Unified Sea Level Rise Projections in Practice

Jayantha Obeysekera, PhD, PE, D.WRE
Chief Modeler, SFWMD

South Florida Hydrologic Society Meeting,
January 27, 2016
Outline

- Unified Sea Level Rise Projections and their application
- Predicting sea level extremes
Sources of Sea Level Rise

Terrestrial Water Input
- Terrestrial water storage, extraction of groundwater, building of reservoirs, changes in runoff, and seepage into aquifers

Land-based Ice
- Glaciers
- Ice Sheets (Greenland and Antarctica)

Thermal Expansion
- Surface and deep ocean circulation changes, storm surges
- Subsidence in river delta region, land movements, and tectonic displacements
- As the ocean warms, the water expands
- Exchange of the water stored on land by glaciers and ice sheets with ocean water
Change in Relative Sea Level

\[ \Delta RSL = \Delta SL_G + \Delta SL_{RM} + \Delta SL_{RG} + \Delta SL_{VLM} \]

**Global:**
\[ f(\text{Scenario, Time epoch}); \]

**Regional:**
- \( \Delta SL_{RM} \): \( f(\text{meteo-oceanographic factors, aka Dynamic Sea Level}) \)
- \( \Delta SL_{RG} \): \( f(\text{Changes in earth's gravitational field due to redistribution effects of rapid ice melt}) \)

**Local:**
\[ VLM = f(\text{Uplift/Subsidence, GIA}) \]
Unified SLR Projections: 2011 versus 2015 (using Key West gage)
Global: \( SLR = at + bt^2 \)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Global Sea Level Rise by 2100</th>
<th>( b ) (m/yr²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USACE Intermediate/NOAA Intermediate Low</td>
<td>0.5 m</td>
<td>2.712620e-05</td>
</tr>
<tr>
<td>IPCC 2013-2014 Median</td>
<td>0.73 m</td>
<td>4.684499e-05</td>
</tr>
<tr>
<td>USACE High</td>
<td>1.5 m</td>
<td>1.128601e-04</td>
</tr>
<tr>
<td>NOAA High</td>
<td>2.0 m</td>
<td>1.557270e-04</td>
</tr>
</tbody>
</table>

For computing \( b \): \( a = 1.7 \text{ mm/yr} \) (global linear rate)
\( b = \) rate of acceleration and \( t = 0 \) in Year 1992

Regional: \( SLR = ct + bt^2 \)

where \( c \) is a site-specific regional rate (2.2 mm/yr for Key West)
Why 1992? And how to translate the curve to a geodetic datum? (NGVD29 or NAVD88)

- Latest tidal-epoch 1982-2001 (1992 is about the midpoint). Nodal cycle (18.6 years, so at least 19 years are needed).

- Need MSL with respect to a geodetic datum. Three approaches are possible:
  1. When there is a tide gage nearby (Harmonic or Subordinate) use the MSL and geodetic datum relationship from tidal datum page
  2. When there is a tide gage nearby and has a long term record, compute the MSL using the most recent 19-year period
  3. When there is no tide gage nearby, use the VDATUM software (NOAA)
Example: Reference to 1992 (using 1983-2001 epoch)

**Elevations on Station Datum**
- **Station:** 8724580, Key West, FL
- **Status:** Accepted (Aug 24 2010)
- **Units:** Meters

<table>
<thead>
<tr>
<th>Datum</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHHW</td>
<td>1.941</td>
</tr>
<tr>
<td>MHW</td>
<td>1.853</td>
</tr>
<tr>
<td>MTL</td>
<td>1.658</td>
</tr>
<tr>
<td>MSL</td>
<td>1.662</td>
</tr>
<tr>
<td>DTL</td>
<td>1.665</td>
</tr>
<tr>
<td>MLW</td>
<td>1.463</td>
</tr>
<tr>
<td>MLLW</td>
<td>1.390</td>
</tr>
<tr>
<td>NAVD88</td>
<td>1.928</td>
</tr>
<tr>
<td>STND</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Key West: Current rate (Reg. Corrected) 2.2 mm/yr: NAVD88 = -0.27 m**

- Low (0.5)
- IPCC AR5 Median (0.73 m)
- High (1.5 m)
- Highest (2 m)
Example: Computing MSL

Key West

19 years

SLR relative to 1992 (m)

Year

1990 2000

0.00 0.05 0.10 0.15 0.20 0.25

SLR NAVD88 (m)

2010 2020 2030 2040 2050 2060

-0.2 0.0 0.2 0.4 0.6 0.8 1.0

MSL 2005 in NAVD88 = -0.235
### Elevations on Station Datum

**Station:** 8723214, Virginia Key, FL  
**Status:** Accepted (Jul 14 2011)  
**Units:** Meters  

<table>
<thead>
<tr>
<th>Datum</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHHW</td>
<td>3.763</td>
<td>Mean Higher-High Water</td>
</tr>
<tr>
<td>MHW</td>
<td>3.747</td>
<td>Mean High Water</td>
</tr>
<tr>
<td>MTL</td>
<td>3.439</td>
<td>Mean Tide Level</td>
</tr>
<tr>
<td>MSL</td>
<td>3.431</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>DTL</td>
<td>3.429</td>
<td>Mean Diurnal Tide Level</td>
</tr>
<tr>
<td>MLW</td>
<td>3.131</td>
<td>Mean Low Water</td>
</tr>
<tr>
<td>MLLW</td>
<td>3.096</td>
<td>Mean Lower-Low Water</td>
</tr>
<tr>
<td>NAVD88</td>
<td>3.608</td>
<td>North American Vertical Datum of 1988</td>
</tr>
</tbody>
</table>

**Source:**  
- **T.M.:** 75  
- **Epoch:** 1983-2001  
- **Datum:** STND  

**Target:**  
- **IIAD83(2011/2007/CORS96/HARN) - North Am...**  
- **Geographic (Longitude, Latitude):**
  - **Latitude:** 25.73  
  - **Longitude:** -80.1600000  
- **Output:**
  - **Height:** -0.2874  
  - **Latitude:** 25.7300000  
  - **Longitude:** -80.1600000  

[Example: VDATUM](http://vdatum.noaa.gov/)
Other adjustments to MSL (if they are not accounted for in the regional rate)

- Vertical Land Movement (From tide gage analysis, GPS etc.)
- Ocean Dynamics Change
  - Decline in Florida Current
  - 15% of the projection (based on IPCC)
  - Inter-annual variability
  - Seasonal Cycle
- Gravitational effects of ice melt
  (Not in Compact)
Decline in Florida Current Transport?
Southeast Florida (rate of rise)

- Lake Worth (3.36)
- Miami Beach (2.39)
- Key West (2.33)
- Vaca Key (3.34)
DoD Coastal Assessment Regional Scenario Working Group: Regionalized Scenarios for Sea-Level Change and Extreme Water Levels Worldwide

DoD Coastal Assessment Regional Scenario Working Group
Vertical Land Movement—Background and Methods

- Post-glacial rebound: Associated with the removal of ice sheets in the northern portion of North America & Europe. Also known as Glacial Isostatic Adjustment (GIA).
- Tectonic uplift (e.g., Alaska) and sedimentation
- Subsidence (e.g., removal of groundwater or oil, oxidation of organic matter)
- Monitored through GPS (relatively short time records) or the analysis of tide-gauge data (NOAA; relatively long time records in many but not all locations); data use sensitive to proximity of data measurement to site location
- Use coarse GIA data if have nothing else
Dynamic Sea-Level Change—Methods

- Dynamic sea level (DSL) is the collective effect of local steric effects and ocean dynamics, expressed as a global “pattern scaling” (Perrette et al. 2013)

- \[ \text{Dyn}_{\text{slr}}(x,t) = \text{global}_{\text{steric-mean}}(t) + \text{scale factor}(x) \times \text{global}_{\text{mean-air-temp}}(t) \]

where \( t \) is time, \( x \) is location, \( e \) is an error term, and the scale factor denotes a normalized value to represent the pattern scaling. The quantities, \( \text{global}_{\text{steric-mean}}(t) \), and \( \text{global}_{\text{mean-air-temp}}(t) \) are the global averages of steric sea level and temperature at time \( t \).
Dynamic Sea Level: Example Results

- Global mean temperature for each scenario and time frame was determined using a regression analysis of the data provided by Perrette et al. (2013)

Pattern and magnitude scaling associated with the 1-m GMSLR scenario at 2100. Scale bar is in meters.

- Highly non-uniform with deviations from global mean sea level that can be significant

Results for individual DoD sites for the 1-m GMSLR scenario at 2100. Scale bar is in meters.
Sea Level “Fingerprints” due to Rapid Melting of Ice

- Ice sheets exert gravitational attraction on the surrounding ocean
- As the ice sheet melts, gravitational force on the ocean decreases
- Water migrates from near field to the far fields

![Maps showing sea level fingerprints](image)
Sea Level “Fingerprints” due to Rapid Melting of Ice—Methods

- Based on Perrette et al. (2013) and Kopp et al. (2014)

- Fingerprint (x) = \[
\frac{\text{SLR Component (x)}}{\text{Global Mean SLR Component}} \]

(\text{where } x \text{ is the coordinates of the location and the component is either glaciers, Greenland, or Antarctica; fingerprint pattern is assumed to be independent of time and takes into account such factors as the spatial distribution of the mass loss and its effect on the geoid, earth’s elastic response, shoreline change, and earth’s rotation})

- Using Kopp’s probability distribution for each component (\text{glaciers, Greenland, Antarctica, thermal expansion, and land water storage}), simulate 500,000 realizations of each for each time horizon to establish the ice melt contribution of components by scenario.

- Lowest GMSL scenarios (0.2, 0.5, and 1.0 m) are associated with RCP2.6, 4.5, and 8.5 scenarios. For the 1.5 and 2.0 m scenarios scaling factors were determined by sampling the high end of the distributions to derive component contributions.
### Ice Melt Contributions—Results
(By GMSLR and Year)

<table>
<thead>
<tr>
<th>Comp</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.2</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIC</td>
<td>2035</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.09</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GrIS</td>
<td>2035</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIS</td>
<td>2035</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.05</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>2035</td>
<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.08</td>
<td>0.10</td>
<td>0.03</td>
<td>0.05</td>
<td>0.09</td>
<td>0.12</td>
<td>0.16</td>
<td>0.04</td>
<td>0.07</td>
<td>0.11</td>
<td>0.16</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW</td>
<td>2035</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2035</td>
<td>0.06</td>
<td>0.09</td>
<td>0.14</td>
<td>0.20</td>
<td>0.27</td>
<td>0.07</td>
<td>0.10</td>
<td>0.17</td>
<td>0.23</td>
<td>0.29</td>
<td>0.07</td>
<td>0.12</td>
<td>0.19</td>
<td>0.25</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIC</td>
<td>2065</td>
<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.05</td>
<td>0.07</td>
<td>0.11</td>
<td>0.12</td>
<td>0.11</td>
<td>0.06</td>
<td>0.10</td>
<td>0.15</td>
<td>0.18</td>
<td>0.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GrIS</td>
<td>2065</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.08</td>
<td>0.11</td>
<td>0.10</td>
<td>0.04</td>
<td>0.06</td>
<td>0.14</td>
<td>0.19</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIS</td>
<td>2065</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.04</td>
<td>-0.04</td>
<td>0.19</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.04</td>
<td>0.15</td>
<td>0.39</td>
<td>0.00</td>
<td>0.04</td>
<td>0.11</td>
<td>0.33</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>2065</td>
<td>0.04</td>
<td>0.08</td>
<td>0.13</td>
<td>0.14</td>
<td>0.12</td>
<td>0.06</td>
<td>0.12</td>
<td>0.21</td>
<td>0.25</td>
<td>0.23</td>
<td>0.07</td>
<td>0.16</td>
<td>0.28</td>
<td>0.36</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW</td>
<td>2065</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2065</td>
<td>0.11</td>
<td>0.20</td>
<td>0.36</td>
<td>0.54</td>
<td>0.73</td>
<td>0.12</td>
<td>0.24</td>
<td>0.44</td>
<td>0.64</td>
<td>0.84</td>
<td>0.13</td>
<td>0.28</td>
<td>0.51</td>
<td>0.74</td>
<td>0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIC</td>
<td>2100</td>
<td>0.06</td>
<td>0.07</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
<td>0.09</td>
<td>0.13</td>
<td>0.20</td>
<td>0.21</td>
<td>0.20</td>
<td>0.12</td>
<td>0.19</td>
<td>0.28</td>
<td>0.29</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GrIS</td>
<td>2100</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
<td>-0.04</td>
<td>-0.21</td>
<td>0.04</td>
<td>0.09</td>
<td>0.23</td>
<td>0.37</td>
<td>0.38</td>
<td>0.07</td>
<td>0.17</td>
<td>0.43</td>
<td>0.79</td>
<td>0.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIS</td>
<td>2100</td>
<td>-0.10</td>
<td>-0.10</td>
<td>-0.11</td>
<td>-0.08</td>
<td>0.17</td>
<td>-0.06</td>
<td>0.02</td>
<td>0.11</td>
<td>0.42</td>
<td>0.95</td>
<td>-0.03</td>
<td>0.14</td>
<td>0.34</td>
<td>0.92</td>
<td>1.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>2100</td>
<td>0.07</td>
<td>0.14</td>
<td>0.27</td>
<td>0.26</td>
<td>0.25</td>
<td>0.12</td>
<td>0.25</td>
<td>0.44</td>
<td>0.48</td>
<td>0.45</td>
<td>0.16</td>
<td>0.35</td>
<td>0.62</td>
<td>0.71</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LW</td>
<td>2100</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2100</td>
<td>0.17</td>
<td>0.41</td>
<td>0.82</td>
<td>1.25</td>
<td>1.63</td>
<td>0.20</td>
<td>0.50</td>
<td>1.00</td>
<td>1.50</td>
<td>2.00</td>
<td>0.23</td>
<td>0.59</td>
<td>1.18</td>
<td>1.75</td>
<td>2.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fingerprint scale bars are ratios of sea level contribution as a function of global mean, whereas the bottom right figure scale bar shows the deviation in meters from the global mean for ice melt from Greenland.
- Methods
  - Hydrodynamic modeling of historic/synthetic storms
  - Statistical modeling of sea level extremes
When MSL increases so does extremes
How high my sea wall (or roadway) should be?

Three approaches (Stationary and Nonstationary)

1. Assume extremes follow MSL and add storm surge estimates to SLR
2. Conduct a non-tidal residual analysis and add the storm surge estimates to an appropriate tidal datum
3. A Nonstationary approach (directly model maximum sea level as a function of “covariates”)
Stationary Approach - I

<table>
<thead>
<tr>
<th>Year</th>
<th>2060</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unified SLR Projection</td>
<td>Intermediate High</td>
</tr>
<tr>
<td>MSL (2005)</td>
<td>-0.235</td>
</tr>
<tr>
<td>Future MSL</td>
<td>0.39</td>
</tr>
<tr>
<td>Ocean Dynamics</td>
<td>0.06</td>
</tr>
<tr>
<td>Gravitational Effects</td>
<td>?</td>
</tr>
<tr>
<td>Interannual Variability</td>
<td>0.05</td>
</tr>
<tr>
<td>RSLR</td>
<td>0.265</td>
</tr>
<tr>
<td>10-Year</td>
<td>0.72</td>
</tr>
<tr>
<td>100-Year</td>
<td>0.9</td>
</tr>
<tr>
<td>Future 10-yr</td>
<td>0.985</td>
</tr>
<tr>
<td>Future-100yr</td>
<td>1.165</td>
</tr>
</tbody>
</table>

Key West, FL

<table>
<thead>
<tr>
<th>Meters above or below Mean Sea Level Datum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

1/27/2016
Stationary Approach - 2

- SWL = Tide (astronomical + MSL seasonal cycle) + Nontidal Residual (storm surge + sea level anomaly)

Credit: W. Sweet
Extreme Value Modeling

1. Extreme Value of Modeling of Block Maxima (BM) (Coles, 2001)
2. Extreme Value Modeling of Peaks Over Threshold (POT) (Coles 2001)
3. Mixture Distributions (MD)
4. Monte-Carlo Joint Probability Methods (Goring et al. 2011)
5. Regional Frequency Analysis (Hosking and Wallis 1997)
Regional Frequency Analysis (RFA)

- RFA is based upon a regional homogeneity assumption.
  - Homogeneous region: group of sites whose extreme storm surge are in response to same mechanism (e.g., Nor’easter impact footprint), defined by proximity, bathymetric-topographic similarities, pattern detection techniques, etc.

- Homogeneity is assessed with a heterogeneity measure (H):
  - L-moments (quantifies distribution shape – mean, standard deviation, skewness, kurtosis) to enable comparing the observed dispersion between sites to the expected dispersion in a homogeneous region.
  - H<1: homogeneous; 1<H<2 possibly homogeneous; H>2: heterogeneous
Regional Frequency Analysis: Local Adjustment

- RFA is used to compute “regional curve” using annual-maximum non-tidal residual (NTR) from 3 to 5 tide gauges < 400 km away that are then fit by the family of Generalized Extreme Value (GEV) distributions.

- Each tide gauge NTR series “normalized” by the average of annual maximum NTR prior to forming the regional GEV curve.

- Local “index event” (i.e., mean annual maximum NTR) is used to scale the regional GEV curve:
  - Category 1 and 2: from local (< 50 km) tide gauge
  - Category 3: average of all tide gauges
  - Category 4: NA
Example application: C-4 basin in Miami
Concept of Return Period and Risk: Paradigm Shift

Key West

Design, $z_{q0}$

$\mu_0$

$p_0 < p_x < p_T$

$t_1$

$t$

Time

Construction → Project Operation

- $\text{Annual Mean}$
- $\text{Annual Maximum}$
- $\text{Trend-Mean}$
- $\text{Trend-Location Parameter}$

Mean, Annual Max. Sea Level

1600 1800 2000 2200 2400 2600 2800

1920 1940 1960 1980 2000

Year
Return Period – non-stationary case (cont.)

- Return Period is defined as the “expected time for the first exceedance” (waiting time)

\[ T = E[X] = \sum_{x=1}^{\infty} xf(x) = \sum_{x=1}^{\infty} xp_x \prod_{t=1}^{x-1} (1 - p_t) \]

- Cooley (2013) provides a nice simplification:

\[ T = E[X] = 1 + \sum_{x=1}^{\infty} \prod_{t=1}^{x} (1 - p_t) \]

Note: Since \( p_t \) is a function \( Z_{q_0} \) (initial design or \( p_1 \)), this can also be used to find \( Z_{q_0} \) for a given \( T \)
Non-stationary Concepts (Risk & Reliability)

- Risk

\[ R = \sum_{x=1}^{n} f(x) = \sum_{x=1}^{n} p_x \prod_{t=1}^{x-1} (1 - p_t) = 1 - \prod_{t=1}^{n} (1 - p_t) \]

- Reliability:

\[ R_\ell = \prod_{t=1}^{n} (1 - p_t) \]
Return Period & Risk Curves

\[ T = 1 + \sum_{x=1}^{\infty} \prod_{t=1}^{x} (1 - p_t) \]

\[ R = 1 - \prod_{t=1}^{n} (1 - p_t) \]

Note: 1-m scenario
"The frequency (of extreme weather situations) is way up," Andrew Cuomo, Governor of New York, 10/31/2012
King Tide Flooding in South Florida

Credits: Rhonda Haag, Jennifer Jurado, Natalie Schneider
Frequency of Flooding under Non-Stationarity (Starting with “Nuisance Flooding”)

- Frequency of flooding increases with time

- Number of floods, $N_T$ has Poisson-Binomial distribution (Hong 2013):

$$PMF: \sum_{A \in F_k} \prod_{i \in A} p_i \prod_{j \in A^c} (1 - p_j)$$

$F_k$ = subset of $k$ integers

From $(1, 2, \ldots, T)$

$$E[N_T] = \sum_{i=1}^{n} p_i \quad Var(N_T) = \sum_{i=1}^{n} (1 - p_i)p_i$$
Frequency of Flooding: Sewell Point

- **Non-Stationary**
- **Stationary**

*Graph showing expected number of exceedences and percent time flooded from 2014 to 50 years.*
Nuisance Flooding as a design criteria

Graph showing the relationship between Design Sea Level above MSL (m) and Expected Number of Events.

- Nonstationary
- Stationary

Graph showing Max Mean Sea Level (m) over the years 1920 to 2000.

- Location
- Fitted
Further Information

Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events

Jose D. Salas, M.ASCE\(^1\); and Jayantha Obeysekera, M.ASCE\(^2\)


Quantifying the Uncertainty of Design Floods under Nonstationary Conditions

Jayantha Obeysekera, M.ASCE\(^1\); and Jose D. Salas, M.ASCE\(^2\)


Frequency of Recurrent Extremes under Nonstationarity

Jayantha Obeysekera, M.ASCE\(^1\); and Jose D. Salas, M.ASCE\(^2\)

(paper accepted for publication in J. Hydrologic Engineering)
Questions?