Relative Sea Level Rise: Coastal Impacts and Risk

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IOGP/JCOMM/WCRP Workshop
Our Future Climate – Understanding the spread of risk for the oil and gas industry

New Jersey Jet Star Roller Coaster after Hurricane Sandy (2012)

Background

- **Climate warming has contributed to global sea level rise of 1.7 mm/yr over the past century and 3.2 mm/yr over the past few decades (Church and White 2011, Merrifield et al. 2013)**
- **Regional sea level dynamics are super-imposed upon global mean sea level change**
  - **Atmosphere-ocean interactions that include storm surge related to seasonal varying storm activity and type;**
    - **Intra-annual, annual, interannual, and decadal variations in sea level anomalies [El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO)]**
    - **Varying sea level anomalies may enhance or suppress factors such as storm surge and regional sea level rise rates.**
  - **Vertical Land motion**
  - **Changes in ocean structure**
  - **Additions to ocean mass from melting land ice**

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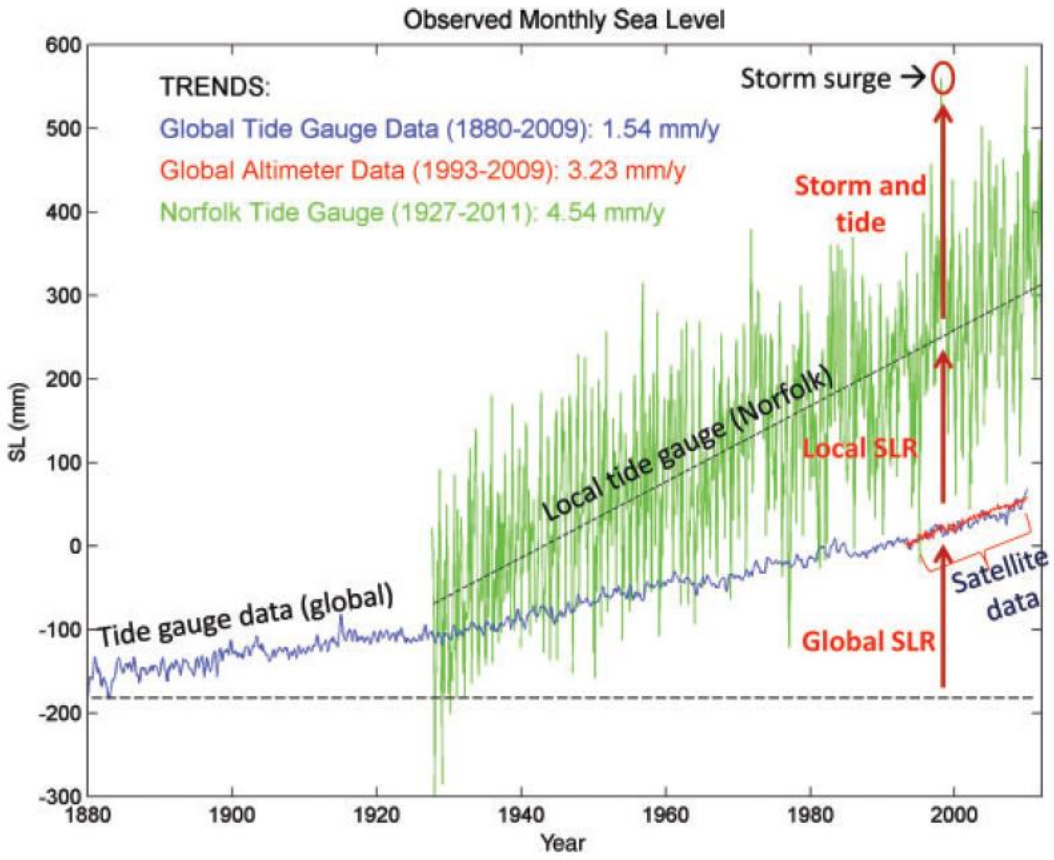
Background

- **Relative sea level rise (RSLR) is most relevant to coastal infrastructure**
    - **Relative to a tidal datum of mean sea level**
    - **Coastal inundation and flooding relative to mean higher high water (MHHW) level.**
- **Consequences of RSLR are:**
    - **Increased frequency or probability of coastal inundation/flooding**
        - **Major events due to storm surge, rainfall, climatic events**
        - **Nuisance flood events due to tidal variations**
- **Intergovernmental Panel on Climate Change (IPCC) recognized that societal impacts of sea level change primarily occur via extreme events rather than as a direct consequence of global mean sea level change.**
- **IPCC notes that the majority of global coastlines will be affected by RSLR by the end of the 21st century [Seneviratne et al., 2012]**

Background



Norfolk, Virginia

(Ezra and Atkinson, 2014 Earth's Future)

Regional / Local Sea Level Rise =

Datum(x) + Global Sea Level (t)+ Vertical Land Movement (VLM)(x,t) + Melting of Land-Based Ice (x,t) + Dynamic Sea Level (DSL)(x,t)

Global Sea Level: t varies over decades to centuries

VLM: x varies from 100 – 1000 km, t varies over 1000s of years

Melting: x varies from 100 – 1000 km, t varies over decades to centuries

DSL: Includes tides, ocean dynamics, atmospheric dynamics
x varies from 10s to 1000s of km, t varies from hours to years

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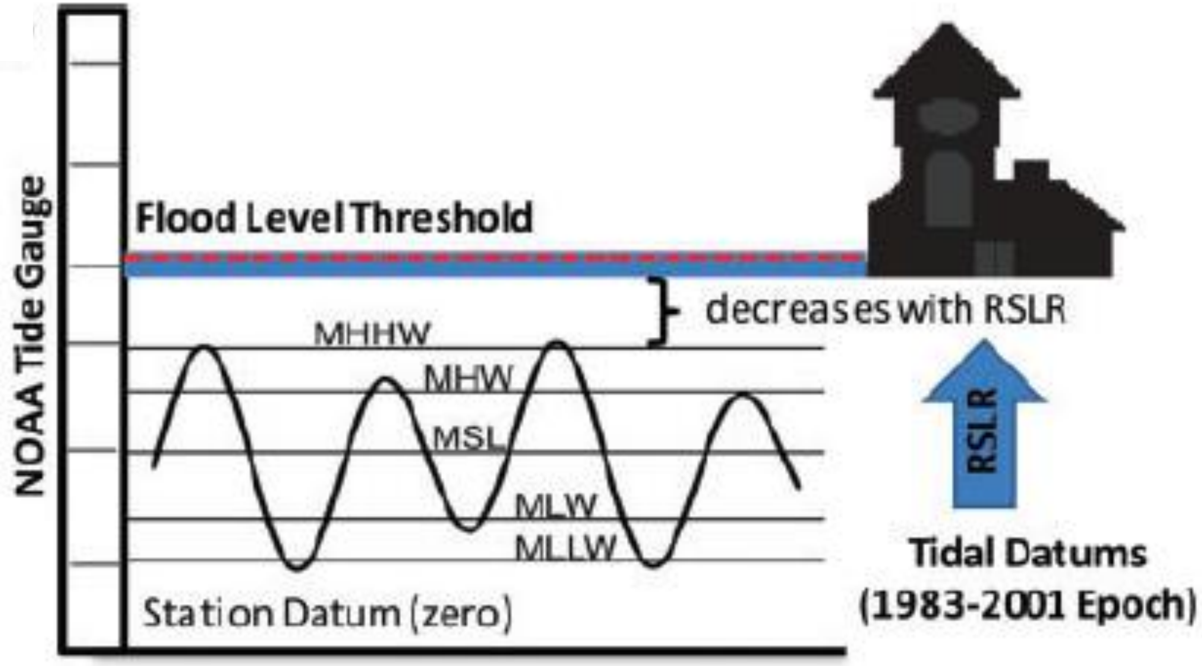
Background

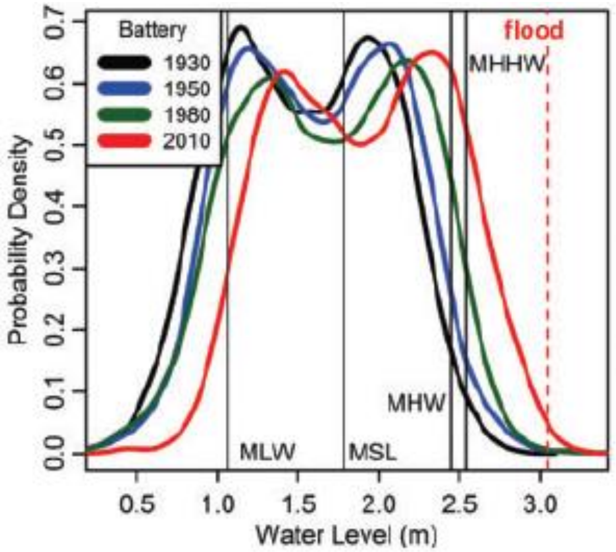
Schematic of water level measurements relative to tidal datums, high tides, and flood level thresholds

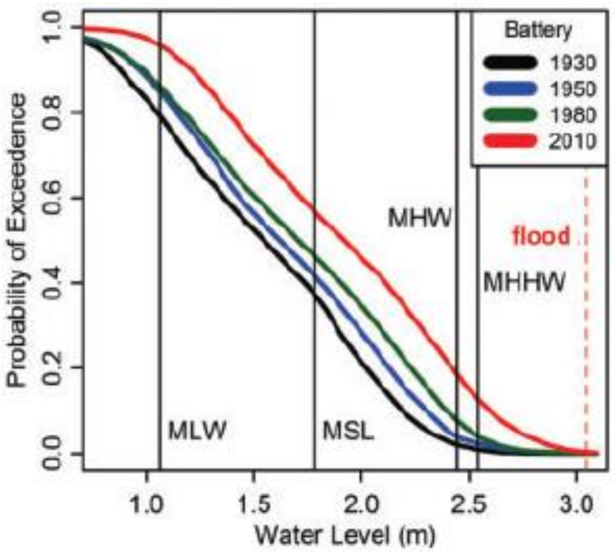


Probability density estimate of hourly water level at the New York City Battery Park tidal gauge.

— = tidal station datums

- - - = elevation threshold for nuisance flood impacts





Probability of exceedance in hourly water level at the New York City Battery Park tidal gauge.

— = tidal station datums

- - - = elevation threshold for nuisance (tidal) flood impacts

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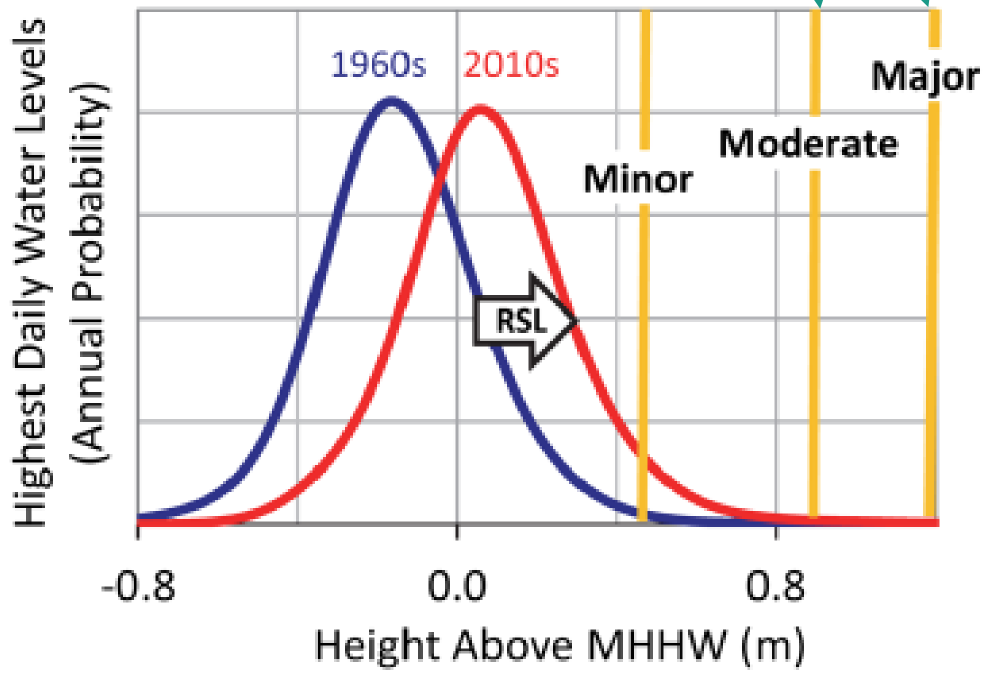
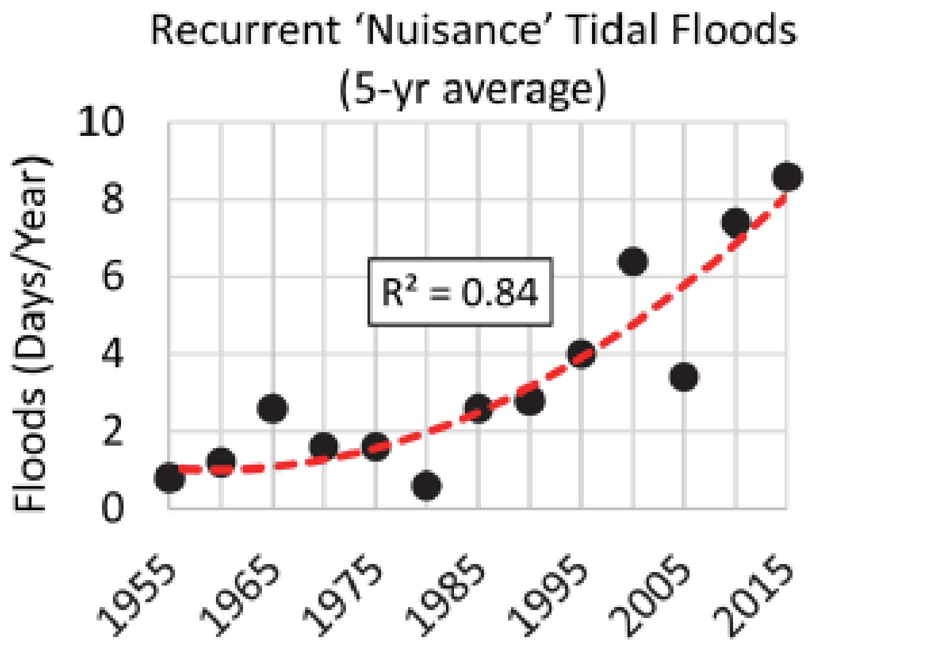
Relative Sea Level Rise: Nuisance (Tidal) Flooding

Empirical distribution of daily highest water levels at Norfolk, Virginia for the 1960s and 2010s.

Flood impact thresholds defined by the U.S. National Weather Service



Annual flood frequencies (based on 5-yr averages) in Norfolk for nuisance flood levels. Red line = quadratic trend fit.



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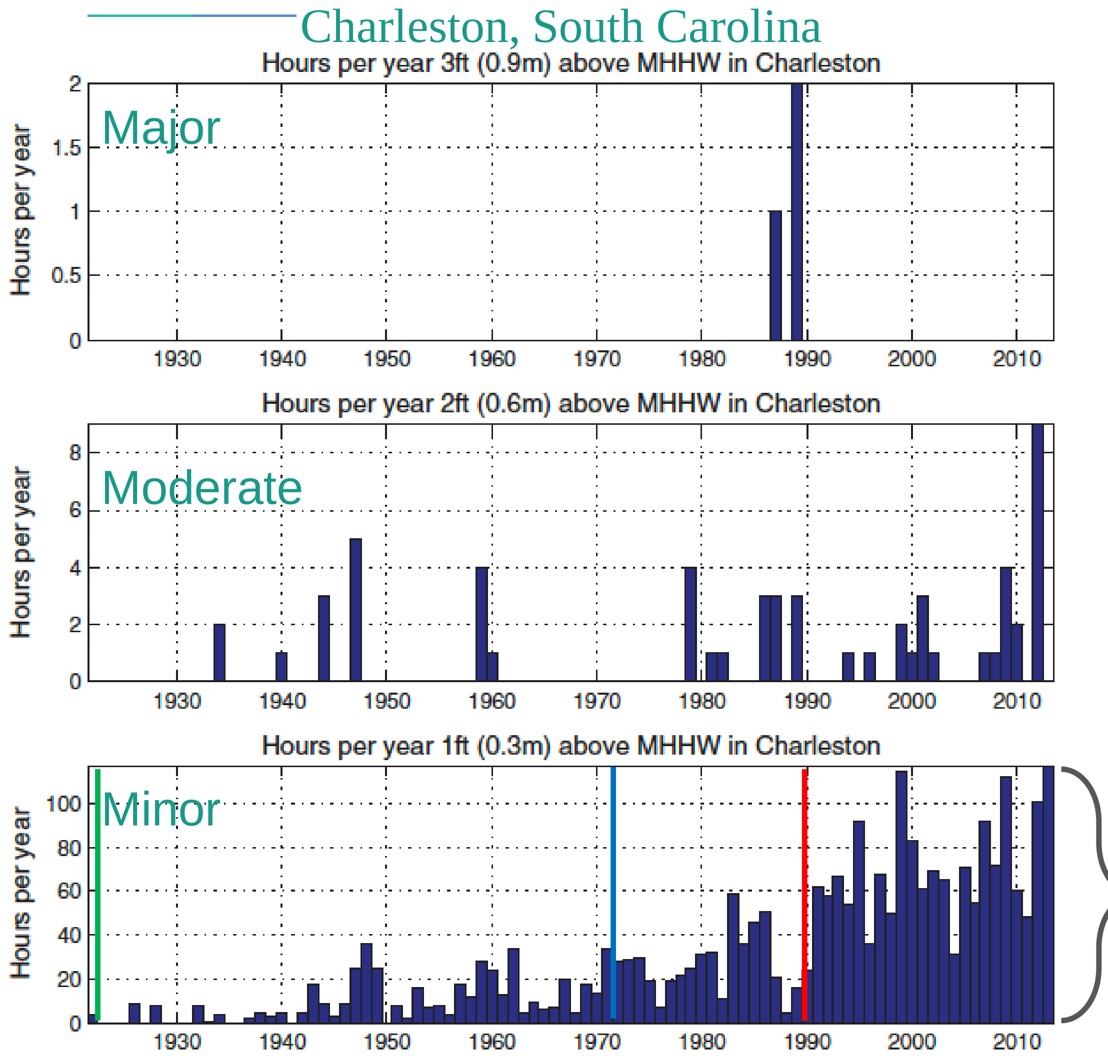
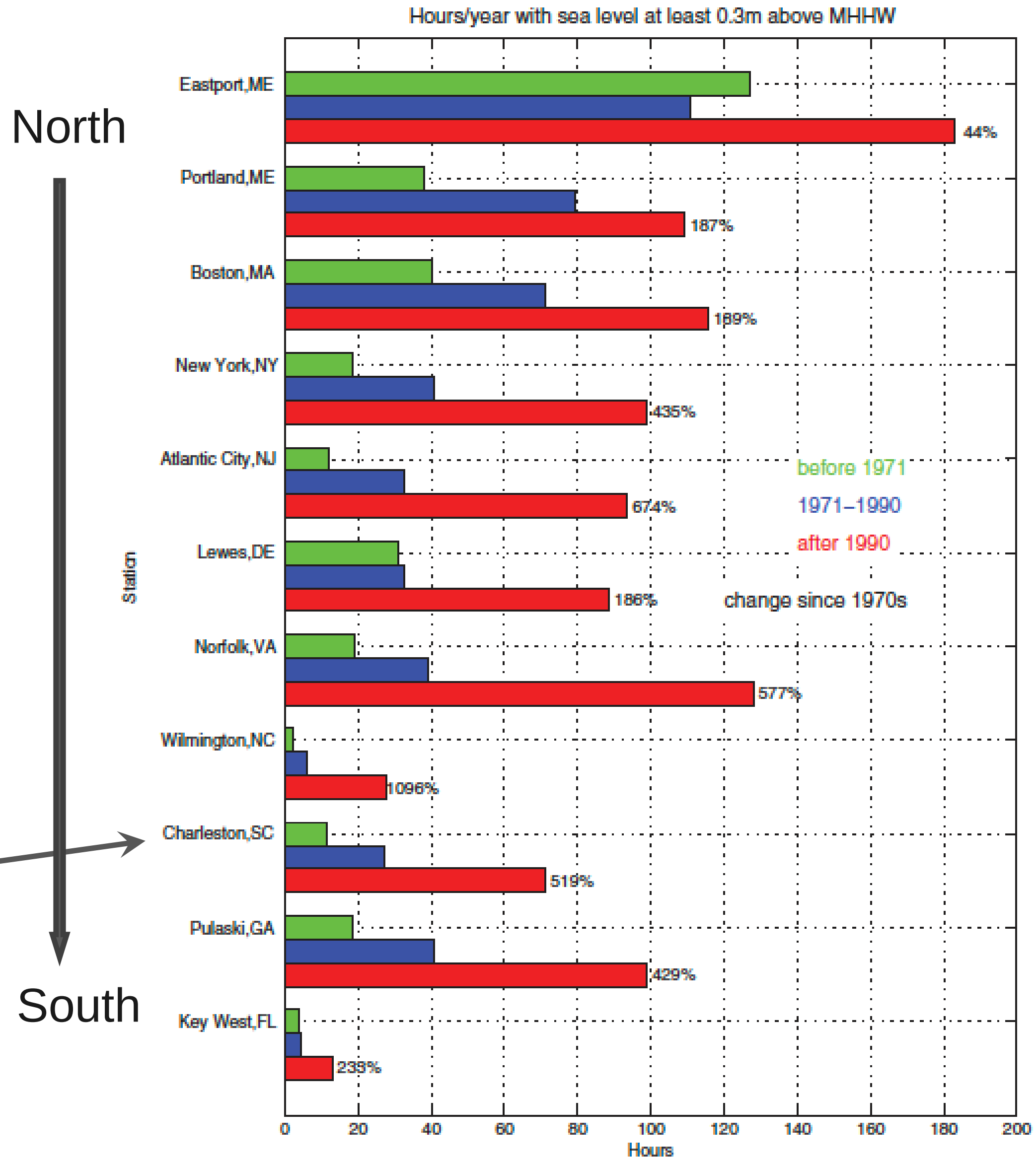
Adapted from Sweet and Park 2014, *Earth's Future*

Relative Sea Level Rise: Flood Categories





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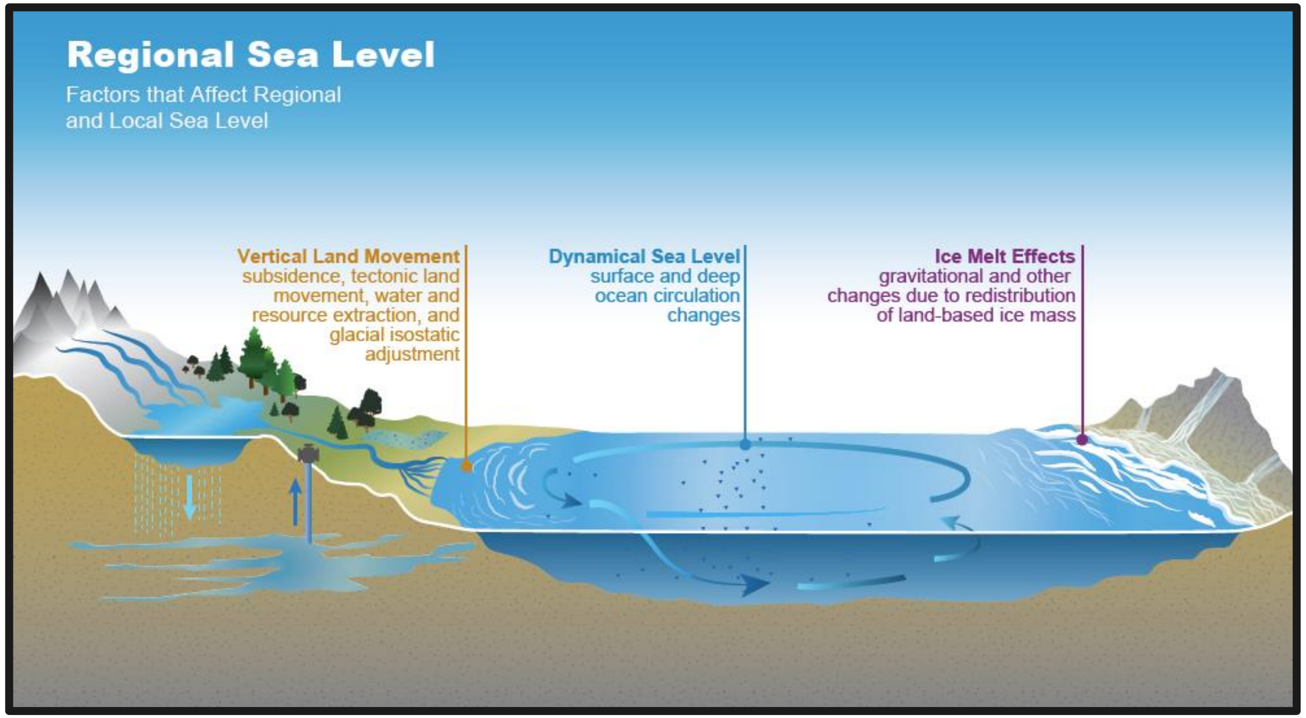
(Ezra and Atkinson, 2014 Earth's Future)

Regional / Local Adjustments to Global Sea Level Rise

Regional / Local Sea Level Rise = Datum(x) + Global Sea Level (t)+ Vertical Land Movement (VLM)(x,t) + Melting of Land-Based Ice (x,t) + Dynamic Sea Level (DSL)(x,t)



Adapted from IPCC 2001

VLM = f (tectonic motion, sediment compaction, groundwater or oil depletion, post-glacial response)

Melting = land-based ice affects

DSL = f (ocean currents, low-level winds, salinity, temperature, tides, storms)

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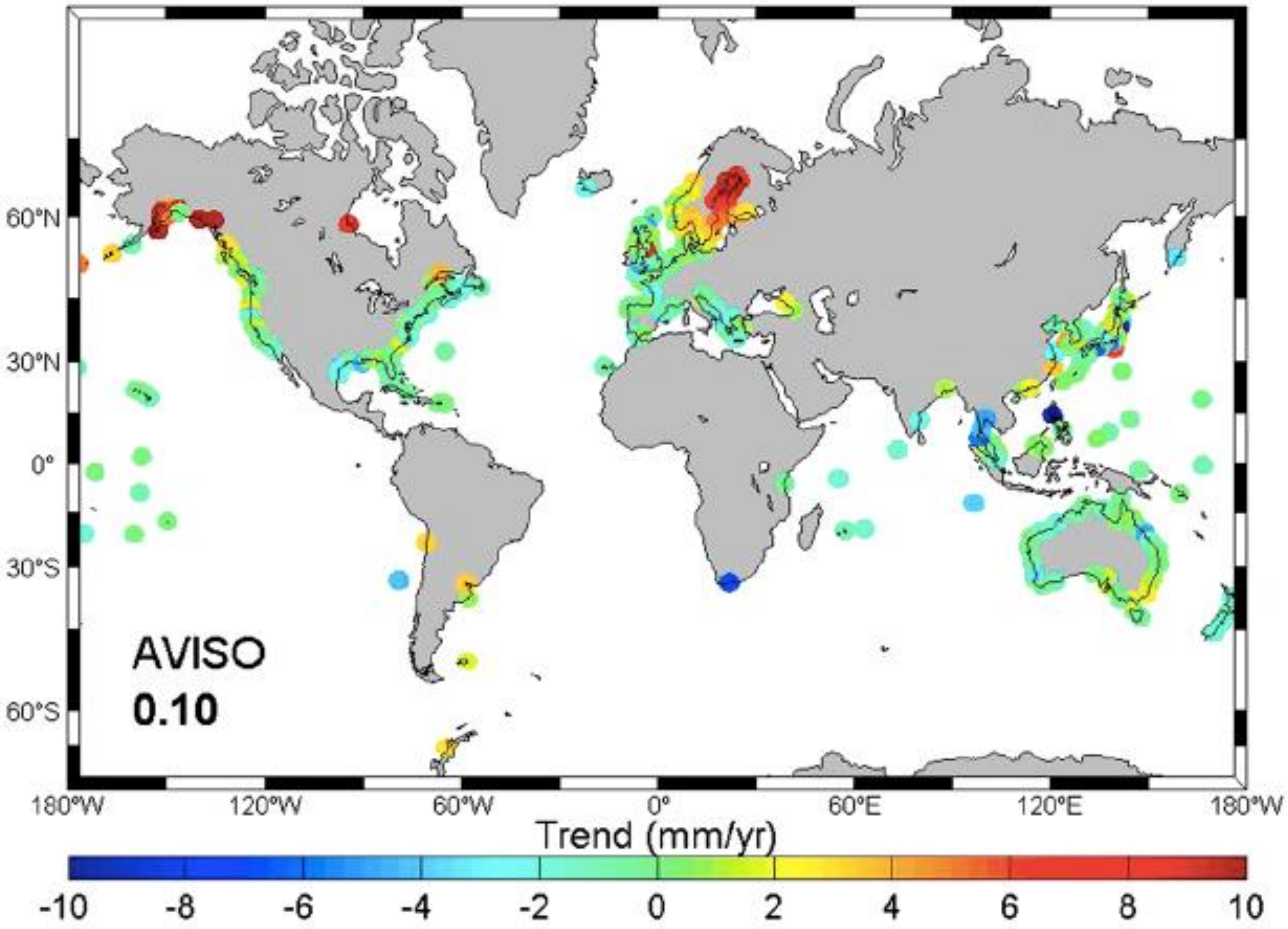
Regional / Local Adjustments to Global Sea Level Rise

Rate of Vertical Land Motion (VLM) at tidal gauge locations

Uplift in Northern Hemisphere high latitudes due to glacial isostatic adjustment

Subsidence over lower latitudes with largest values over southeast Asia and the northern coast of the Gulf of Mexico

Wöpplemann and Marcos (2016), *Rev. Geophys.*



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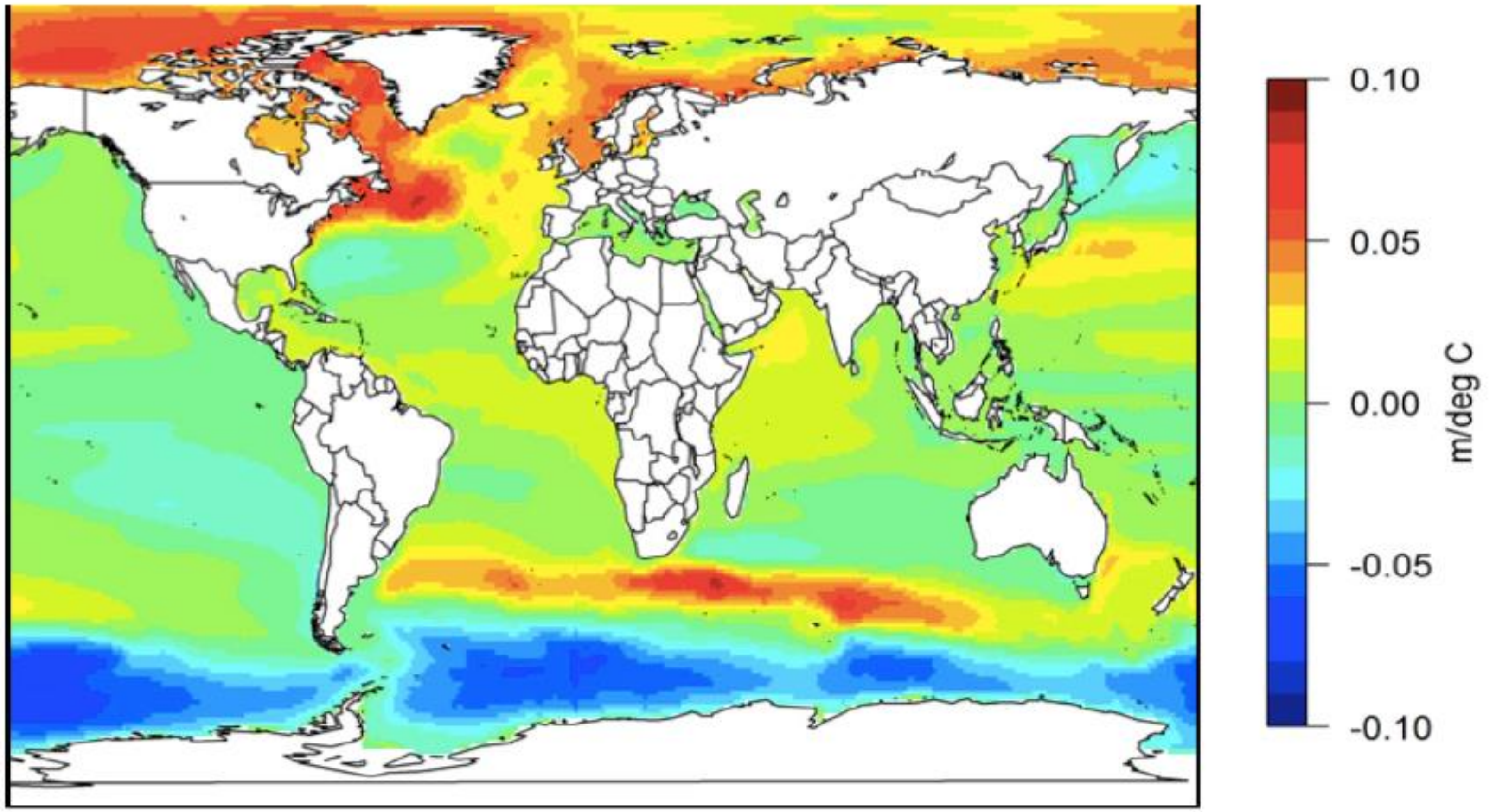
Regional / Local Adjustments to Global Sea Level Rise

Dynamic Sea Level

DSL defined as the deviation of dynamic sea level from the mean steric sea level rise (thermal expansion) scaled by global mean temperature:

DSL(x,t) = global steric mean(t) + scale(x,t) * global mean temperature(t)



Normalized DSL patterns for RCP 8.5 and the year 2100

Perrette et al. 2013, *Earth System Dynamics*

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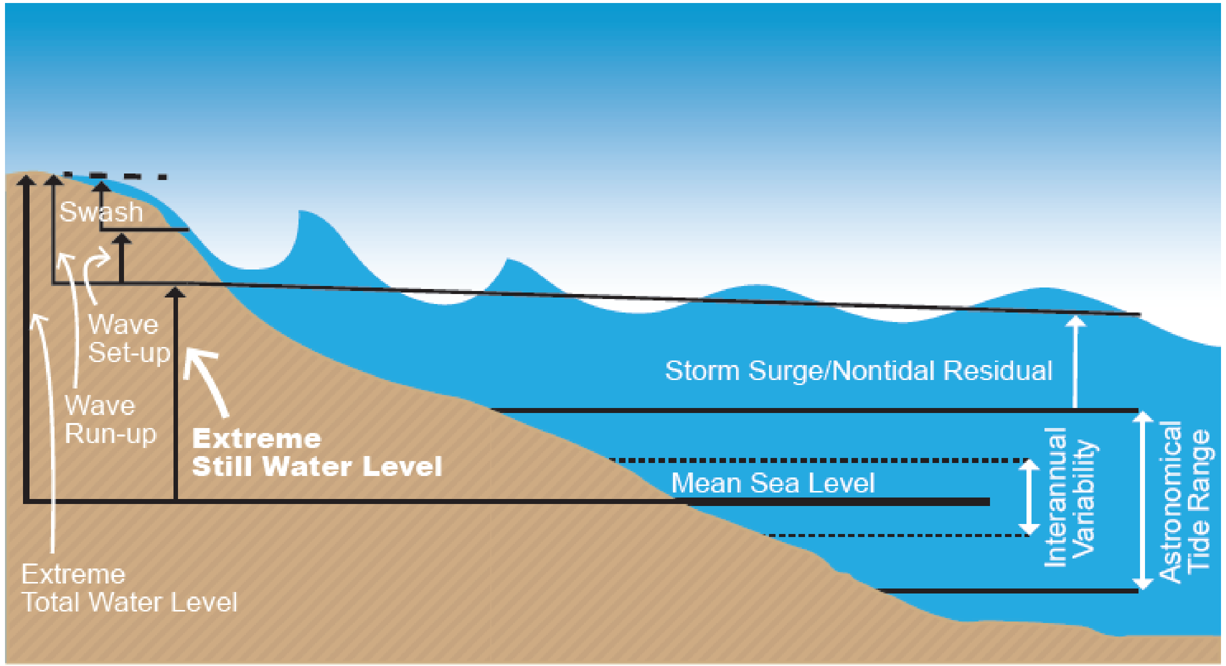
Regional / Local Adjustments to Global Sea Level Rise

Extreme Still Water Level (EWL) = Tide (astronomical + seasonal) + Non-Tidal Residual (Storm Surge + Sea Level Anomaly)



Adapted from Moritz et al. 2015: U.S. Army Corp of Engineers document

Regional physical factors:
- Tropical cyclones
- Extratropical cyclones
- Local bathymetric characteristics

EWL does not include surface wave run-up, which includes wave set up and swash.

Water levels reported relative to a tidal datum estimated over a multi-year epoch.

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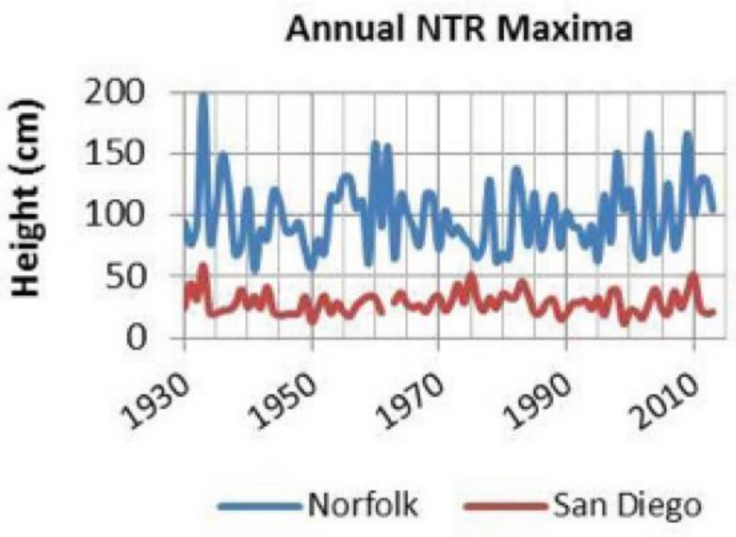
Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

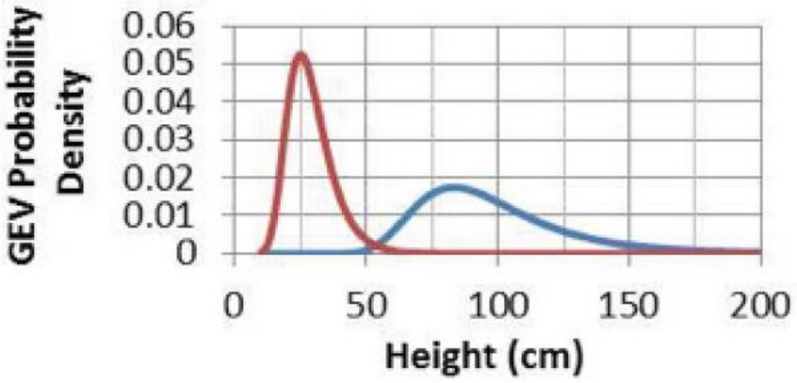
Extreme Value Statistics:

Maximum water level over a specified time interval: Generalized Extreme Value(GEV) Distribution

Water level that exceeds a pre-determined threshold: Peaks over Threshold and the Generalized Pareto Distribution (GPD)

Each distribution has three parameters:
Location: **Median/mean of water level values**
Scale: **Spread in the water level values**
Shape: **Skewness of the distribution and relation to the occurrence of rare (extreme events).**





	Location	Scale	Shape
Norfolk	85	21	0.07
San Diego	25	7	-0.02

Positive shape is associated with a thin trail – relatively rare extreme events.

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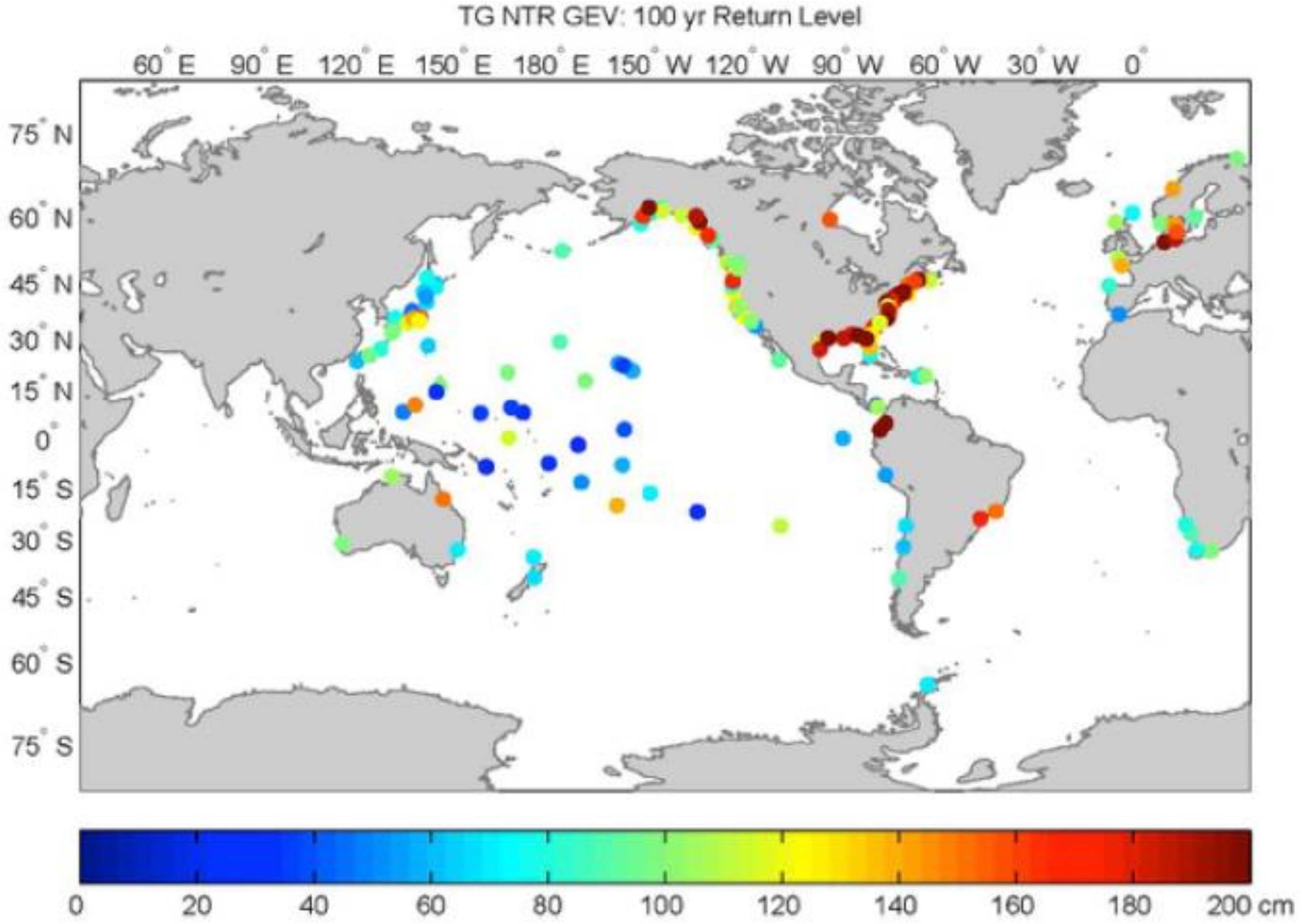
Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

Define probability estimates of exceeding a specified extreme sea level:

Non-Tidal Residual water heights for the 100-yr event probability at select tidal gauge locations using the GEV distribution on annual maximum water levels.



Hall et al. 2015, Sweet et al. 2014

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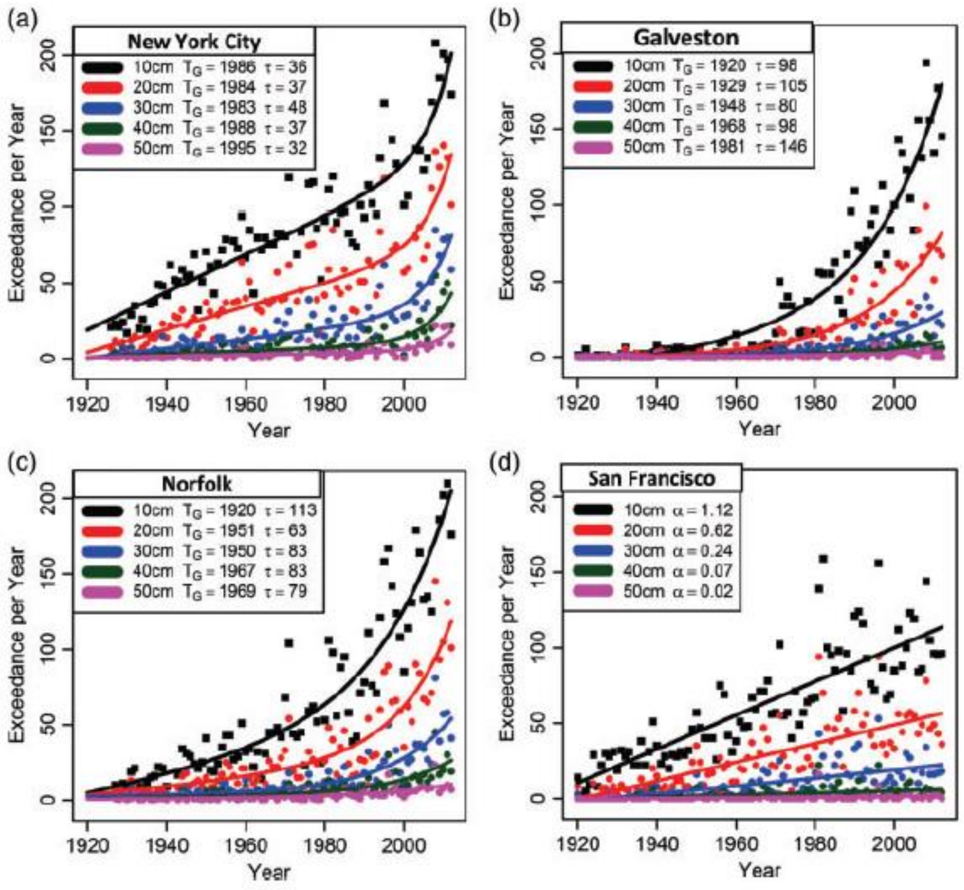
Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

Temporal evolution of exceedances (days/year) and growth model fits (solid lines) above elevation thresholds of 10, 20, 30, 40 and 50 cm above MHHW

New York City: Linear until recent decades when exponential growth begins

Galveston and Norfolk: exponential growth began early

San Francisco: Linear throughout the time period



Sweet and Park, 2014, *Earth's Future*

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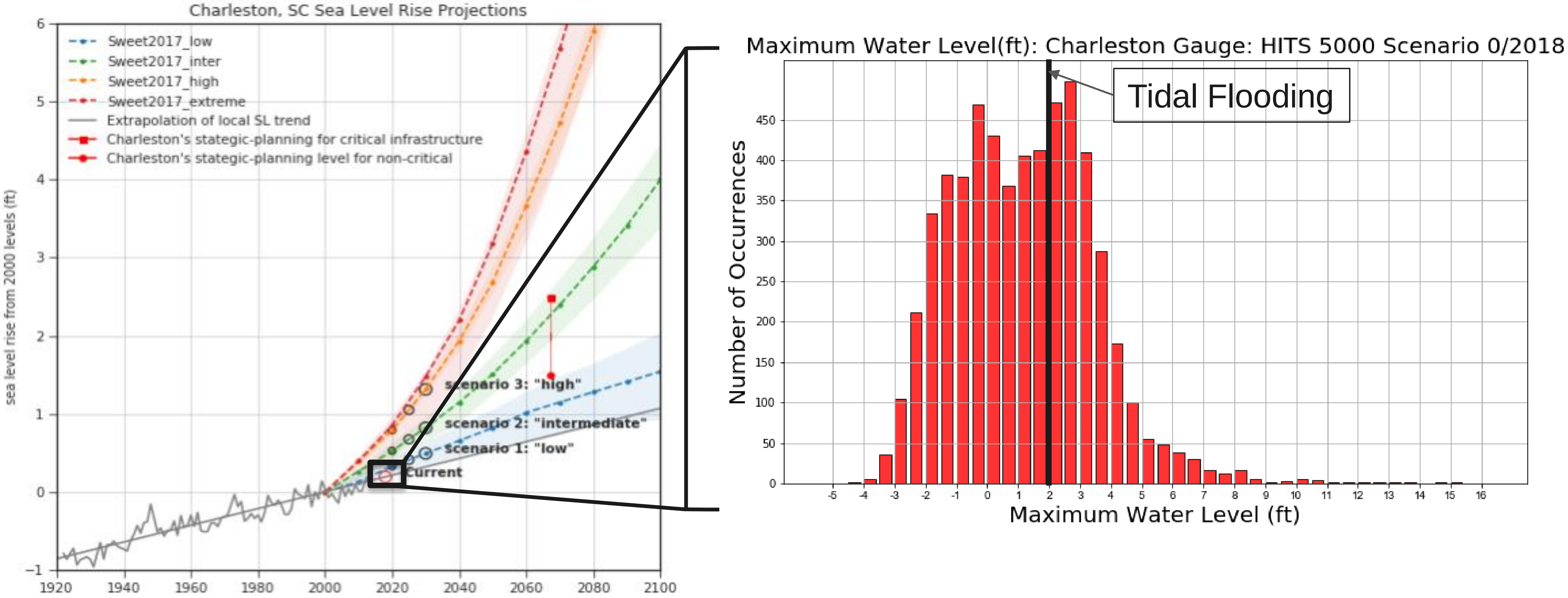
Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

Empirical Analysis of 5000 Synthetic Tropical Cyclones and SLOSH-Derived Water Levels at Charleston



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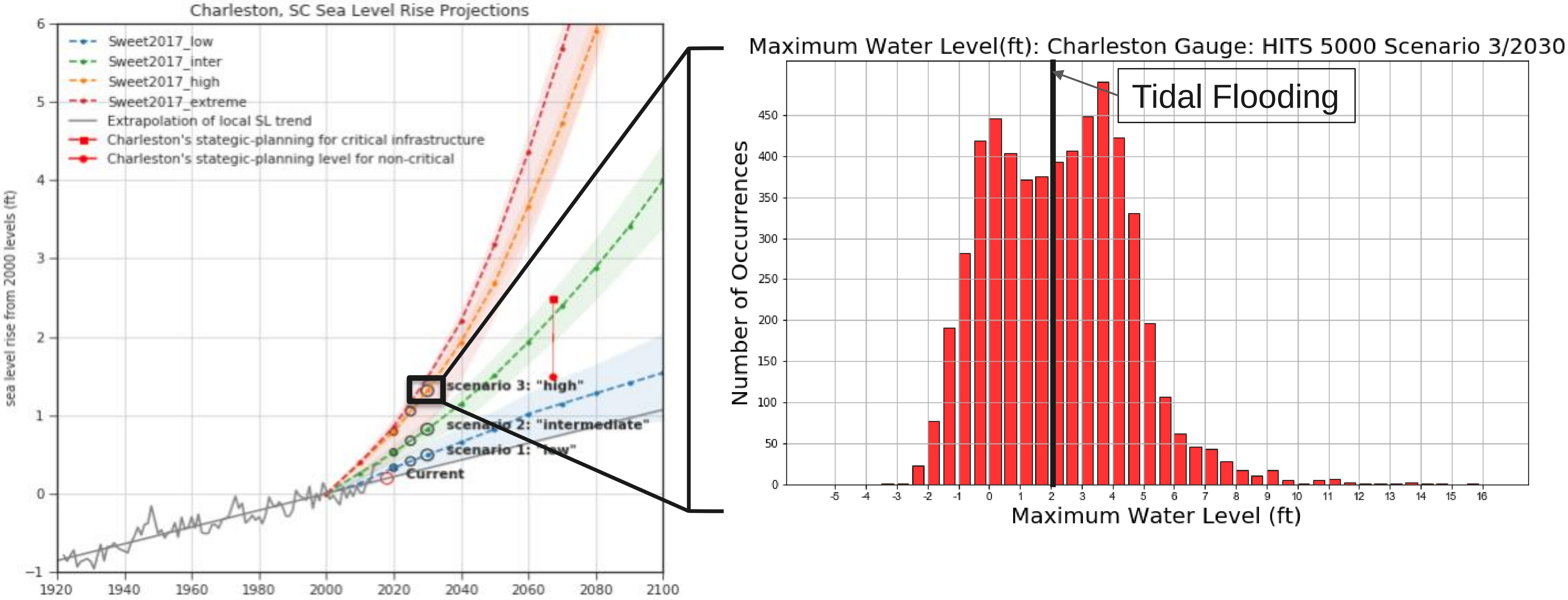
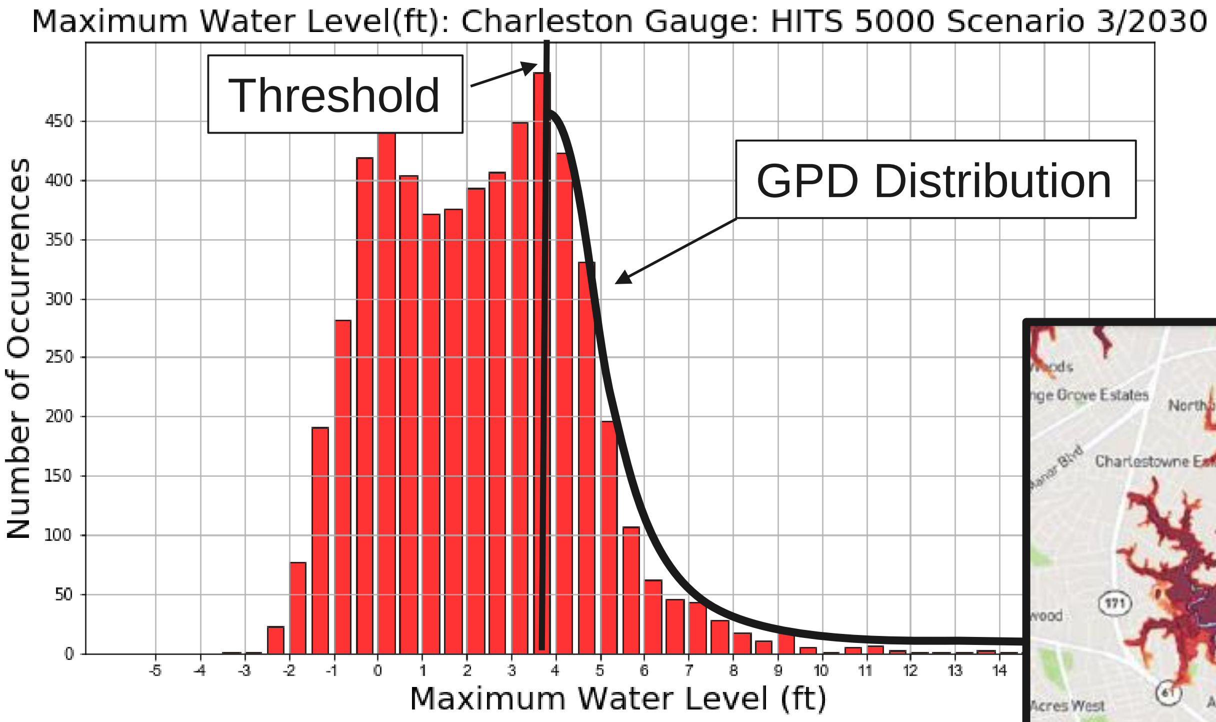


Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

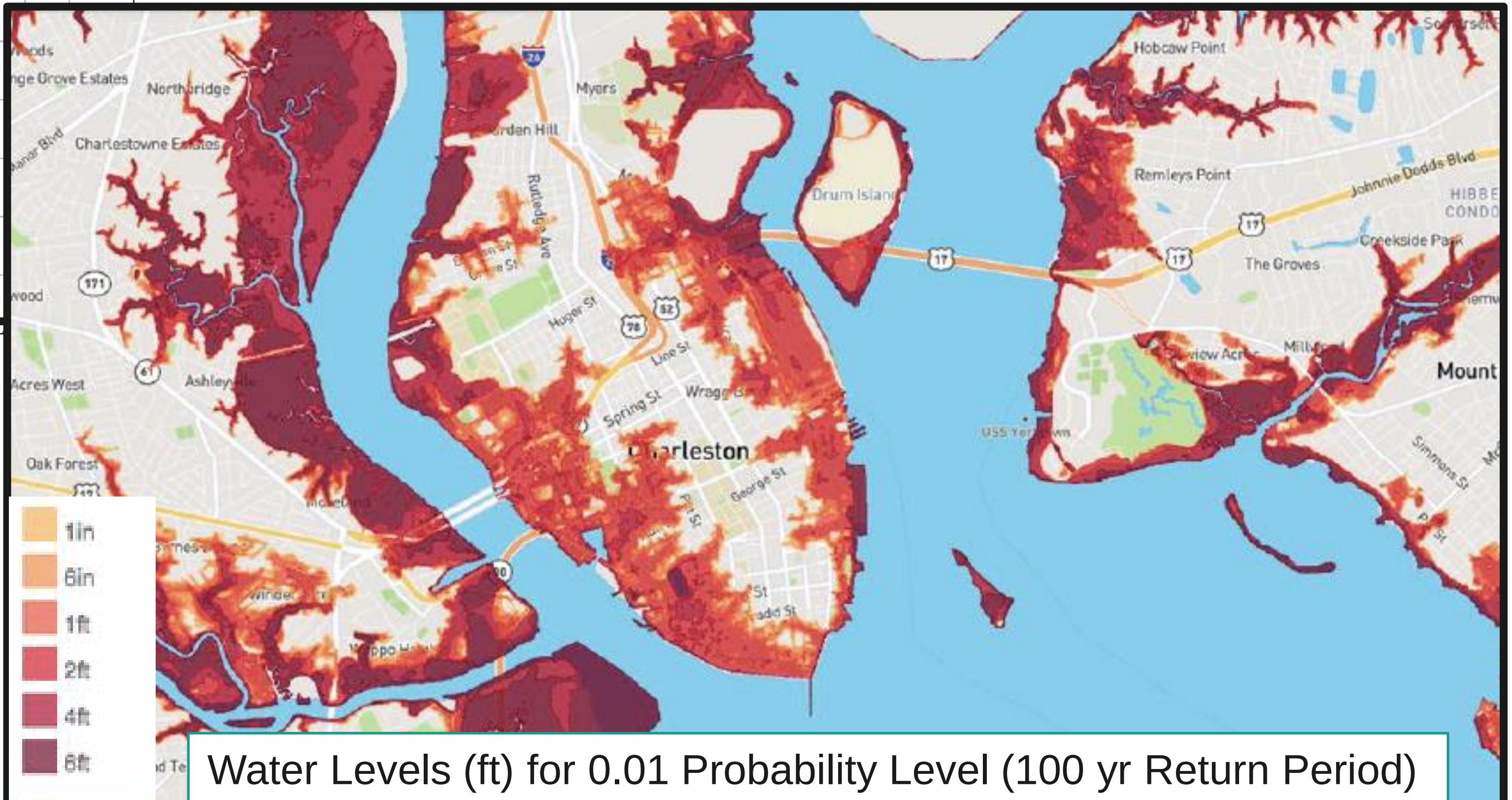


Peaks over Threshold (PoT) analysis

Fit a Generalized Pareto Distribution (GPD) to maximum water levels above a threshold unique to spatial location and attributed to storm surge from tropical cyclone only, non tropical cyclone only, precipitation only, and combined impacts.

Extreme Value Analysis:
Tropical Cyclone-induced Storm Surge

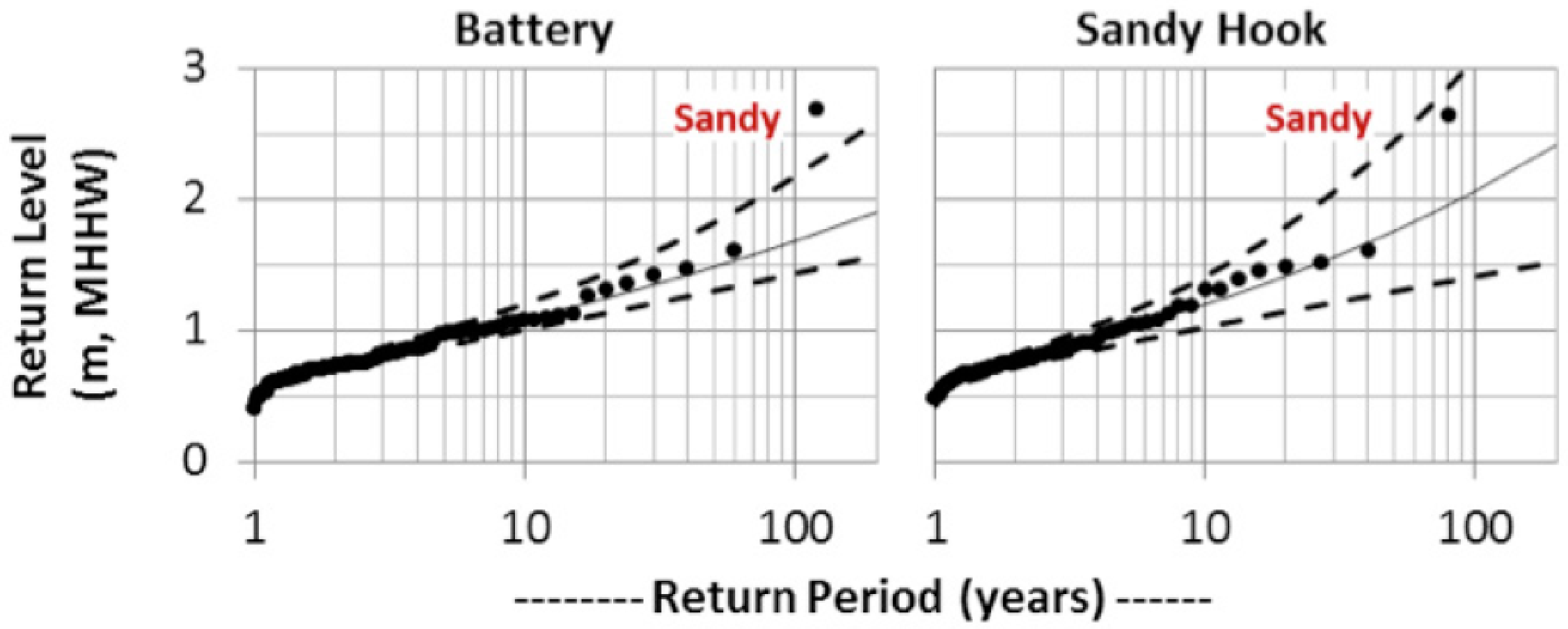
Water levels generated through storm surge simulations using synthetic tropical cyclone tracks



Water Levels (ft) for 0.01 Probability Level (100 yr Return Period)

Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

Extreme Value Analysis is sensitive to location, distribution character, and uncertainties related to maximum likelihood estimates of the three parameters.



Analysis of tidal gauge data at two relatively close locations results in different return periods associated with the Sandy event in New York Harbor and in relation to the confidence intervals about the return levels. (Lin et al. 2010)

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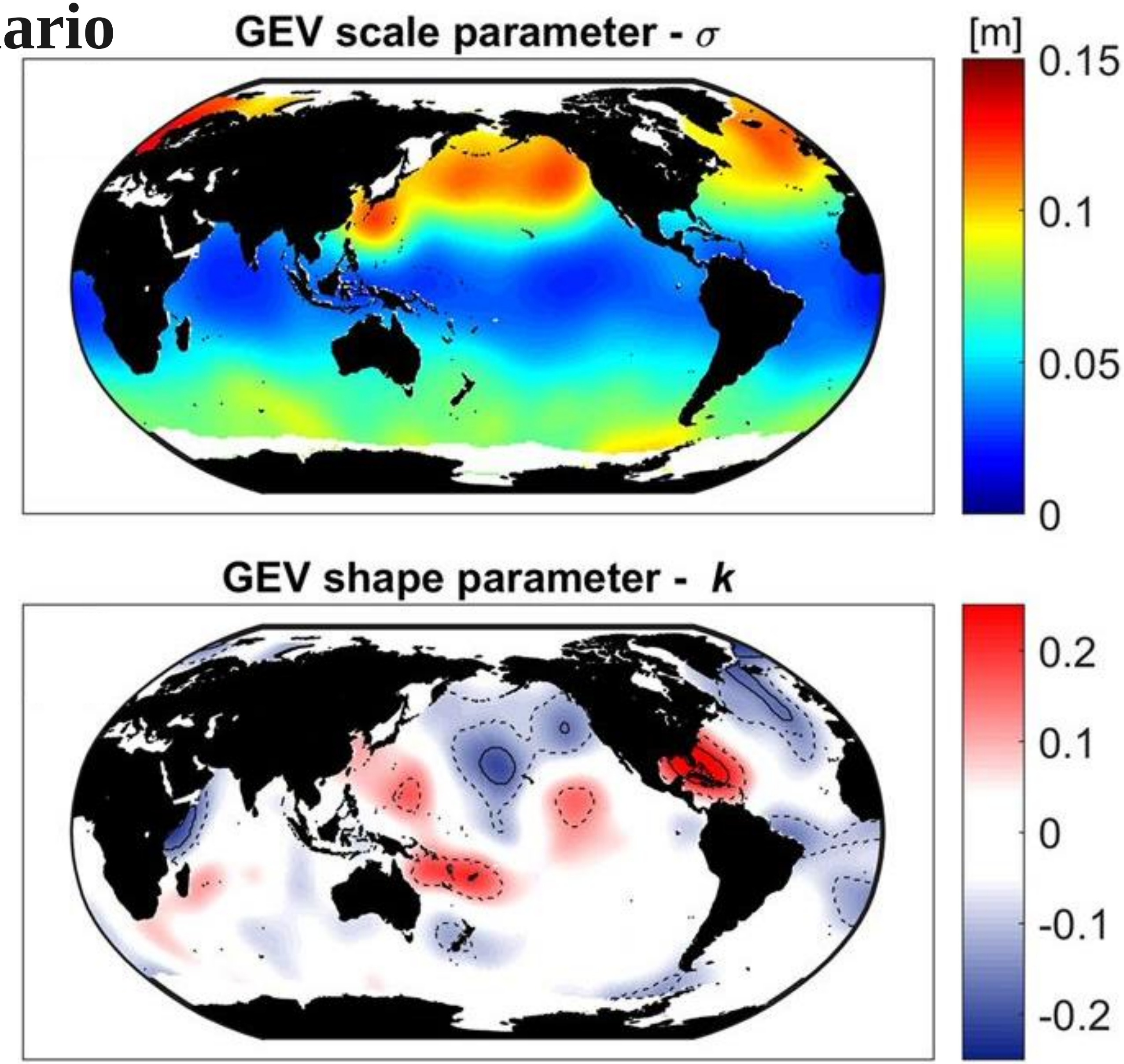
Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

Parameters of the GEV distribution of extreme water levels (sum of tide and storm surge)

The scale parameter varies by latitude as increased storminess at higher latitudes increases the variability in water levels.

The shape parameter is most positive in regions where infrequent but extreme events produce high water levels and a thin right-hand tail to the water level distribution.

These are regions in which tropical cyclones occur.



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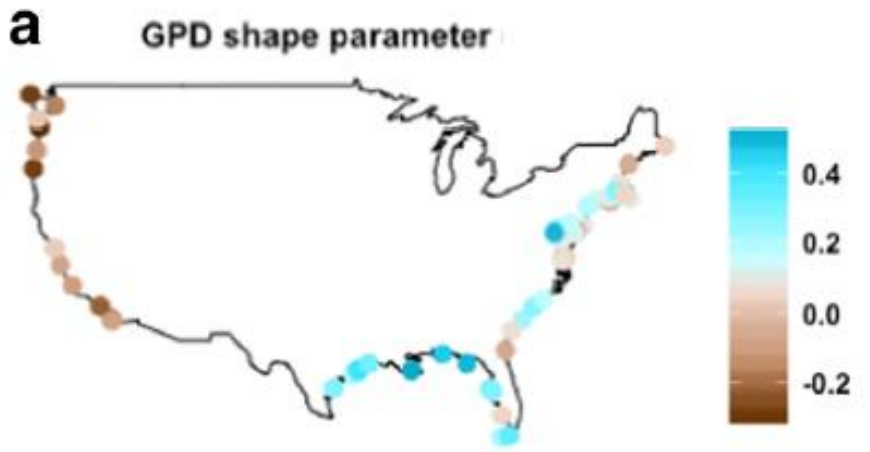
Regional / Local Design Life in a Relative Sea Level Rise Scenario: Allowances



The GPD shape parameter is positive (thin right-hand tail) for the east coast of the U.S. and the northern Gulf of Mexico:

Relatively rare, extreme events (tropical cyclones)

Sea level rise allowances:

Height adjustment from historic flood levels. That maintain under uncertainty the annual expected probability of flooding.

Account for:

- Risk Tolerance
- Time horizon
- Confidence in the sea level rise projections

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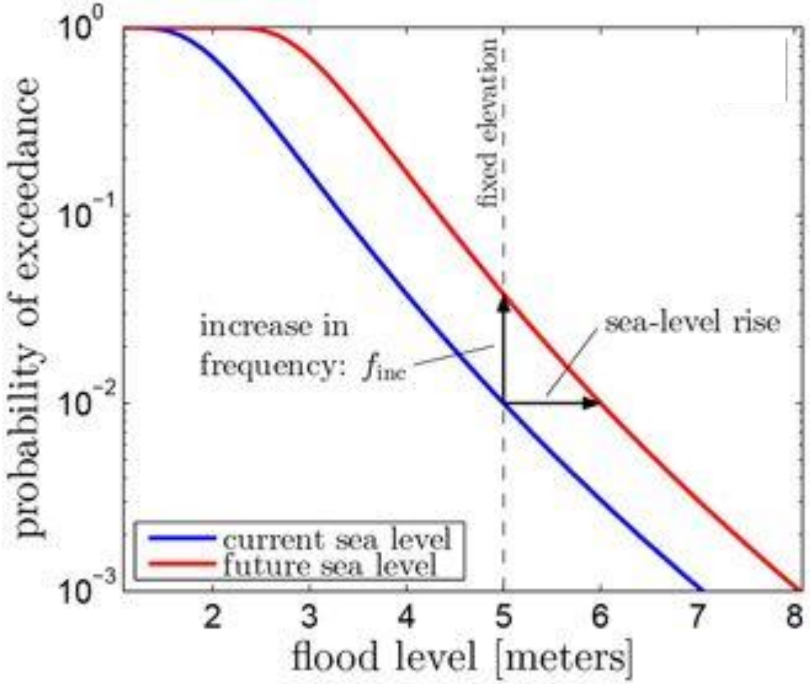
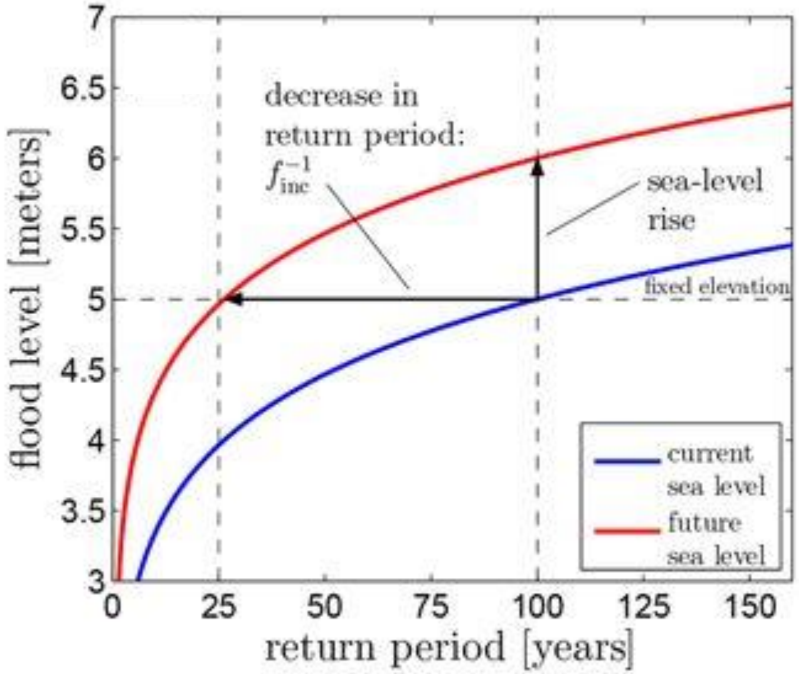
Regional / Local Probabilities of EWL in a Relative Sea Level Rise Scenario

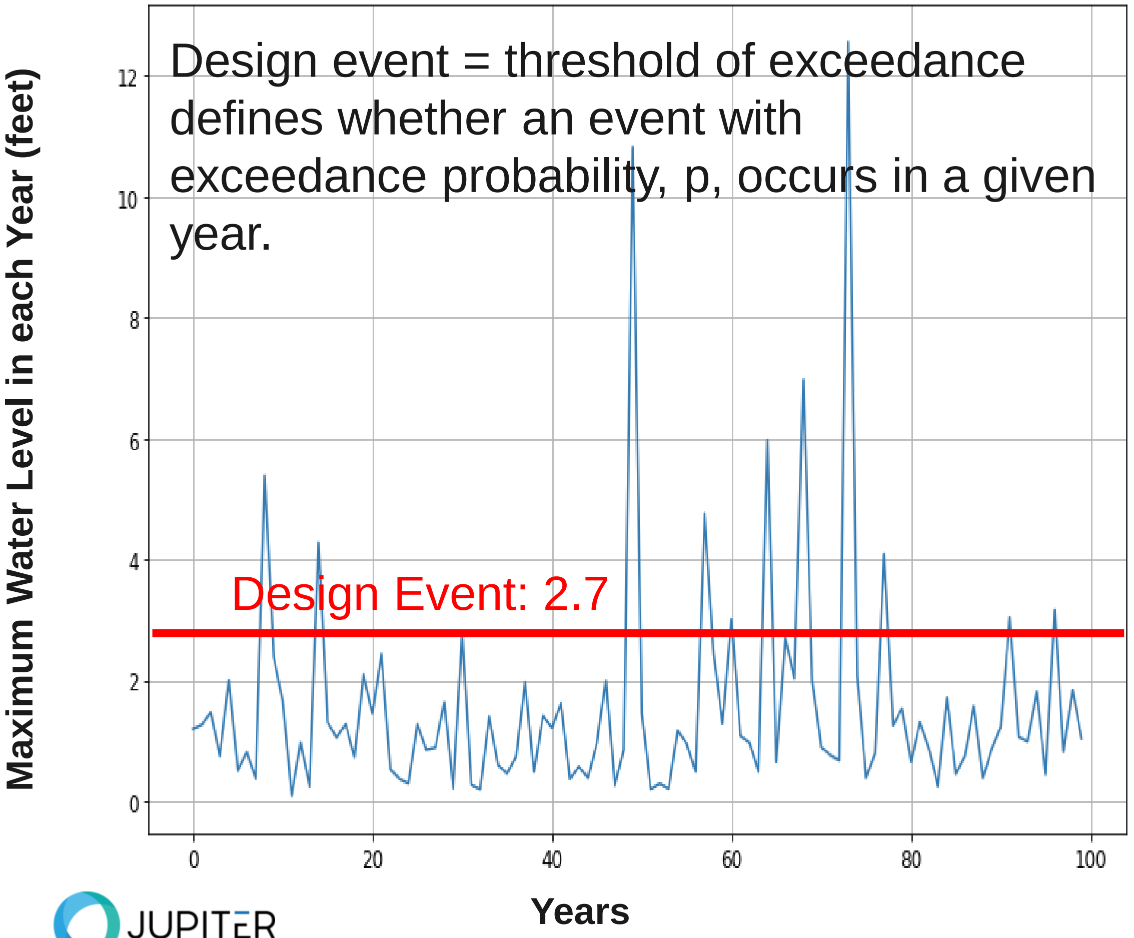
A 1 m increase in sea level increases the exceedance probability and lowers the return period (right) 5 m-flood level.

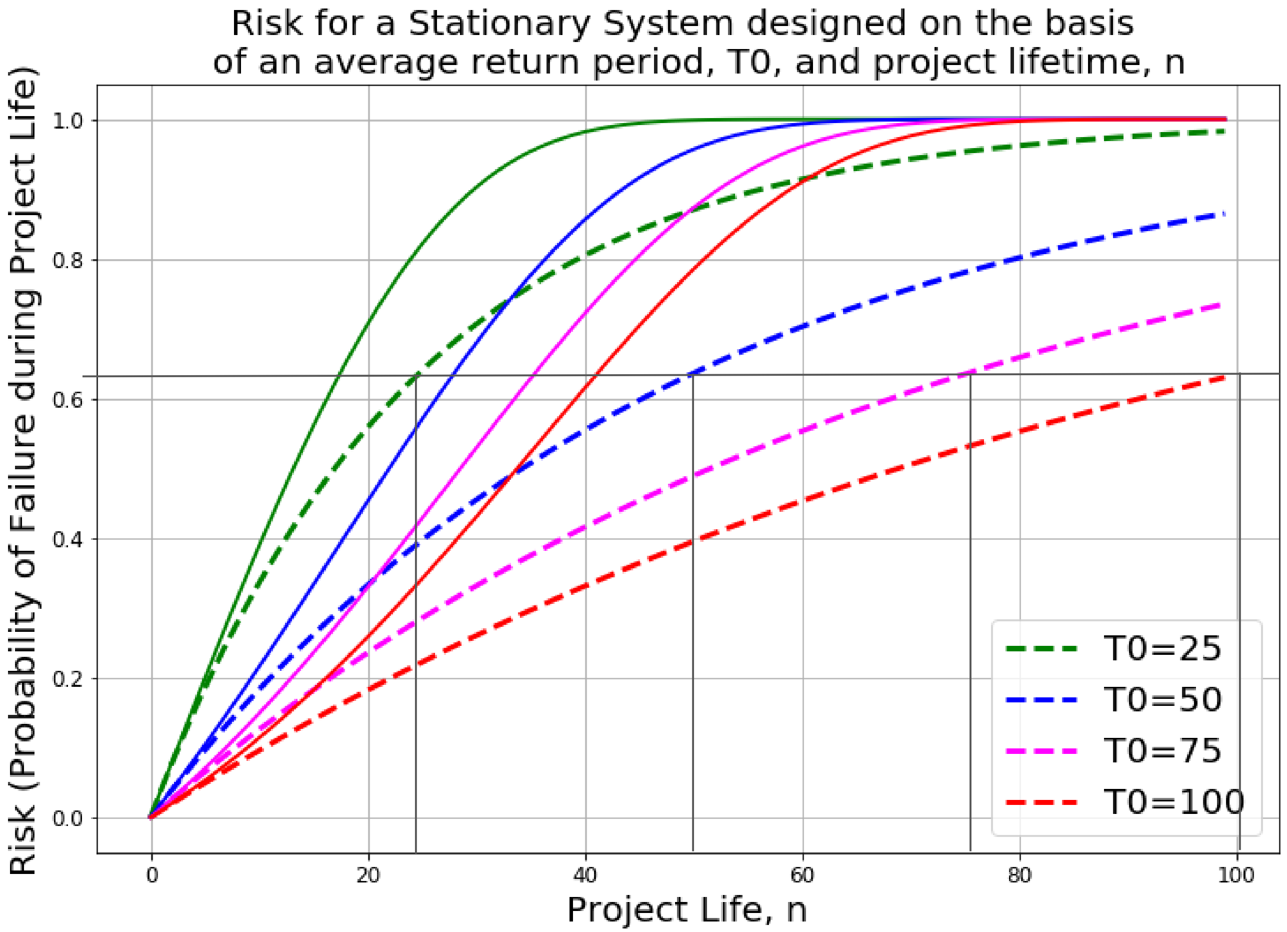




A region with low variability in flood level (steep exceedance probability distribution) will have larger increases in flooding frequency under sea level rise. (Vitousak et al. 2017, Scientific Reports)

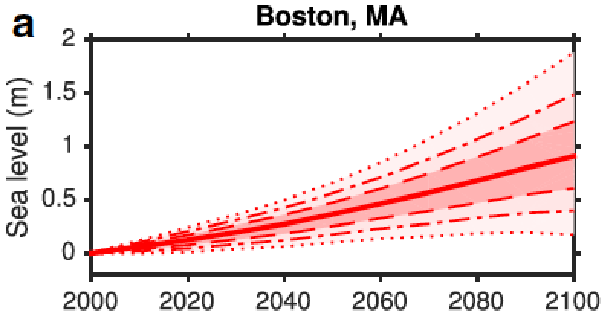
Regional / Local Design Life in a Relative Sea Level Rise Scenario





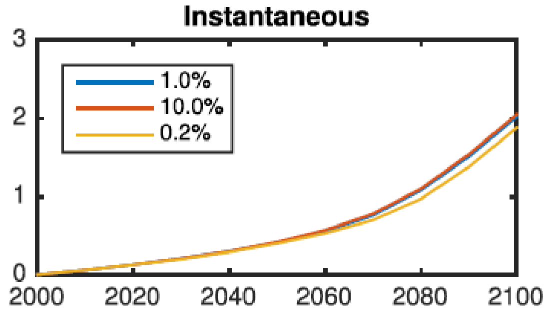
Dashed curve = $1-(1-p)^n$ where n is the design life of the project and p is the probability of an event exceeding the design value

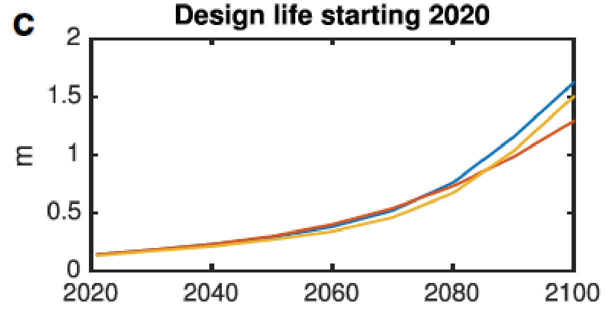
Regional / Local Design Life in a Relative Sea Level Rise Scenario: Allowances



Sea level rise projection for Boston, MA

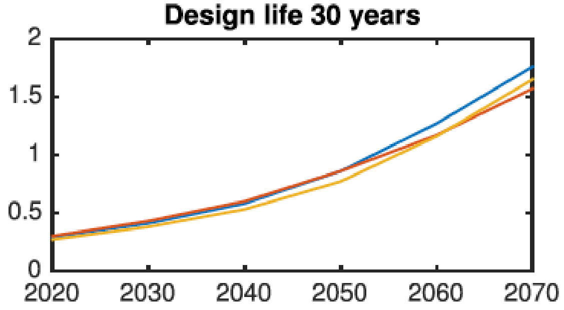
Instantaneous allowance for various risk levels

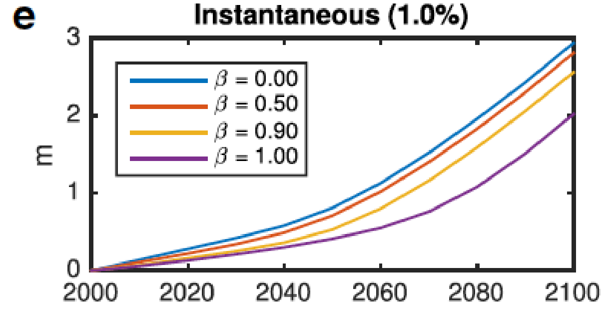




Design life allowances starting in 2020 for project lengths of 1 to 81 years

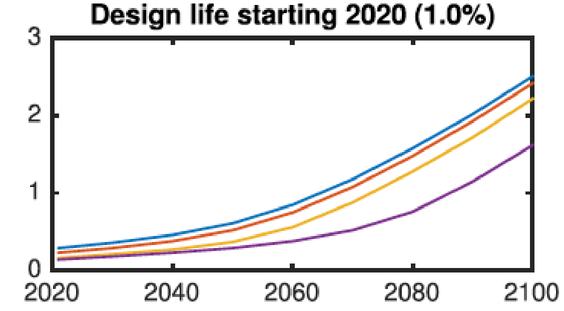
Design life allowances starting for 30 year projects with variable start dates from 2020 - 2070





1% Instantaneous allowances with limited degree of confidence in future projections, β

1% design life allowances with limited degree of confidence in future projections, β



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Buchanan et al. 2016, *Climate Change*

Conclusions

- Regional variations in global sea level rise has important consequences for coastal impacts due to inundation and flooding.
- Acceleration in relative sea level rise rates, which are projected to occur during the 21st century, will continue to intensify inundation impacts and further reduce the time between flood events.
- Under extreme events with low probability (i.e., tropical cyclones, 100-yr return periods relative sea level rise has already begun and will continue to nonlinearly compress recurrence probabilities smaller storm surges will increasingly impact fixed elevations [Hunter 2010; Park et al., 2011; Tebaldi et al., 2012; Sweet et al., 2013].
- Lesser extremes due to tidal flooding are increasing in time
- Availability of probabilistic sea level rise projections provide an opportunity to better coastal flood risk decision making and management.
- Risk-based decision and information can be placed in the context of design life flood levels, instantaneous allowances, and design-life allowances, which account for asset-specific time frames and large uncertainties in sea level rise projections
- Not accounting for a non-stationary climate can compromise design life standards of projection even for short duration low probability events.

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Outstanding Issues

- **Regional attributes:**
  - Prioritization
  - Relative contributions and cancellations
  - Data sources
- **Data**
  - Homogeneity across regions and sources
    - homogeneity
    - formats
  - Exchange [atmosphere and ocean]
  - Quality
- **Models**
  - Understanding of current capabilities
  - Validation
  - Incorporate model-based projections of factors that contribute to extreme water levels
    - Storm structures
    - Storm frequencies
    - Storm intensities
- **Methods**
  - Compute, understand, and convey uncertainties
  - Incorporate future climate states