SEA LEVEL RISE AROUND PUERTO RICO: A PROJECTION

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For additional discussions related with sea level rise, please visit
https://coastalhazardspr.wordpress.com/

NOTE: In this report whenever a verbatim quote is given, it will be enclosed in quotations (“”).

EXECUTIVE SUMMARY:

It is important to understand that this report deals with permanent flooding, not flooding due to extreme meteorological events, like storm surges and winter storm waves. The latter is often traumatic and painful, but is ultimately temporary. Residents and businesses can evacuate and then come back to rebuild, even if it takes years. Technology and engineering may even allow for flood proofing that prevents major disruptions. Sea level rise, on the other hand, is happening slowly and steadily over time with serious and permanent consequences for a growing number of places. The flood waters of sea level rise won’t recede once a storm passes. They will be permanent and over time will inundate our streets and homes, intrude into our drinking water aquifers, fill our tunnels, basements and storm drains, saturate our brownfields and other contaminated sites and eventually overwhelm low-lying rail lines and wastewater treatment and power plants. They will permanently change our coastline. And sea level rise exacerbates the impact of storm surges, extending its reach inland.

The task I was asked for by PRCCC was to use the US Army Corps of Engineers (USACE) Sea Level Rise calculator to make projections of sea level rise for the year 2100. After assessing many reports, and peer-reviewed literature, I decided to also include estimates based on climate models, by looking what has been done in Southeast Florida, New York, and New Jersey. And, luckily, a January 2017 report which does include Puerto Rico and the USVI (Sweet et al., 2017).

All reports emphasize the large uncertainty of making projections for 2100, mainly due to the present difficulty of predicting the future behavior of ice shelves. This is somewhat taken care of by the presentation of scenarios, which have different probabilities of happening. And all reports discuss the special consideration that has to be given to the High and Extreme scenarios due to the consequences of them happening.

Having stated this, the projections I make are the following for Local Relative Sea Level (LRSLR) rise:

Based on the USACE Sea Level Rise calculator, and using the satellite-derived Global Mean Sea Level Rise of 3.3 mm/year (Leuliette and Scharroo, 2010; Nerem et al., 2010; Cazenave et al., 2014; Leuliette and Nerem, 2016), the 2100 projection of Local Sea Level (LSL) rise:

- ***USACE and NOAA Low:*** ***LRSL rise = 0.36 m***
- ***USACE Intermediate/NOAA Intermediate Low:*** ***LRSL rise = 0.67 m***
- ***NOAA Intermediate High:*** ***LRSL rise = 1.37 m***
- ***USACE High:*** ***LRSL rise = 1.67 m***
- ***NOAA High:*** ***LRSL rise = 2.17 m***

Based on six process-based (climate models) scenarios presented in Sweet et al., 2017, and using results for Puerto Rico and the USVI (values within parenthesis are Global Mean Sea Level Rise projections for 2100 for the respective scenario):

- ***Low (0.3 m) Scenario:*** ***LRSL rise = 0.33 to 0.36 m.***
- ***Intermediate-Low (0.5 m) Scenario:*** ***LRSL rise = 0.45 to 0.50 m.***
- ***Intermediate (1.0 m) Scenario:*** ***LRSL rise = 1.0 to 1.1 m.***
- ***Intermediate-High (1.5 m) Scenario:*** ***LRSL rise = 1.95 to 2.1 m.***
- ***High (2.0 m) Scenario:*** ***LRSL rise = 2.8 to 3.0 m.***
- ***Extreme (2.5 m) Scenario:*** ***LRSL rise = 3.5 to 3.75 m.***

We should also have in mind the more dramatic projections by Hansen et al. (2016) and DeConto and Pollard (2016), which use very sophisticated modeling.

INTRODUCTION:

The Puerto Rico Climate Change Council asked me to supply information about what could be expected in terms of sea level elevation for the years 2050 and 2100, basically by running the US Army Corps of Engineers (USACE) Sea Level Rise Calculator. It has been attributed to the great Yogi Berra the statement "It's tough to make predictions, especially about the future". Given this wise caveat, I will try my best, given the time allowed, to make an intelligent guess based on the vast literature about the topic. It should be understood that this is a "moving target", where things are constantly changing. And predictions vary widely. Figure 1 shows present predictions going from 1987 up to 2013. It should be noted that an important projection missing from Figure 1 is the one by James Hansen, and his group (Hansen et al., 2016). In the paper, Hansen and his group of 18 colleagues, use numerical climate simulations, paleoclimate data, and modern observations to state that "Humanity faces near certainty of eventual sea level rise of at least Eemian proportions, 5–9 m, if fossil fuel emissions continue on a business-as-usual course, e.g., IPCC scenario A1B that has CO^2 ~ 700 ppm in 2100." And such sea level rise in a, relatively speaking, short period of time, has been documented to have happened in the past. Another recent modeling attempt to project sea level rise to 2100, also including ice-fracture processes with inferences from paleoclimatic data, comes to a projection for Global Mean Sea Level Rise (GMSLR) of 1.84 m and an uncertainty range that extends above 2 m (DeConto and Pollard, 2016).

As can be seen from Figure 1, there is a relatively wide menu to choose from, especially so if you include Hansen et al. 2016, and DeConto and Pollard (2016) predictions. Based on reading multiple peer-reviewed articles it looks to me that a minimum of 1 m by 2100 is gaining more credibility as time passes by. Which puts it in the range of all, but three, of the investigations listed in Figure 1 (approximately 79% of the investigations in Figure 1, including Hansen et al.).

ETL 1100-2-1
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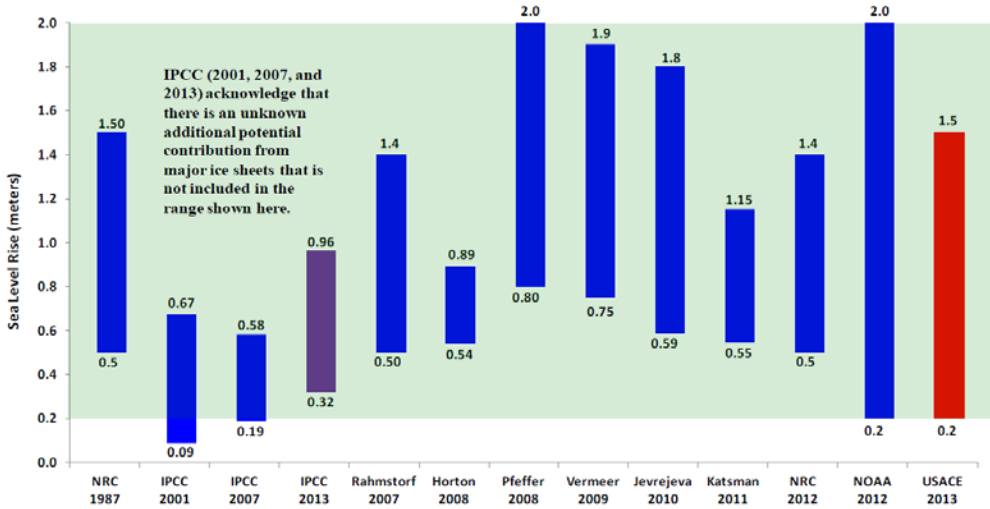

Figure 2. Comparison of maximum and minimum estimates of global sea level rise by 2100.

Figure 1 – Table of sea level rise projections, taken from USACE, ETL 1100-2-1, expiration date of March 2019, page 2-2.

In general, predictions of Sea Level Rise (SLR) can be broken down into process-based (like Hansen et al, 2016), and much simpler ones based on extrapolations into the future of simpler curve fitting equations (Visser et al, 2015), data-based functions (Wu et al., 2007), or just the assumption that the future rise will behave in some nonlinear fashion, usually assumed to be like a 2nd order polynomial (National Research Council, 1987).

CALCULATION OF THE PROJECTION:

USACE SLR Calculator

For the previous PRCCC Puerto Rico's State of the Climate 2010-2013 report (PRCCC, 2013) use was made of a SLR calculator freely available on the Internet (http://www.corpsclimate.us/ccaceslcurves.cfm), which is based on USACE, 2013.

It is important to recognize that we must distinguish between Global Sea Level (GSL) rise – or Global Mean Sea Level (GMSL) rise and Local Sea Level (LSL) rise. "Local sea-level changes differ significantly from global-mean sea-level change as a result of (1) non-climatic, geological background processes; (2) atmosphere/ocean dynamics; and (3) the gravitational, elastic, and rotational "fingerprint" effects of ice and ocean mass redistribution. Though the research communities working on these different effects each have a long history, the integration of all these different processes into interpretations of past changes and projections of future change is an active area of research." (Kopp et al., 2015)

The philosophy behind the method of predicting future SLR used in the USACE calculator is best understood as follows (Obeysekera et al., 2013).

- Total sea level rise, T(t), is expressed as the sum of two components: a eustatic plus steric component, representing global sea level rise, G(t), and a local component, L(t), representing

factors such as uplift/subsidence (Vertical Land Motion – VLM), Global Isostatic Adjustment (GIA), and other natural and anthropogenic-induced subsidence

$$T(t) = L(t) + G(t). \quad (1)$$

Obviously, this is very simplified vision of what's happening, in which various very complex sources of SLR are consolidated into just two components.

- For the eustatic and steric component, G(t), guidance from the US National Research Council (NRC 1987) is followed:

$$G(t) = b\,t + 0.5at^2 \quad (2)$$

where "b" and "a" are coefficients representing a base rate and acceleration of sea level rise, respectively. The factor 0.5 is introduced so that "a" has the physical interpretation of acceleration.

- The local component, L(t), exhibits significant spatial and interannual variability, because it represents localized oceanographic, meteorological, and geophysical forcings. Following NRC (1987), it is assumed that L(t) ~ t, varies linearly with time. They justify this by stating that models available for GIA provide estimates that look linear in time over the typical planning horizons of coastal projects. Although it is possible that GIA could present a nonlinear behavior, there is no reliable data yet to complicate things. Thus L(t) linearly proportional to time (t) is a justified first step. This is especially true for Puerto Rico, where GIA effects are very small, if any at all.
- Thus, Eqt. 1 becomes

$$T(t) = L(t) + G(t) = [L(t) + b\,t] + 0.5\,a\,t^2 = c\,t + 0.5a\,t^2 \quad (3)$$

where now "c" incorporates both <u>linear</u> contributions from <u>global</u> rise, as well as the <u>local</u> rise component. With this formulation, the coefficients "c" and "a" represent the current rate of sea level rise and acceleration, respectively. The variable "a "is based on proposed scenarios about the future, and how they might impact the acceleration.

NOTE: We must be careful in not confusing the notation. Variable "a" (which stands for "acceleration") is the same as variable "b" used in the USACE calculator manual.

Actually, the quadratic curve was selected by "some of the scientific community for simplicity" (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, 2015).

In the USACE calculator, "t" is years since 1992. So for example, if you want a forecast in the year 2060, then t = 2060 – 1992 = 68. Due to a present lack of information, assuming a constant "a" is as good as any other approach, with the exception of full-blown climate models.

NOTE:
The year 1992 has been selected as the initial year of the projection because it is the center of the current mean sea level National Tidal Datum Epoch of 1983-2001. A tidal datum epoch is a 19 year period adopted by the National Ocean Service as the official time segment over which

tide observations are used to establish tidal datums such as mean sea level, mean high water etc. The National Tidal Datum Epoch is revised every 20-25 years to account for changing sea levels and land elevations.

When one activates the program one sees a screen as shown in Figure 2.

1. Project Start Year (set to 2017)
2. Project End Year (set to 2100)
3. Output Units (set to Meters)
4. Output Datum (set to Local Mean Sea Level – LMSL; changing it to NAV88 introduces no change at all)

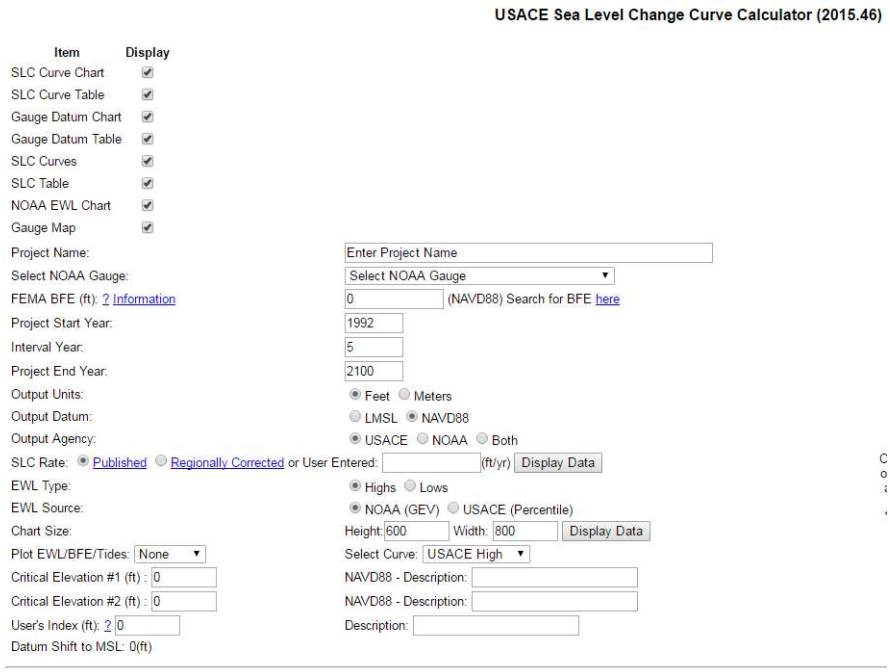

Figure 2

5. SLC Rate. This is the variable "c" in Equation 3 above. According to the USACE calculator manual, "c" is a generally accepted eustatic (i.e., global, with contributions from ice melt and steric effects) SLR (taken as 1.7 mm/year by USACE in the manual), plus any VLM. The VLM is obtained from Zervas et al., 2013. Thus, if the VLM = -1.23, say, then the land is subsiding and, therefore, c = 1.7 mm/year + 1.23 mm/year = 2.93 mm/year. The GMSL rate of rise is increased. Since the land is subsiding, then we must add the (negative) VLM value to the eustatic rate of SLR. In the case where VLM is positive, like shown in Zervas et al. (2013) for San Juan and Magueyes (that is, both are rising), then c = 1.7 – 0.02 = 1.68 mm/year for San Juan, and c = 1.7 – 0.49 = 1.21 mm/year for Isla Magueyes.

But according to the legend in Figure 3 the VLM values used in the calculator for the PRCCC 2013 study have opposite signs from the ones discussed in the paragraph above.

6. If one sets Output Agency = Both, one will get 5 SLR curves, one for each of 5 scenarios (or accelerations):

i) USACE/NOAA Low Rate (as stated above, this should be an extrapolation of the historic, linear, rate of sea level rise – starting in 1992. Thus there is no acceleration: a = 0, is used.)

ii) USACE Intermediate, NOAA Intermediate Low (a = 2.71×10^{-5})
iii) NOAA Intermediate High Rate (a = 8.71×10^{-5})
iv) USACE High Rate (a = 1.13×10^{-4})
v) NOAA High Rate (a = 1.56×10^{-4})

A word of caution about the scenarios listed above. First, the goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures (http://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/index.html, IPCC Data Distribution Centre, Scenario Processes for AR5). Second, the use of different scenarios is the chosen way to deal with uncertainties due to trends in concentration of GHG and other influences on the climate (Moss et al., 2010).

The other options shown in Figure 2 are of no consequence for the projection desired. For both San Juan and Isla Magueyes several options will be presented, according to varying values of the variable "SLC Rate". The other input variables are left fixed.

The first attempt I tried was to reproduce the results for PRCCC 2013, shown in Figure 3. Notice that the projection in question extends up to 2150.in our case we will stop at 2100. This was done by setting SLC Rate = 0.0017, as given in the legend of Figures 52 and 53 in the PRCCC 2013 report (see Figure 3). Figure 4 shows the input screen, and Figure 5 shows the output SLR curves as obtained from the input data shown in Figure 4. The results are:

- Figure 3 shows a Relative Rise of approximately 1.5 m (San Juan) for what is called the High (Modified NRC Curve 3). It should be added that it is USACE High. According to Teeple et al. (2013; page 16), this USACE projection is for "historic, modified NRC Curve I and modified NRC Curve III rates of sea level change developed for Northeast Florida per USACE Engineering Circular (EC) 1165-2-212. This EC is based on guidance in the National Research Council (NRC) report, Responding to Changes in Sea Level; Engineering Implications dated September, 1987. The projections are developed using the historic rate of sea level rise at Mayport as reported by NOAA (2.29 mm/yr)." The assumed Global SLR by 2100 for this scenario is +1.5 m (Teeple et al., 2013). Figure 5 shows a value of 1.5 for the USACE High Scenario.
- Figure 3 shows a Relative Rise of approximately 0.4 m (San Juan) for what is called the Intermediate (Modified NRC Curve 1). Again, it is USACE Intermediate. The assumed Global SLR by 2100 for this scenario is +1.2 m (Teeple et al., 2013). Figure 5 shows a value of 0.5 for the USACE Intermediate Scenario.
- Figure 3 shows a Relative Rise of approximately 0.1 to 0.2 m (San Juan) for what is called the Low (Historic). Which just a linear extrapolation of the present historic trend. Figure 5 shows a value of approximately 0.2 for the USACE Low Scenario. It should be mentioned that during September-October 2015 the monthly means sea level elevations for San Juan went slightly higher than 0.2 m. So this Low scenario is out of consideration.
- Therefore, I was able to recreate the work done for PRCCC 2013, which is encouraging.

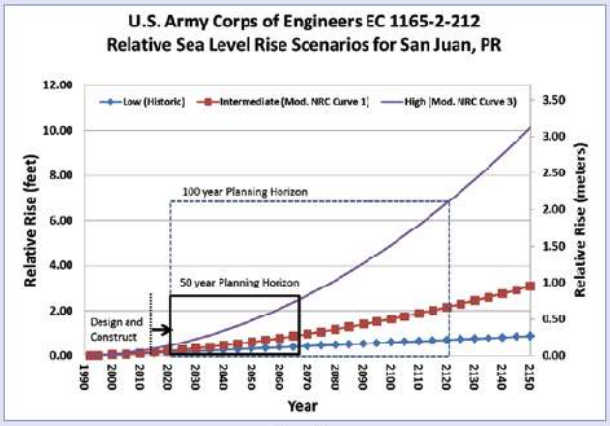

Figure 52

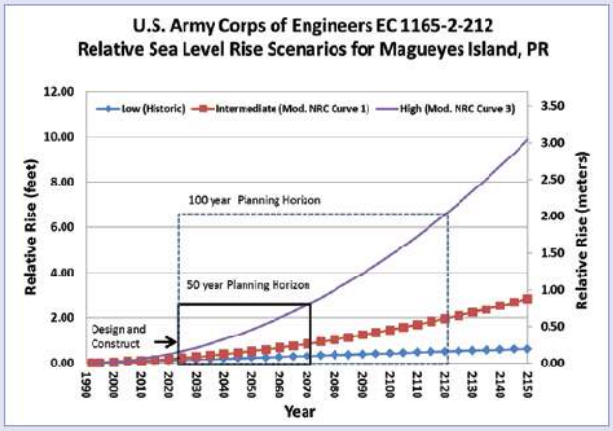

Figure 53

Figures 52 and 53: The U.S. Army Corps of Engineers' sea level rise curves are computed using the global rate of sea level rise (1.7 mm/year), NOAA tide gauge data for Puerto Rico (1.65 mm/year rise for San Juan since 1962 and 1.35 mm/yr rise for Magueyes Island since 1955), and the estimated local vertical land movement rates of -0.02 mm/yr for San Juan and -0.49 mm/year for Isla Magueyes. The Figures show a 50 year and 100 year planning horizon for adaptation with sea level rise estimates ranging from 0.07 to 0.57 meters (0.20 to 1.87 feet) above current mean sea level by the year 2060 and between 0.14 and 1.70 meters (0.40 to 5.59 feet) above current mean sea level by the year 2110.

Figure 3 - Results of SLR projections for Puerto Rico as shown in Figure 66 of the report PRCCC (2013).

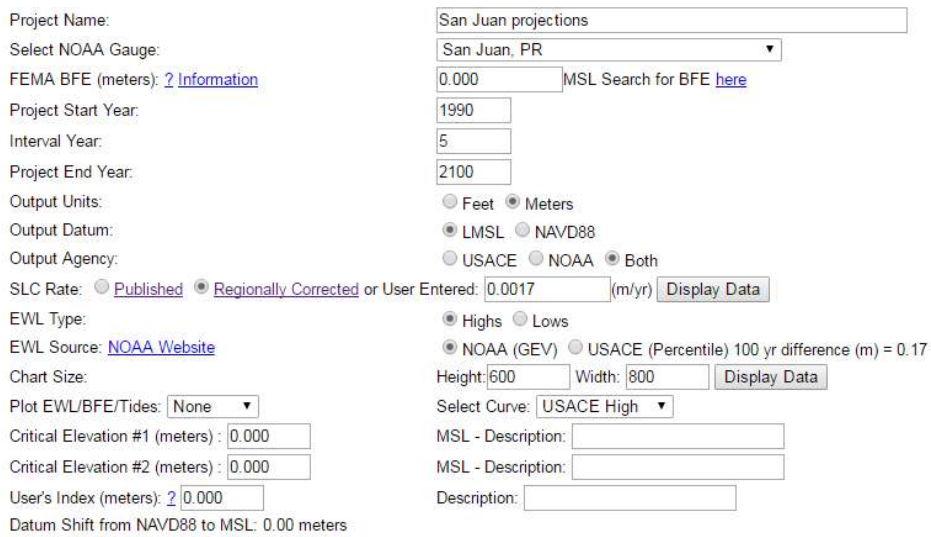

Figure 4 – Input screen for attempt to recreate the PRCCC 2013 results.

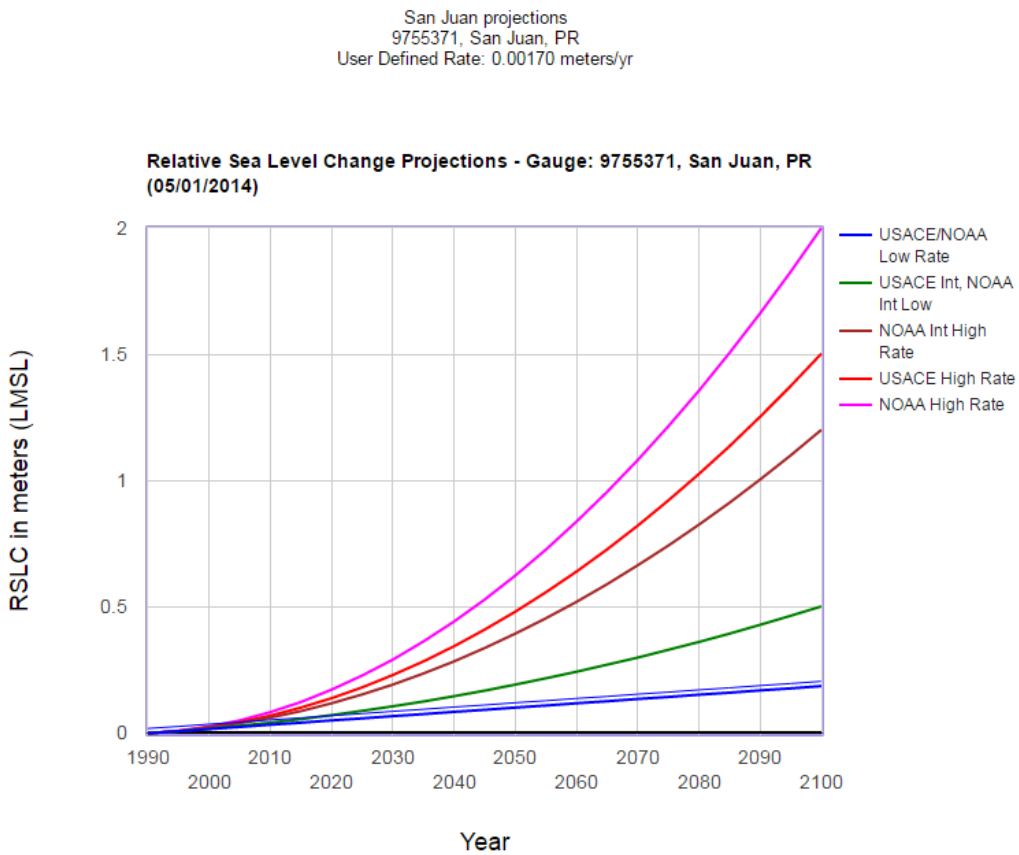

Figure 5 – Output for the inputs shown in Figure 4.

In what follows I will use the calculator with three different values for "c". This is done in the SLC Rate line of the input screen, using Regionally Corrected and manually entering in the rectangular box the value to be used, as discussed below:

- Option 1: "c" is given by the generally accepted present global SLR of approximately 3.3 mm/year, obtained from satellite data (Leuliette and Scharroo, 2010; Nerem et al., 2010; Cazenave et al., 2014; Leuliette and Nerem, 2016), almost twice the 1.7 value used in PRCCC 2013. Still accepting the VLM results from Zervas et al. (2013) (which were derived using a GMSLR of 1.7 mm/year), we then get the following estimates for "c" (I am using the correct sign for the VLM values):

  San Juan: c = 3.3 – 0.02 = 3.28 mm/year
  Magueyes: c = 3.3 – 0.49 = 2.81 mm/year

  Note that the global mean sea level rise of 3.3 mm/year is being corrected by a local factor, which is the stated VLM for San Juan and Isla Magueyes, in agreement with the discussion above stated right after Eqt. 3. The difference with what was done for PRCCC (2013) is that we have increased the global mean sea level rise from 1.7 mm/year to the presently accepted value of 3.3 mm/year.

  > *A note of caution should be stated about the use of the variable SLC Rate in the calculator. If we use "Published" it automatically uses values available for the tide gauges up to 2015: 2.02 mm/year for San Juan and 1.7 mm/year for Isla Magueyes (these values appear in the NOAA web page https: //tidesandcurrents.noaa.gov/sltrends/sltrends.html). This page shows Local Relative MSL (LRMSL) trends as computed from tide gauge data. They are not Global MSL Rise (GMSLR), as the USACE calculator manual states in pages 4 and 5. In the manual of the USACE SLR calculator, version 2015.46, page 5, it is stated that one should use a "generally accepted eustatic sea level rise rate", corrected for VLM. They assume a eustatic rate of 1.7 mm/year, which seems low by today's measurements. The problem is that the values used by the calculator are different from the above two values of 2.02 (San Juan) and 1.7 (Isla Magueyes), even after correcting for VLM. When one does the calculation, for San Juan it comes up with 1.65 mm/year, and for Isla Magueyes it comes up with 1.35 mm/year. Apparently the USACE calculator is using old rates. It is not doing what it is supposed to do, which is to go to the above link and pick out the LRMSL rate corresponding to the study site. So I won't be using this option (Published).*

- Option 2: "c" is given by the long-term, historical, SLR rate as obtained by doing a LLS fit to all of the data for San Juan and Magueyes (obtained from the NOAA web page). My most up-to-date long term estimate using a Linear Least Squares – LLS – fit to all of the San Juan data (updated up to December 2016; see https://coastalhazardspr.wordpress.com/; you can get to this page by using the previous link, or by using http://coastalhazards.uprm.edu) is 2.04 mm/year = 0.00204 m/year since 1965, which is slightly larger than the "Published" value at the NOAA web page https: //tidesandcurrents.noaa.gov/sltrends/sltrends.html, and larger than the one automatically picked out by the calculator by a factor of 1.24. This is the value used for San Juan. And for Isla Magueyes I used 1.8 mm/year = 0.0018 m/year, larger by a factor of 1.33. So,

instead of evaluating "c" as the satellite-derived GMSLR – but corrected for VLM - (3.3 mm/year, see above), one is consistent with the calculator if one uses the historical Local MSLR, as estimated from LLS fit of the tide gauge data for San Juan and Isla Magueyes. These values are 2.04 mm/year (San Juan) and 1.80 mm/year (Isla Magueyes). These values come from fitting all of the data, and thus are robust. After correcting for VLM we get:

San Juan: c = 2.04 – 0.02 = 2.02 mm/year
Isla Magueyes: c = 1.80 – 0.49 mm/year = 1.31 mm/year.

- Option 3: And then there is a 3rd option. An issue with Option 2 above is that the values used for "c" are the results of a LLS fit starting in 1962 for San Juan and 1955 for Isla Magueyes. The calculator manual states in page 7 that "Relative sea level change will always begin its computations in 1992, …". So it is reasonable to wonder what would be the results if we modify Option 2 by using the results of a Linear Least Squares fit of the Puerto Rico data starting in 1993, the start of satellite observations. Not starting in 1962 for San Juan, and 1955 for Isla Magueyes. In appendix B of the document 2 – SEA LEVEL RISE WATCH AROUND PUERTO RICO_v2 (found in https://coastalhazardspr.wordpress.com/) this new rate is computed for both San Juan and Isla Magueyes, and it gives 3.95 mm/year and 4.20 mm/year for San Juan and Isla Magueyes, respectively. Therefore, we get:

  San Juan: c = 3.95 – 0.02 = 3.93 mm/year
  Magueyes: c = 4.20 – 0.49 = 3.71 mm/year

  To summarize, for both San Juan and Isla Magueyes three options will be used, both falling under the option "User Entered":

  Option 1 for SLC Rate (based on the satellite-derived Global Mean Sea Level Rise):
  San Juan: c = 3.3 – 0.02 = 3.28 mm/year
  Magueyes: c = 3.3 – 0.49 = 2.81 mm/year

  Option 2 for SLC Rate (based on Local Linear Historical SLR trend – All of the data):
  San Juan: c = 2.04 – 0.02 = 2.02 mm/year
  Isla Magueyes: c = 1.80 – 0.49 mm/year = 1.31 mm/year.

  Option 3 for SLC Rate (based on Local Linear SLR trend since 1993):
  San Juan: c = 3.95 – 0.02 = 3.93 mm/year
  Magueyes: c = 4.20 – 0.49 = 3.71 mm/year

Finally, out of curiosity, there are two other options that I would like to test. No use of the USACE calculator.

- **Option 4:** This is fit a 2nd order polynomial to the data, starting in 1992, without any preconceived values. Just a pure 2nd order fit, and use it to extrapolate all the way to 2100. Recall that the calculator does not know the history of how sea level is rising in the island, with

the exception of the overall rate of sea level rise. It is a fact (see document 2 – SEA LEVEL RISE WATCH AROUND PUERTO RICO_v2 (found in https://coastalhazardspr.wordpress.com/) that since approximately 2001 there has been an almost monotonic acceleration in the long term (historical) data. And that in 2010-2011 the acceleration further increased, as documented in peer-reviewed literature (to be discussed in https://coastalhazardspr.wordpress.com/). Let's see what the 2nd order least square fit gives.

- **Option 5**: This is a LLS fit (1st order polynomial) starting in 2010-2011, the start of what looks like a noticeable acceleration, and use it to extrapolate all the way to 2100. The time derivative of a 1st order polynomial in time gives a constant. That is, the acceleration is constant. In other words, let's see what we get for 2100 if the acceleration observed starting in 2010-2011 remains constant.

The curves for all of these scenarios, including NOAAs, are presented in the SLR curves to be shown below.

In what follows, for each option (1 to 5), we will see an image of the input screen to the USACE calculator, followed by a table listing the output values that go into plotting the sea level rise curves that follow. One sea level rise curve for each of five scenarios adopted by the calculator.

It should be mentioned that Option 1 is the only one that uses a Global Sea Level Rise value (the satellite-based GMSLR). In this sense, the equations in page 3 above would give the same result everywhere on the planet if it were not for the suggested local correction due to local VLM.

SEA LEVEL RISE PROJECTIONS (based on the USACE Calculator):

SAN JUAN

a) Option 1: SLC Rate: 3.93 mm/year

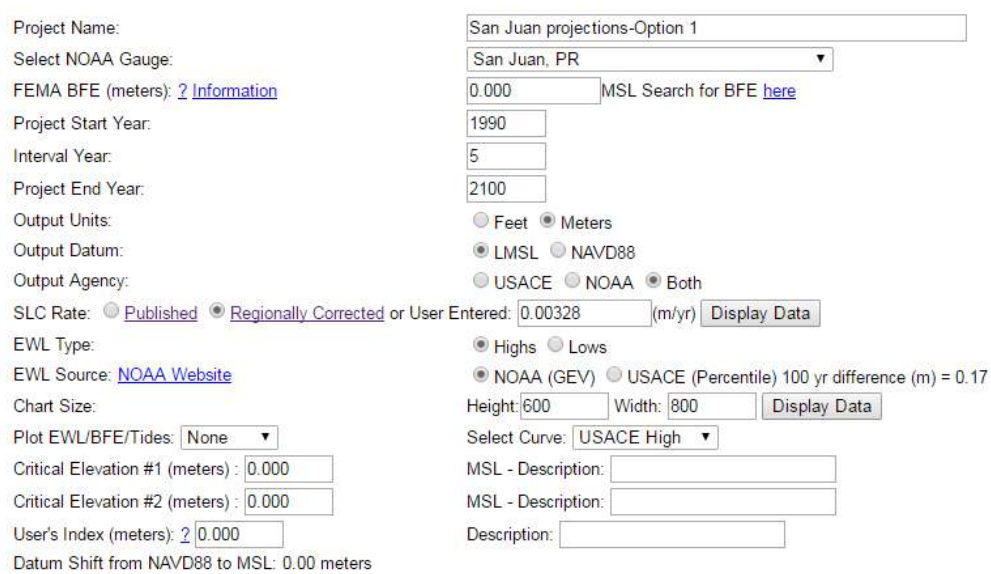

Figure 6 – Input configuration for Option 1, San Juan

Table 1: SLR for Option 1, San Juan.

San Juan projections-Option 1
9755371, San Juan, PR
User Defined Rate: 0.00328 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low NOAA Low	USACE Int NOAA Int Low	NOAA Int High	USACE High	NOAA High
1990	-0.01	-0.01	-0.01	-0.01	-0.01
1995	0.01	0.01	0.01	0.01	0.01
2000	0.03	0.03	0.03	0.03	0.04
2005	0.04	0.05	0.06	0.06	0.07
2010	0.06	0.07	0.09	0.10	0.11
2015	0.08	0.09	0.12	0.14	0.16
2020	0.09	0.11	0.16	0.18	0.21
2025	0.11	0.14	0.20	0.23	0.28
2030	0.13	0.16	0.25	0.29	0.35
2035	0.14	0.19	0.30	0.35	0.43
2040	0.16	0.22	0.36	0.42	0.52
2045	0.17	0.25	0.42	0.49	0.61
2050	0.19	0.28	0.48	0.57	0.71
2055	0.21	0.31	0.55	0.66	0.83
2060	0.22	0.35	0.63	0.75	0.94
2065	0.24	0.38	0.70	0.84	1.07
2070	0.26	0.42	0.79	0.94	1.20
2075	0.27	0.46	0.87	1.05	1.35
2080	0.29	0.50	0.96	1.16	1.49
2085	0.31	0.54	1.06	1.28	1.65
2090	0.32	0.58	1.16	1.41	1.82
2095	0.34	0.63	1.26	1.54	1.99
2100	0.35	0.67	1.37	1.67	2.17

NOTE: During September-October 2015 the monthly mean sea level for the San Juan tide gauge was above 0.2 m (0.203 for September and 0.206 for October; these are elevation relative to the Mean Sea Level (MSL) taken from the last National Tidal Elevation Epoch of 1983-2001). It is important to realize that these elevations surpass the 2055 projection for the USACE Low/NOAA Low projections, the 2035 projection for the USACE Int/NOAA Int Low projections, the 2025 projection for the NOAA Int High projection, the 2020 USACE High projection, and are almost there with the 2020 projection of the NOAA high projection. During those peaks many things happen, like inundation of streets and houses (see https://coastalhazardspr.wordpress.com/), critical beach erosion (Loiza is a good example), erosion of offshore sandy islets (tourists' attractions), and drainage problems when it rains (including the critical facility of the Luis Muñoz Marin International Airport, and elsewhere).

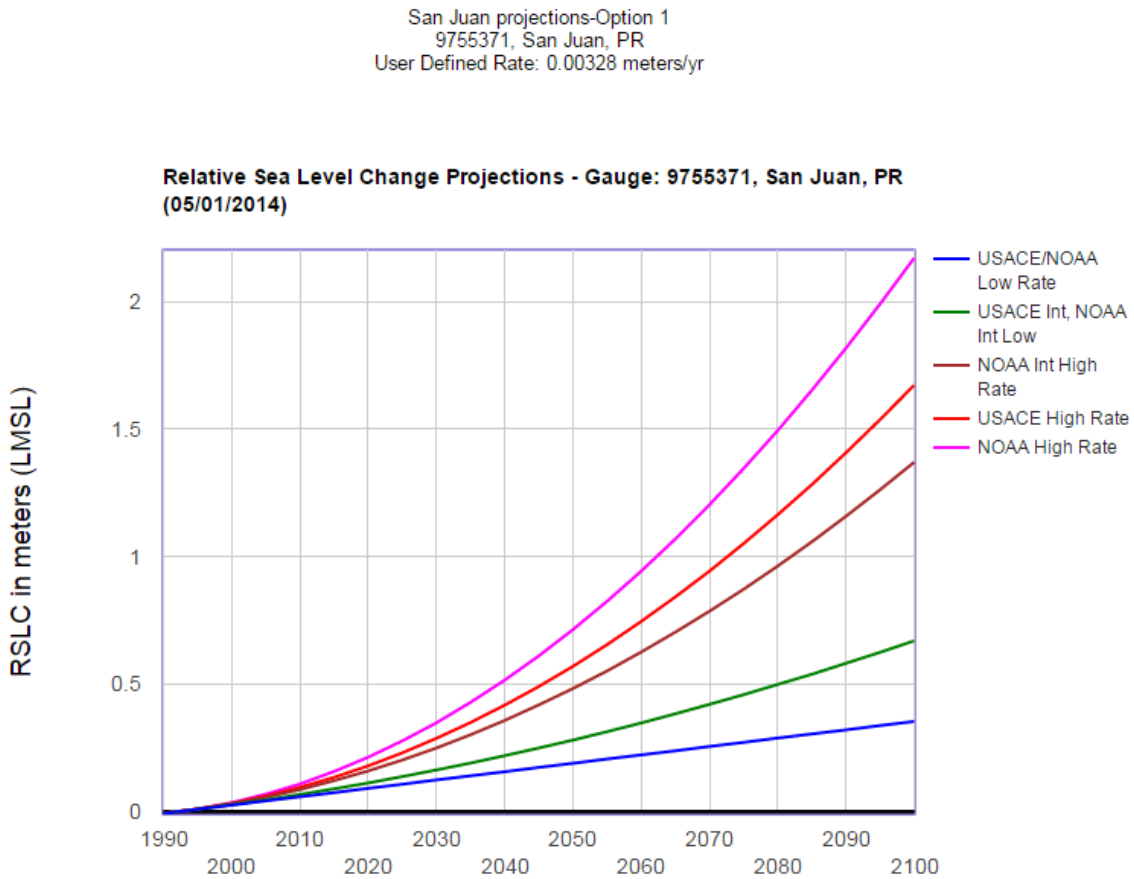

Figure 7 – Sea Level Rise curves; Option 1, San Juan.

b) Option 2: SLC Rate: 2.02 mm/year

Project Name: San Juan projections-Option 2
Select NOAA Gauge: San Juan, PR
FEMA BFE (meters): ? Information 0.000 MSL Search for BFE here
Project Start Year: 1990
Interval Year: 5
Project End Year: 2100
Output Units: Feet Meters
Output Datum: LMSL NAVD88
Output Agency: USACE NOAA Both
SLC Rate: Published Regionally Corrected or User Entered: 0.00202 (m/yr) Display Data
EWL Type: Highs Lows
EWL Source: NOAA Website NOAA (GEV) USACE (Percentile) 100 yr difference (m) = 0.17
Chart Size: Height: 600 Width: 800 Display Data
Plot EWL/BFE/Tides: None Select Curve: USACE High
Critical Elevation #1 (meters) : 0.000 MSL - Description:
Critical Elevation #2 (meters) : 0.000 MSL - Description:
User's Index (meters): ? 0.000 Description:
Datum Shift from NAVD88 to MSL: 0.00 meters

Figure 8 – Input configuration for Option 2, San Juan

Table 2: SLR for Option 2, San Juan.

San Juan projections-Option 2
9755371, San Juan, PR
User Defined Rate: 0.00202 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low NOAA Low	USACE Int NOAA Int Low	NOAA Int High	USACE High	NOAA High
1990	-0.00	-0.00	-0.00	-0.00	-0.00
1995	0.01	0.01	0.01	0.01	0.01
2000	0.02	0.02	0.02	0.02	0.03
2005	0.03	0.03	0.04	0.05	0.05
2010	0.04	0.05	0.07	0.07	0.09
2015	0.05	0.06	0.09	0.11	0.13
2020	0.06	0.08	0.13	0.14	0.18
2025	0.07	0.10	0.16	0.19	0.24
2030	0.08	0.12	0.20	0.24	0.30
2035	0.09	0.14	0.25	0.30	0.38
2040	0.10	0.16	0.30	0.36	0.46
2045	0.11	0.18	0.35	0.42	0.54
2050	0.12	0.21	0.41	0.50	0.64
2055	0.13	0.24	0.47	0.58	0.75
2060	0.14	0.26	0.54	0.66	0.86
2065	0.15	0.29	0.61	0.75	0.98
2070	0.16	0.32	0.69	0.85	1.11
2075	0.17	0.35	0.77	0.95	1.24
2080	0.18	0.39	0.85	1.05	1.38
2085	0.19	0.42	0.94	1.17	1.54
2090	0.20	0.46	1.03	1.28	1.69
2095	0.21	0.50	1.13	1.41	1.86
2100	0.22	0.53	1.23	1.54	2.03

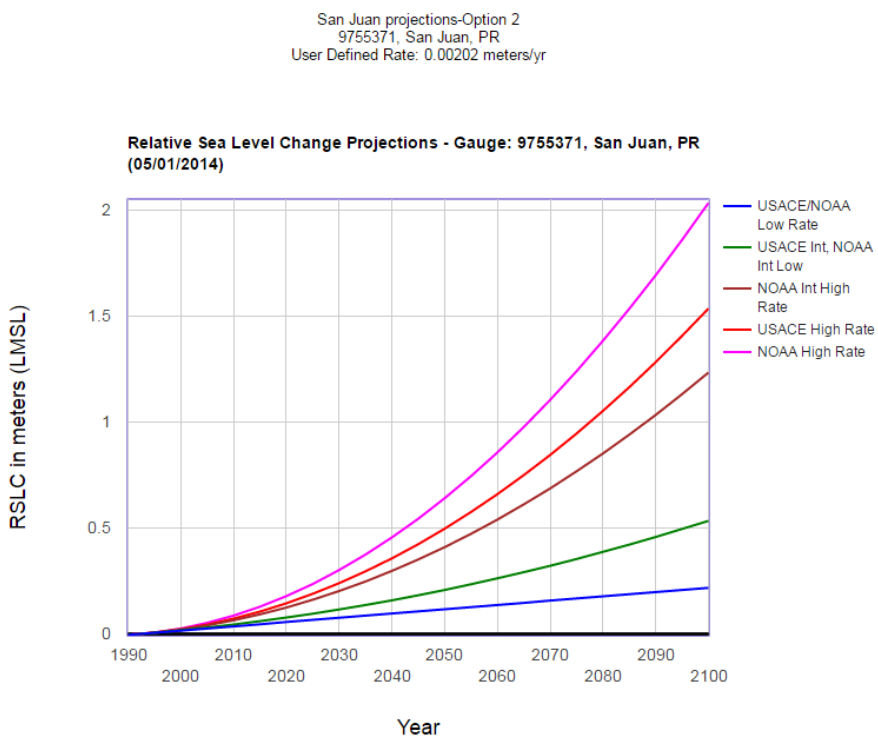

Figure 9– Sea Level Rise curves; Option 2, San Juan.

c) Option 3: SLC Rate: 3.93 mm/year

Project Name: San Juan projections-Option 3
Select NOAA Gauge: San Juan, PR
FEMA BFE (meters): ? Information 0.000 MSL Search for BFE here
Project Start Year: 1990
Interval Year: 5
Project End Year: 2100
Output Units: Feet Meters
Output Datum: LMSL NAVD88
Output Agency: USACE NOAA Both
SLC Rate: Published Regionally Corrected or User Entered: 0.00393 (m/yr) Display Data
EWL Type: Highs Lows
EWL Source: NOAA Website NOAA (GEV) USACE (Percentile) 100 yr difference (m) = 0.17
Chart Size: Height: 600 Width: 800 Display Data
Plot EWL/BFE/Tides: None Select Curve: USACE High
Critical Elevation #1 (meters) : 0.000 MSL - Description:
Critical Elevation #2 (meters) : 0.000 MSL - Description:
User's Index (meters): ? 0.000 Description:
Datum Shift from NAVD88 to MSL: 0.00 meters

Figure 10 – Input configuration for Option 3, San Juan

Table 3: SLR for Option 3, San Juan.

San Juan projections-Option 3
9755371, San Juan, PR
User Defined Rate: 0.00393 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low NOAA Low	USACE Int NOAA Int Low	NOAA Int High	USACE High	NOAA High
1990	-0.01	-0.01	-0.01	-0.01	-0.01
1995	0.01	0.01	0.01	0.01	0.01
2000	0.03	0.03	0.04	0.04	0.04
2005	0.05	0.06	0.07	0.07	0.08
2010	0.07	0.08	0.10	0.11	0.12
2015	0.09	0.11	0.14	0.15	0.17
2020	0.11	0.13	0.18	0.20	0.23
2025	0.13	0.16	0.23	0.25	0.30
2030	0.15	0.19	0.28	0.31	0.37
2035	0.17	0.22	0.33	0.38	0.46
2040	0.19	0.25	0.39	0.45	0.55
2045	0.21	0.28	0.45	0.53	0.65
2050	0.23	0.32	0.52	0.61	0.75
2055	0.25	0.36	0.59	0.70	0.87
2060	0.27	0.39	0.67	0.79	0.99
2065	0.29	0.43	0.75	0.89	1.12
2070	0.31	0.47	0.84	0.99	1.25
2075	0.33	0.51	0.93	1.11	1.40
2080	0.35	0.56	1.02	1.22	1.55
2085	0.37	0.60	1.12	1.34	1.71
2090	0.39	0.65	1.22	1.47	1.88
2095	0.41	0.69	1.33	1.60	2.06
2100	0.42	0.74	1.44	1.74	2.24

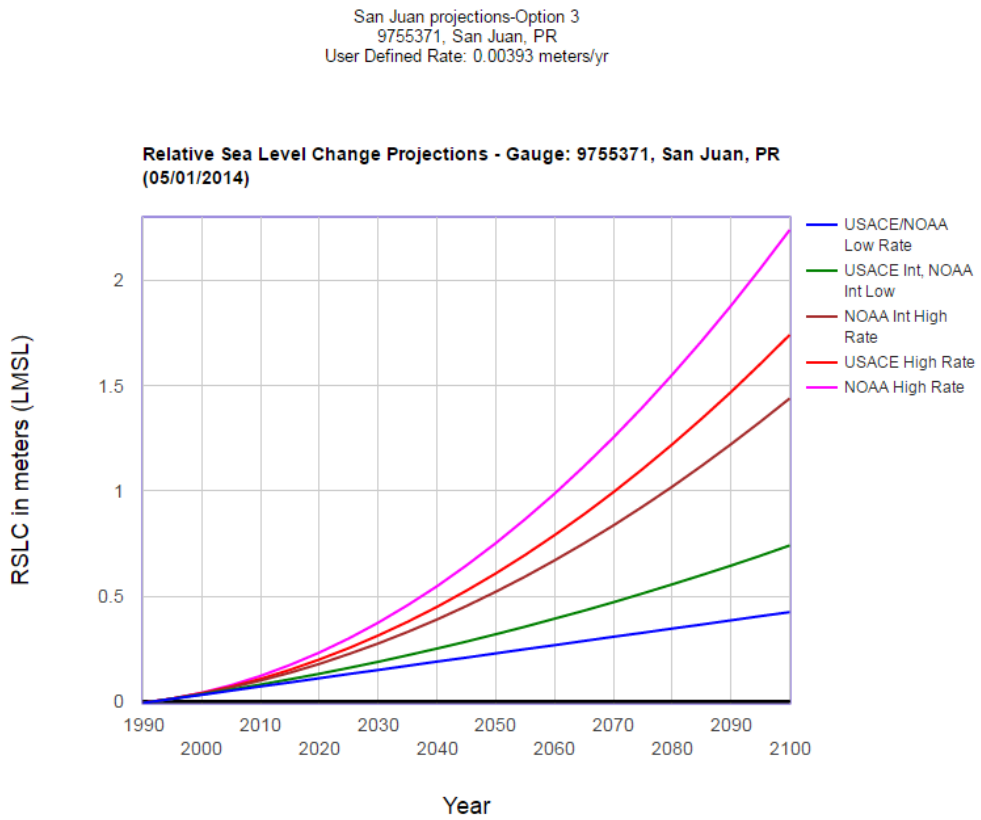

Figure 11 – Sea Level Rise curves; Option 3, San Juan.

ISLA MAGUEYES

a) Option 1: SLC Rate: 2.81 mm/year

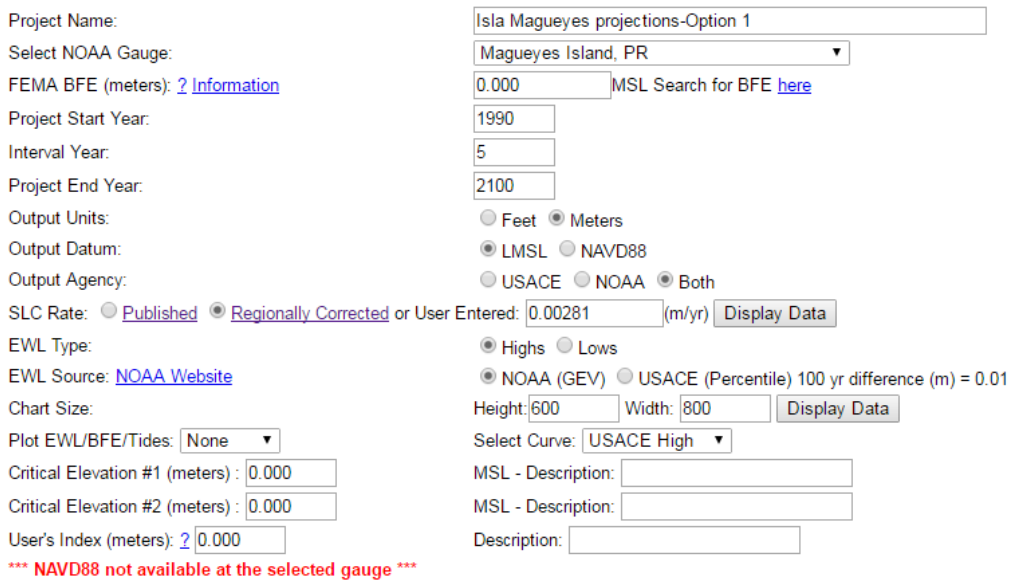

Figure 12 – Input configuration for Option 1, Isla Magueyes.

Table 4: SLR for Option 1, Isla Magueyes.

Isla Magueyes projections-Option 1
9759110, Magueyes Island, PR
User Defined Rate: 0.00281 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low NOAA Low	USACE Int NOAA Int Low	NOAA Int High	USACE High	NOAA High
1990	-0.01	-0.01	-0.01	-0.01	-0.01
1995	0.01	0.01	0.01	0.01	0.01
2000	0.02	0.02	0.03	0.03	0.03
2005	0.04	0.04	0.05	0.06	0.06
2010	0.05	0.06	0.08	0.09	0.10
2015	0.07	0.08	0.11	0.12	0.15
2020	0.08	0.10	0.15	0.17	0.20
2025	0.09	0.12	0.19	0.22	0.26
2030	0.11	0.15	0.23	0.27	0.33
2035	0.12	0.17	0.28	0.33	0.41
2040	0.14	0.20	0.34	0.40	0.49
2045	0.15	0.23	0.39	0.47	0.59
2050	0.16	0.25	0.46	0.54	0.69
2055	0.18	0.28	0.52	0.63	0.80
2060	0.19	0.32	0.59	0.71	0.91
2065	0.21	0.35	0.67	0.81	1.03
2070	0.22	0.38	0.75	0.91	1.17
2075	0.23	0.42	0.83	1.01	1.31
2080	0.25	0.46	0.92	1.12	1.45
2085	0.26	0.50	1.01	1.24	1.61
2090	0.28	0.54	1.11	1.36	1.77
2095	0.29	0.58	1.21	1.49	1.94
2100	0.30	0.62	1.32	1.62	2.12

Isla Magueyes projections-Option 1
9759110, Magueyes Island, PR
User Defined Rate: 0.00281 meters/yr

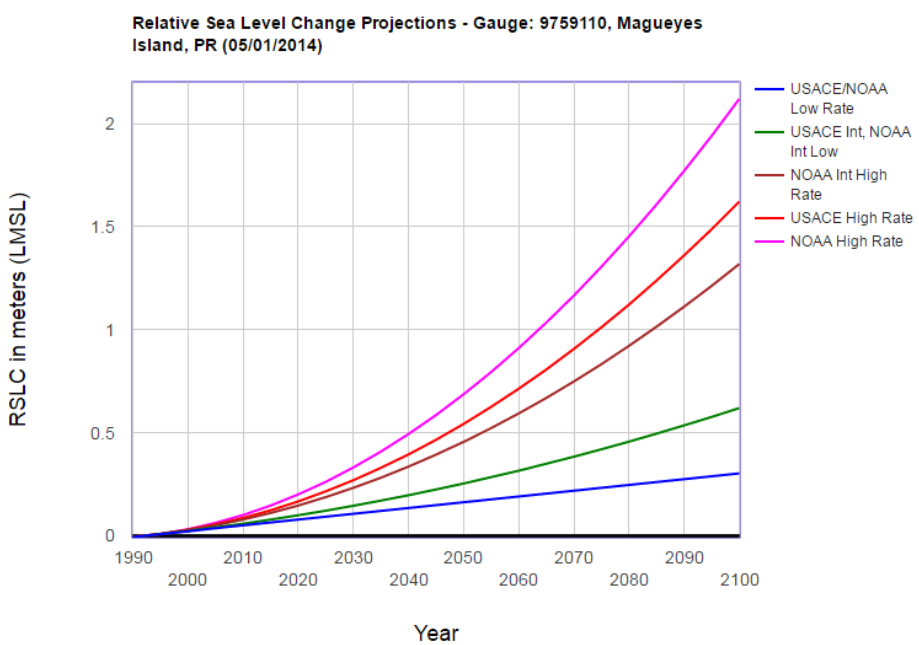

Figure 13– Sea Level Rise curves; Option 1, Isla Magueyes.

b) Option 2: SLC Rate: 1.31 mm/year

Project Name: Isla Magueyes projections-Option 2
Select NOAA Gauge: Magueyes Island, PR
FEMA BFE (meters): ? Information 0.000 MSL Search for BFE here
Project Start Year: 1990
Interval Year: 5
Project End Year: 2100
Output Units: Feet Meters
Output Datum: LMSL NAVD88
Output Agency: USACE NOAA Both
SLC Rate: Published Regionally Corrected or User Entered: 0.00131 (m/yr) Display Data
EWL Type: Highs Lows
EWL Source: NOAA Website NOAA (GEV) USACE (Percentile) 100 yr difference (m) = 0.01
Chart Size: Height: 600 Width: 800 Display Data
Plot EWL/BFE/Tides: None Select Curve: USACE High
Critical Elevation #1 (meters) : 0.000 MSL - Description:
Critical Elevation #2 (meters) : 0.000 MSL - Description:
User's Index (meters): ? 0.000 Description:
*** NAVD88 not available at the selected gauge ***

Figure 14 – Input configuration for Option 2, Isla Magueyes.

Table 5: SLR for Option 2, Isla Magueyes.

Isla Magueyes projections-Option 2
9759110, Magueyes Island, PR
User Defined Rate: 0.00131 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low NOAA Low	USACE Int NOAA Int Low	NOAA Int High	USACE High	NOAA High
1990	-0.00	-0.00	-0.00	-0.00	-0.00
1995	0.00	0.00	0.01	0.01	0.01
2000	0.01	0.01	0.02	0.02	0.02
2005	0.02	0.02	0.03	0.04	0.04
2010	0.02	0.03	0.05	0.06	0.07
2015	0.03	0.04	0.08	0.09	0.11
2020	0.04	0.06	0.11	0.13	0.16
2025	0.04	0.07	0.14	0.17	0.21
2030	0.05	0.09	0.18	0.21	0.28
2035	0.06	0.11	0.22	0.27	0.34
2040	0.06	0.13	0.26	0.32	0.42
2045	0.07	0.15	0.31	0.39	0.51
2050	0.08	0.17	0.37	0.46	0.60
2055	0.08	0.19	0.43	0.53	0.70
2060	0.09	0.21	0.49	0.61	0.81
2065	0.10	0.24	0.56	0.70	0.93
2070	0.10	0.27	0.63	0.79	1.05
2075	0.11	0.30	0.71	0.89	1.18
2080	0.12	0.33	0.79	0.99	1.32
2085	0.12	0.36	0.88	1.10	1.47
2090	0.13	0.39	0.97	1.21	1.62
2095	0.14	0.42	1.06	1.33	1.79
2100	0.14	0.46	1.16	1.46	1.96

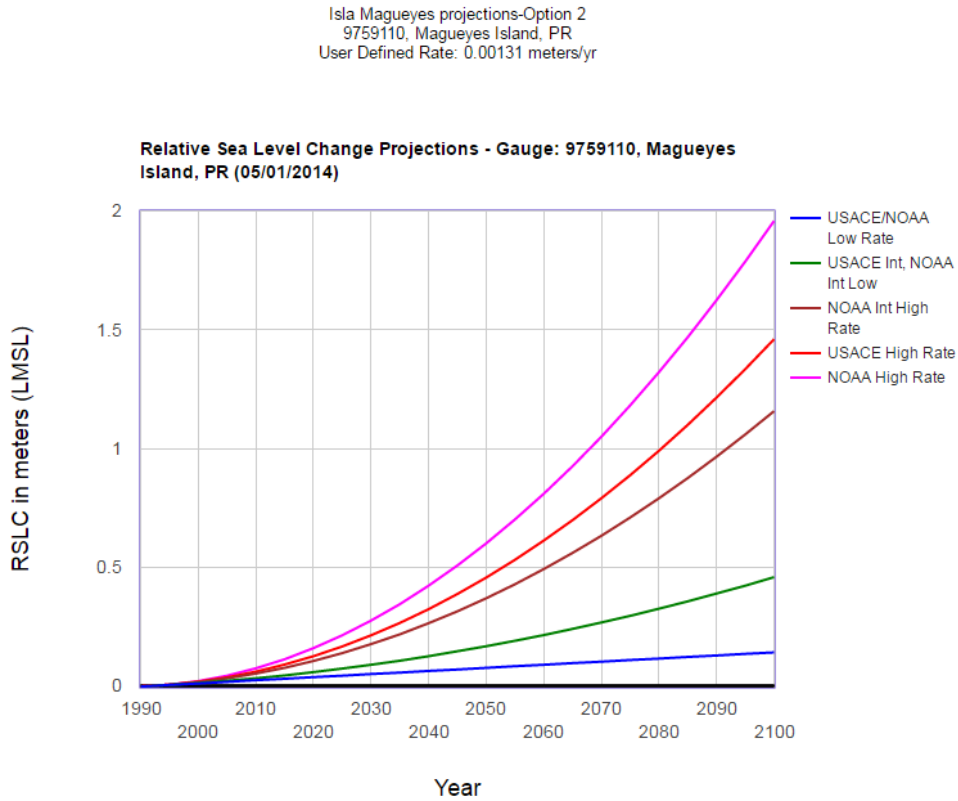

Figure 15– Sea Level Rise curves; Option 2, Isla Magueyes.

c) Option 3: SLC Rate: 3.71 mm/year

Project Name: Isla Magueyes projections-Option 3
Select NOAA Gauge: Magueyes Island, PR
FEMA BFE (meters): ? Information 0.000 MSL Search for BFE here
Project Start Year: 1990
Interval Year: 5
Project End Year: 2100
Output Units: Feet Meters
Output Datum: LMSL NAVD88
Output Agency: USACE NOAA Both
SLC Rate: Published Regionally Corrected or User Entered: 0.00371 (m/yr) Display Data
EWL Type: Highs Lows
EWL Source: NOAA Website NOAA (GEV) USACE (Percentile) 100 yr difference (m) = 0.01
Chart Size: Height: 600 Width: 800 Display Data
Plot EWL/BFE/Tides: None Select Curve: USACE High
Critical Elevation #1 (meters) : 0.000 MSL - Description:
Critical Elevation #2 (meters) : 0.000 MSL - Description:
User's Index (meters): ? 0.000 Description:
*** NAVD88 not available at the selected gauge ***

Figure 16 – Input configuration for Option 3, Isla Magueyes.

Table 6: SLR for Option 3, Isla Magueyes.

Isla Magueyes projections-Option 3
9759110, Magueyes Island, PR
User Defined Rate: 0.00371 meters/yr
All values are expressed in meters relative to LMSL

Year	USACE Low NOAA Low	USACE Int NOAA Int Low	NOAA Int High	USACE High	NOAA High
1990	-0.01	-0.01	-0.01	-0.01	-0.01
1995	0.01	0.01	0.01	0.01	0.01
2000	0.03	0.03	0.04	0.04	0.04
2005	0.05	0.05	0.06	0.07	0.08
2010	0.07	0.08	0.10	0.10	0.12
2015	0.09	0.10	0.13	0.14	0.17
2020	0.10	0.13	0.17	0.19	0.23
2025	0.12	0.15	0.22	0.25	0.29
2030	0.14	0.18	0.27	0.30	0.37
2035	0.16	0.21	0.32	0.37	0.45
2040	0.18	0.24	0.38	0.44	0.54
2045	0.20	0.27	0.44	0.51	0.63
2050	0.22	0.31	0.51	0.60	0.74
2055	0.23	0.34	0.58	0.68	0.85
2060	0.25	0.38	0.66	0.78	0.97
2065	0.27	0.42	0.74	0.87	1.10
2070	0.29	0.45	0.82	0.98	1.24
2075	0.31	0.50	0.91	1.09	1.38
2080	0.33	0.54	1.00	1.20	1.53
2085	0.35	0.58	1.10	1.32	1.69
2090	0.36	0.62	1.20	1.45	1.86
2095	0.38	0.67	1.31	1.58	2.03
2100	0.40	0.72	1.42	1.72	2.22

Isla Magueyes projections-Option 3
9759110, Magueyes Island, PR
User Defined Rate: 0.00371 meters/yr

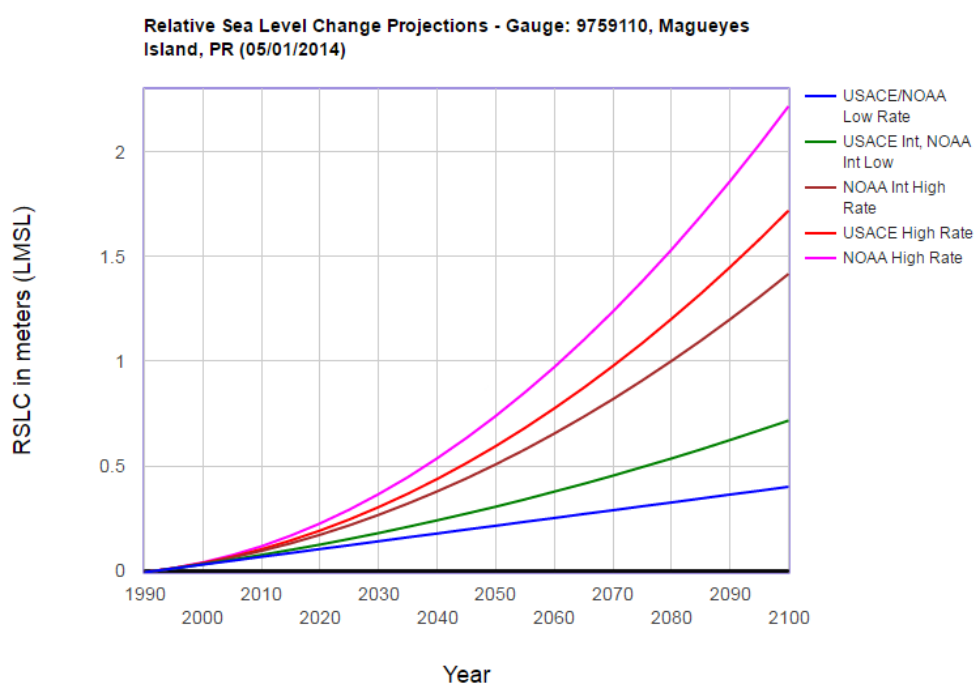

Figure 17– Sea Level Rise curves; Option 3, Isla Magueyes.

SAN JUAN (USACE calculator not used)

d) Option 4: Fit of a 2nd Order Polynomial Starting in 1992

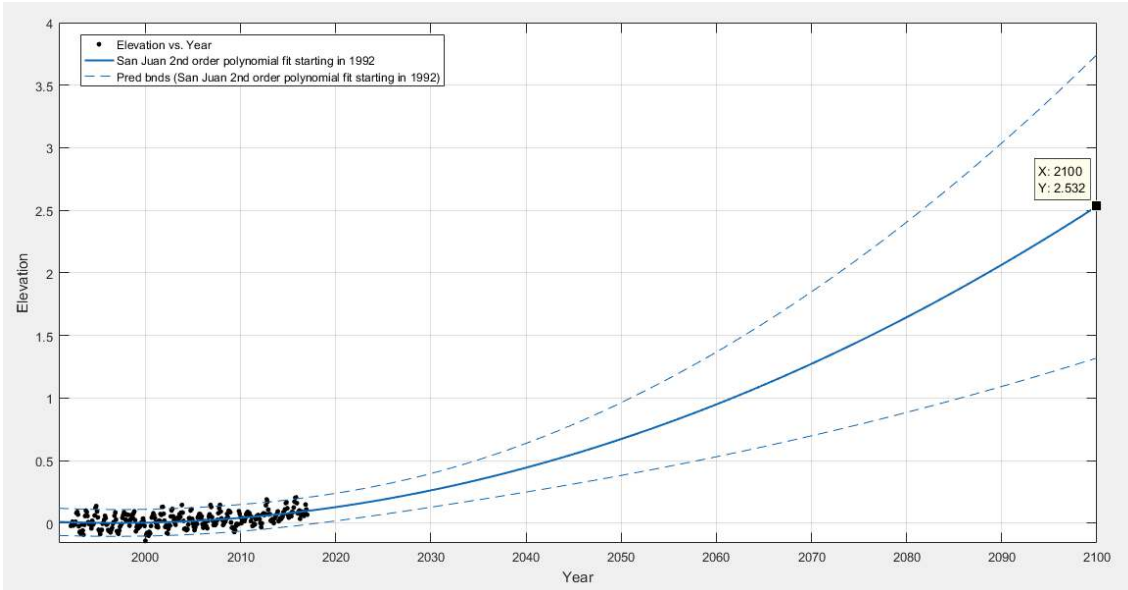

*Figure 18 – Dashed lines are the 95% Confidence Intervals. Polynomial: f(x) = p1*x^2 + p2*x + p3; Coefficients (with 95% confidence bounds): p1 = 0.0002383 (0.0001053, 0.0003714); p2 = -0.9519 (-1.485, -0.4184); p3 = 950.4 (415.7, 1485). Software used: Matlab.*

e) Option 5: Fit of a 1st Order Polynomial Starting in 2010.5

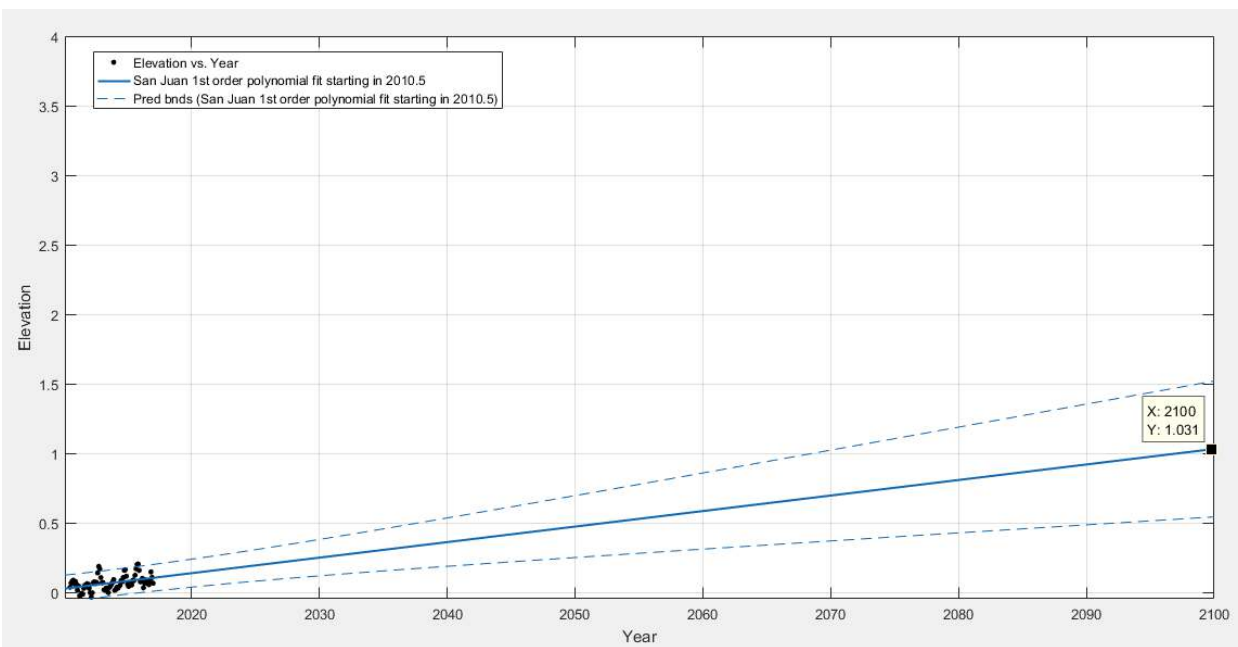

*Figure 19 – Linear extrapolation of San Juan data starting in 2010.5. Dashed lines are the 95% Confidence Intervals. Linear model Poly1: f(x) = p1*x + p2; Coefficients (with 95% Confidence bounds): p1 = 0.0116 (0.005608, 0.01672); p2 = -22.41 (-33.59, -11.22). Software used: Matlab.*

ISLA MAGUEYES (USACE calculator not used)

d) Option 4: Fit of a 2nd Order Polynomial Starting in 1992

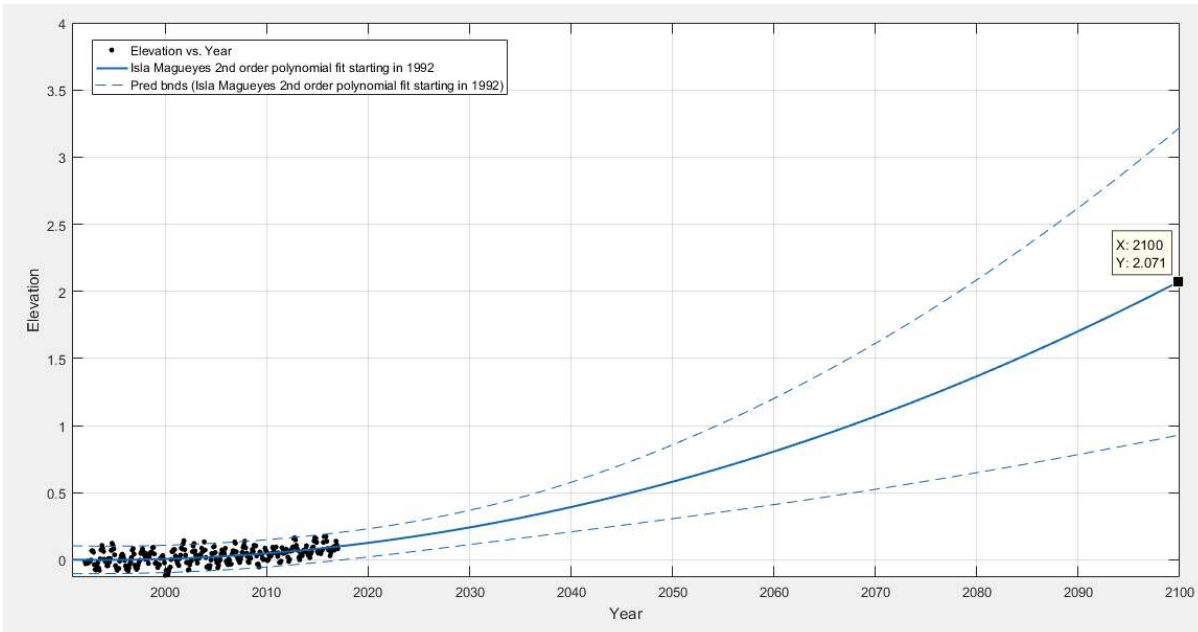

*Figure 20 – The value at 2100 is 2.07 m. Dashed lines are the 95% Confidence Intervals. Polynomial: f(x) = p1*x^2 + p2*x + p3; Coefficients (with 95% confidence bounds): p1 = 0.0001838 (5.818e-05, 0.0003093); p2 = -0.7327 (-1.236, -0.2293); p3 = 730.4 (225.8, 1235). Software used: Matlab. Software used: Matlab.*

e) Option 5: Fit of a 1st Order Polynomial Starting in 2010.5

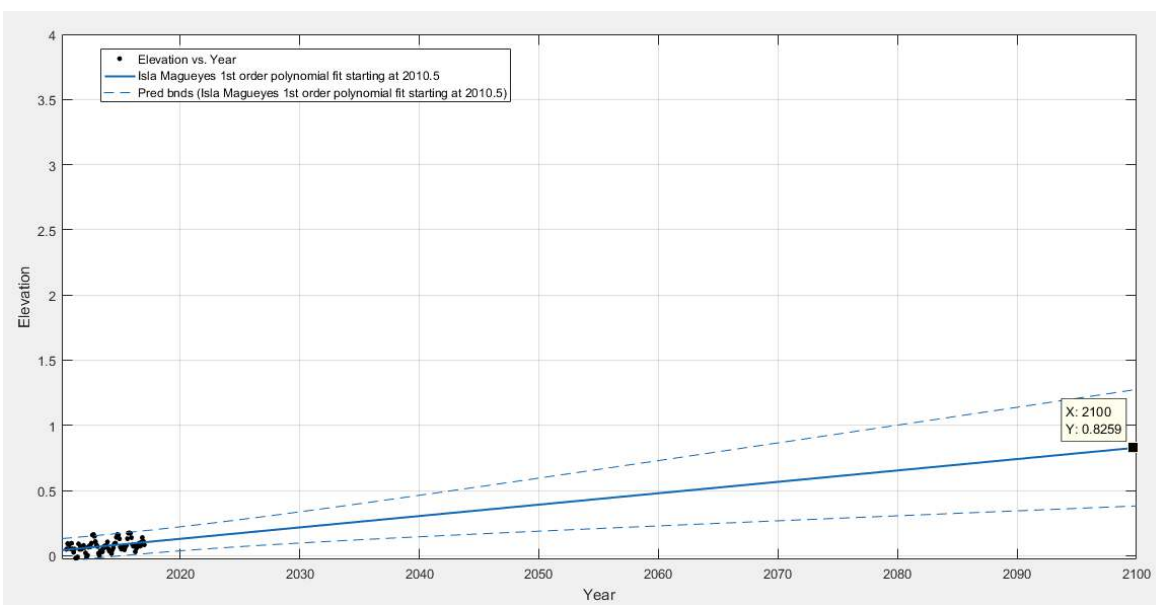

*Figure 21 – Linear extrapolation of Isla Magueyes data starting in 2010.5. Dashed lines are the 95% Confidence Intervals. Linear model Poly1: f(x) = p1*x + p2; Coefficients (with 95% confidence bounds): p1 = 0.008742 (0.003656, 0.01383); p2 = -17.53 (-27.77, -7.289). Software used: Matlab.*

We can see that results do not vary widely among Options 1 to 3 for a given scenario of sea level rise acceleration. As mentioned in page 11, Option 1 is the only one that uses a Global Mean Sea Level Rise value (the satellite-based GMSLR), consistent with the expressed methodology of the USACE calculator. On the other hand, Options 2 and 3 use locally derived (linear) sea level rise trends. Since a decision has to be made in order to simplify things, I will base my projection for sea level rise for 2100 on the results for Option 1 for both San Juan and Isla Magueyes.

Option 4 (fitting a 2nd order polynomial to the data starting in 1992) gives a larger value than the USACE calculator for the NOAA High Rate for both San Juan and Isla Magueyes, but not by much. Option 4 was just an attempt to see what the fitting of a 2nd order polynomial to the actual of San Juan and Isla Magueyes data gave (starting in 1992). And both the USACE and Option 4 results fall below the Sweet et al. (2017; to be discussed below) projection for 2100.

Option 5, for both San Juan and Isla Magueyes, is an attempt to see what a linear extrapolation of the observed trend since 2010-2011 would give.

<u>In any case, the fact that a linear extrapolation of the rate of SLR starting in 2010.5 (Option 5) comes close to 1 m, leads me to use 1 m as the lower bound for the 2100 projection.</u> This implies that even with no more accelerations in the future, we are bound for SLR of approximately 1 m for 2100. Notice that the 95% Confidence Interval for 2100 is approximately $\pm$0.5 m.

The final values to be chosen will depend on specific situations, like what is at stake. It is logical to assume that users will have very different risks tolerances in their planning.

HOW DOES IT COMPARE WITH WHAT HAS BEEN ADOPTED ELSEWHERE:

SOUTHEAST FLORIDA (this location is of relevance since not only it is the closest continental USA location to us, but as will discussed below, oceanographic factors that affect sea level along SE Florida should also be felt, first, along the north and south coasts of Puerto Rico)

The following figure (Figure 1 in the Florida report; Figure 22 in this report) shows the curves adopted by Southeast Florida (Southeast Florida Sea Level Rise Work Group, 2015). Since the concept of Representative Concentration Pathways (RCP) is mentioned, these will be summarized in Appendix C. Some highlights from the report are quoted below:

- The report is made for planning purposes to aid in understanding of potential vulnerabilities and to provide a basis for developing risk informed adaptation strategies for the region.
- They used the USACE calculator in order to adapt the global mean sea level change curves for the unified South Florida projection.
- Sea level rise in South Florida has been of similar magnitude as the global average over 1992 to 2015 over the same period, but is anticipated to outpace the global average due to ongoing variations in the Florida Currents and Gulf Stream.

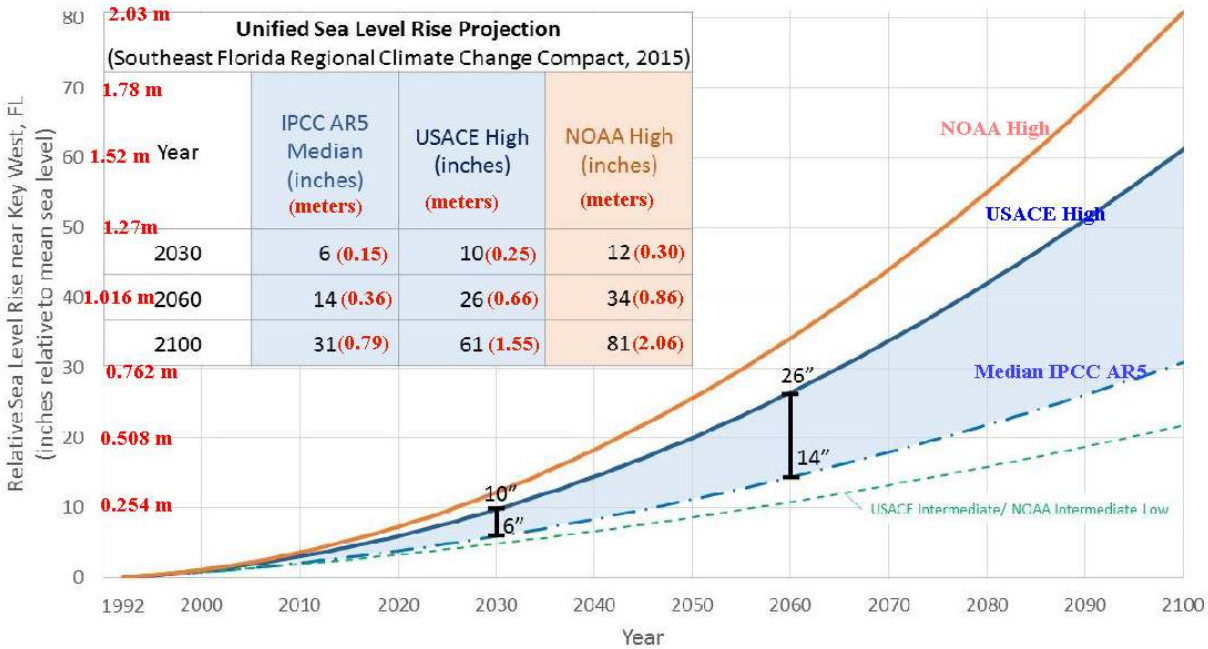

Figure 1: Unified Sea Level Rise Projection. These projections are referenced to mean sea level at the Key West tide gauge. The projection includes three global curves adapted for regional application: the median of the IPCC AR5 RCP8.5 scenario as the lowest boundary (blue dashed curve), the USACE High curve as the upper boundary for the short term for use until 2060 (solid blue line), and the NOAA High curve as the uppermost boundary for medium and long term use (orange solid curve). The incorporated table lists the projection values at years 2030, 2060 and 2100. The USACE Intermediate or NOAA Intermediate Low curve is displayed on the figure for reference (green dashed curve). This scenario would require significant reductions in greenhouse gas emissions in order to be plausible and does not reflect current emissions trends.

Figure 22 – This figure has been edited in order to show values in meters (in red). Taken from Southeast Florida Sea Level Rise Work Group, 2015.

- They use three planning horizons (It is quite possible that many of the decision-making approaches could be very helpful for us in Puerto Rico. That's why I am including them in this report):

  1) short term, by 2030, sea level is projected to rise 0.15 to 0.25 m (6 to 10 inches) above 1992 mean sea level,
  2) medium term, by 2060, sea level is projected to rise 0.36 to 0.66 m (14 to 34 inches) above 1992 mean sea level,
  3) long term, by 2100, sea level is projected to rise 0.79 to 2.06 m (31 to 81 inches) above 1992 mean sea level.
- In relation to the above figure (in what follows I may have lost track of what is taken verbatim, or not):

  - "The lower boundary of the projection (blue dashed line) can be applied in designing low risk projects that are easily replaceable with short design lives, are adaptable and have limited interdependencies with other infrastructure or services.
  - The shaded zone between the IPCC AR5 RCP8.5 median curve and the USACE High is recommended to be generally applied to most projects within a short -term planning horizon. It reflects what the Work Group projects will be the most likely range of sea level rise for the remainder of the 21st Century.

  - The upper curve of the projection should be utilized for planning of high risk projects to be constructed after 2060 or projects which are not easily replaceable or removable, have a long design life (more than 50 years) or are critically interdependent with other infrastructure or services."

- On page 9 of the Southeast Florida report it is stated that the US Atlantic coast has experienced a "rapid acceleration" in the rate of sea rise since 2000, exactly what we have been observing in Puerto Rico since approximately that year (see http://coastalhazards.uprm.edu). But since 2010-2011 we have experienced an even large acceleration that has also been observed in southeast Florida (http://www.rsmas.miami.edu/news-events/press-releases/2016/new-study-shows-increased-flooding-accelerated-sea-level-rise-in-miami-over; Goddard et al., 2015; Wdowinski et al., 2016). Wdowinski et al. (2016) also analyzed the nearby Virginia Key tide gauge record and found a significant acceleration in the rate of sea level rise since 2006. The average rate of regional sea level rise since 2006 is 9±4 mm/yr, which is similar to what has been observed in Puerto Rico since 2010-2011 (due to the short record – 201-2011 up to now - this statistic is not very robust; but we are entering the 7th year with rates varying around 10 mm/yr).
- "The blue shaded portion of the projection (Fig. 22) can be applied to most infrastructure projects, especially those with a design life expectancy of less than 50 years. It represents the *likely* range of sea level rise for the region. The designer of a type of infrastructure that is easily replaced, has a short lifespan, is adaptable, and has limited interdependencies with other infrastructure or services must weigh the potential benefit of designing for the upper blue line with the additional costs. Should the designer opt for specifying the lower curve, she/he must consider the consequences of under-designing for the potential likely sea level condition. Such consequences may include premature infrastructure failure. Additionally, planning for adaptation should be initiated in the conceptual phase. A determination must be made on whether or not threats can be addressed mid-life cycle via incremental adaptation measures, such as raising the height of a sluice gate on a drainage canal."
- Projects in need of a greater factor of safety related to potential inundation should consider designing for the upper limit of the blue-shaded zone. Examples of such projects may include evacuation routes planned for reconstruction, communications and energy infrastructure and critical government and financial facilities.
- Due to a community's fundamental reliance on major infrastructure, existing and proposed critical infrastructure should be evaluated using the upper curve of the projection, the orange curve (Figure 22, NOAA High). Critical projects include those projects which are not easily replaceable or removable, have a long design life (more than 50 years), or are interdependent with other infrastructure or services. If failure of the critical infrastructure would have catastrophic impacts, it is considered to be high risk. Examples of high risk critical infrastructure include power plants, wastewater treatment facilities, levees or impoundments, bridges along major evacuation routes, airports, seaports, railroads, and major highways.
- For low risk infrastructure projects, the lowermost curve of the projection (Figure 22, IPCC AR5 RCP8.5 curve) may be applied. Low risk projects include infrastructure expected to be constructed and then replaced within the next 10 years, projects that are easily replaceable and adaptable or projects with limited interdependencies and limited impacts when failure occurs. An example of such a project may be a small culvert in an isolated area.

- It is acknowledged that a substantial increase in sea level rise within this century is likely and may occur in rapid pulses rather than gradually.
- At the end, the final recommendation for southeast Florida is to use the NOAA High Curve (orange solid), the USACE High Curve (USACE, 2015; blue solid) and the median of the IPCC AR5 RCP8.5 scenario (IPCC, 2013; blue dashed) as the basis for a Southeast Florida sea level rise projection for the 2030, 2060 and 2100, respectively, planning horizons.
- The four curves shown in Figure 22 were generated as follows:
    - NOAA High Curve: a = 1.56×10^{-4}
    - USACE high Curve: a = 1.13×10^{-4}
    - IPCC AR5 RCP8.5 Median Curve (IPCC, 2013): a = 4.684499×10^{-5}
    - NOAA Intermediate Low/ USACE Low Curve that is not part of the projection but included on the graph for reference (green dashed line) : a = 2.71262×10^{-5}
- The Southeast Florida report quotes a sea level rise acceleration, between 1993 and 2015, of 0.04 mm/yr^2 (Watson et al., 2015). This should be compared with the acceleration for 2001 to 2016 for Puerto Rico of 0.03 mm/yr^2 for both San Juan and for Isla Magueyes (see https://coastalhazardspr.wordpress.com/). And after 2010-2011 the acceleration has been even larger, but there is no sufficient data to give a reliable estimate.
- The southeast Florida report provides a summary of the factors influencing sea level rise, justifying why their estimates (as of 2015) are larger than IPCC's 2014 and their own previous report for southeast Florida (2011). And as of today, March 2017, the news are even scarier. Since the summary very well serves for Puerto Rico, I have copied it in Appendix A. This should serve as a background for the final projection of sea level rise around Puerto Rico. If time allows, the list of references that have come out since 2015 will be added to the list of references.

CALIFORNIA, OREGON, WASHINGTON (they did not use the USACE calculator)

Date of publication: 2012 (things are changing so fast that it is necessary to first look for the year of publication)

This report (California, Oregon, and Washington) is briefly discussed as an example of projections that did not use the USACE calculator. But in order to do that the state has to count with a large group of experts, very knowledgeable in the climate models, or their interpretation. The west coast of the USA is very far away, and the factors causing RSLR are, some of them either different (for example, VLM, El Niño/La Niña, etc.), or of different magnitude. But finding out which methodology they used for the projection, will be educational.

- First of all, the latest report I could find was dated 2012.
- The planning horizons of 2030, 2050, and 2100.
- They used model results and extrapolation approached to make projections. The committee projected global sea-level rise (Task 1) using model results from the IPCC Fourth Assessment Report, together with a forward extrapolation of land ice that attempts to capture an ice dynamics component. This is a process-based approach that tries to take into consideration the factors thought to influence sea level on a global scale (see Figure 23). The committee also considered results from semi-empirical projections, which are based on the observed correlation between global temperature and sea-level change (e.g., Vermeer and Rahmstorf, 2009). For the projections of sea-level rise along the U.S. west coast (Task 2), the committee

derived local values using regional ocean information extracted from global models, GPS data from along the coast, and ice loss rates of large or nearby glaciers.

- Evaluation should be made of not only GMSLR, but also of regional and local factors (ocean and atmospheric circulation patterns in the northern Pacific Ocean, the gravitational and deformational effects of land ice mass changes, and tectonics along the coast) that could lead to different (from the GMSLR) estimates along that very long coast.

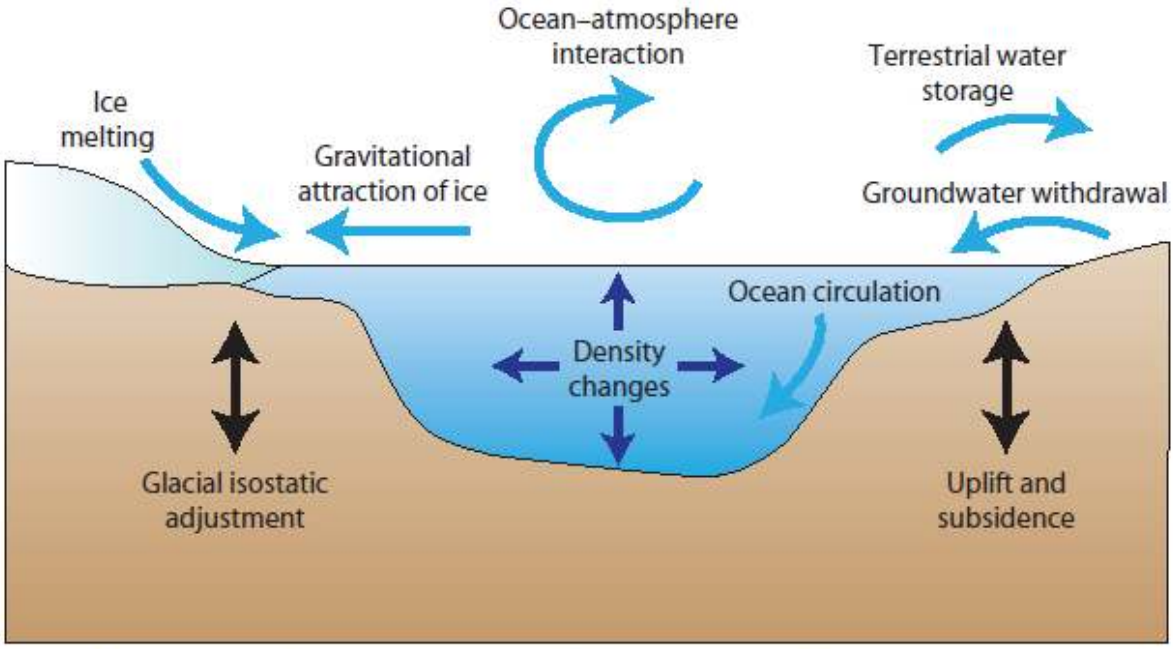

FIGURE 1.4 Processes that influence sea level on global to local scales. SOURCE: Modified from Milne et al. (2009).

Figure 23 – Taken from [Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future](#) (NRC, 2012).

- So here is how they did it. Taken verbatim from the Summary of the report titled Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future (NRC, 2012). The following pertains only to the GMSLR estimate. The local effects are added later: "The committee projected the steric component of sea-level rise using output from global ocean models under an IPCC (2007) mid-range greenhouse gas emission scenario. The land ice component was extrapolated using the best available compilations of ice mass accumulation and loss (mass balance), which extend from 1960 to 2005 for glaciers and ice caps, and from 1992 to 2010 for the Greenland and Antarctic ice sheets. The contributions were then summed. The committee did not project the land hydrology contribution because available estimates suggested that the sum of groundwater extraction and reservoir storage is near zero, within large uncertainties."
    - GMSLR for 2030: 0.08 to 0.23 m relative to the year 2000 (it should be mentioned that already in Puerto Rico we have felt the effects of a - monthly mean - sea level rise on the order of, and even higher, than 0.2 m during the fall months of 2012 and 2015 – relative to the MSL obtained from the average of tidal elevations for the NTDE of 1983-2001). So we are already there!

  - GMSLR for 2050: 0.18 to 0.48 m relative to the year 2000 (again, during September-October 2015 we already surpassed the monthly mean of 0.2 m)
  - GMSLR for 2100: 0.50 to 1.40 m relative to the year 2000
- "The ranges reflect uncertainties related to the fit of the data; the level of future greenhouse emissions, which affects the steric component; and any future changes in the rate of ice flow, which affects the total ice contribution. These uncertainties, and hence the ranges, grow with the length of the projection period."
- Now for the local projections. "These local effects include steric variations; wind-driven differences in ocean heights; gravitational and deformational effects (sea-level fingerprints) of melting of ice from Alaska, Greenland, and Antarctica; and vertical land motions along the coast. The local steric and wind-driven components were estimated by extracting northeast Pacific data from the same ocean models used for the global projections. The cryosphere component was adjusted for gravitational and deformational effects and then extrapolated forward. Finally, vertical land motion was projected using continuous GPS measurements for two tectonically distinct areas: Cascadia, where the coastline is generally rising, and the San Andreas region, where the coastline is generally subsiding."
  - For the California coast south of Cape Mendocino, the committee projects that sea level will rise (relative to 2000)
    - 0.04 – 0.30 m by 2030
    - 0.12 - 0.61 m by 2050
    - 0.42 - 1.67 m by 2100
  - For the coasts of California, Oregon, and Washington north of Cape Mendocino, the committee projects that sea level will rise (relative to 2000) (negative values are sea-level fall due to VLM)
    - -0.04 – 0.23 m by 2030
    - -0.03 - 0.48 m by 2050
    - +0.10 - 1.43 m by 2100
- "Major sources of uncertainty in the regional projections are related to assumptions about future ice losses and a constant rate of vertical land motion over the projection period. Uncertainties are larger for the regional projections than for the global projections because more components are considered and because uncertainties in the steric and ocean dynamic components are larger at a regional scale than at a global scale"." The actual sea-level rise will almost surely fall somewhere within the wide uncertainty bounds, although the exact value cannot be specified with high confidence."
- In what it will be useful for the following section on What Is at Stake?, they followed the IPCC 4th Assessment Report as it relates to expressing the estimate's uncertainties, the major components of global sea-level rise were estimated at the 90 percent confidence level (Bindoff et al., 2007). That is, values given as $x \pm e$ mean that there is a 90 percent chance that the true value is in the range $x - e$ to $x + e$.

New Jersey - Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel

Date of Report: October 2016

Although New Jersey is much farther away from Puerto Rico than southeast Florida, it will be instructional to assess how this state prepared this very recent report. And also what projections they've got.

- The first thing that the state of New Jersey did was to create a Science and Technical Advisory Panel (STAP) to "to help identify options for planning guidelines and criteria that practitioners could apply to enhance the resilience of New Jersey's people, places, and assets to rising sea levels, the potential change of coastal storms, and changes in the frequency and intensity of coastal flooding." That is, the mandate was to provide practical options for stakeholders to incorporate science into risk-based decision processes.
- Here the USACE sea level rise calculator was not used. In order to be able to approximately compare their approach with results based on NOAA/USACE scenarios (as shown in the first part of this report for Puerto Rico; called the "federal curves"), they suggest that the STAP's "likely range" represents the NOAA Intermediate-High Curve. While the STAP's high-end scenarios represent either the NOAA or USACE 'High' curves.
- "The STAP concluded that practitioners should use a range of SLR estimates, given the range of future exposures and vulnerabilities that exist among people, places, and assets in New Jersey communities. The majority of practitioners indicated it would be practical to use two or three SLR scenarios for most of their work. Certain applications require more detailed analysis that considers the full range of projections. The SLR values in Table ES-1 represent projections under continued fossil-fuel-intensive global economic growth through 2050 because differences in SLR projections between emissions scenarios are minor in the first half of the century (with low-emissions projections for 2050 being about 0.1 feet lower than high-emissions projections). Differences in projections related to greenhouse gas emissions are only germane for those practitioners with planning horizons that extend beyond 2050."
- The STAP focused on the highest and the lowest of the RCPs, RCP 8.5 referred as the 'high emissions' scenario, and RCP 2.6 as the 'low emissions' scenario.
- The SLR conclusions reached by the STAP are shown in Figure 24 below. The values inside parenthesis (in red) show the results in meters. The year 2030 was chose for near-term projection, and 2050 for mid-term projection.
  NOTE: The above sentence is very useful for interpretation of the USACE calculator results for Puerto Rico since it helps in assigning the NOAA Intermediate-High Curve as a "likely" scenario.
- "Practitioners consulted as part of the STAP process advised that decision-makers should incorporate the STAP SLR projections into projections of future flood levels for exposure assessment. The STAP concluded that any assessment of flood exposure should include the evaluation of at least one estimate in the 'likely range' and an additional SLR estimate that represents high-end outcomes (See Table ES-1). The 'likely range' of SLR may be more appropriate for planning scenarios that assess exposure of people, places and assets for which vulnerabilities to flooding are limited or for which the consequences of damage or failure are limited. High-end estimates of SLR may be used to develop planning scenarios that consider exposures of people, places and assets that are particularly vulnerable to flooding, or for which the consequences of damage and failure have significant magnitude."
- It is worth mentioning that STAP acknowledges that "A worst-case SLR (defined as a 1 in 1000 chance) of 2.8 ft. (0.85 m) by 2050 and 10 ft.(3.05 m) by 2100 is physically possible in New Jersey." Values in meters were introduced by me.

Table ES-1: Projected SLR Estimates for New Jersey (ft.)

	Central Estimate	Likely Range	1-in-20 Chance	1-in-200 Chance	1-in-1000 Chance
Year	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*	*0.1% probability SLR meets or exceeds...*
2030	(0.24 m) 0.8 ft	(.18-.30 m) 0.6 – 1.0 ft	(0.34 m) 1.1 ft	(0.40 m) 1.3 ft	(0.46 m) 1.5 ft
2050	(0.43 m) 1.4 ft	(.3-.55 m) 1.0 – 1.8 ft	(0.61 m) 2.0 ft	(0.73 m) 2.4 ft	(0.85 m) 2.8 ft
2100 Low emissions	(0.70 m) 2.3 ft	(.52-.94 m) 1.7 – 3.1 ft	(1.16 m) 3.8 ft	(1.80 m) 5.9 ft	(2.53 m) 8.3 ft
2100 High emissions	(1.04 m) 3.4 ft	(0.73-1.37 m) 2.4 – 4.5 ft	(1.62 m) 5.3 ft	(2.19 m) 7.2 ft	(3.05 m) 10 ft

Estimates are based on Kopp et al. (2014). Columns correspond to different projection probabilities. For example, the 'Likely Range' column corresponds to the range between the 17th and 83rd percentile; consistent with the terms used by the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010). All values are with respect to a 1991-2009 baseline. Note that these results represent a single way of estimating the probability of different levels of SLR; alternative methods may yield higher or lower estimates of the probability of high-end outcomes.

Figure 24 – Taken from Table ES-1, page 2, of the New Jersey report. The table was edited in order to show – in red – values in meters. As far as I could determine, these are Regional estimates.

- Among the many useful recommendations suggested in the New Jersey report is the following: Convene a meeting of resilience practitioners to provide insights "on barriers and opportunities for integrating the STAP's conclusions into practice. The purpose of the meeting of practitioners was to gather input on the scientists' initial recommendations for planning and decision-making. The practitioners were asked to respond to 4 questions:
    1. How can the STAP's consensus results be structured and communicated in ways to ensure effective integration into practice?
    2. What are the barriers and opportunities associated with applying the results of the STAP's deliberations to state and local policymaking, practice and decision-making?
    3. What additional science and technical information related to SLR and changing coastal storms would be helpful for enhancing resilience and climate adaptation actions in New Jersey's coastal region?
    4. What additional issues outside the charge of the STAP do practitioners need to enhance coastal resilience and climate adaptation in policy, decision-making, and practice for New Jersey? "
- Another piece of advice they give is to give extra consideration to high-end outcomes when assessing highly vulnerable or highly consequential people, places and assets.
- Other recommendations are:
    - "Practitioners should evaluate at least one water level that is representative of each of three flooding conditions: permanent inundation, tidal flooding, and coastal storms."
    - "A practical approach practitioners can choose is to use at least two projections, with one being a SLR estimate in the likely range and one being a high-end estimate, in order to assess exposure to a range of future flood conditions. Practitioners with highly vulnerable or consequential people, places, and assets in their communities should assess exposure to high-end SLR estimates as a conservative and protective practice. Practitioners may also wish to evaluate higher magnitude low-probability, high-

consequence SLR projections (e.g., 1-in-1000 Chance) to account for additional flood attributes that are not quantified using this methodology (e.g. changes in shoreline, wave action, development patterns, etc.) and to account for uncertainty related to advances in climate science that may result in an increase in the magnitude of high-end outcomes. The consideration of high-end outcomes is particularly important because alternative methods or new science may yield higher (or lower) estimates of the probability of high-end outcomes."
NOTE: Along the line of higher magnitude low-probability, high-consequence SLR projections, Abadie et al., 2016, show that despite their low probability of occurrence, the huge scale of damage that tail events (located at the tail of Probability Density Functions) means that they should be carefully considered in coastal vulnerability analysis. This, and previous mention of higher magnitude low-probability, high-consequence SLR projections, and its consequences, are emphasized since a high end projection for 2100 has to be given, and the value given may seem farfetched to some.

The report urges local, regional, and national policy-makers not to settle for traditional approaches to calculating climate impacts but instead seek to introduce risk assessments under uncertainty into their decision-making processes. The author's say that in line with the level of risk in each coastal city and the risk aversion of decision-makers, adaptation measures will need to be implemented in the near future in order to avoid critical damage and major losses.

New York – Regional Plan Association – Under Water – How Sea Level Rise Threatens the Tri-State Region. A Report for the Fourth Regional Plan (R. Freudenberg et al., 2016)

Date of Report: December 2016

- They mention three scenarios:
  1. One foot (0.30 m) as soon as the 2030s
  2. Three feet (0.91 m) as early as the 2080s
  3. Six feet (1.83 m) early in the next century
- "With the first damaging consequences of sea level rise already affecting some of the region's neighborhoods, our current generation of elected officials, policy makers, planners, advocates, scientists, developers and residents are the only ones that can choose a different course from the one we're on. We are the only ones who can choose not to purchase, approve or develop in places that will be flooded in a matter of decades. There is no future generation left to figure this out. Broadly speaking, there are three ways to protect ourselves from rising seas in the places most at risk:
  1. We can develop engineering solutions, continually pumping more sand onto beaches or building higher berms and sea walls around communities and infrastructure, installing pumps to keep the water out;
  2. We can learn to live with the water, elevating more structures and infrastructure and adjusting to a new life on less dry ground; or
  3. We can phase out new development and retreat from at risk places over the coming decades, returning the land to nature.

All of these options present significant obstacles, raise tough questions and would require substantial investment and political leadership. We will need to figure out what combination of these approaches is best for each community at risk – and what policy and fiscal tools will be needed."

- All of this requires "significant adaptation investments, changes in future development policies and comprehensive buyout programs across the region will be required to ensure we are adequately planning for and confronting sea level rise". Exactly what we are not doing in Puerto Rico.

Global and Regional Sea Level Rise Scenarios for the United States (January 2017; NOAA Technical Report NOS CO-OPS 083) – Sweet et al.

The last report that I am going to discuss very well could be the one of most relevance, due to its nationwide scope, and because how recent it has been published. The report is titled Global and Regional Sea Level Rise Scenarios for the United States (January 2017; Sweet et al.; NOAA Technical Report NOS CO-OPS 083). It was prepared by NOAA, USGS,EPA, and Rutgers University, provides regional sea-level rise scenarios and tools for coastal preparedness planning and risk management. It also reviews recent scientific literature on "worst-case" global average sea-level projections and on the potential for rapid ice melt in Greenland and Antarctica. It develops updated scenarios of GMSL rise, and then regionalizes these global scenarios for the entire U.S. coastline, to serve as inputs into assessments of potential vulnerabilities and risks in the coastal environment. And also serves as a key technical input into the in-progress USGCRP Climate Science Special Report (CSSR), in which Puerto Rico and the US Virgin Islands are now involved. In what follows in this section, sentences taken verbatim from the report will be identified by quotations (""). The USACE sea level rise calculator is not used, but the given projections are process-based projections.

There are a myriad of peer-reviewed papers proposing sea level projections. A very good list of these references is found in the references section of the NOAA Tech. Rep. discussed here. Since they all have been evaluated by the large group who wrote this report, I will skip them and just discuss the report's conclusions.

"The Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force, jointly convened by the U.S. Global Change Research Program (USGCRP) and the National Ocean Council (NOC) focused its efforts on three primary tasks: 1) updating scenarios of global mean sea level (GMSL) rise, 2) integrating the global scenarios with regional factors contributing to sea level change for the entire U.S. coastline, and 3) incorporating these regionally appropriate scenarios within coastal risk management tools and capabilities deployed by individual agencies in support of the needs of specific stakeholder groups and user communities. This technical report focuses on the first two of these tasks and reports on the production of gridded relative sea level (RSL, which includes both ocean-level change and vertical land motion) projections for the United States associated with an updated set of GMSL scenarios."

In order to reduce the wide uncertainty in SLR scenarios for 2100, they assessed the most up-to-date scientific literature on scientifically supported upper-end GMSL projections, including recent observational and modeling literature related to the potential for rapid ice melt in Greenland and Antarctica. They also evaluated the most up-to-date set of methodologies for regionally adjusting a given GMSL rise scenario. They conclude:

- The scientific literature "provide evidence to support a physically plausible GMSL rise in the range of 2.0 meters (m) to 2.7 m, and recent results regarding Antarctic ice-sheet instability indicate that such outcomes may be more likely than previously thought." Note that it is GLOBAL.
- They recommend "a revised 'extreme' upper-bound scenario for GMSL rise of 2.5 m by the year 2100, which is 0.5 m higher than the upper bound scenario from Parris et al. (2012) employed by the Third NCA (NCA3)." In a matter of 5 years the (maximum) sea level bar has been raised 0.5 m! Approximately 0.1 m/yr, which is approximately 10 times the approximate sea level rise trend around the island since 2010-2011 (~1 cm/yr). This bar raising is to be expected as the world becomes warmer, relevant data becomes more plentiful, and models climate improve.
- "In addition, after consideration of tide gauge and altimeter-based estimates of the rates of GMSL change over the past quarter-century and of recent modeling of future low-end projections of GMSL rise, we revise Parris et al. (2012)'s estimate of the lower bound upward by 0.1 m to 0.3 m by the year 2100."
- <u>That is, they come up with a lower bound of 0.3 m and an upper bound of 2.5 m, both for 2100.</u> The high end estimate merits to mention the following sentence from the report (page 5): "In very general terms, synthesis and assessment of the best-available science to most effectively support risk assessment should not only aim to address the question, "What is most likely to occur?" but also "How bad could things get?".
- It is of interest that the upper bound coincides with the projection for San Juan shown in Figure 18 (disregarding the 95% Confidence Interval), a 2nd order polynomial of the San Juan data for 2100. The lower bound is smaller than the linear extrapolation of the linear fit of the tide gauge data starting in the middle of 2010.
- The report recognizes a very important fact that is seldom discussed. And that is that there is a "long-term GMSL rise commitment (lagged GMSL response)."
- The GMSL range of 0.3 to 2.5 m is discretized by 0.5 m increments. They make use of six GMSL rise scenarios (recall these are **<u>GLOBAL</u>** scenarios):
    - Low scenario: 0.3 m (GLOBAL)
    - Intermediate-Low scenario: 0.5 m (GLOBAL)
    - Intermediate scenario: 1.0 m (GLOBAL)
    - Intermediate-High: 1.5 m (GLOBAL)
    - High scenario: 2.0 m (GLOBAL)
    - Extreme scenario: 2.5 m (GLOBAL)
- These GMSL rise scenarios are used to derive regional RSL responses on a 1-degree grid covering the coastlines of the U.S. mainland, Alaska, Hawaii, the Caribbean, and the Pacific island territories, as well as at the precise locations of tide gauges along these coastlines.
- Next they go into the LOCAL projections. For these they considered 1) shifts in oceanographic factors such as circulation patterns; 2) changes in the Earth's gravitational field and rotation, and the flexure of the crust and upper mantle, due to melting of land-based ice (the so-called "ice melt fingerprints"); and 3) vertical land movement (VLM; subsidence or uplift) due to glacial isostatic adjustment (GIA, which also changes Earth's gravitational field and rotation, as well as the overall shape of the ocean basin), sediment compaction, groundwater and fossil fuel withdrawals, and other nonclimatic factors.
- Figure 25 shows the results for Total RSL change for all USA states and territories. Locations with colors above 0 in the colorbar at the bottom imply that the Local RSL will be greater than the GMSL rise. For example, if you go to Figure 25, look at the colors for the localization of Puerto Rico and the USVI, the Extreme (2.5 m) Scenario, the colorbar gives a range of 0.4-0.5.

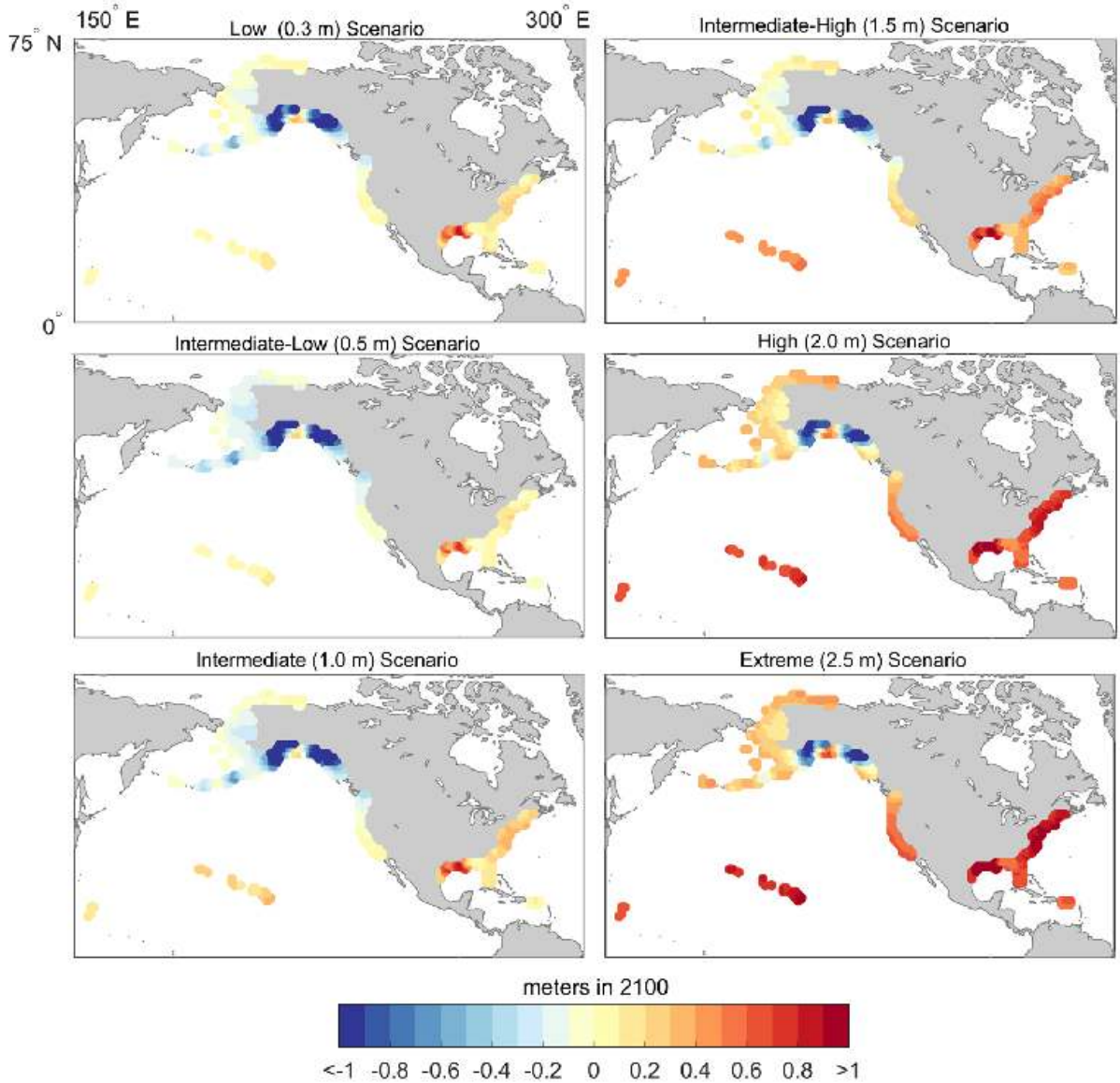

Figure 13. Total RSL change at 1-degree resolution for 2100 (in meters) relative to the corresponding (median-value) GMSL rise amount for that scenario. To determine the total RSL change, add the GMSL scenario amount to the value shown.

Figure 25 – Taken from Figure 13 in Sweet et al., 2017.

- This implies that RSL rise at these locations is higher than the GMSL rise of 2.5 m by 0.4 to 0.5 times the GMSL rise. That is, RSL = GMSL rise + (0.4 to 0.5)·GMSL rise = GMSL rise ·[1 + (0.4 to 0.5)]. This gives the result that for Puerto Rico and the USVI the Extreme Scenario RSL rise projection for 2100 varies between 3.5 and 3.75 m. ***The six process-based scenarios for Puerto Rico and the USVI are (the values inside parenthesis are the GMSL rise estimates given above):***
    - ***Low (0.3 m) Scenario: Colorbar range: 0.1-0.2 ⇒ RSL rise = 0.33 to 0.36 m.***
    - ***Intermediate-Low (0.5 m) Scenario: Colorbar range: -0.1-0.0 ⇒ RSL rise = 0.45 to 0.50 m.***

- ***Intermediate (1.0 m) Scenario: Colorbar range: 0.0-0.1 ⇒ RSL rise = 1.0 to 1.1 m.***
- ***Intermediate-High (1.5 m) Scenario: Colorbar range: 0.3-0.4 ⇒ RSL rise = 1.95 to 2.1 m.***
- ***High (2.0 m) Scenario: Colorbar range: 0.4-0.5 ⇒ RSL rise = 2.8 to 3.0 m.***
- ***Extreme (2.5 m) Scenario: Colorbar range: 0.4-0.5 ⇒ RSL rise = 3.5 to 3.75 m.***

- As expected, the results are site dependent. But, in general, with the exception of the Pacific Northwest and Alaska, according to Figure 25 Local RSL rise is projected to be greater than the global average for almost all future GMSL rise scenarios (e.g., 0.3-0.5 m or more RSL rise by the year 2100 than GMSL rise under the Intermediate scenario).
- Along almost all U.S. coasts outside Alaska, Local RSL is projected to be higher than the global average under the Intermediate-High, High and Extreme scenarios (e.g., 0.3-1 m or more Local RSL rise by the year 2100 than GMSL rise under the High scenario).

WHAT IS AT STAKE?

In this section I will use NOAAs Sea Level Rise viewer (https://coast.noaa.gov/slr/beta/#/splash) to show the potential flooding that can be expected for 1.8 m of sea level rise by 2100. This value is the worst case scenario available in the viewer which, as we have seen, falls short for the more extreme projections given by the USACE Sea Level rise calculator, and for the three more extreme projections resulting from Sweet et al., 2017. From Table 1 above we can see that this elevation is lower than the 2.17 m obtained by the USACE calculator for the NOAA High scenario (2.17 m), but is higher than the 1.67 m obtained for the USACE High scenario. The purpose is to have a rough idea of what is at stake at some of the major coastal cities around the island. Although the NOAA viewer is capable of showing other sea level elevations (0.3, 0.6, 0.9, 1.2, and 1.5 m), presenting images for all of these other elevations, for the San Juan metropolitan area, for Mayaguez, Ponce, and Arecibo would make this document too large. This can be done in a separate document. This will be followed by maps prepared by the organization Ciudadanos del Karso (CDK) back in 2010. These maps show the impact of SLR of 1, 2, and 3 m. At the time, the last two scenarios were considered farfetched, but the NOAA Technical Report discussed above suggests that we weren't so far off. Actually, the 3 m scenario shown by the CDK 3 m map cannot capture the Sweet et al., 2017, Extreme (2.5 m GMSL rise) Scenario. These are the surprises that we are bound to receive in the future.

In the NOAA viewer, areas that are hydrologically connected to the ocean (according to the digital elevation model used) are shown in shades of blue. Low-lying areas on land that are not directly linked to the ocean are shown in green. Based solely on elevation, it is likely the green areas will flood, but this requires a more detailed analysis to determine the true flooding susceptibility. Remember, the data in the maps do not consider natural processes such as erosion, subsidence, or future construction, and the information provided should be used only as a screening-level tool.

Another piece of information from the NOAA viewer that is of relevance is that the maps take into account the hydroconnectivity of inundated areas, which distinguishes them from a simple bathtub approach. However, the maps also show low-lying areas, which are considered hydrologically "unconnected" areas that may flood. Both hydrologically connected and unconnected areas are determined solely by how well the elevation data capture the area's hydraulics.

Regarding coastal erosion in areas of loose sediments, a rule of thumb used by many (including UNESCO; http://www.unesco.org/csi/pub/info/info410.htm, accessed on March 3, 2017), and which has been verified elsewhere (like in Hawaii – Romine et al., 2013; Anderson et al., 2015) is that given a sea level rise of X meters, sandy coastlines will tend to erode by a factor two orders of magnitude the value of X. UNESCO suggest using a factor of 100. Henceforth, for X = 1.8 m, the shoreline could move inland by approximately 180 m. There are not many beaches in the island with widths surpassing 180 m. Sooner or later, the retroceding shoreline will hit an immovable object, and that's the end of it.

Figure 26 –NOAA Sea Level Rise viewer. Sea level elevation: 1.8 m. Overview of the whole island.

Figure 27 – San Juan metropolitan area. SLR = 1.8 m. NOAA. Note the airport is gone, large parts of Cataño, and a large fraction of the south part of Isleta de San Juan. Also large portions of Punta Las Marias north of the Baldorioty de Castro highway, like the Luis Llorens Torres housing complex. But long before flooding occurs, those areas will be made inoperative due to drainage and water upwelling problems.

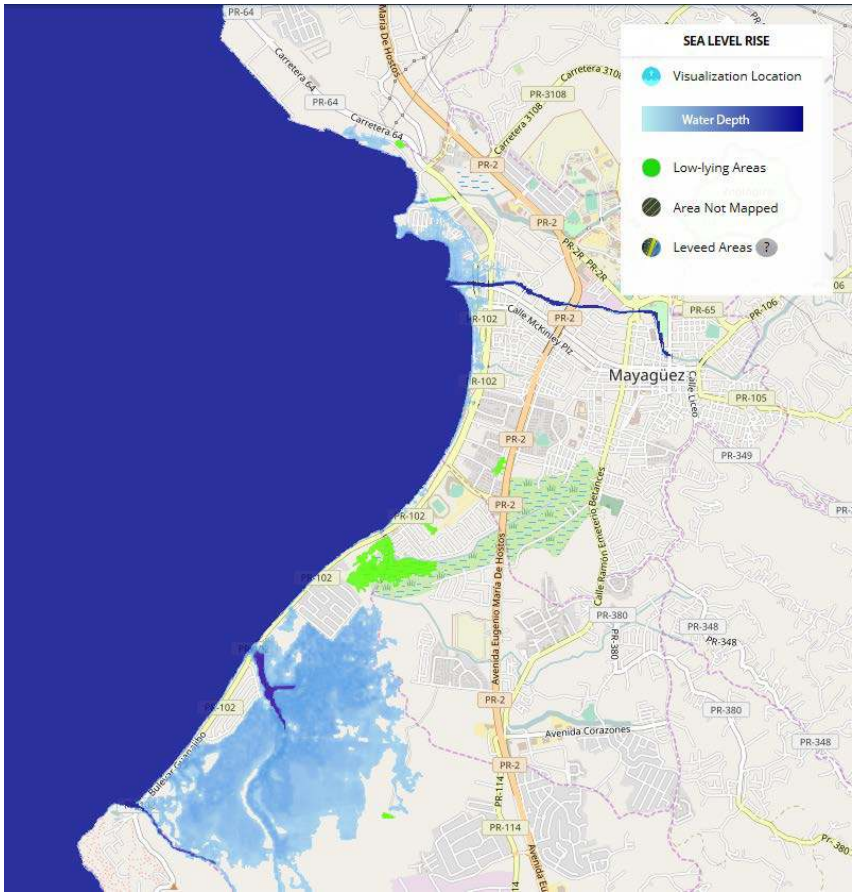

Figure 28 –Mayagüez. SLR = 1.8 m. NOAA.

Figure 29 – Ponce. SLR = 1.8 m. NOAA.

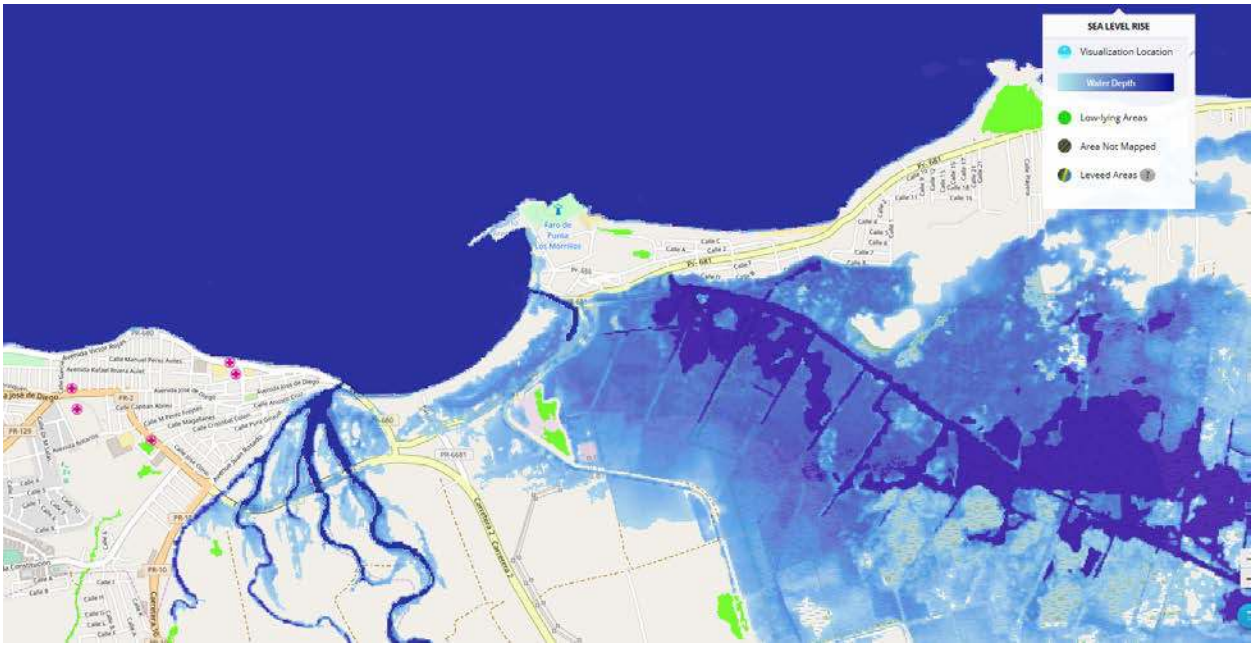

Figure 30 – Arecibo. SLR = 1.8 m. NOAA.

In 2010, the organization Ciudadanos del Karso de Puerto Rico (http://cdk-pr.org) used new Digital Elevation Models (DEM) prepared by NOAA's National Centers for Environmental Information (NCEI) (formerly the **National Geophysical Data Center**) for tsunami flood mapping, in order to prepare maps showing potentially floodable areas for several major cities along the islands coasts. The maps resolution is 10 x 10 meters. The way this was modelled is by simply shading, or painting, all areas lying below a prescribed sea surface rise elevation. This was a pure “bathtub method”. No hydroconnectivity was considered. As such, it could show less potential floodability than the maps from the NOAA viewer. The maps will show SLR elevations of 1, 2, and 3 meters. It is important to realize that the CDK maps are not associated with a given projection year. They simply illustrate (approximately) coastal areas which could be flooded is se level rises by 1, 2, and 3 meters, irrespective of whether it is purely GMSLR, or GMSLR plus local effects.

Figure 31 – CDK map for the San Juan metropolitan area for SLR = 1 m.

Figure 32 – CDK map for the San Juan metropolitan area for SLR = 2 m.

Figure 33 – CDK map for the San Juan metropolitan area for SLR = 3 m.

Figure 34 – CDK map for Mayaguez area for SLR = 1 m.

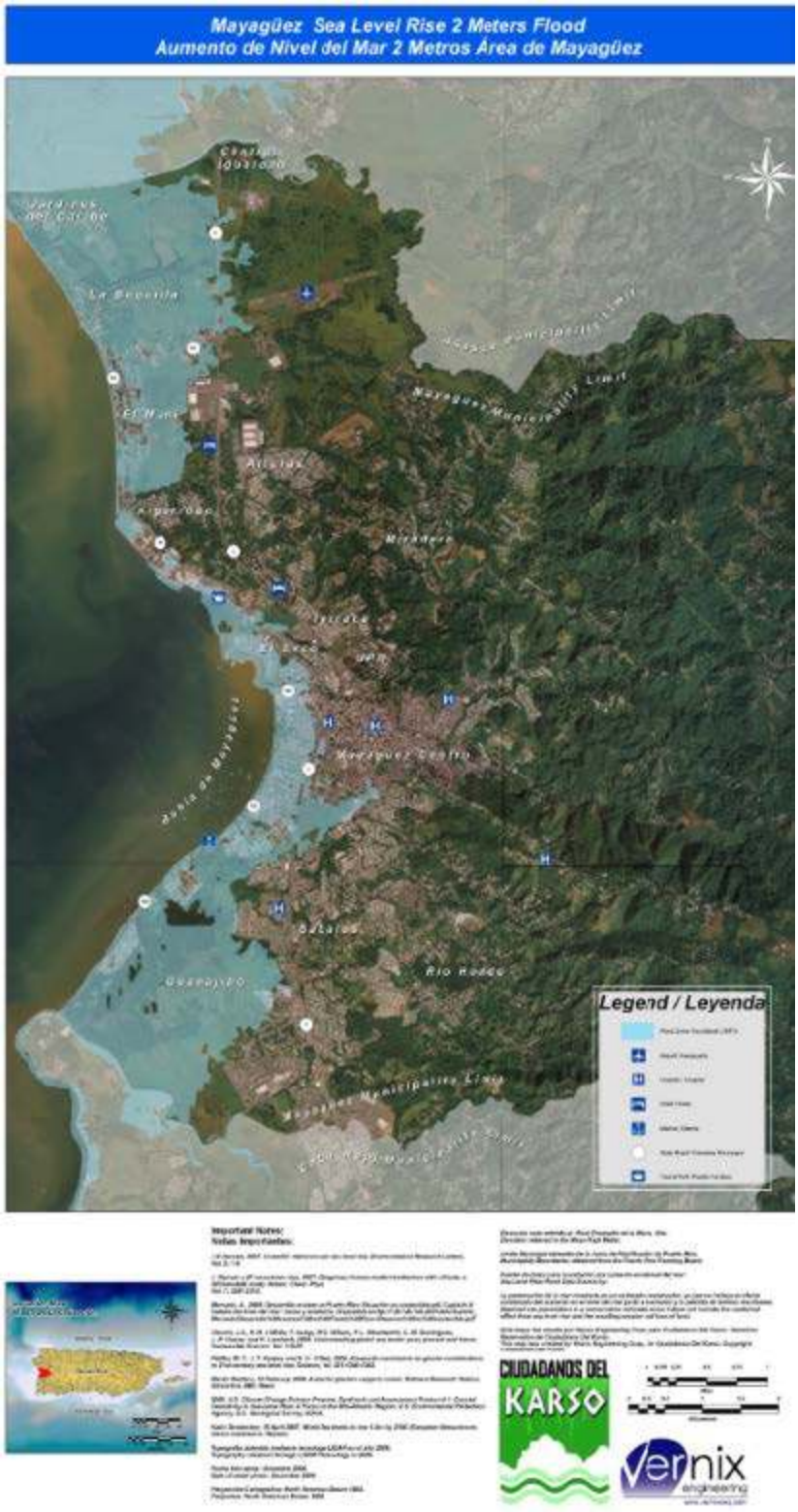

Figure 35 – CDK map for Mayaguez area for SLR = 2 m.

Figure 36 – CDK map for Mayaguez area for SLR = 3 m.

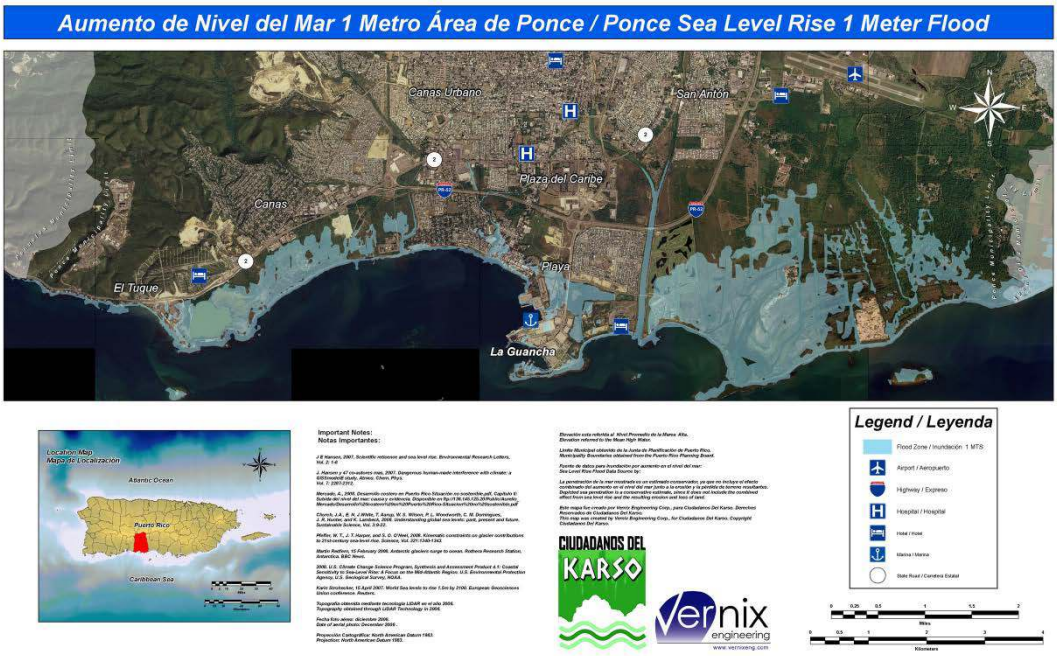

Figure 37 – CDK map for Ponce area for SLR = 1 m.

Figure 38 – CDK map for Ponce area for SLR = 2 m.

Figure 39 – CDK map for Ponce area for SLR = 3 m.

Figure 40 – CDK map for Arecibo area for SLR = 1 m.

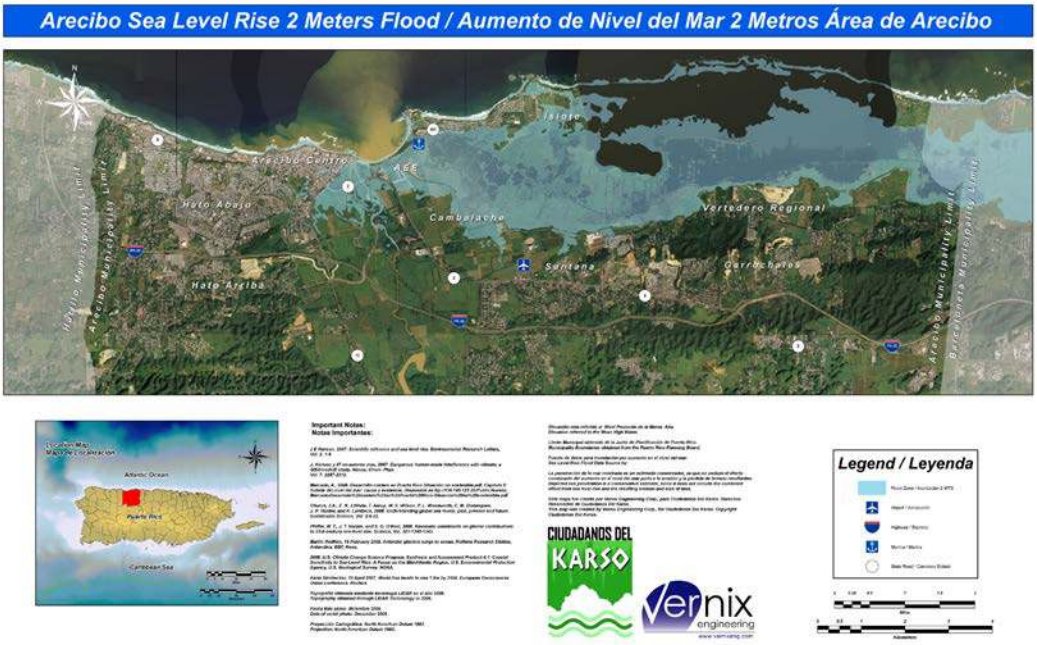

Figure 41 – CDK map for Arecibo area for SLR = 2 m.

Figure 42 – CDK map for Arecibo area for SLR = 3 m.

CONCLUSION

Oppenheimer and Alley (2016) make some comments that are of relevance:

"These and other scientific developments (*1*, *3*, *4*) are emerging too fast to be captured by the comprehensive IPCC assessments, which are published every 6 to 7 years. Policy- makers are left without a means to contextualize recent estimates, which remain highly uncertain. Taking an engineering approach and defending against the highest projections available at a given time, plus a margin of error, can be prohibitively expensive. But ignoring such estimates could prove disastrous." This is the quandary in which we humans find ourselves nowadays."

They continue by stating that high sea levels (6 – 9 m) during the Last Interglacial (130,000 to 116,000 years ago) higher that today "can only be explained through mass loss from the ice sheets in response to a sustained forcing that is likely to be exceeded before 2100 under high emissions pathways." (emphasis mine). So it looks as if these two highly regarded researchers have joined the J. Hansen bandwagon in discussing the possibility of SLR of several meters by 2100. They also state that if very fast (ice sheet) retreat occurs, it might present a challenge to adaptation capacity worldwide.

Oppenheimer and Alley (2016) continue by stating:

"Scientists can contribute to improving the basis for policy judgments by presenting policymakers with projections that are as fully probabilistic as possible while also characterizing deep uncertainties, rather than just them handing the worst-case or most-likely estimates. Coastal protection is a risk management issue, and risks cannot be fully managed outside a probabilistic context."

That's why different scenarios are presented, and which choice to take depends strongly on what is at stake. A nuclear power plant? An airport? A hospital? A school to be constructed? A Fire Department?

In light of all of these, should Puerto Rico follow the so-called Precautionary Principle?

> ***The Precautionary Principle*** *is a strategy to cope with possible risks where scientific understanding is yet incomplete. The Precautionary Principle is defined as follows:*
> *When human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm. Morally unacceptable harm refers to harm to humans or the environment that is*
>
> - *threatening to human life or health, or*
> - *serious and effectively irreversible, or*
> - *inequitable to present or future generations, or*
> - *imposed without adequate consideration of the human rights of those affected.*
>
> *The judgement of plausibility should be grounded in scientific analysis. Analysis should be ongoing so that chosen actions are subject to review. Uncertainty may apply to, but need not be limited to, causality or the bounds of the possible harm.*
>
> *Actions are interventions that are undertaken before harm occurs that seek to avoid or diminish the harm. Actions should be chosen that are proportional to the seriousness of the potential harm, with consideration of their positive and negative consequences, and with an assessment of the moral*

implications of both action and inaction. The choice of action should be the result of a participatory process.

Source: UNESCO COMEST report The Precautionary Principle

If practitioners in Puerto Rico want to evaluate future scenarios of coastal flooding due to extreme meteorological events, they can consult the Puerto Rico Storm Surge Atlas. In this Atlas coastal flood maps are shown for the five Saffir-Simpson hurricane categories under three sea level rise scenarios: present, +0.5 and +1.0 m, above present. As this is being written we are adding flooding due to wave runup/overtopping to the present sea level scenario maps, as part of a project sponsored by the Puerto Rico Coastal Zone Management Program (PRCZMP). History has shown that in islands like Puerto Rico and the USVI the additional flooding by wave runup/overtopping can greatly increase the inland flooding due to a meteorological event. The addition of wave runup/overtopping to the other two sea level rise scenarios will have to wait for a sponsor.

Based on the USACE Sea Level Rise calculator, 2100 projection of LSLR (using Option 1):

- ***USACE and NOAA Low:*** ***LRSL rise = 0.36 m***
- ***USACE Intermediate/NOAA Intermediate Low:*** ***LRSL rise = 0.67 m***
- ***NOAA Intermediate High:*** ***LRSL rise = 1.37 m***
- ***USACE High:*** ***LRSL rise = 1.67 m***
- ***NOAA High:*** ***LRSL rise = 2.17 m***

Based on six process-based (climate models) scenarios, and using results for Puerto Rico and the USVI (values within parenthesis are the Global Mean Sea Level rise estimates for that given scenario and for 2100):

- ***Low (0.3 m) Scenario:*** ***LRSL rise = 0.33 to 0.36 m.***
- ***Intermediate-Low (0.5 m) Scenario:*** ***LRSL rise = 0.45 to 0.50 m.***
- ***Intermediate (1.0 m) Scenario:*** ***LRSL rise = 1.0 to 1.1 m.***
- ***Intermediate-High (1.5 m) Scenario:*** ***LRSL rise = 1.95 to 2.1 m.***
- ***High (2.0 m) Scenario:*** ***LRSL rise = 2.8 to 3.0 m.***
- ***Extreme (2.5 m) Scenario:*** ***LRSL rise = 3.5 to 3.75 m.***

We should also have in mind the more dramatic projections by Hansen et al. (2016) and DeConto and Pollard (2016), which use very sophisticated modeling, including the latest in ice sheets physics.

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APPENDIX A:

STATE OF SCIENCE UPDATE REPORT (verbatim from Southeast Florida 2015 report)

ACCELERATION OF SEA LEVEL RISE

A statistically significant acceleration of sea level rise has been documented in the latter half of the 20th century continuing through recent years (Church and White, 2011; Calafat and Chambers, 2013; Hay et al. 2015; IPCC, 2013; Watson et al., 2015). Hay et al. (2015) reported the global sea level rise rate from 1901 to 1990 to be 1.2 +/- 0.2 mm/yr (a value which had been overestimated in previous studies). Since 1993, an increase in the average global mean sea level rise rate has been observed (Hay et al., 2015; Watson et al., 2015). Watson et al. (2015) has most recently reported the average global mean sea level rise rate to be more than double the rate of the previous century, indicating an acceleration; the observed rate was 2.6+0.4 mm/yr from 1993 to 2015 with an acceleration of 0.04 mm/yr2. This acceleration indicates sea level will rise more rapidly in the future than it has historically. The global and regional processes driving sea level rise and its acceleration are discussed in the following sections.

FACTORS INFLUENCING SEA LEVEL RISE

GLOBAL PROCESSES

In 2011, the Work Group noted studies describing a variety of reinforcing (positive) feedbacks that are accelerating ice sheet melt in Greenland and Antarctica and also accelerating Arctic pack ice melt, permafrost thaw and organic decay, and methane hydrate release from the warming Siberian Shelf, in addition to other global processes affecting sea level rise i.e. increasing greenhouse gas concentrations, changes in volcanic forcing and tropospheric aerosol loading (Compact, 2011). Since then, numerous additional reinforcing feedbacks have been documented and previously recognized feedbacks have intensified.

ACCELERATION OF ICE MELT

Accelerated melting of the ice sheets on Greenland and Antarctica (Rignot et al., 2011; Talpe et al., 2014) is expected to be the predominant factor affecting sea level rise acceleration during the 21st Century. Melting is caused by increasing temperatures and warming of the atmosphere, warm currents moving along the coast of Greenland, and warm ocean water moving under and up into ice sheets through deep outlet glacial fjords in Antarctica. Recent observations have indicated ice sheets are more vulnerable to melting than previously realized due to the extent of deep valleys within the ice sheets connecting warmer ocean water to the internal areas of the ice sheets thus causing rapid melting and peripheral thinning (Jenkins et al., 2010; Jacobs et al., 2011; Morlighem et al., 2014; Rignot et al., 2014; Greenbaum et al., 2015). Accelerated melting results in large discharges of fresh water which raises the local sea level near the ice sheets (8 inches around Antarctica over past 20 years) (Rye et al., 2014). This release of freshwater has resulted in a seasonal increase in the amount of sea ice in the Antarctic (Bintanja et al., 2013; Rye et al., 2014) and slower circulation of North Atlantic surface water, also known as Atlantic Meridional Overturning Circulation (Rahmstorf et al., 2015). The slowdown in circulation may contribute to increased local sea level rise along the Florida coast, as discussed in the ***Regional/ Local Processes*** section. The IPCC projections do not include the factors related to acceleration of ice melting processes described above, and as a result are likely an underestimate of future sea level rise (Rignot et al., 2011).

ICE SHEET DISINTEGRATION

Indicators of ice sheet disintegration include retreat of the ice sheet's outer boundary and rapid thinning. Lateral flow of the Greenland Ice Sheet margin, the outer boundary, has dramatically accelerated in the past two decades in response to surface melt waters penetrating fractures in the ice and warming and softening the ice (Bell et al., 2014). In addition to retreat, the ice sheets have initiated a rapid thinning process due to basal melt (Pritchard et al., 2012), signaling the initiation of prolonged ice sheet degradation based on historic analysis (Johnson et al., 2014). Joughin et al. (2011) have used numerical models to look at the sensitivity of the outlet glaciers of the West Antarctic Ice Sheet to ocean water melt and have concluded that the West Antarctic Ice Sheet collapse is already underway; the extent of the collapse in the future is not yet known. As part of the Gravity Recovery and Climate Experiment (GRACE) satellite monitoring program, ice sheet mass loss has been quantified as 280±58 gigatons per year (Gt/yr) from Greenland and up to 180±10 Gt/yr in Antarctica (Velicogna et al., 2014). As a reference for the magnitude of a gigaton, one could estimate one gigaton to equal the mass of over one hundred million elephants. In addition, significant recent work was completed to verify the estimated contribution of ice sheet disintegration to sea level rise using satellite data (Jacob et al., 2012; King et al., 2012; Gardner et al., 2013) with the conclusion that ice sheet melt accounted for 29±13% of sea level rise from 2003 to 2009 (Gardner, 2013). In order to further refine the estimates and projections of the magnitude of ice sheet degradation and their contribution to sea level rise, the complex dynamics driving ice sheet melt need to be better understood, in particular the mechanisms driving interactions between ice sheets and warm currents.

WARM CURRENTS

In 2011, the Work Group acknowledged the effects of warm ocean water currents accelerating summer pack ice melt and causing melting beneath the outlet glaciers. Recent work has further clarified the compounding mechanisms driving the flow and temperature changes of warm currents. Spence et al. (2014) analyzed the poleward shift in direction of the southern hemisphere westerly winds since the 1950's and simulated the intense warming of coastal waters associated with such a shift in order to explain and forecast the significant temperature increase in ocean waters interacting with the base of ice sheets and floating ice shelves. This study serves to validate the projection of the persistence of this wind trend and the resulting melting due to warm current interaction. Separate from wind forcing, an increase in ocean surface stress due to thinning of the formerly consolidated sea-ice cover near Antarctica is proposed to result in a redirection of warm ocean currents into submarine glacial troughs and further expediting melting of the deep ice-shelf base based on ocean-ice modeling (Hellmer et al., 2012). Ice sheet melt as a result of interaction with warm currents is one of the dominant factors contributing to recent global sea level rise (IPCC, 2013); however, as discussed in the next section, land based contributions to global warming may further exacerbate sea level rise in the future.

THAWING PERMAFROST

The potential for significant additional emissions of carbon dioxide and methane from thawing permafrost and the rate of occurrence continues to be investigated. The intricate feedback mechanisms associated with permafrost are not well understood; as such, the IPCC did not include permafrost thaw in its projections (Collins et al., 2013). This deficiency was criticized publicly due to the theorized potential for permafrost carbon emissions to exceed emissions from fossil fuel use. Schuur et al. 2013 conducted a survey of experts to quantify permafrost change in response to four global warming

scenarios and found despite risk for significant contributions of emissions from thawing, fossil fuel combustion was likely to remain the main source of emissions and climate forcing until 2100 based on the proposed warming scenarios.

Following the release of the IPCC (2013) report, demand for research to understand the dynamics of the physical and chemical permafrost processes has increased in order to confirm the estimates of emissions from thawing. As an initial step, the occurrence of significant submarine permafrost thawing was confirmed by Overduin et al. (2014) when 8 to 10°C of warming within the permafrost layer was observed in less than 1,000 years, resulting in a degradation of ice-bearing permafrost at the rate of 3 cm/yr. In addition, seawater seeping through soil pores was identified as the source of sulfate necessary to oxidize methane in the upper layer of the thawing permafrost. Although site specific, studies such as Overduin et al. (2014) will begin to provide the information necessary to incorporate permafrost thawing into models and projections in the near future.

REGIONAL/ LOCAL PROCESSES

VERTICAL LAND MOVEMENT (this section is more location specific; it is shown for completeness)

Vertical earth movements, which regionally and locally modify the globally averaged rate of sea level change, result in a relative rate of change that varies from one location to another. These land motions have been inferred from historical tide data and geodesic measurements. When added to projected rates of global mean sea level rise, they result in a perceived change ranging from increased rise in regions of subsidence (e.g., New Orleans) to falling sea levels where the land is being uplifted (e.g., along the northern border of the Gulf of Alaska). Other regions are geologically stable and have only small differences with respect to the global rate of change. In South Florida, in general, coastal land elevations are considered to be relatively stable meaning that the land is not experiencing significant uplift nor subsidence. It is also important to note, the vertical land movement that is occurring is non-uniform across South Florida and movement measured at specific monitoring stations sites may not reflect vertical land movement in adjacent areas.

The Continuously Operating Reference (COR) network of permanent Global Positioning System (GPS) receivers provides precise measurements of vertical land movement in four locations throughout Southeast Florida (Key West, Virginia Key, Pompano Beach, and Palm Beach) over periods of nine to eleven years. Additional continuous GPS measurements have been acquired in eight other sites in the region over various time periods (two to eleven years). Precise analysis of these data reveals negligible vertical movements at most stations (less than 1 mm/yr) (Snay et al., 2007; Santamaría-Gómez et al., 2012; NGL, 2015). However, some stations show 1 to 6 mm/yr of subsidence, reflecting mostly local unstable conditions of the GPS antenna monument (e.g., local building movements) (e.g., Bock et al., 2012).

National Geodetic Survey has operated continuous GPS stations at Key West, Fort Lauderdale, Miami and Palm Beach Gardens. The GPS data of these sites were processed by the Nevada Geodetic Laboratory, who presents the results at GPS time series (http://geodesy.unr.edu/index.php). The rates of vertical land movement at these stations are shown in Table 1 (Blewitt et al., 2015). It should be noted vertical land movement is non-uniform across South Florida as a result of geology variations and the non-uniform compaction of fill placed during development of the region. Subsidence at tide stations is closely monitored to ensure the accuracy of sea level rise measurements. The regional rate of sea

level rise is affected by such localized subsidence and is accounted for in the regional sea level rise acceleration variable incorporated in the projections adapted for the region.

Table 1: Continuous GPS Operation in Southeast Florida (Blewitt et al., 2015)

Site	Location	Duration	Vertical rate (mm/yr)
KYW1	Boca Chica Key	1997-2008	-0.5 ± 0.1
KYW5	Boca Chica Key	2007-present	0.1 ± 0.1
KYW6	Boca Chica Key	2007-present	1.0 ± 0.1 (uplift)
KWST	Key West airport	2003-present	-1.5 ± 0.1
CHIN	Key West, 500 m south of tide gauge	2008-presnt	-1.6 ± 0.5
LAUD	Fort Lauderdale Executive Airport	2005-2014; 2014-2015	-0.5± 1.1
ZMA1	Miami Airport	2004-2008; 2008-present	0.2± 0.9
FLC6	Florida City	2009-present	-1.8± 1.2
PBCH	North Palm Beach County Airport	2005-present	1.0± 1.0 (uplift)

Additionally, in some regions, the effects of changing ocean currents can further modify the relative local rate of sea level rise. Such is the case of the east coast of Florida, as is discussed in the next section, **Ocean Dynamics, Gulfstream/ Circulation**

OCEAN DYNAMICS, GULFSTREAM/ CIRCULATION

> *[MY COMMENTS: As can be seen in Figure 36 below, the Florida Current (which goes through the Florida Straits) and the Gulf Stream derive a large part of their transport from the North Equatorial Current (NEC). This NEC (in contradistinction to what the report about the gas port submitted by consultants to PREPA said, that it was generated on the beaches of Jobos Bay, PR.; sorry to disappoint the so-called, well-paid, consultants – si no lo digo, reviento) divides into two branches, one south and the other north of Puerto Rico. The point that I am trying to drive is that whatever is observed (as mentioned below) along the Atlantic Florida coasts, and the eastern seaboard of the USA (at least up to where the Gulf Stream separates from the USA shelf) should also be felt along both the north and south coasts of Puerto Rico.]*

Ocean circulation has changed little during the current period of scientific observation, but in the future it can considerably alter the relative rate of sea level rise in some regions, including Southeast Florida. A slowing of the Florida Current and Gulf Stream will result in a more rapid sea level rise along the east coast of North America. By 2100, these circulation changes could contribute an extra 8 inches of sea level rise in New York and 3 inches in Miami according to Yin et al. (2009). Most of the global climate models used by the IPCC (IPCC, 2007; 2013) project a 20-30% weakening of the Atlantic Meridional Overturning Circulation (AMOC), of which the Gulf Stream and Florida Current are a part. Measurements

of the AMOC have yet to conclusively detect the beginning of this change, however there has been a report of a recent decline in AMOC strength by Smeed et al. (2014) that coincides with the mid-Atlantic hotspot of sea level rise reported by Ezer et al. (2013) and Rahmstorf et al. (2015). Recent analysis of the Florida Current transport has detected a decrease in circulation over the last decade, which appears to account for 60% of South Florida sea level rise over the decade and contribute to a positive acceleration (Park and Sweet, 2015). If a long-term slowdown of the AMOC and Florida Current. Rahmstorf et al. (2015) use a proxy method also suggesting that a slowdown of the AMOC has begun. If a long-term slowdown of the AMOC does occur, sea level rise along the Florida east coast could conceivably be as much as 20 cm (8 inches) greater than the global value by 2100.

According to the most recent estimates by the IPCC (IPCC 2013, FigureB-1), the combined differential due to regional ocean heating and circulation change along the Southeast Florida coast would be in the range of 10%-20% greater than the globally averaged rise by 2090. For a median (50% probability) sea level rise of one meter by 2100, this would give about 10-20 cm (4-8 inches) of additional rise along the Southeast Florida coast, which is within the range of estimates by Yin et al. (2009). However, the IPCC models do not have the horizontal resolution required to effectively estimate these changes at the scale of the Florida Current and more research with higher resolution ocean models will be required. As such, it is prudent to add ~15% to the global mean sea level rise values projected by the IPCC in order to use them for Southeast Florida planning. This adjustment is accounted for in the regional sea level rise coefficients incorporated in the projections adapted for the region.

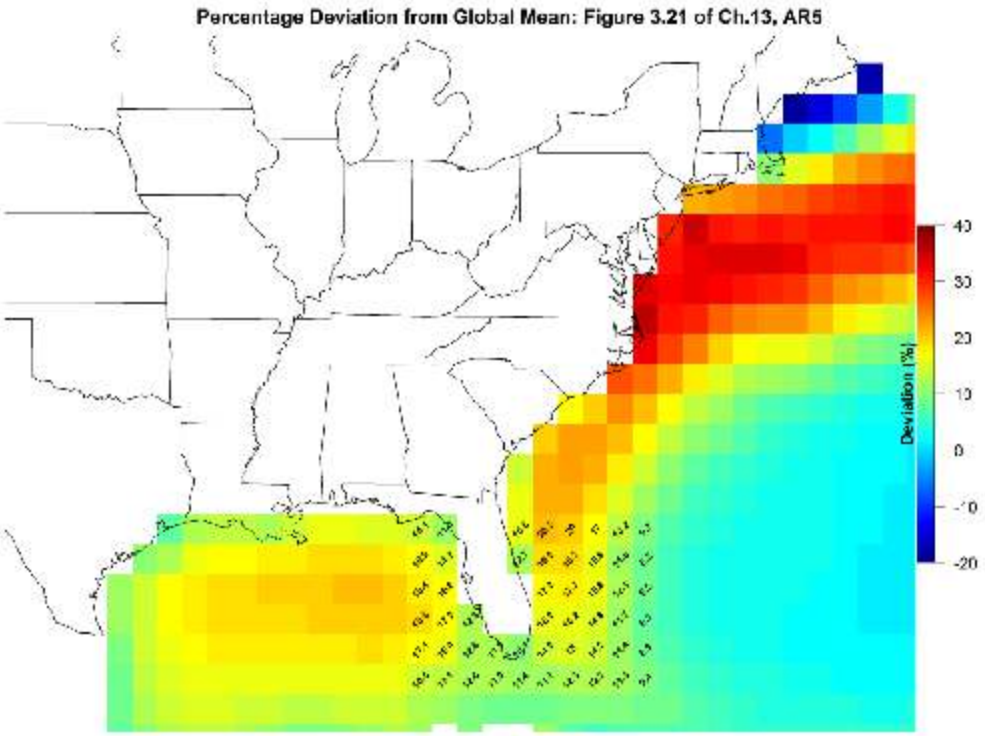

Figure B-1. Percentage of the deviation of the ensemble mean regional relative sea level change between 1986-2005 and 2081-2100 from the global mean value, based on Figure 13.21, IPCC (2013). The figure was computed for RCP4.5, but to first order is representative for all Representative Concentration Pathways (RCP). RCPs are the four greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5).

Figure 43 – From Figure B-1 in the Southeast Florida report.

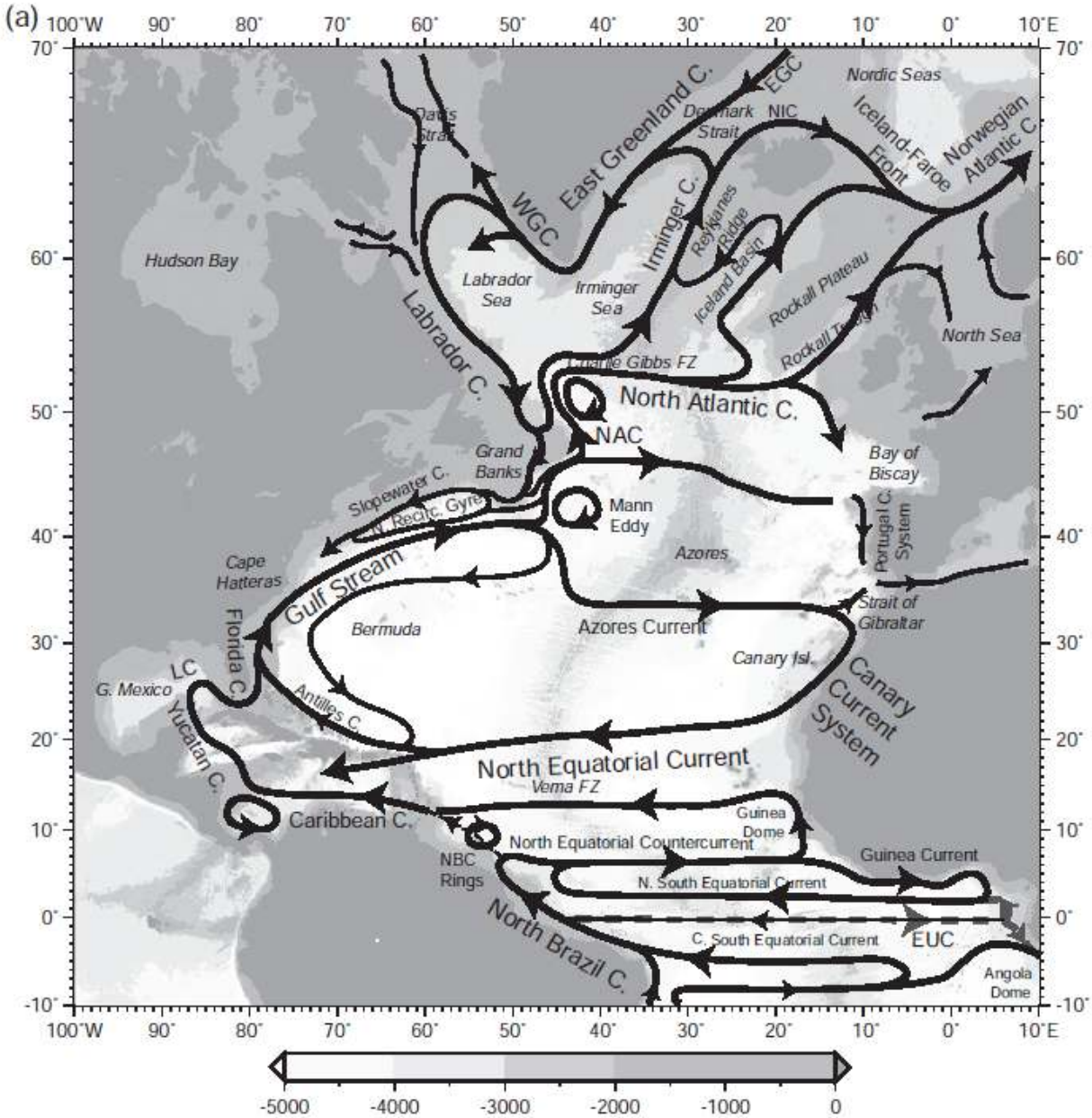

FIGURE 9.1 Atlantic Ocean surface circulation schematics. (a) North Atlantic and (b) South Atlantic; the eastward EUC along the equator just below the surface layer is also shown (gray dashed).

Figure 44 - Taken from Descriptive Physical Oceanography: An Introduction (Sixth Edition). LYNNE D. TALLEY, GEORGE L. PICKARD, WILLIAM J. EMERY, JAMES H. SWIFT. Elsevier 2011

APPENDIX B

IS PUERTO RICO SINKING OR RISING?

As we have seen, Vertical Land Motion (VLM) can play a large role in the overall picture. The legend in Figure 3 in this report (Figures 52 and 53 in the PRCCC 2013 report), values of VLM of -0.02 and -0.49 mm/yr are given for the tide gauge in San Juan, and Isla Magueyes, respectively. These values were taken from Zervas et al., 2013. According to the sign notation, a negative sign implies the land is subsiding. The equation goes like this (Sweet et al., 2017)

$\Delta RSL = \Delta SSH - VLM$

where ΔRSL is the Relative Sea Level Rise, and ΔSSH is the Sea Surface Height. As expected, for VLM < 0 the Relative Sea Level is increasing. The problem is that in Table 1 in Zervas et al., 2013, the values for San Juan and Isla Magueyes are given with a positive sign, implying that at both sites land is going up, which, according to the equation above, decreases ΔRSL.

For the San Juan tide gauge the values is so small, possibly falling within the error bounds, that it doesn't make much of difference. But for Isla Magueyes that's not necessarily so.

In the report by Sweet et al., 2017, they present a figure (Figure 5 in their report) showing GPS-derived VLM (see Figure 44). The density, and size of the circles does not allow estimation of values for Puerto Rico, even after trying to zoom in (Figure 45). One can see a mixture of positive and negative trends. Therefore, I went to the JPL link given in the legend of the figure, and this is what I got (see Figures 44 to 49). Information about the sinking/rising trend is given for 5 stations in the island. Four of them are in the coast: San Juan, Mayaguez, Isabela, and Caja de Muertos.

Considering the confidence intervals, it looks as if San Juan and Caja de Muertos are stable, Isabela seems to be slightly sinking, but Mayaguez is certainly sinking. Unfortunately, Isla Magueyes falls somewhat in between Mayaguez (sinking) and Caja de Muertos (stable). Comparing with the results from Zervas et al., 2013, San Juan seems to agree, but Isla Magueyes doesn't seem so. Mayaguez is sinking, and Caja de Muertos is stable. And Zervas et al., 2013, say it is rising. Time will tell.

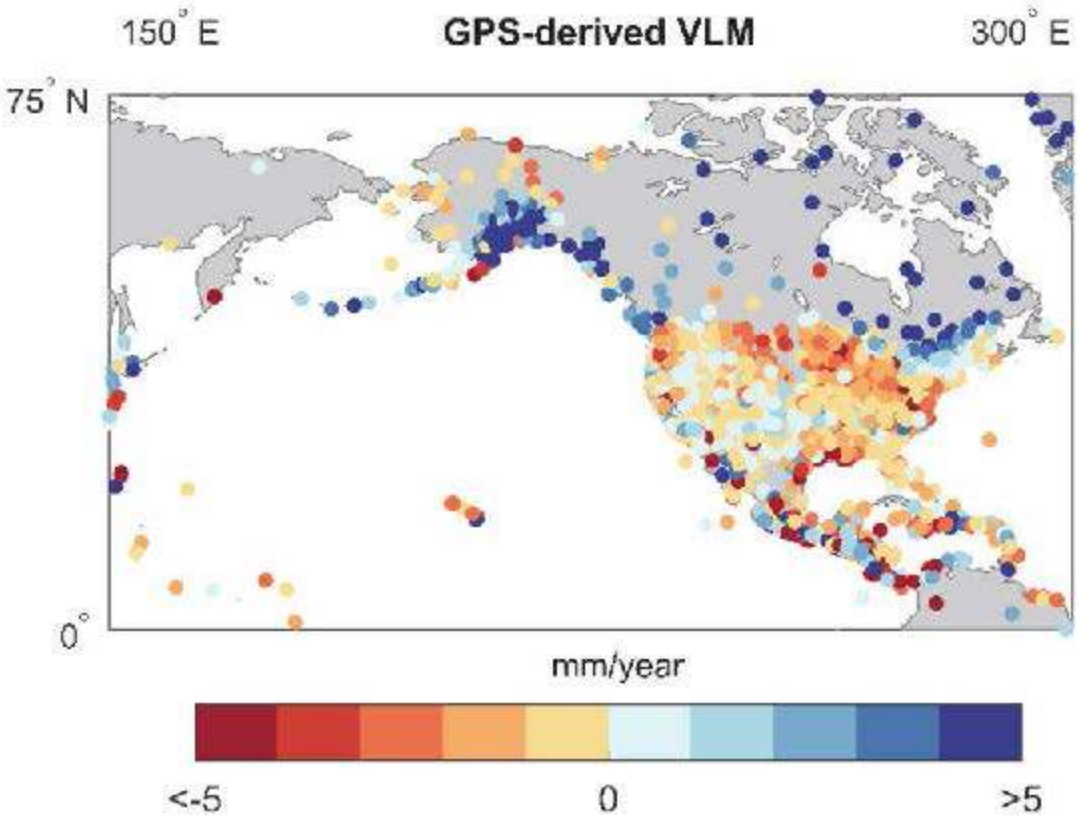

Figure 45 – GPS-derived VLM. From Sweet et al., 2017.

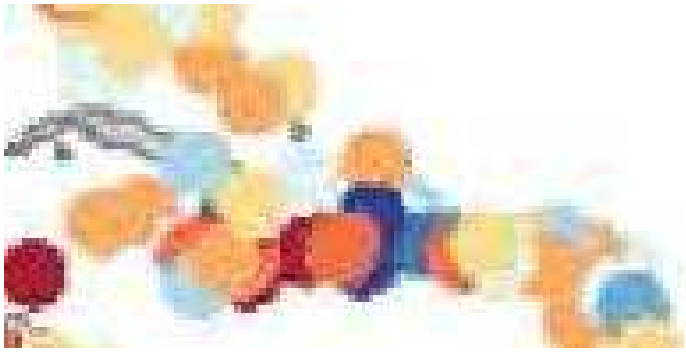

Figure 46 – Attempted zoom of Figure 44 above.

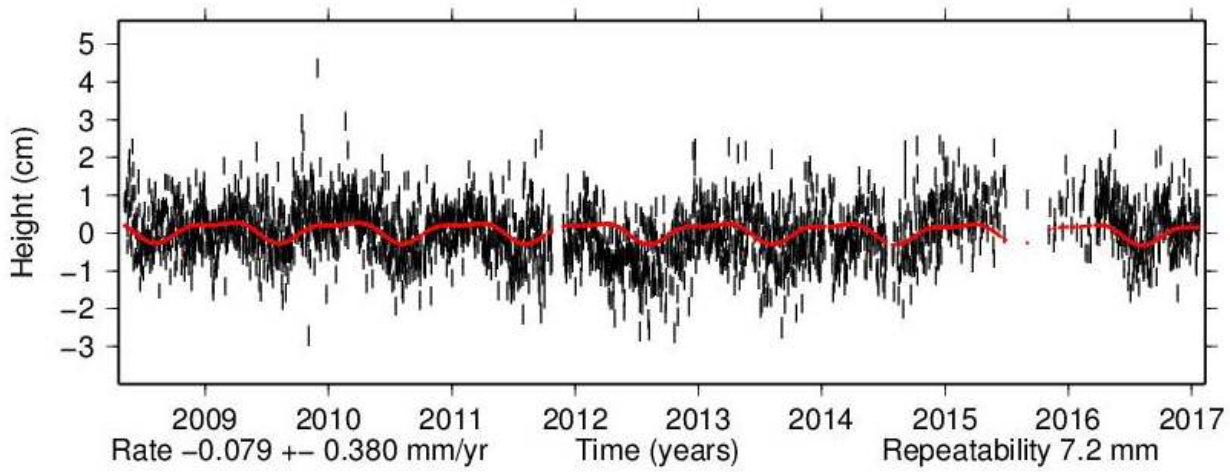

Figure 47 – GPS-derived VLM for the San Juan tide gauge (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). Note the very small slope of the red curve, in agreement with the listed Rate (mm/yr). The true value lies within +0.301 and -0.459 mm/yr. Thus we cannot say whether San Juan is rising, or sinking. Seems to be stable.

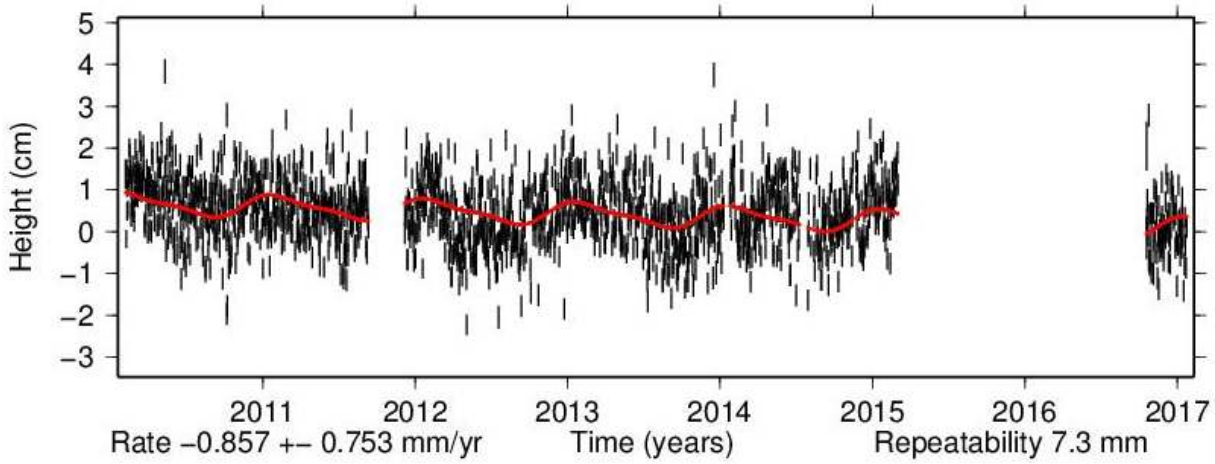

Figure 48 – GPS-derived VLM for the Mayaguez tide gauge (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). Just by eyeballing it we can see a negative trend for the red curve, in agreement with the two bounds of -0.104 to -1.61 mm/yr (the true value lies within these two bounds). Thus Mayaguez is sinking.

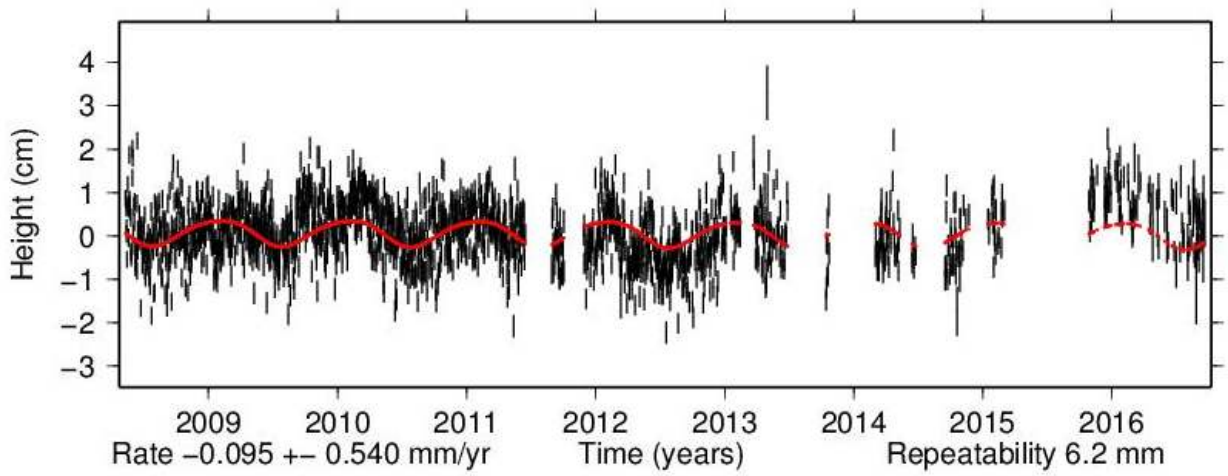

Figure 49 - GPS-derived VLM for the Caja de Muertos tide gauge (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). The true value lies within the bounds +0.445 to -0.635 mm/yr. As in San Juan, no obvious trend is seen.

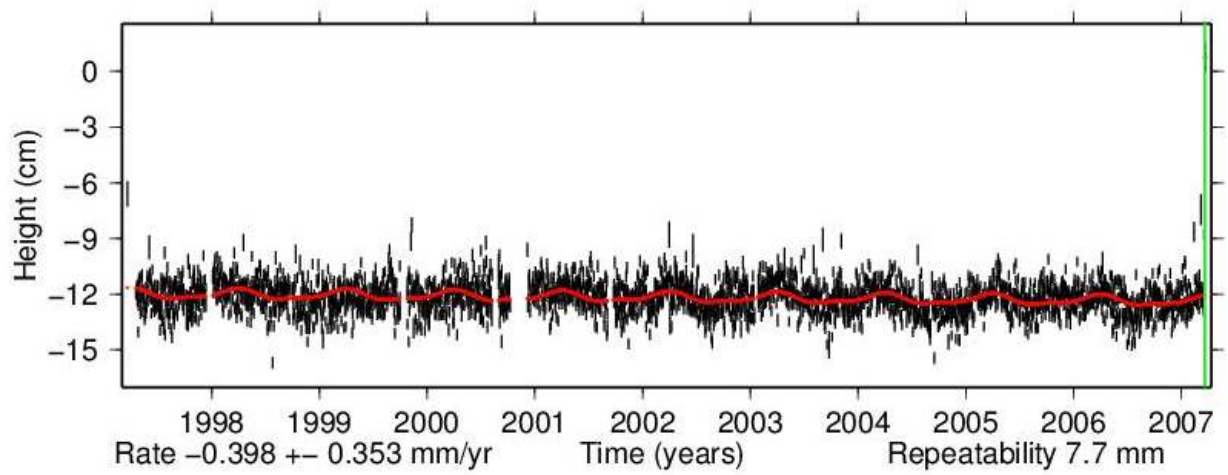

Figure 50 - GPS-derived VLM for the Isabela station (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). The true value lies within the bounds +0.045 to -0.751 mm/yr. As in San Juan, no obvious trend is seen. But it looks as if it were sinking.

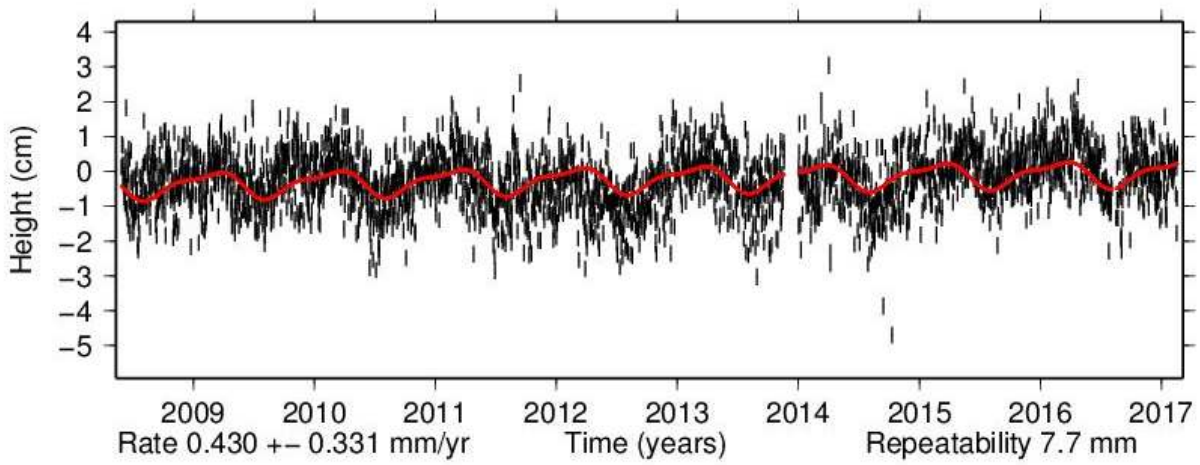

Figure 51 - GPS-derived VLM for the Ponce station (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). The true value lies within the bounds +0.761 to +0.099 mm/yr. There a positive trend. It looks as if Ponce is rising.

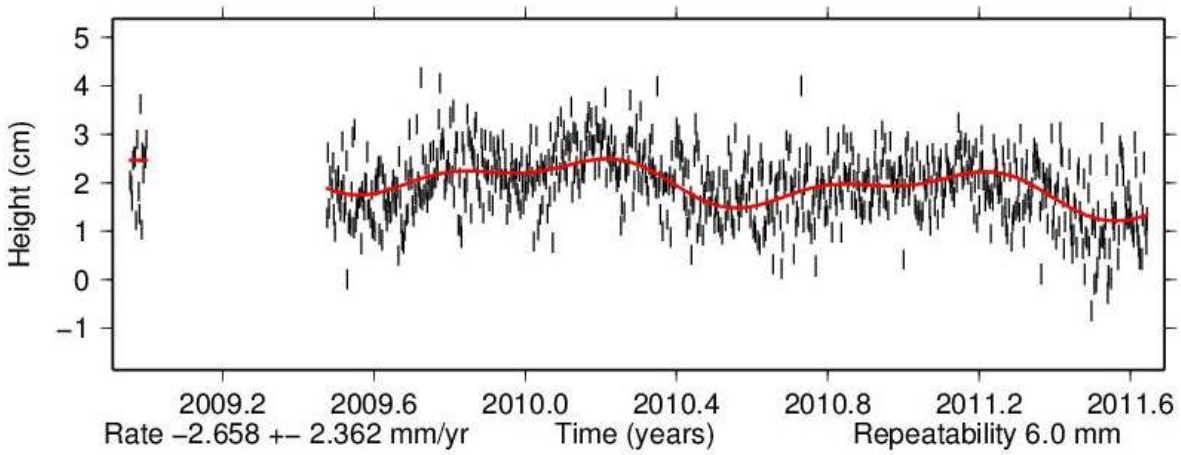

Figure 52 - GPS-derived VLM for the Mona Island station (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). The true value lies within the bounds -0.296 to -5.02 mm/yr. There a negative trend. It looks as if Mona Island is sinking.

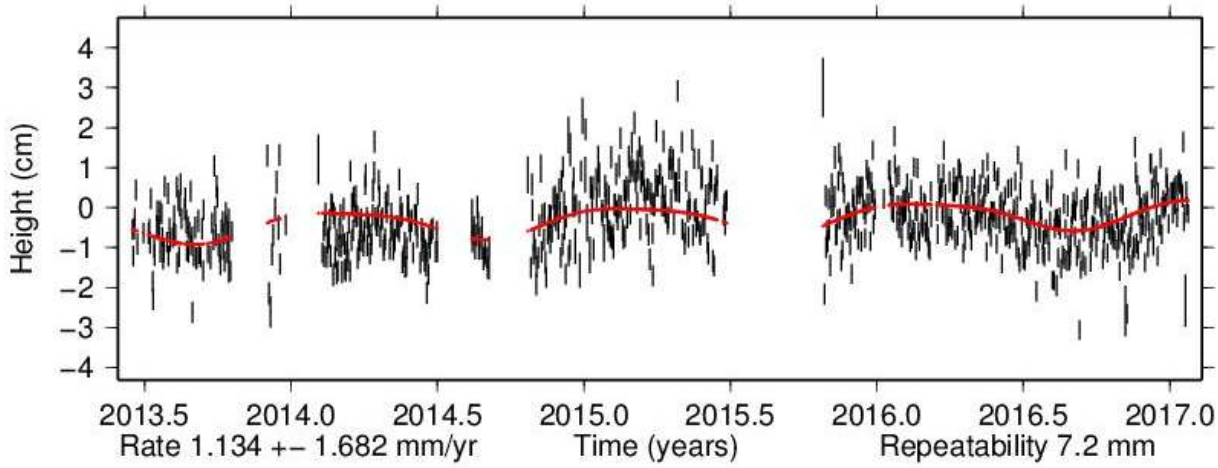

Figure 53 - GPS-derived VLM for the Charlotte Amalie station (from (http://sideshow.jpl.nasa.gov/post/series.html - accessed February 6, 2017). The true value lies within the bounds 2.816 to -.0548 mm/yr. There a positive trend. It looks as if Charlotte Amalie is rising.

APPENDIX C (taken verbatim from Wikipedia – accessed on March 1, 2017)

Representative Concentration Pathways

Representative Concentration Pathways (**RCPs**) are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. The RCPs are consistent with a wide range of possible changes in future anthropogenic (i.e., human) greenhouse gas (GHG) emissions.

- RCP 2.6 assumes that global annual GHG emissions (measured in CO_2-equivalents) peak between 2010-2020, with emissions declining substantially thereafter. RCP 2.6 is more consistent with global policy aiming to keep the likely increase in global mean temperature above pre-industrial levels below 2°C (3.6°F); under RCP 2.6., global CO^2 emissions decline by about 70% between 2015 and 2050.
- Emissions in RCP 4.5 peak around 2040, then decline.
- In RCP 6, emissions peak around 2080, then decline.
- In RCP 8.5, emissions continue to rise throughout the 21st century. Often referred to as a "Business-As-Usual" scenario, is consistent with a future in which there are few global efforts to limit or reduce emissions. Under RCP 8.5, global CO^2 emissions nearly double between 2015 and 2050.

The four RCPs are consistent with certain socio-economic assumptions but are to be substituted with the Shared Socio-economic Pathways which are anticipated to provide flexible descriptions of possible futures within each RCP.

AR5 global warming increase (°C) projections[5]

	2046-2065	2081-2100
Scenario	Mean and *likely* range	Mean and *likely* range
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6.0	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)