Charleston 2040 – Add 1 Foot to Present Sea Level; At Least!

Like a lot (maybe all) of coastal scientists and researchers out there I am constantly considering how sea level rise (SLR) is going to change the results I am generating in the here and now. Along those lines, I just read an article about how FEMA's maps are going to be off the mark as climate change continues to drive results from the known probabilistic toward the lesser known but continuing long-term trends. The processes driving SLR have been occurring for decades, but they have recently started to accelerate. That means we are not talking about new processes just quicker change.

An unavoidable fact is that today's sea level (the average) is different than 40 or 100 years ago, i.e., there is a trend to deal with. This is not game changer, however, and we still move forward with predictions, planning, and engineering to name a few. We don't need to predict the sea level perfectly – that is not even an option, the variability of the natural world makes certain of it (keep reading).

For example, I am looking to define within about 5 -10 cm (a few inches) what the water levels will be in 2040 for the Charleston, SC area. Many would agree that it depends on what curve you use; I can hear you saying, "go with the lower intermediate". Anyway, picking from about six curves means it is basically rolling the dice and that means getting emotional (I favor the lower intermediate because …), which I am trying to avoid. I want to use the data we have gone through great lengths to collect and verify to define the near future.

I feel like we get wrapped around the axle of uncertainty and variability and are too uncomfortable to move on with conviction based on the data we have and start looking at 'black box' values. Consider mean sea level (MSL) as an example, or in this case MSL, MHHW, MHW, MTL, MLW, MLLW, and the highest monthly level. These different measures of the water surface are semi-independent when analyzed on a daily basis but certainly related when looking at a month. On a daily measure the high and low tide trends are typically contrary – emphasis on typically – with the higher the high, the lower the low (note the negative slope in Figure 1). But if we look at it as a monthly average it is very clear that they are related (note the almost 1.0 slope and high R^2 value; Figure 2).

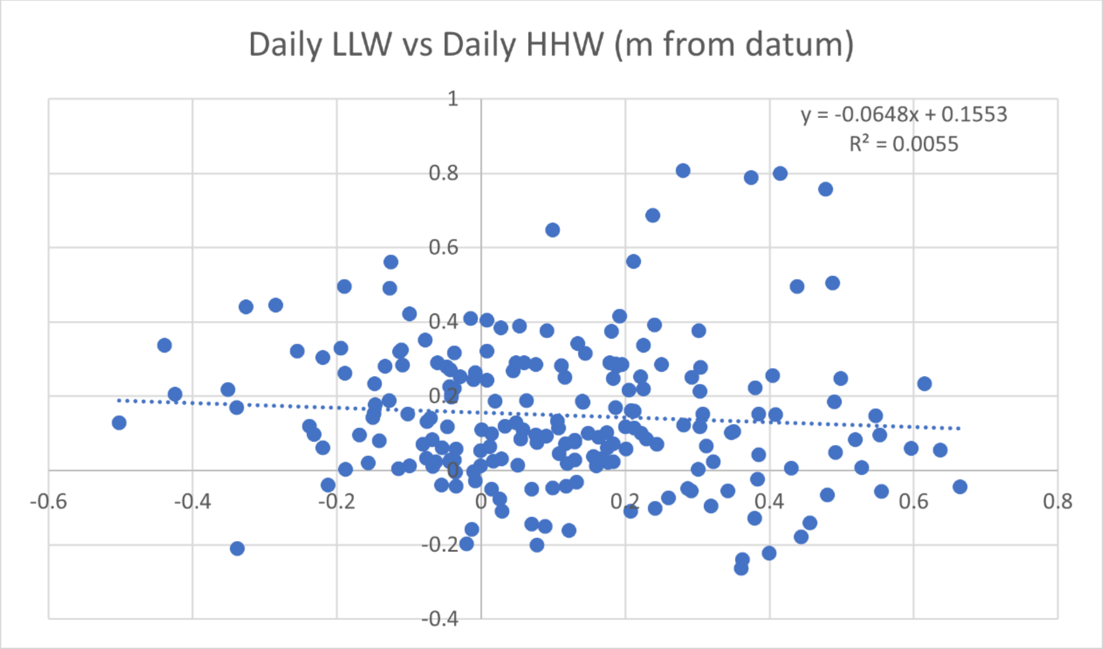

Figure 1. Relationship between daily low low water and high high water; values in meters from present datums.

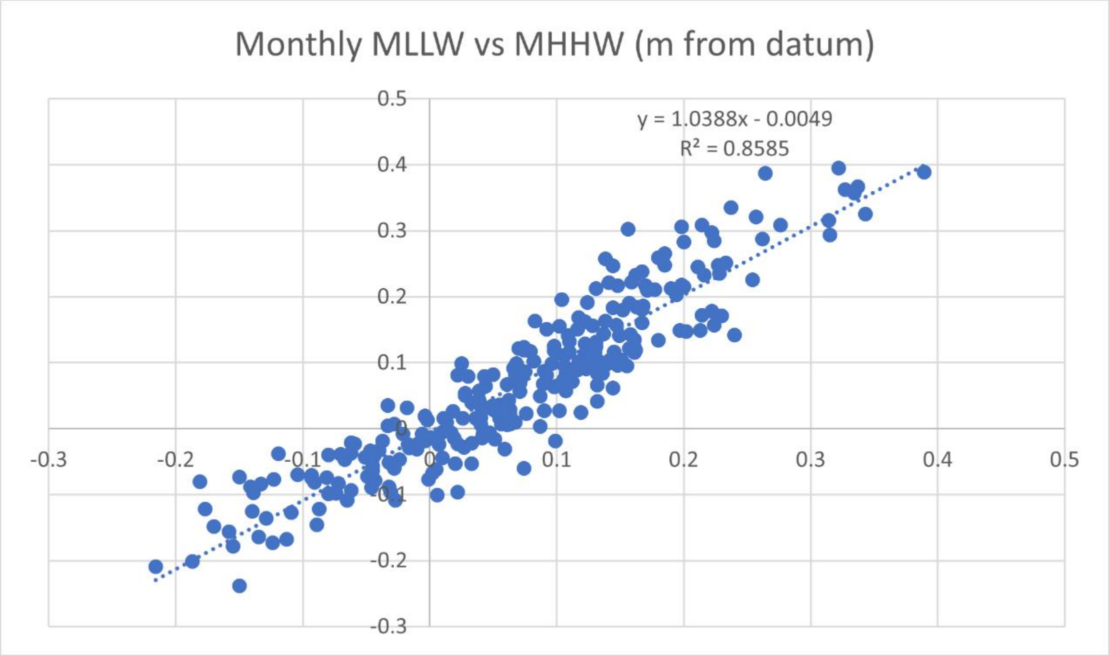

Figure 2. Relationship between monthly average low low water and high high water; values in meters from present datums.

Monthly Trends

So, it if these two apparently contrary or at least non-correlated daily measures have such a strong monthly correlation then maybe we can collectively use MSL, MHHW, MHW, MTL, MLW, and MLLW as separate measures to arrive at a stronger assessment of the local sea level trends. But before we get there, let's look at the variability – which is high on a monthly basis. The graph (Figure 3) of the monthly MHHW over the past 20 years highlights this variability. In the past year or two the average monthly

MHHW has varied by about 1 foot (30 cm)! And we are not talking about the maximum values of the month (which by the way varied by about the same amount). So that makes a perfect prediction on a monthly level next to impossible when we are talking about trying to discern 5mm to 1 cm changes a year. Yet we commonly see that monthly data is used to make assess the linear changes on a yearly basis.

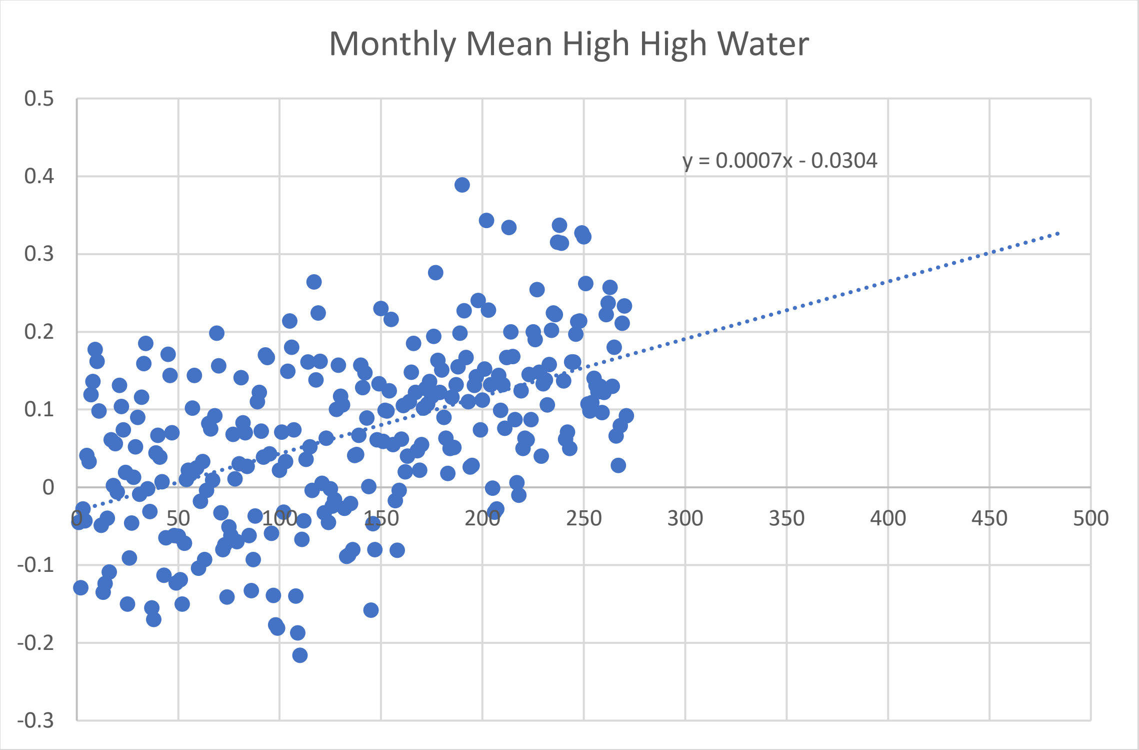

Figure 3. Monthly Mean Higher High water. Vertical values in meters from present datum; horizontal value in months since January 1, 2000

To make it more inclusive the average linear trends for the sea level indices (MSL, MTL, MHHW, etc.) between 2000 and present all converge around 0.70 mm/month (Table). Yeah, that is getting close to a 1 cm a year and is from the linear trend, which is a low estimator (a bit more about that later). Anyway, the standard deviation of the indices averages around 120 mm/month – they are all pretty consistent and are within about 5 mm/month. So, that is like 15 years of trend to get past normal variability (68% of values within 1 standard deviation) of month-to-month averages.

Table 1. Velocity of sea level rise as measured by six different datums and the variability of raw monthly values.

	MHHW	MHW	MSL	MTL	MLW	MLLW	Average
Slope (mm/month)	0.737	0.77	0.73	0.69	0.62	0.63	0.70
Slope for last 10 years (mm/month)	0.89	0.67	0.88	0.87	1.08	1.10	0.91
Standard Deviation (mm)	113	117	121	118	122	126	119

I feel like I am getting closer to my answer but know that linear trends are not going to capture the future as we move towards 2040 (what SLR prediction have you seen that is a straight line recently). Still, I am confident that 1 cm of year is probably a good lower estimate (18 cm or 6 inches by 2040 at least) since the last 10 years trend is higher (now past 1 cm/yr) and it works out to about 1 ft higher than the datum (month 480; 33 cm). What would happen if I used the mostly accepted representation of SLR as a polynomial trend. It would be closer to 2 feet higher than the present datum (Figure 4). This is a lot of difference, and it is from the same data.

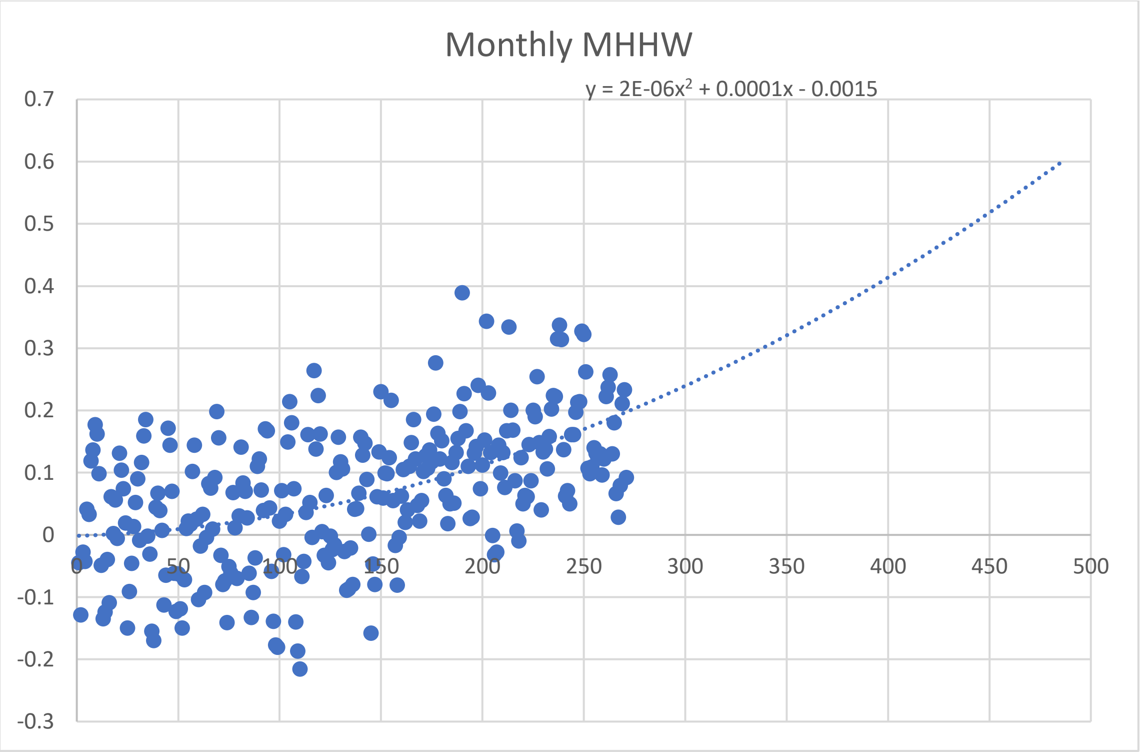

Figure 4. Same data as in Figure 3 but using a polynomial trend to extrapolate to 2040 (Month 480).

Yearly Trends

So, I am comfortable with a range of SLR by 2040 between 1 and 2 feet from the present datum – these are considerable either way. My goal, however, is to get a cleaner data set and/or make some sense of the variability to narrow in on a defensible value. Averages and random samples (bootstrapping) are some ways to clean the data and get a better handle on variability ranges. Since we are talking about years (e.g., what is the increase in SL by 2040) looking at the yearly average based on all the datums (i.e., difference from MHHW, MHW, MSL, MTL, MLW, MLLW) is where I start. I understand that there will be month to month variability; that is a constant and should not change with future climates. It would not be out of the question for one month to have an average 15 to 20 cm higher than the next.

The yearly average is based on the monthly averages of 6 datums, this comes down to 72 values per year to define the yearly average – not just MSL. Since we are talking years, I have gone back to 1990 to increase the data set. This does influence the linear trend moving forward with higher slopes in the later years, which highlights the problems with a linear trend (Figure 5). The polynomial representation has issues as well. It was a surprise to see that the trend (polynomial) was higher for middle range than for the recent – but then I do remember some noticeable high tides back around 2009-2012. If I set the "0.0" point as 1992 (the middle of the present datum) when theoretically the sea level was 0 then the trends become closer (Figure 6), and the extrapolated values extend beyond 2 feet by 2040. Another issue with the polynomial representation is that it cannot predict past values before 1992 – for example the sea level is hindcasted to be above 2000 values in 1980.

Figure 5. Unconstrained trends from 1990 to 2021. The upper graph are the linear trends, the lower graph the polynomial trends.

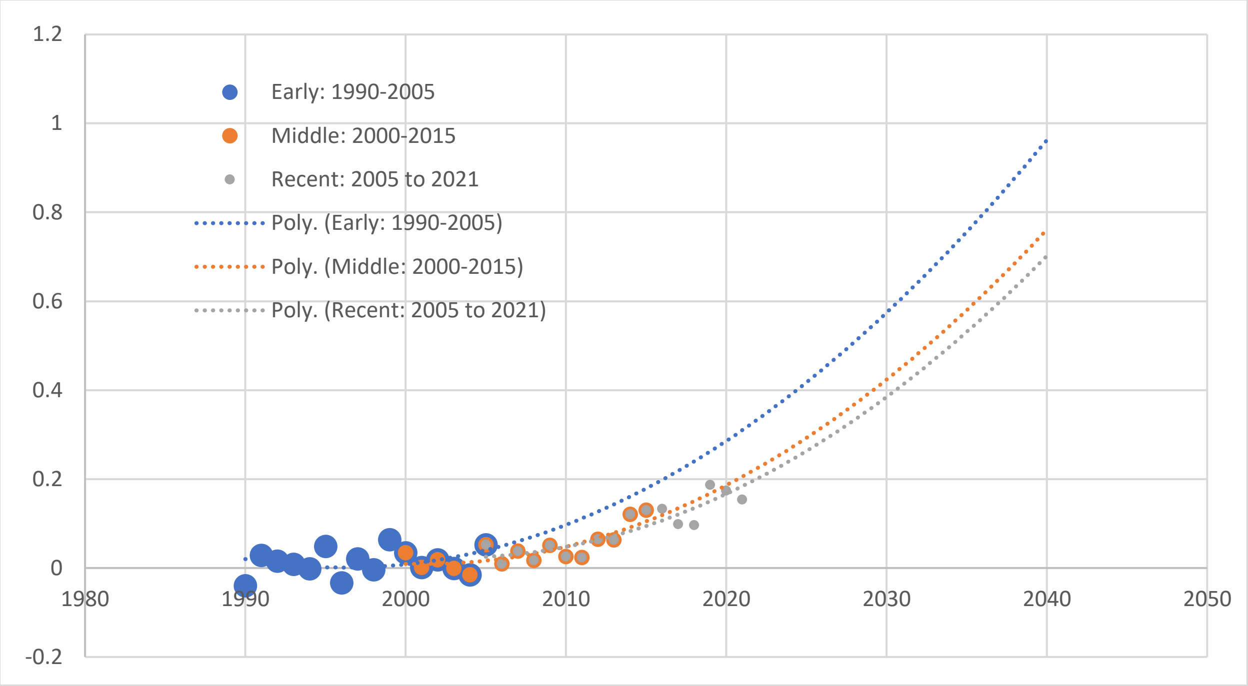

Figure 6. Polynomial representation with a fixed zero sea level at 1992 levels.

Monte Carlo Simulations

Another way to look at this is with Monte Carlo simulations which basically consists of lots of random selections from the overall population and uses them as unique solutions. I took the different solutions (48 for the yearly and 160 for the monthly) from random samples of 25% of the monthly values and 67% of the yearly data to generate trends – both linear and polynomial – and generate statistics of them. I did not get too wound up by the correct statistical number of random samples and Monte Carlo simulations, but I am really looking at some pretty simple statistics so it should not matter much.

Table 2. Predictions from bootstrapping and mathematical trends for sea level deviation from the present datums in meters

Year	Monthly Average Polynomial		Monthly Average Linear		Yearly Average Polynomial		Yearly Average Linear		Best Estimate (Monthly Hybrid)	
	Ave	Std Dev	Ave	Std Dev	Ave	Std Dev	Ave	Std Dev	Ave	Std Dev
2021	0.170	0.026	0.130	0.019	0.160	0.019	0.125	0.017	0.15	0.02
2030	0.322	0.062	0.179	0.030	0.293	0.049	0.175	0.017	0.25	0.04
2040	0.525	0.146	0.230	0.041	0.492	0.097	0.225	0.029	0.39	0.08
2050	0.879	0.272	0.293	0.051	0.680	0.158	0.277	0.037	0.58	0.13

I am interested in 2040 but wanted to look at a couple time frames to get a feel for the trends. If I go with a polynomial solution, it is about 0.5 m (1.5 feet) between the present datums and 2040; while the linear solution is about 0.25 m (0.75 feet). That is obviously low since we are almost at that value at this point (0.15 m) and the linear rate at present is near 1 cm/yr (this would be about 35 cm at 2040). As a result, I have generated a Best Estimate that is an average of the polynomial and linear equations (not the resulting values) that were generated using the Monte Carlo simulations. This Best Estimate technique/equation also allows for the ability to hindcast values (which neither linear nor polynomial trends could do), although it is not that important it does add some confidence to the technique.

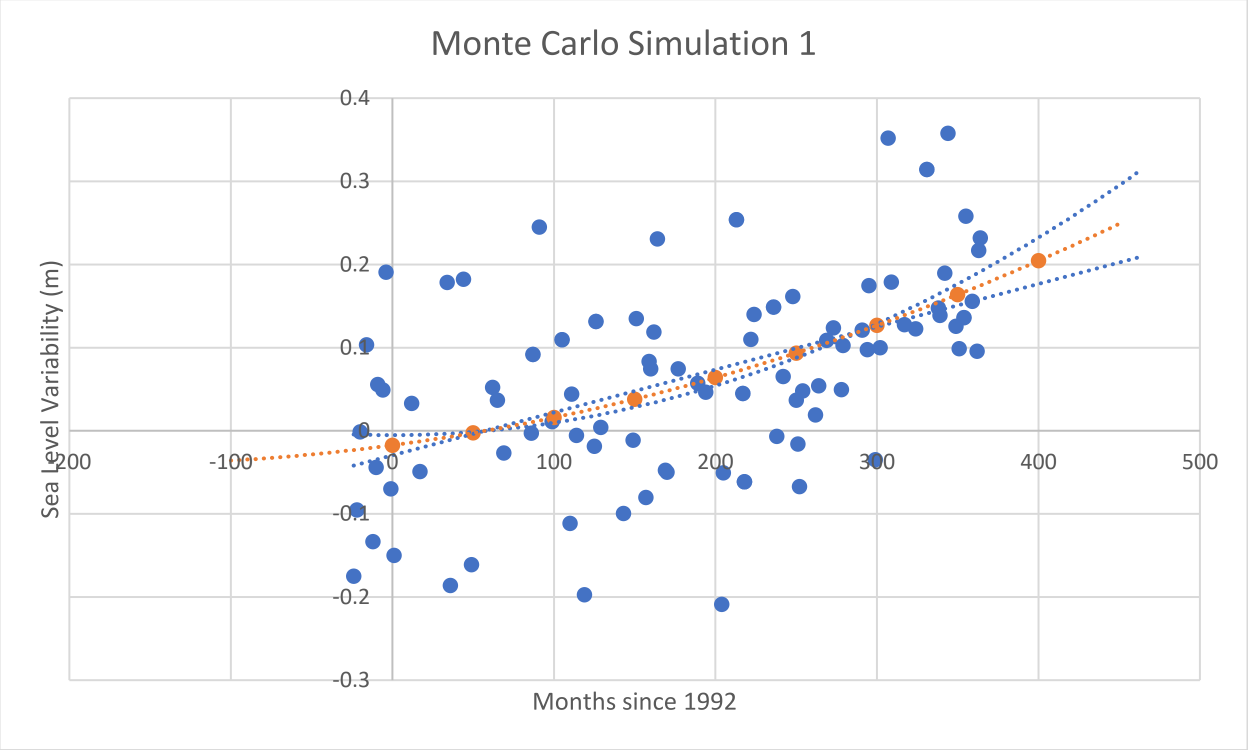

Figure 7. Example of 1 of 160 random selections with the polynomial, linear, and hybrid (orange) solutions.

Results

In the end I am comfortable using the Best Estimate which is the outcome of 160 solutions using the monthly average of MHHW, MHW, MSL, MTL, MLW, and MLLW (i.e., each point is the average of 6 monthly averages). Based on the data, in 2040 it is as likely as not that the sea level will be about 0.4 m above the present datum, but it is also possible – about 15% chance – that it is 0.5 m above the current datums (Average plus 1 standard deviation). Since I am using this information for planning purposes I would build in some safety margin, especially since the monthly variability is on the order of twice the standard deviation of the sea level estimate. That puts the sea level at 1.25 to 1.5 feet above the present datums in 2040, which is about the Intermediate-High rate from NOAA.

As for yearly increases in sea level – a major issue for marsh health – the yearly increase in sea level based on the best estimate from local data is presently at 1.0 cm/yr and by 2040 it will be at least 1.5 cm/yr. Somewhere between 1 and 1.5 cm/year is when marshes in South Carolina can no longer keep up (around 1.3 cm; from Morris et al.). So around 2030-35 is the tipping point for marshes.