Unified Sea Level Rise Projections in Practice

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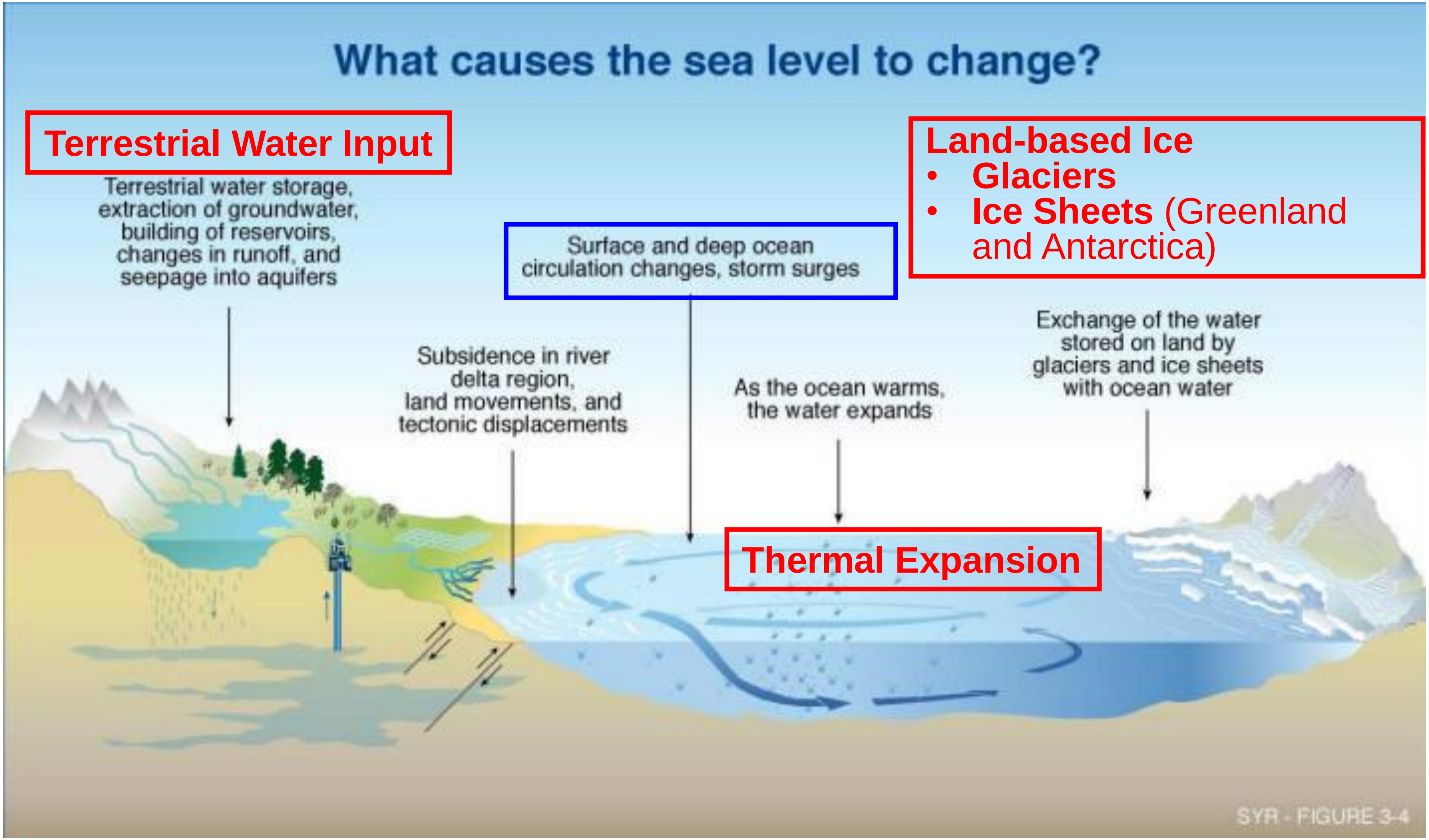
Outline

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

Sources of Sea Level Rise



Terrestrial Water Input

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

Thermal Expansion

Change in Relative Sea Level

$$\Delta\mathrm{RSL} = \Delta\mathrm{SL}_{\mathrm{G}} + \Delta\mathrm{SL}_{\mathrm{RM}} + \Delta\mathrm{SL}_{\mathrm{RG}} + \Delta\mathrm{SL}_{\mathrm{VLM}}$$

Global: f(Scenario, Time epoch);

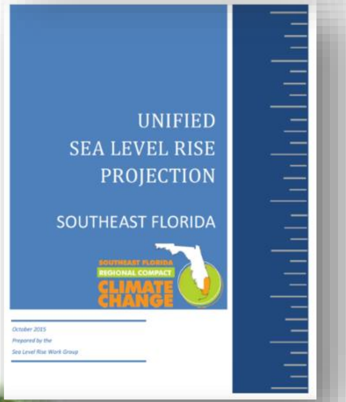
Regional: f(meteo-oceanographic factors, aka **Dynamic** Sea Level)

Regional: f(Changes in earth's **gravitational** field due to redistribution effects of rapid ice melt)

Local: **VLM**= f(Uplift/ Subsidence, GIA)

Unified SLR Projections: 2011 versus 2015 (using Key West gage)

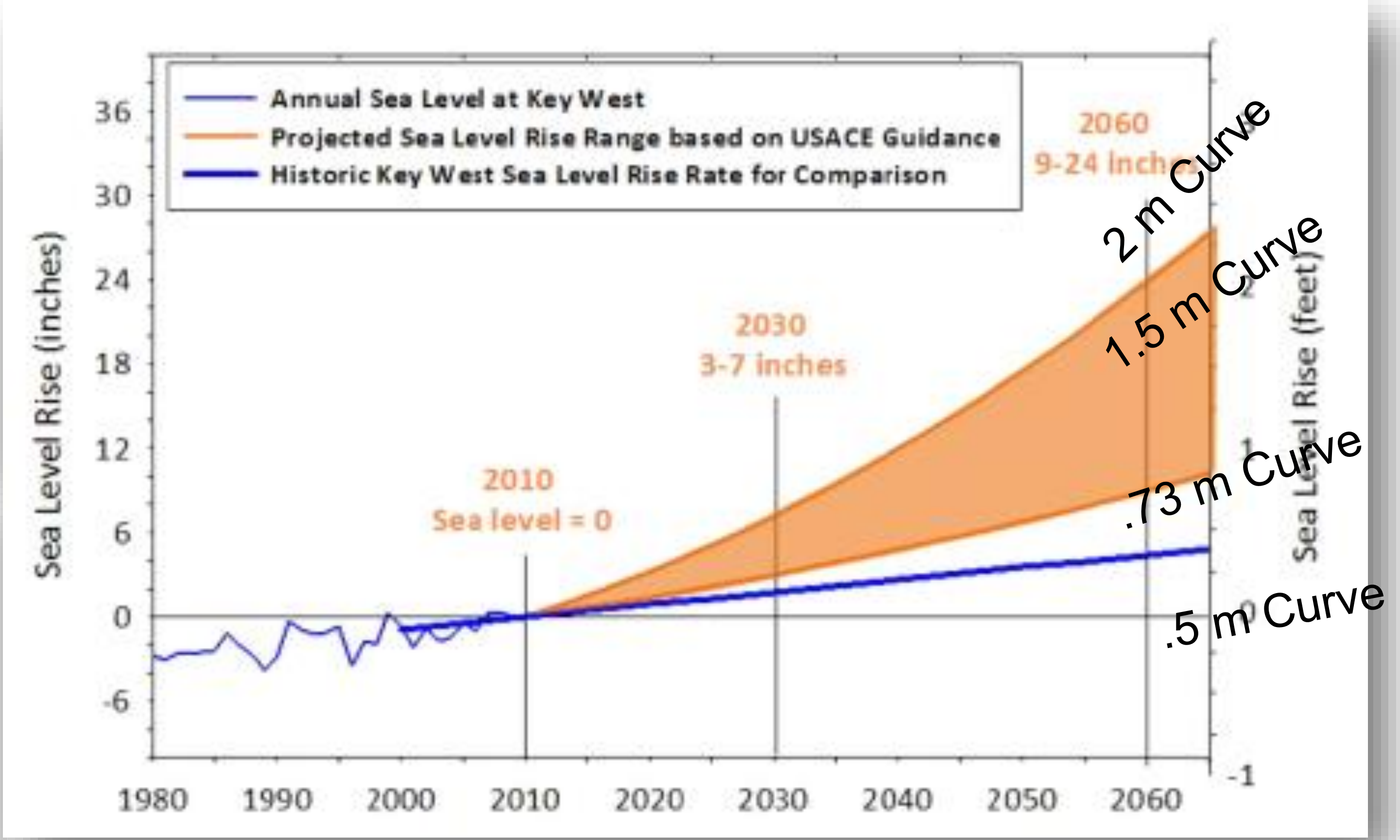
Multi-year composite of Land Sat images from http://glovis.usgs.gov/


UNIFIED
SEA LEVEL RISE
PROJECTION

SOUTHEAST FLORIDA

SOUTHEAST FLORIDA
REGIONAL COMPACT
CLIMATE CHANGE

October 2015
Prepared by the
Sea Level Rise Work Group



2 m Curve

1.5 m Curve

.73 m Curve

.5 m Curve

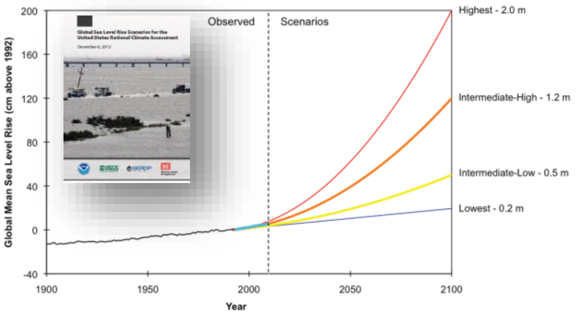
How the curves were developed

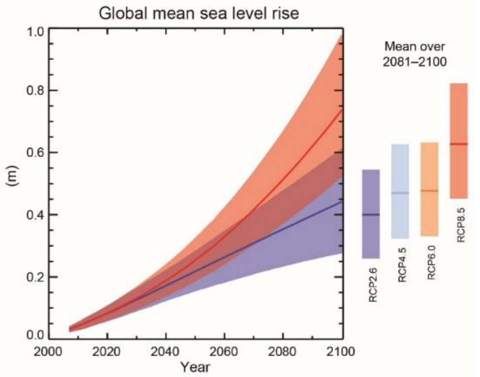
http://www.corpsclimate.us/ccaceslcurves.cfm

$$\textbf{Global}: SLR = at + bt^2$$

Scenario	Global Sea Level Rise by 2100	b (m/yr^2)
USACE Intermediate/NOAA Intermediate Low	0.5 m	2.712620e-05
IPCC 2013-2014 Median	0.73 m	4.684499e-05
USACE High	1.5 m	1.128601e-04
NOAA High	2.0 m	1.557270e-04

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





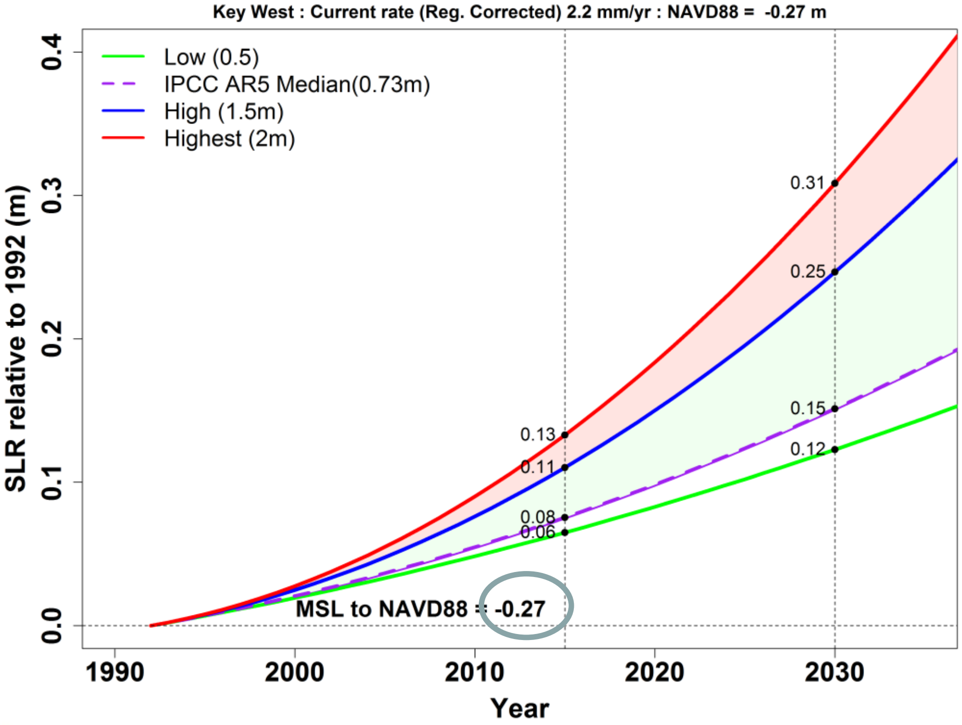
Regional: $SLR = ct + bt^2$
where c is a site-specific regional rate (2.2 mm/yr for Key West)

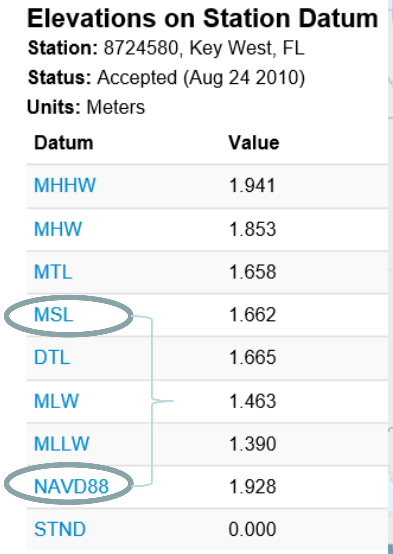
Why 1992? And how to translate the curve to a geodetic datum? (NGVD29 or NAVD88)

- 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)

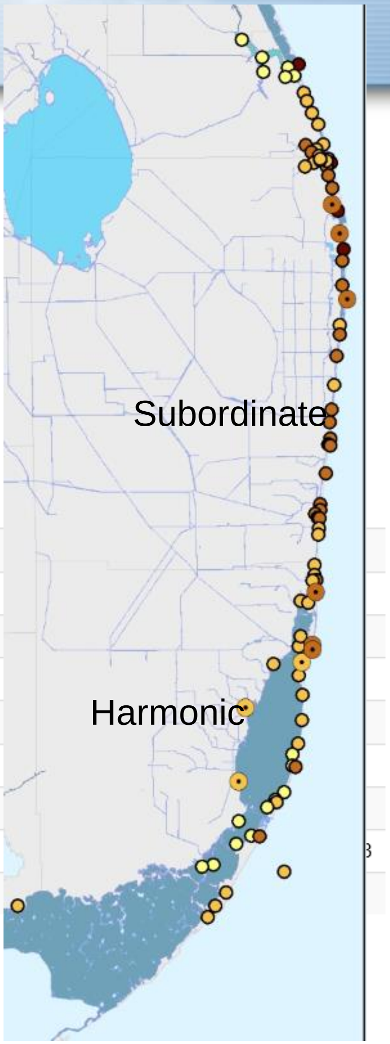




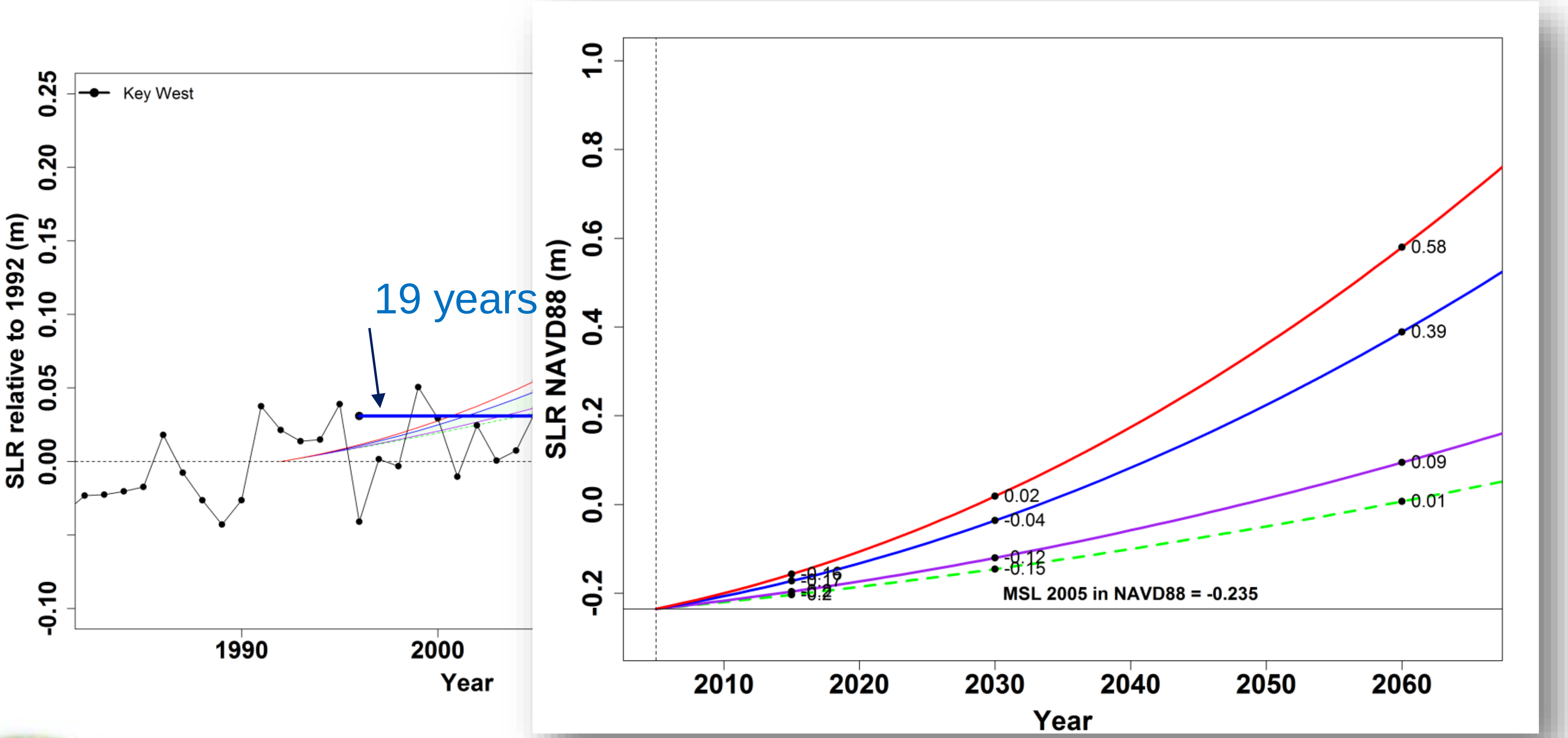
Elevations on Station Datum

Station: 8724580, Key West, FL
Status: Accepted (Aug 24 2010)
Units: Meters

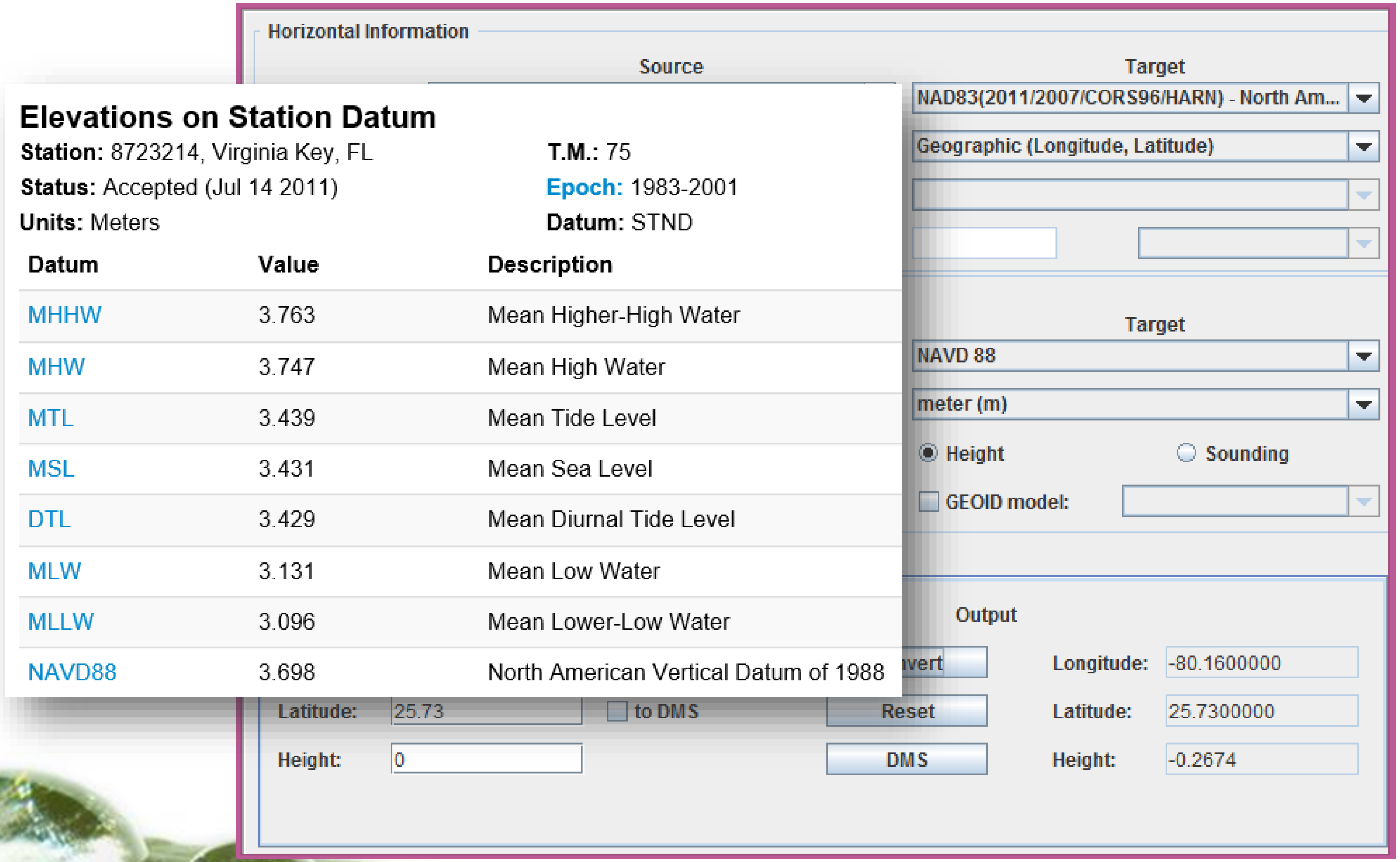
Datum	Value
MHHW	1.941
MHW	1.853
MTL	1.658
MSL	1.662
DTL	1.665
MLW	1.463
MLLW	1.390
NAVD88	1.928
STND	0.000



Example: Computing MSL



Example: VDATUM (http://vdatum.noaa.gov/)



Elevations on Station Datum

Station: 8723214, Virginia Key, FL
Status: Accepted (Jul 14 2011)
Units: Meters
T.M.: 75
Epoch: 1983-2001
Datum: STND

Datum	Value	Description
MHHW	3.763	Mean Higher-High Water
MHW	3.747	Mean High Water
MTL	3.439	Mean Tide Level
MSL	3.431	Mean Sea Level
DTL	3.429	Mean Diurnal Tide Level
MLW	3.131	Mean Low Water
MLLW	3.096	Mean Lower-Low Water
NAVD88	3.698	North American Vertical Datum of 1988

Horizontal Information
Source
Target: NAD83(2011/2007/CORS96/HARN) - North Am...
Geographic (Longitude, Latitude)

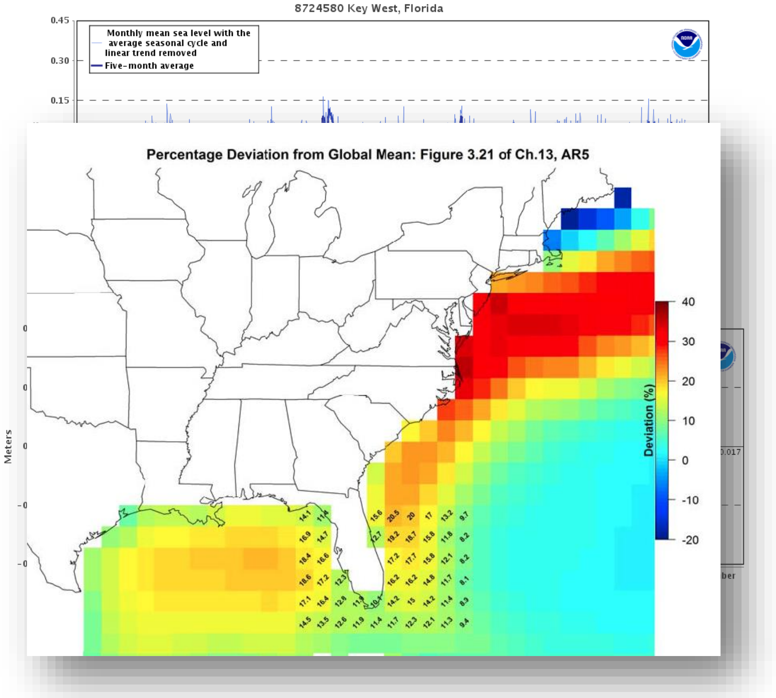
Target: NAVD 88
meter (m)
● Height ○ Sounding
☐ GEOID model:

Latitude: 25.73
☐ to DMS
Height: 0

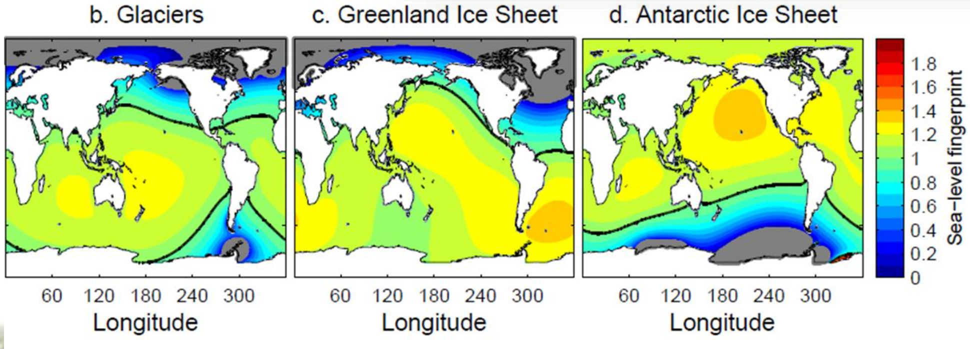
Output
Longitude: -80.1600000
Latitude: 25.7300000
Height: -0.2674

Other adjustments to MSL (if they are not accounted for in the regional rate)

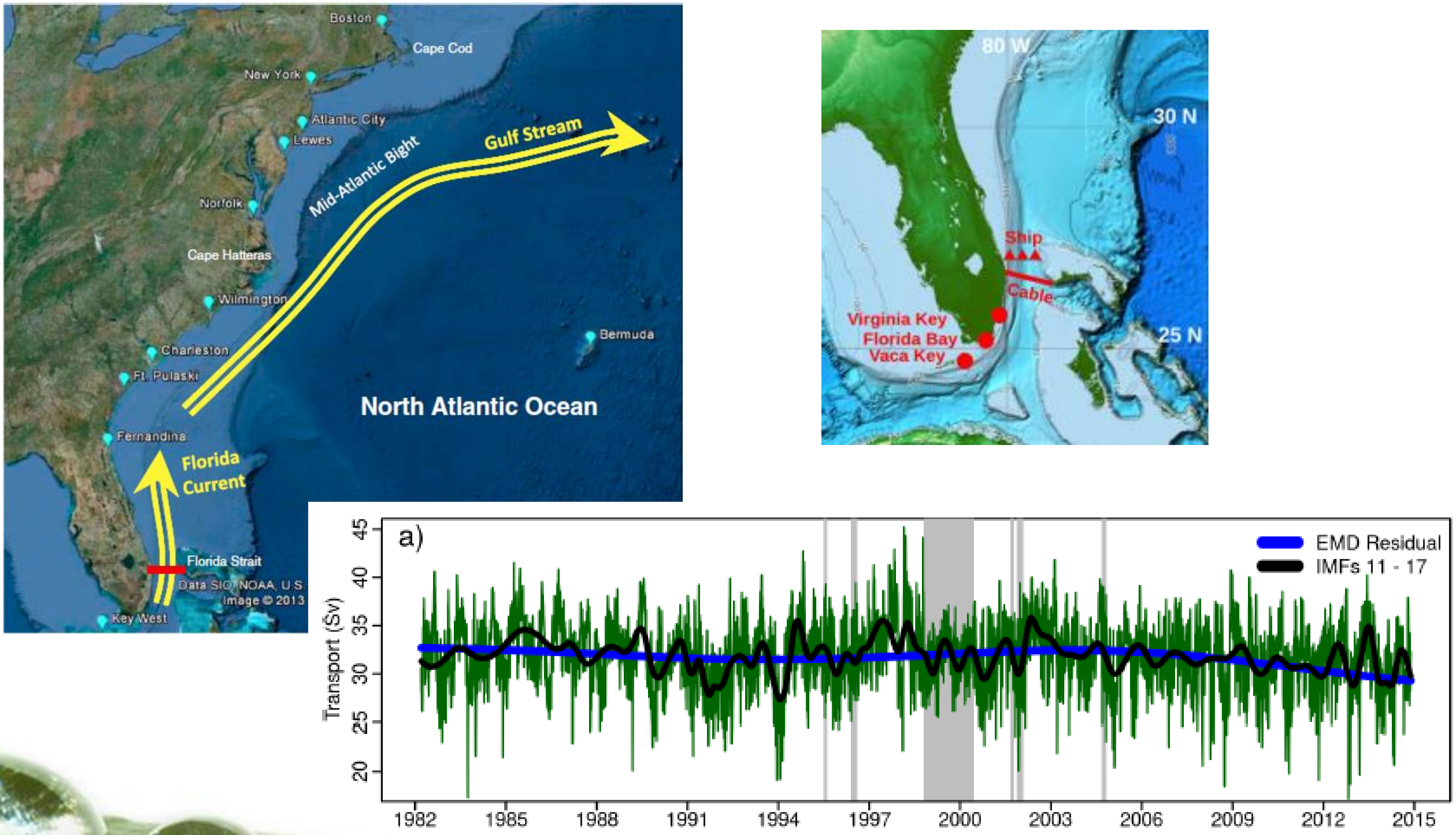
- Vertical Land Movement (From tide gage analysis, GPS etc.)
- Ocean Dynamics Change
  - Decline in Florida Current
  - 15% of the projection (based on IPCC)
  - Inter-annual variability
  - Seasonal Cycle
- Gravitational effects of ice melt



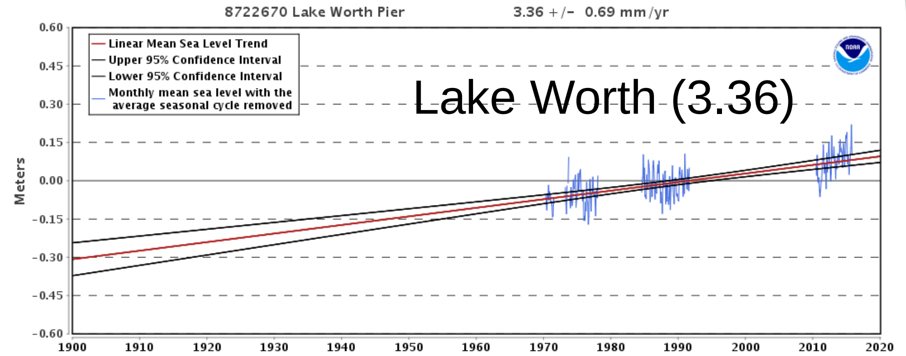
(Not in Compact)



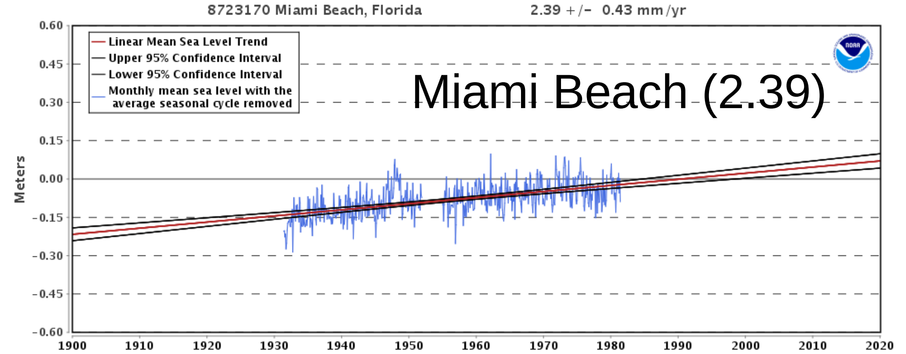
Decline in Florida Current Transport?



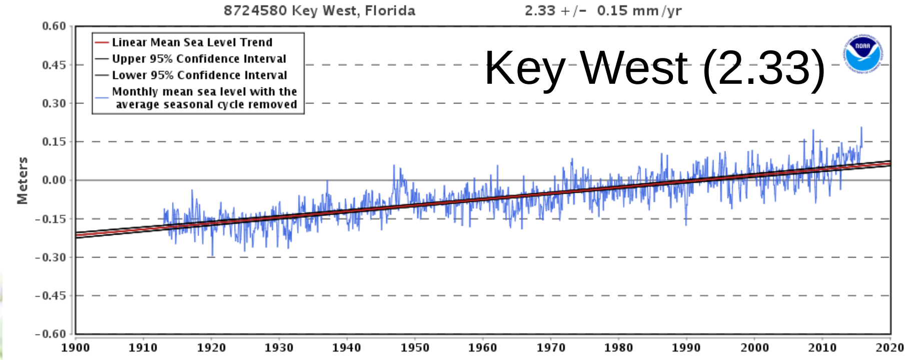
Southeast Florida (rate of rise)


8722670 Lake Worth Pier 3.36 +/- 0.69 mm/yr

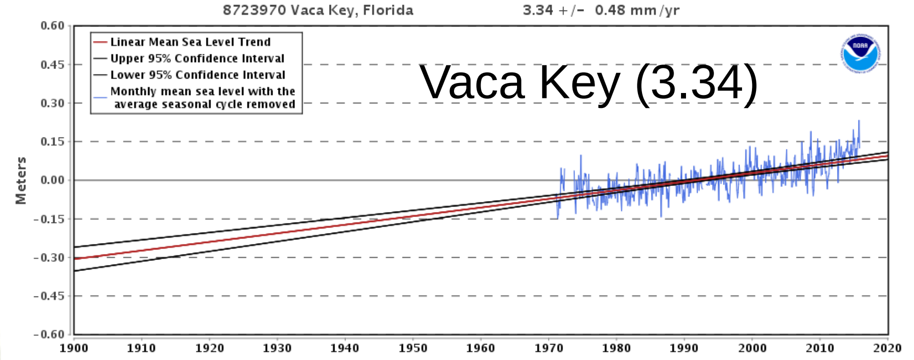
Lake Worth (3.36)


8723170 Miami Beach, Florida 2.39 +/- 0.43 mm/yr

Miami Beach (2.39)


8724580 Key West, Florida 2.33 +/- 0.15 mm/yr

Key West (2.33)


8723970 Vaca Key, Florida 3.34 +/- 0.48 mm/yr

Vaca Key (3.34)

DoD Coastal Assessment Regional Scenario Working Group: Regionalized Scenarios for Sea-Level Change and Extreme Water Levels Worldwide

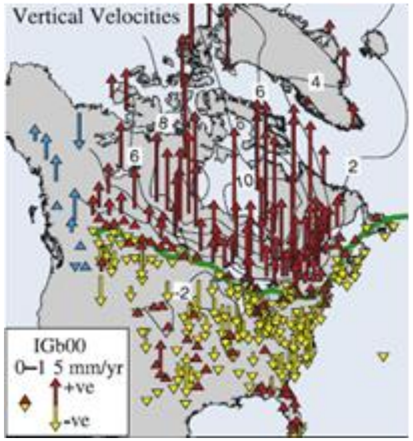
DoD Coastal Assessment Regional Scenario Working Group

SERDP
DOD ▪ EPA ▪ DOE

ESTCP

Vertical Land Movement—Background and Methods

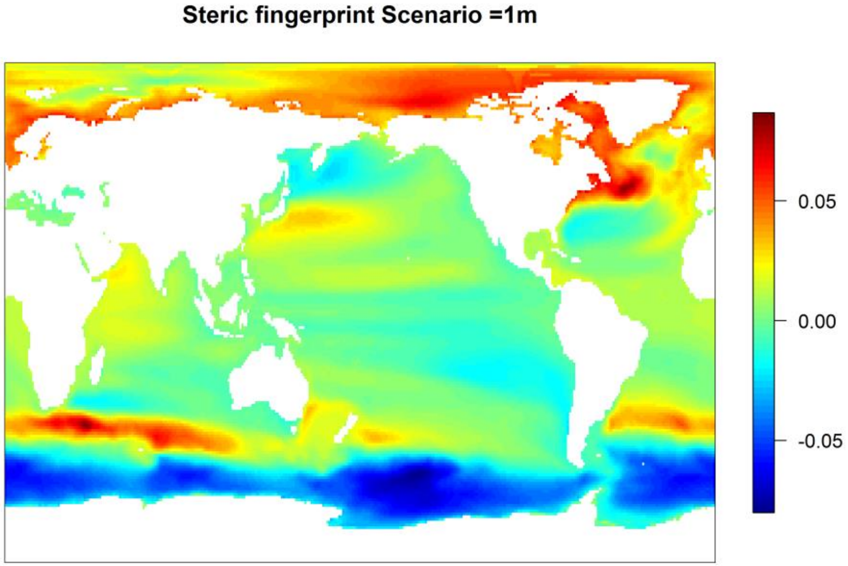
- Post-glacial rebound: Associated with the removal of ice sheets in the northern portion of North America & Europe. Also known as Glacial Isostatic Adjustment (GIA).
- Tectonic uplift (e.g., Alaska) and sedimentation
- Subsidence (e.g., removal of groundwater or oil, oxidation of organic matter)
- Monitored 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)
- Dyn_slr (x,t) = global_steric_mean (t) + scale factor (x) * global_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, global_steric_mean (t), and global_mean_air_temp (t) are the global averages of steric sea level and temperature at time t.

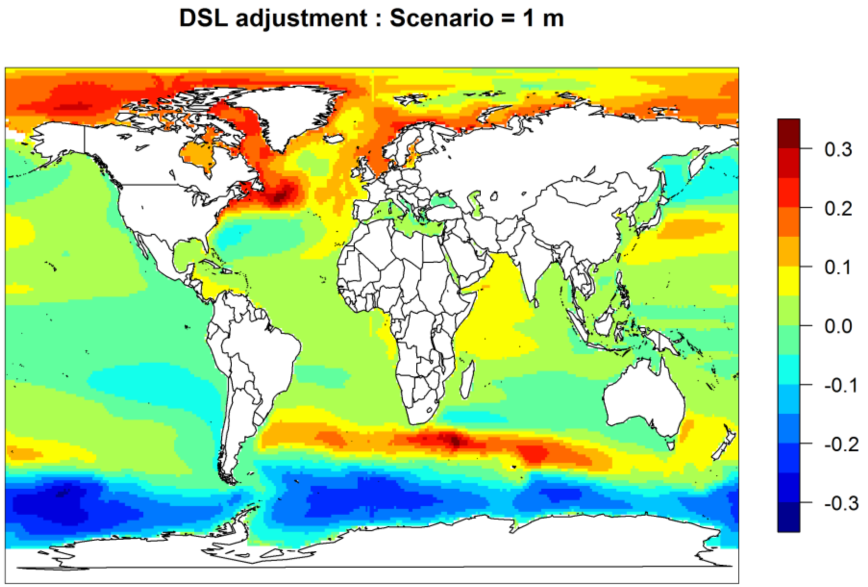


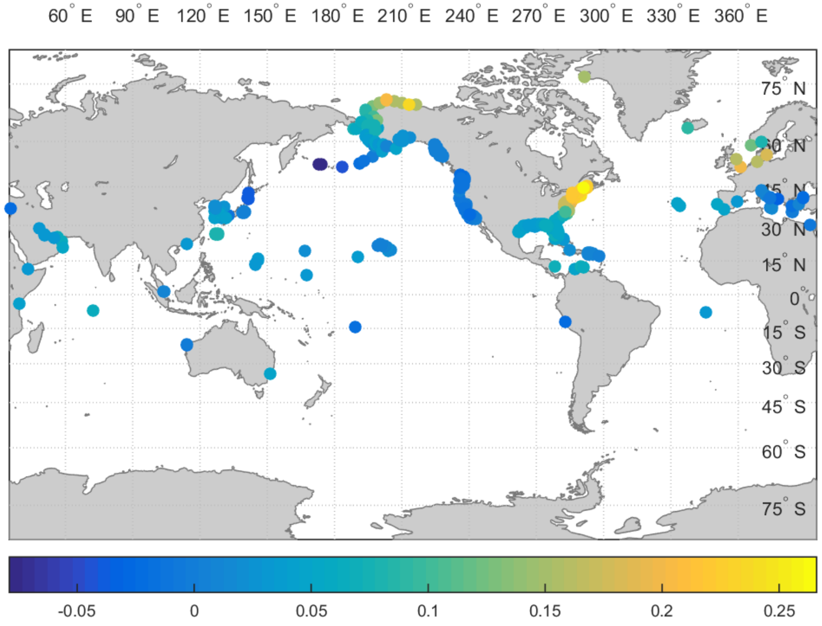
Scale bar shows the pattern-scaling in meters per degree Centigrade

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.



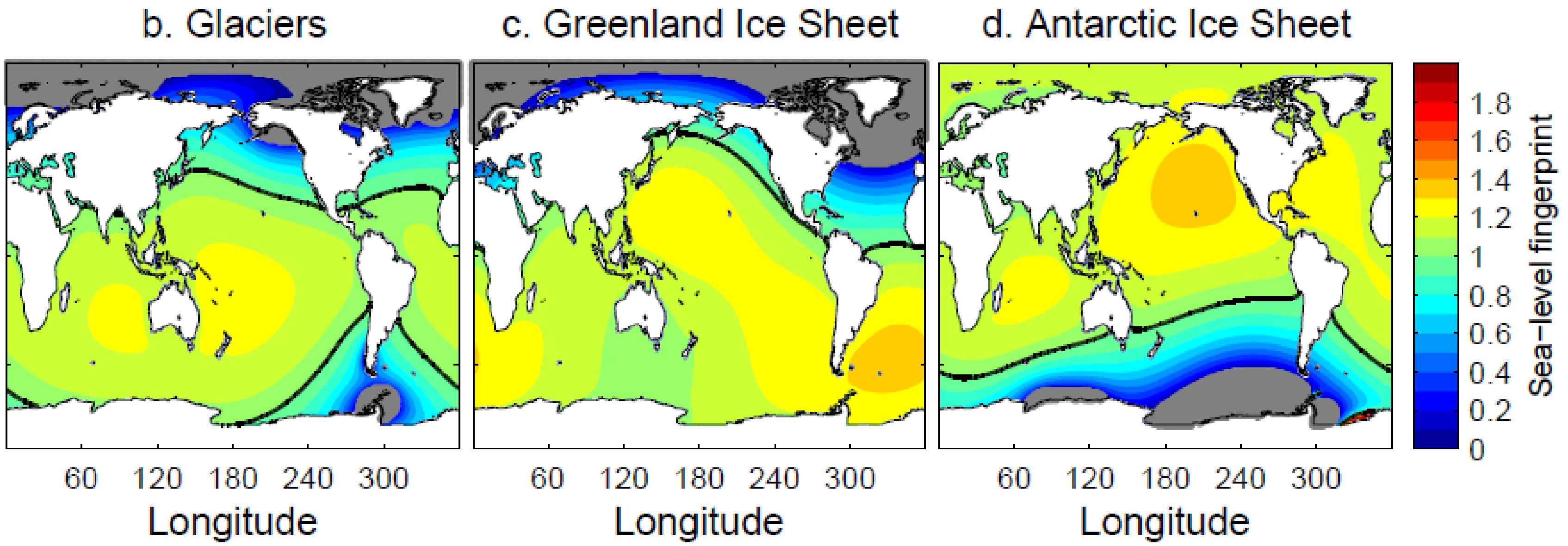


Results for individual DoD sites for the 1-m GMSLR scenario at 2100. Scale bar is in meters.

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

Sea Level "Fingerprints" due to Rapid Melting of Ice

- Ice sheets exert gravitation 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



Sea Level “Fingerprints” due to Rapid Melting of Ice—Methods

- Based on Perrette et al. (2013) and Kopp et al. (2014)
- Fingerprint (x) = $\dfrac{\text{SLR Component (x)}}{\text{Global Mean SLR Component}}$

  (where x 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 (**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.

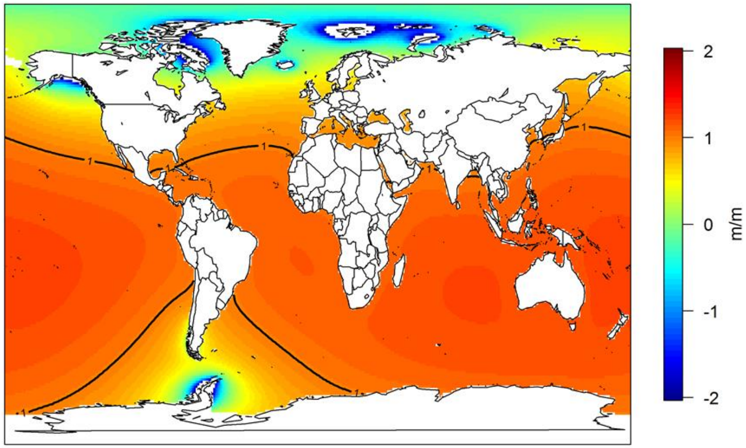
Ice Melt Contributions—Results

(By GMSLR and Year)

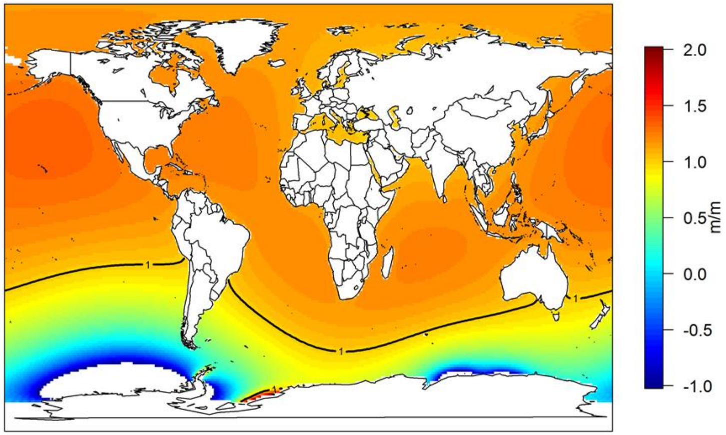
		5%					Median					95%				
Comp	Year	0.2	0.5	1	1.5	2	0.2	0.5	1	1.5	2	0.2	0.5	1	1.5	2
GIC	2035	0.01	0.02	0.02	0.03	0.03	0.02	0.03	0.05	0.06	0.07	0.03	0.04	0.07	0.09	0.11
GrIS	2035	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.03
AIS	2035	0.00	0.00	0.00	-0.01	-0.02	0.00	0.01	0.01	0.02	0.03	0.01	0.01	0.03	0.05	0.08
T	2035	0.02	0.04	0.06	0.08	0.10	0.03	0.05	0.09	0.12	0.16	0.04	0.07	0.11	0.16	0.22
LW	2035	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01
Total	2035	0.06	0.09	0.14	0.20	0.27	0.07	0.10	0.17	0.23	0.29	0.07	0.12	0.19	0.25	0.31
GIC	2065	0.03	0.04	0.06	0.06	0.06	0.05	0.07	0.11	0.12	0.11	0.06	0.10	0.15	0.18	0.17
GrIS	2065	0.02	0.02	0.02	0.02	0.01	0.03	0.04	0.08	0.11	0.10	0.04	0.06	0.14	0.19	0.18
AIS	2065	-0.02	-0.03	-0.04	-0.04	0.19	-0.01	0.01	0.04	0.15	0.39	0.00	0.04	0.11	0.33	0.58
T	2065	0.04	0.08	0.13	0.14	0.12	0.06	0.12	0.21	0.25	0.23	0.07	0.16	0.28	0.36	0.34
LW	2065	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Total	2065	0.11	0.20	0.36	0.54	0.73	0.12	0.24	0.44	0.64	0.84	0.13	0.28	0.51	0.74	0.95
GIC	2100	0.06	0.07	0.12	0.12	0.12	0.09	0.13	0.20	0.21	0.20	0.12	0.19	0.28	0.29	0.28
GrIS	2100	0.01	0.00	0.02	-0.04	-0.21	0.04	0.09	0.23	0.37	0.38	0.07	0.17	0.43	0.79	0.98
AIS	2100	-0.10	-0.10	-0.11	-0.08	0.17	-0.06	0.02	0.11	0.42	0.95	-0.03	0.14	0.34	0.92	1.72
T	2100	0.07	0.14	0.27	0.26	0.25	0.12	0.25	0.44	0.48	0.45	0.16	0.35	0.62	0.71	0.66
LW	2100	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	2100	0.17	0.41	0.82	1.25	1.63	0.20	0.50	1.00	1.50	2.00	0.23	0.59	1.18	1.75	2.37

Ice Melt “Fingerprints”—Results

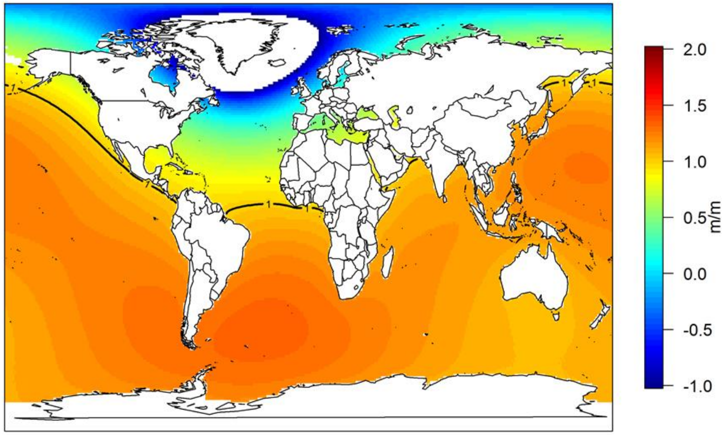
Glacier fingerprint Scenario =1 m



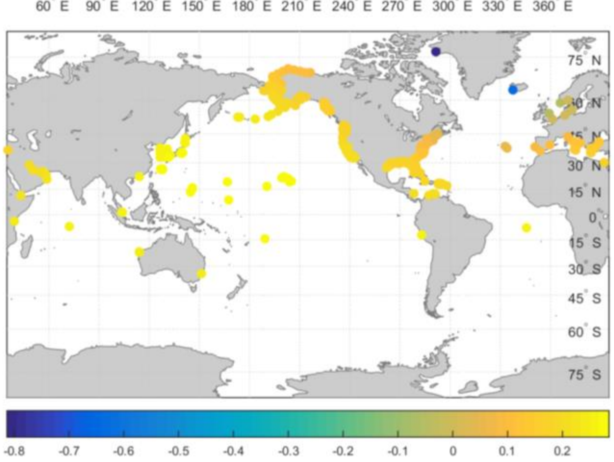
Antarctica fingerprint Scenario =1 m



Greenland fingerprint Scenario =1 m

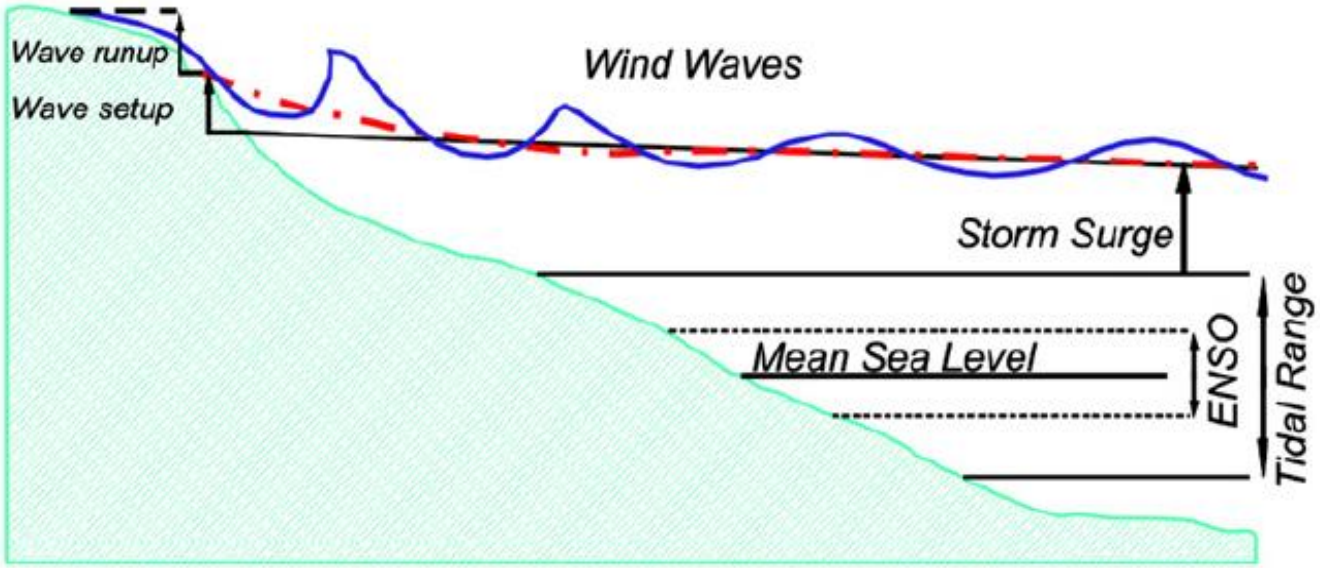


Ice melt adjustment for Greenland at 2100 for the 1–m GMSLR scenario.



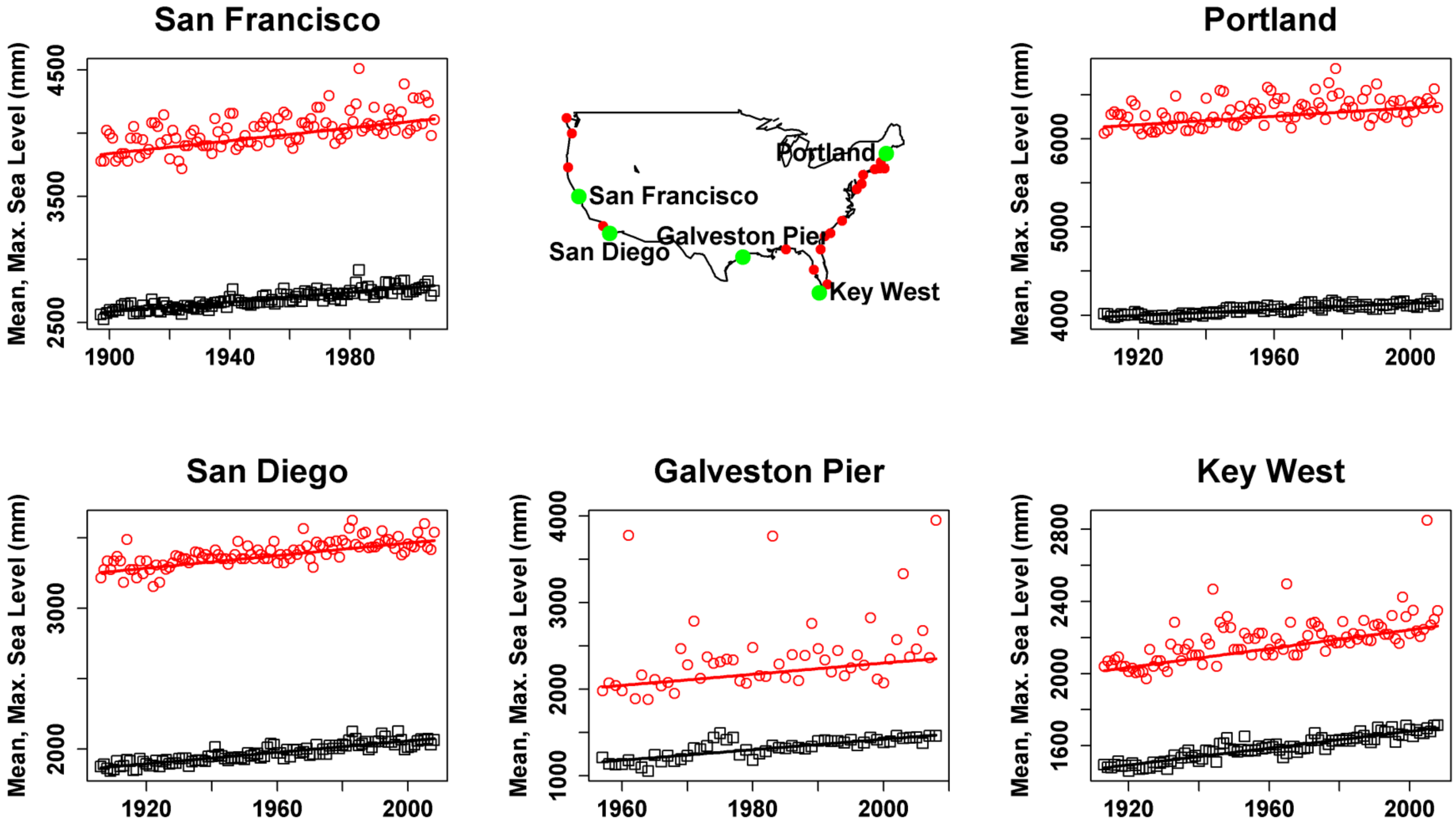
Fingerprint scale bars are ratios of sea level contribution as a function of global mean, whereas the bottom right figure scale bar shows the deviation in meters from the global mean for ice melt from Greenland.

Sea Level Extremes



- Methods
  - Hydrodynamic modeling of historic/synthetic storms
  - Statistical modeling of sea level extremes

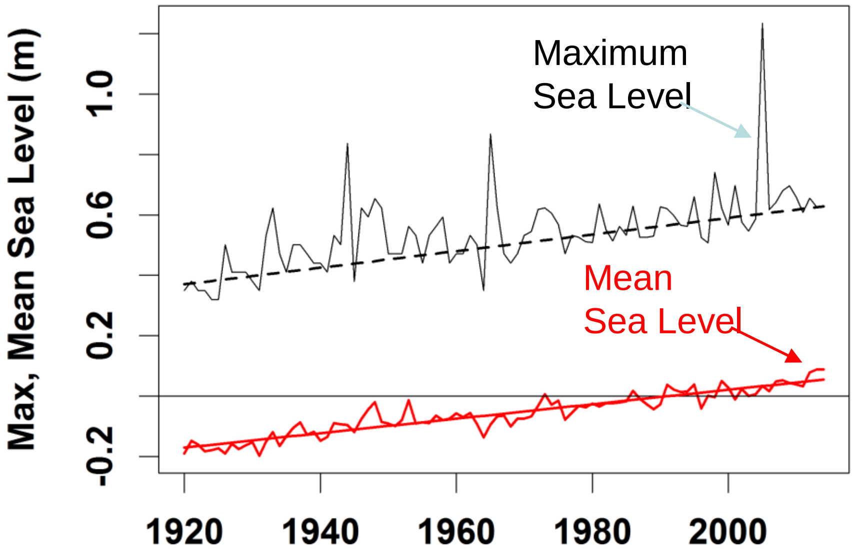
When MSL increases so does extremes



How high my sea wall (or roadway) should be?

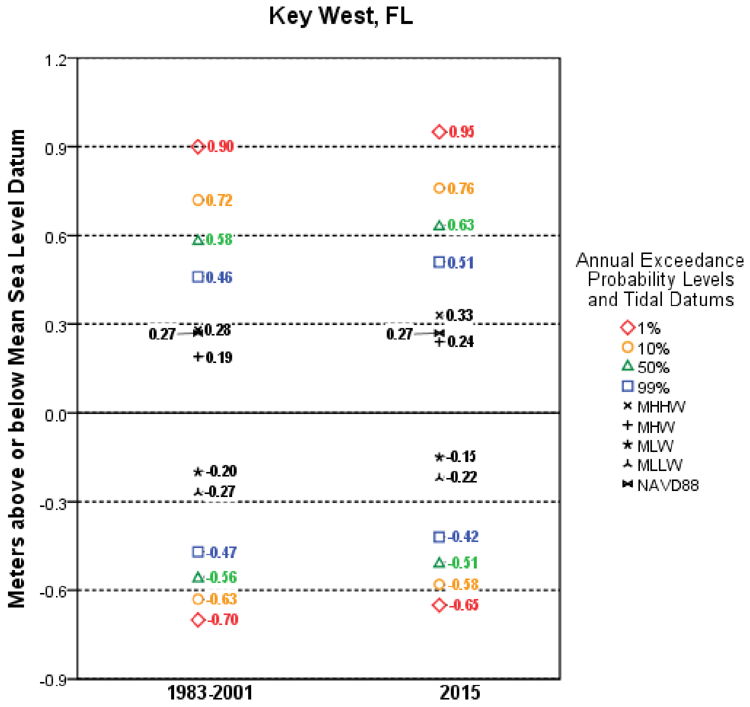
Three approaches (Stationary and Nonstationary)

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")



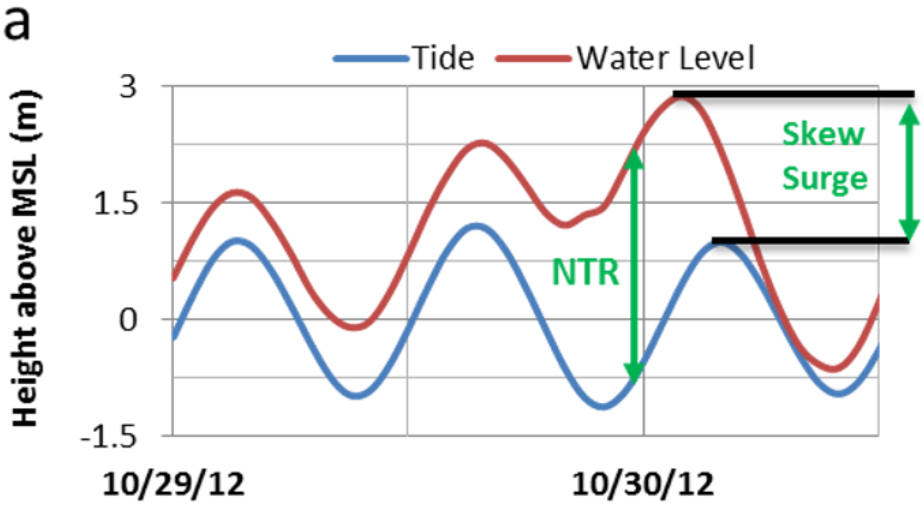
Stationary Approach - I

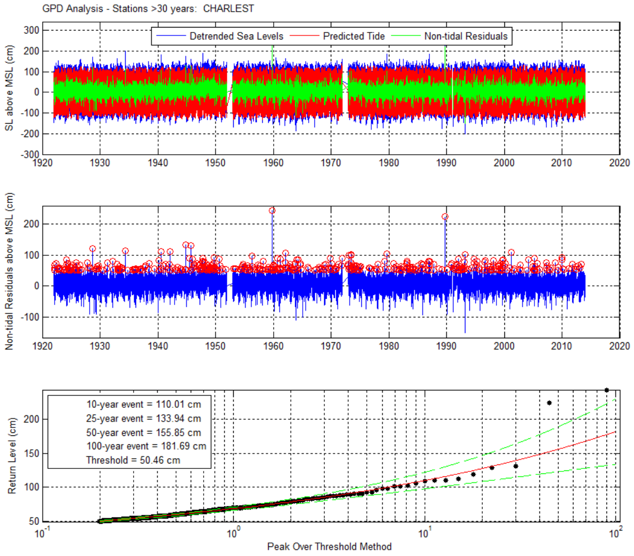
Year	2060
Unified SLR Projection	USACE Intermediate High
MSL (2005)	-0.235
future MSL	0.39
Ocean Dynamics	0.06
Gravitational Effects	?
Interannual Variability	0.05
RSLR	**0.265**
10-Year	0.72
100-Year	0.9
Future 10-yr	**0.985**
Future-100yr	**1.165**



Stationary Approach - 2

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



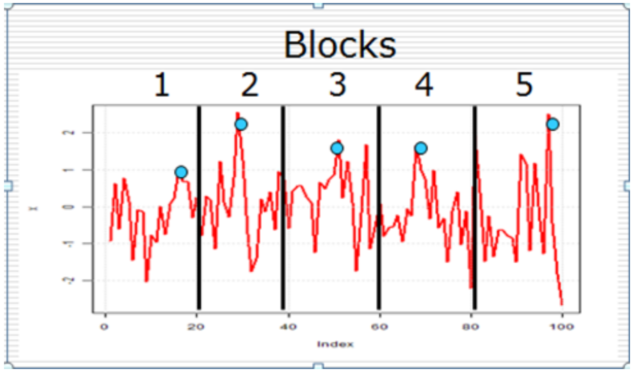


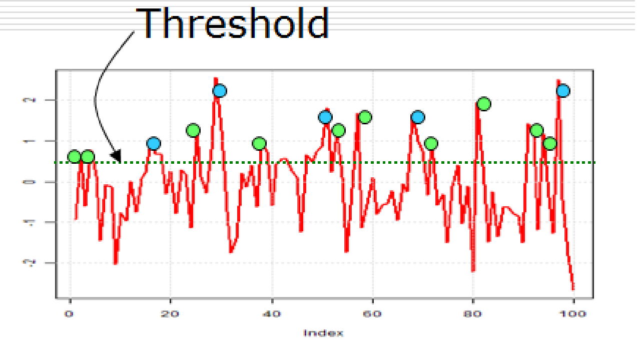
10-year event = 110.01 cm
25-year event = 133.94 cm
50-year event = 155.85 cm
100-year event = 181.69 cm
Threshold = 50.46 cm

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)

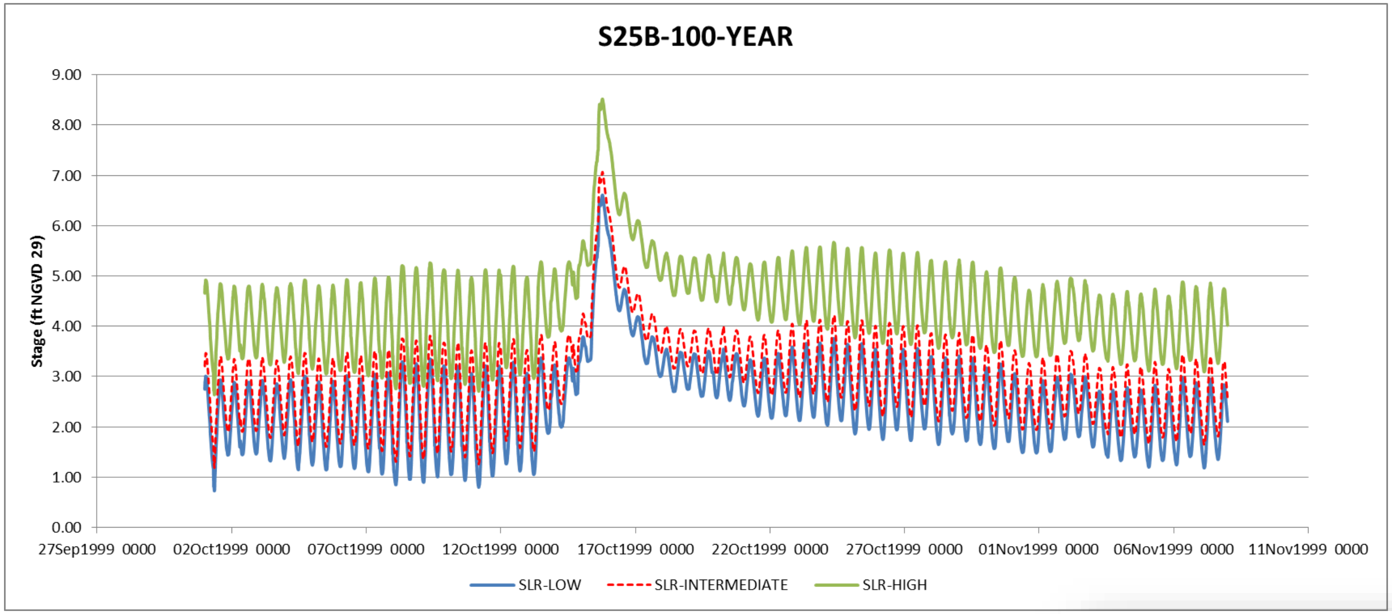
- RFA is based upon a regional homogeneity assumption.
  - ☐ Homogeneous region: group of sites whose extreme storm surge are in response to same mechanism (e.g., Nor' easter impact footprint), defined by proximity, bathymetric-topographic similarities, pattern detection techniques, etc.

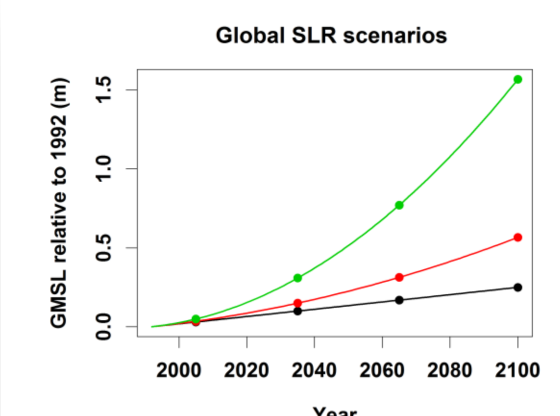
- Homogeneity is assessed with a heterogeneity measure (H):
  - ☐ L-moments (quantifies distribution shape – mean, standard deviation, skewness, kurtosis) to enable comparing the observed dispersion between sites to the expected dispersion in a homogeneous region.
  - ☐ H<1: homogeneous; 1<H<2 possibly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

Regional Frequency Analysis: Local Adjustment

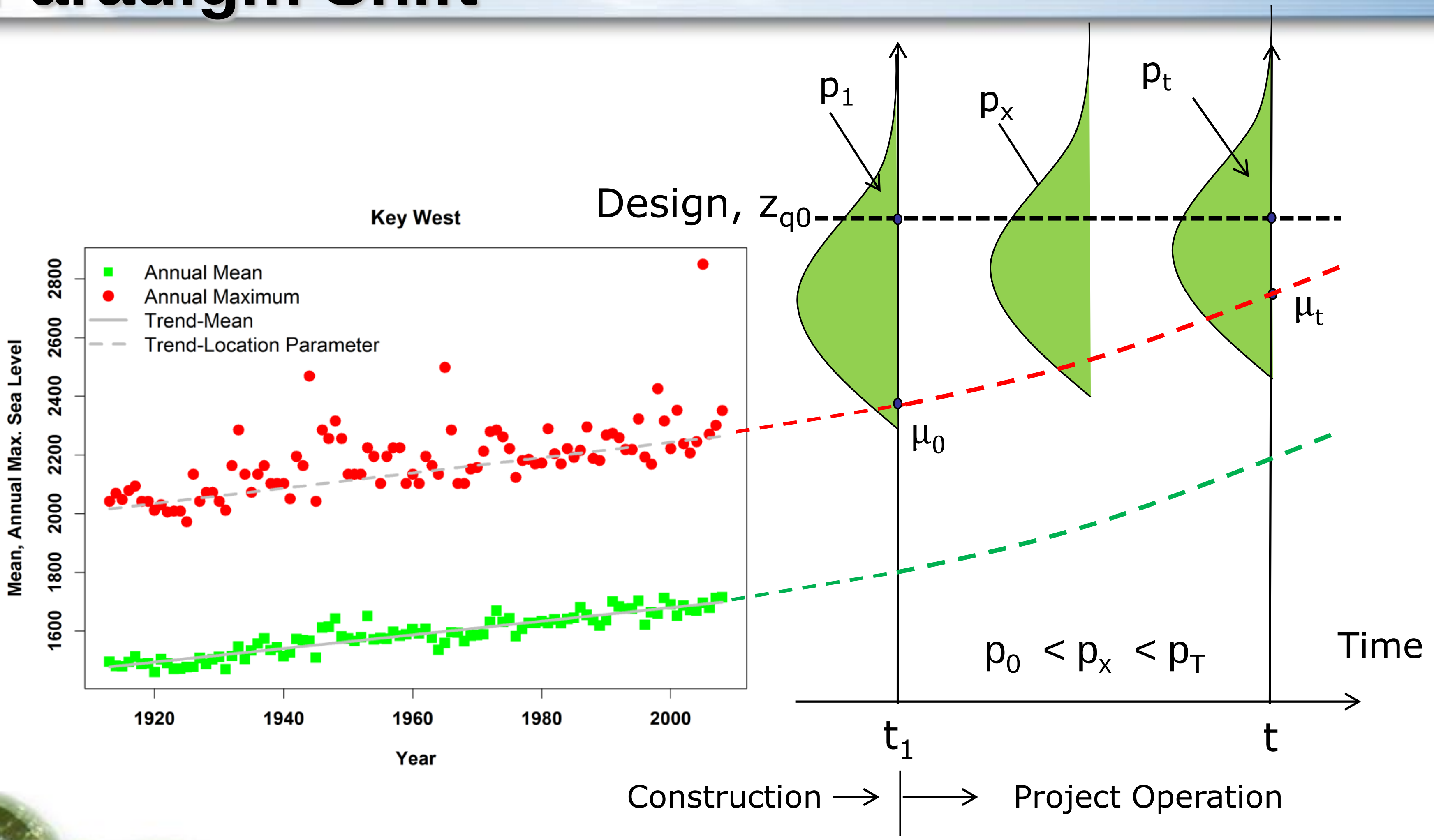
- RFA is used to compute “regional curve” using annual-maximum non-tidal residual (NTR) from 3 to 5 tide gauges < 400 km away that are then fit by the family of Generalized Extreme Value (GEV) distributions
- Each tide gauge NTR series “normalized” by the average of annual maximum NTR prior to forming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



Return Period – non-stationary case (cont.)

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

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

- 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_{q0} (initial design or p_1), this can also be used to find Z_{q0} for a given T

Non-stationary Concepts (Risk & Reliability)

- Risk

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

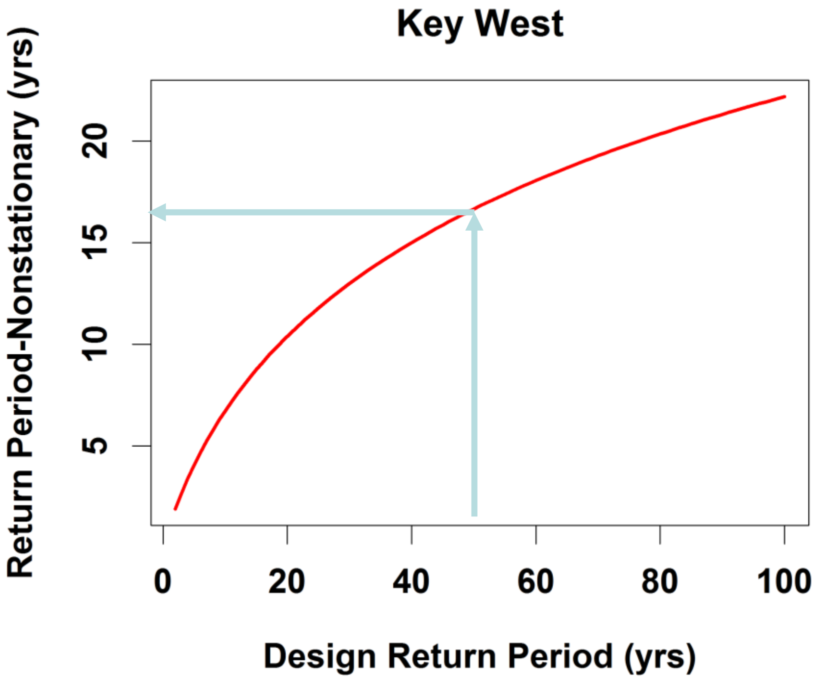
- Reliability:

$$R_\ell = \prod_{t=1}^{n} (1 - p_t)$$

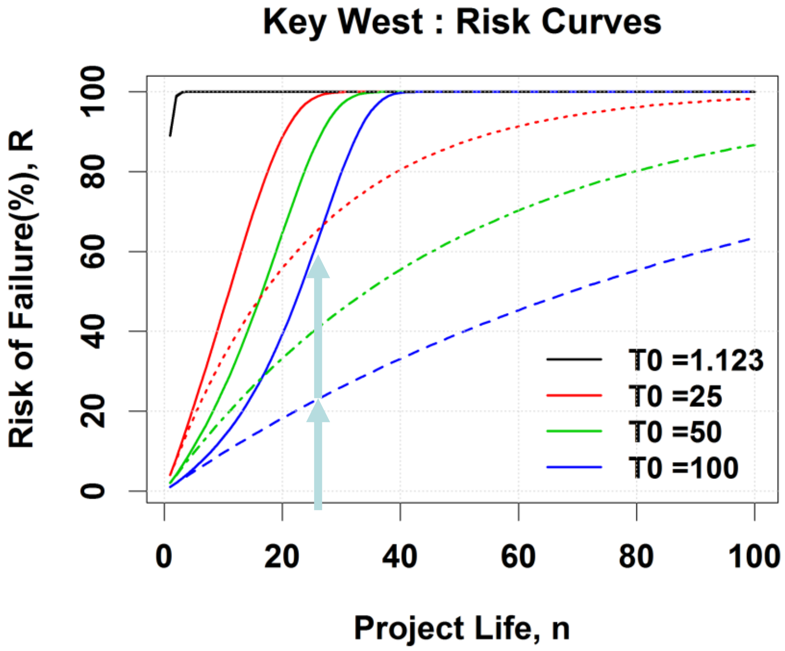
Return Period & Risk Curves

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

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



Note: 1-m scenario



---- Stationary

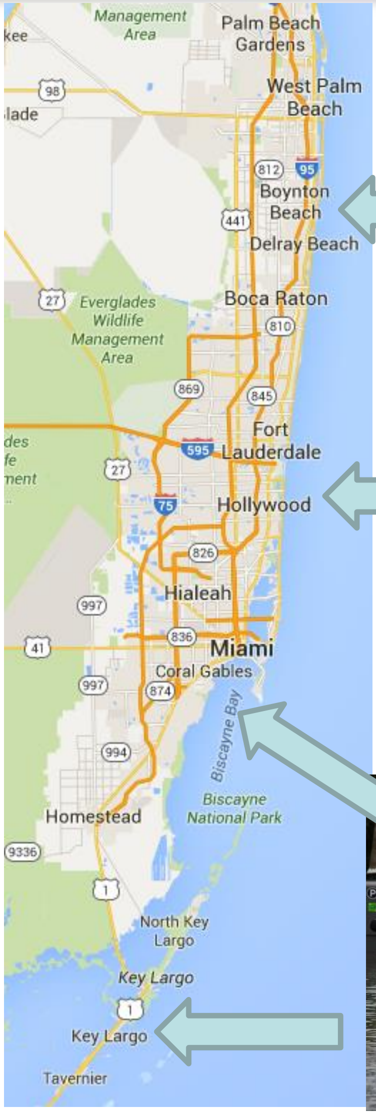
—— Non-stationary

Hurricane Sandy

REUTERS/LANDOV

"The frequency (of extreme weather situations) is way up," Andrew Cuomo, Governor of New York, 10/31/2012

King Tide Flooding in South Florida




Boca


Delray


Lantana


Hollywood


SFWMD-S13


Pompano Beach


Miami Beach

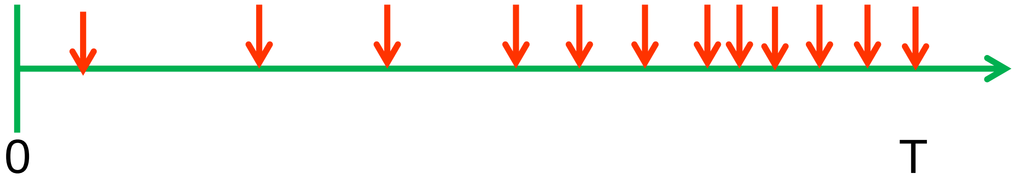

Big Pine Key


Key Largo

Credits: Rhonda Haag, Jennifer Jurado, Natalie Schneider

Frequency of Flooding under Non-Stationarity (Starting with "Nuisance Flooding")

- Frequency of flooding increases with time



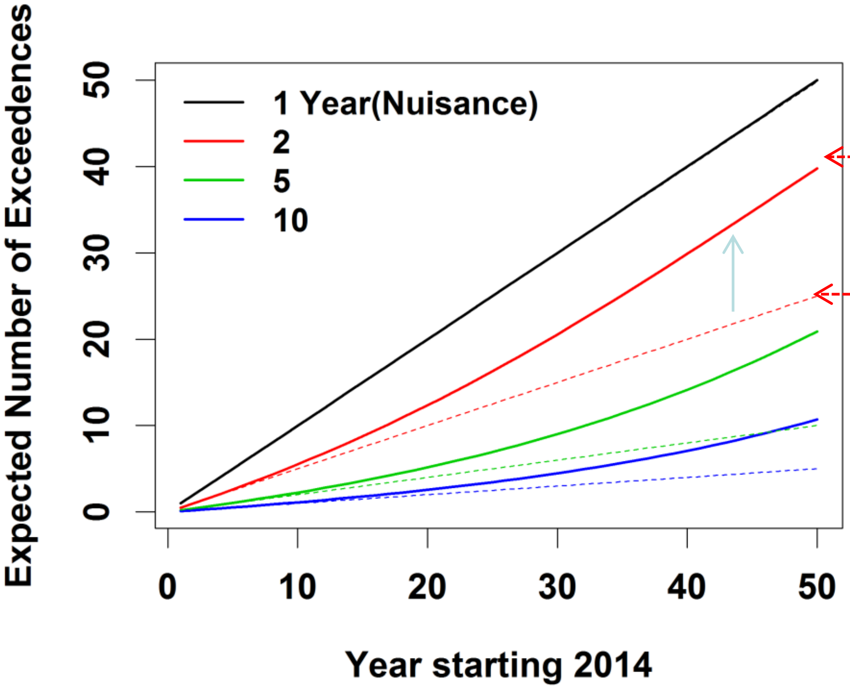
- Number of floods, N_T has Poisson-Binomial distribution (Hong 2013) :

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

F_k = subset of k integers From (1,2,..T)

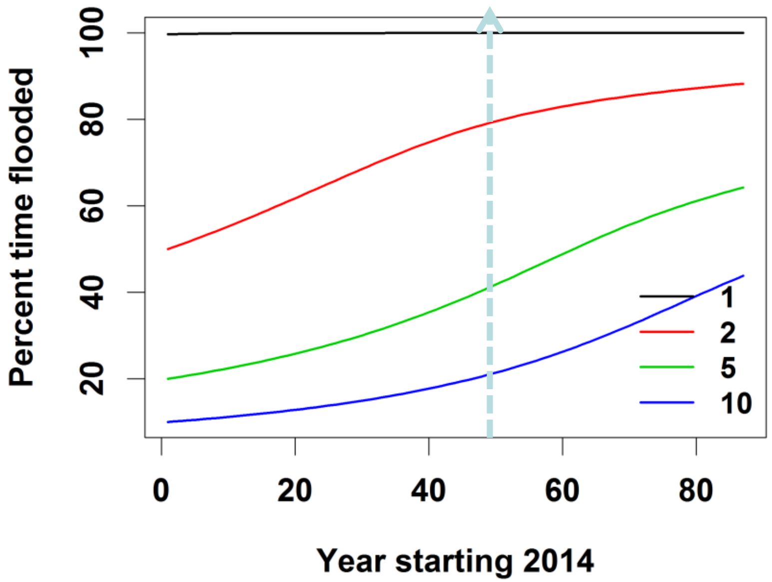
$$E[N_T] = \sum_{i=1}^{n} p_i \qquad Var(N_T) = \sum_{i=1}^{n} (1 - p_i) p_i$$

Frequency of Flooding: Sewell Point

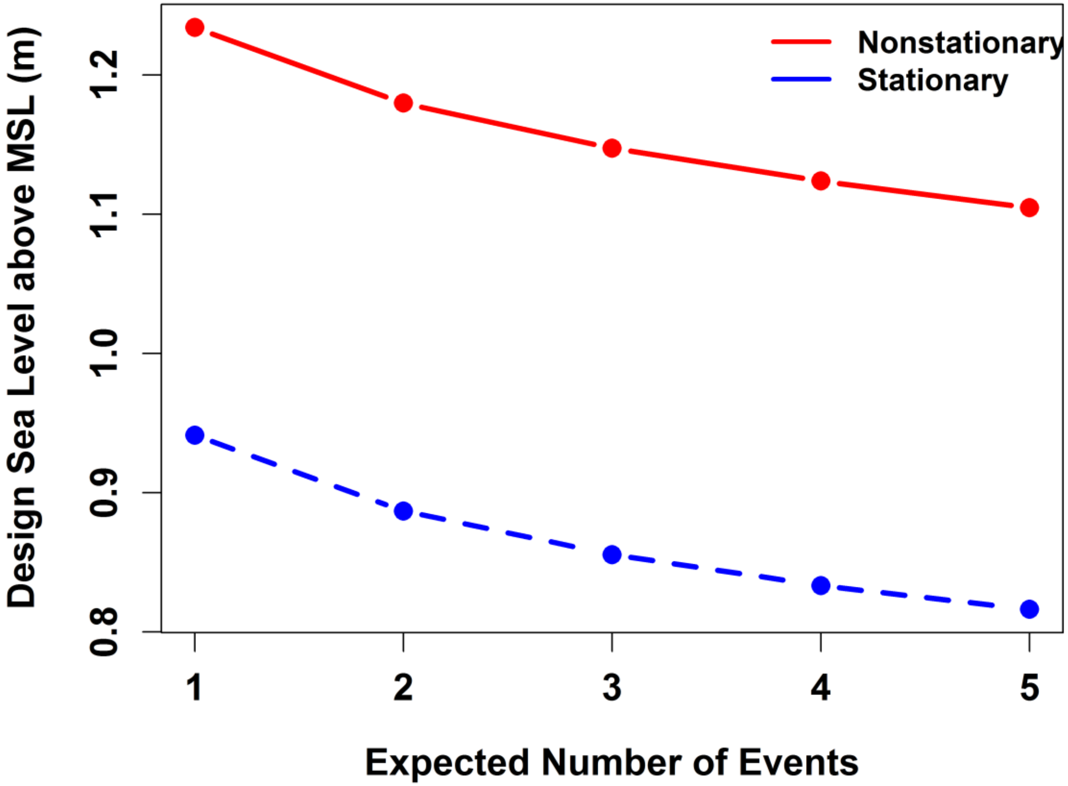


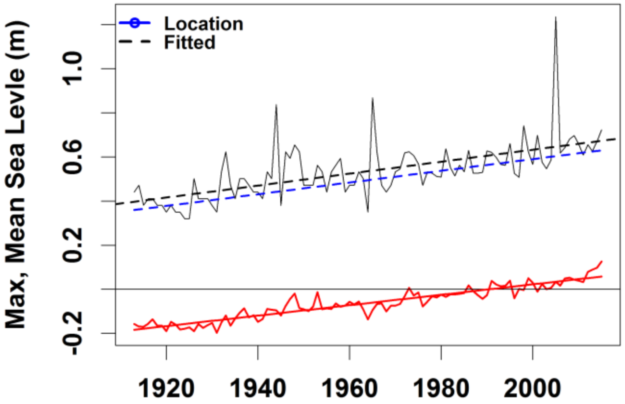
Non-Stationary

Stationary



Nuisance Flooding as a design criteria





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]

J. Hydrol. Eng. 2014.19:554-568.

Quantifying the Uncertainty of Design Floods under Nonstationary Conditions

Jayantha Obeysekera, M.ASCE[1]; and Jose D. Salas, M.ASCE[2]

J. Hydrol. Eng. 2014.19:1438-1446.

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?