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Rates of Relative Sea Level Rise Along the United States East Coast

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ABSTRACT

Recent studies have indicated that some coastal areas, including the East Coast of the United States, are experiencing higher rates of sea level rise than the global average. Rates of relative sea level rise are affected by changes in ocean dynamics, as well as by surface elevation fluctuations due to local land subsidence or uplift. In this study, we derived long-term trends in annual mean relative sea level using tide gauge data obtained from the Permanent Service for Mean Sea Level for stations along the United States East Coast. Stations were grouped by location into the Northeast, Mid-Atlantic, and Southeast regions of the United States East Coast, with the intent of investigating relative sea level rise variability between the three regions. Trends for each region were calculated using stations with a minimum record length of at least 30 years; the longest record began in 1856. Records that were less than 70 percent complete were rejected. For the three-year moving averages, Northeast trends were calculated to be 2.79 mm/yr, Mid-Atlantic trends were calculated to be 4.02 mm/yr, and Southeast trends were calculated to be 2.92 mm/yr. For the five-year moving averages, Northeast trends were calculated to be 2.81 mm/yr, Mid-Atlantic trends were calculated to be 4.04 mm/yr, and Southeast trends were calculated to be 2.91 mm/yr. The Mid-Atlantic region of the United States East Coast was determined to be experiencing significantly higher rates of relative sea level rise than the other regions.

Keywords: Rates of relative sea level rise, United States East Coast, Mid-Atlantic, Relative sea level rise variability

INTRODUCTION

The consequences of climate change vary for different geographic locations around the world, but for the U.S. East Coast, climate change induced factors are forcing the issue of rising sea levels to take center stage (Davis and Vinogradova, 2017). From 1993 to 2010, global sea levels rose at a rate of 3.2 millimeters per year (mm/yr); however, rates of sea level rise (SLR) vary spatially across the globe due to geologic and oceanographic factors making rates of local, or relative sea level rise (RSLR), more extreme in certain areas compared to others (Wong et al., 2014). RSLR is the resulting combination of global (eustatic) sea level rise, geologic factors such as glacial isostatic adjustment (GIA), land subsidence due to extensive groundwater pumping, increased coastal erosion, and various sea factors including thermal expansion, melting glaciers and ice sheets, and slowing ocean currents (North Carolina Coastal Resources Commission Science Panel, 2015). Different rates of RSLR and its drivers impact coastal communities through the accelerated erosion of shorelines, increases in the magnitude and frequency of flooding, and the alteration of wetland and coastal ecosystems (Eggleston and Pope, 2013). Low-lying cities such as Norfolk, Virginia have already experienced escalations in flooding related to RSLR (Ezer, 2018).

The U.S. East Coast has become an area of interest for SLR due to the variability in rates between locations (Davis and Vinogradova, 2017). Studies have found accelerated rates of SLR north of Cape Hatteras along the east coast (Ezer and Atkinson, 2014), which corresponds with an offshore shift and weakening of the Gulf Stream (Ezer et al. 2013). Accelerated SLR was also highly correlated with accelerations in minor flooding. While the U.S. East Coast was found to be a "hotspot of accelerated flooding," the Mid-Atlantic coastal area north of Cape Hatteras, specifically, has experienced substantial increases in flooding (Ezer and Atkinson, 2014). However, it was not until 2009 that the first observational study was performed that identified differences in rates of SLR along the U.S. East Coast (Engelhart et al., 2009). Engelhart et al. (2009) found increasing RSLR from Maine to South Carolina, with a maximum in the Mid-Atlantic. After removing the GIA signal from the tide-gauge data, a significant amount of spatial variability in SLR was identified for the 20th century, indicating ocean steric effects and/or the melting of the Greenland Ice Sheet may be responsible rather than vertical land motion. Highlighting which regions of the East Coast are most vulnerable to rising sea levels provides policymakers the opportunity to plan for SLR related hazards. Rather than attribute significantly different rates of RSLR in a region to any specific factors, the goal of this study is to simply determine if there are any statistically meaningful differences in rates of RSLR between three tidal-gauge data groups along the U.S. East Coast. For this comparative analysis, we sub-divided the available U.S. East Coast tidal-gauge data set into three contiguous geographic regions and compared observed rates of RSLR for each region.

MATERIALS AND METHODS

Annual tide gauge data recorded in millimeters (mm) was downloaded from the Permanent Service for Mean Sea Levels (Holgate et al., 2013; PSMSL, 2018). Located in Liverpool at the National Oceanography Centre, PSMSL maintains, publishes, analyzes, and interprets sea level data from a global network of tide gauges. PSMSL exercises quality control with established requirements that contributing organizations adhere to while submitting data. Furthermore, PSMSL provides instructions for the treatment of incomplete tidal records and the calculation of monthly and annual mean sea levels. For quality control in this study, data was downloaded from a tide gauge station only if two conditions were satisfied: the time series extended for at least 30 years and the data set was at least 70 percent complete. Overall, 37 stations from Maine to Florida satisfied these conditions.

Three and five-year moving averages for the annual RSLR data were calculated for each station. We created time series graphs for each moving average and generated linear trendlines for each graph. The slope of each linear trendline was interpreted to be the rate of RSLR for each station in mm/yr.

We sub-divided the U.S. East Coast tidal-gauge data set into three contiguous geographic regions to evaluate and compare rates of RSLR for each region: the Northeast, the Mid-Atlantic (approximately between latitudes of 40° 28' 0" N and 36° 49' 18" N), and the Southeast (Figure 1). The latitudes chosen in the study were estimated and based on a definition created by the United States Geological Survey (Greene et al., 2005). The Northeast region was designated to be all coastal states north of the Mid-Atlantic region along the U.S. East Coast; the Southeast region was determined to be all coastal states south of the Mid-Atlantic region along the U.S. East Coast. The Northeast and Mid-Atlantic regions each contained tidal gauge data from 14 stations, the Southeast region contained tidal gauge data from nine stations. The data did not satisfy the normality assumption, therefore a nonparametric Kruskal-Wallis H Test was conducted to compare rates of RSLR for both the three- and five-year moving averages from each region to determine if there were any significant statistical differences in rates of RSLR between the three regions along the U.S. East Coast. A pairwise post-hoc test was also performed to establish which region had significantly different rates of RSLR.

RESULTS

Interpreted rates of RSLR for the three-year moving average were calculated to be 2.79 mm/yr in the Northeast, 4.02 mm/yr in the Mid-Atlantic, and 2.92 mm/yr in the Southeast. Trends of RSLR for the five-year moving average were calculated to be 2.81 mm/yr in the Northeast, 4.04 mm/yr in the Mid-Atlantic, and 2.91 mm/yr in the Southeast. Stations located in the Mid-Atlantic region generally showed visibly higher rates of RSLR than for stations in both the North and Southeast regions (Figures 2 - 4). Additionally, the most Southerly station in the Northeast region and most Northerly station in the Southeast region also showed visibly higher rates of RSLR than for other stations in their respective regions. Furthermore, all stations in each region displayed distinct trends of increasing rates of RSLR throughout each record. Within each region, trends of RSLR calculated for the three and five-year moving averages were similar.

The calculated variance for the three-year moving averages of interpreted trends of RSLR rates was lowest for stations in the Mid-Atlantic region (0.53), and highest among stations in the Southeast region (0.83). For the five-year moving averages, the calculated variance of interpreted trends of RSLR rates was lowest for stations in the Mid-Atlantic region (0.57), and highest among stations in the Southeast region (0.95). At an alpha level of 0.05, the Mid-Atlantic region showed significantly higher rates of RSLR than the Northeast region for both the three-year moving averages ($P = 0.001$) and five-year moving averages ($P = 0.001$). While calculated rates of RSLR were closer between the Mid-Atlantic and Southeast regions, the Mid-Atlantic region showed significantly higher rates of RSLR for both the three-year moving averages ($P = 0.01$) and five-year moving averages ($P = 0.01$). Rates of RSLR were not significantly different between the Northeast and Southeast stations for either the three-year moving averages ($P = 1$) or the five-year moving averages (P = 1). For the three and five-year moving averages, the Northeast region had an outlier (Bergen Point, NJ) the Mid-Atlantic region had an outlier (Chesapeake Bay Bridge Tunnel, VA) and the Southeast region had an outlier (Duck Pier, NC) (Figures 5 and 6).

DISCUSSION

The results of this study have determined that the Mid-Atlantic region of the U.S. East Coast is experiencing significantly higher rates of RSLR compared to the Northeast and Southeast regions (Tables 1 and 2). This study was a preliminary examination of a dataset and purely a statistical analysis that did not attempt to determine which factors are responsible for this significant difference in rates of RSLR. Our results are in agreement with previous work that examines SLR and RSLR along the U. S. East Coast. The SLR acceleration found by Ezer and Atkinson (2014) likely has influenced this statistically significant difference found in rates of RSLR between the Mid-Atlantic region and other regions along the U. S. East Coast. Due to the variety of factors affecting eustatic SLR and vertical land motion, it is plausible that a combination of factors that play smaller roles in rates of RSLR for the Northeast and Southeast regions of the U. S. East Coast, are more prominent in the Mid-Atlantic region and have resulted in increased rates of RSLR. Although significant portions of the Atlantic Coast are experiencing land subsidence due to GIA, other processes have led to spatial and temporal variability in crustal movement within the Atlantic coastal plain (Karegar et al., 2016). Portions of the Mid-Atlantic region, including the southern Chesapeake Bay region, are experiencing substantial rates of land subsidence related to aquifer compaction caused by extensive groundwater withdrawal, as well as subsidence due to GIA from the past melting of the Laurentide Ice sheet (Eggleston and Pope, 2013). There is also evidence that a weakening of the Atlantic Meridional Overturning Circulation caused by a diminished temperature gradient between the Arctic and equator has resulted in a slowdown of the Gulf Stream, leading to a pile-up of water along the Mid-Atlantic region further increasing RSLR (Ezer et al., 2013).

Our division of the U.S. East Coast was not optimized to look at any specific cause of observed differences in RSLR, as our averaging over large areas might be averaging in hotspots and local causes of increased RSLR. Ezer et al. (2013) suggested that ocean dynamics including changes in ocean circulation may have significant effects in coastal sea level changes, which also corresponds with increased RSLR rates in the Mid-Atlantic region due to its proximity to the Gulf Stream. As indicated by Ezer et al. (2013) and Englehart et al. (2009), spatial variations in ocean dynamics play significant roles in SLR and RSLR variability. Future work could involve different regional groupings based on geographic distributions of climate change signals, to establish what factors of RSLR are impacting different regions. The identification of significant differences in rates of RSLR and flooding can enable local and state government officials with the information necessary to appropriately modify their infrastructure to withstand potential flood events. Further research will be required to isolate which factors have the largest impact on RSLR, allowing policymakers to properly develop plans to mitigate the effects of rising sea levels on coastal areas.

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Table 1. Kruskal-Wallis H Test between the three regions of U.S East Coast with a pairwise post-hoc test to determine which regions were significantly different for 3 year moving average RSLR rates.

Sample 1 RSLR Rates Vs. Sample 2 RSLR Rates	Test Statistic	Standard Error	Standard Test Statistic	Significance	Adjusted Significance
Northeast 3-Year Moving Averages Vs. Southeast 3-Year Moving Averages	-1.88	4.63	-0.41	0.68	1
Northeast 3-Year Moving Averages Vs. Mid-Atlantic 3-Year Moving Averages	-15.21	4.09	-3.72	0	0.001
Southeast 3-Year Moving Averages Vs. Mid-Atlantic 3-Year Moving Averages	13.33	4.63	2.88	0.004	0.01

Table 2. Kruskal-Wallis H Test between the three regions of U.S East Coast with a pairwise post-hoc test to determine which regions were significantly different for 5 year moving average RSLR rates.

Sample 1 RSLR Rates Vs. Sample 2 RSLR Rates	Test Statistic	Standard Error	Standard Test Statistic	Significance	Adjusted Significance
Northeast 5-Year Moving Averages Vs. Southeast 5-Year Moving Averages	-1.81	4.63	-0.39	0.7	1
Northeast 5-Year Moving Averages Vs. Mid-Atlantic 5-Year Moving Averages	-15.07	4.09	-3.68	0	0.001
Southeast 5-Year Moving Averages Vs. Mid-Atlantic 5-Year Moving Averages	13.26	4.63	2.87	0.004	0.01

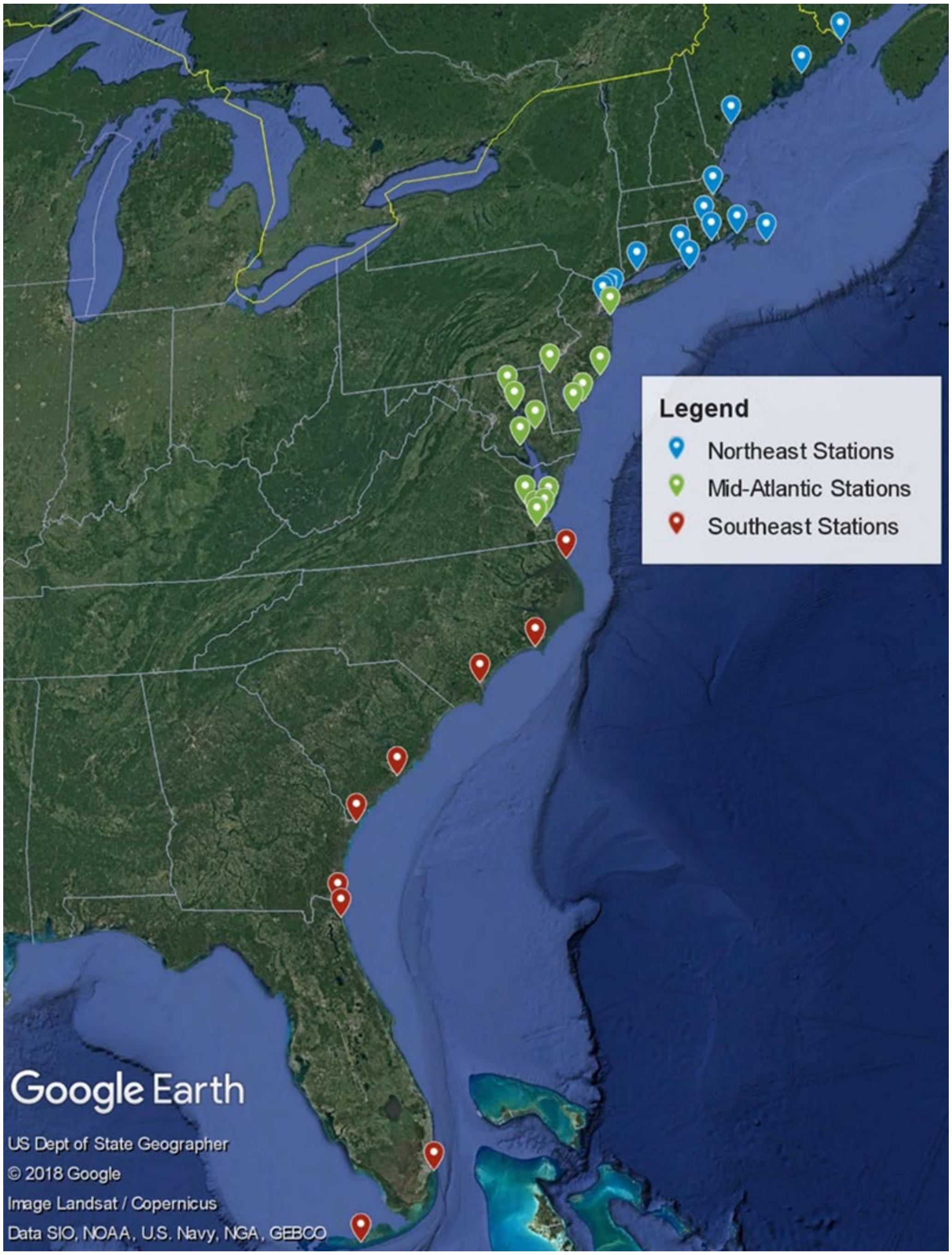

Figure 1. Map of U.S. East Coast showing the locations of tide gauge stations comprising each region. Blue markers represent Northeast stations, green represents Mid-Atlantic stations, and blue represent Southeast Stations.

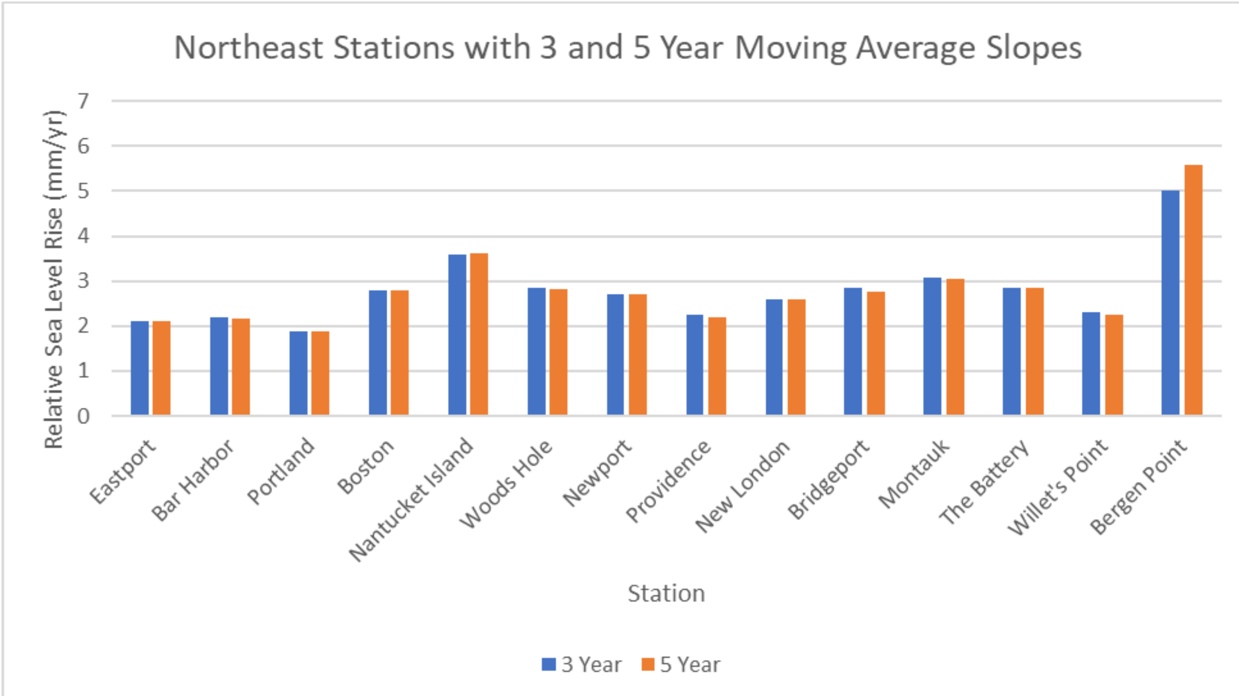

Figure 2. U.S. East Coast Northeast tide gauge station locations and their interpreted RSLR rates.

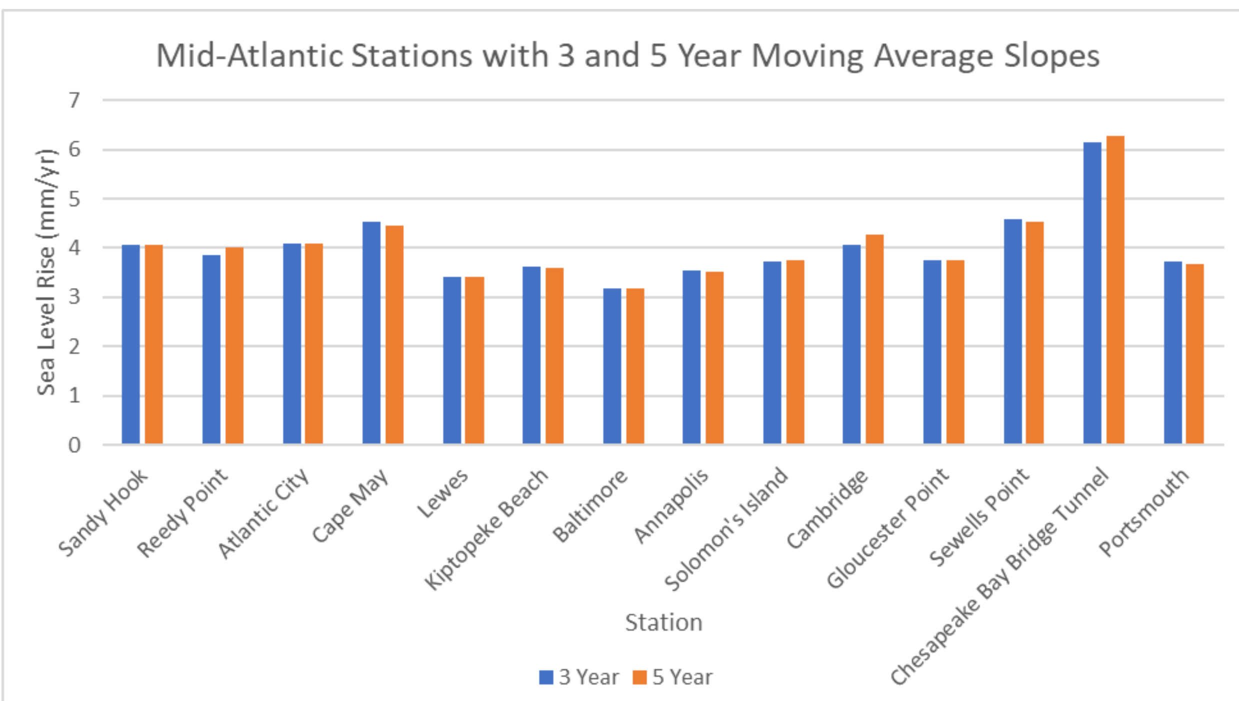

Figure 3. U.S. East Coast Mid-Atlantic tide gauge station locations and their interpreted RSLR rates.

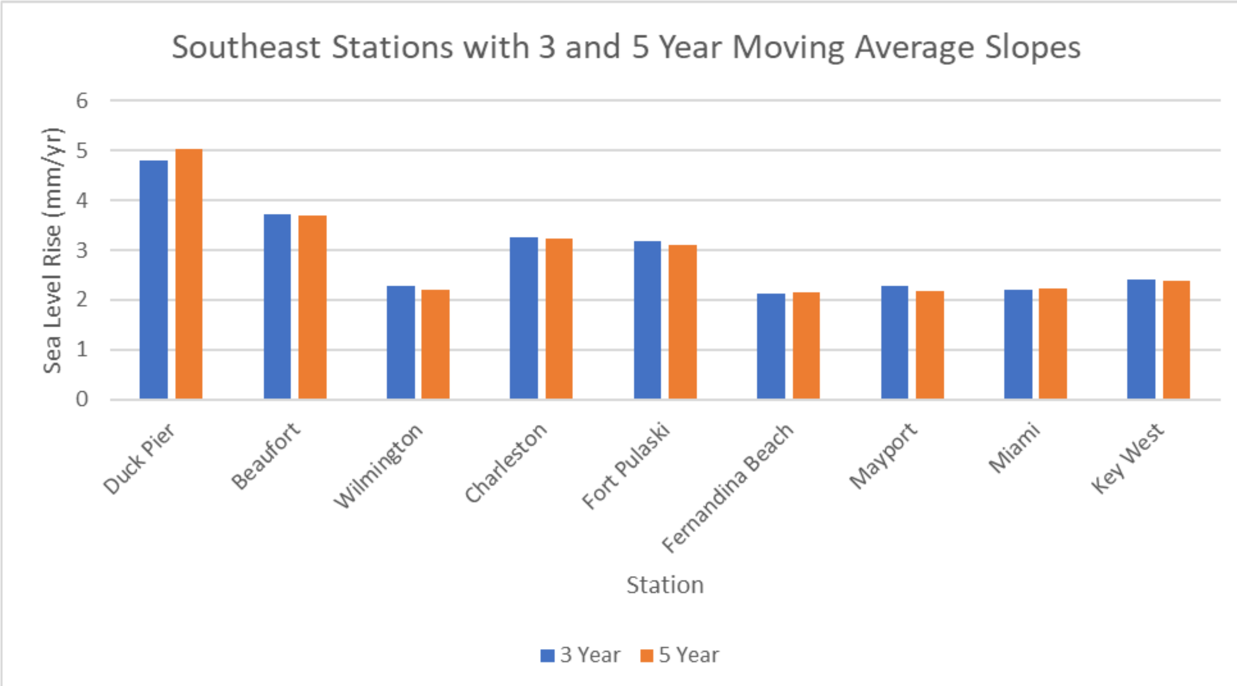

Figure 4. U.S. East Coast Southeast tide gauge station locations and their interpreted RSLR rates.

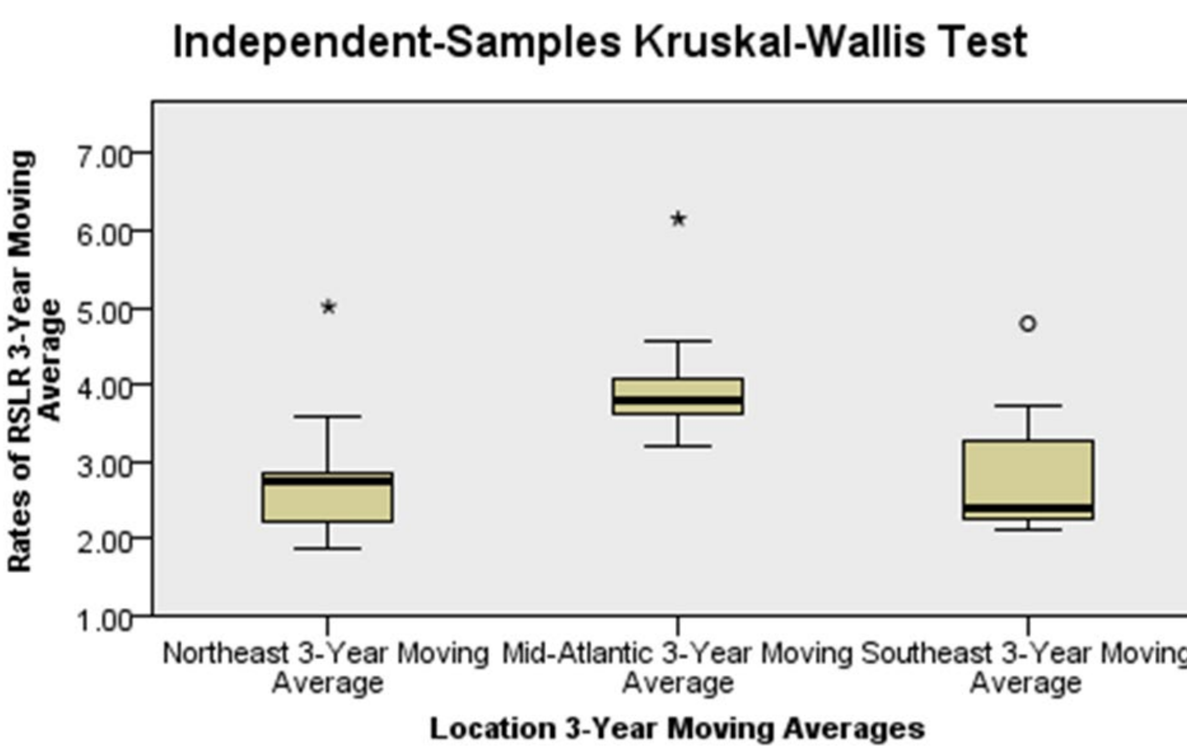

Figure 5. Box and whisker plot showing distributions of 3-year moving average rates of RSLR for each region of U.S East Coast.

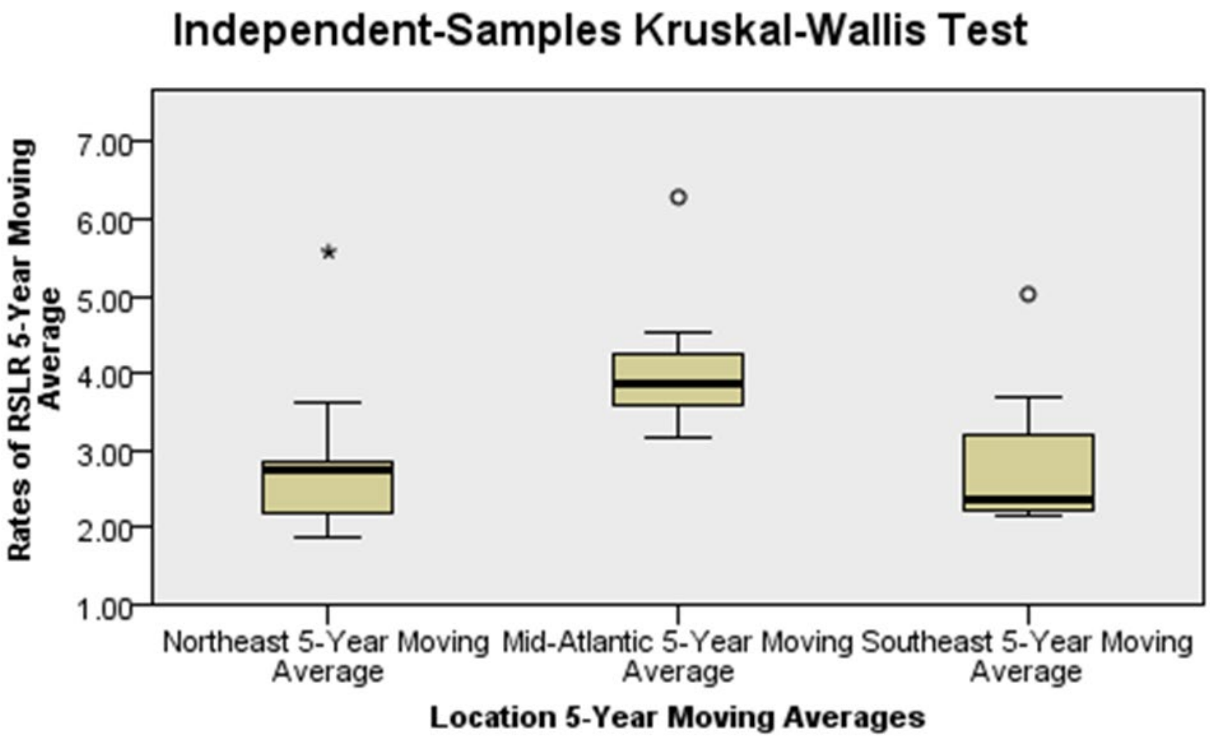

Figure 6. Box and whisker plot showing distributions of 5-year moving average rates of RSLR for each region of U.S East Coast.