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Relative Sea Level Rise in the Winyah Bay-Waccamaw River Tidal System Over the Last Thirteen Years

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Abstract. Prediction of sea level rise (SLR) in response to climate change has been the focus of worldwide research, most focusing on the impact by human development. The research has been limited to estuaries and tidal rivers near harbors dealing with the hydrodynamics of reversing tidal flows. This article focuses on the Waccamaw River National Wildlife Refuge in coastal South Carolina where freshwater unidirectional flow is common. We examined the record of water levels in the Waccamaw and Pee Dee Rivers over the period 2007–2019 and the length of record of the United States Geographical Survey (USGS) gauge at Pawleys Island on the Waccamaw River. The Atlantic Ocean, off the southeastern coast of the US, has experienced accelerated SLR since 2000. National Oceanic and Atmosphere Administration (NOAA) tide gauges from Fort Pulaski on Cockspur Island in Georgia to Beaufort, North Carolina, show significant increase in long-term SLR since then with an average since 2007 of approximately 10 mm y^{-1}. Since the study period was less than the 18.6-year cycle of lunar precession, tidal ranges were expanding for much of the study period resulting in the rate of rise of Mean Higher High Water (MHHW; the average of the highest tide levels during each day) being greater than the rate of increase of Mean Lower Low Water (MLLW; the average of the lowest tide levels during each day) in all ocean stations. We examined water levels at NOAA and USGS gauges from Oyster Creek, in North Inlet to Conway on the Waccamaw River and Near Bucksport on the Pee Dee River. We found mean water levels increased more rapidly with distance from the ocean with an apparent SLR > 40 mm y^{-1} at Conway on the Waccamaw and Bucksport on the Pee Dee. In contrast to the ocean NOAA gauges, the estuary/river gauges showed more rapid increase of daily minimum water level (an approximation of MLLW) than daily maximum water level (an approximation of MHHW) with an extreme of apparent rise of minimum water levels of 58 mm y^{-1} at Bucksport on the Pee Dee. Nearly 50% of the increase in apparent SLR was due to an increase in the annual average freshwater flow of the Pee Dee and Waccamaw Rivers. Over the past 13 years the Waccamaw National Wildlife Refuge has experienced an apparent SLR that was more than double that observed at the edge of the ocean. The rise has been greater in the height of daily low water than in the height of daily high water. The increase was driven by both tidal hydrodynamics and an increase in the rate of flow in the Pee Dee and Waccamaw Rivers. These findings have important implications for land managers, policymakers, and homeowners in the region as people in the middle to upper estuaries need to plan for rates of relative SLR rise much greater than the frequently discussed rates in the ocean.

INTRODUCTION

In 2019, we received a simple inquiry from the Waccamaw National Wildlife Refuge: "How will sea level rise (SLR) impact the refuge?" To answer that question we obtained water level records from the USGS gauge 021108125 Waccamaw River Near Pawleys Island, South Carolina, which is located adjacent to the refuge boundary, and did a simple trend analysis of the data. The results of that analysis indicated a rise in average water level near 1 inch (25 mm) per year. Although such rapid rise seemed unreasonable, it would have great impact on the hydrology and ecological functioning of the refuge and wetlands associated with the Winyah Bay estuary/tidal river system (Foti et al. 2012) Winyah Bay is one of the major estuaries on the South Carolina coast. Mechanisms leading to accelerated increase in water levels there could also occur in other estuaries along the coast.

BACKGROUND AND RELATED WORK

Although harbor water depths have been measured around the world for hundreds of years, in the US those measures were developed into tidal predictions in 1924 (Schureman 1958) and combined into a national sea level datum. That sea level datum became the National Geodetic Vertical Datum of 1929 (NGVD29) and was extended by profile leveling across the US. It was the datum of all USGS topographic maps for most of the twentieth century. The common term of “feet above sea level” on those maps referred to the NGVD29 datum.

The term “above mean sea level” was correct only for a period after 1929, since mean sea level is a tidal datum that is updated approximately once every 25 years to fit the latest 19-year tidal epoch (Parker 2007). Due to lunar precession, the astronomical forcing of tides has a period of 18.6 years. Therefore, a precise estimate of tidal mean, variance, and range cannot be made with less than 19 years of continuous data (Parker 2007). However, prior to the era of satellite observations, imprecision in estimates of sea level due to tidal variation was less than the imprecision caused by data from only a limited number of coastal stations that related to national datums of several countries. For example, tide level in New York could not be related to tide level in London or Shanghai as there was no common point of reference.

By 1993, satellite altimetry allowed accurate land elevations and a global average sea level to be measured (Albain et al. 2017) and a great deal of American geodesy changed. Horizontal position is now generally determined in the North American Datum of 1983 (NAD83). Vertical position is now generally given as North American Vertical Datum of 1988 (NAVD88). Both are now permanent position and elevation-related points that can be surveyed across the nation. They can also be related to satellite orbits used by GPS receivers. The position of any place on Earth can be determined precisely by qualified surveyors with the proper quality GPS instruments. During the period 1993–2009 Church and White (2011) reported average global SLR as 3.2 ± 0.04 mm y-1 based on satellite positioning compared to an average of 2.8 ± 0.8 mm y-1 based on tide gauges referring to various national datums.

Craft et al. (2009) were among the first to predict estuary and adjacent wetland inundation based on the latest estimate of SLR. They used 3 arc second topographic data and National Wetlands Inventory maps to predict inundation based on 32 centimeters of SLR in the next 100 years (3.2 mm y-1). Their analysis was limited by the resolution of the topographic data and did not consider tidal fluctuations. As LiDAR derived elevation data became available, the inundation caused by SLR could include tidal fluctuation into the prediction. Sweet et al. (2018) predicted impacts of SLR on periodic flooding by adding SLR onto the predicted MHHW for North American sites with relative SLR determined from long-term tide records.

Charleston, South Carolina, was among the sites Sweet et al. (2018) analyzed for tidal flooding. Morris and Renken (2020) revised those estimates to include the linear SLR trend like Sweet et al. (2018) and an acceleration factor, based on changes in the trend over the last 100 years. They then applied tidal harmonics to the predicted tide levels and compared them to LiDAR Digital Elevation Model of the Charleston peninsula to predict number of days of flooding at various locations through 2068. Morris and Renken (2020) used a long-term acceleration estimate but Vaale-Leveinson et al. (2017) found that the southeastern US has been experiencing much larger short-term apparent sea level rise with rates well over 10 mm y-1. They related these decade-length accelerations to changes in ocean circulation in the Atlantic (North Atlantic Oscillation) and found timing was influenced by ENSO (El Nino Southern Oscillation).

The prediction of tidal flooding for Charleston is one of many site-specific predictions made in the last decade (Talke et al. 2020). However, there are few that have attempted to propose generalized predictions (Talke and Jay 2020). Most attempts to generalize predictions rely on analytic or numerical solutions to tidal motions in idealized estuaries (Khojasteh et al. 2021). These studies generally indicate sea level rise will increase tidal ranges in estuaries with strong convergence (flow cross-sectional area decreases rapidly with upstream distance) and significant tidal reflection. Those studies do not generally include tidal river processes, as the tidal propagation equations are less valid when tidal flow is not significantly greater than river flow (Kukulka and Jay 2003).

WINYAH BAY-PEE DEE BASIN ESTUARY AND RIVER SYSTEM

The Waccamaw National Wildlife Refuge is located upstream of the Winyah Bay estuary in the tidally influenced sections of the Waccamaw and Pee Dee Rivers (Figure 1). Winyah Bay and a portion of the Waccamaw River are within the Intracoastal Waterway system and multiple tidal predictions over the entire length of that system are available at the NOAA website (NOAA “Water levels-Station selection”). Those predictions came from a series of temporary and permanent tide gauges that monitored levels in the coastal ocean and within the bay and rivers, producing data on tidal range in relation to the latest tidal epoch from 1983–2001 (Figure 1). These data indicate that the Winyah Bay estuary tidal river system is a strongly attenuating system, meaning the tidal range decreases from the ocean to the head of the tide. In the Winyah Bay system the tidal range declines by an average decrease of –2.8 mm km-1 in MHHW and an increase of 9.9 mm km-1 in MLLW, for a total decline of range of 12.7 mm km-1 (Figure 2). Likewise, the tidal wave becomes more asymmetrical with distance from the ocean as

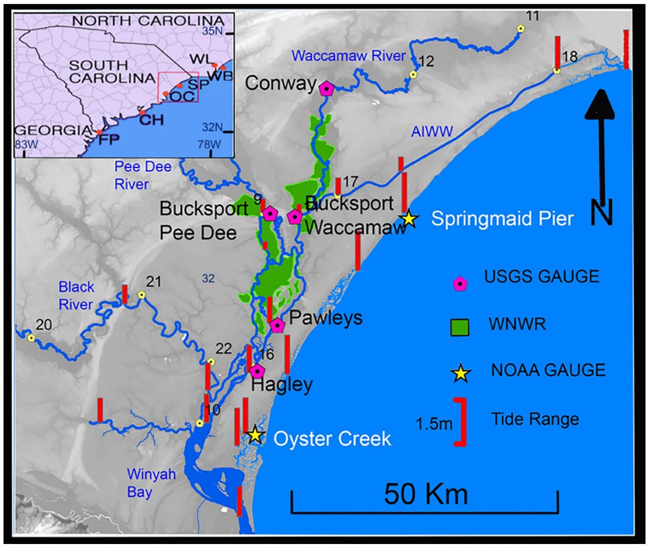

Figure 1. Winyah Bay estuary/tidal river system with location of USGS gauges, tidal ranges based on NOAA 1983–2001 tidal datums, and an outline of the Waccamaw National Wildlife Refuge (WNWF). Locations of sites used for evaluation of SLR along the coast are included in location map in upper left by codes: FP is Fort Pulaski, Georgia; CH is Charleston, South Carolina; OC is Oyster Creek, South Carolina; SP is Springmaid Pier, South Carolina; WL is Wilmington, North Carolina; WB is Wrightsville Beach, North Carolina.

high tide is delayed less than low tide, with an apparent speed of 13.6 km h-1 for high tide and only 11.3 km h-1 for low tide (Figure 3). For example, 60 kilometers from the ocean's high tide arrives four hours and nine minutes after high tide in the ocean while low tide arrives five hours and twelve minutes after low tide in the ocean. A single tide record from September 10, 2019, demonstrates the decrease in tidal range, the attenuation in time, and the distortion of the tidal wave at Bucksport on the Waccamaw, which is 64 kilometers from the ocean (Figure 4). Based on the analysis of Talke et al. (2020), Khojasteh et al. (2021), and the NOAA data for 1983–2001, Winyah Bay is not the type of estuary where SLR should cause rapid changes to tidal ranges.

PROJECT OBJECTIVES/GOAL

It has been over 20 years since data was collected for NOAA tidal estimates. Local sea levels have been rising at an accelerated rate (Valle-Levinson et al. 2017; Morris and Renkin 2020) during the last two decades. Since at least 2007, several NOAA and USGS stations in and near the Winyah Bay tidal river system have records indicating sea level rise. From those records we have attempted to test the hypothesis that apparent sea level rise in the Waccamaw National Wildlife Refuge was the same as apparent sea level rise measured in nearby coastal NOAA tide gauges for the period of 2007–2019.

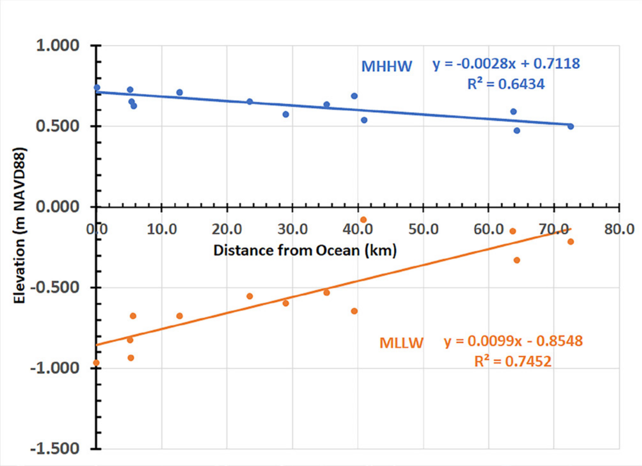

Figure 2. Reduction in tidal range with distance from the ocean within the Winyah Bay estuary tidal river system. Tidal datums for 1983–2001 were obtained from the NOAA Tides and Currents at points depicted in Figure 1. Distance was calculated along river centerlines obtained from SCDNR.

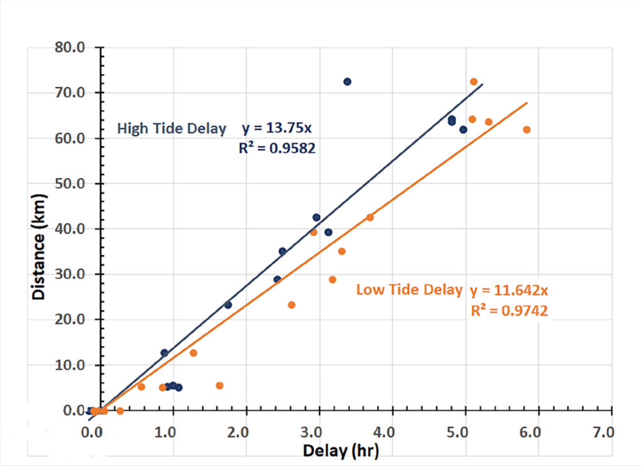

Figure 3. Estimation of the speed of the tidal wave as it moves inland from the ocean. Data are at locations as shown in Figures 1 and 2.

MATERIALS AND METHODS

All data used in this article were obtained from websites at USGS (USGS "Current Water Data") and NOAA (NOAA "Water levels-Station selection"). Tide data were obtained for gauges listed in Table 1 from the NOAA website. For each gauge, hourly data were collected for each year of available data listed in Table 1. River water levels (daily maximum, mean, and minimum) were obtained for USGS gauges listed in Table 1.

All retrieved data were converted into Microsoft Excel spreadsheets for each station. Daily mean, maximum, and minimum values were calculated from the tidal hourly

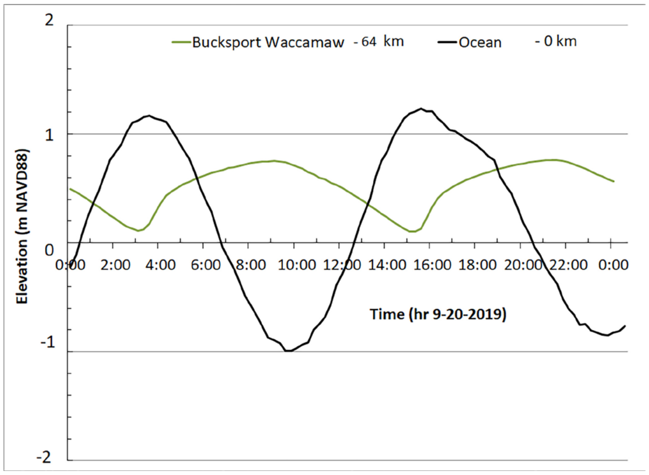

Figure 4. Example tidal attenuation on the Waccamaw River near the town of Bucksport, South Carolina, 64 kilometers from the ocean. Tidal wave is distorted by more rapid travel of high tide than low tide as demonstrated in Figure 3.

NOAA data. Annual average daily mean, maximum, and minimum values were then calculated at each site for each year from 2007–2019. USGS data are available as daily mean, maximum, and minimum elevations. All USGS data were converted to NAVD 88 using factors listed in Williams et al. (2020) except Bucksport Pee Dee station, which has an updated NAVD 88 datum of 8.85 feet (2.7036 m). The new published datum was used for all data from this site. Since all USGS data were in English units and the NOAA website allowed optional units, daily averages of all tidal data were also obtained in English units referenced to the NAVD88 datum. Once average annual values were calculated, all data were converted from feet to meters.

Linear regression of monthly mean values is the common method to estimate SLR (Sweet et al. 2018). However, the published harmonic constituents from Springmaid Pier (https://tidesandcurrents.noaa.gov/harcon.html?id=8661070) showed the amplitude of the solar semi-annual and solar annual constituents to be 7% and 11% of the dominant semi-diurnal lunar constituent (M2). That suggested we could reduce the variability of the average level by at least 18% by using annual means instead of monthly values. The rate of water surface rise at each station was estimated by linear regression of the average annual elevation with number years since 2006 to make all values positive and minimize the value of the intercept. The slope value "b" of the regression ($y = a + bx$) was used as a least squares estimate of the annual increase of water level. That value was then converted into the commonly used units of mm y-1. Significance of the regression was determined using the "r" statistic. Significance of differences in the rate of rise (slope "b") among sites and between maximum and minimum rates at a site were calculated using a "Student's T" statistic. The appropriate sums of squares values to compute the T statistic and the probability of exceedance (Steele and Torrie 1960) were calculated using Excel functions.

For each regression an analysis of residuals was conducted (Steele and Torrie 1960) using Excel functions. Distribution of residuals were then compared to annual averages of average daily discharge for the Waccamaw River at Conway and Pee Dee River at Bucksport Pee Dee. These residual errors were then regressed with the annual average rate of flow for each Waccamaw and Pee Dee individually. The r2 of these regressions was reviewed to examine the amount of residual error that could be attributed to change in annual daily average flow of each river.

Table 1. Sources of data used in this study.

	ID Number	Title	Years Included	Short Title
NOAA Gauges	8670870	Fort Pulaski, GA	1977–2019	Ft. Pulaski
	8665530	Charleston, Cooper River Entrance, SC	1974–2019	Charleston
	8662245	Oyster Landing (N Inlet Estuary), SC[1]	2005–2019	Oyster Creek
	8661070	Springmaid Pier, SC	1977–2019	Springmaid Pier
	8658120	Wilmington, NC	1977–2019	Wilmington
	8658163	Wrightsville Beach, NC	2004–2019	Wrightsville Beach
USGS Gauges	02110815	Waccamaw R Nr Hagley Land. Nr Pawleys Island, SC	1999–2019	Hagley
	021108125	Waccamaw River Near Pawleys Island, SC	2007–2019	Pawleys
	02110802	Waccamaw River at Bucksport, SC	2006–2019	Bucksport Waccamaw
	02110704	Waccamaw River at Conway Marina at Conway, SC	2002–2019	Conway
	02135200	Pee Dee River at Hwy 701 Nr Bucksport, SC	2002–2019	Bucksport Pee Dee

[1] As of June 15, 2020, the Oyster Creek ID 8662245 is no longer listed an active.

NOAA gauges available at https://tidesandcurrents.noaa.gov/inventory.html?id=(id number).

USGS gauges available at https://waterdata.usgs.gov/sc/nwis/current/?type=flow&group_key=basin_cd; main page with paths to individual stations by ID number

RESULTS

An inspection of tidal constituents for Springmaid pier, as well as all the other sites in the NOAA active and inactive stations, showed only Sa (solar annual) and SSa (solar semi-annual) constituents had periods greater than 30 hours. Therefore, an annual average value contains all possible values for each tidal constituent and multiple replications of the common diurnal and semi-diurnal constituents. Evaluation of the Charleston and Oyster Creek data reveals the power and limitation of the technique to detect a linear increase in water level (Figure 5). The rate of annual average water level rise was between 8.8 and 12.9 mmy-1, which is significantly greater than 0. However, the difference between the two sites is not significantly different. Although high water has been rising faster than low water at both sites (12.9 vs. 8.8 mm y-1 at Charleston and 12.5 vs. 10.1 mm y-1 at Oyster Creek) these differences are also not significant.

We evaluated the rate of rise of the daily low water level, high water level, and daily mean water level at five ocean sites to assess the rate of SLR during the 13-year period (Figure 6). The rate of rise of mean water level was between 9.0 and 15.8 mm yr-1. All rates of rise, but the daily minimum at Fort Pulaski, were significant at α = 0.05. There were no significant differences between stations. There was a clear trend of the maximum level rising faster than the minimum level. However, only at Fort Pulaski was the rate of rise of the maximum significantly greater than the rate of rise of the minimum. The rate of rise of the mean daily level was generally between the maximum and minimum, but not necessarily halfway, and at Wilmington the rise of the mean exceeded that of the maximum. Data from Wilmington, North Carolina, and Springmaid Pier, South Carolina, may be less reliable. Wilmington has been subject to tidal changes due to deepening of the navigation channel (Familkhalili and Talke 2016). Hurricane Matthew damaged the gauge at Springmaid Pier, and only annual averages for 11 years could be used.

Water level rise within the tidal river systems was the main focus of this study. In the river analysis the readings at Oyster Creek were used as an analog of the ocean since it was similar to Charleston (Figure 5) and the rise of the mean daily level, 12.5 mm y-1, was very close to the average of all five ocean stations, 11.8 mm y-1. Our analysis provided clear indication that water levels in the tidal river section of the system have risen significantly faster than water level in the ocean (Figure 7). For all stations, Hagley and upstream, the rate of rise for the daily minimum was faster than the rate of the daily maximum. That difference was significant at α = 0.05 at Pawleys and at α = 0.01 at Bucksport Waccamaw. Data from Bucksport Pee Dee was not significant due to the missing data at that site. The rate of rise at Bucksport Pee Dee was nearly identical to Conway. Slopes of maximum, minimum, and mean were significantly uniform with β = .05 (note the β error is associated with the probability two means are seen a similar but are actually different, essentially the inverse of the α error; Steele and Torrie 1960). However, poor power of the test resulted in nonsignificant differences at Bucksport Pee Dee. Because two years of data were missing at Bucksport Pee Dee, comparison of regression slopes with this site had only 18 degrees of freedom instead of 22 like the other comparisons.

DISCUSSION

These results are astounding and lead to questions of accuracy and the source of the extreme increase in water levels detected in the tidal Pee Dee and Waccamaw Rivers. Morris and Reinken (2020) established the rate of sea level rise acceleration at Charleston, South Carolina, by comparing a quadratic regression of monthly mean NOAA data for the last 100 years. They found the average rate over the twentieth century at 2.5 mm y-1 with an acceleration factor of 0.13 mm y-2. We analyzed 44 years of hourly data (1975–2019),

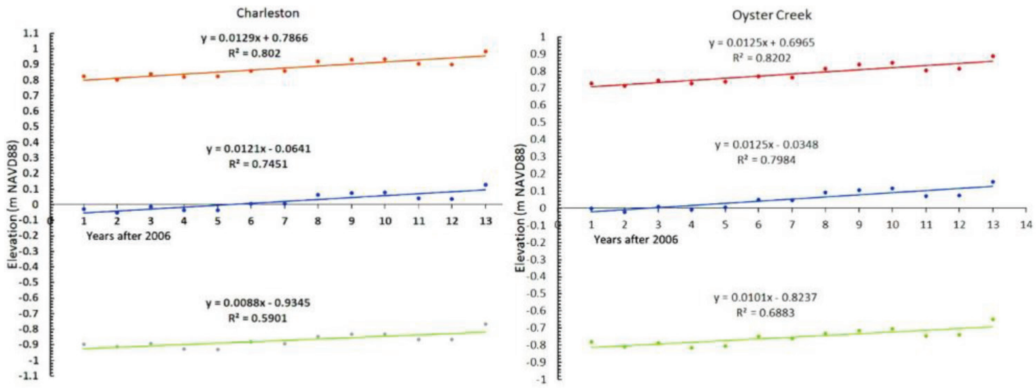

Figure 5. Comparisons of annual averaged daily water levels (maximum: orange; mean: blue; minimum: green) over the period from 2007–2019 and linear regression of elevation versus year since 2006. Note all slopes are significantly different from 0 but not from each other.

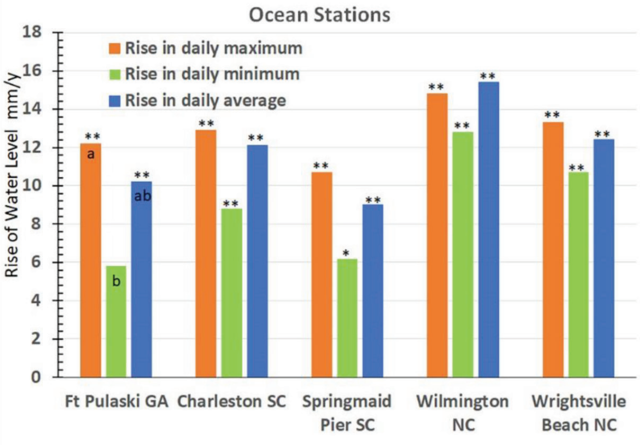

Figure 6. Estimations of the average rise of water levels along the southeastern coast between 2007 and 2019. *Indicates regression significant at α = 0.05 and ** indicates regression significant at α = 0.01. The small letters on the Fort Pulaski bars indicates the rise in maximum water level was significantly greater than the rise of the minimum water level.

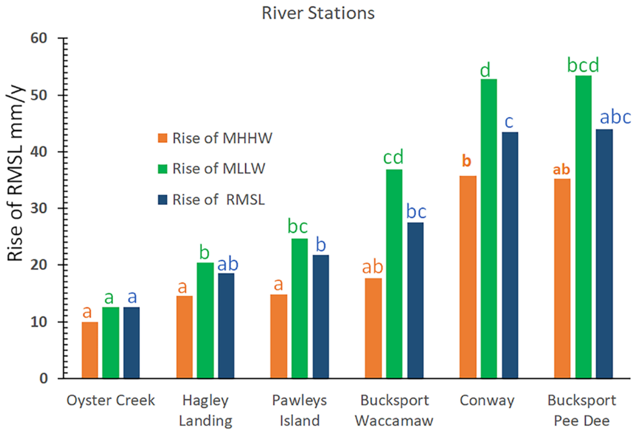

Figure 7. Estimations of the average rise of tidal river water levels between 2007 and 2019. All regression estimates are significant at α = .01, except those of Bucksport Pee Dee that are significant at α = .05. Small letters above bars differ for values that are significantly different α = .05. Note that comparisons are made only in the same series, that is maximums are compared only to maximums and so forth. Maximum was significantly different from minimum at Pawleys α = .05 and Bucksport Waccamaw α = .01.

using annual averages, as in this article. We found a quadratic regression of that data to have a mean rate of 2.5 mm y-1 and an acceleration rate of 0.20 mm y-2. We essentially reproduced their estimates with the analysis techniques used in this article.

We also examined the 18.6 lunar modal cycle by calculating annual average tidal ranges from monthly NOAA data since 1975. The 18.6-year cycle was very evident in this data (Figure 8). That data shows the current tidal epoch (1983–2001) closely corresponds to a single nodal cycle at Charleston. Our analysis period (2007–2019) included more years with an expanding range than declining. The tidal range increased 5.5 centimeters and the great tidal range increased 5.6 centimeters during the 13 years of analysis for an average rate of 4.3 mm y-1. Our analysis showed the rate of rise of daily maximum was 12.1 mm y-1 while rate of rise of the daily minimum at Charleston was 8.8 mm y-1 to produce an increase of tidal range of 3.3 mm y-1. Since we could closely repeat other methods of analysis for data at Charleston, we have no reason to believe the results are erroneous. That leaves the question, “What possible mechanism could be responsible for the minimum daily low water to rise 25.9 mm y-1 at Pawleys and 52.8 mm y-1at Conway?”

The tidal river estuary system is bounded by the ocean inlet at the downstream end, where water flows into and out of the estuary with the rise and fall of the tide. At the upstream end of the system there is a continuous flow of water downstream in the upland river. As the tidal wave approaches from the ocean, water at the inlet rises and ocean water follows into the estuary and mixes with the water there. As the tidal wave moves up the estuary, flow reverses and incoming water mixes with increasingly fresh water. A classic definition of the estuary stretches from the ocean to the point where the mixture has a salinity of one part per thousand. The tidal freshwater river begins at this point (Hoitlink and Jay 2016). Throughout the length of the estuary, the energy of the tidal wave decreases. The size of the tidal wave at the upper end of the estuary depends on the energy of the incoming wave, which is proportional to the product of tide height and inlet cross sectional area, bottom friction and turbulence, and the cross-sectional area of the lower end of the tidal river. In Winyah Bay, the upper estuary boundary is generally considered to be near the confluence of the Waccamaw and Black/Pee Dee Rivers at Georgetown, South Carolina, 23 kmkilometers the coast.

The role of the tide in the estuary is relatively well understood since the primary source of energy driving water velocity is the energy of the ocean tide. Harmonic analysis (Parker 2007) can be used to analyze the energy of the tidal wave and to define an equivalent ideal estuary where basic fluid flow equations can be solved (Savenije 1992; Cai et al. 2012). The early solutions assumed no freshwater flow as the freshwater flow in the estuary is small compared to upstream flow created by the tide. Harmonic analysis was used for the NOAA analysis and prediction of tides in Winyah Bay and the ICWW outlined in the introduction and only included periods when flows of the Pee Dee and Waccamaw Rivers were minimal. Cai et al. (2014) expanded those solutions to include a method to estimate freshwater flow by examination of alteration of the tidal wave, since freshwater added to

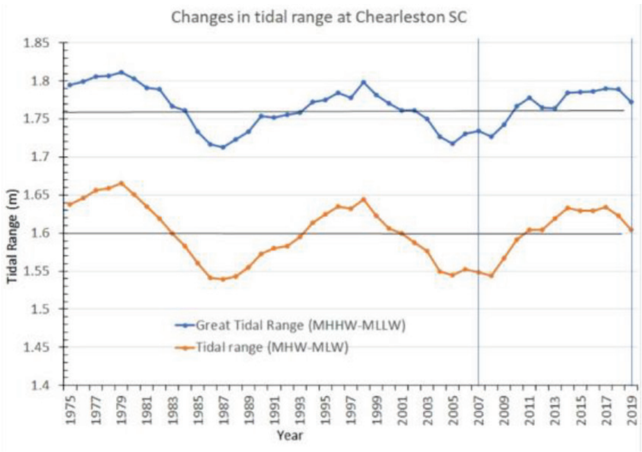

Figure 8. Variation in tidal range over the 18.6-year lunar nodal cycle for Charleston, South Carolina, from 1975–2019. Period of interest for this article is between blue lines and represents an expansion of tidal rage during the 2007–2019 period.

the ebb tide, delaying the timing, and increasing the height of MLW (mean low water). One interesting aspect of these solutions was the influence of freshwater was simplified by modeling as increased bottom friction as it behaves like the so-called shallow water effect (Parker 2007) in distorting timing and the relationship of MHW (mean high water) and MLW. These solutions assume a fully symmetrical repeating sine wave (as does harmonic analysis) for ocean water level, so MHW and MHHW are identical. Khojasteh et al. (2021) used multiple runs and systematic variation of parameters with this type of model to evaluate the impact of increasing sea level on a wide range of estuary types. They found attenuating (decreasing in tidal range with distance) estuaries were likely to remain as such and high tides would not rise faster than ocean SLR.

Obviously, the assumption that freshwater flow is small compared to upstream tidal flow must break down somewhere along the tidal river. Jay and Flinchem (1999) presented an alternative to harmonic analysis for the tidal river where tidal currents do not dominate the water surface elevation. Horrevoets et al. (2004) extended the (Savenije 1992) method to specifically include a large freshwater flow. Their analysis identified a critical point where the energy of the tide exactly matched that of the freshwater flowing into the tidal river. They called this point "tidal stagnation point," since at that point water would flow neither upstream nor downstream and would be, at least temporarily, stagnant. Above the stagnation point flow no longer reverses but is gradually varied throughout the tidal cycle, from maximum during peak ebb (ebbing tide flows downstream) and minimum during peak flood (flooding tide flows upstream). When it comes to water level, the stagnation point has two important factors. Freshwater flow will raise both maximum and minimum water level above the stagnation point (Jay and Flinchem 1999). Maximum water level is fixed by the tide height below the point of stagnation and freshwater flow rate influences only the position of the stagnation point and the minimum level of the water in the river below that point.

The rates of rise in Figure 7 are consistent with an explanation that rises in water levels in the WNWR have been driven by an accelerated rate of SLR along the southeastern coast of the US and an increase in the average rate of freshwater flow into the system. The rate of rise in Oyster Creek and all the ocean stations are not significantly different, and the mean rate at Oyster Creek is 89.5% and likely to be the same as Charleston or significantly the same at $\beta = 0.15$. The rate of rise of the average daily highest level was not significantly different between Oyster Creek and Bucksport Waccamaw (Figure 7). However, the rate of rise of the average daily minimum was significantly different between Oyster Creek and all upstream stations. These results are consistent with a stagnation point usually occurring somewhere upstream of Pawleys and downstream of Bucksport on the Waccamaw. We estimated only flows over 90,000 cfs (2,540 m3 s-1) would cause the stagnation point to move downstream from Pawleys but flows over 4,000 cfs (113 m3 s-1) would cause the stagnation point to be downstream from Bucksport Waccamaw (Williams et al. 2020). Both this tidal rise data and the flooding analysis (Williams et al. 2020) agree that the stagnation point in the Waccamaw most often occurs between Bucksport and Pawleys. Configuration of the channels (Figure 1) also support that conclusion as the most upstream connection of the Pee Dee and Waccamaw, Bull Creek, occurs in that reach. Width of the Waccamaw River also decreases above that confluence, about 6 kilometers downstream of Bucksport.

Residual analysis of linear regression can reveal structure of the residual error. We again used linear regression to determine the portion of residual error that could be accounted for by river flow. Residual error from each regression was calculated and compared to average annual mean daily discharge (Table 2). These results also agree with the interpretation that freshwater flow has no impact near the ocean and does not have a major impact below the average point of stagnation. Above that point it explains up to about 35% of the residual variation. For all stations, except Conway, the discharge of the Pee Dee River is more important than the Waccamaw. That probably should be expected as the flow of the Pee Dee is usually nearly 10 times larger. However, the residual does not measure the entire influence of freshwater as discharge also shows a significant increase over time, r = 0.65 at Conway and r = 0.67 at Bucksport Pee Dee. Average mean daily flow on the Pee Dee has increased an average 19.7 m3 s-1 y-1 while on the Waccamaw it has increased 4.3 m3 s-1 y-1.

Table 2. Percent of variation of annual average water level that is explained by linear regression with time (r2 x 100) and the percentage of residual error (r2 x100) attributable to flow of the Waccamaw and Pee Dee Rivers.

Station	Explained by time %			Residual explained by Waccamaw Discharge %			Residual explained by Pee Dee Discharge %		
	Max	*Min*	*Mean*	*Max*	*Min*	*Mean*	*Max*	*Min*	*Mean*
Oyster Creek	74.8	85.2	83.8	0.32	0.002	.01	0.21	0.27	0.39
Hagley	85.1	79.3	83.7	19.6	22.7	19.7	33.5	36.3	32.5
Pawleys	79.6	77.8	81.9	11.1	9.3	9.8	19.8	18.2	18.4
Bucksport Waccamaw	72.5	71.9	74.6	36.9	26.4	30.2	45.3	45.3	48.6
Conway	67.5	72.3	70.8	52.4	47.2	47.2	44.5	44.5	44.8
Bucksport Pee Dee	54.6	56	56.3	26.3	22.9	24.5	44.6	44.6	45.6

RECOMMENDATIONS

Over the last 13 years water levels in the Winyah Bay—tidal Waccamaw/Pee Dee River system—have risen significantly at a rate much exceeding the global and even the regional rate of SLR. Daily mean water levels have risen from 13.4 mm y-1 near the ocean to 43.5 mm y-1 at Conway and 44.6 mm y-1 at Bucksport on the Pee Dee. Downstream of the Pawleys gauge increase of the mean water level was driven by an increase in the daily minimum water level. Upstream of the Pawleys gauge both average daily maximum and average daily minimum levels have increased significantly. Much of the increase in rate of rise appears to be due to increased freshwater flow that occurred during the period. Freshwater influenced daily minimum values at all stations upstream of Georgetown and daily maximum water levels upstream of the Pawleys gauge. Data gaps at Bucksport Pee Dee reduced the power of statistical tests but values there were comparable to the Waccamaw River where more complete data allowed more rigorous statistical evaluation.

In this article we have addressed the subject of water level changes due to hydrodynamic processes. We have not addressed the subject of subsidence, which has been discussed as a reason for flooding in the local media. All data discussed in this paper have come from USGS sources that relate specifically to the North American Vertical Datum of 1988. Tectonically, the region is stable or slightly rising at 1m /million years (Cronin 1981). Stagg et al. (2016) did find root zone subsidence in tidal freshwater forested wetland along the Waccamaw River but no changes in the deeper sediments. We can be quite confident that the rise in water level we have measured is not due to surface subsidence. Although it is obvious that even shallow subsidence would increase the apparent depth of flooding on the wetland surface.

Our findings that mean low water (the height of daily lowest tide) is rising significantly faster than daily mean or high water (daily highest tide) has several important implications. Firstly, this may partially inhibit perceptions of the significance of the magnitude of SLR occurring across the Pee-Dee Waccamaw estuary, since people are more prone to recognize changes in high water levels relative to local benchmarks (piers, bulkheads, roads, back yards, etc.). This, combined with usual practice for scientists and media to focus on rates of ocean SLR, could be misleading to interests along the upper estuary and tidal river. Secondly, low tide heights are significant for managed wetlands along the estuary and activities that depend on low water dropping below a specific point (e.g., to facilitate draining an impoundment) will be significantly impacted by rapidly rising low water.

Finally, the rising low water elevations translates to increasing inundation (flooding) times, hydroperiod, in the tidal wetlands along the estuary and tidal river. Increasing saturation is driven by how often sediments can drain. An example from our data at Pawleys (Figure 9) demonstrates the changes in soil saturation associated with rise of minimum water levels. At Pawleys, the older (1983–2001) NOAA data indicates MLLW was about –0.4m NAVD88, which indicates, on average, water will drop that low once every day. We examined the daily tide levels for each lunar month (28 days) from 2007–2019 to determine the number of days the tide dropped below the estimated MLLW. In 2007, the data are as one might expect with a few days a month, probably associated with neap tides, when the tide does drop that low. By 2010, the number of days low tides above –0.4m commonly exceeded 15 days and in 2013 water stayed above that level for an entire month. By 2018, saturation exceeding a month was common. Since soil saturation is a direct control on a whole host of biogeochemical processes, and root inundation affects plant functions, these findings may have significant implications for the biogeochemistry (e.g., dissolved organic carbon export) and ecological function of the wetland systems in the refuge.

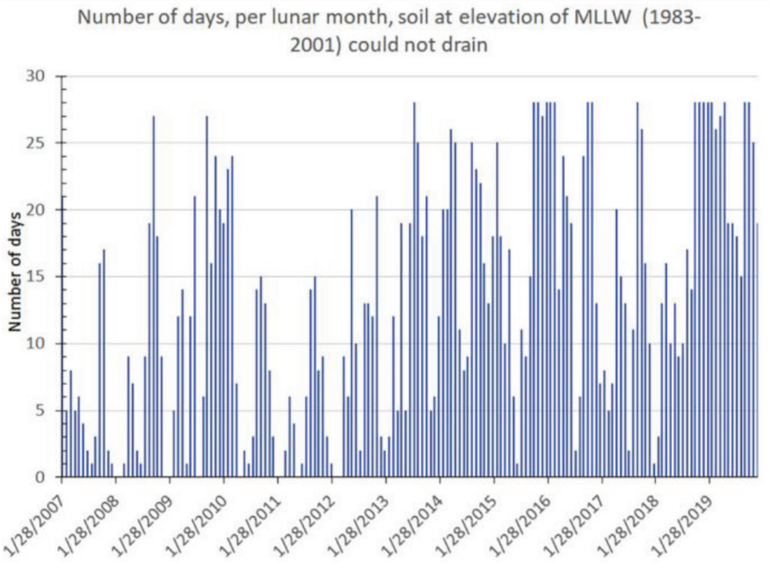

Figure 9. Minimum water levels at the Pawleys gauge expressed as number of days, per lunar month, that soil at the elevation of MLLW would not drain. Blue bars that reach 28 days indicate the site would be saturated the entire month.

We are unable to reliably predict how SLR will impact the Waccamaw National Wildlife Refuge but have shown that daily water levels have increased at a rate much higher than anticipated SLR over the last 13 years. Much of that rise appears to be caused by increased freshwater flow into the system over that same period. Yet accelerated SLR has also been apparent along the southeastern coast. It appears that planning based on a 3 or even 5 mm y-1 global rate of SLR will not be prudent. Ignoring the interaction of SLR and other climatic changes in the freshwater tidal river may lead to substantial underestimates of local water level increase.

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