
Thomas W. Doyle

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SLR Handbook Outline

- Understanding Sea-Level Change
  - Methods for Reconstructing and Observing SLR

- Predicting Sea-Level Rise Impacts
  - Models for Simulating SLR Effects on Ecosystems
Understanding Sea-Level Change

• Earth’s Hydrosphere
  – Volume Static
  – Form Dynamic

• Reconstructing Sea-Level History
  – Effects of Plate Tectonics (Size of Ocean Basins)
  – Effects of Glaciation (Orbital Cycles)
  – Holocene Sea-Level Rise (Since Last Glacial Maximum)

• Contemporary Sea-Level Record
  – Long-term Tide Gage Relative Sea-Level Rise
  – Satellite Sea-Surface Height Observations
  – Land Motion and Subsidence/Uplift

• Future Sea-Level Projections
Earth’s Hydrosphere

What causes the sea level to change?

- Terrestrial water storage, extraction of groundwater, building of reservoirs, changes in runoff, and seepage into aquifers
- Surface and deep ocean circulation changes, storm surges
- Subsidence in river delta region, land movements, and tectonic displacements
- Exchange of the water stored on land by glaciers and ice sheets with ocean water
- As the ocean warms, the water expands

SYR - FIGURE 3-4
Temperature Effect on Water Expansion

EXPLANATION
- Volume change at 34° C
- Volume change at 17° C
- Reference volume at 0° C

Height, in centimeters

Salinity 35

Salinity 0

Parts, per thousand
Effects of Plate Tectonics

EXPLANATION
- 101-point moving average (Haq and others, 1987 data)
- 10 mil yrs moving average (Kominz et al. 2008 data)

Era
- Mesozoic
- Cenozoic

Period
- Triassic (252–201 million years)
- Jurassic (201–145 million years)
- Cretaceous (145–66 million years)
- Paleogene (66–23 million years)
- Neogene (23–2.6 million years)
Effects of Glaciation

A

Thousands of years (Ka)

Sea level relative to current level (m)

Oxygen isotope ratio

EXPLANATION

Sea level relative to oxygen isotope ratio
(Miller et al. 2011 and Lisiecki and Raymo 2005)

Holocene epoch

Pleistocene epoch

B

Current CO₂ July 2013

Highstand

Holocene period

Pleistocene epoch

450 500 100 150 200 250 300 350 400

Vostok carbon dioxide, in parts per million by volume

Thousands of years (Ka)

EXPLANATION

Ice volume (Imbrie and others, 2011)

Vostok carbon dioxide, in parts per million by volume (Petit and others, 1999)

Quaternary period

Holocene epoch

Pleistocene epoch

200 150 100 50 0

Ice volume, arbitrary scale

-3 -2 -1 1 2

Ice volume, arbitrary scale
Holocene Sea-Level Rise
Balsillie and Donoghue 2004

EXPLANATION
- 7-point floating average
- Tahiti Corals
  (Bard and others, 1996)
- New Guinea Corals
  (Edwards and others, 1993)
- Barbados Corals
  (Fairbanks, 1989, 1990)
- Red Sea Forams
  (Siddall and others, 2003)

Quaternary period
- Holocene epoch (0–11,000 years)
- Pleistocene epoch (11,000–25,000 years)
Contemporary Sea-Level Rise

Sea level measurements from 23 long tide gauge records in geologically stable environments show a rise of around 20 centimeters per century (2 mm/year). Source: IPCC 2001
Relative Mean Sea-Level Rise

- \( \text{RSLR} = \text{Relative Sea-Level Rise} \)

- \( \text{RSLR} = f(\Delta \text{sea level} + \Delta \text{land surface elevation}) \)

- \( \Delta \text{Sea height} = f(\text{eustacy, gravity, winds, waves, etc.}) \)

- \( \Delta \text{Land height} = f(\text{subsidence, deposition, erosion, etc.}) \)
Relative Sea-level Rise for Gulf Coast USA

- Pensacola, FL
  - RSLR = 2.14 mm/yr
  - Stable Geology

- Grand Isle, LA
  - RSLR = 9.85 mm/yr
  - Deltaic Plain

- Galveston, TX
  - RSLR = 6.5 mm/yr
  - Chenier Plain
US Topex/Poseidon/Jason Satellite Records

TPJason Merged Satellite 1994-2012

\[
y = 3.4248x - 6883.7
\]

\[R^2 = 0.146\]

\[
y = -0.1476x^2 + 594.85x - 599339
\]

\[R^2 = 0.1525\]

<table>
<thead>
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<tbody>
<tr>
<td>Value</td>
<td></td>
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</tbody>
</table>
US TPJ Merged vs Euro AVISO Satellite
Gulf of Mexico

\[ y = 3.4249x - 6884 \]
\[ R^2 = 0.1361 \]

\[ y = 3.4248x - 6883.7 \]
\[ R^2 = 0.146 \]

-200.0 -150.0 -100.0 -50.0 0.0 50.0 100.0 150.0
Modeling and Comparing SLR Trends
Tide Gage vs Satellite Records

- Rectifying to the Same Datum!
- Comparing the Same Time Periods!
- Complete Records - No Data Gaps!
U.S. Tide Gage Relative SLR Trends
Satellite Era (1994-2012)
# Satellite vs Tide Gages 1994-2012

<table>
<thead>
<tr>
<th>Observation Platform Location</th>
<th>SLR Trend (1994-2012) mm/yr</th>
<th>Residual Land Motion mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Topex/Poseidon/Jason</td>
<td>3.32*</td>
<td>-</td>
</tr>
<tr>
<td>European AVISO</td>
<td>3.32*</td>
<td>-</td>
</tr>
<tr>
<td>Key West, FL gage</td>
<td>4.42</td>
<td>1.10</td>
</tr>
<tr>
<td>Pensacola, FL gage</td>
<td>4.92</td>
<td>1.60</td>
</tr>
<tr>
<td>Grand Isle, LA gage</td>
<td>7.34</td>
<td>4.02</td>
</tr>
<tr>
<td>Galveston, TX gage</td>
<td>5.87</td>
<td>2.55</td>
</tr>
</tbody>
</table>
# Tide Gage SLR for earlier Tidal Epochs

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>KeyWest, FL</td>
<td>Missing data</td>
<td>4.20</td>
<td>5.38</td>
<td>3.02</td>
<td>4.42</td>
</tr>
<tr>
<td>Pensacola, FL</td>
<td>Missing data</td>
<td>4.06</td>
<td>3.87</td>
<td>4.33</td>
<td>4.92</td>
</tr>
<tr>
<td>Galveston, TX</td>
<td>4.56</td>
<td>6.91</td>
<td>10.40</td>
<td>8.23</td>
<td>5.87</td>
</tr>
<tr>
<td>** Grand Isle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.34</td>
</tr>
</tbody>
</table>
Key West, FL  Gage vs Satellite

**Key West, FL MHHW 1994-2012**

- **Graph 1:**
  - X-axis: Year (1990 to 2015)
  - Y-axis: Elevation (mm NAVD88)
  - Data points show fluctuations in elevation over time.

**Key West Land Motion Residual 1994-2012**

- **Graph 2:**
  - X-axis: Year (1990 to 2015)
  - Y-axis: Elevation (mm NAVD88)
  - Linear equation: $y = 1.0919x - 1758.9$
  - $R^2 = 0.0129$
  - Quadratic equation: $y = 0.3673x^2 - 1470.9x + 1E+06$
  - $R^2 = 0.0482$

*USGS*
Pensacola, FL  Gage vs Satellite

Pensacola, FL MH HW 1994-2012

Pensacola Land Motion Residual 1994-2012
Grand Isle, LA  Gage vs Satellite

Grand Isle, LA MHHW 1994-2012

Grand Isle Land Motion 1994-2012

\[ y = 0.3887x^2 - 1551.6x + 2E+06 \]

\[ R^2 = 0.227 \]
Galveston, TX  Gage vs Satellite
Predictive Models of Sea-Level Rise

- Sea-level Rise Simulation and Inundation Models
- GIS Sea-level Rise Mapping Tools
- Wetland Change Models
- Surface Elevation and Shoreline Erosion Models
- Niche-Based Species Distribution Models
- Leaf to Landscape Ecosystem Models
## Table 3. Sea-Level Rise Simulation and Inundation Model attributes

<table>
<thead>
<tr>
<th>Model</th>
<th>Agency/Organization</th>
<th>Appropriate scale</th>
<th>Spatial resolution</th>
<th>Temporal scale</th>
<th>Input parameters</th>
<th>Output parameters</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoastCLIM Sea-level Simulator (component of the SimCLIM system)</td>
<td>CLIMsystems</td>
<td>Local, regional, global</td>
<td>Varies, determined by data availability and computation demands</td>
<td>Variable depending on impact model being run</td>
<td>Elevation, climatologies, site time-series data, patterns of climate and sea-level changes from GCMs, impact models</td>
<td>Maps of areas/habitats potentially vulnerable to inundation. May estimate adaptation costs.</td>
<td>Warrick 2006; Warrick and Cox 2007</td>
</tr>
<tr>
<td>NOAA Inundation Frequency Analysis</td>
<td>NOAA</td>
<td>Local</td>
<td>Not applicable</td>
<td>1 month - 5 years</td>
<td>Tide station, reference elevation, date range</td>
<td>Inundation duration, frequency of high water elevation or duration (tabular or graph format)</td>
<td><a href="http://tidesandcurrents.noaa.gov/inundation/">http://tidesandcurrents.noaa.gov/inundation/</a>, Inundation Analysis Users' Guide</td>
</tr>
<tr>
<td>SLRRP Sea-Level Rectification Program</td>
<td>U.S. Geological Survey</td>
<td>Local, regional</td>
<td>Not applicable</td>
<td>Historic tide range + projection to 2100, monthly to annual time step</td>
<td>Tide station, local subsidence rate (historic or custom), GCM sea-level rise rate</td>
<td>Cumulative sea-level rise, flood inundation potential for given elevation</td>
<td>Keim et al. 2008</td>
</tr>
<tr>
<td>Temperature-based Sea-Level Rise Model</td>
<td>Potsdam Institute for Climate Impact Research</td>
<td>Global</td>
<td>Not applicable</td>
<td>1990-2100</td>
<td>Global mean sea level, mean temperature, time</td>
<td>Future mean sea level</td>
<td>Rahmstorf 2007</td>
</tr>
</tbody>
</table>
Sea-level Rise Simulation and Inundation Models

- CoastCLIM
- NOAA Inundation Frequency Analysis
- SLRRP, Sea-level Rise Rectification Program
- Temperature-based SLR Projections
- Soil Salinity Models
- Expert Hydrodynamic Engineering Models
  HECRAS, Delft3D, MikeII, Mike3FM, SLOSH, ADCIRC, ...
Customized Subsidence and Eustacy Rates
(USGS SLRRP Model, Keim et al. 2008)
Sea Level Mean Monthly Forecast
(USGS SLRRP Model, Keim et al. 2008)
Seawater Flood Inundation Model
(USGS SLRRP Model, Keim et al. 2008)
GIS Sea-level Rise Mapping Tools

NOAA Sea-level Viewer

University of Arizona WEB Map Visualization Tool

USGS Sea-Level Rise Animations

Also known as “Bathtub Models” or visualizations with arbitrary water level (unrectified) such that when water elevation exceeds land elevation, cells are converted from habitat or land classification to submerged open water.
University of Arizona WEB Map Visualization
http://climategem.geo.arizona.edu/slrsr48prvi/index.html
USGS Sea-Level Rise Animations

http://cegis.usgs.gov/sea_level_rise.html

Sea Level Rise Animation - Texas

- Sea Level Rise: 6 Meters
- Population Affected: 729,331
- Total Population: 9,236,574

- State Borders
- Cities
- Highways
WETLAND Change Models

- **CELSS**, Coastal Ecological Landscape Spatial Simulator
  - Same as BTELSS, Barataria-Terrebonne model application

- **SLAMM**, Sea-Level Affecting Marshes Model

- **SLOPE**, Sea-Level Over Proportional Elevation

These models predict habitat or vegetative cover type with change in land surface submergence.
Coastal Ecological Landscape Spatial Simulator
Barataria-Terrebonne application, BTELSS

Sea-Level Affecting Marshes Model

http://www.warrenpinnacle.com/prof/SLAMM/

St. Marks NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.
Sea-Level Over Proportional Elevation Model

Doyle et al. 2010
Surface Elevation and Shoreline Erosion Models

- Coastal Vulnerability Index
- Marsh Geochronology Methods
- Saltmarsh Stratigraphy and Evolution Models
- **Surface Elevation Tables – SET**
- Tidal Channel Network Models
Coastal Vulnerability Index
http://woodshole.er.usgs.gov/project-pages/cvi/
Surface Elevation Table

http://www.pwrc.usgs.gov/set/
Niche-based Species Distribution Models

Baldcypress Range – Ancient Sea Level
Mangrove Latitudinal Expansion
Sherrod and McMillan 1985
Leaf to Landscape Ecosystem Models

- WETLANDS, Species Occurrence by Elevation
- SELVA, Spatially Explicit Landscape Vegetation Analysis
- MANGRO, Mangrove Forest Stand Simulator

Models with predictive measures at the species, organism, or organelle level of ecosystem organization
SELVA-MANGRO SLR Application
Doyle et al. 2003
Questions!

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