Integration of Sea-Level Rise and Climate Change into Hurricane Flood Level Statistics

Galveston
Hurricane Ike

Galveston
1900 Hurricane

Jen Irish and Don Resio
November 1, 2011
3rd Coastal Hazards Symposium

Sponsored by U.S. Department of Energy
U.S. Army Corps of Engineers
and NOAA Sea Grant

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Limit to ~15 slides (20-minutes total)

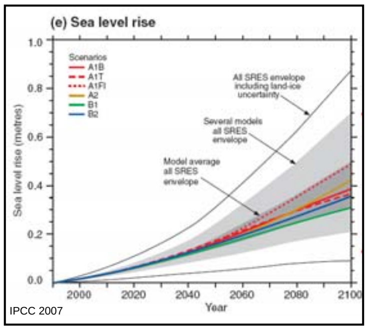
Climate, SLR, and Flood Level Statistics
Motivation

A method for determining hurricane flood level extreme-value statistics which considers long-term environmental trends:

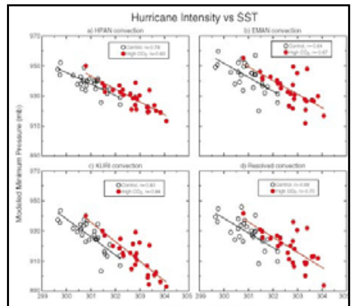
- Sea level rise
- Hurricane frequency
- Hurricane tracks
- Hurricane intensity

Type of storm	Number of observed storms (average storms per year)	Number of storms in control (average storms per year)	Ensemble warmed climate (every year; percent change)	Ensemble warmed climate* (percent change)	GFDL-CM2.1 warmed climate* (percent change)	MRI-CGCM warmed climate* (percent change)	MPI-ECHAM5 warmed climate* (percent change)	UKMO-HADCM3 warmed climate* (percent change)
Tropical storms and hurricane	9.0	10.9	−28%	−28%	−4%	−22%	−33%	−49%
Hurricane (33 m/s or above)	5.3	8.0	−32%	−33%	−7.5%	−24%	−40%	−60%
Major hurricane	2.4	2.7	−18%	−18%	40%	8%	−30%	−60%
Category 4 and 5	1.4	0.59	81%	75%	110%	110%	21%	−53%
Winds greater than 65 m/s	0.52	0.11	250%	220%	160%	180%	80%	−60%

Bender et al. 2010



IPCC 2007



Knutson & Tuleya 2004

Climate, SLR, and Flood Level Statistics
Conclusions & Methods Summary

Conclusions:

- JPM-OS viable approach for future extreme-value statistics
- Mean flood statistics not too sensitive to climate scenario selected
- Error in projected future mean climate trends leads to error in mean flood statistics
- Differences in mean flood statistics on the order of model + sampling uncertainty
- *Uncertainty significantly reduced by using adaptive management approach*

Methods summary:

- Use joint probability method with optimal sampling
- Consider an alongshore, uniform coast
- Consider three possible future climate scenarios: B1, A1B, A1FI
- Consider hurricane rate-of-occurrence and intensity, sea-level rise (SLR)

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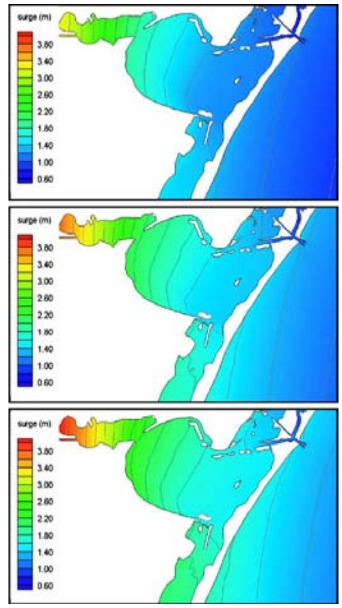
Climate, SLR, and Flood Level Statistics
Outline

- Motivation
- Conclusions & methods summary
- Statistical framework
- Climate change scenarios
    - Rate of occurrence
    - Intensity
    - Sea-level rise
- Application on an idealized coast
- Quantification of uncertainty
- Results
    - Mean flood statistics
    - Errors due to projection means
    - Adaptive management approach
- Conclusions (revisited)

c_p = 950 mb (historical)

c_p = 933 mb

c_p = 924 mb



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From Mousavi et al. 2011 Climatic Change

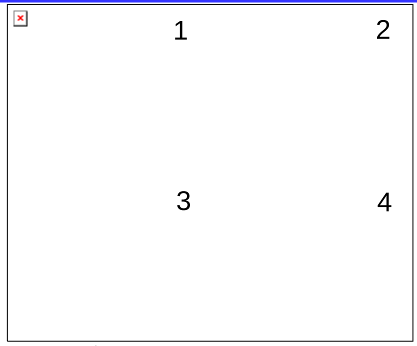
Climate, SLR, and Flood Level Statistics
Statistical Framework – JPM with Optimal Sampling (JPM-OS)

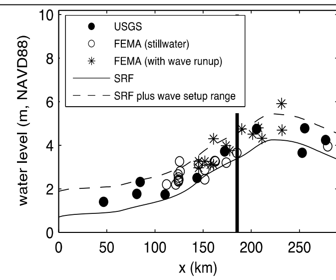
$$z_{\max}\left(x\right) = \phi(x, p_o, R_p, v_f, \theta, x_o, MSL) + \varepsilon_z$$

$$\varepsilon_z^2 = \varepsilon_{tide}^2 + \varepsilon_{surge\ simulation}^2 + \varepsilon_{waves}^2 + \varepsilon_{winds}^2 + \ldots$$

where:

- ϕ is a continuous flood response function
- x is location of interest
- x_o is landfall location
- R_p is hurricane pressure radius near landfall
- θ is hurricane track angle with respect to the shoreline
- v_f is hurricane forward speed near landfall
- MSL is mean sea level
- ε_z is uncertainty in the flood response





From Irish et al., 2009 Natural Hazards and Irish et al. 2011 GRL

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Climate, SLR, and Flood Level Statistics

Statistical Framework – JPM with Optimal Sampling (JPM-OS)

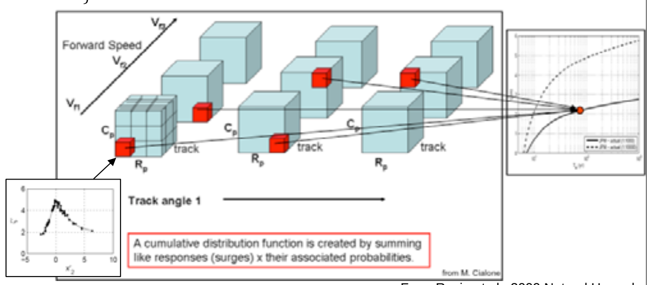
$$T_R\left(z_{\max}\right)=\left\{1-\int_{p_o}\int_{R_p}\int_{v_f}\int_{\theta}\int_{x_o} f(p_o,R_p,v_f,\theta,x_o)\left[H\left(z_{\max}-\left[\phi(x,p_o,R_p,v_f,\theta,x_o,MSL)+\varepsilon_z\right]\right)\right]dx_o\,d\theta\,dv_f\,dR_p\,dp_o\right\}^{-1}$$

$$f(p_o,R_p,v_f,\theta,x_o)=\Lambda_1\Lambda_2\Lambda_3\Lambda_4\Lambda_5$$

$$\Lambda_1=f(p_o\,|\,x_o)=\frac{1}{a_1(x_o)}\exp\left[-\frac{\Delta p-a_o(x_o)}{a_1(x_o)}\right]\exp\left\{-\exp\left[-\frac{\Delta p-a_o(x_o)}{a_1(x_o)}\right]\right\}(Gumbel\ Distribution)$$

← Extreme-value distribution

$$\Lambda_2=f(R_p\,|\,p_o)=\frac{1}{\sigma(\Delta p)\sqrt{2\pi}}\exp\left\{-\frac{\left(\overline{R_p}(\Delta p)-R_p\right)^2}{2\sigma^2(\Delta p)}\right\}(Normal\ Distribution)$$



From Resio et al., 2009 Natural Hazards

Climate, SLR, and Flood Level Statistics
Statistical Framework – JPM with Optimal Sampling (JPM-OS)

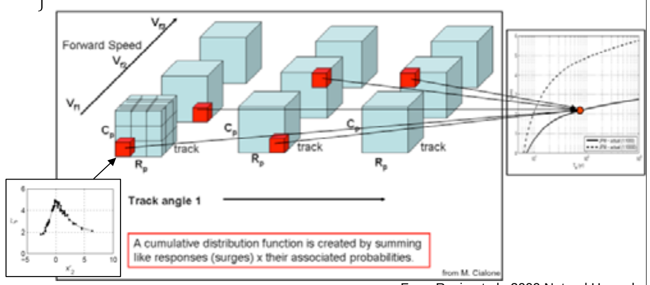
$$T_R\left(z_{\max}\right)=\left\{1-\int_{p_o}\int_{R_p}\int_{v_f}\int_{\theta}\int_{x_o} f(p_o,R_p,v_f,\theta,x_o)\left[H\left(z_{\max}-\left[\phi(x,p_o,R_p,v_f,\theta,x_o,MSL)+\varepsilon_z\right]\right)\right]dx_o\,d\theta\,dv_f\,dR_p\,dp_o\right\}^{-1}$$

$$f(p_o,R_p,v_f,\theta,x_o)=\Lambda_1\Lambda_2\Lambda_3\Lambda_4\Lambda_5$$

$$\Lambda_3=f(v_f\,|\,\theta)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left\{-\frac{\left(\overline{v_f}(\theta)-v_f\right)^2}{2\sigma^2}\right\}(Normal\ Distribution)$$

$$\Lambda_4=f(\theta\,|\,x_o)=\frac{1}{\sigma(x_o)\sqrt{2\pi}}\exp\left\{-\frac{\left(\overline{\theta}(x_o)-\theta\right)^2}{2\sigma^2(x_o)}\right\}(Normal\ Distribution)$$

$$\Lambda_5=g\left(\lambda,x_o\right)$$



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From Resio et al., 2009 Natural Hazards

Climate, SLR, and Flood Level Statistics

Statistical Framework – JPM with Optimal Sampling (JPM-OS)

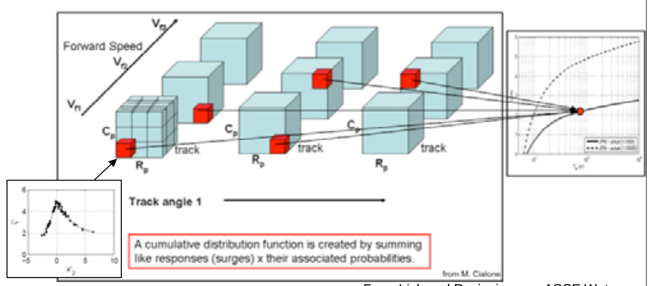
$$T_R\left(z_{\max}\right)=\left\{1-\int_{SST}\int_{p_o}\int_{R_p}\int_{v_f}\int_{\theta}\int_{x_o} f(p_o,R_p,v_f,\theta,x_o)\left[H\left(z_{\max}-\left[\phi(x,p_o,R_p,v_f,\theta,x_o,MSL)+\varepsilon_z\right]\right)\right]dx_o\,d\theta\,dv_f\,dR_p\,dp_o\,dSST\right\}^{-1}$$

$$f(SST,p_o,R_p,v_f,\theta,x_o)=\Lambda_{SST}\Lambda_1\Lambda_2\Lambda_3\Lambda_4\Lambda_5$$

$$\Lambda_1=f(p_o\,|\,x_o)=\frac{1}{a_1(x_o,t)}\exp\left[-\frac{\Delta p-a_o(x_o,t)}{a_1(x_o,t)}\right]\exp\left\{-\exp\left[-\frac{\Delta p-a_o(x_o,t)}{a_1(x_o,t)}\right]\right\}\ (Gumbel\ Distribution)$$

$$\Lambda_5=g\left(\lambda(t),x_o\right)$$

$\Lambda_{SST}=$?



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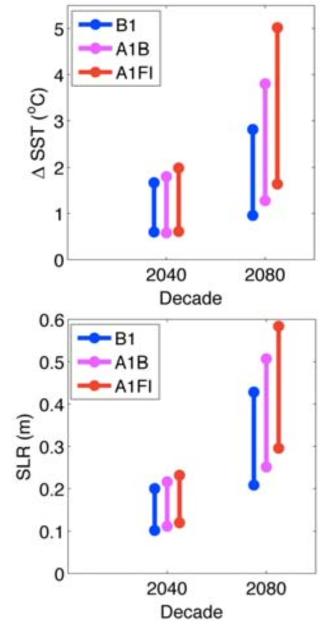
From Irish and Resio, in prep. ASCE Waterw.

Climate, SLR, and Flood Level Statistics
Climate Scenarios – SST and SLR

- IPCC 2007 climate projection scenarios:
  - B1 – global carbon emissions minimized
  - A1B – global carbon emissions moderated
  - A1FI – global carbon emissions are high
- MAGICC/SCENGEN (Wigley 2004):
  - Sea-surface temperature (SST):
  - Sea-level rise (SLR, eustatic only)
- Two time periods: 2040s and 2080s



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B1: This scenario assumes future use of clean-energy and energy-efficient technologies such that future global carbon emissions are minimized.

A1B: This scenario assumes a future balanced portfolio of energy sources such that future global carbon emissions are moderated.

A1FI: This scenario assumes continued dominance of fossil energy sources such that future global carbon emissions are high.

Climate, SLR, and Flood Level Statistics
Climate Scenarios – Hurricane Rate of Occurrence

Type of storm	Number of observed storms (average storms per year)	Number of storms in control (average storms per year)	Ensemble warmed climate (every year; percent change)	Ensemble warmed climate* (percent change)	GFDL-CM2.1 warmed climate* (percent change)	MRI-CGCM warmed climate* (percent change)	MPI-ECHAM5 warmed climate* (percent change)	UKMO-HADCM3 warmed climate* (percent change)
Tropical storms and hurricane	9.0	10.9	−28%	−28%	−4%	−22%	−33%	−49%
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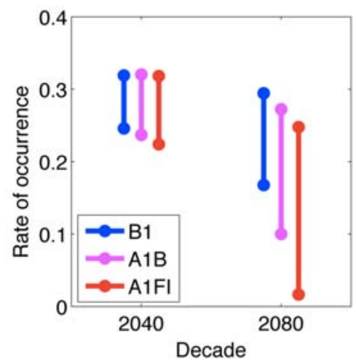
Winds greater than 65 m/s	0.52	0.11	250%	220%	160%	180%	80%	−60%

Bender et al. 2010

$$\lambda_{\Delta SST} = \lambda_o\left[1-\left(0.19+\varepsilon_\lambda\right)\left(\Delta SST+\varepsilon_{\Delta SST}\right)\right]$$



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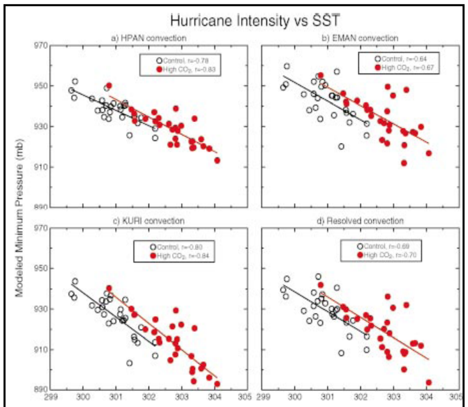
33%/1.72oC = 19%/1oC

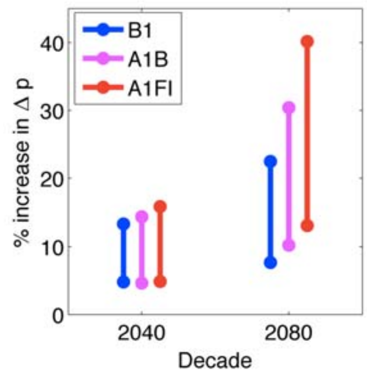
Climate, SLR, and Flood Level Statistics

Climate Scenarios – Hurricane Intensity

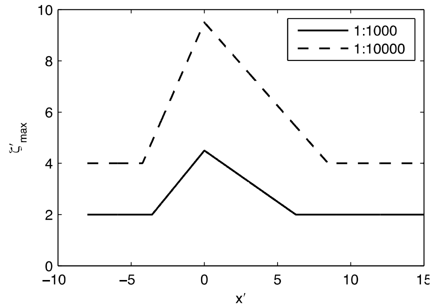


Knutson & Tuleya 2004

$$p_{\Delta SST} = p_o - \left\lfloor \left(0.08 + \varepsilon_p\right)\left(\Delta SST + \varepsilon_{\Delta SST}\right) \right\rfloor \Delta p$$



Climate, SLR, and Flood Level Statistics
Application – Idealized Coast



- Alongshore-uniform:
  - Slope = 1:1000 & 1:10000
  - 2000 km (~ US GOM length)
- Surge response functions from idealized ADCIRC simulations
- Assume $\phi = \zeta_{\max} + \Delta MSL$

$$\zeta'_{\max}(x) = \frac{\gamma \zeta_{\max}(x)}{\Delta p} + m(x)\Delta p$$

$$x' = \frac{(x - x_o)}{R_p} - \delta$$

$\zeta'_{\max}(x)$ is dimensionless surge,

x' is dimensionless alongshore distance from location of interest to peak surge,

γ is specific weight of water,

$m(x)$ is a location-dependent constant, and

δ is the average distance between landfall location (x_o) and peak alongshore surge normalized by R_p.

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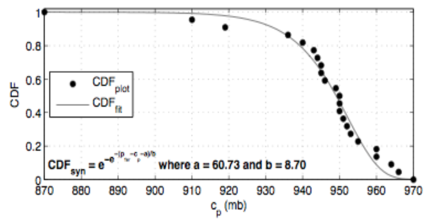
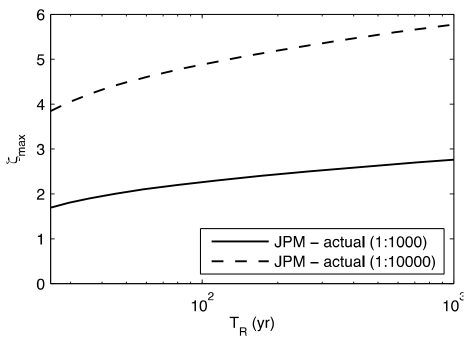
From Irish et al. 2011 JGR

Climate, SLR, and Flood Level Statistics
Application – Idealized Coast





- Simplified JPM:

  $f(SST, p_o, R_p, x_o) = \Lambda_{SST}\Lambda_1\Lambda_2\Lambda_5$

- Historical GOM meteorology:

  $\lambda_o = 0.36$

- Assume uniformly distributed:

  $\Lambda_5 = \frac{\lambda(t)}{N_x}$

- Assume uniformly weighted:

  $\Lambda_{SST} = \text{constant}$

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From Irish et al. 2011 JGR

Climate, SLR, and Flood Level Statistics
Quantification of Uncertainty

$$\varepsilon^2 = \varepsilon^2_{Sampling} + \varepsilon^2_{\text{Bootstrapping}} + \varepsilon^2_z + \varepsilon^2_{\text{Climate}}$$

Aleatory = 0.23 m, T_R = 50 yr
0.55 m, T_R = 500 yr

$$\varepsilon^2_{\Delta SST} + \varepsilon^2_{SLR} + \varepsilon^2_p + \varepsilon^2_\lambda + \ldots$$

Epistemic = 0.70 m

$$\varepsilon^2_{tide} + \varepsilon^2_{surge\ simulation} + \varepsilon^2_{waves} + \varepsilon^2_{winds} + \ldots$$

Aleatory + **Epistemic** = 0.74 m, T_R = 50 yr
0.89 m, T_R = 500 yr

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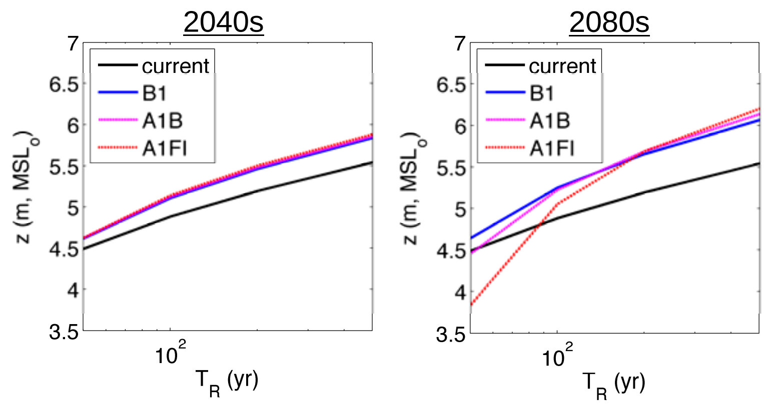
From Irish and Resio, in prep. ASCE Waterw.

Resampling - accounts for not knowing population exactly

Bootstrap – if population known exactly

Climate, SLR, and Flood Level Statistics

Results – Mean Statistics and *Uncertainty*



Parameter	Mean 2040 / 2080	Standard Deviation 2040 / 2080
Rate of occurrence:	0.28 to 0.29 / 0.14 to 0.24	0.02 to 0.03 / 0.04 to 0.07
Intensity (% change in deficit):	8.7 to 9.9 / 14.3 to 25.3	2.7 to 3.5 / 4.7 to 8.6
SLR (m):	0.15 to 0.17 / 0.31 to 0.43	0.03 to 0.04 / 0.07 to 0.09

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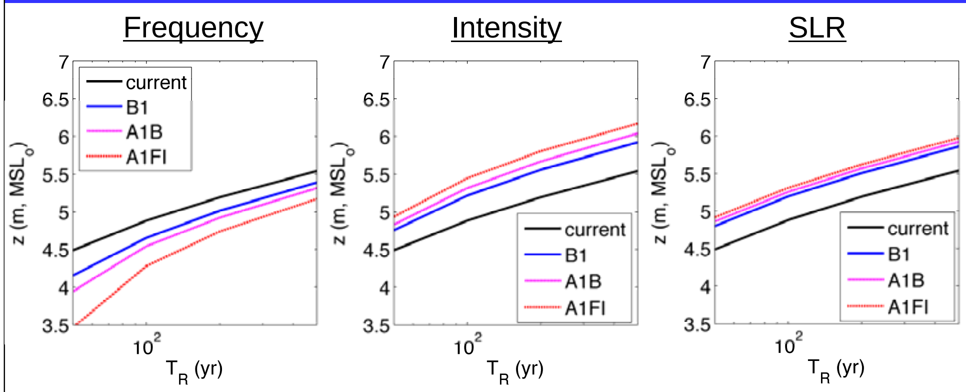
Max delta =0.80 m for 2080s B1 vs A1FI at Tr=50 yrs

Climate, SLR, and Flood Level Statistics

Results – Mean Statistics and *Uncertainty*



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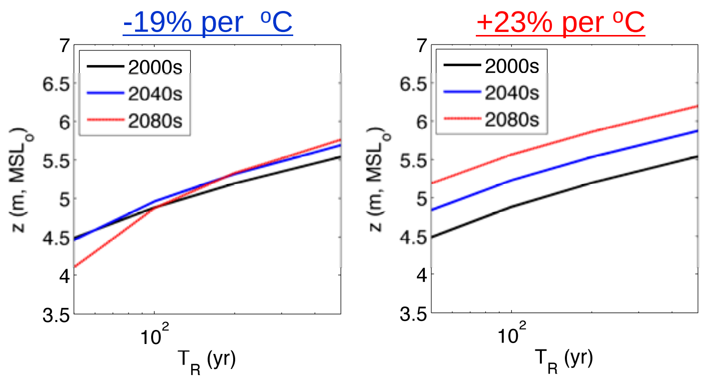
2080s results in plots, only

Climate, SLR, and Flood Level Statistics

Results – Sensitivity to Error in Mean Climate Projections



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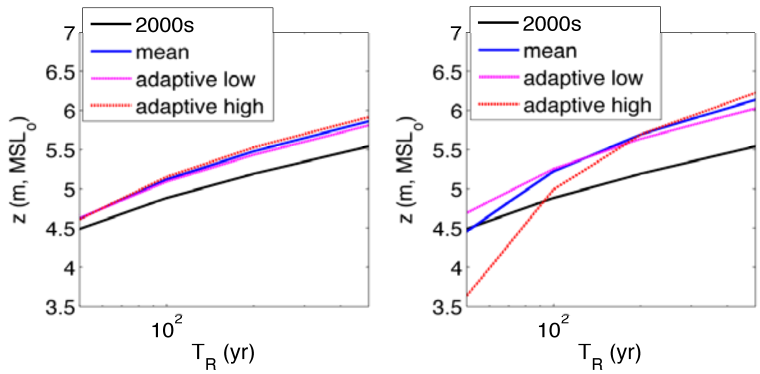
10000 only

Climate, SLR, and Flood Level Statistics
Results – Adaptive Management

2040s 2080s



Parameter	**Standard Deviation** 2040 / 2080	**St. Dev. with Adaption** 2040 / 2080
Rate of occurrence:	0.02 to 0.03 / 0.04 to 0.07	0.01 to 0.02 / 0.01 to 0.02
Intensity (% change in deficit):	2.7 to 3.5 / 4.7 to 8.6	1.2 to 2.0 / 1.0 to 2.5
SLR (m):	0.03 to 0.04 / 0.07 to 0.09	0.02 / 0.02 to 0.03

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From Irish and Resio, in prep. ASCE Waterw.

St dev ranges for all three scenarios

Climate, SLR, and Flood Level Statistics
Conclusions & Future Work

Conclusions:

- JPM-OS viable approach for future extreme-value statistics
- Mean flood statistics not too sensitive to climate scenario selected
- Error in projected future mean climate trends leads to error in mean flood statistics
- Differences in mean flood statistics on the order of model + sampling uncertainty
- *Uncertainty significantly reduced by using adaptive management approach*

Future work:

- Quantify climate uncertainty
- What about barrier islands, wetlands, human adaptation…?

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Questions?

www.coastal.cee.vt.edu