Storm Surge Modeling and Validation

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Coastal Hazards & Storm Surge

With the rapid advancement of computational science, we are able to construct all kinds of natural systems using mathematical models and numerical methods. Coastal hazards, which lies under the domain, is considered to be a major concern because nearly 40% of the world population reside close to the coastline. Among all coastal hazards, the most common, wide-spread hazard is the **storm surge**, which is the abnormal and significant rise of sea water level caused by storm systems like hurricanes and typhoons. Storm surges can be disastrous to coastal communities.

In 2021, category 1 hurricane Elsa (AL052021) had a severe impact on the west Florida region and caused around 1 billion in damage along its track. It was also responsible for 13 direct fatalities.[1] Consequently, to perfect the current numerical state-of-art model for storm simulation by simulating and validating various major storms is considered to be consequential work.

Theoretical Background

Clawpack, GeoClaw, and Numerical Approach[2][3]

The **Clawpack** (Conservation Law Package) software suite is designed to solve nonlinear conservation law problems, balance laws, and many more other hyperbolic partial differential equations which are not necessarily in conservation form. **GeoClaw**, a variant of the Clawpack software, is developed to specifically solve the two-dimensional shallow water equations over topography for modeling various geophysical flows like hurricane, tsunami, or dam break.

The **mathematical model** implemented in GeoClaw is the classical shallow water equations with the addition of appropriate source terms for bathymetry, bottom friction, wind friction, non-constant surface pressure and Coriolis forcing which can be written as

$$
\begin{aligned}
&\frac{\partial}{\partial t}h + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0,\\
&\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu^2 + \frac{1}{2}gh^2) + \frac{\partial}{\partial y}(huv) =\\
&\qquad fhv - gh\frac{\partial}{\partial x}b + \frac{h}{\rho}\left(-\frac{\partial}{\partial x}P_A + \rho_{air}C_w|w|W_x - C_f|\vec{u}|u\right),\\
&\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}(hu^2 + \frac{1}{2}gh^2) =\\
&\qquad -fhu - gh\frac{\partial}{\partial y}b + \frac{h}{\rho}\left(-\frac{\partial}{\partial y}P_A + \rho_{air}C_w|w|W_y - C_f|\vec{u}|u\right),
\end{aligned}
$$

where h is the fluid depth, u and v the depth-averaged horizontal velocity components, g the acceleration due to gravity, ρ the density of water, ρ_{air} the density of air, b the bathymetry, f the Coriolis parameter, $W = [W_x, W_y]$ the wind velocity at 10 meters above the surface, C_w the wind friction coefficient, C_f the bottom friction coefficient, C_w defined by Garratt's drag formula, and C_f determined using a hybrid Chezy-Manning's n type friction law.

Adaptive Mesh Refinement Algorithm (AMR)[2]

The key benefit of adaptive mesh refinement is the ability to change resolution as the simulation progresses. This is done in a process that involves using a local criteria to flag each cell that requires refinement to the next level, aiming to minimize the number of grids created and the number of grid cells unnecessarily refined.

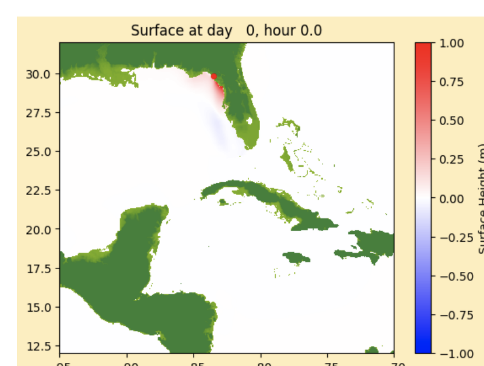
Major Hurricanes in 2021 Atlantic Hurricane Season

Four major hurricanes in the 2021 Atlantic Hurricane Season were studied, including hurricane Elsa (AL052021), hurricane Grace (AL072021), hurricane Ida (AL092021), and hurricane Nicholas (AL142021). Hurricane Elsa's result is selected and presented below.

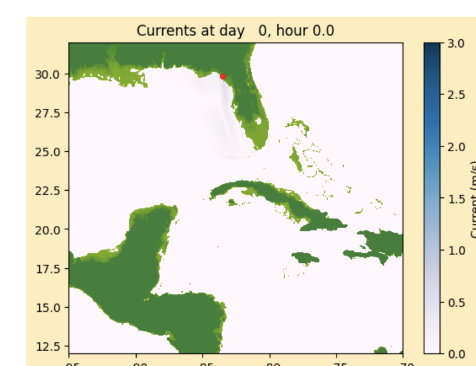
Hurricane Elsa (AL052021)

Elsa was formed over the central tropical Atlantic. It affected many countries including Barbados, the Dominican Republic, Haiti, Cuba, and the United States. Elsa affected the Florida Keys and the west coast of Florida along its path before making landfall in the Big Bend region on 6th and 7th July. After the Florida landfall, Elsa turned toward the northeast and accelerated towards the U.S. eastern seaboard.[1]

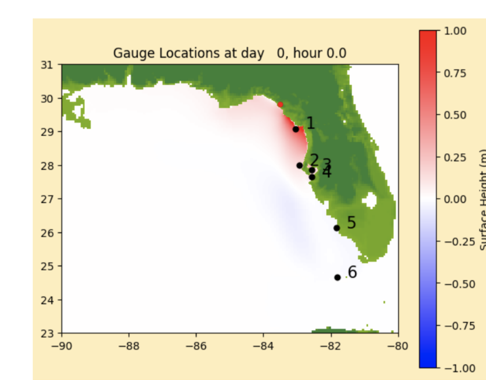
Simulation & Validation Results



(a) Surface Height

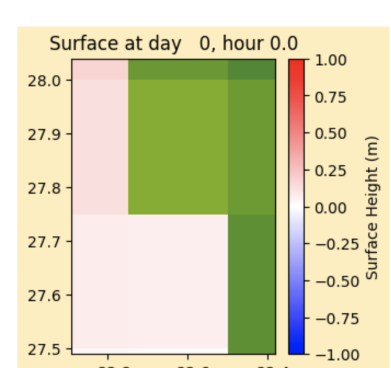


(b) Current Speed

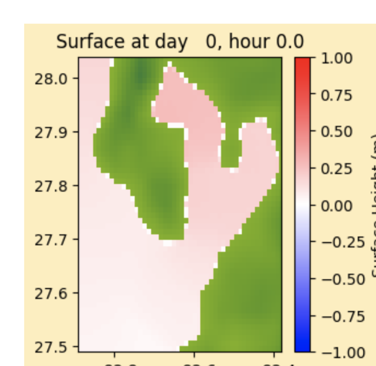


(c) Gauge Location

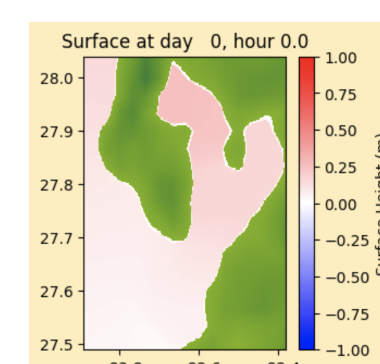
Figure 1. Hurricane Track & Gauge Location General View



(a) No Refinement

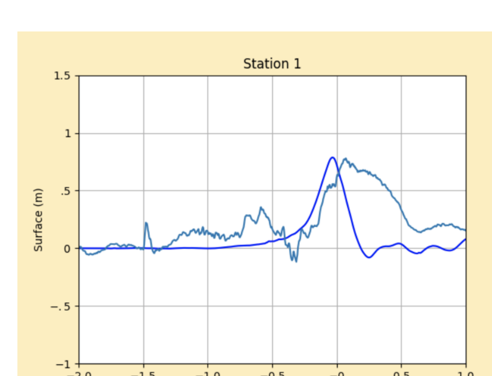


(b) Medium Refinement

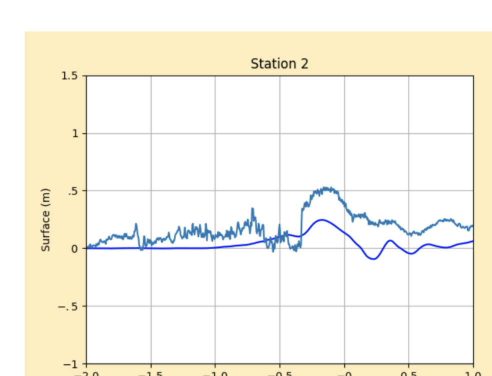


(c) Large Refinement

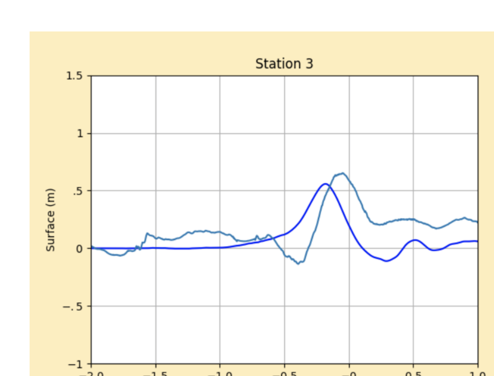
Figure 2. Comparison of Non-Resolved, Partially Resolved, & Well Resolved Region



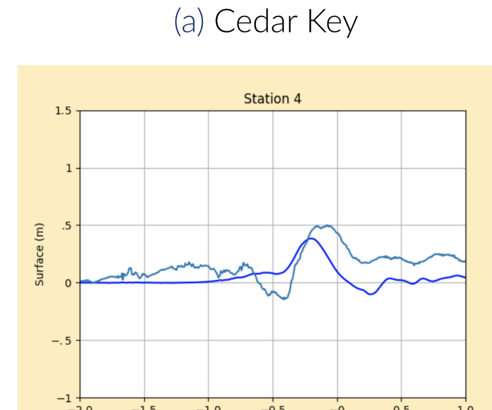
(a) Cedar Key



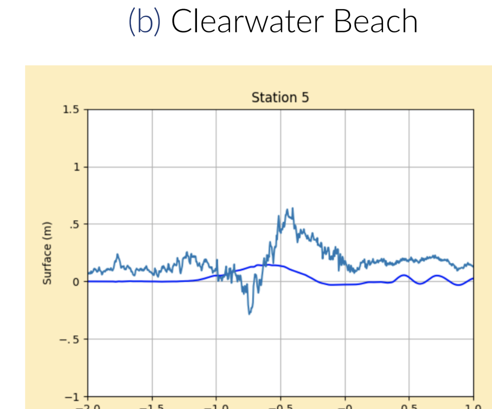
(b) Clearwater Beach



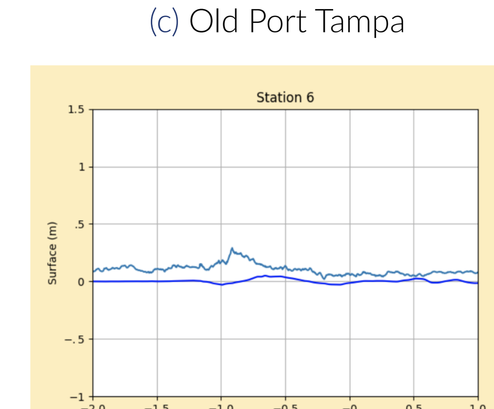
(c) Old Port Tampa



(d) Port Manatee



(e) Naples



(f) Key West

Figure 3. Gauges Water Level Simulation (Dark Blue) & Observation (Light Blue)

Automated Analysis for Storms

Given the complexity of data collection and run-time parameter selection, a python program was developed to automatically analyze and assist users on storm surge modeling and validation projects. Three key features are presented and explained.

1. *generate_time*: Report availability of storm specific data.
2. *generate_gauge*: Report details of auto-selected stations from NOAA stations' metadata for validation studies.
3. *generate_significance*: Report maximum surge detected and distance to storm eye at each recommended station for users to target abnormality.

	Key West	Port Manatee	St. Petersburg, Tampa Bay	Old Port Tampa
max surge	0.236	0.384	0.463	0.542
distance	90.360	94.016	86.006	93.364

	Clearwater Beach	Cedar Key	Yorktown USCG Training Center	Lewes
max surge	0.404	0.646	0.291	0.387
distance	68.608	55.343	94.545	53.779

	Ocean City Inlet	Bishops Head	Cambridge	Solomons Island
max surge	0.267	0.290	0.281	0.340
distance	36.533	51.057	52.515	83.415

	Lewisetta	The Battery	Sandy Hook	New London	New Haven
max surge	0.346	0.409	0.393	0.478	0.443
distance	95.562	89.209	79.235	55.175	66.451

	Bridgeport	Montauk	Fall River	Newport	Conimicut Light
max surge	0.478	0.422	0.461	0.445	0.461
distance	79.951	33.007	55.978	33.248	46.054

	Providence	Quonset Point	Boston	Woods Hole	Bar Harbor
max surge	0.518	0.443	0.241	0.531	0.186
distance	51.637	31.867	39.569	59.583	44.273

(a) *generate_significance*

Figure 4. Selected Feature of Automated Analysis Logging Result for Hurricane Elsa

Future Work

Selecting efficient and precise refinement regions and levels remain to be primary problems for storm modeling and validation. A quantitative procedure could be further investigated to solve the problem. The lack of consideration of rainfall and flooding in GeoClaw's model might directly result in major discrepancies between observed data and simulated data in gauge plots. Future research can explore possibilities to include precipitation data and coastal flooding data in GeoClaw.

Acknowledgement

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Selected References

[1] National hurricane center tropical cyclone reports. *https://www.nhc.noaa.gov/data/tcr/index.php*.

[2] Kyle T. Mandli Clint N. Dawson. Adaptive mesh refinement for storm surge. *Ocean Model 75*, pages 36–50, 2014.

[3] Kyle T. Mandli et al. Clawpack: building an open source ecosystem for solving hyperbolic pdes. *Peerj Comput. Sci.*, page 68, 2016.