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

George A. Maul

Florida Institute of Technology, Melbourne, FL 32901

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:

$$\textit{Total Risk} = \textit{Hazard} \times \textit{Elements at Risk} \times \textit{Vulnerability},$$

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.

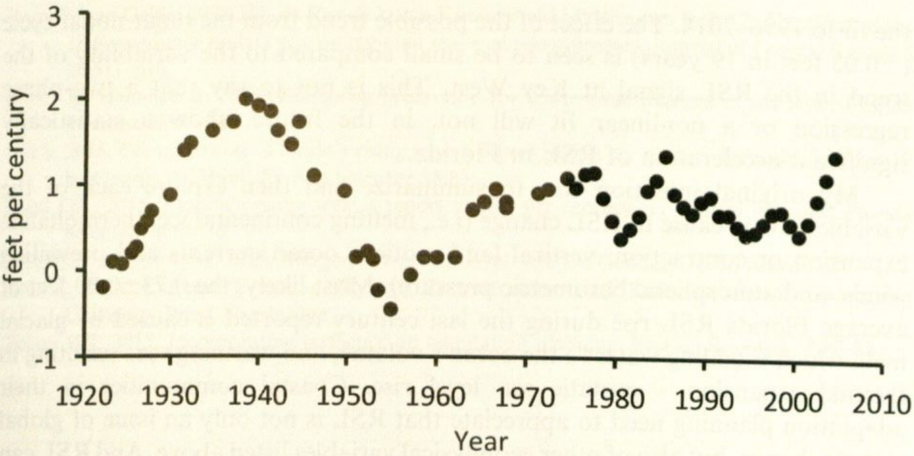

Figure 1. Linear least-squares trend at Key West, Florida, as a function of a running 19-year cycle emulating the 18.61 lunar nodal cycle. The ensemble trend at Key West (1913–2014) is $h(t)=7.68 \times 10^{-3} \times \text{year} - 1.11$; $r^2 = 0.89$.

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.

References

Adams D. 2014. South Florida sea level rise needs urgent action: task force. Reuters http://www.reuters.com/article/2014/07/01/us-usa-florida-sealevel-miami-idUSKBN0F65IN20140701. Accessed: February 18, 2015.

Baart F, van Gelder PHAJM, de Ronde J, van Koningsveld M, Wouters B. 2012. The effect of the 18.6-year lunar nodal cycle on regional sea-level rise estimates. Journal of Coastal Research 28:511–516.

Bolter K, Heimlich B. 2015. Exercising precaution for irreversible changes in sea level. Florida Scientist 78:77–79.

Gill S. 2015. Comments on "Florida's rising seas: a report in feet per century for coastal interests" by George A. Maul. Florida Scientist 78:83.

Maul GA. 2015. Florida's rising seas: a report in feet per century for coastal interests. Florida Scientist 78:64–76.

Maul GA, Martin DM. 2015. Merged Miami sea level. Marine Geodesy 38: in press.

Nott J. 2006. Extreme Events – Physical Reconstruction and Risk Assessment. Cambridge University Press, Cambridge.

Torres HR. 2015. Incorporating resilience on adaptation planning. Florida Scientist 78:80–82.