Level Acceleration

Sliding windows have been applied to detect trend behavior and acceleration in tide gauge observations by the discussant and other authors (Boon, 2012; Boon and Mitchell, 2015; Jevrejeva et al., 2013; Sallenger, Doran, and Howd, 2012) along with nonparametric methods (Ezer, 2013; Ezer, Haigh, and Woodworth, 2016). In Boon (2012) and Boon and Mitchell (2015), serial trends were investigated using monthly RMSL data, with seasonal cycle removed, to detect periods of approximately linear change in the rate of sea level rise (or fall), providing evidence of constant acceleration (or deceleration). Having found such a period beginning around 1969 (Boon and Mitchell, 2015), we then applied a more rigorous statistical procedure, the moving block bootstrap (MBB; Mudelsee, 2010), which has confirmed acceleration and, in some cases, deceleration, at many U.S. and Canadian coastal locations in the post-1969 period. In contrast, the discussant presents several figures showing acceleration widely varying between positive and negative rates at a given station, with few discernable patterns other than averaging near-zero throughout periods of record dating back to 1906. We suspect that much of the heightened variability seen in these figures is due to the small sample size employed in his determinations based on 46-year records, centered on each year across a series of years. The data therein consist of annual mean sea level, rather than monthly values, which then provides only 46 data points for each least-squares regression yielding an acceleration estimate. Error bands on the estimates are not shown, and serial correlation often present in raw times-series data is not accounted for. The MBB method used in Boon and Mitchell (2015) employs 552 random-block data points per estimate and then computes 9000 independent (serially uncorrelated) replicates to provide Bayesian probability distributions for our paired regression parameters as well as our year 2050 projections.

Our Sea-Level Projections

A *projection* here is an inference drawn from a quadratic regression model over a reasonable prediction period beyond the latest RMSL observation available. Thus, we refer to the

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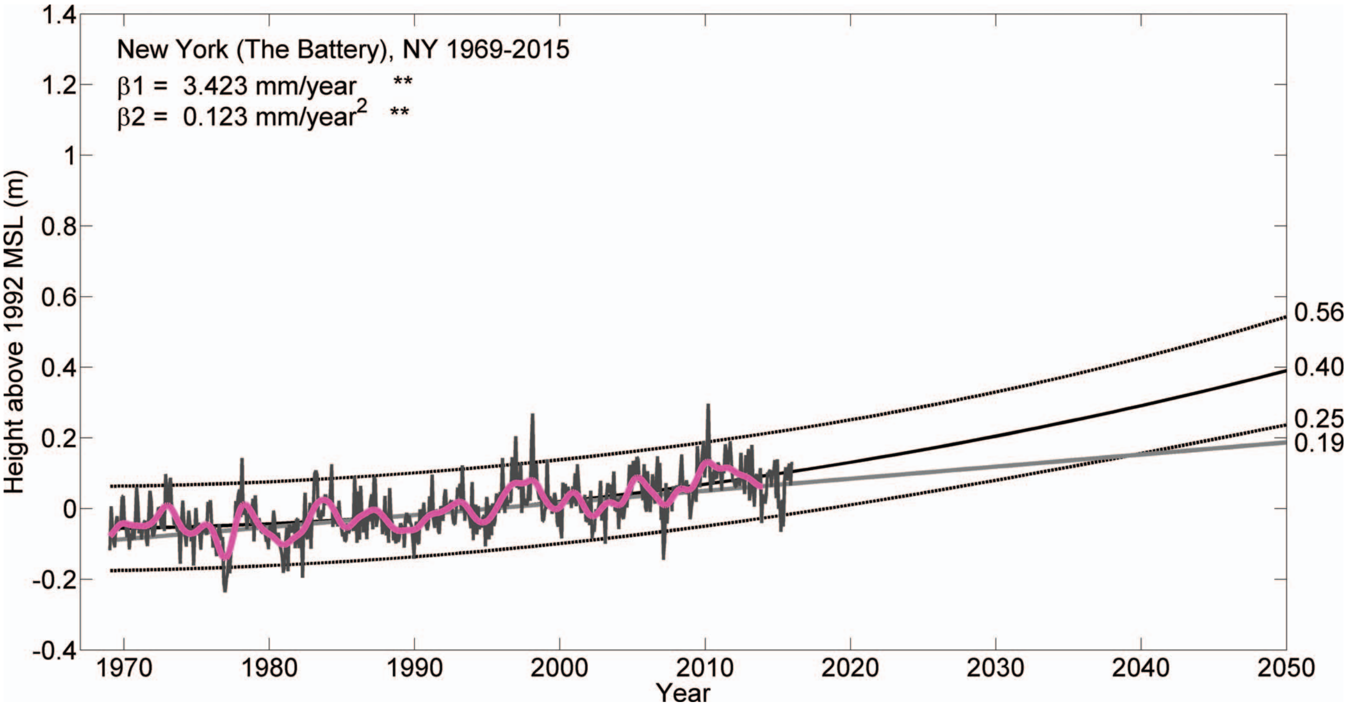

Figure 1. Quadratic regression applied to NOAA 1969–2015 monthly mean sea-level series at The Battery, New York, after removal of the seasonal cycle. Double asterisks (**) indicate derived values of rise (β_1) and acceleration (β_2) are significant at 99% level of confidence. Confidence bands (dotted lines) surrounding the quadratic projection to the year 2050 (solid black line) include approximately 95% of monthly observations. Linear projection to the year 2050 is shown by the solid-gray line with low-pass filtered, decadal signal (magenta) superposed on monthly observations.

year 2050 height percentiles in Boon and Mitchell (2015) as belonging to a 36-year projection (2014–2050), rather than 58 years (1992–2050), as the discussant has done. Monthly mean sea-level data now available for New York (NOAA National Ocean Service, 2016), with seasonal cycle removed by us, illustrate the relationship between our present 47-year (1969–2015) series of observations and the remaining 35-year projection from 2015 to 2050 (Figure 1). Although 0.40 m is projected from the single regression shown in Figure 1, our latest MBB median projection of 0.41 m is 0.06 m less than previously reported for New York (Boon and Mitchell, 2015; Table 1).

We agree that decadal variation (the magenta curve in Figure 1) is responsible for this change. However, rather than corrupting the data and rendering it unusable, the decadal signal we have examined using a third-order Butterworth filter with a 24-month cutoff instead modulates the fitted quadratic. Projections are then seen to vary in a well-defined cyclical pattern, as illustrated in Figure 2 using the New York data. A variation period of about 8 years is evident for the modulated quadratic projection (Figure 2), which is only slightly longer than the zero–up-crossing period of 6–7 years found for the decadal signal (Figure 1). In both figures, the curve representing the quadratic projection is bounded by confidence intervals that include approximately 95% of all monthly observations, the latter representing the expected range of the individual observations, as opposed to the predicted average in any given year (Draper and Smith, 1998). As expected, the confidence intervals in Figure 2 are wide at first but converge toward a fixed interval as the length of the observed time series increases. This interval will extend to 2050 and reminds us that sea-level in a given month, then as now, may be as much as 0.2 m higher or lower than the annual RMSL mean or median. Providing the decadal signal and underlying acceleration persist, a net RMSL rise of about 0.5 m above 1992 levels by 2050 now seems likely, or between two and three times the 0.19-m linear projection at New York, as seen in Figure 2. We find very similar patterns at Boston, Massachusetts; Baltimore, Maryland; and Norfolk, Virginia.

Comparison with USACE/NOAA Sea-Level Projections

Version 2015.46 of the U.S Army Corps of Engineers (USACE, 2016) online Sea-Level Change Curve Calculator provides year 2050 projections starting in 1992 by both USACE and NOAA. Figure 3 compares our 2.5%, 50%, and 97.5% probability percentile projections, given 1969–2014 observations at 45 tide stations, with the highest and lowest of four scenarios developed by NOAA for these stations. The *lowest* scenario is represented by a straight line based on NOAA's published linear rate of sea-level change at NOAA tide stations; the *highest* scenario is represented by a quadratic equation, $E(t) = at + bt^2$, whose quadratic coefficient (one-half acceleration) is a constant ($b = 0.156$ mm/y^2), which, when combined with the 20th century global rate ($a = 1.7$ mm/y), projects a rise of 2.0 m by 2100 (*i.e.* t = 2100–1992 = 108 years). One consequence of applying constant acceleration everywhere is

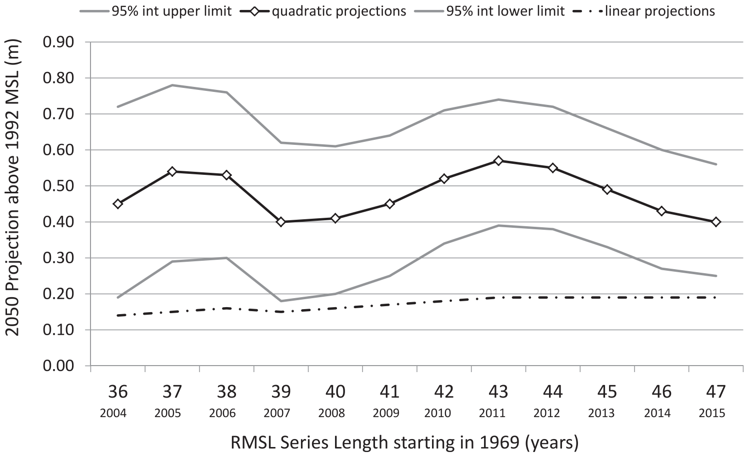

Figure 2. Plot of 2050 projections (m) above 1992 mean sea level (MSL) as a function of series length (years) since 1969 at The Battery, New York. Decadal signal modulation of quadratic projection (the solid line with the diamond markers) is apparent as an ongoing, well-defined cycle with little effect on rising linear projections (dash–dot line). Note 95% confidence bands (gray lines) converge to an expected limit of about ±0.15 m on monthly deviations from the quadratic regression.

that the range interval for NOAA's 2050 high–low projections (the length of the gray bars in Figure 3) is also constant at 0.52–0.53 m throughout. A second consequence results from using NOAA's published linear rates for the coefficient *a*. Because acceleration is assumed constant, station-to-station change in 2050 projection heights (the vertical position of the gray bars in Figure 3) is governed entirely by NOAA's historical sea-level trends. Whether these linear trends are based on records as long as 159 years (The Battery, New York) or a short as 50 years (Nantucket, Massachusetts), the NOAA 2050 high–low projections are very similar across any one region.

Information on *actual* acceleration or deceleration is presently absent in the USACE calculator projections, which is why we believe it is important that we offer the inferences we have made based on the recent RMSL observations available from NOAA's National Ocean Service. This is consistent with USACE policy and post-Katrina guidance requiring that "… all coastal projects be evaluated with respect to changes in sea level throughout the project life-cycle" (USACE *Sea Level Change Curve Calculator User Manual 2015.46*, p. 3). The following is a brief discussion of our principal findings by region.

U.S. Atlantic Stations

Our 2050 projections for the Atlantic stations in Figure 3 clearly show a break in accelerated rise rates decreasing south of Cape Hatteras, North Carolina, as first observed by Sallenger, Doran, and Howd (2012) in confirming recent model predictions based on ocean dynamics (Yin, Schlesinger, and Stouffer, 2009). Specific features of the North Atlantic western-boundary ocean circulation involved have been further described by Ezer (2013), Ezer et al. (2013), and Yin and Goddard (2013), along with additional observations by Boon (2012) and Boon and Mitchell (2015). To be sure, uncertainty exists as to how coastal sea level will respond to open-ocean processes and existing cycles as both evolve with time. Rather than an excuse not to, this is a reason *for*, continuing to analyze new RMSL observations as soon as they become available.

U.S. Gulf Stations

Among 2050 projections for the Gulf stations in Figure 3, most of ours are in good agreement with those by NOAA. However, the probable range [95% highest density interval (HDI)] we show for Galveston (Pier 21), Texas, is clearly lower

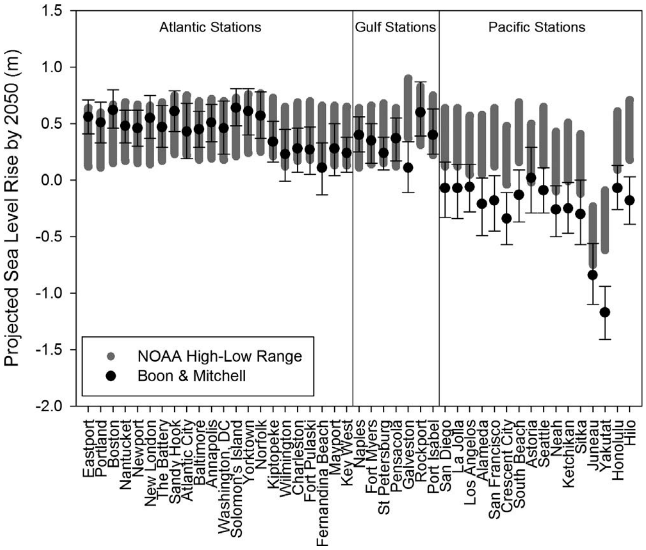

Figure 3. Comparison of year 2050 mean sea-level projections relative to 1992 mean sea level (MSL) by Boon and Mitchell (2015) with NOAA projections at 45 U.S. tide stations. Thin bars represent the 95% highest density interval (95% HDI) as described in Boon and Mitchell (2015) with the black dot indicating median probability density. Thick-gray bars represent NOAA highest and lowest 2050 projections taken from the USACE online Sea-Level Change Curve Calculator, Version 2015.46.

than the high–low scenarios offered by NOAA, the latter being the highest among the 45 U.S. stations included in our analyses. The reason, we believe, is due to a substantial decline in land-subsidence rates following broad replacement of extensive ground-water mining by surface water supplies during the 1970s in the heavily industrialized Houston–Galveston region (Galloway, Jones, and Ingebritsen, 1999). Our analysis underscores the uncertainty associated with future sea-level change at Galveston before a state of equilibrium has definitely returned. In this instance, the full 108-year tide record now available at Galveston is more indicative of past rather than future sea level change.

U.S. Pacific Stations

Here, our 2050 projections in Figure 3 fall well below those by NOAA, even at Juneau and Ketchikan, Alaska, where rapid coastal emergence drives falling RMSL. We state, once again, that our analyses and projections are based on the 1969–2014 period and not on the 1855–2050 straw man the discussant erects at San Francisco, California. Bromirski et al. (2011) noted that both tide-gauge measurements and altimetry since 1983 indicate virtually no increase in sea level along the Pacific coast. These authors attribute the suppression of regional sea-level rise along this coast to a dramatic change in Pacific ocean-wind stress curl after a mid-1970s regime shift, which recent evidence suggests may soon revert to its previous state followed by resumption of the expected normal—accelerated—sea-level rise. That may well be the case, but the presumption here, and implicit in the USACE sea-level curve calculator, is that global sea-level acceleration in any one scenario is ubiquitous and easily downscaled to fit one location, as well as the next, anywhere, after an adjustment for the historical linear trend. We will continue to look at the latest observations.

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