Storm surge reanalysis of Hurricane Idalia using a spatial Bayesian model

NH21D-06 - Late-Breaking Contributions for the Maui and Canadian Wildfires and 2023 Cyclone Activity I

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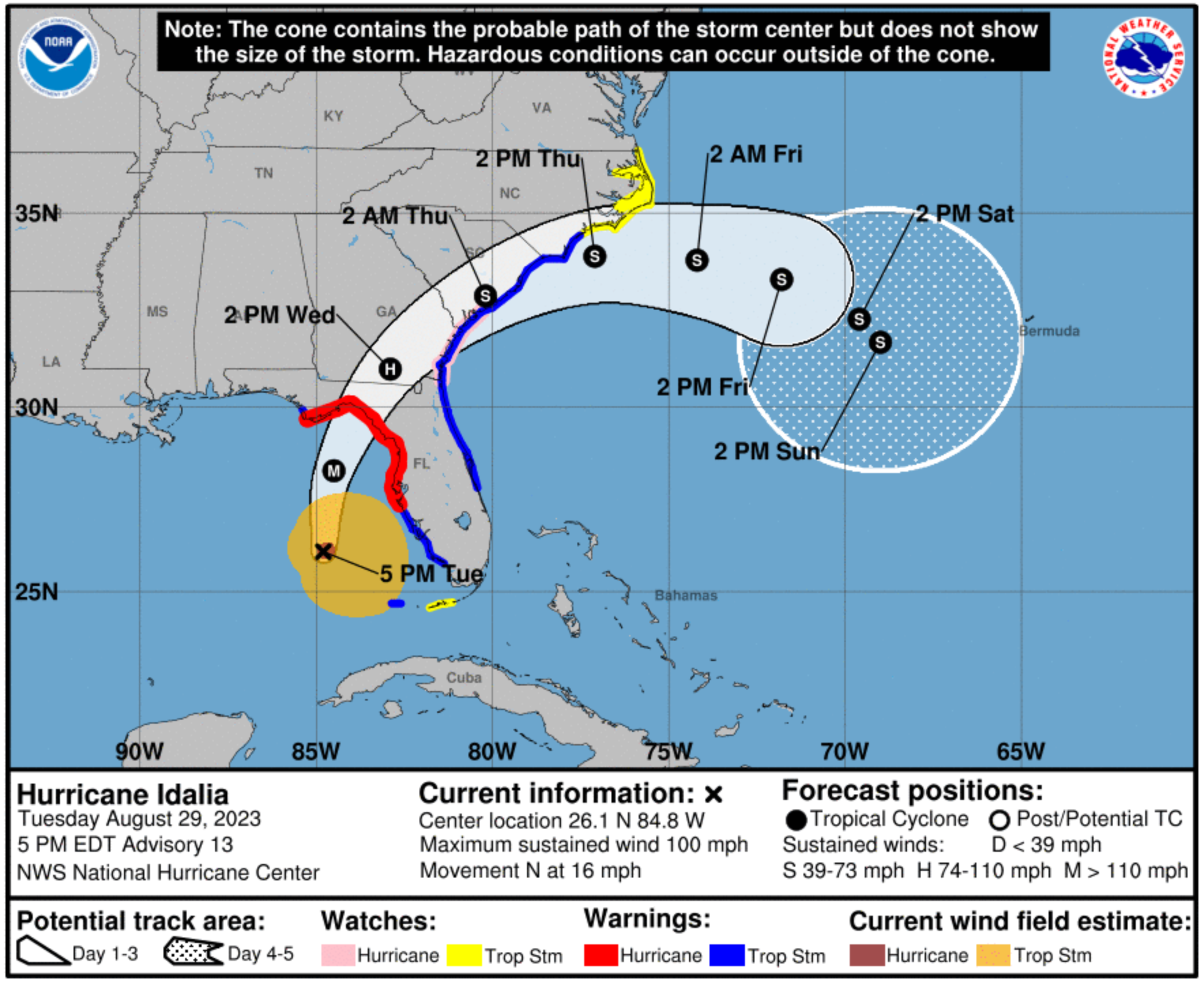
National Oceanography Centre

Hurricane Idalia: at a glance…



- Made Landfall as a Category 3 Hurricane
  - Strongest in Big Bend region since 1896
- Reports of peak storm tide (surge + tide) reached 7 to 12 feet above ground level

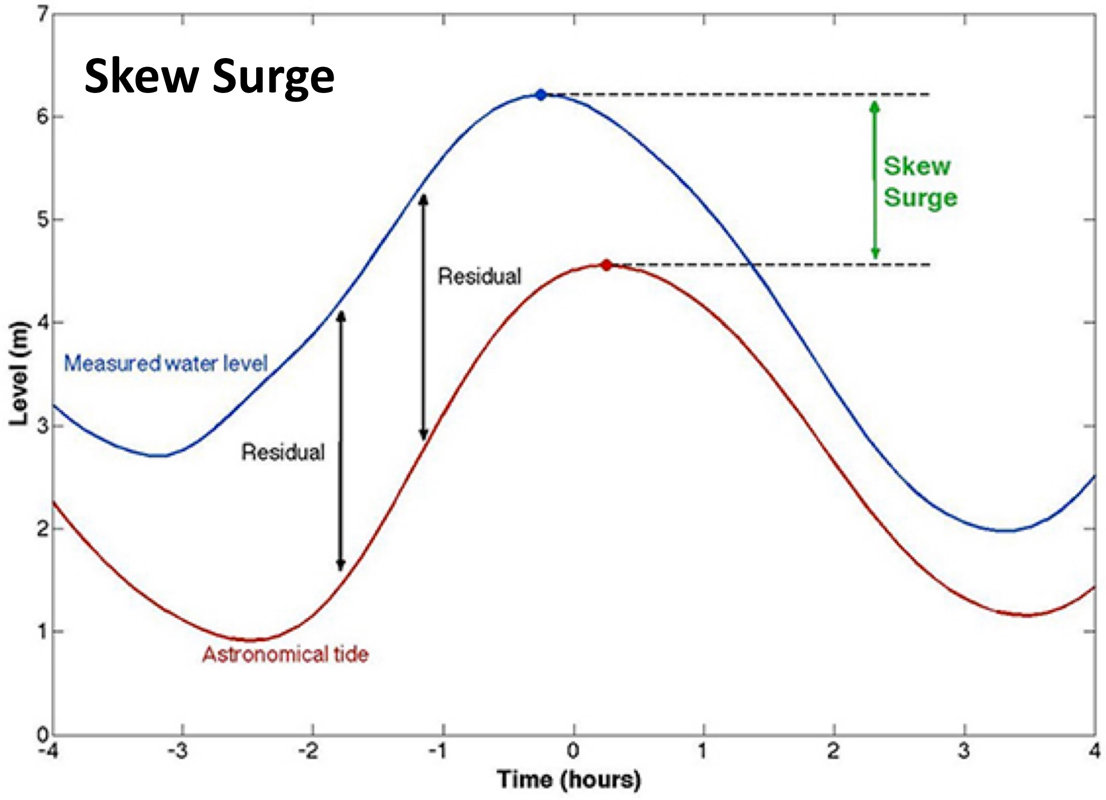
Source: "Hurricane Idalia Strikes the Florida Big Bend August 30, 2023", National Weather Service

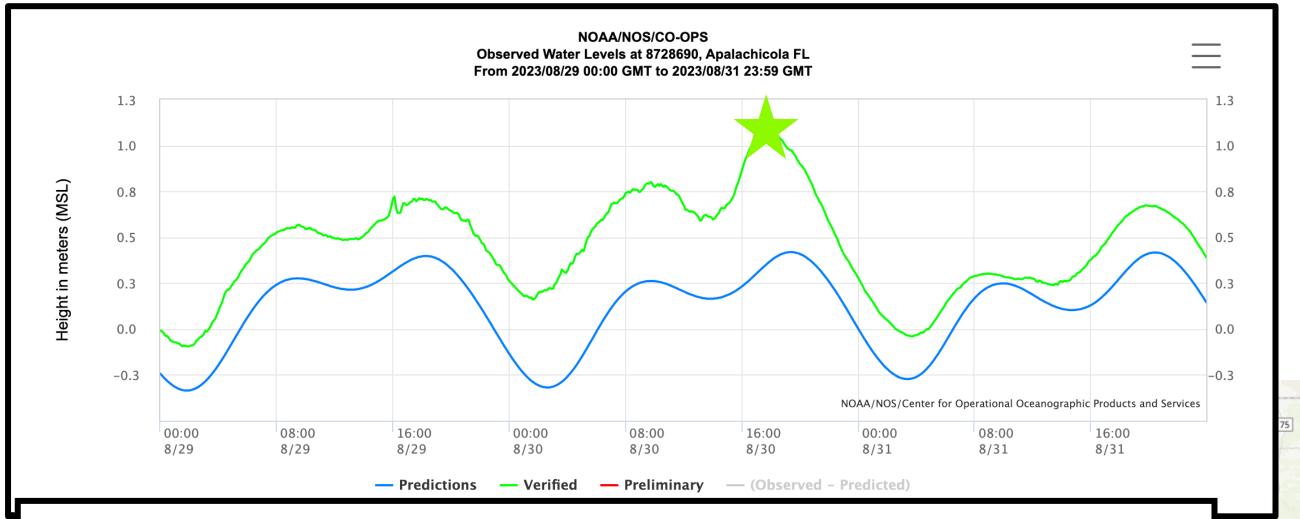
Hurricane Idalia's storm surge in historical context

Hurricane Idalia storm surge amounts rivaled those from the 1993 "Storm of the Century"

	Date	Skew Surge	Storm Name
1	**8/30/2023**	**1.96 m (6.4 ft)**	**Hurricane Idalia**
2	3/13/1993	1.88 m (6.2 ft)	"Storm of the Century"
3	9/2/2016	1.51 m (5.0 ft)	Hurricane Hermine
4	6/9/1966	1.42 m (4.7 ft)	Hurricane Alma
5	8/31/1985	1.37 m (4.5 ft)	Hurricane Elena

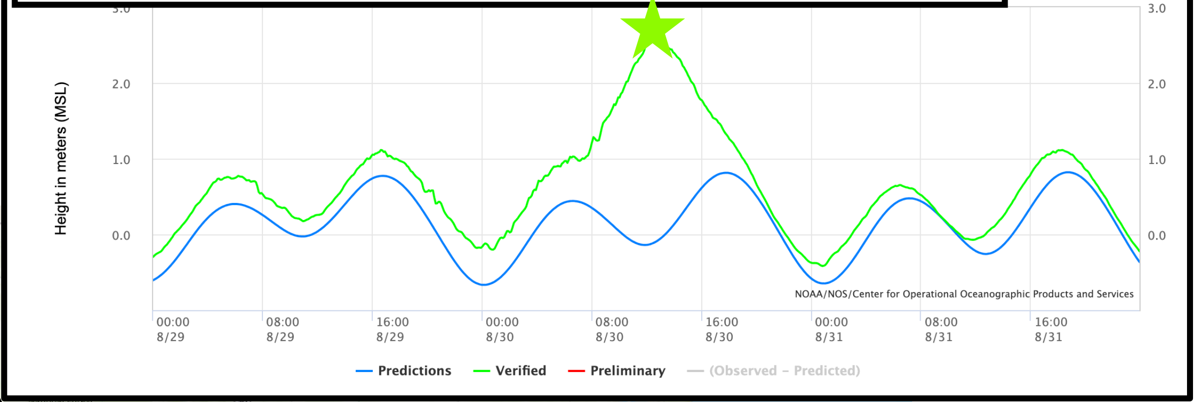
Cedar Key Tide Gauge (1950 to present); NOAA Tides and Currents

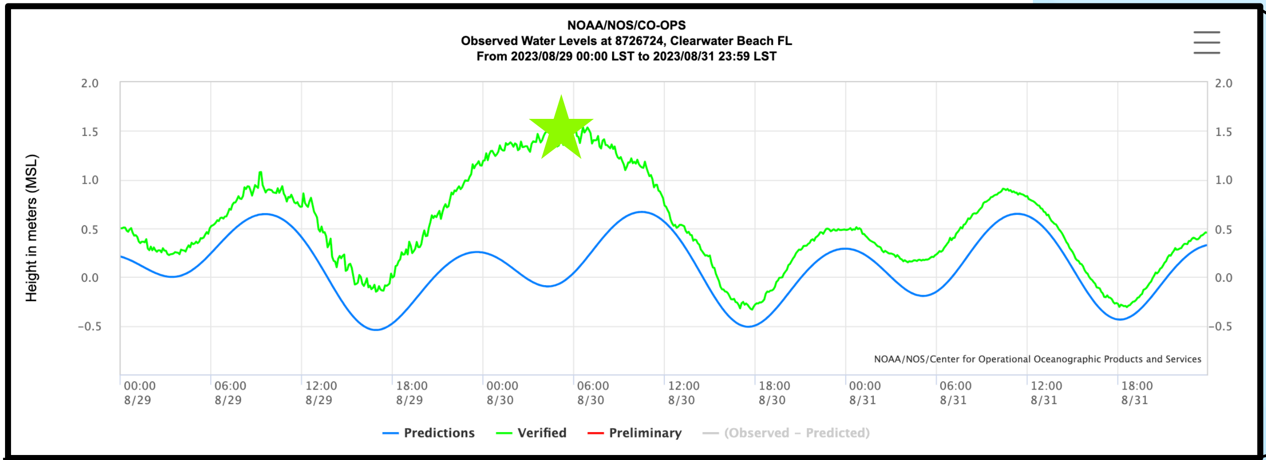




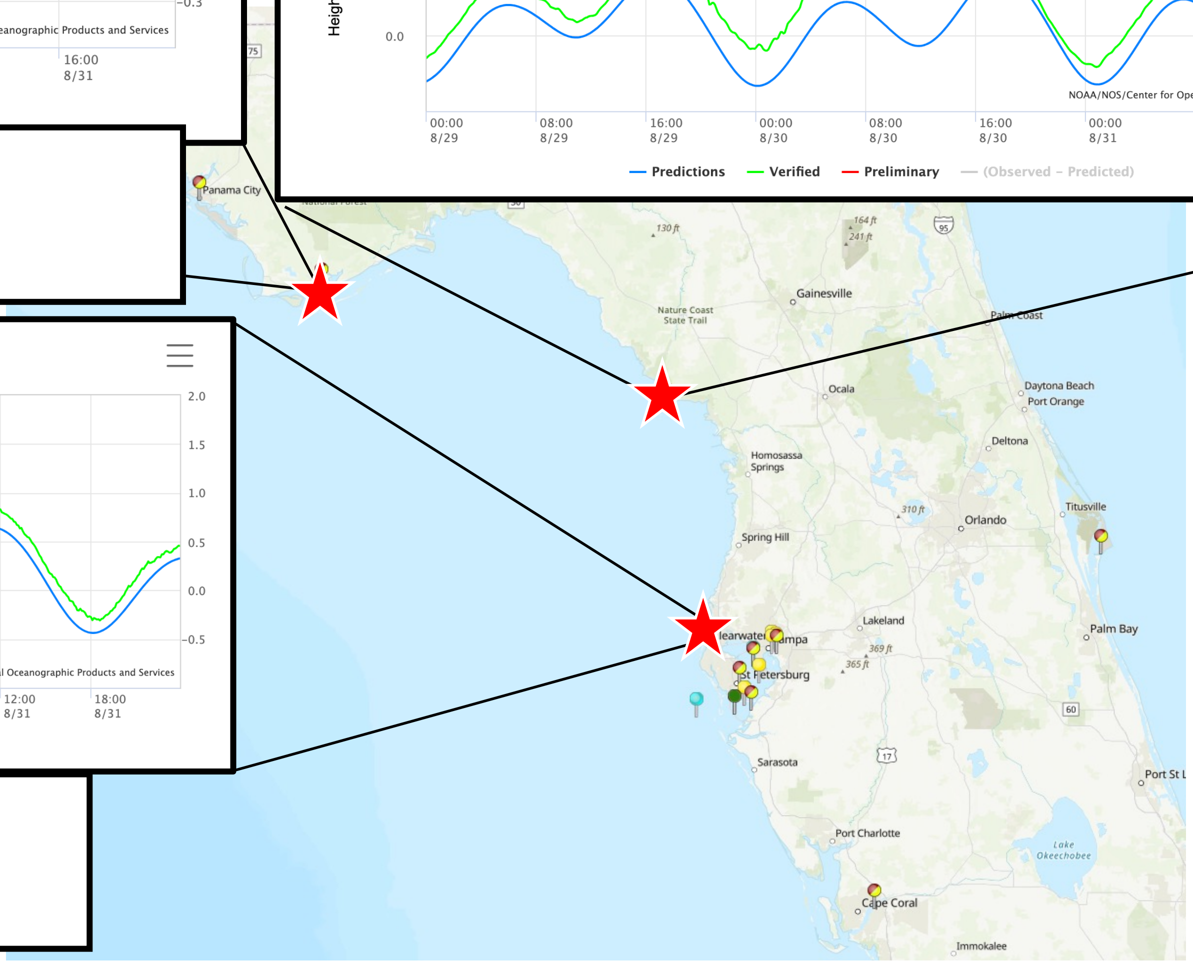
Apalachicola Tide Gauge
Peak Storm Tide: 1.08 m (3.5 ft) above Mean Sea Level
Skew Surge: 0.5 m (1.6 ft)

Cedar Key Tide Gauge
Peak Storm Tide: 2.63 m (8.6 ft) above Mean Sea Level
Skew Surge: 1.96 m (6.4 ft)





Clearwater Beach Tide Gauge
Peak Storm Tide: 1.56 m (5.1 ft) above Mean Sea Level
Skew Surge: 1.0 m (3.3 ft)



Limited observations… Peak storm surge levels not completely sampled in landfalling area

Presentation Overview

Ringling bridge in Sarasota, FL (Thomas Bender)

- Explain Bayesian Hierarchical Models (BHMs)
- Application of a BHM to estimate Hurricane Idalia’s peak surge
- Storm surge probabilities for Florida
  - How frequent was Idalia, from a storm surge perspective?

BHMs make fully probabilistic inferences from data to predict unobserved quantities

Data Model (A | B, C)

- What is observed
- Conditional on latent processes (level below)

Process Model (B | C)

- Conditional on unknown parameters (level below)
- Describe the underlying processes of interest (latent/hidden)

Parameter Model (C)

- User-defined priors
- BHM solves for the posterior distributions of parameters

(Cressie and Wilke, 2015)

Bayes' Rule allows for inferring posterior parameters of the data and processes…

P(processes, parameters | data) ∝ P(data | processes, parameters) * P(processes | parameters) * P(parameters)

↑ Posterior — ↑ Data model — ↑ Process model — ↑ Parameter model

Our BHM for storm surge estimates has been featured recently in…

PNAS

RESEARCH ARTICLE | EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

Probabilistic reanalysis of storm surge extremes in Europe

Francisco M. Calafat and Marta Marcos Authors Info & Affiliations

Edited by Anny Cazenave, Centre National d'Etudes Spatiales, Toulouse, France, and approved December 9, 2019 (received for review July 29, 2019)

January 13, 2020 | 117 (4) 1877-1883 | https://doi.org/10.1073/pnas.1913049117

nature

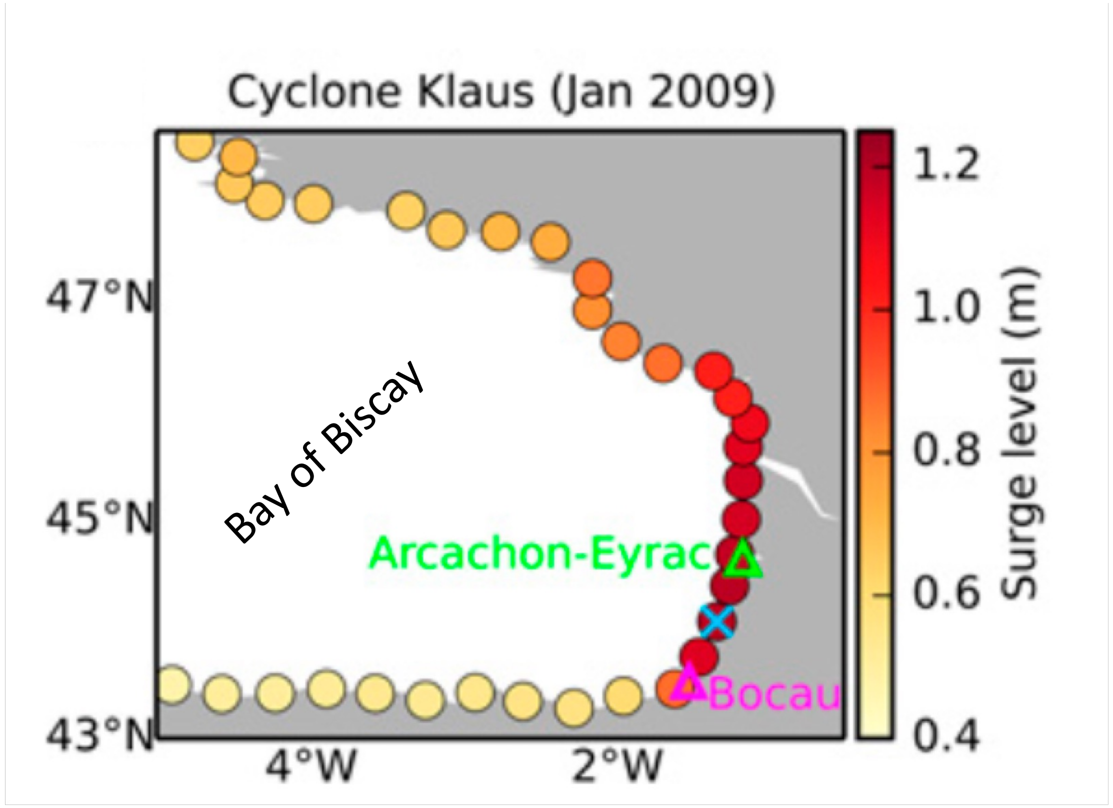
Article | Published: 30 March 2022

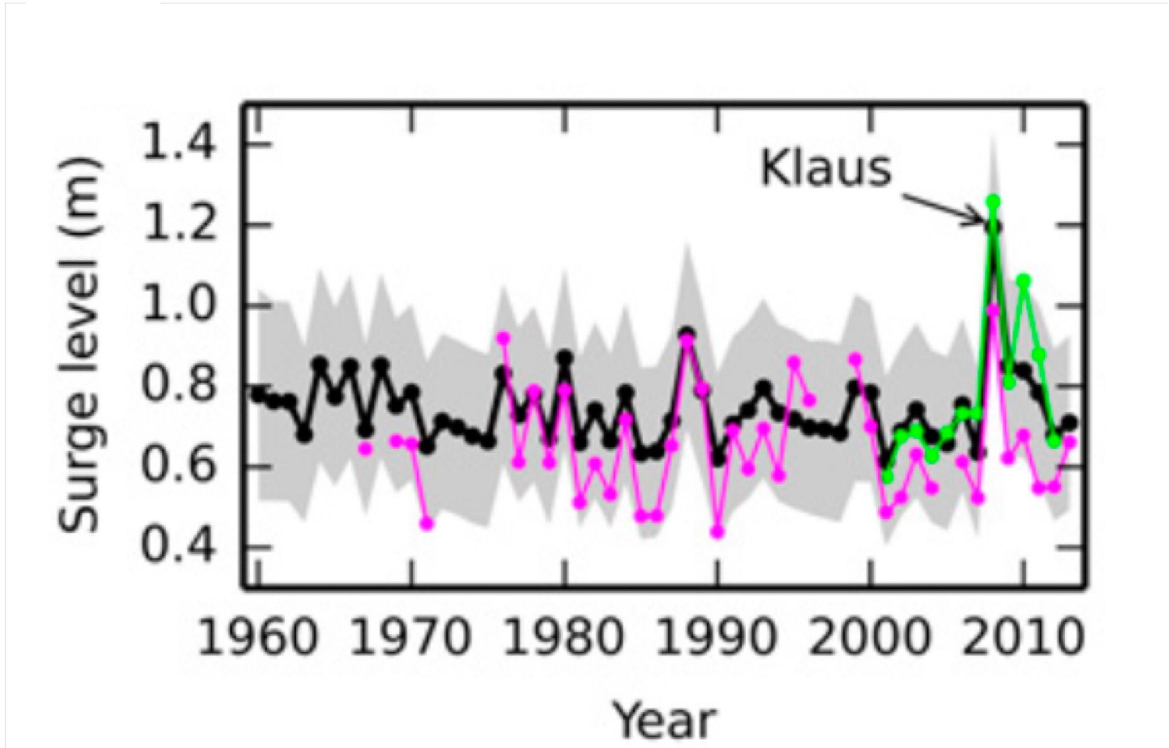
Trends in Europe storm surge extremes match the rate of sea-level rise

Francisco M. Calafat, Thomas Wahl, Michael Getachew Tadesse & Sarah N. Sparrow

Nature **603**, 841–845 (2022) | Cite this article

A BHM can estimate peak surges at ungauged locations





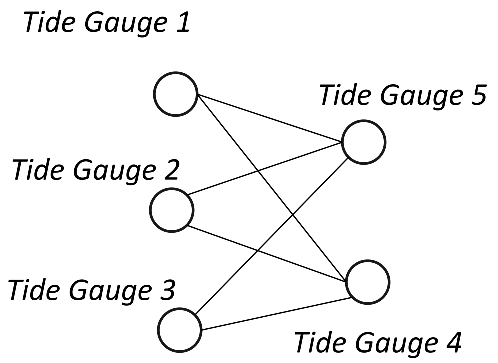
Calafat and Marcos (2019), PNAS

BHM setup for inferring unobserved peak surge values

Data Model (What is observed)
- Annual maximum skew surge values at tide gauges
- Continental shelf width covariates

Spatial Process Model (Describes the underlying spatiotemporal processes)
- *Residual dependence of annual maxima*
  - Modeled with random effects at spatial "knots"
- *Climatological dependence*
  - Model Generalized Extreme Value (GEV) parameters with Gaussian processes
    - Describe the frequency of extreme skew surges

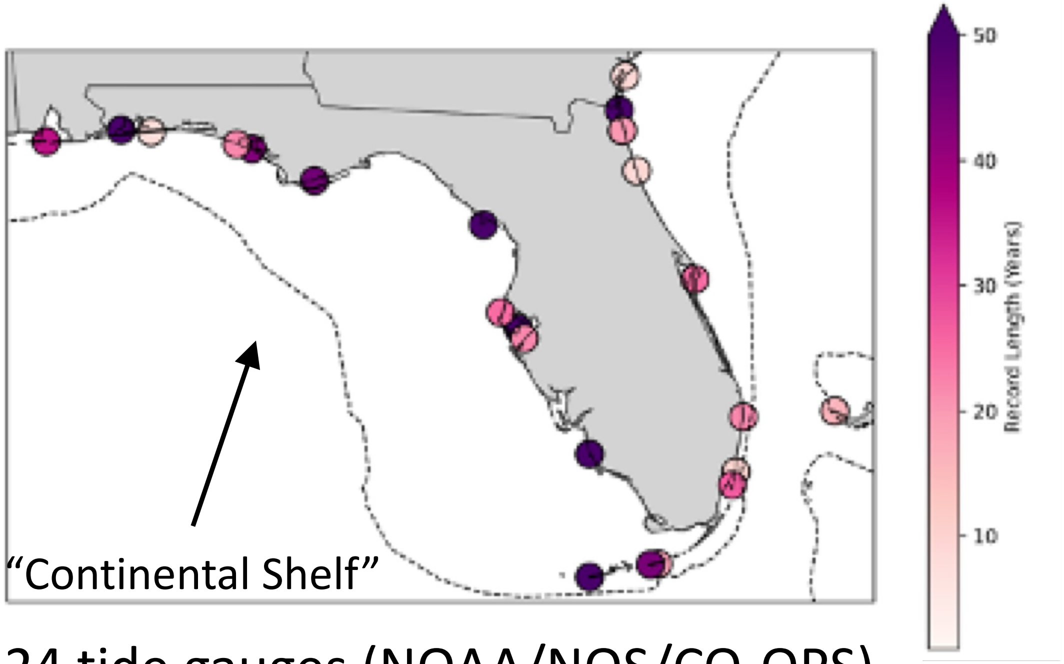
Parameter Model (User-defined priors)
- All parameters prescribed either an informative of non-informative prior



Hierarchical framework enables sharing of information across tide gauges

Model has been thoroughly tested: e.g., Calafat and Marcos (2019), Calafat et al. (2022), Morim et al., (in prep.)

BHM input data



24 tide gauges (NOAA/NOS/CO-OPS)

Width of “continental shelf” used as model covariate

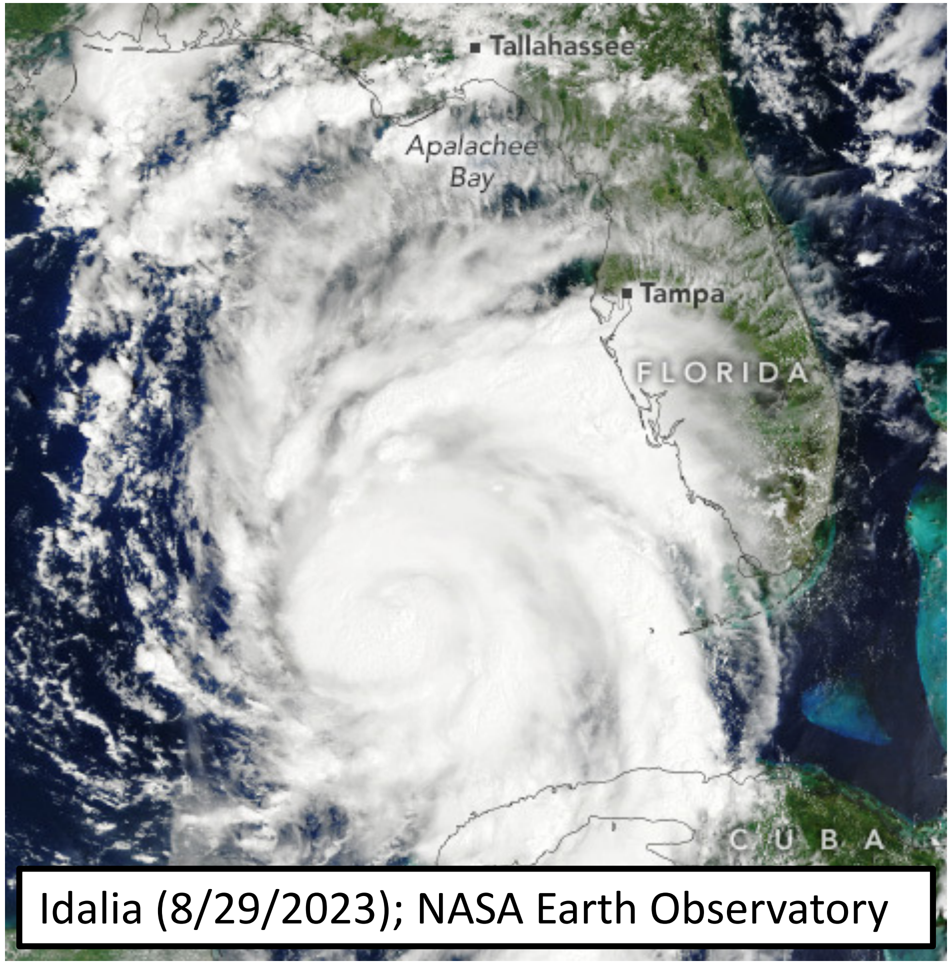
- 200 m depth contour from Natural Earth bathymetry

Tide gauge observations

- NOAA Tides and Currents (1950 through 2023)
- Excluded stations within small inlets and bays
- Removed seasonal trends and annual means
- Calculate skew surge for each tidal cycle
    - Removes astronomical tide
- Must have > 70% of data to calculate an annual maximum

Cedar Key Tide Gauge

BHM inference



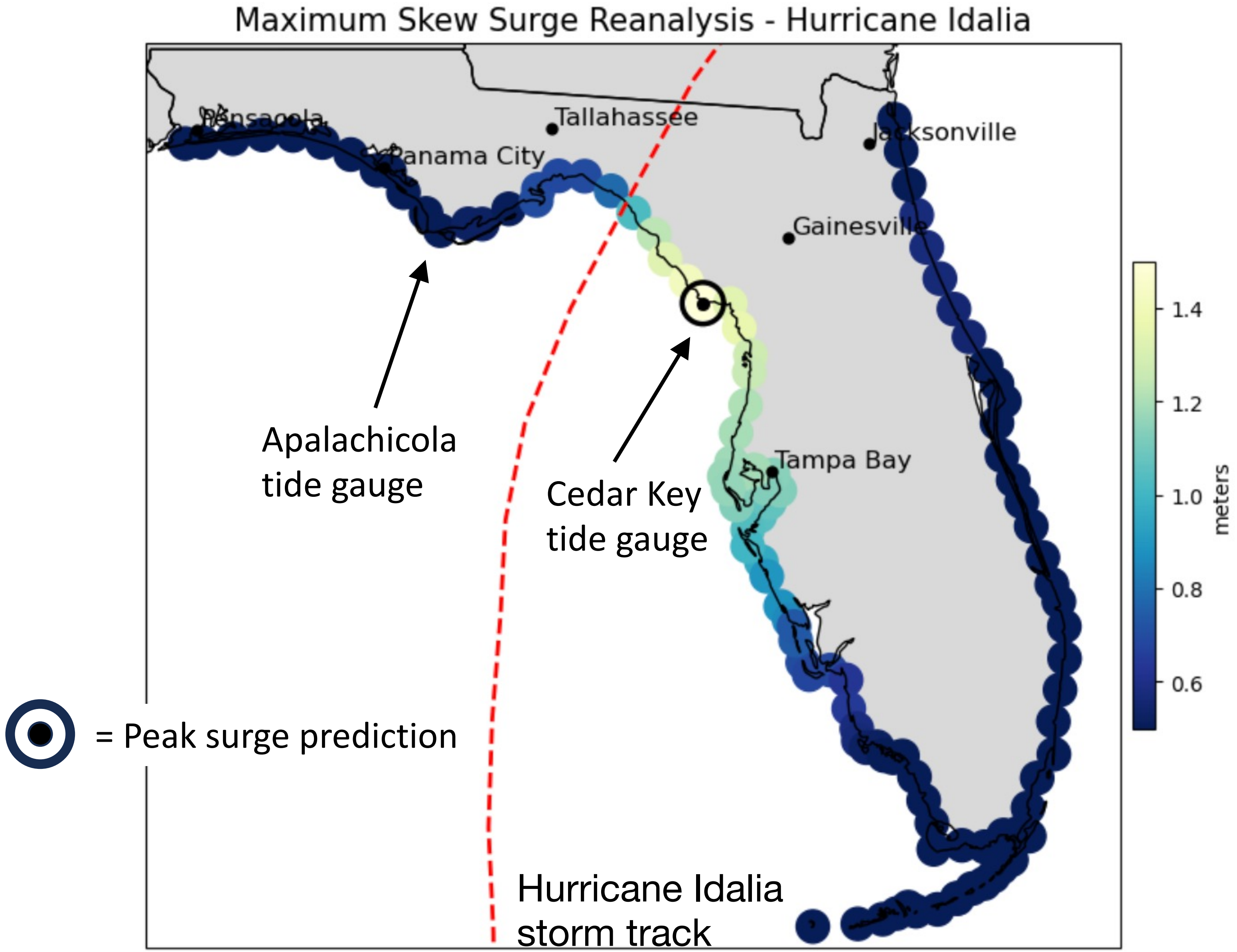
Idalia (8/29/2023); NASA Earth Observatory

- BHM integration performed with Markov Chain Monte Carlo (MCMC) with No U-Turn Sampler (NUTS), as implemented by the Stan probabilistic programming language
- Run sampler with four MCMC chains of 2,000 iterations each
- All runs converged and had good mixing

NumPy

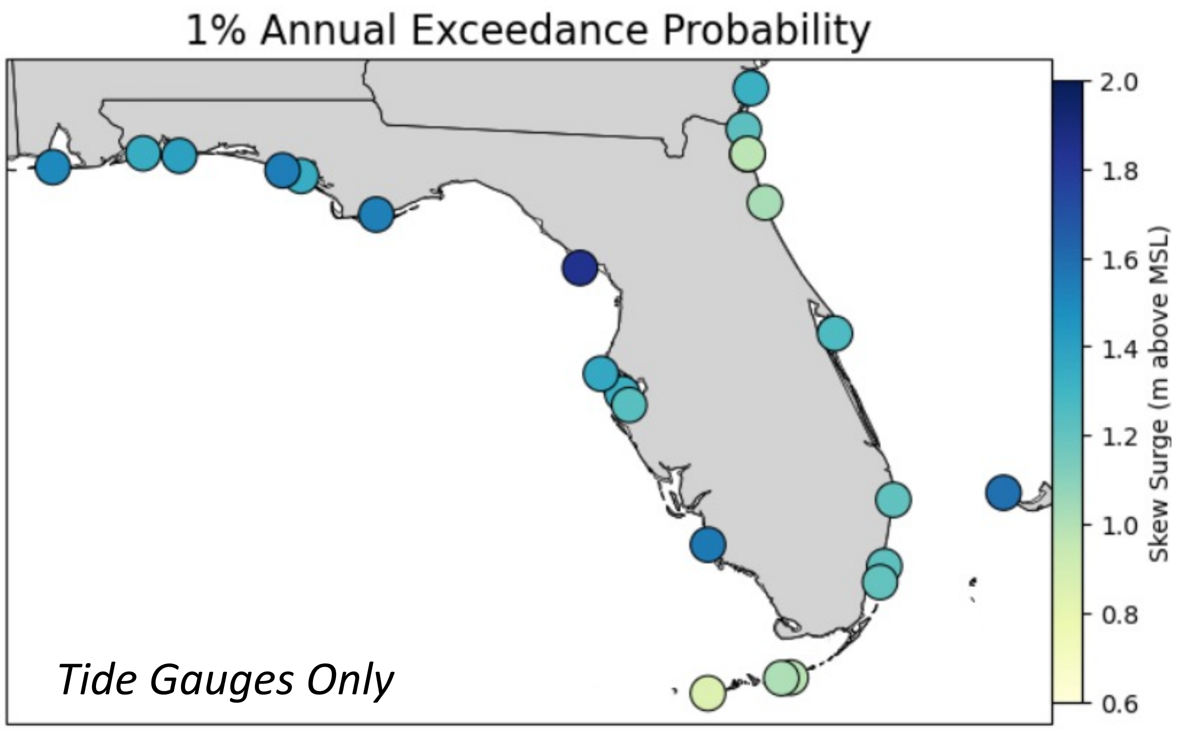
PyStan

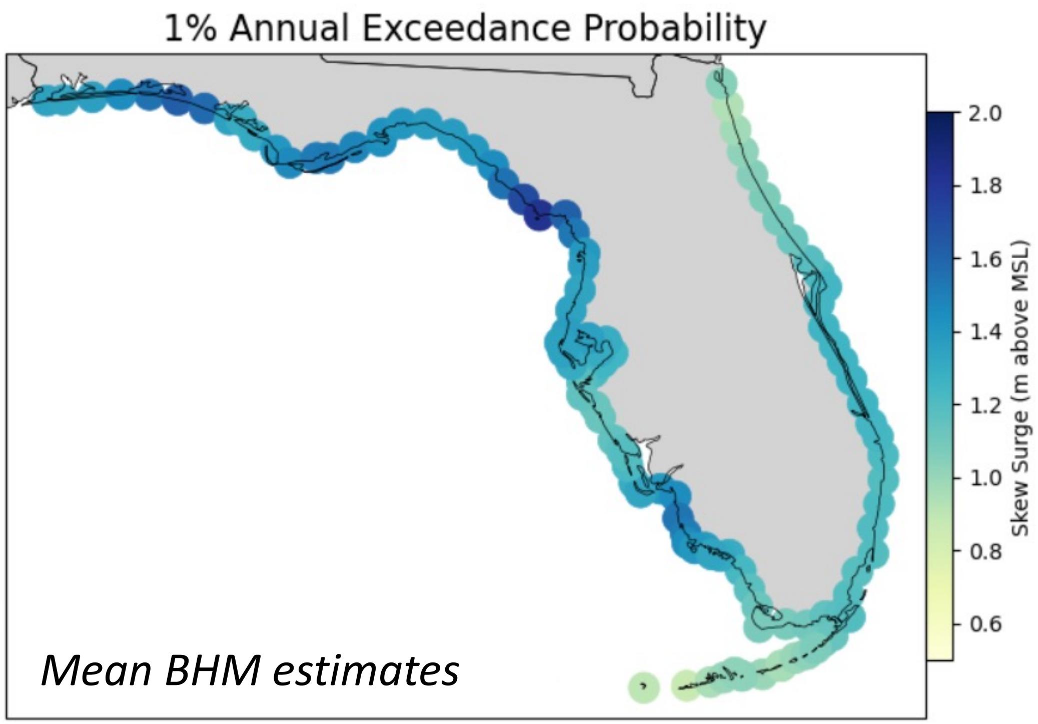
BHM captures Idalia's peak surge "footprint", but values underpredicted



- Surge occurs to the right of Idalia's track
- Peak surge from BHM is around 1.45 m
- Peak skew surge is underpredicted by ~0.5 meters at Cedar Key tide gauge (1.96 m)
- Surge tapers off quickly up and along Big Bend coastline

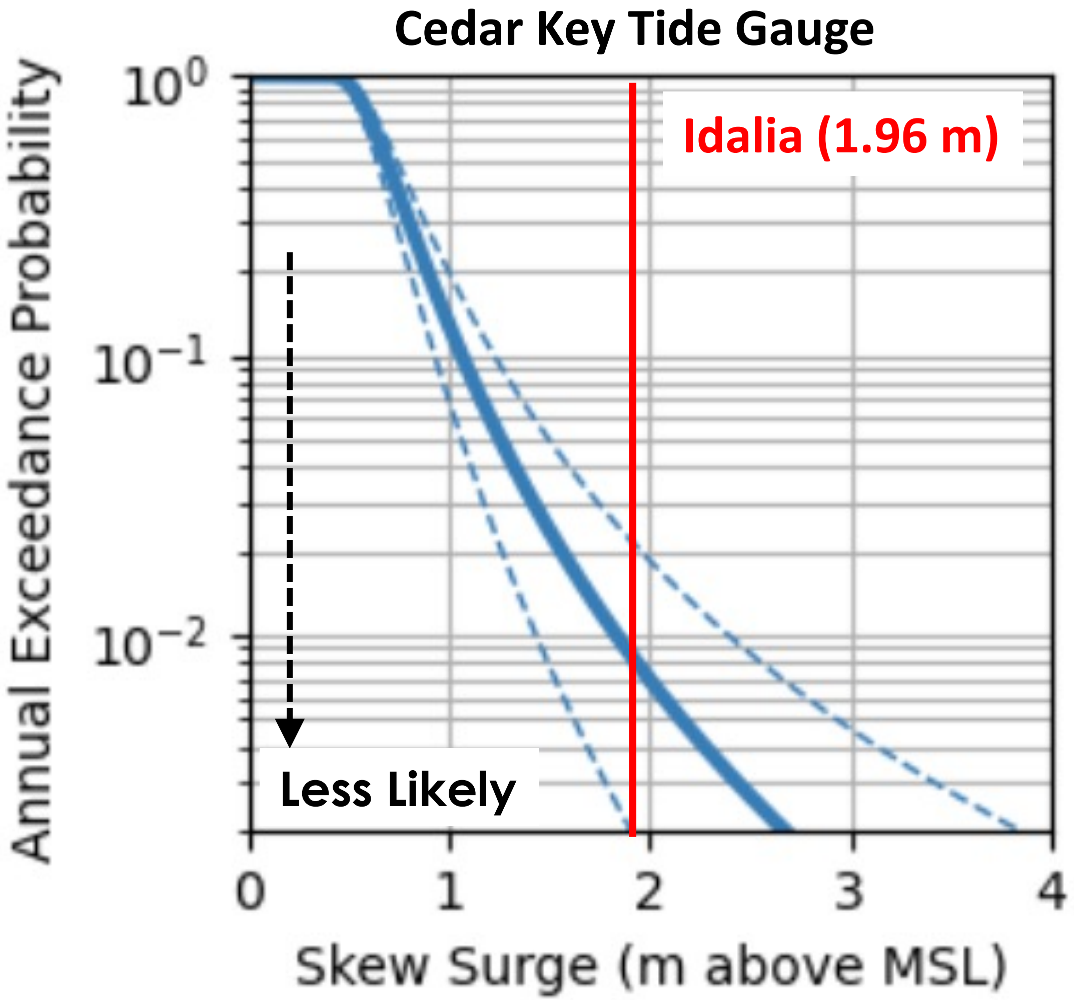
The BHM can estimate extreme value distribution parameters, from which probabilistic estimates of skew surge return periods can then be derived (with uncertainty)





We are working on the rest of the United States, including Alaska, Hawaii, Puerto Rico and Virgin Islands… forthcoming in Joao Morim et al. (*in preparation*)

Hurricane Idalia skew surge at Cedar Key has **roughly a 0.8% chance of occurring each year** (mean estimate), with a $5^{th}/95^{th}$ percentile range of 0.2% to 2%.



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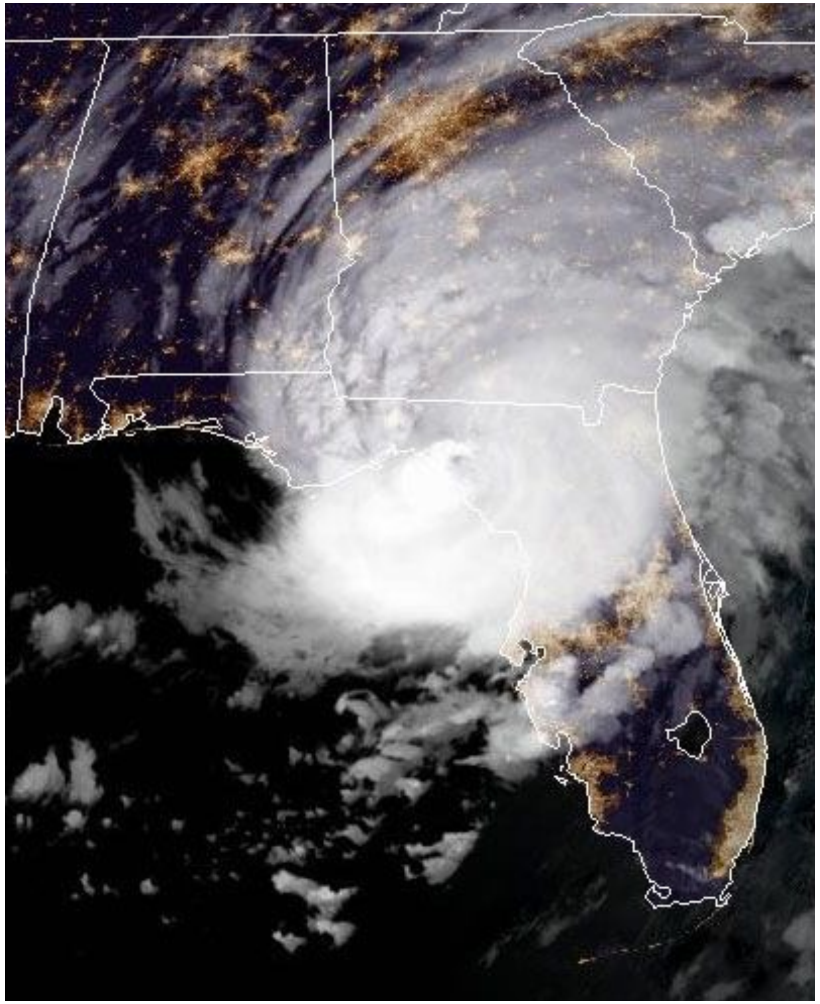
Source: NOAA Tides and Currents

BHM estimates

Summary



Idalia, 30 August 2023; Source: NOAA

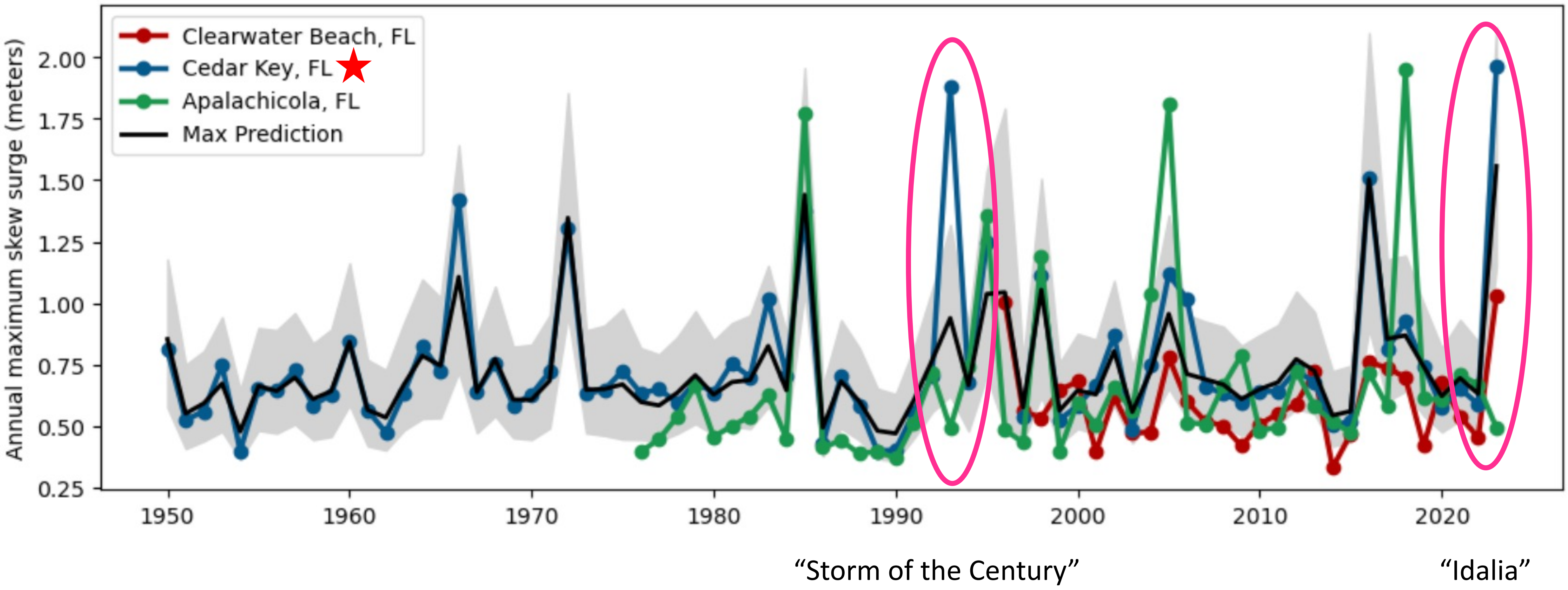
- The BHM may struggle to reproduce peak surges for some storms
  - Roughly a 0.5 m underprediction at Cedar Key tide gauge
- BHMs can provide estimates of storm surge frequencies
  - 1.96 m surge at Cedar Key has an annual exceedance probability between a 0.2% and 2% (mean estimate of 0.8%).

See other storm surge applications of BHMs at AGU23

- "A Probabilistic Data-driven Framework for Seamless Spatial-Temporal Prediction of Storm Surge Extremes" (GC13H-0998)
- "A spatial Bayesian model for comprehensive storm surge hazard assessment along the US Gulf Coast" (H23C-02)

Extra Slides

BHM predictions adjacent to Cedar Key tide gauge are sometimes too low: e.g., Storm of the Century and Hurricane Idalia



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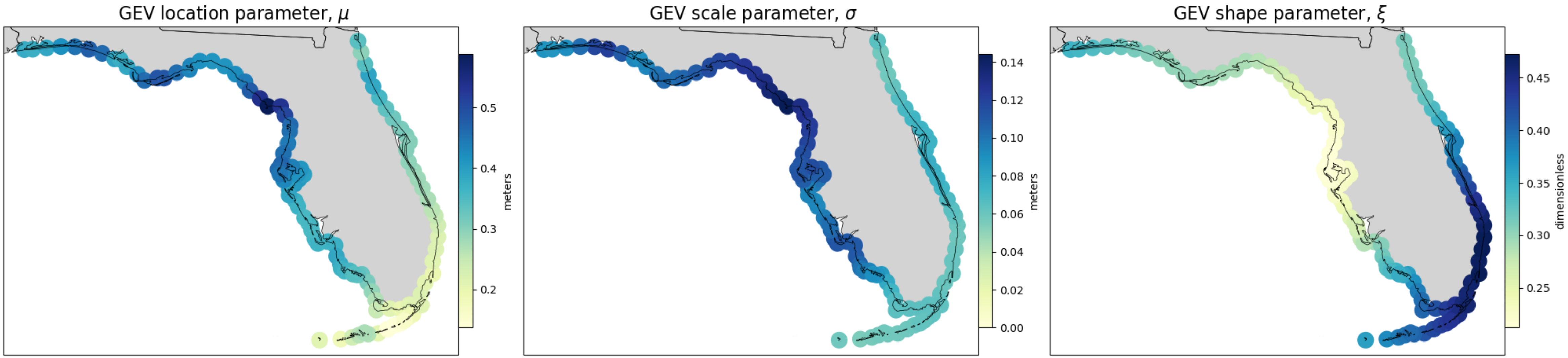
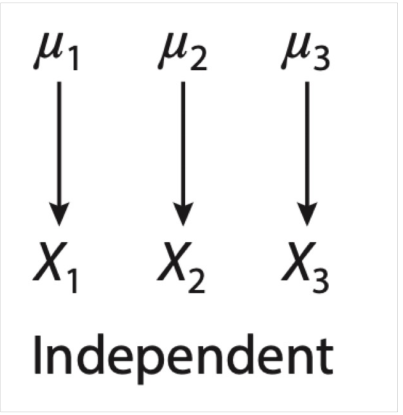
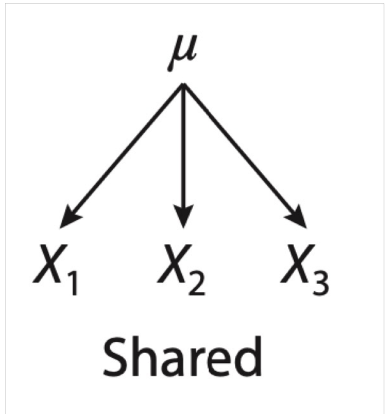
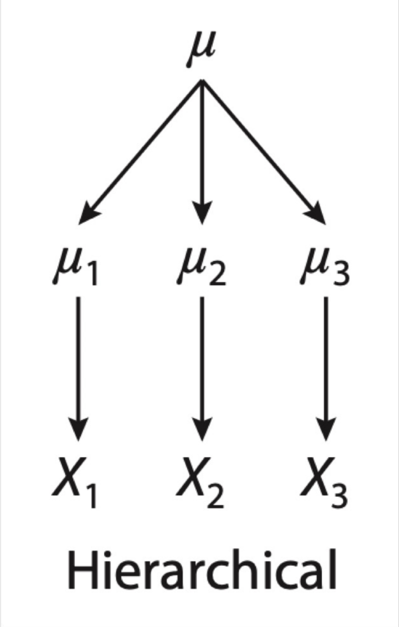


Mean estimates

Hierarchical models consider variability both within and across sites







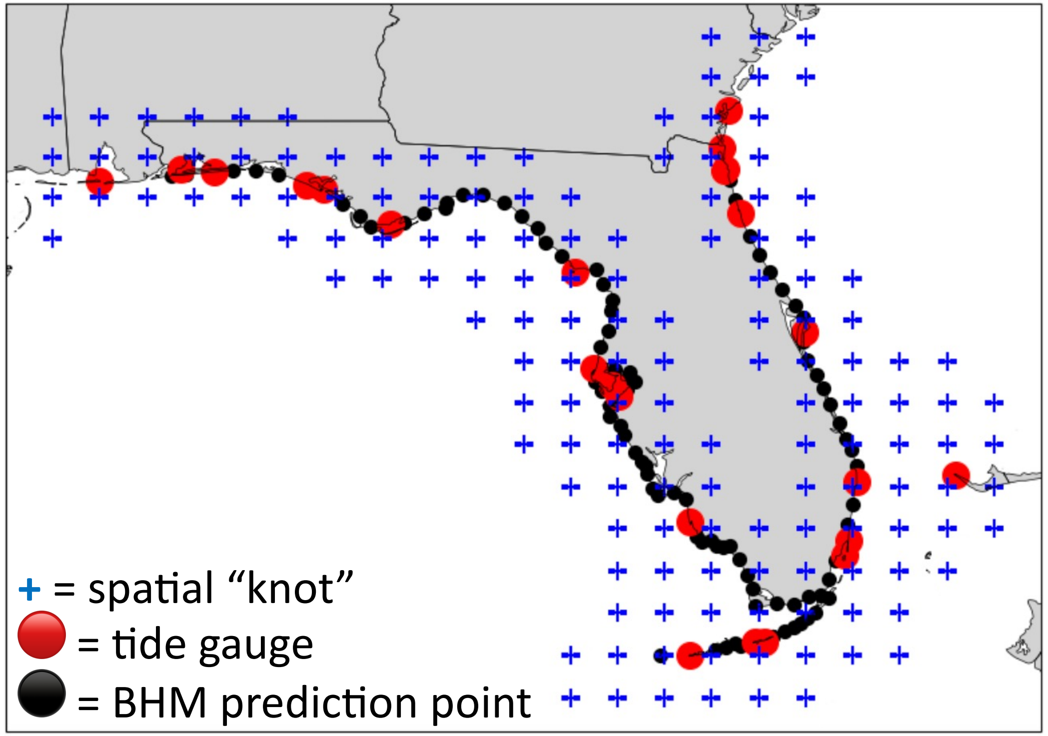
$\boldsymbol{\mu_i}$ is the site mean

Where… $\mathbf{X_1}$, $\mathbf{X_2}$, $\mathbf{X_3}$ are geographic sites

Hierarchical models model the continuum between independent and shared

Dietze (2017)

BHM setup for inferring unobserved peak skew surge values during Idalia



Data Model

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$$\mathrm{GEV}(x) = \exp\left\{-\left[1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right]_{+}^{-1/\xi}\right\}$$

Computing the return level z_p such that $\mathrm{GEV}(z_p) = 1 - p$

$$z_p = \mathrm{GEV}^{-1}(1-p)$$

Hence, $\boxed{z_p = \mu + \frac{\sigma}{\xi}\left([-\ln(1-p)]^{-\xi} - 1\right)}$