Florida

Scientist

EDITORIAL

FEATURED PAPER

RESEARCH ARTICLES

Featured articles and reviewer acknowledgement

James D. Austin

This issue marks the first featured article in the *Florida Scientist*. The goal for featured articles is to highlight topics that should broad interest to the scientific community in Florida and Southeast U.S. Typically, these papers will be accompanied by brief Forum pieces that may provide a contrary view of the feature article, or emphasize an aspect of the featured paper, or both!

Without the assistance of willing reviewers, regional journals like the Florida Scientist would not be able to persist. Reviewers will be acknowledged annually, however the list below covers reviewers since the start of my tenure as editor.

The editor would like to thank the following reviewers for their service since the start of his tenure (* indicates multiple contributions):

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Florida's rising seas: a report in feet per century for coastal interests

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Abstract Global sea level has been rising for the last 20,000+ years at rates ranging from 0.3–3.3 feet/century, and has submerged Florida's pre-Holocene coast by over 400 feet. The instrumental record started in Key West in 1845, but had many gaps until 1913, after which it is nearly continuous; the rate of rise there since 1913 is 0.74±0.03 feet per century. For the ensemble of all other near-century-long Florida records (Pensacola [0.71 feet/century], Cedar Key [0.53 feet/century], St. Petersburg [0.82 feet/century], Miami Beach [0.75 feet/century], Mayport [0.77 feet/century], and Fernandina Beach [0.65 feet/century]) the average rate of rise is 0.73±0.09 feet per century. At Key West during 1913–2013, there is no statistically significant evidence of accelerated sea level rise. Guidance for estimating future sea level from NOAA and from the US Army Corps of Engineers relies on using projections of global sea level adapted to a local site; such federal criteria for Florida would place sea level in 2100 anywhere from 0.7–6.6 feet above the 2001 level; United Nations projections are between 0.9–3.3 feet by 2100.

Keywords Florida sea level rise

Introduction

Coastal managers and engineers are faced with the often difficult task of planning infrastructure, such as drainage systems, seawalls, roads, and power plants, with vulnerability to changing sea level. Such planning must be based on the best evidence of past sea level change and the most credible projections into mid-century and beyond. For Florida, with many cities and structures already within a few feet of mean sea level, the issue is of paramount importance. With a readership of coastal managers, coastal engineers, and government officials in mind, the information herein is, wherever possible, reported and discussed in units of feet per century rather than the usual scientific practice using the metric system.

Geological evidence shows that our planet has been experiencing rising seas for at least the last 20,000 years (Fleming et al. 1998; Figure 1a), but has shown many rises and falls over time-scales of thousands to millions of years. As Earth warmed at the end of the Pleistocene Epoch (20,000 years ago), melting continental ice filled the ocean basins and eustatic sea level rose about 400 feet. Thermal expansion in the warmer seas contributed to global sea level rise as well. Florida's surface area shrank by half between 20,000 and

a

b
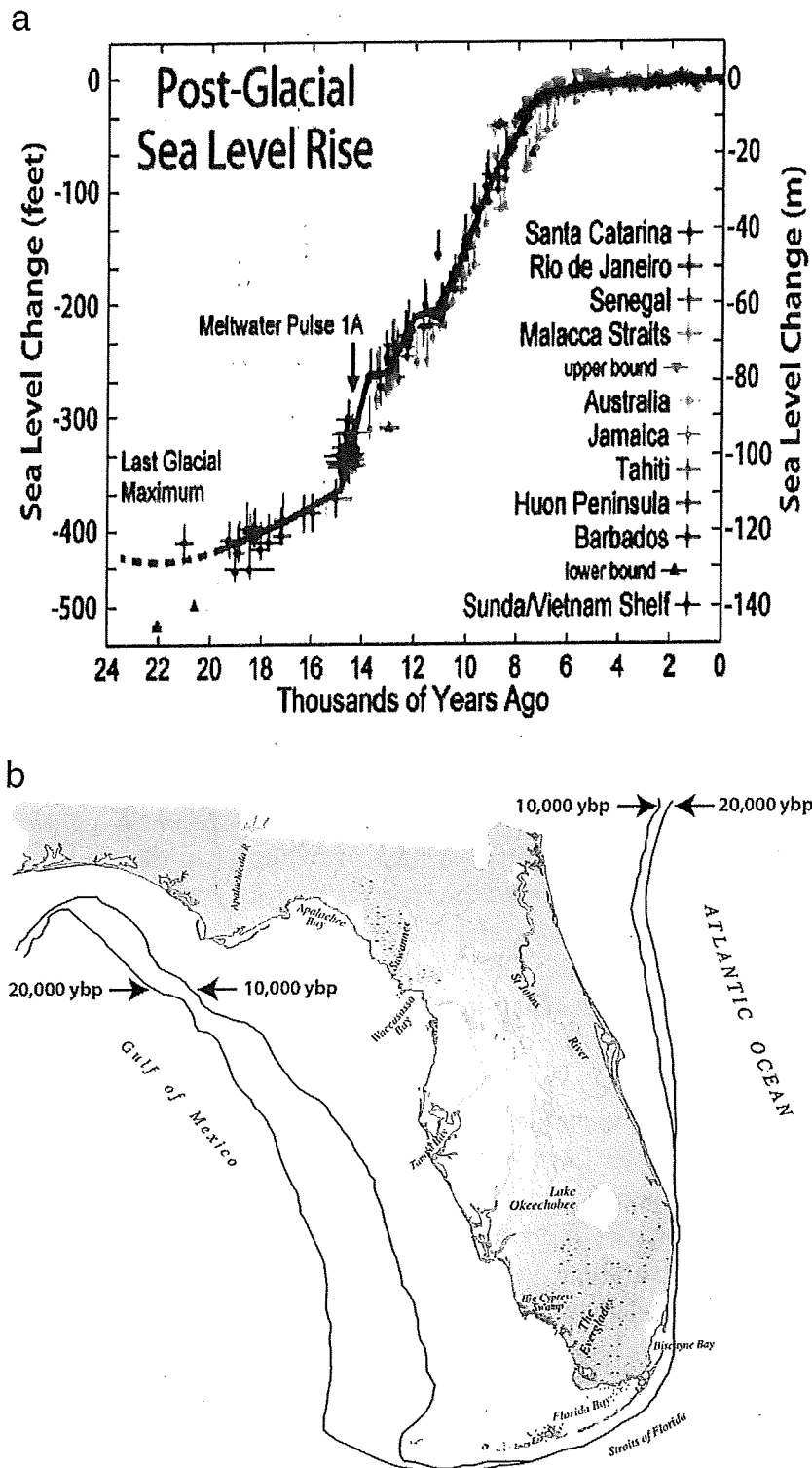
Figure 1a. Global sea level rise during the past 24 millennia (data from Fleming et al. 1998); image created by Robert A. Rohde / Global Warming Art. To scale from meters to feet, note that 120 meters is approximately 400 feet.

Figure 1b. Approximate location of Florida's coastlines as Earth left the glacial period (20,000 ybp) and approached the Holocene Warm Period about 6,000 ybp. The coastline 5,000 ypb at this scale is nearly identical to the current coastline.

6,000 years before the present (ybp), and became fairly stable entering the current interglacial period, starting ca. 6,000 ybp – the Holocene Optimum.

The rate of sea level rise varied during the change from the last ice age to the present interglacial epoch. During the period of maximum sea level rise, 18,000 – 8,000 ybp, the rate of global rise was about 3.3 feet per century. In the last 5,000 years or so, the rate slowed to about 0.3 feet per century. These rates are all based on paleogeological evidence, and are estimates of global values not local rates (Fleming et al. 1998). Figure 1b shows Florida's approximate coastline 10,000 ybp and 20,000 ybp based on current bathymetric data.

Direct measurement of Florida sea level by instruments known as tide gauges began in the 19th century. In Florida it is the tide gauge at Key West that gives the longest instrumental record in the Western Hemisphere (Maul and Martin 1993). During the period 1846–1992, Key West relative sea level (RSL) rose at the rate of about 0.7 feet per century. The RSL rise at Key West 1846–1992 was steady, and showed no evidence of acceleration or change of rate due to a "hinge" point (Maul and Martin 1993). It should be noted, however, that Douglas (1992) and Houston and Dean (2011), amongst others, report evidence of acceleration in global sea level.

RSL is the change of sea level with respect to fixed tidal benchmarks, or survey markers, on the juxtaposed land. A number of factors affect RSL rise including melting continental ice, thermohaline expansion or contraction, vertical land motion, ocean currents and prevailing winds, and atmospheric barometric pressure (the inverted barometer effect). The rate of RSL rise at a particular location depends on the interplay of these factors, and for the 20th century in the southeastern US, ranges between 3.3 feet per century in Louisiana to 0.7 feet per century in southern Florida (Mitchum 2011).

Data and Analysis

Relative sea level is the variable of central importance to coastal interests. It is the height of the water level with respect to the land, and affects coastal communities that depend on a vertical difference between the level of the sea and that of water on the land for drainage, amongst other things. RSL has several components as already mentioned, in general the largest of which are vertical land motion and local steric sea level rise or fall over time. Tide gauges and other water level instruments measure RSL with respect to tidal benchmarks. It is the geodetic connection between the tide gauge and the tidal benchmark that allows century-long records of RSL to be obtained even if the tide gauge is destroyed and then replaced, or moved.

RSL is rising in Florida (e.g. Walton 2007, Mitchum 2011, Kemp et al. 2014), but in other areas such as southern Alaska and Scandinavia, it is falling over time (e.g. Douglas et al. 2001, IPCC 2013). Falling RSL is due to upward vertical land motion being larger than local sea level change. Figure 2 shows these relationships graphically. Perhaps the worst relative sea level rise scenario is land sinking and water rising; such is the case for southern Louisiana.

LAND STABLE, SEA LEVEL RISING

LAND RISING, SEA LEVEL RISING
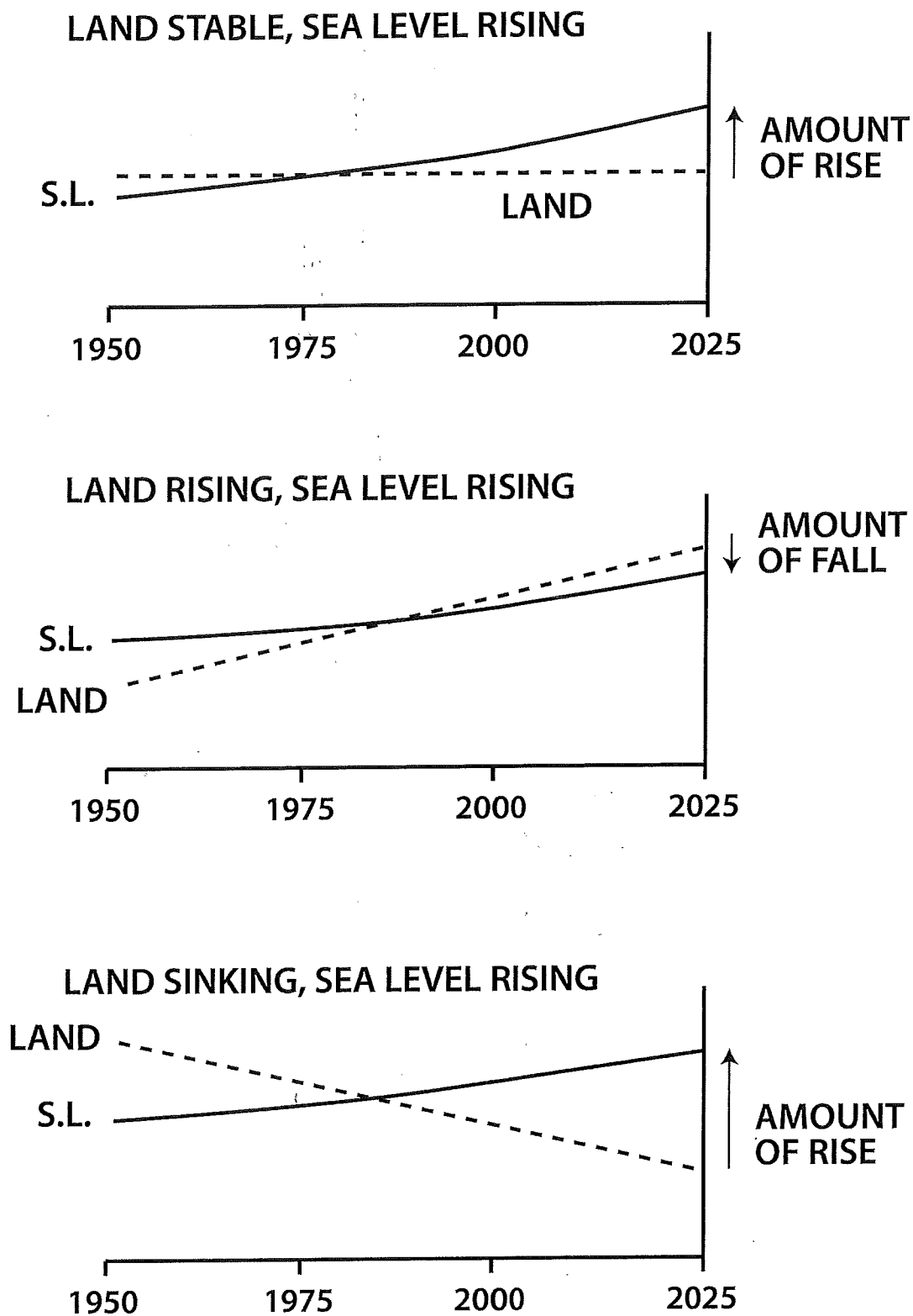

LAND SINKING, SEA LEVEL RISING

Figure 2. Scenarios of relative sea level (RSL) to vertical land motion and absolute water level change as connected to a tidal benchmark by differential leveling surveys (redrawn from Hendry, 1993).

Table 1. Florida sea level trends.

Station	Longitude (°W)	Latitude (°N)	Trend (Feet/ Century)	SE (Feet/ Century)	Epoch	N (Years)
Cedar Key	83.03	29.14	0.53	±0.06	1939–2012	61
Fernandina Beach	81.46	30.67	0.65	±0.04	1898–2012	94
Key West	81.81	24.56	0.74	±0.03	1913–2013	100
Mayport	81.43	30.39	0.77	±0.06	1929–2000	71
Miami Beach	80.16	25.73	0.75	±0.09	1932–1980	44
Pensacola	87.21	30.40	0.71	±0.05	1924–2012	85
St. Petersburg	82.63	27.76	0.82	±0.05	1947–2012	66
MEAN ± SD			0.73±0.09			

Sella et al. (2007) used the Global Positioning System (GPS) to directly measure vertical land motion in much of North America, and show for example, that areas of eastern Canada are rising due to the offloading of the ice from the last deglaciation (20,000 – 6,000 ybp), a phenomena known as post-glacial rebound. Other areas, the mid-Atlantic United States in particular, are showing negative vertical land motion, making RSL to be larger than in other regions. These data from Sella et al. (2007) are an analysis of GPS signals collected at Continually Operating Reference Stations (CORS) over about 10 years. Note that their GPS/CORS data suggest that vertical land motion in Florida is quite small, but on average is positive.

Referring back to Figure 2, this then is interpreted that Florida RSL is less than at sites where the land is subsiding. If the actual sea level is rising uniformly in the southeastern region of the Atlantic, then RSL for major cities to the north of Florida such as Savanah, Charleston, and Wilmington, is greater (q.v. Figure 2). This negative vertical land motion north of Florida exacerbates the RSL in those communities (Mitchum 2011).

Sella et al. (2007) had 23 CORS stations in Florida, which are analyzed herein for a mean and standard deviation. The resulting statistics are that Florida's vertical land motion is +0.12 feet/century ± 0.60 feet/century. While the mean shows vertical land motion is rising slightly, the large ensemble uncertainty (±0.60 feet per century) precludes rejecting the null hypothesis; that is, there is no statistically significant evidence that Florida is experiencing vertical land motion (either positive or negative) based on these CORS data.

Using the technique of (essentially) subtracting the 20th century rate of global sea level rise (+0.56 feet/century) from individual stations, Zervas et al. (2013) estimated vertical land motion for many sites in the United States. They had 12 stations in Florida; the summary statistics from the Florida portion of their study is −0.14 feet/century ± 0.16 feet/century. Zervas et al. (2013) note the limitations of their approach, yet the result is of opposite sign to Sella et al. (2007). With regard to relative sea level then, Florida in general seems to be a stable landform (although there may be local exceptions).

Table 1 is a summary of seven long-term Florida RSL records; the stations were chosen because their time-frame is near or longer than 3 lunar nodal
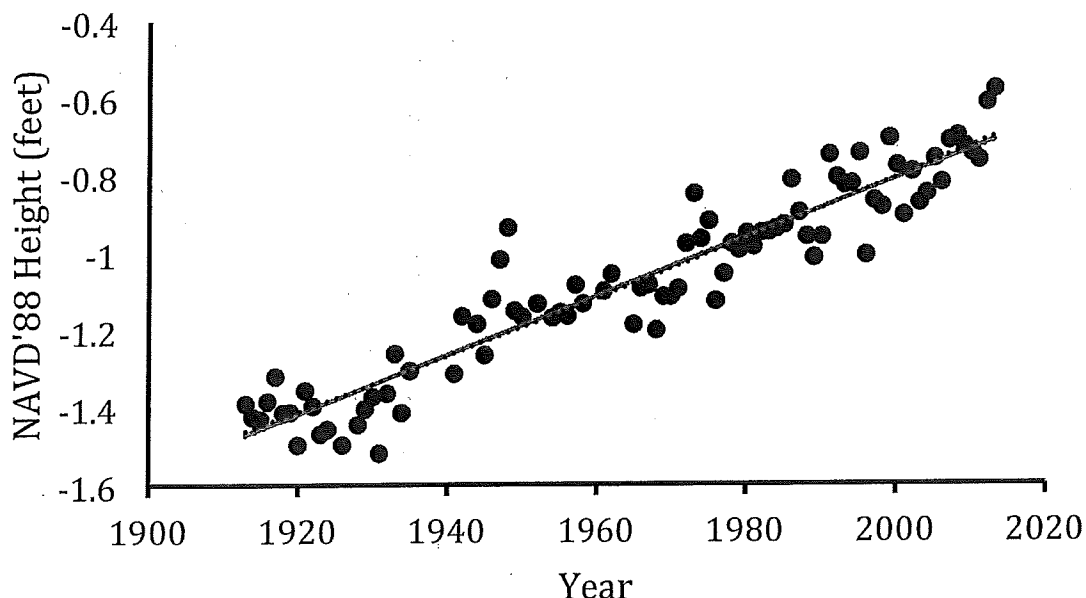
Figure 3. Relative sea level at Key West, Florida for the epoch 1913–2013 with respect to the North American Vertical Datum of 1988 (NAVD'88). All three least-squares curves (linear, logarithmic, and polynomial) are plotted superimposed against the annual means (differences are not visible in chart).

cycles (18.61 years per cycle). Records of this length (56 years or so and longer) are less likely to bias the calculation of linear least-squares parameters than shorter records. The data used to calculate the results in Table 1 are from NOAA reports to the Permanent Service for Mean Sea Level (PSMSL), which lists annual mean sea level values as a function of year. All data except Key West are from the PSMSL's revised local reference file (converted from millimeters to feet), which is of the highest quality-control; Key West is directly from the NOAA Tides and Currents website (so as to include 2013).

Table 1 lists the linear least squares trend for each of the seven stations and the standard error of each trend. At Cedar Key for example, the RSL trend ± the standard error is +0.53 ± 0.06 feet/century, and is interpreted to be that the trend value of +0.53 is highly significant and the null hypothesis of no trend can be rejected. This conclusion is the same for all data in Table 1. The ensemble mean trend for Florida is 0.73 ± 0.09 feet/century, where the ± in this statistic is the standard deviation of the ensemble mean. Thus it is seen that RSL rise along Florida's west, south, and east coasts has been very similar during the last century.

It should be noted that there may be local exceptions as alluded to above. Geographically St. Petersburg is closest to Cedar Key, yet the trends (0.82±0.05 and 0.53±0.06 feet/century, respectively) have the largest differences within the State. Student's two-tailed t-test shows these two trends are statistically different at the 98% confidence level. Accordingly, coastal managers and engineers need to be aware that there may be important local RSL differences within Florida, and to include such contrasts in decision-making.

Most projections of future global sea level are that the rise will be non-linear, and this raises the question of "is there evidence of non-linearity in the Florida RSL record?" Figure 3 shows the 1913–2013 data from Key West with

Table 2. Key West Sea Level least-squares parameters by year (y).

Equation	Least-Squares Fit	Variance Explained
Linear	$KWSL=7.591\times10^{-3}y-1.599\times10^{1}$	89.10%
Logarithmic	$KWSL=1.490\times10^{1}\ln(y)-1.140\times10^{2}$	89.07%
Polynomial	$KWSL=5.854\times10^{-6}y^{2}-1.539\times10^{-2}y+6.555$	89.14%

the least squares analysis for linear, logarithmic, and second-order polynomial equations; all three equations are plotted as an overlay of the annual mean sea levels; the equation parameters are listed in Table 2. Visually there appears to be no difference in the three mathematical curves during the century-long epoch.

The parameters for the linear equation and for the polynomial equation may seem mismatched. However, if the time-series were centered on year (y) 1960 the equations would be $7.59\times10^{-3}y\text{-}1.11$ for the linear equation and $5.85\times10^{-6}y^{2}+7.56\times10^{-3}y\text{-}1.12$ for the polynomial equation, resulting in closely matched linear parameters. Variance explained is unchanged after centering on 1960. For ease of computation, and to minimize confusion, the equations reported in Table 2 are so the user can simply insert the Julian year (y) of interest.

The three coefficients of determination (R^{2}) are also shown in Table 2. R^{2} times 100 gives the percentage of the variance explained by each equation. It is seen that 89% of the variance is explained by either a linear least-squares equation, or a logarithmic least-squares equation, or a second-order polynomial least-squares equation. Thus it is proper to conclude that there is no statistical evidence of non-linearity (i.e. acceleration) in Key West sea level over the epoch studied (1913–2013).

Global sea level rise however is not uniform as can best be determined from satellite altimetry (NOAA 2012), and is an estimate of sea level change since 1992 when altimeters such as TOPEX/Poseidon were declared operational. Twenty years is a very short time (1992–2012) to estimate sea level change, however, for the waters juxtaposed to the southeastern United States, the linear trend appears to be negative. In as much as these twenty years are indicative of a longer trend, the environs of Florida should be seeing a lower change in RSL than other states in the southeast. However, the linear trend at Key West for the same period (1992–2012; not shown but q.v. Figure 3) is positive not negative.

Another factor affecting Florida RSL is volume transport in the Florida Current, at least it is so in the Straits of Florida (Maul et al. 1990). If there is a trend in volume transport, then there should be a corresponding trend in coastal sea level; the relationship is inverse, that is increasing volume transport is statistically related to lowering of east-coast Florida sea level, and vice versa.

Figure 4 shows volume transport in the Straits of Florida for the last several decades. Again, short time-series such as this must be scrutinized with care lest sinusoidal fluctuations be interpreted as a trend. The summary statistics are that the trend is $-7.1\times10^{5}\pm9.5\times10^{5}$ cubic feet per second per
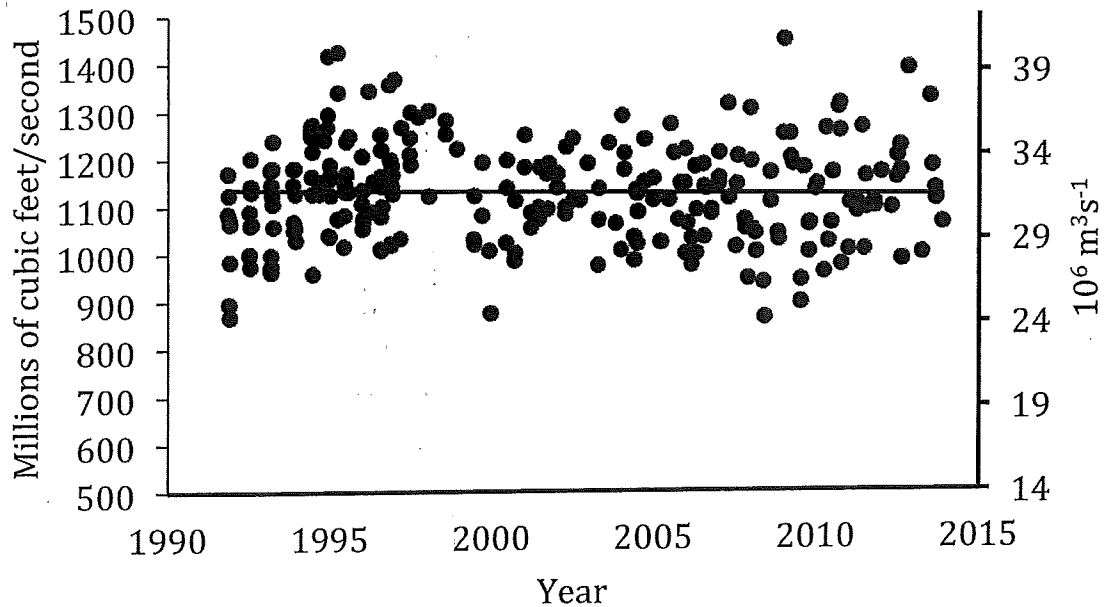
Figure 4. Volume transport in the Florida Current between Florida and the Bahamas. These Florida Current cable and section data are freely available on the Atlantic Oceanographic and Meteorological Laboratory web page (www.aoml.noaa.gov/phod/floridacurrent/) and are funded by the NOAA Climate Observation Division.

century (-0.020×10^6 m^3 s^{-1} $\pm$ 0.027×10^6 m^3 s^{-1} per century). Since the standard error of the trend is larger than the trend itself, the null hypothesis of no statistically significant trend cannot be rejected (cf. Meinen et al. 2010). Thus these volume transport data, due to the natural annual and interannual variability in North Atlantic Ocean circulation, can be interpreted to show there is no statistically significant Florida Current influence on sea level trend over the timeframe shown on Figure 4.

Atmospheric sea level pressure (SLP) also affects sea level through a mechanism known as the inverted barometer effect (IBE). The height change of the water ($\Delta\eta$) is related to the change in atmospheric pressure (Δp_A) through the hydrostatic equation, $\Delta\eta = \dfrac{-\Delta p_A}{\rho g}$, where ρ is seawater density and g is the acceleration of gravity. A 1″ drop in SLP as measured by the height of a mercury barometer will raise sea level 13.3 inches through the IBE ($1\,mb \approx 1\,cm$). Figure 5 shows the trend in SLP from iCOADS (Woodruff et al. 1998) for the 2° latitude by 2° longitude box in the vicinity of Key West. The trend in Δp_A is negative and would result in a rise in sea level of about 0.03 feet per century if the measurements are not due to instrumental issues (for example, if the average height of the barometers on ships rose by about 25 feet in the last 100 years as ships grew bigger, and if the barometers were not calibrated to sea level). Yet there is some evidence that SLP is changing (Gillett et al. 2005), and if the data in Figure 5 are correct, then Δp_A may account for about 4% of the signal in Figure 3.

Winds also affect mean sea level when the slope of the water surface ($\dfrac{\Delta\eta}{\Delta x}$) is balanced by the friction of the air. As wind patterns change, a wind-setup sea
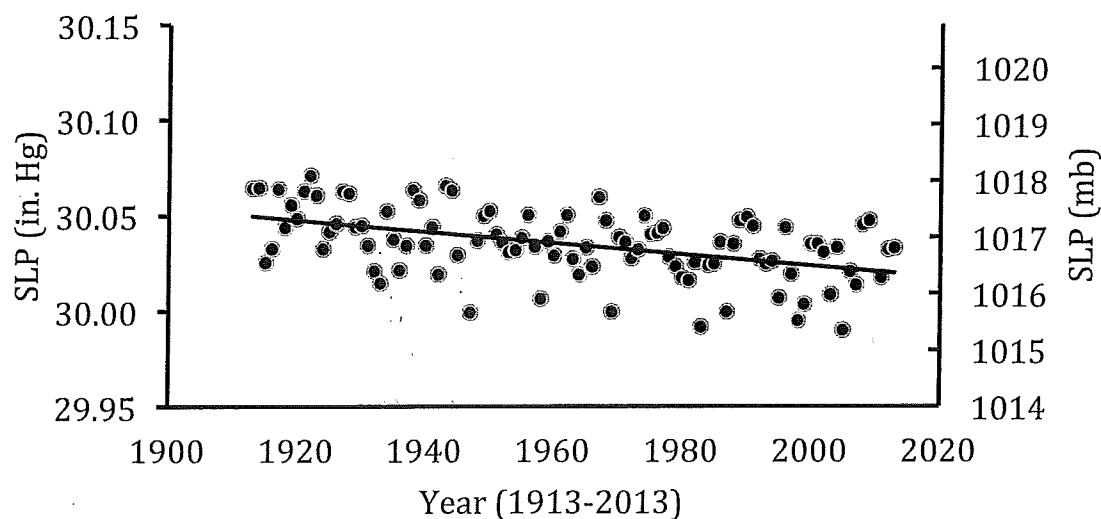
Figure 5. Annual average atmospheric sea level pressure (SLP) for the environs of Key West from iCOADS 24–26°N, 80–82°W.

level effect (Pugh 1987) can be estimated from $\dfrac{\Delta\eta}{\Delta x} = \dfrac{\tau_{wind}}{\rho_{water}gH}$ where the wind stress $\tau_{wind} = \rho_{air}C_Dv_{air}^2$, and where the drag coefficient $C_D \approx 2x10^{-3}$. Mean winds over Florida are from the east at about 5.9 knots (3.0 m·s^{-1}), and seemed to have increased about 1.07 ± 0.26 knots (0.55±0.14 m·s^{-1}) over the last 100 years (data from the same iCOADS region as used in Figure 5). Assuming a fetch (Δx) of 50 nautical miles across the Straits of Florida and a depth of H=33 feet (10 meters) in the shallows surrounding the Key West tide gauge, the change in sea level ($\Delta\eta$) due to the change in wind stress (τ_{wind}) would be about 0.007 feet per century. On the east coast of Florida the wind-setup is positive with an equal amount of opposite sign on the west coast. Clearly this small change in wind stress is negligible in the context of Florida's rising seas.

Discussion

Southeastern U.S. sea level rise, when viewed over the timescale of the last 2.5 millennia (Kemp et al. 2014) has the characteristic "hockey stick" shape published by many climate scientists; that is, global sea level rise since the dawn of the industrial revolution is rising faster than before (q.v. Figure 1). Church et al. (2011) give source estimates of this global pattern as: Antarctica (0.14 feet/century), Greenland (0.10 feet/century), glaciers (0.32 feet/century), and thermal expansion as 0.29 feet/century. The total from Church et al. (2011) is 0.85 feet per century, a value not considerably different from the Florida average of 0.73±0.09 feet per century reported herein. If Florida has little vertical land motion as Sella et al. (2007) and Zervas et al. (2013) report, then the historical contributions to Florida's rising sea may well be as Church et al. (2011) write.

Many articles have been written projecting Florida sea level of late, including Walton (2007), Mitchum (2011), and the Southeast Florida Regional

Table 3. Baseline mean sea level datums (Epoch: 1983–2001).

Station	NAVD'88	NGVD'29	Difference
Cedar Key	−0.22 feet	0.45 feet	−0.67 feet
Fernandina Beach	−0.53 feet	0.62 feet	−1.15 feet
Key West	−0.24 feet	1.10 feet	−1.33 feet
Mayport	−0.53 feet	0.57 feet	−1.10 feet
Miami Beach*	−0.87 feet	0.69 feet	−1.56 feet
Pensacola	0.30 feet	0.41 feet	−0.11 feet
St. Petersburg**	−0.36 feet	0.53 feet	−0.89 feet

[*] Miami Beach discontinued in 1981; datum is for currently operating station at Virginia Key.
[**] Estimated from several juxtaposed stations.

Climate Compact (2011), amongst others. Federal guidance in this matter has been given by NOAA (2012) and by the U.S. Army Corps of Engineers (USACE 2011). United Nations projections of future global sea level are given by the IPCC (2013) in their Fifth Assessment Report (AR5). Projections for the year 2100 of global sea level rise range from 0.7 feet to 6.6 feet depending on the source. The linear rise noted for past Florida RSL herein (0.73 ± 0.09 feet per century) is at the lowest end of the 21st century global AR5 sea level rise projections.

Coastal interests also need the baseline elevation (datum) for the area under consideration. Land elevations on NOAA nautical charts are reckoned from mean sea level (US Chart No. 1 2013), and MSL (mean sea level) is of course changing. Newer documents use the North American Vertical Datum of 1988 (NAVD'88) as the datum; older documents use the National Geodetic Vertical Datum of 1929 (NGVD'29); the two datums differ from site to site. Table 3 lists the relationship between NAVD'88 and NGVD'29 of MSL at the seven sites given in Table 1. Land elevations for coastal planning based on one datum or the other will yield different results depending on the map or chart used. The differences can be quite large as the right-hand column on Table 3 shows.

The conundrum facing coastal interests then is choosing a value for local RSL rise over the timeframe of interest, using the proper datum from which to calculate the rise. Such a choice must include an evaluation of vertical land motion as NOAA (2012) advises (but cf. USACE 2011). As the work of Sella et al. (2007) and others on vertical land motion is extended and refined, coastal managers and engineers will have another data point to consider. For the moment though, choosing a global curve as USACE (2011) recommends, still leaves a very large range of uncertainty. There is no simple solution as Mitchum (2011) notes.

In Figure 6, global sea level rise observations and projection scenarios from NOAA (2012) are shown. The values given for the year 2100 are from 0.7 feet to 6.6 feet, an almost impossibly large range for coastal planning. Figure 6 should be considered in the context of the maximum rate of rise during the great deglaciation 18,000-8,000 ybp, which was no more than
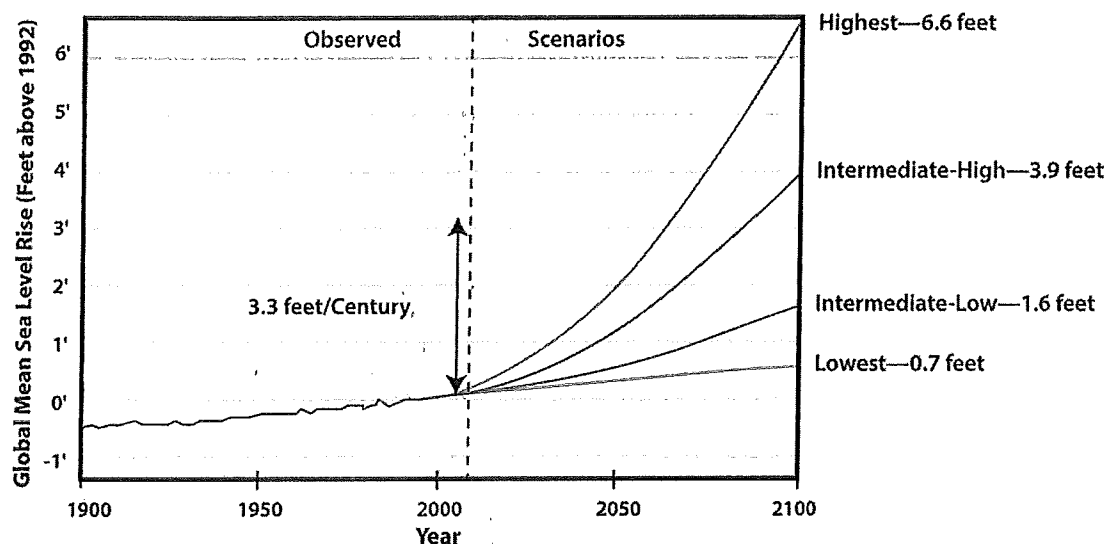
Figure 6. Observations and projections of global sea level rise redrawn from NOAA (2012). The shaded area emphasizes the maximum rate of rise (3.3 feet per century) during the Pleistocene-Holocene transition, 8,000–18,000 years before the present.

3.3 feet per century. NOAA's assessment of up to 6.6 feet (2 meters) by 2100 requires a rate of rise twice that experienced at the Pleistocene – Holocene transition (ca. 12,000 ybp).

Placing these estimates in context, consider that the average depth of the ocean is 13,000 feet (4,000 meters). If this water column is warmed from an average of 3°C today to 4°C (37.4°F to 39.2°F) and the salinity is kept at an average value of 35‰, then from the hydrostatic equation and the equation of state for seawater, the steric water column can be calculated to be 1.3 feet higher. The ocean of course would not warm uniformly by 1°C (1.8°F), but such a calculation gives a bound on what might be expected in a warming planet. Condon and Sheng (2011) used future sea level values for southwest Florida between 0.7 feet and 4.9 feet in 2100 for their study of hurricane storm surge inundation. The calculations of NOAA (2012) and the IPCC (2013) should be scrutinized within these contexts.

For Florida, the rise in sea level has been rather steady for more than 150 years (q.v. Maul and Martin 1993), but this is not necessarily the case for the next half century. All climate model projections are that sea level rise will accelerate, but no one forecast can be considered more definitive than the other. The parameters and form (logarithmic, polynomial, and exponential) of the forecast equation are uncertain, but clearly the Key West data to date show no statistically significant acceleration in sea level. Choosing too large or too small a value for future RSL has significant socioeconomic ramifications in coastal management (Berry et al. 2012), as does choosing the proper datum (q.v. Table 3).

Berry et al. (2012) recommend following the USACE (2011) estimates of 0.25–0.58 feet by 2030 and 0.75–2.0 feet by 2060. For the next decade or two, using the linear projection (0.11±0.01 feet 2015–2030) based on the data provided herein (q.v. Figure 3; Table 3) would be a factor of 2–5 less than the

USACE (2011) or NOAA (2012) forecasts. Re-evaluating decade by decade as the time-series of RSL observations (and vertical land motion) grows (Long et al. 2014) is a necessary course of action. If too large a projected rise is chosen, the investment in infrastructure may be unnecessarily costly; similarly, with not projecting adequately, coastal populations and investments may be placed at too high a risk. Consideration of the life-expectancy of coastal structures needs to be factored in as well.

Conclusions

Florida relative sea level rise for the last 100 years or so has been about ¾ feet (Table 1), a value not materially different from the global value of about 1 foot. The trend at Key West (Figure 3) shows that there is no statistically significant difference between a linear and a non-linear least-squares explanation of the variance (89% in all three cases analyzed; Table 2). This seems to be due to a combination of stability of vertical land motion, fairly constant volume transport in the Florida Current (Figure 4), small inverted barometer effect (Figure 5), small wind-setup, and perhaps a lower rate of regional sea level change (as measured by satellite altimetry; NOAA 2012). Whether or not these variables remain constant in the future is unknown, but it certainly illustrates the complexity of forecasting future Florida sea level.

As to decisions by coastal interests, with the wide range of global sea level forecasts (0.7 to 6.6 feet by 2100), the path forward should include the expected service-life of the infrastructure under consideration. Except for major projects such as power plants, which have a service-life on the order of 50+ years, linear sea level rise projections, plus a safety factor of at least 2X, for decadal-scale Florida projects (2015–2030) may be the most cost-effective decision. Other issues, such as coastal flooding from tropical storms, will of course, be exacerbated by sea level rise (Condon and Sheng 2011).

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Reply: Adaptation to Florida sea level rise will require creating resilient communities using forecasts constrained by verified observational data

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A discussion of resilience is valuable to the issue of sea level rise, especially in southeast Florida as Torres (2015) points out. Admittedly it was not the focus of my article, rather my objective was to present the sea level data in feet per century to coastal residents, and therefore to make the information more readily understood by using common units of measure. It was not intended that proposing the use of a linear projection with a safety factor for decadal-scale projects would encompass the planning needs for all coastal hazards, especially storm surge, rogue waves, and tsunamis. Damage and danger from such events is clearly exacerbated by sea level rise.

As part of appreciating Torres' dialog on resilience and adaptation planning, the issue of Total Risk (Nott 2006) should be incorporated into the discussion. Nott defines *Total Risk* as:

$$Total\ Risk = Hazard \times Elements\ at\ Risk \times Vulnerability,$$

where *Hazard* is the probability of occurrence, *Elements at Risk* is a measure of population, infrastructure, and economies affected by a hazard, and *Vulnerability* quantifies societal attitudes and preparedness. For Florida sea level rise, the probability of occurrence is clearly equal to unity, the socioeconomic effect varies around the state and is highest in heavily developed urban areas, and vulnerability – the awareness of risk – is the responsibility of educators and reporters and civil servants and elected officials.

It is the *Vulnerability* term in Nott's equation that is most worrisome as coastal development grows, as aquifers are drawn down and saltwater intrusion increases, and as infrastructure is stressed, all by relative sea level (RSL) rise. If "…an adaptive resilience framework will allow planning to begin even in the face of uncertainty, focusing on innovation and experiential learning…" (Torres 2015), then awareness of vulnerability is at the forefront of community planning, and *Total Risk* is thus not overwhelmed by one term in the equation.

Perhaps, taking a clue from the National Weather Service's programs to create StormReady® and TsunamiReady® communities, an effort to develop "ClimateReady" cities and counties and states will reduce further the *Vulnerability* term in *Total Risk* assessment, and lead to more resilience from increased awareness.
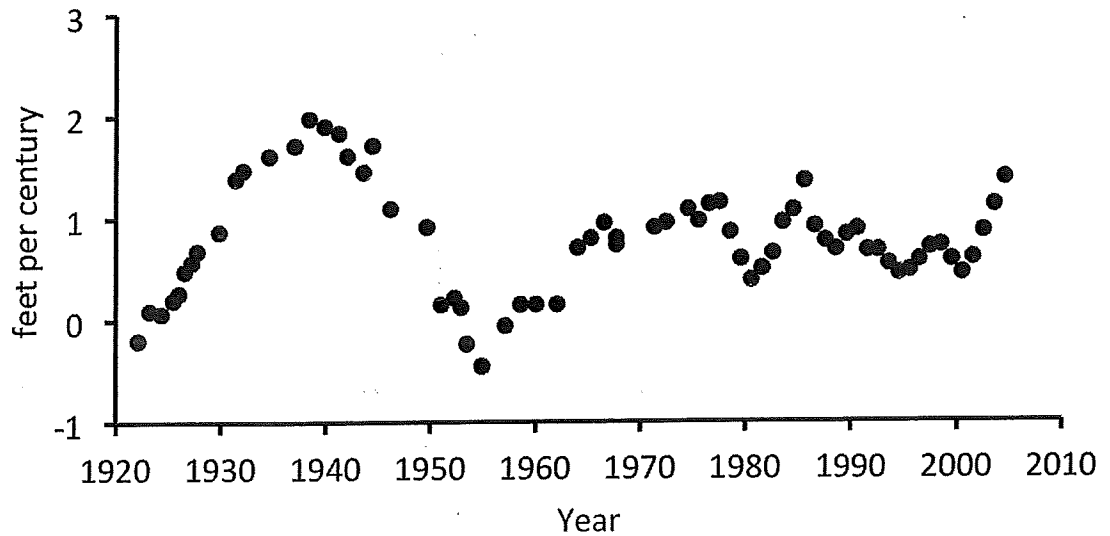
Figure 1. Linear least-squares trend at Key West, Florida, as a function of a running 19-year cycle emulating the 18.61 lunar nodal cycle. The ensemble trend at Key West (1913–2014) is h(t)=7.68 × 10^{-3} × year − 1.11; $r^2 = 0.89$.

Bolter and Heimlich (2015) have added many additional references to the issue of sea level rise, and this enhances the literature for Florida coastal interests. They write (he) "...recommends a linear projection or other conservative estimates to avoid 'unneeded' costs," but this fails to mention that I limited the use of such a linear projection (plus a safety factor) to *decade-scale* projects. For multi-decadal scale projects, the difficulty of choosing future global sea level heights from a range between 0.7 feet and 6.6 feet at the end of this century is fully recognized (Maul 2015; Figure 6). To put things into context, I noted that the maximum rate of global sea level rise during the last deglaciation ca. 18,000–8,000 years before the present, was 3.3 feet per century; NOAA projects a value double that of both the IPCC AR5 and the geological record for their upper range exponential scenario.

Bolter and Heimlich also wrote "Satellite altimetry... since 1993 shows that global sea level rise has increased significantly to 3.2 mm/yr." Using short records to estimate linear trend is compromised by the fact that a sine wave of the form $h(t) = a\sin(\omega t - \varnothing)$, when fitted with a least-squares linear equation, will have a trend depending on the amplitude a and the phase $\varnothing$. For example, for $\omega = \frac{2\pi}{T}$, where T is the 18.61 year period of the lunar nodal tide, $a = 2.2$ cm (Baart et al. 2012), and if $\varnothing = \pi$, the linear least-squares fit is $h(t) = 0.165y - 1.54$; $r^2 = 0.43$, where y is the year in the lunar nodal cycle. This is a worst case scenario, but it could add about h = 1.5 cm (0.05 feet), depending on the phase, to a short record such as the current estimate from satellite altimetry. To reduce this potential error, record lengths of at least three lunar nodal cycles (56 years) are preferred as this would reduce the maximum potential error to h = ±0.6 cm (±0.02 feet) in half a century.

For sea level at Key West, a series of 19-year linear trends is fitted to the 1913–2014 tide gauge record and is shown in Figure 1. The first point is the fit to 1913–1931, the second point is the fit to 1914–1932, etc., and the last point is

the fit to 1996–2014. The effect of the possible trend from the lunar nodal cycle (±0.05 feet in 19 years) is seen to be small compared to the variability of the trend in the RSL signal at Key West. This is not to say that a two-phase regression or a nonlinear fit will not, in the future, show a statistically significant acceleration of RSL in Florida.

My original intention was to summarize and then explore each of the variables giving cause to RSL change (i.e., melting continental ice, thermohaline expansion or contraction, vertical land motion, ocean currents and prevailing winds, and atmospheric barometric pressure). Most likely, the 0.73 ± 0.09 feet of average Florida RSL rise during the last century reported is caused by glacial melt, which is adding water to the ocean's volume, and warming seas resulting in thermal expansion – eustatic sea level rise. Coastal communities in their adaptation planning need to appreciate that RSL is not only an issue of global climate change, but also of other geophysical variables listed above. And RSL can have very different rates from locale to locale, as I illustrated using St. Petersburg (0.82 ± 0.05 feet per century) and Cedar Key (0.53 ± 0.06 feet per century).

Many RSL records are not from a single site, but from multiple sites within a small area. The tide gauge at Key West for example, was moved as the causeway to Fort Taylor was turned into a lawn, and several times thereafter, but the record of water levels is continuous due to the quality of the differential leveling surveys from the gauges to the juxtaposed tidal benchmarks. Because of impeccable record keeping, survey accuracies, and professional integrity, NOAA data is the gold standard. Confidence in such geodetic connections and tide gauge observations allowed us to merge the three separate records at Miami into a single record (Maul and Martin 2015). There, as with other Florida RSL records (and along the Dutch coast as well; Baart et al. 2012), there is no statistically significant evidence of accelerated RSL.

That "Florida had recorded 5–8 inches of sea level rise in the last 50 years" (Adams 2014) is simply not consistent with the record; Maul and Martin (2015) report 9.2 ± 0.5 inches per century or 4.6 ± 0.3 inches in 50 years based on the merged Miami RSL record. Scientific integrity demands using only the best available and refereed information in public disclosure. "Putting local sea level variations in proper context is most important for local decision-makers" (Gill 2015), and for the credibility of scientists, engineers, and planners. The *Survey of the Coast* was founded by President Thomas Jefferson in 1807, and NOAA continues the proud tradition of providing the most reliable and accurate sea level information to the coastal community. RSL data from Gill's NOAA office is undoubtedly a national pride and one without which I could not have explored Florida's sea level history with confidence.

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