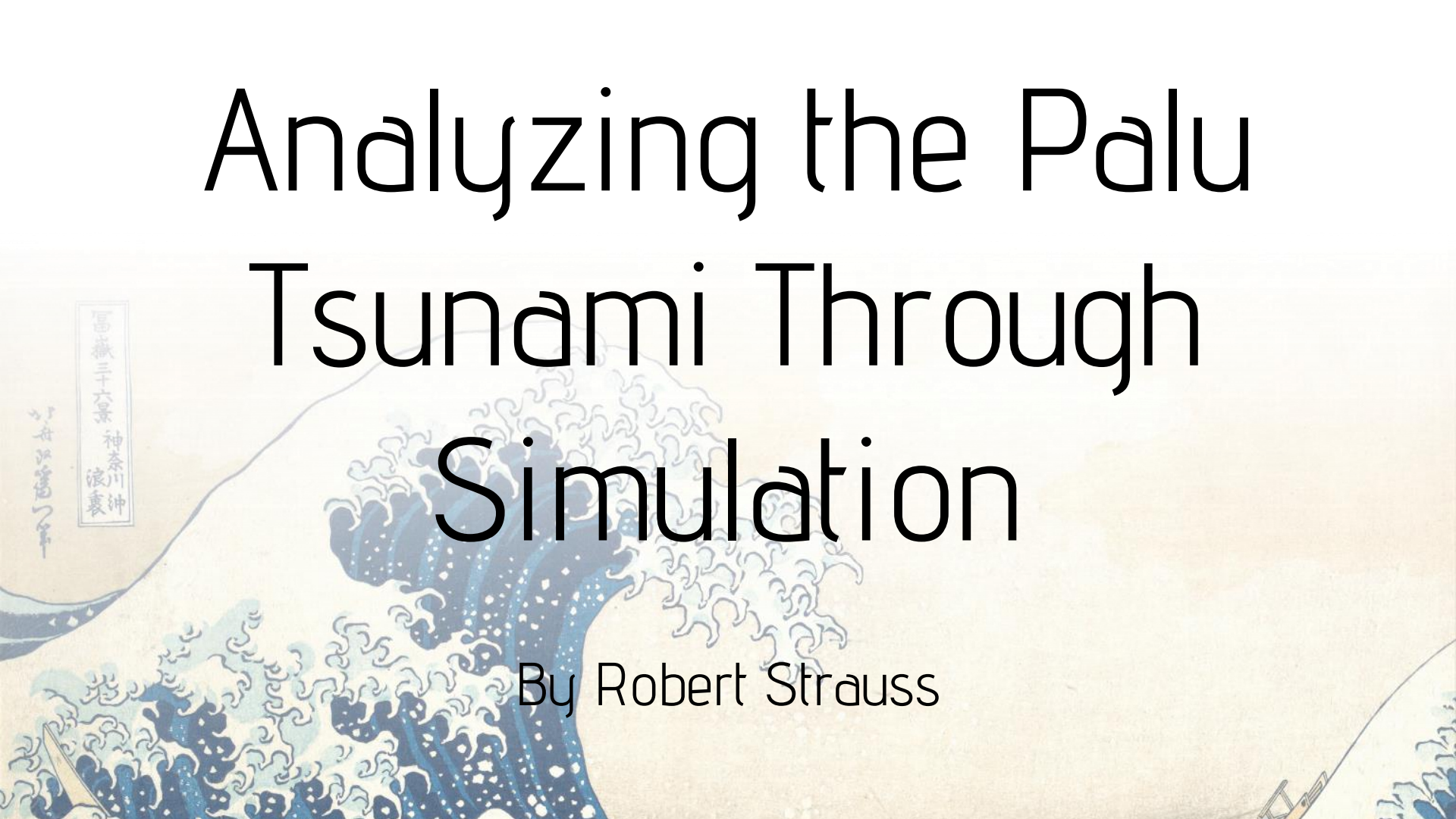
Analyzing the Palu Tsunami Through Simulation



By Robert Strauss

Tsunami in Palu, Indonesia

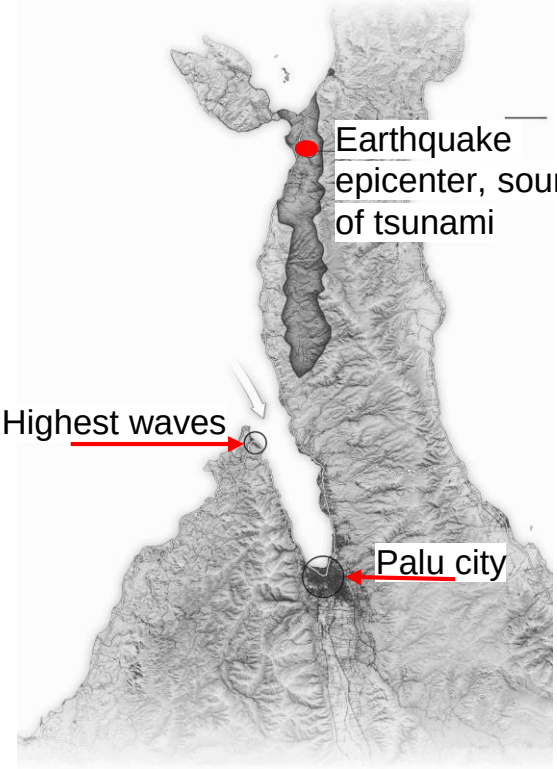
In 2018 a tsunami devastated Palu.

- More than 800 people were killed.
- Over 500 were severely injured.
- 48,000 were made homeless

The inundation was greater than expected for the 7.5 magnitude of the earthquake.

> Despite the frequent earthquakes, Palu hadn't previously experienced such devastation from a tsunami.

The highest waves crested near the mouth of the bay



(New York Times)

Damage to Palu shaded

What if … in the Palu tsunami?

Question

- Why was the Palu tsunami so unexpected and devastating?
    - **What if** it had been slightly different?
        - Tsunami started elsewhere?

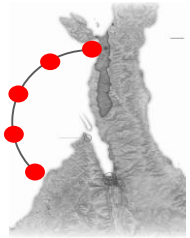
Experts speculated:

Bay's shape?, Bathymetry?, Orientation of the bay to epicenter?

Hypothesis

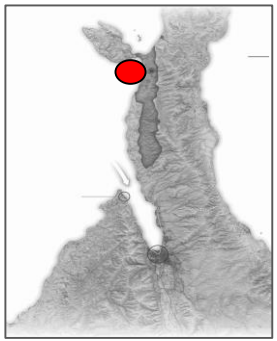
With computer simulations I can qualitatively answer **What if…** questions, and thus isolate contributing factors to its severity

Approach

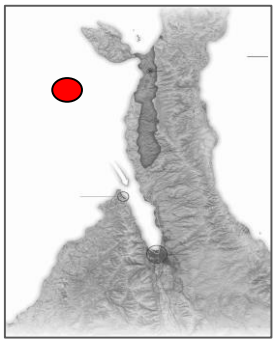


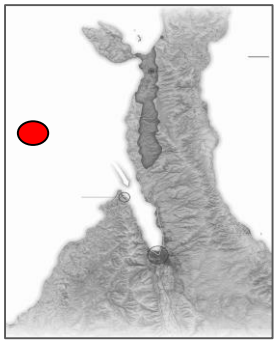
- Initial tsunami location

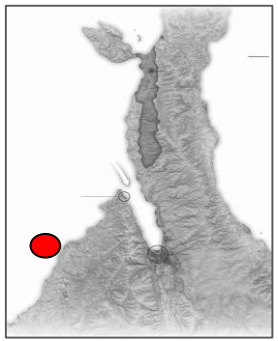
- Independent variable: Initiate tsunamis in various places around Palu
  - Arc around mouth of Palu bay, constant distance.



Real event



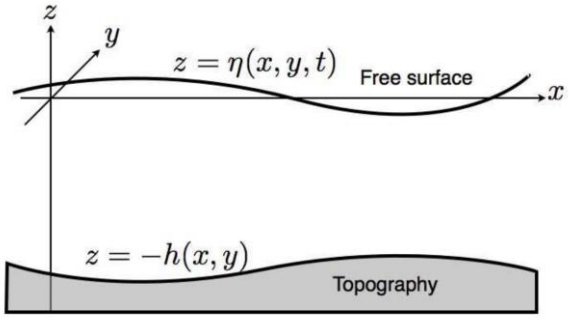




- Dependent variable: Resulting maximum water heights in Palu bay

Method: Simulation via The Shallow Water Equations

- Differential equations describing water
- Can work in deep water



$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x}\left((\eta + h)\, u\right) - \frac{\partial}{\partial y}\left((\eta + h)\, v\right)$$

$$\frac{\partial u}{\partial t} = Coriolis + Advection + Gravity + Attenuation$$

$$= +fv + \left(\kappa \nabla^2 u - (u, v) \cdot \vec{\nabla} u\right) - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho(h+\eta)}\mu u\sqrt{u^2 + v^2}$$

$$= +fv + \left(\kappa\frac{\partial^2 u}{\partial x^2} + \kappa\frac{\partial^2 u}{\partial y^2} - u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y}\right) - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho(h+\eta)}\mu u\sqrt{u^2 + v^2}$$

$$\frac{\partial v}{\partial t} = -fu + \left(\kappa \nabla^2 v - (u, v) \cdot \vec{\nabla} v\right) - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho(h+\eta)}\mu v\sqrt{u^2 + v^2}$$

$$= -fu + \left(\kappa\frac{\partial^2 v}{\partial x^2} + \kappa\frac{\partial^2 v}{\partial y^2} - u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y}\right) - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho(h+\eta)}\mu v\sqrt{u^2 + v^2}$$

h - bathymetry (depth)

η - surface height deviation

u - X speed (East)

v - Y speed (North)

f - Coriolis force $\propto$ sin(latitude)

κ - viscous damping

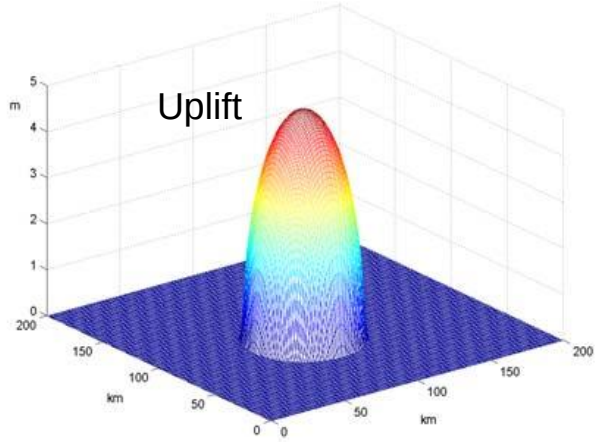
μ - friction coefficient

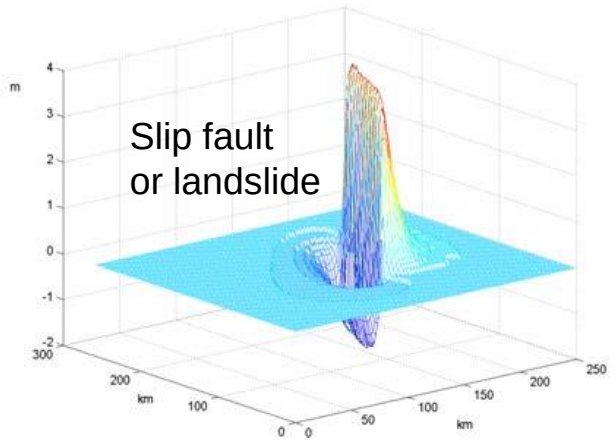
g - gravity

Design

- Apply shallow water equations in computer model
  - Discretization - chop space and time into discrete chunks to calculate on
  - Bathymetry data - depth of the ocean, shape of land
- Run simulation with Palu's bathymetry
- Alter factors: location and type of the initial wave
- Observe effects and make conclusion on cause of severity of tsunami in Palu
- Boundary conditions
  - Shallow water equations misbehave at shore so instead approximate with reflective boundary at ~15 M deep
  - Borders: multiply values at borders by 0.95 every iteration to dissipate outgoing waves to mimic exiting

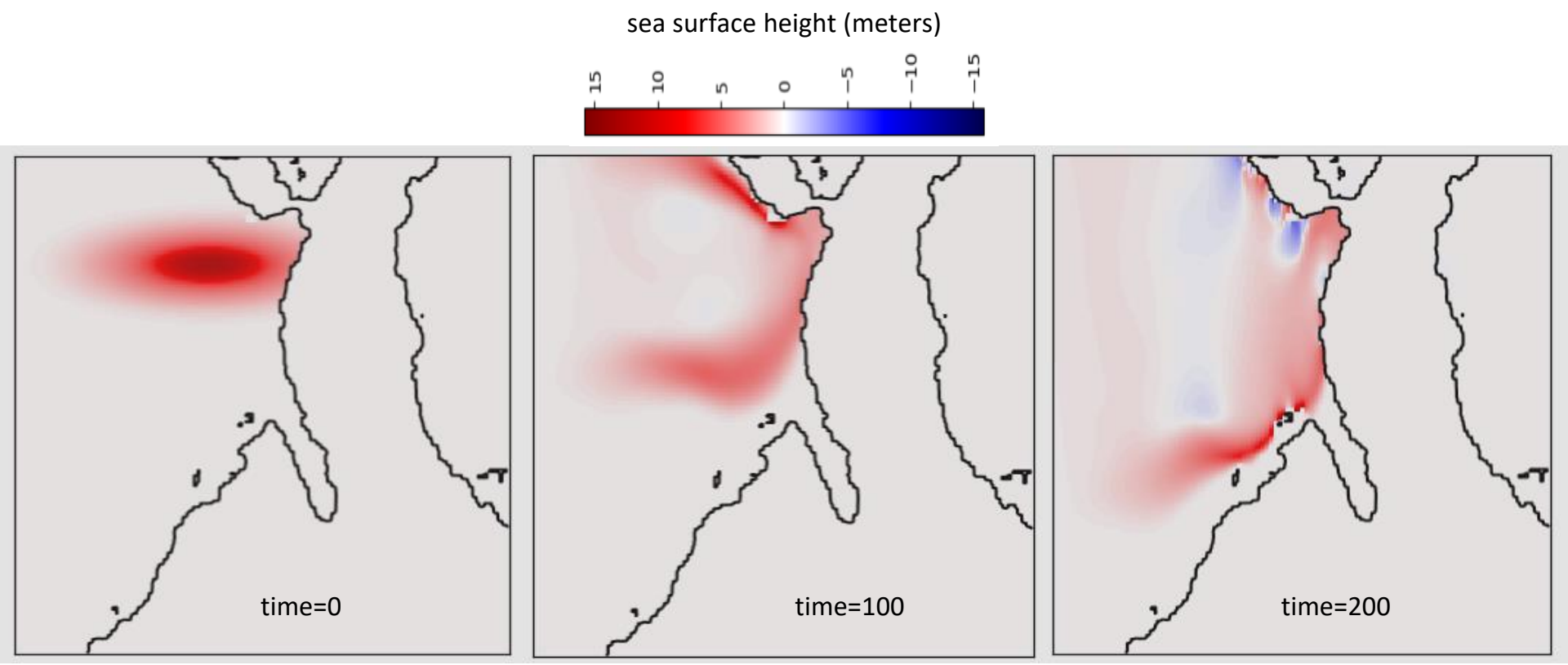
Initial conditions

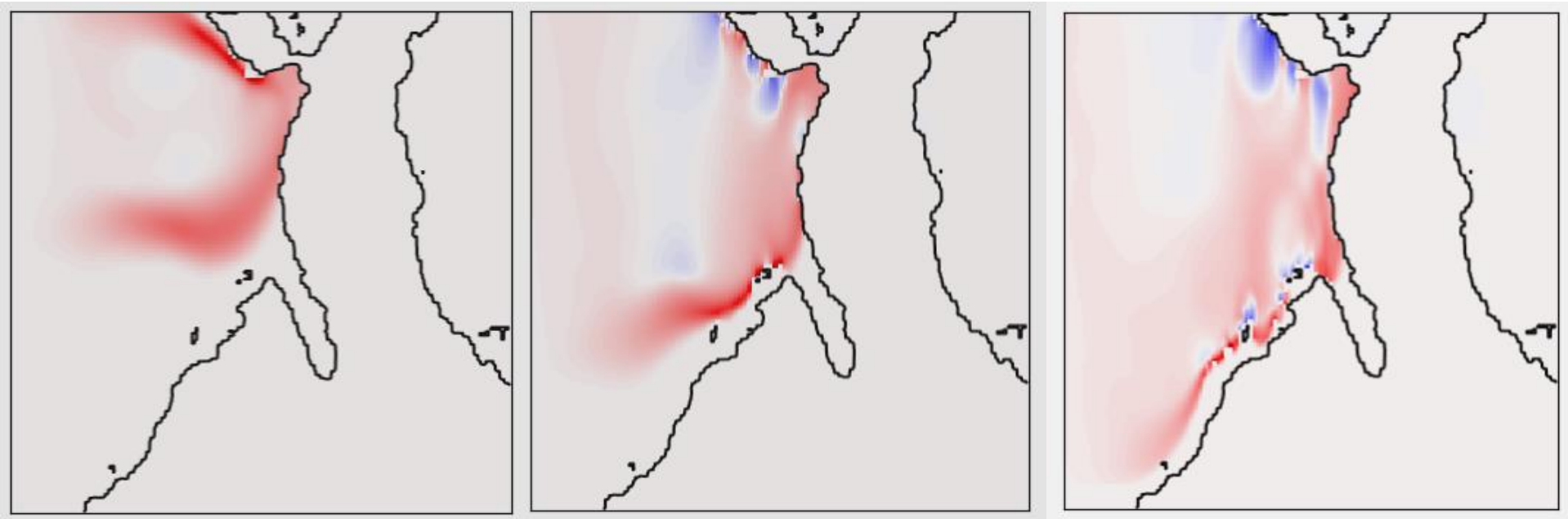


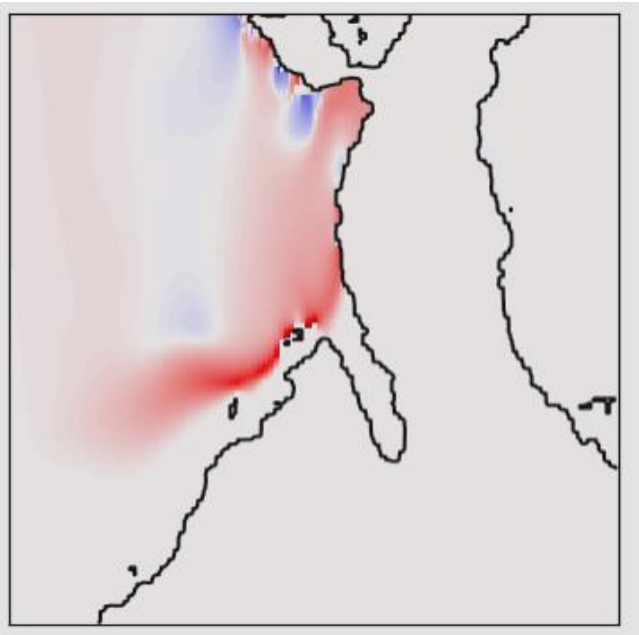


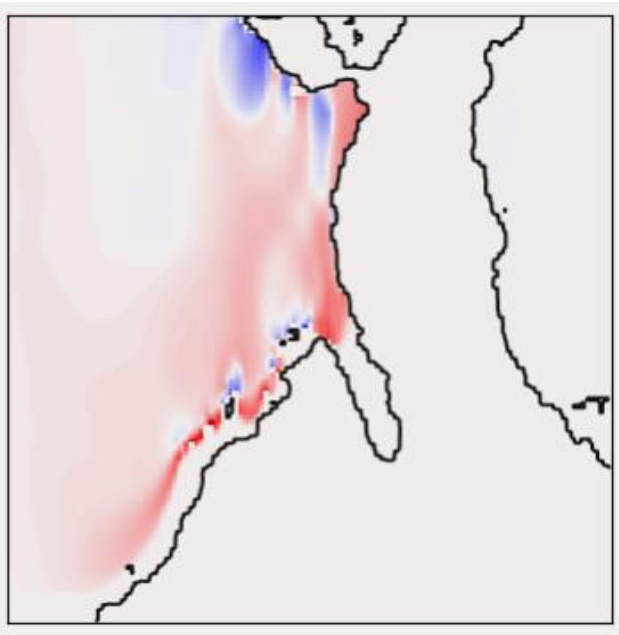
My Computer Model

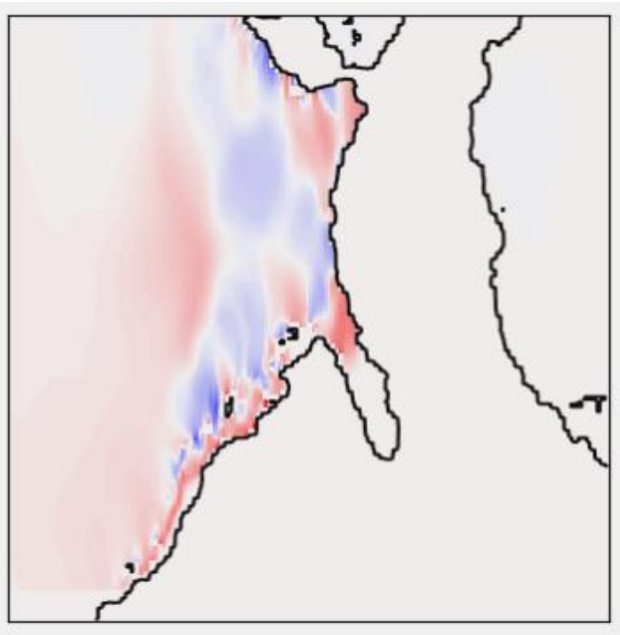
- I wrote over 1,341 lines of code, including simulation, unit tests, and graphics
  - Differential equations and time step integrator written from scratch.
- Implemented my idea in python with NumPy library
- Used Jupyter ipython notebooks to capture code and graphics
- Parallel processing with 8 CPUs with SIMD vector processing
  - Able to run on GPU, but that was not efficient on small scales

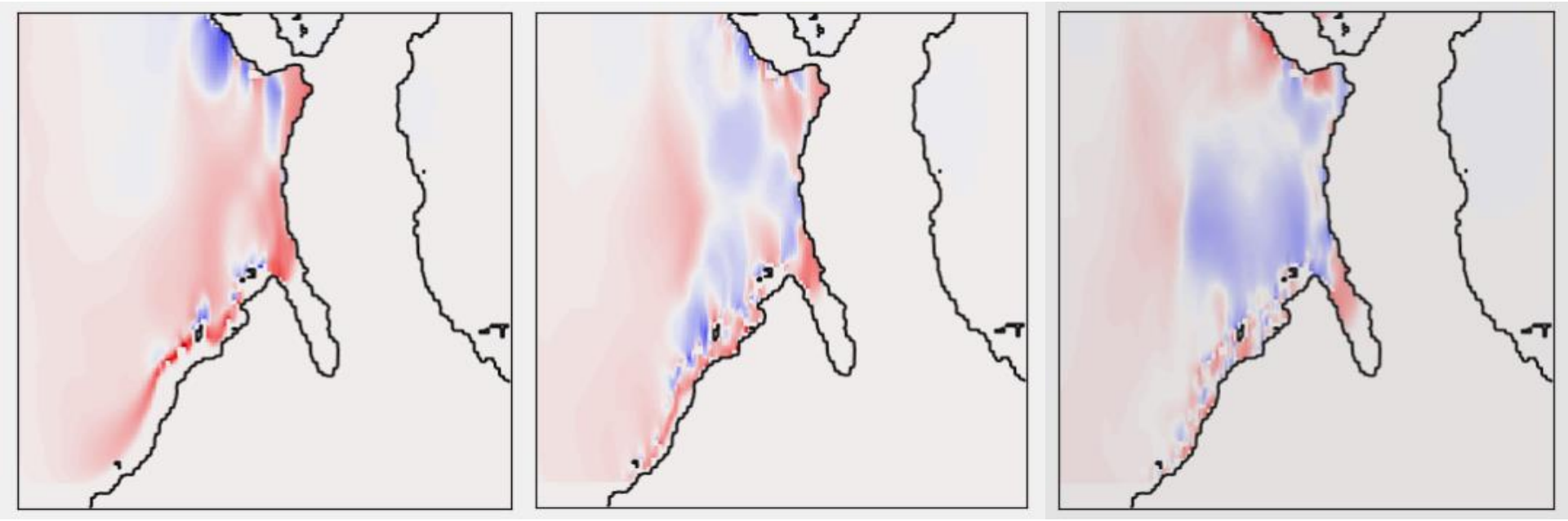

sea surface height (meters)
15
10
5
0
−5
−10
−15
time=0
time=100
time=200

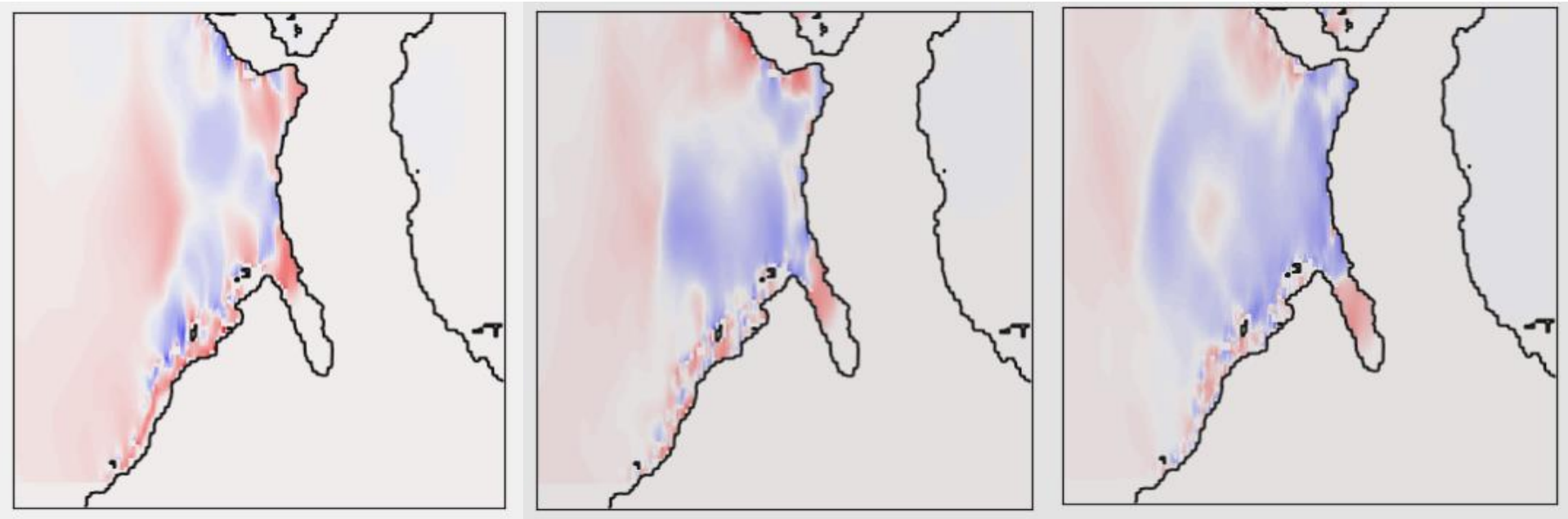


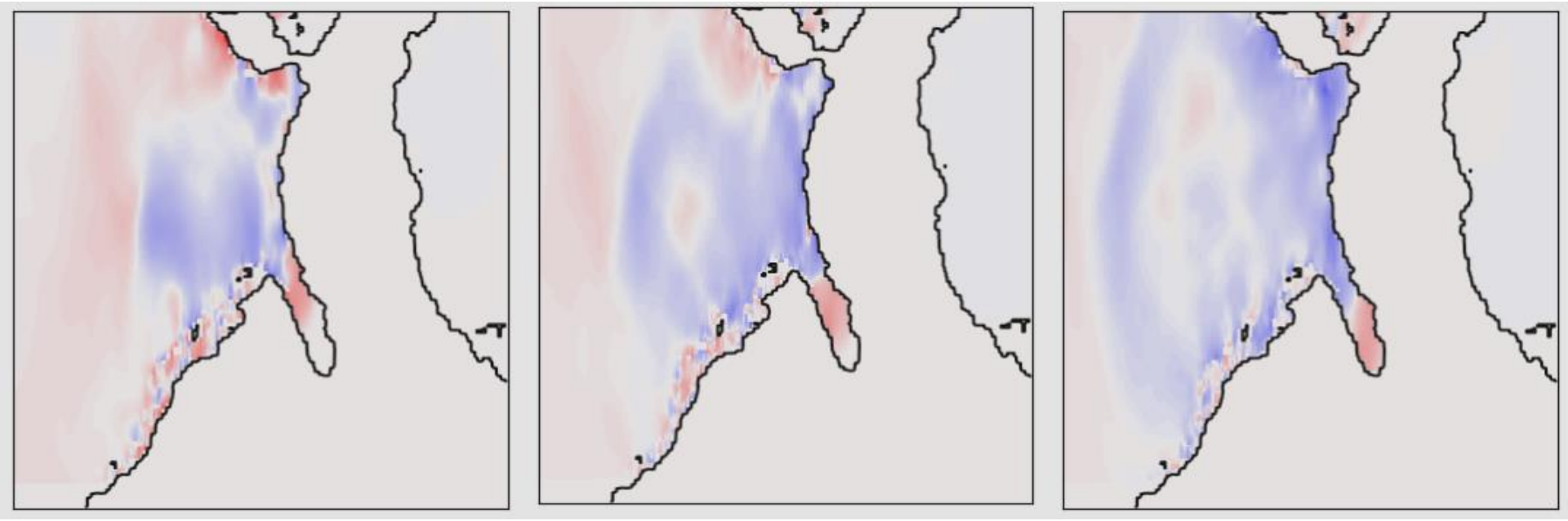


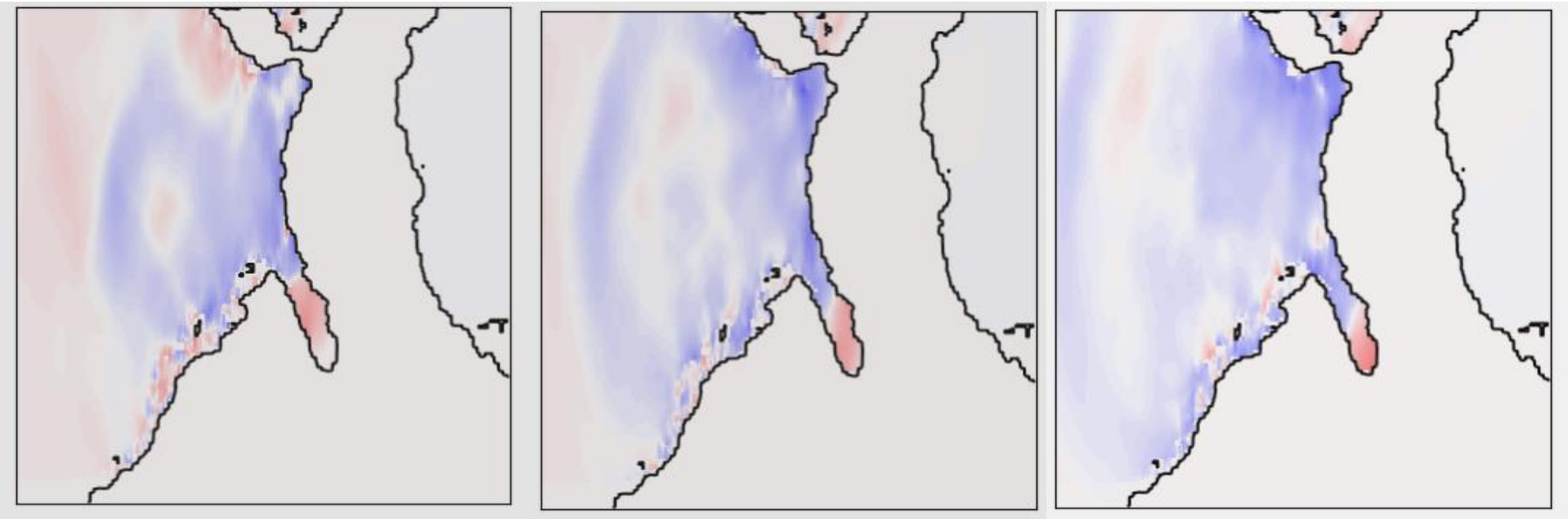


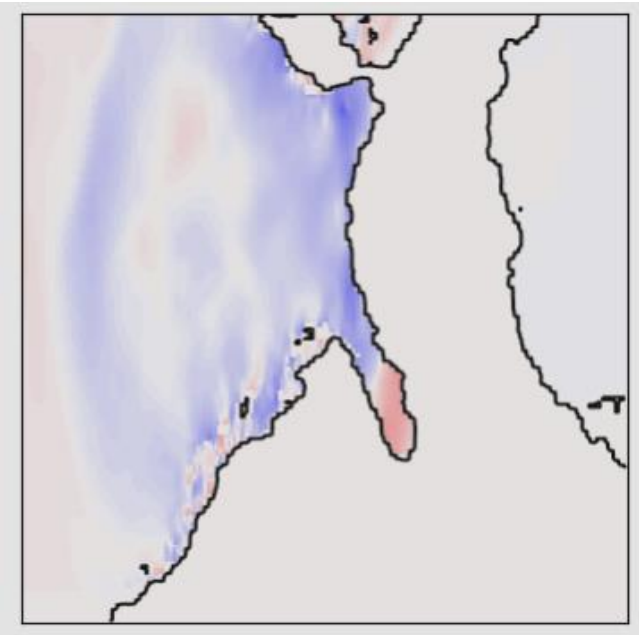


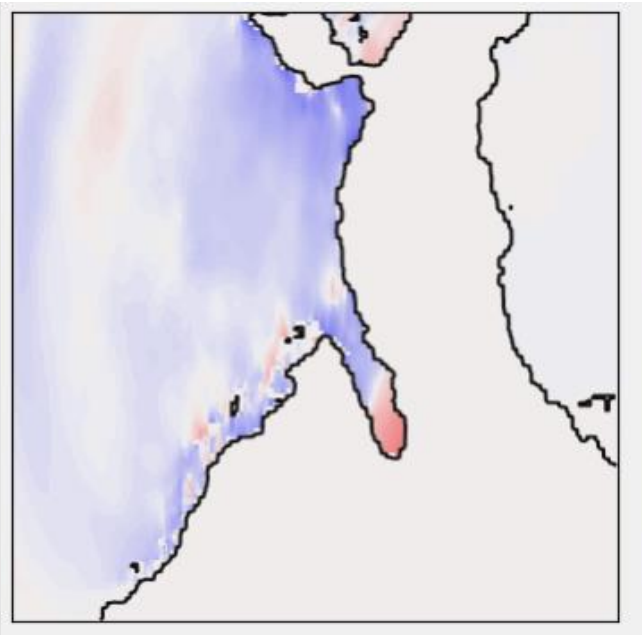


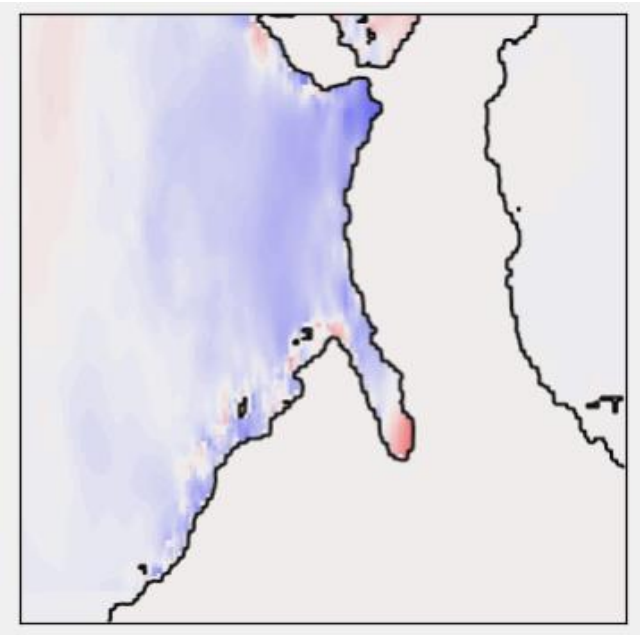




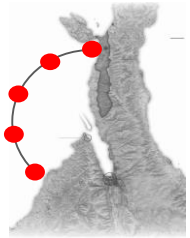






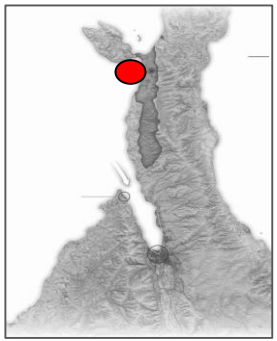


Approach

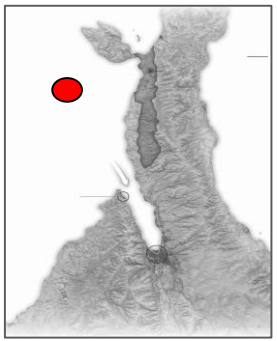


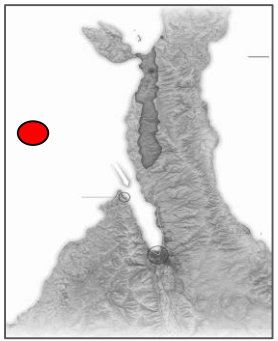
- Initial tsunami location

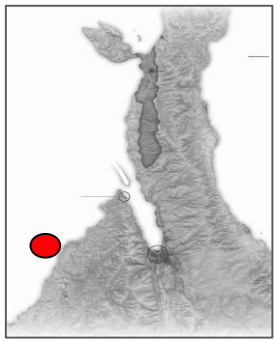
- Independent variable: Initiate tsunamis in various places around Palu
  - Arc around mouth of Palu bay, constant distance.



Real event

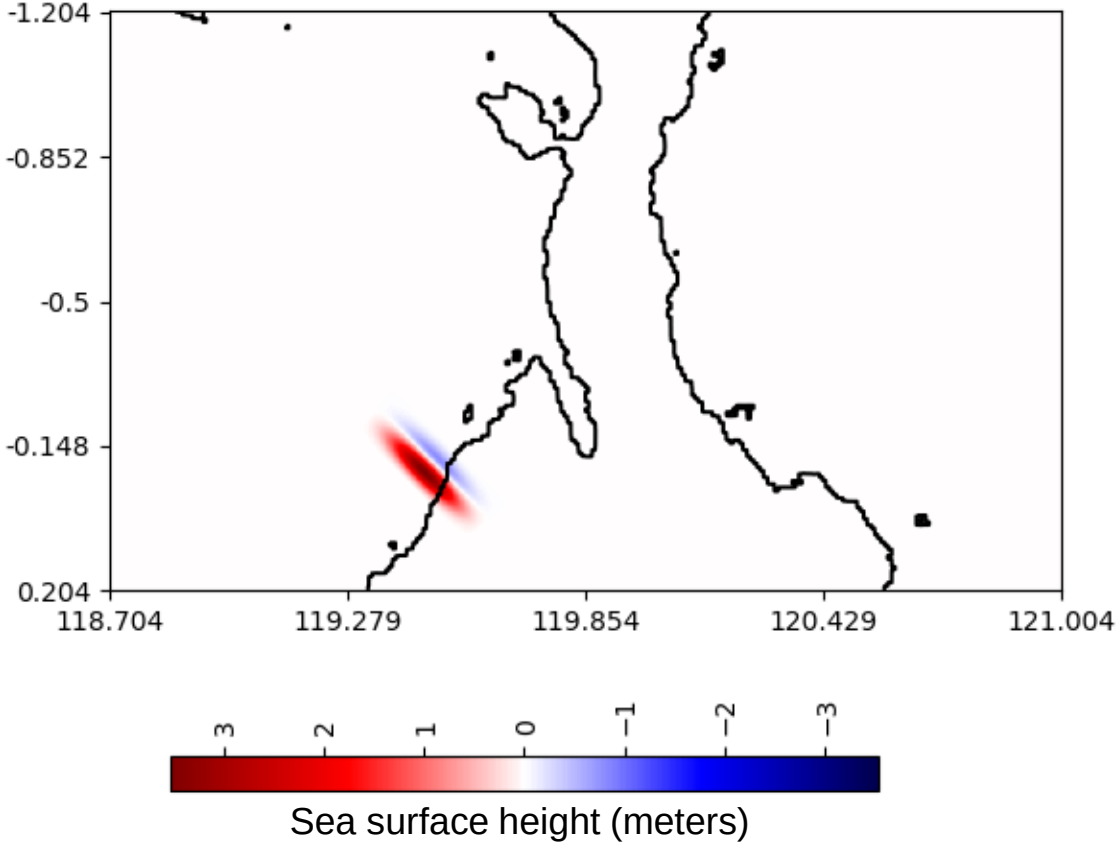




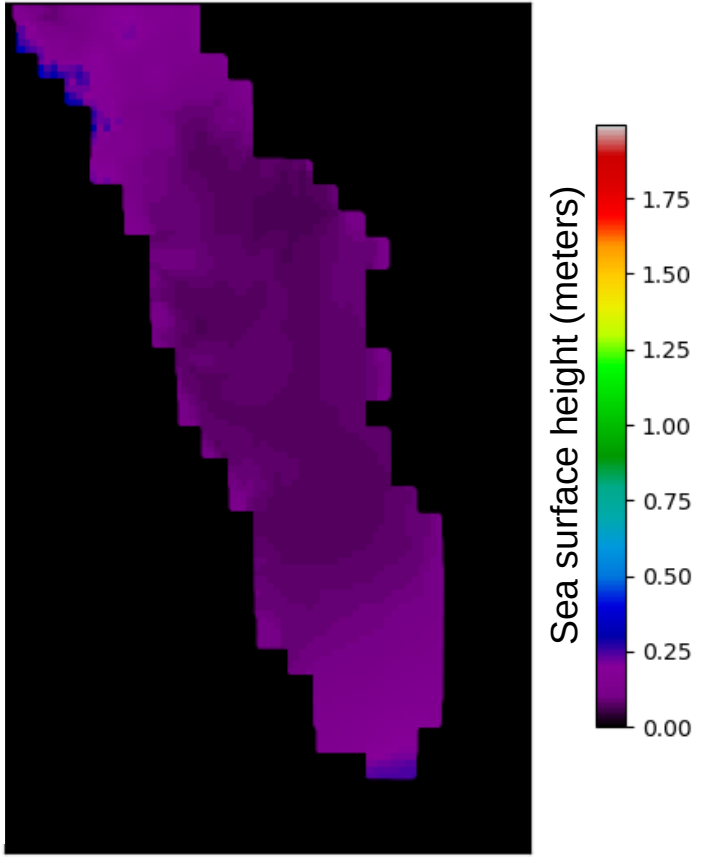


- Dependent variable: Resulting maximum water heights in Palu bay

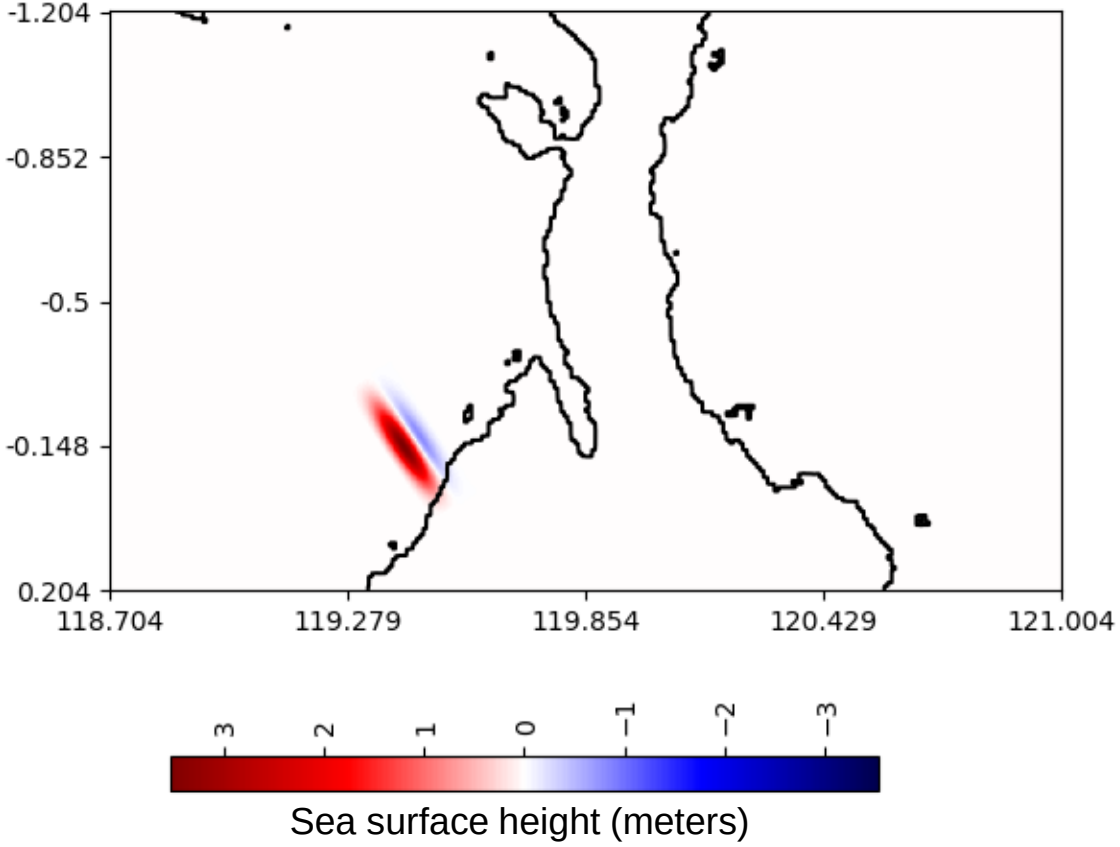
Sulawesi, Indonesia
Seismic Initial condition



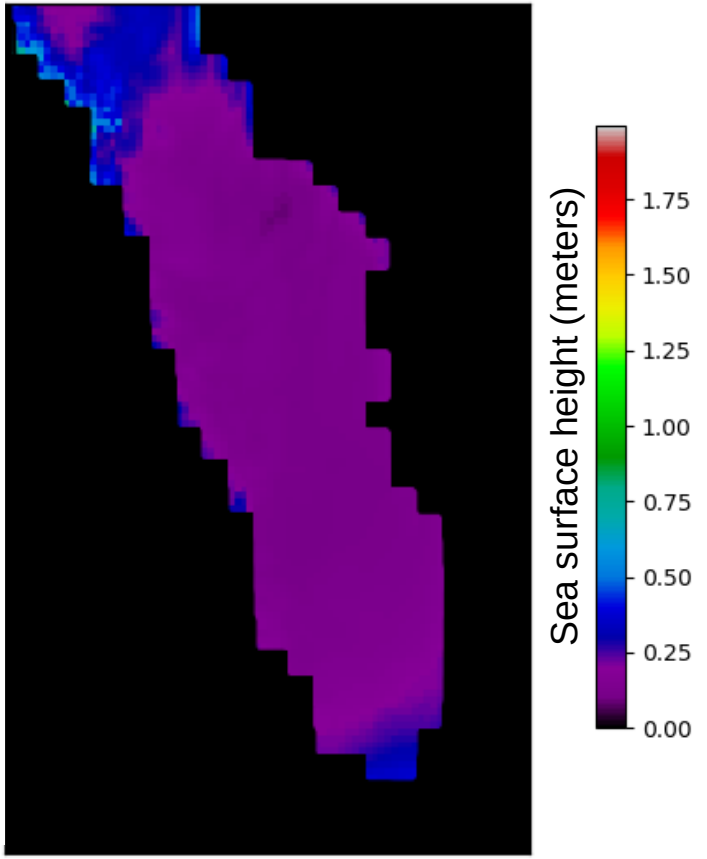
Resulting maximum heights in Palu bay



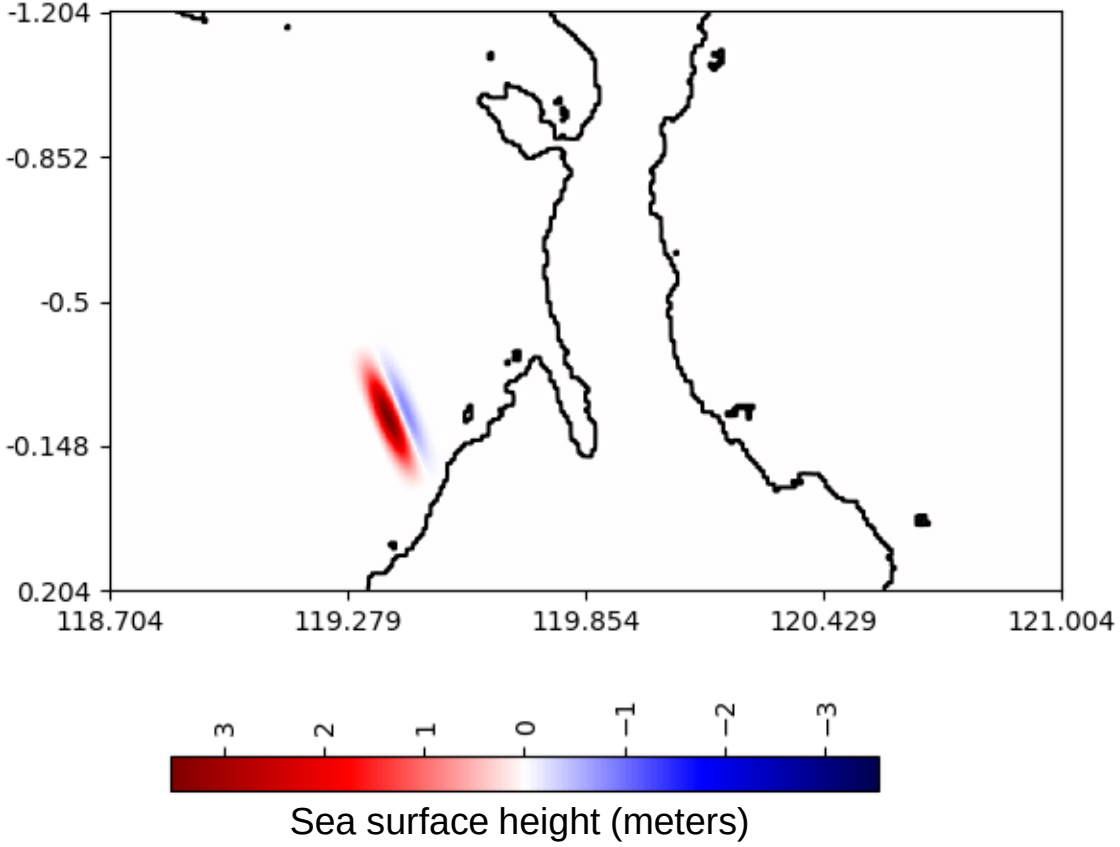
Sulawesi, Indonesia
Seismic Initial condition



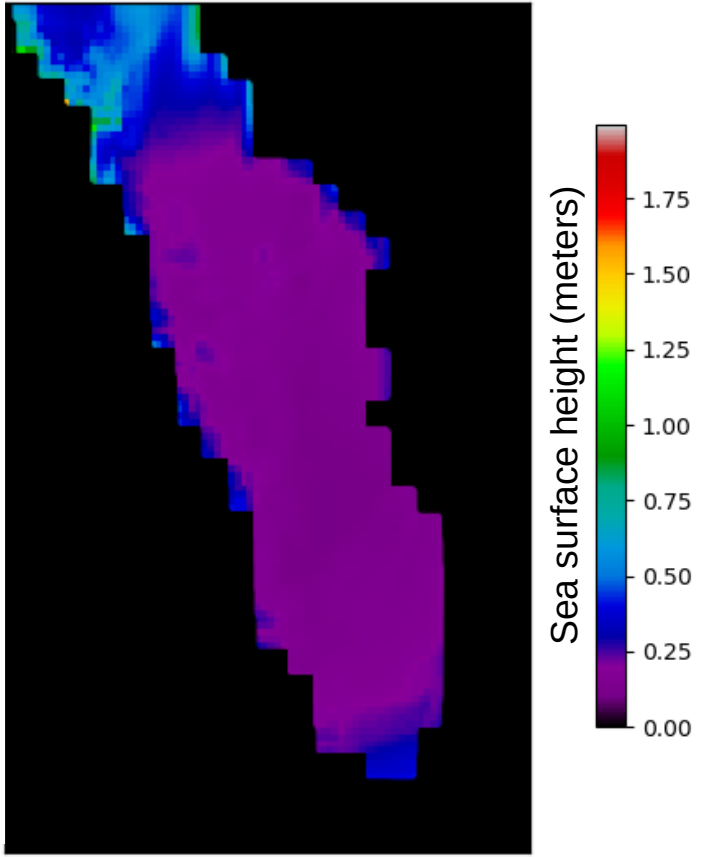
Resulting maximum heights in Palu bay



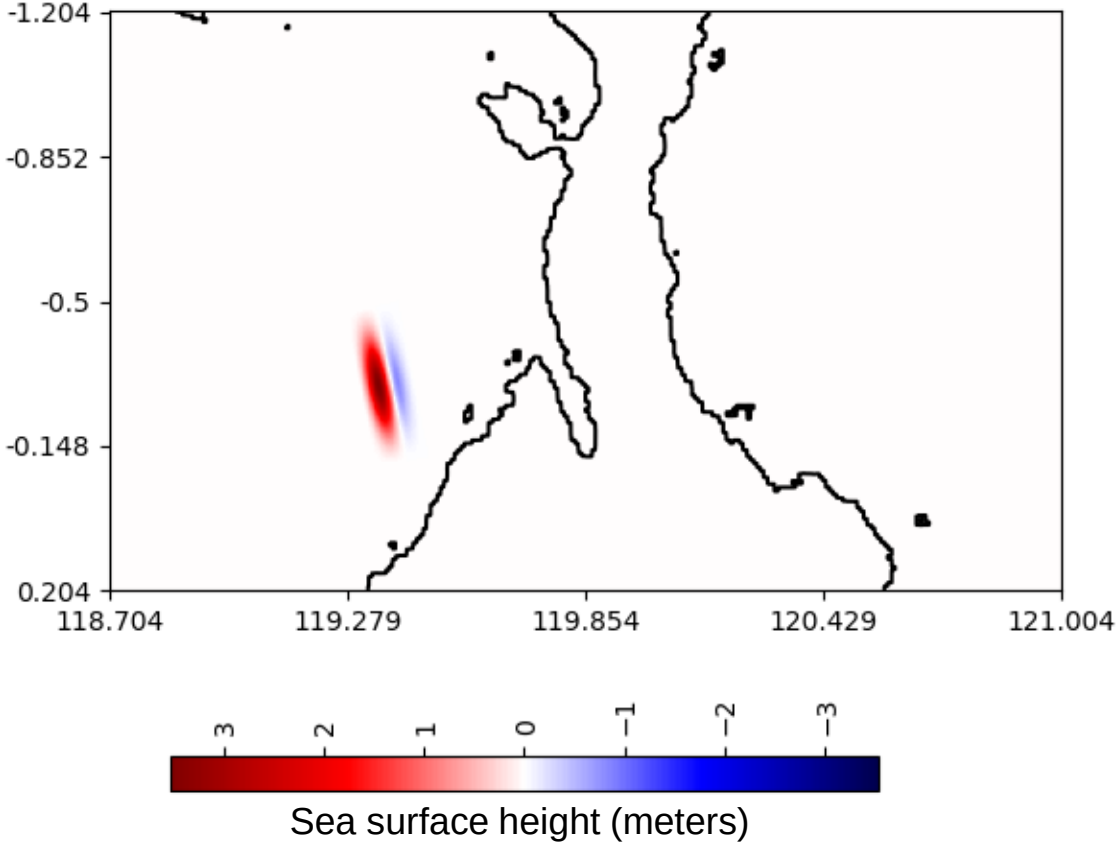
Sulawesi, Indonesia
Seismic Initial condition



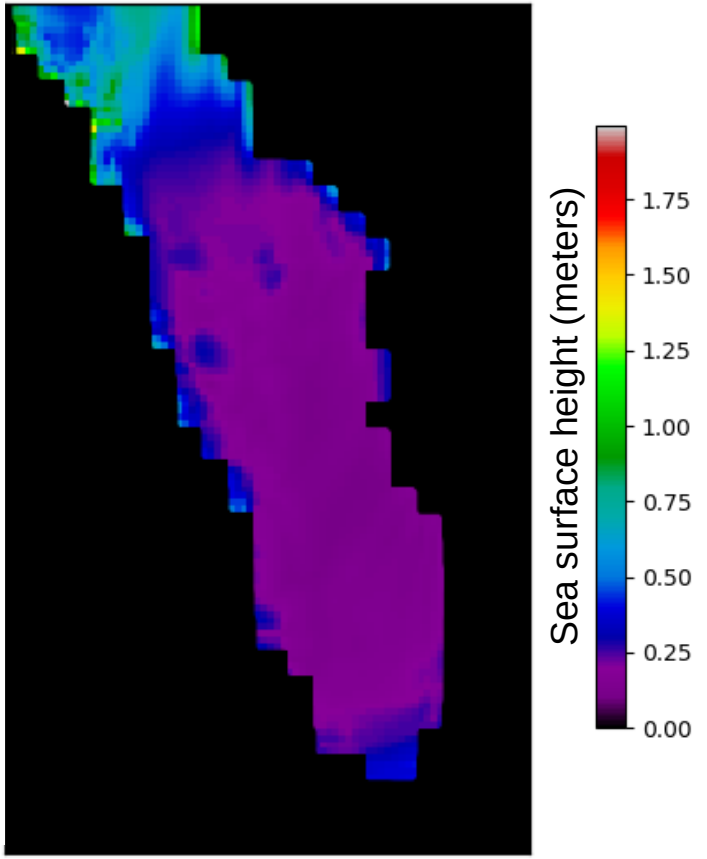
Resulting maximum heights in Palu bay



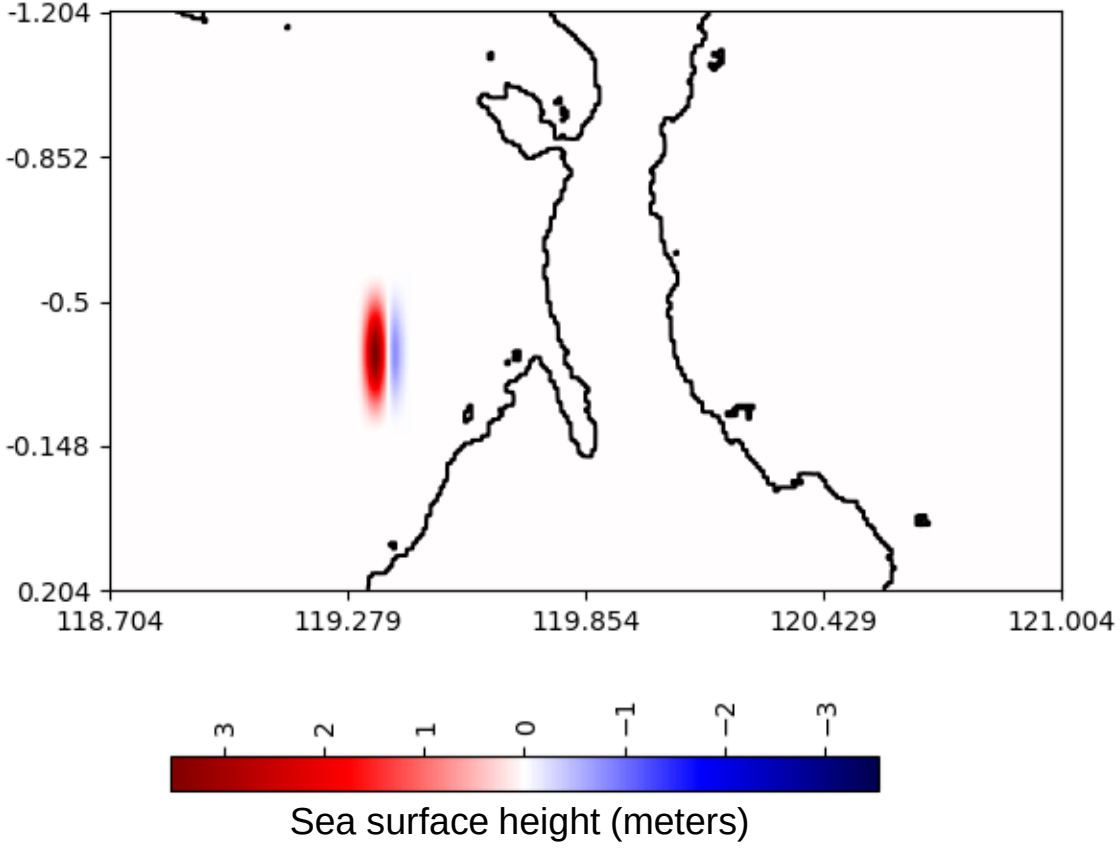
Sulawesi, Indonesia
Seismic Initial condition



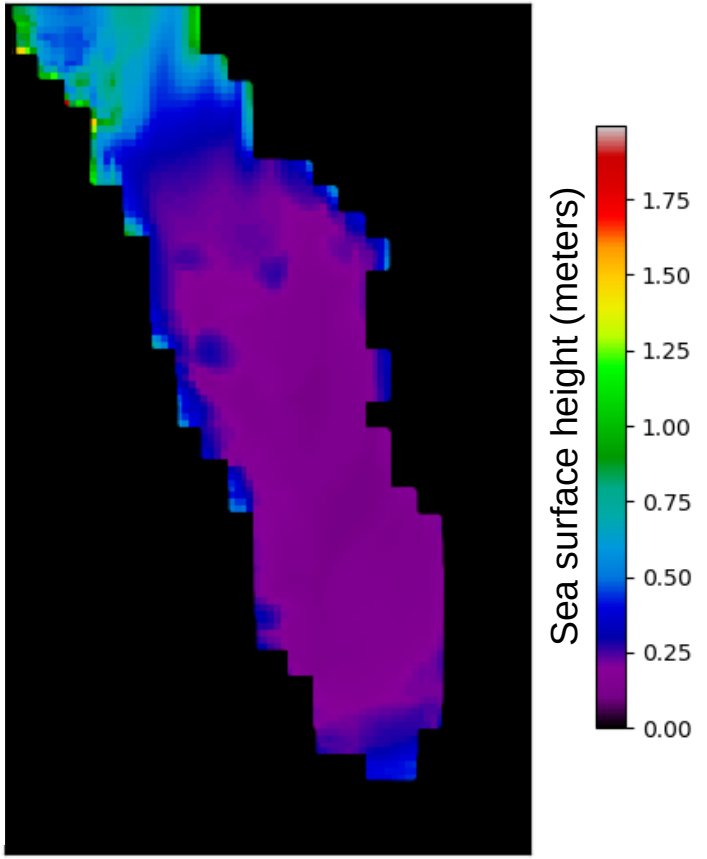
Resulting maximum heights in Palu bay



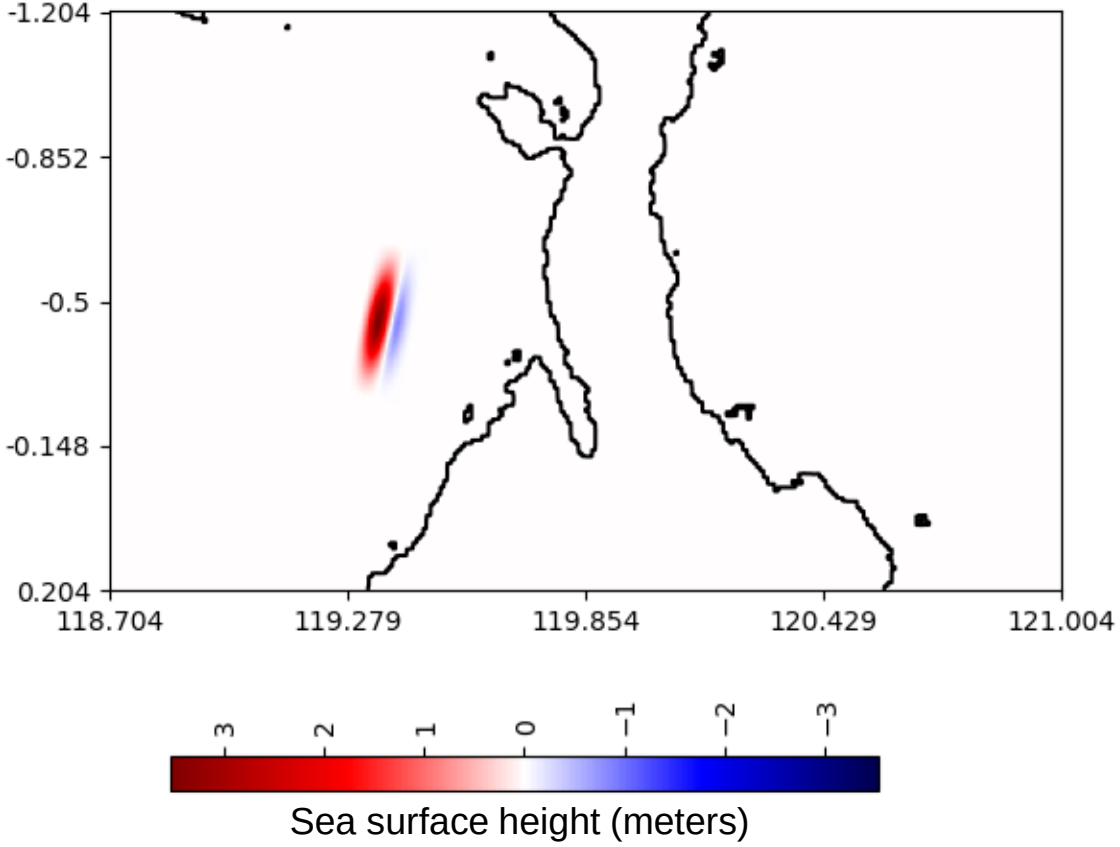
Sulawesi, Indonesia
Seismic Initial condition



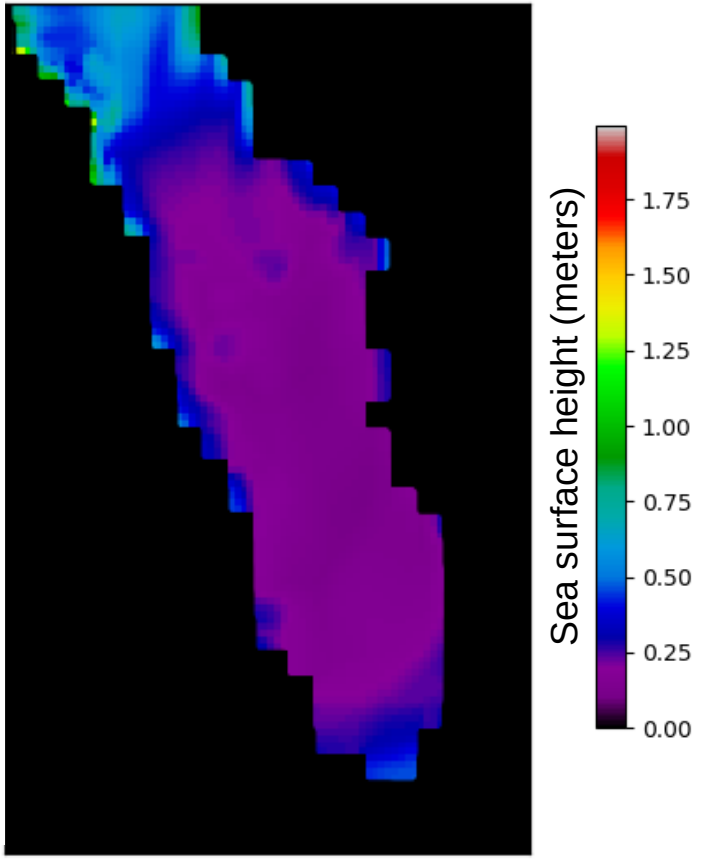
Resulting maximum heights in Palu bay



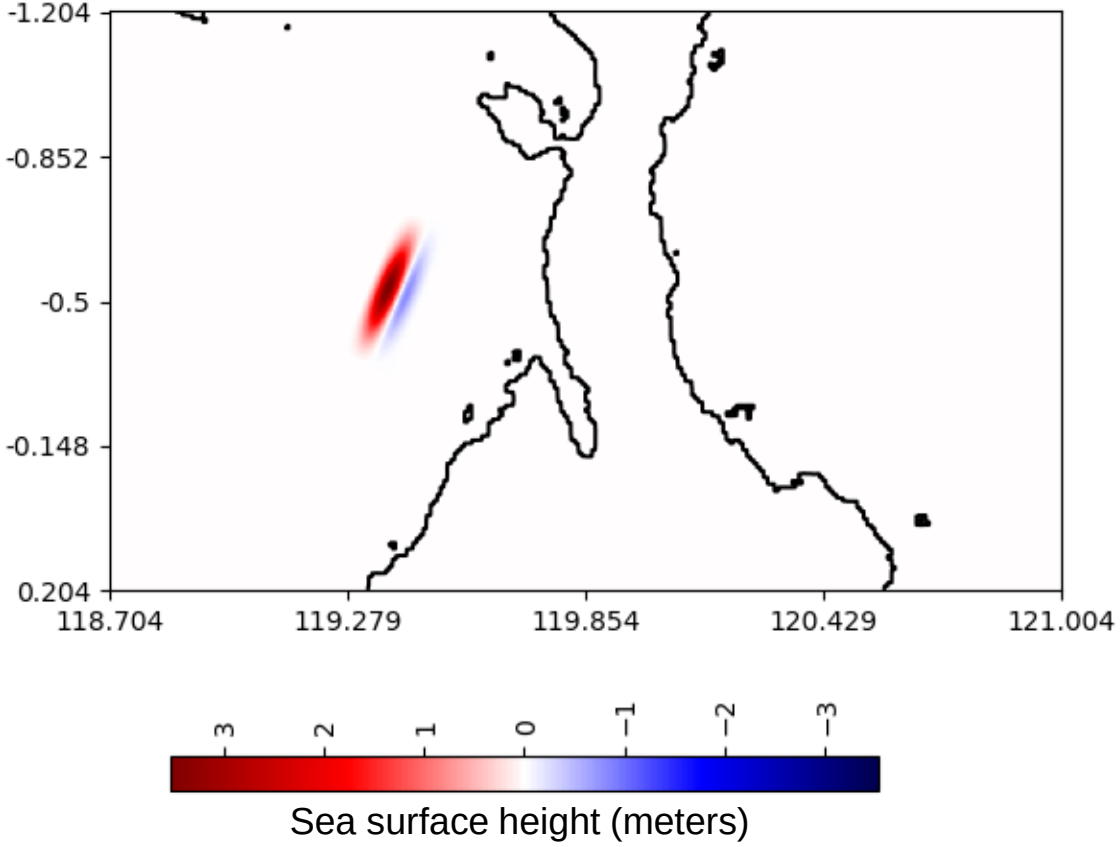
Sulawesi, Indonesia
Seismic Initial condition



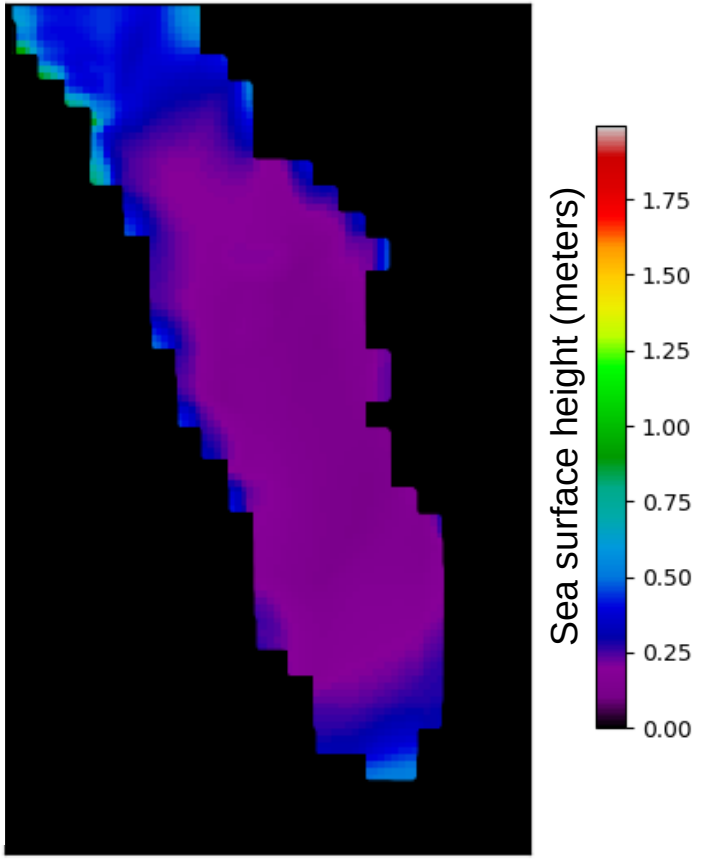
Resulting maximum heights in Palu bay



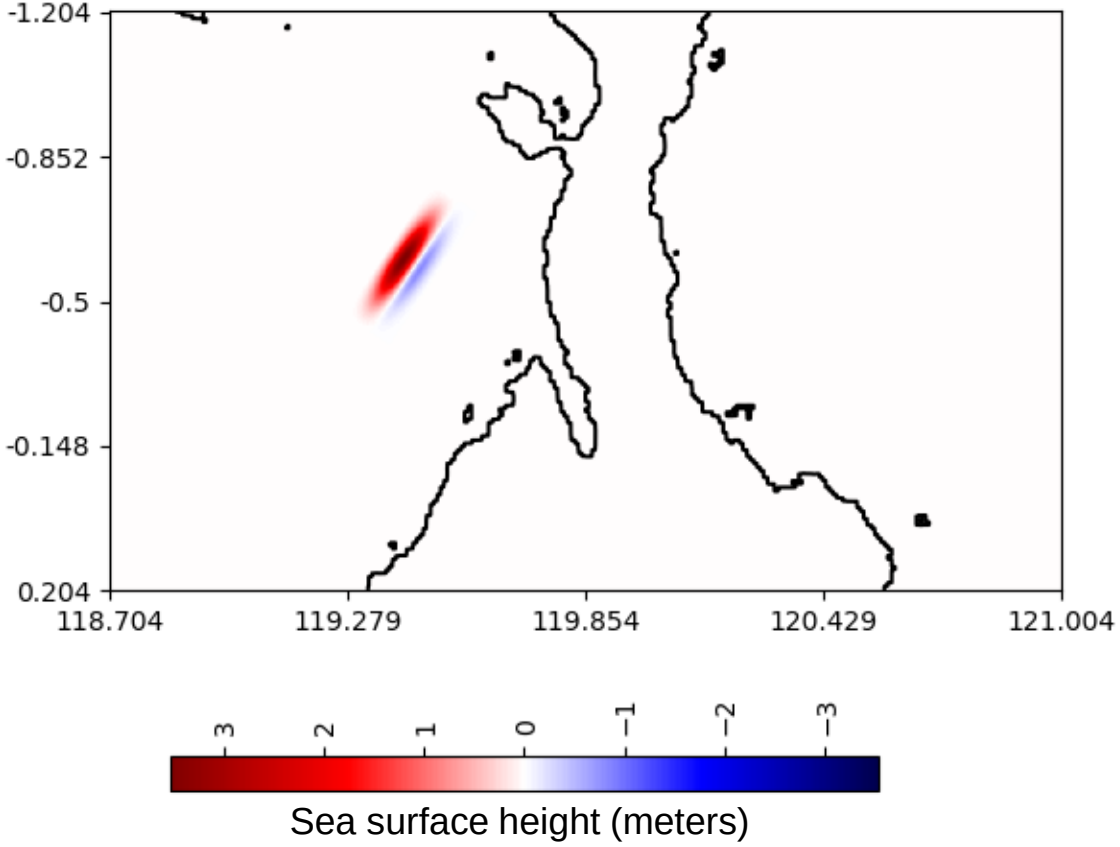
Sulawesi, Indonesia
Seismic Initial condition



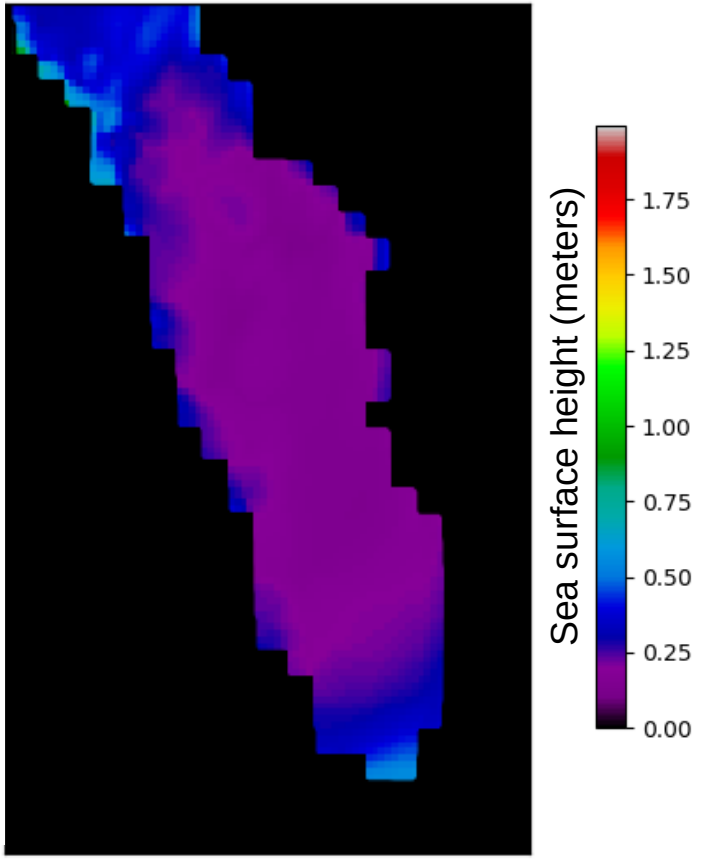
Resulting maximum heights in Palu bay



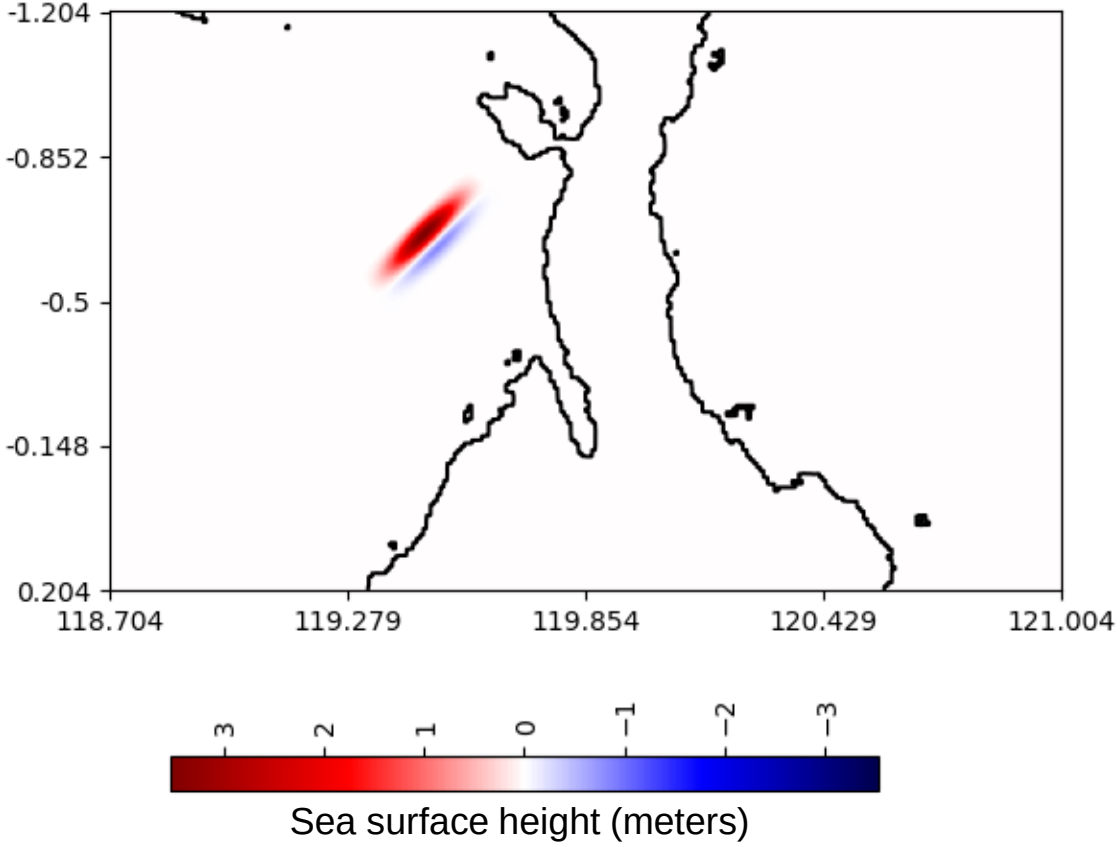
Sulawesi, Indonesia
Seismic Initial condition



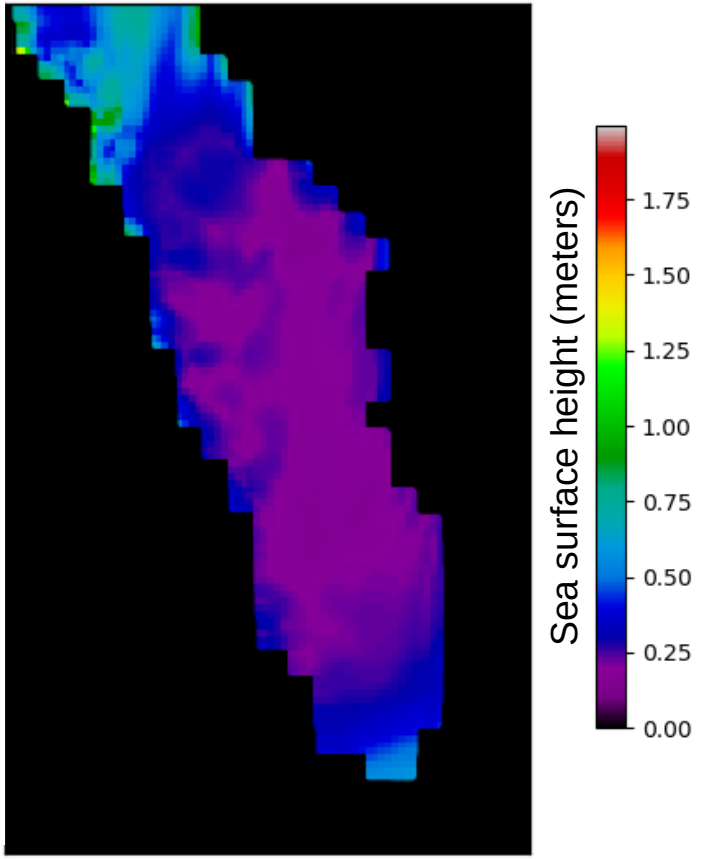
Resulting maximum heights in Palu bay



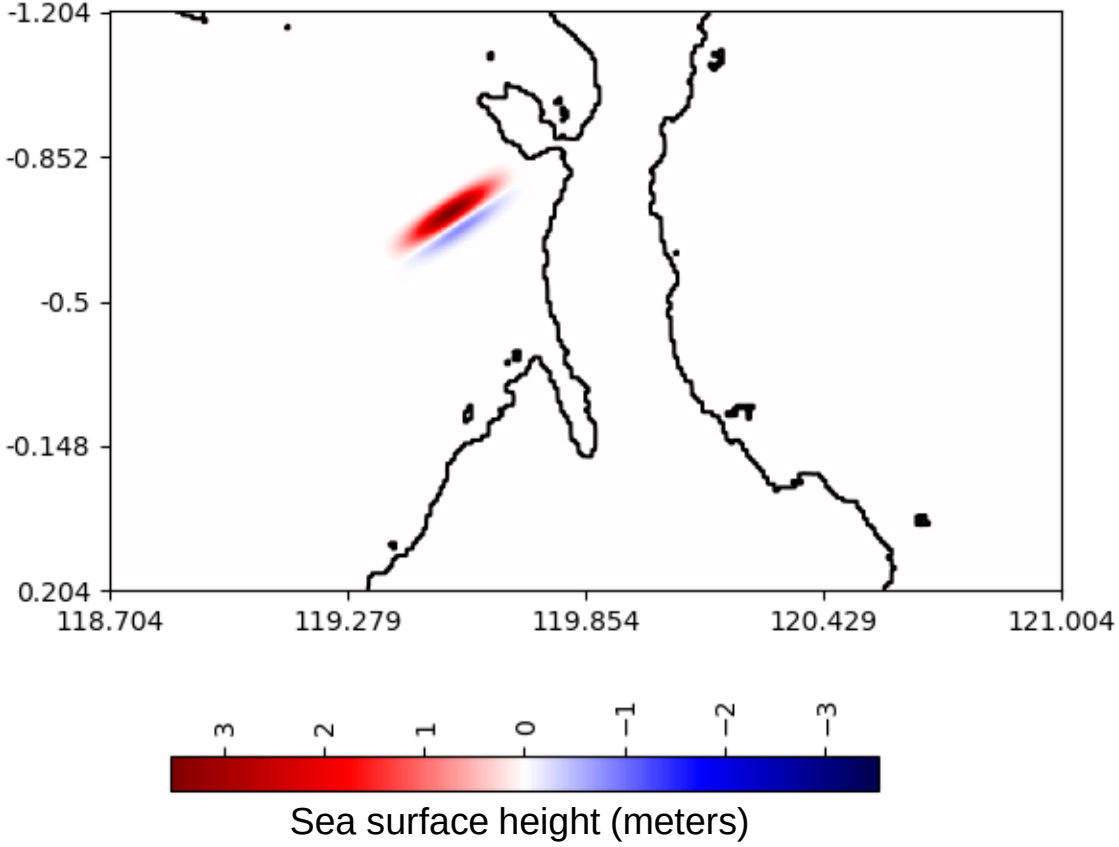
Sulawesi, Indonesia
Seismic Initial condition



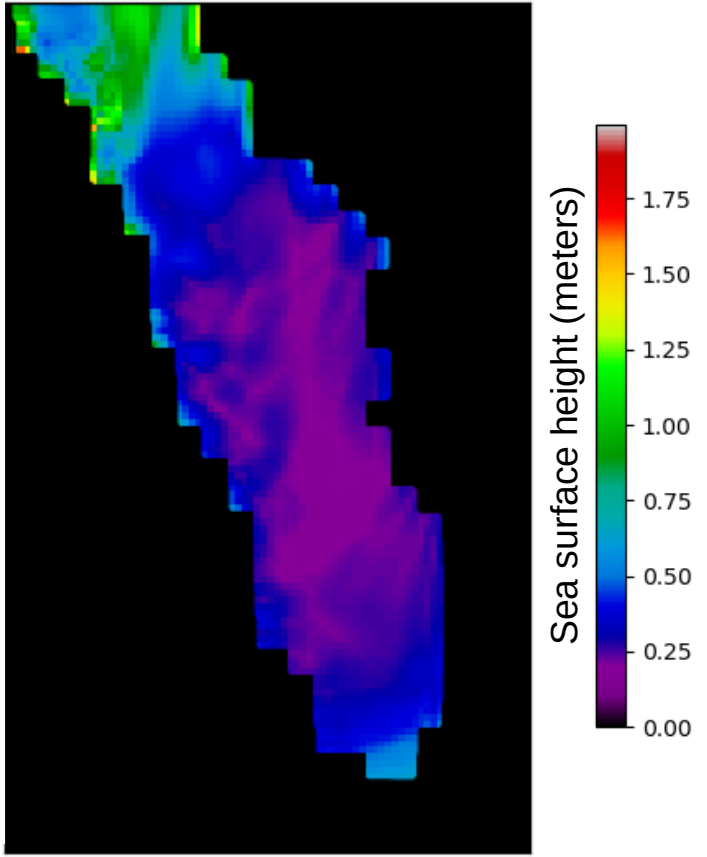
Resulting maximum heights in Palu bay



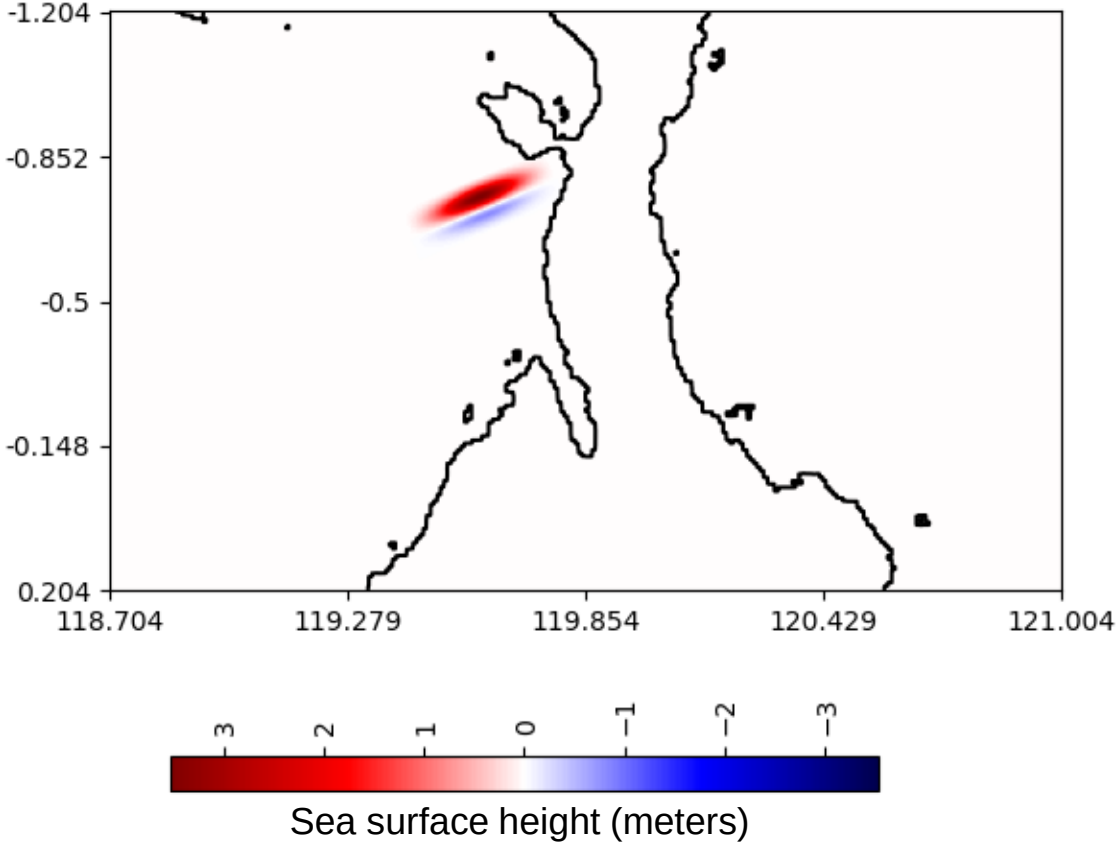
Sulawesi, Indonesia
Seismic Initial condition



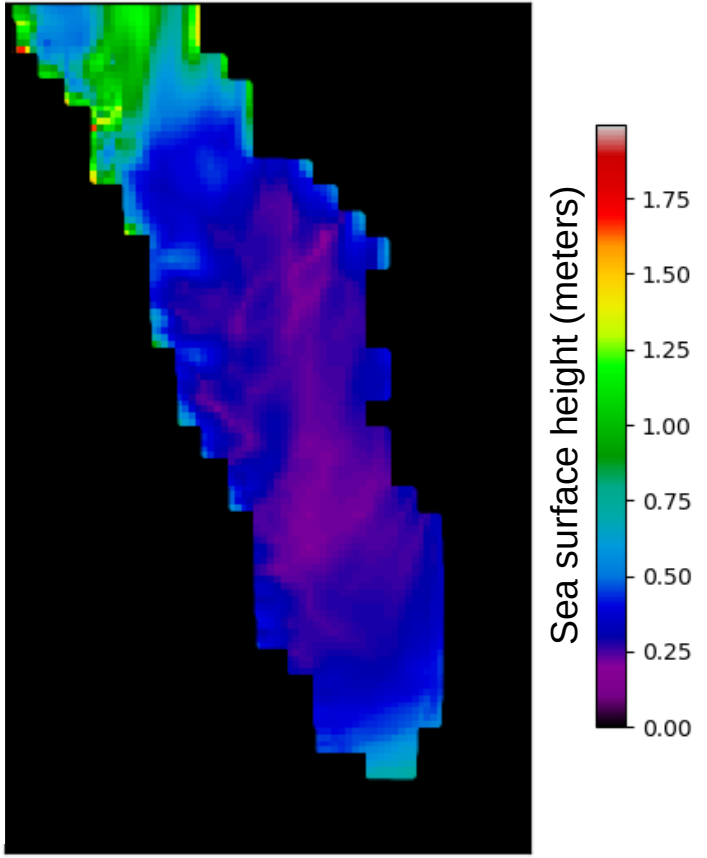
Resulting maximum heights in Palu bay



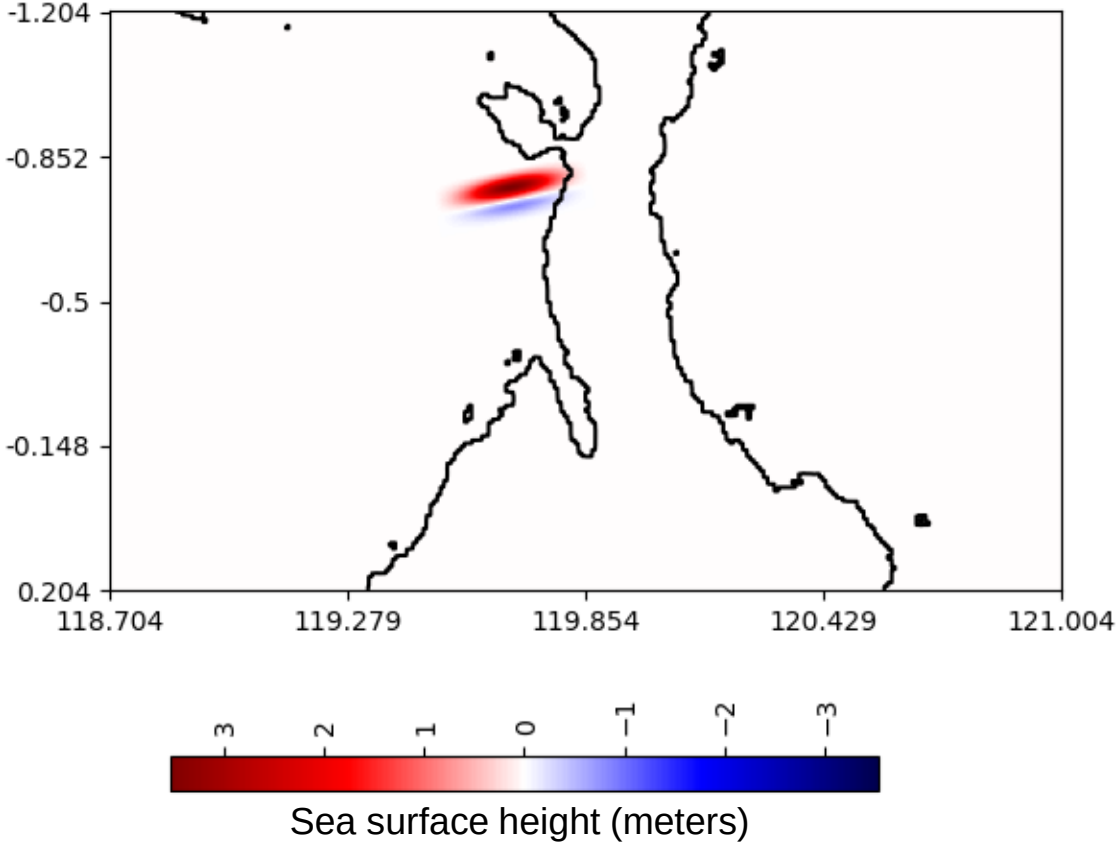
Sulawesi, Indonesia
Seismic Initial condition



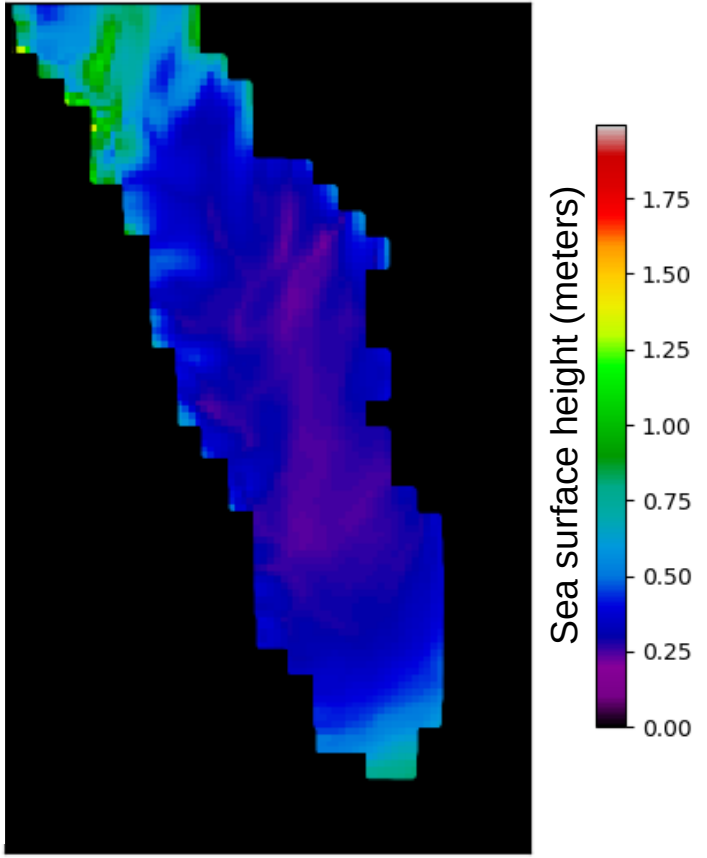
Resulting maximum heights in Palu bay



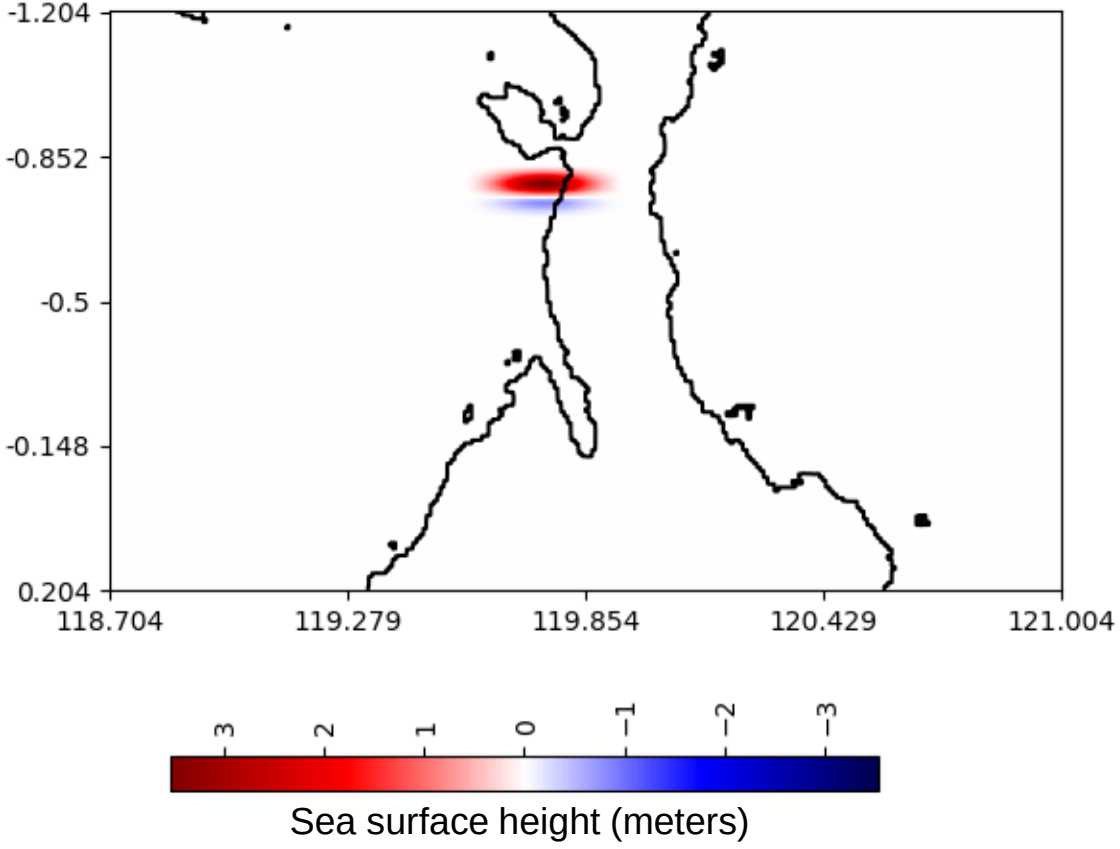
Sulawesi, Indonesia
Seismic Initial condition



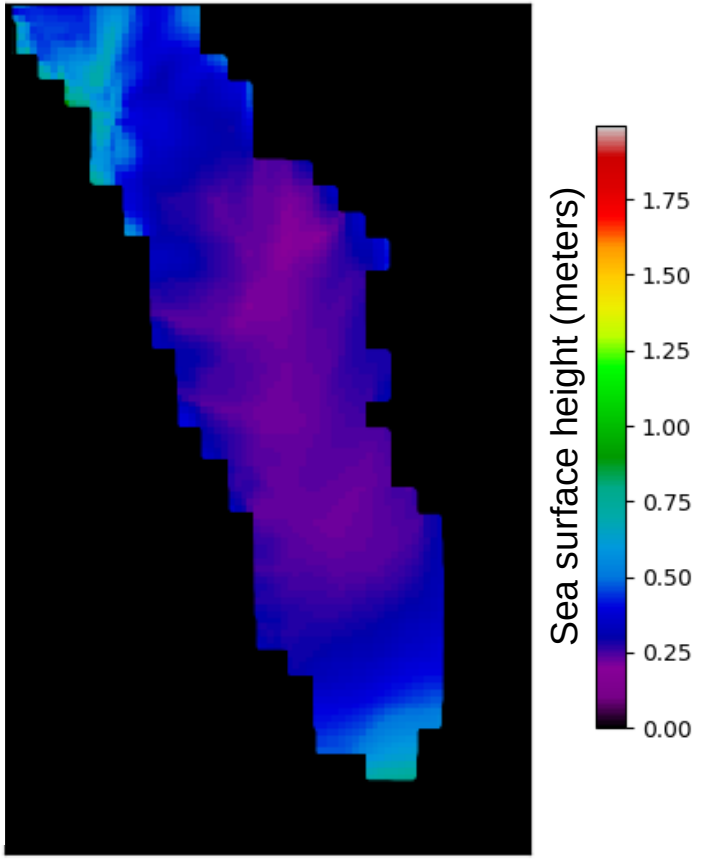
Resulting maximum heights in Palu bay



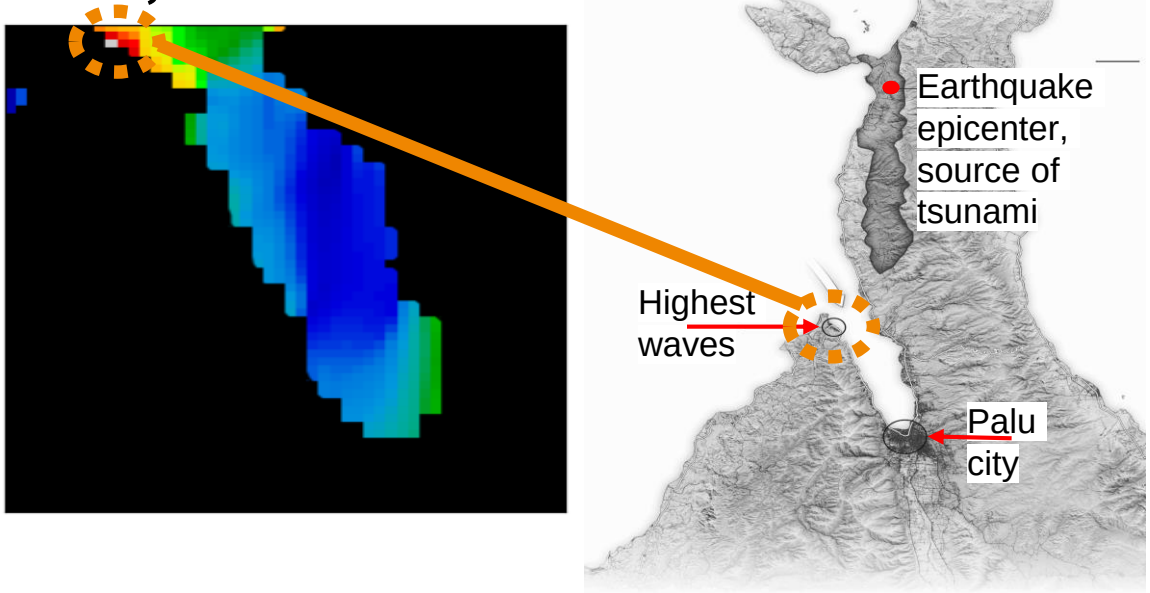
Sulawesi, Indonesia
Seismic Initial condition



Resulting maximum heights in Palu bay



Analysis

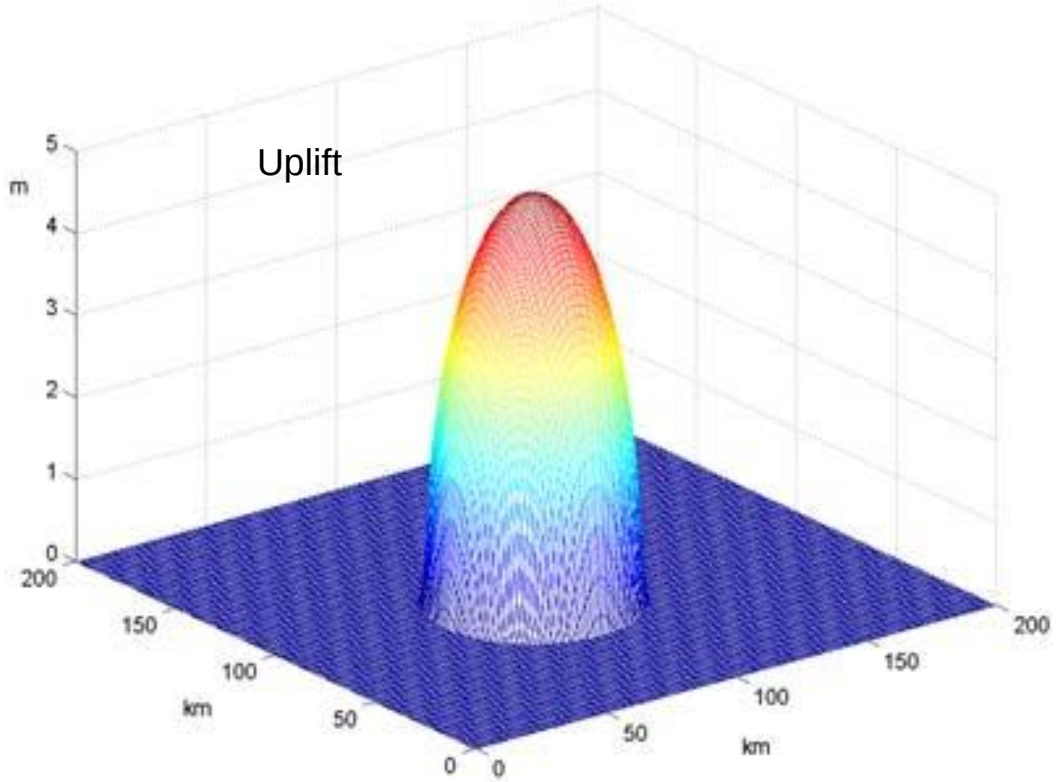


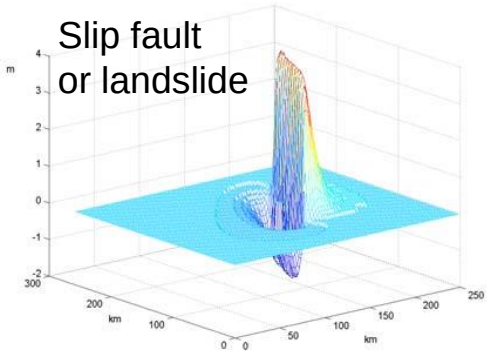
(New York Times)

- Maximum wave heights were largest when the tsunami was pointing directly down Palu bay
- Tsunamis originating lower than angle of Palu bay have much smaller effects.

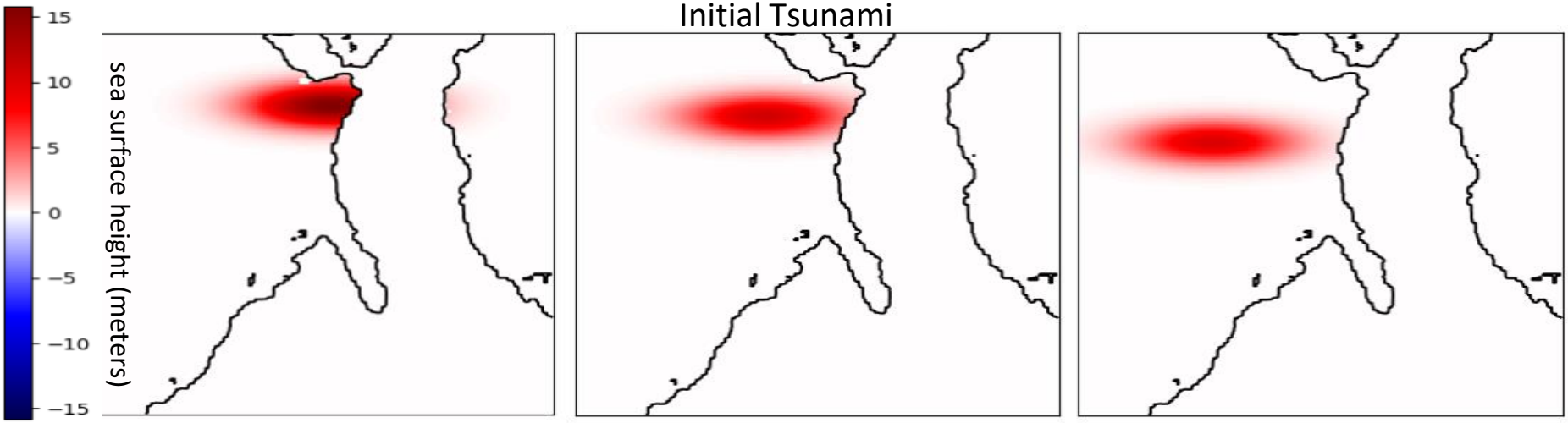
observed even larger maximum wave heights near the mouth of the bay, where the highest waves really were.

Effect of Initial Condition

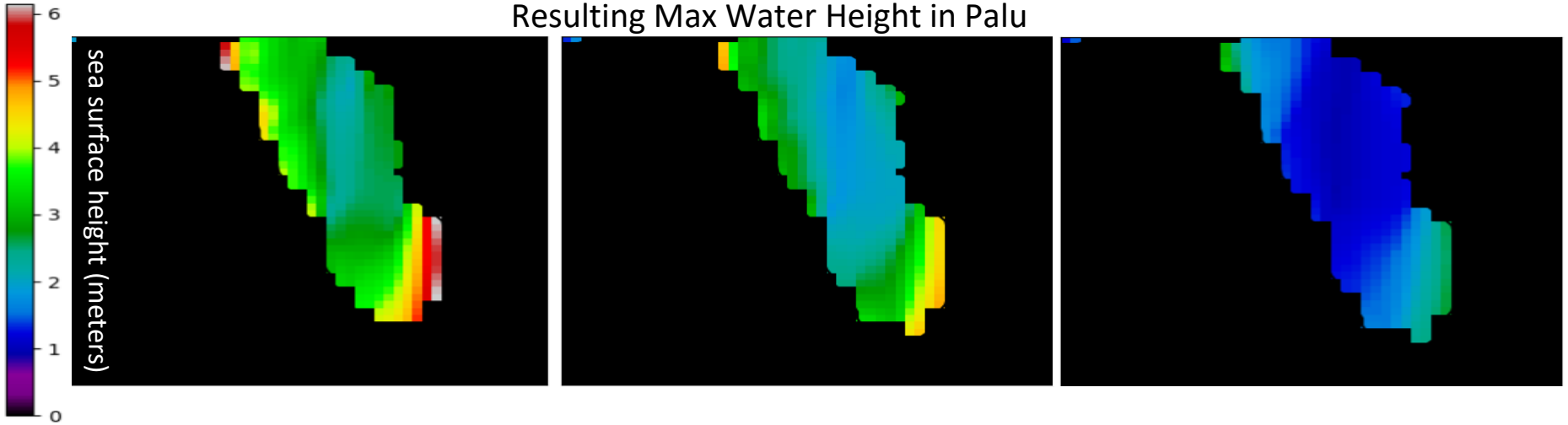




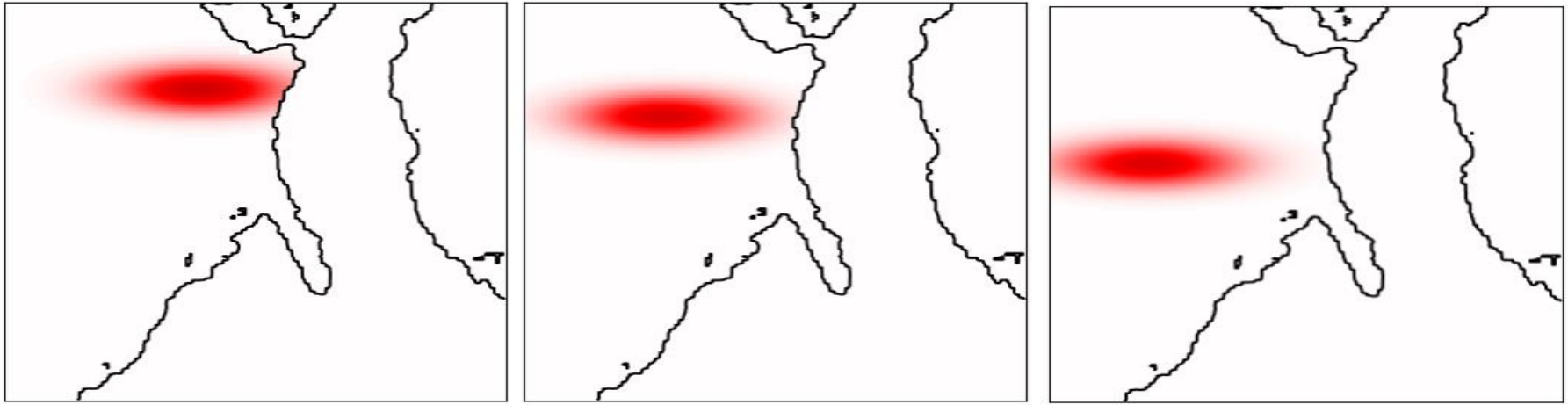
Initial Tsunami



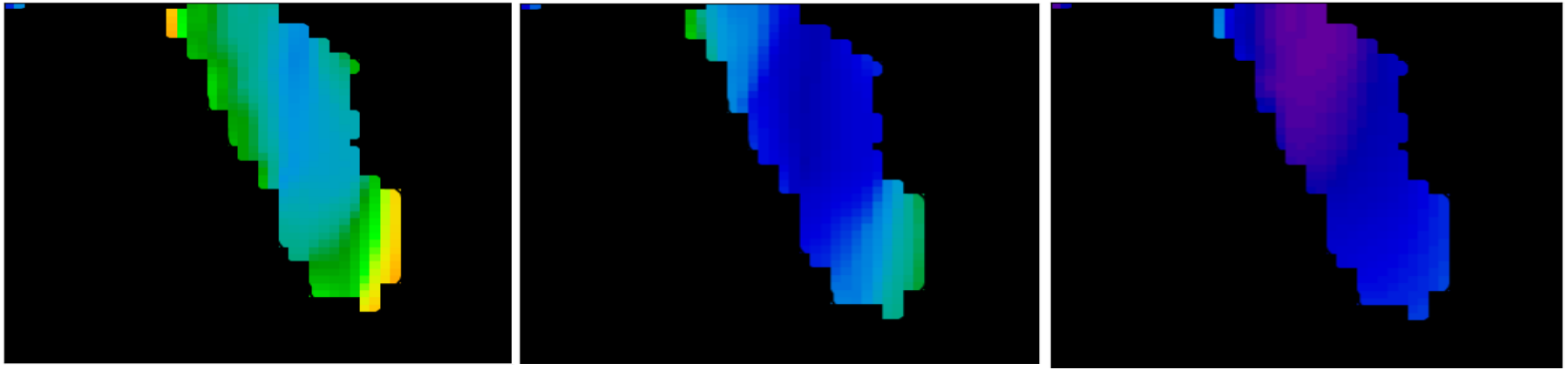
Resulting Max Water Height in Palu



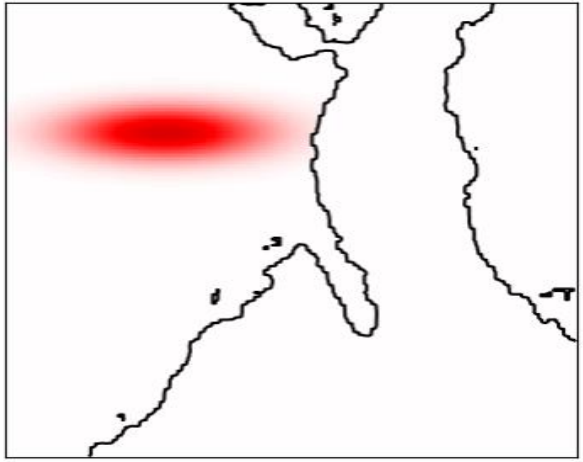
Initial Tsunami

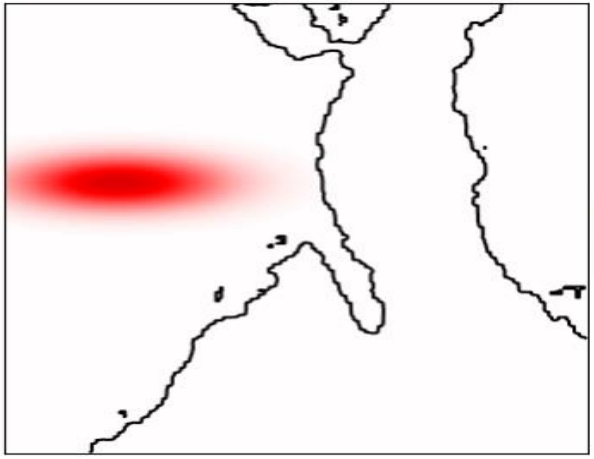


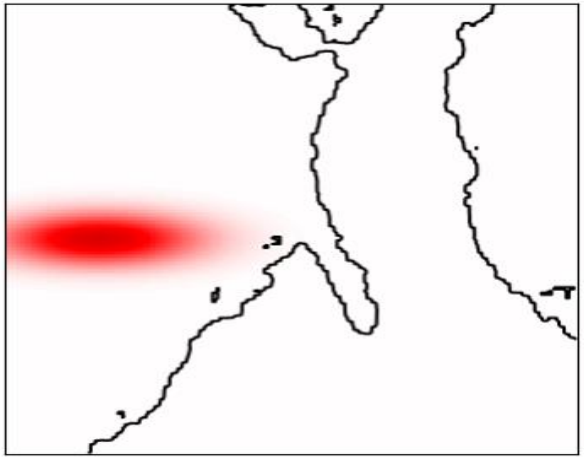
Resulting Max Water Height in Palu



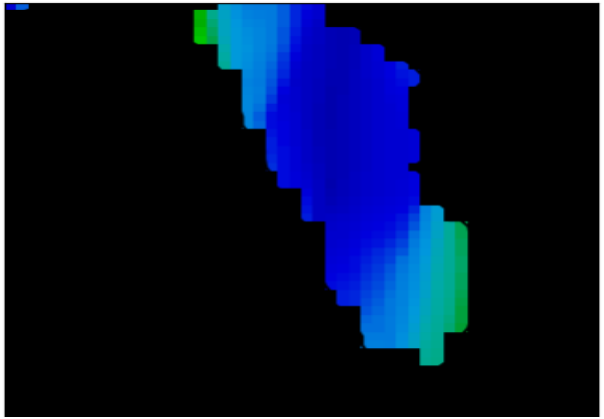
Initial Tsunami

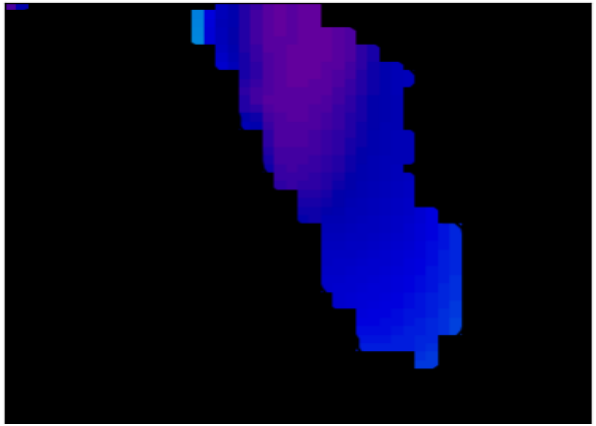


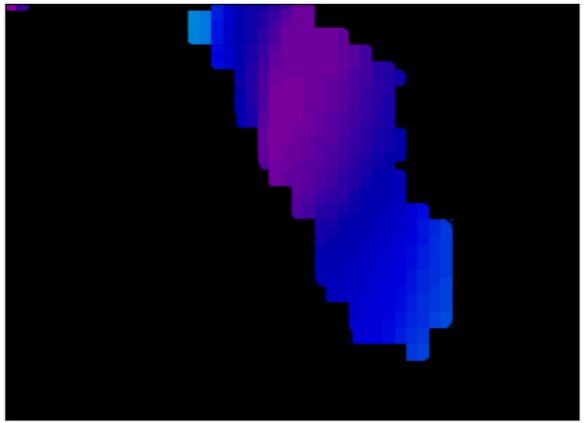




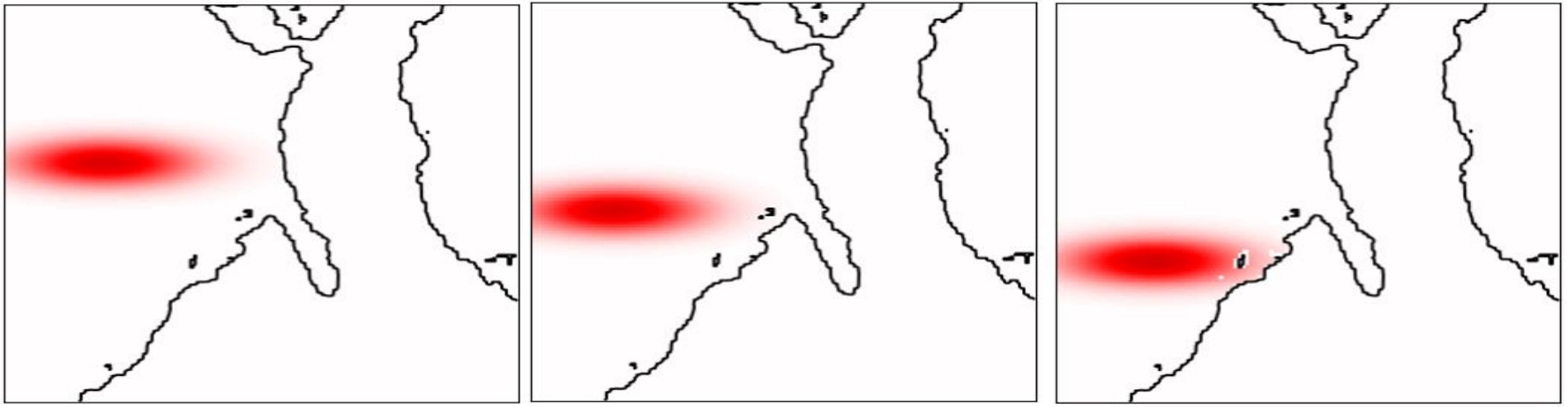
Resulting Max Water Height in Palu



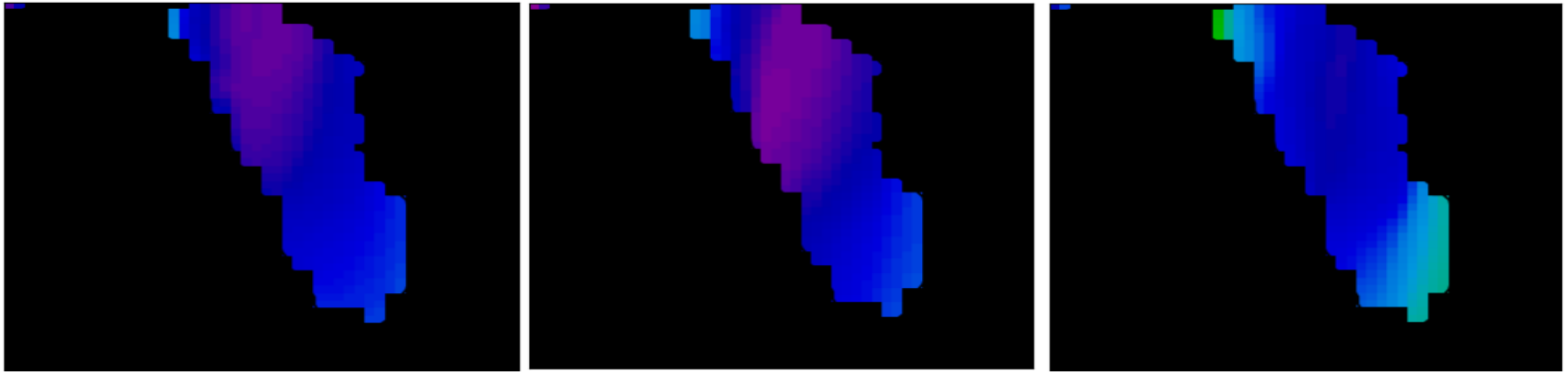




Initial Tsunami



Resulting Max Water Height in Palu



Method: Simulation via The Shallow Water Equations

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x}\left((\eta + h)\,u\right) - \frac{\partial}{\partial y}\left((\eta + h)\,v\right)$$

$$\frac{\partial u}{\partial t} = Coriolis + Advection + Gravity + Attenuation$$

$$= +fv + \left(\kappa \nabla^2 u - (u, v) \cdot \vec{\nabla} u\right) - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho(h+\eta)}\mu u\sqrt{u^2 + v^2}$$

$$= +fv + \left(\kappa\frac{\partial^2 u}{\partial x^2} + \kappa\frac{\partial^2 u}{\partial y^2} - u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y}\right) - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho(h+\eta)}\mu u\sqrt{u^2 + v^2}$$

$$\frac{\partial v}{\partial t} = -fu + \left(\kappa \nabla^2 v - (u, v) \cdot \vec{\nabla} v\right) - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho(h+\eta)}\mu v\sqrt{u^2 + v^2}$$

$$= -fu + \left(\kappa\frac{\partial^2 v}{\partial x^2} + \kappa\frac{\partial^2 v}{\partial y^2} - u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y}\right) - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho(h+\eta)}\mu v\sqrt{u^2 + v^2}$$

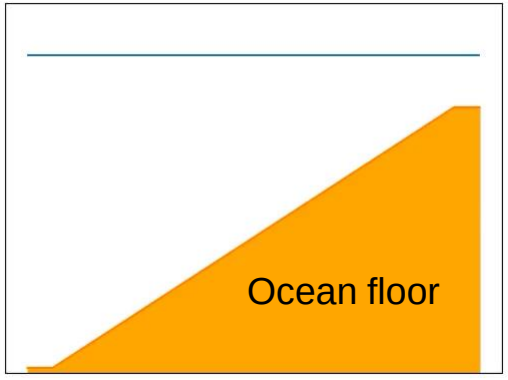
Used forward-backward predictor-corrector integration method for accuracy and stability

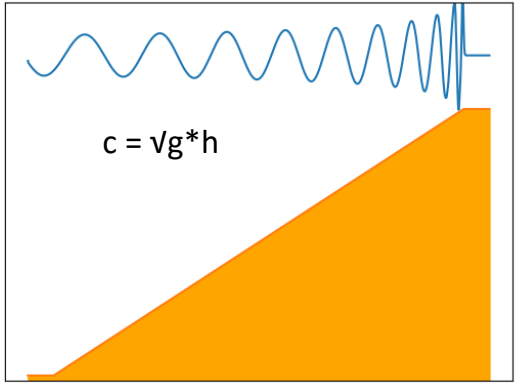
Need to satisfy CFL condition or finite element instabilities arise

dt < ½ dx / maximum wave speed

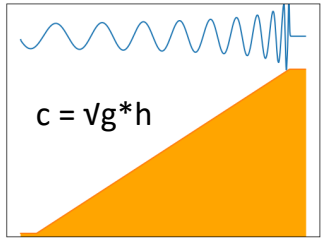
Advection term caused instabilities

Added friction term and viscous term to diffuse small-scale spikes in energy





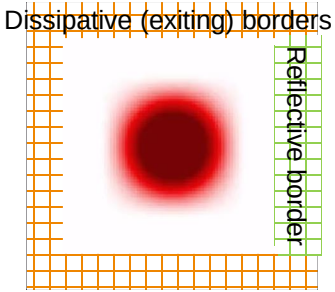
Verification & validation



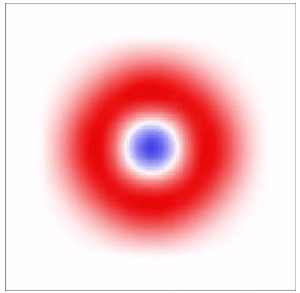
- Created unit test for wave speed
  - Assuming n is much smaller than h wave speed can be approximated
    - c = √g*h
  - Calculated how far the wave traveled and compare to expected value of √g*h

Validation

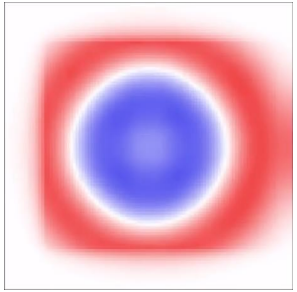
- Used same equations as Caribbean paper with validation, and verified correct implementation
- Watch initial hump propagate out just like a stone in a lake

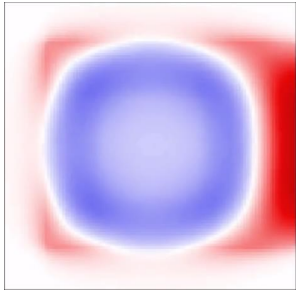


Initial disturbance

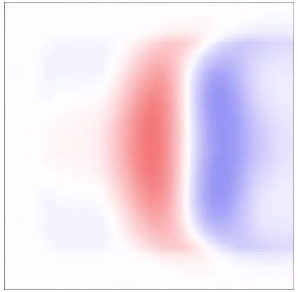


Collapses into ring

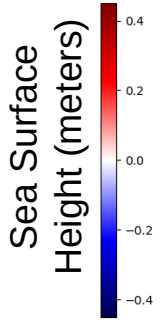




Piles up at reflective wall



Reflects & propagates



Conclusion & Future

- Accomplished my goal of creating water physics simulation from scratch.
- Key insights into the Palu case:
  - tsunamis are more severe in Palu when north of the angle of Palu bay.
  - But tsunamis can be guided to Palu by the coast.
  - Type of tsunami had small effect
  - Bathymetry amplifies impact: channels and slopes
- In the future, I may continue this project by doing larger scale simulations.
- Could run a simulation in the Arctic, where the stronger Coriolis force could cause unexpected effects.

Works Cited & Acknowledgements

Mentor: Mark Peterson

Ali, Hani, et al. “APPLICATION OF THE SHALLOW WATER EQUATIONS TO REAL FLOODING CASE.” Proceedings of the VII European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS Congress 2016), Institute of Structural Analysis and Antiseismic Research School of Civil Engineering National Technical University of Athens (NTUA) Greece, 2016, pp. 735–49. Crossref, doi:10.7712/100016.1849.10225.

Center, National Geophysical Data. Tsunami Events Full Search, Sort by Date, Country. https://www.ngdc.noaa.gov/nndc/struts/results?bt_0=&st_0=&type_8=EXACT&query_8=None+Selected&op_14=eq&v_14=&st_1=&bt_2=&st_2=&bt_1=&bt_10=&st_10=&ge_9=&le_9=&bt_3=&st_3=&type_19=EXACT&query_19=74&op_17=eq&v_17=&bt_20=&st_20=&bt_13=&st_13=&bt_16=&st_16=&bt_6=&st_6=&ge_21=&le_21=&bt_11=&st_11=&ge_22=&le_22=&d=7&t=101650&s=70. Accessed 16 Dec. 2018.

Coastal National Elevation Database (CoNED) Project - Topobathymetric Digital Elevation Model (TBDEM) | The Long Term Archive. https://lta.cr.usgs.gov/coned_tbdem. Accessed 6 Dec. 2018.

Indonesia Tsunami Worsened by Shape of Palu Bay: Scientists. https://www.yahoo.com/news/indonesia-tsunami-worsened-shape-palu-bay-scientists-025002225.html. Accessed 16 Jan. 2019.

Kristina, W. Effective Coastal Boundary Conditions for Tsunami Simulations. 2014.

---. Effective Coastal Boundary Conditions for Tsunami Simulations. 2014.

Randall, David A. “The Shallow Water Equations.” Selected Papers, p. 11.

Shallow.Pdf. http://kestrel.nmt.edu/~raymond/classes/ph589/notes/shallow/shallow.pdf. Accessed 6 Dec. 2018.

“Simulating Tsunamis in Coastal Channels and Bays.” Google Docs, https://docs.google.com/presentation/d/1r-KPPCN_ASiEi0QDy-BieDRNACZmZleDxC-yyBBvmlo/edit?ouid=100907157052794008657&usp=slides_home&ths=true&usp=embed_facebook. Accessed 16 Jan. 2019.

Synolakis, C. E., et al. “Validation and Verification of Tsunami Numerical Models.” Pure and Applied Geophysics, vol. 165, no. 11–12, Dec. 2008, pp. 2197–228. Crossref, doi:10.1007/s00024-004-0427-y.

---. “Validation and Verification of Tsunami Numerical Models.” Tsunami Science Four Years after the 2004 Indian Ocean Tsunami: Part I: Modelling and Hazard Assessment, edited by Phil R. Cummins et al., Birkhäuser Basel, 2009, pp. 2197–228. Springer Link, doi:10.1007/978-3-0346-0057-6_11.

Thacker, William Carlisle. “Some Exact Solutions to the Nonlinear Shallow-Water Wave Equations.” Journal of Fluid Mechanics, vol. 107, June 1981, pp. 499–508. Cambridge Core, doi:10.1017/S0022112081001882.

Time-Stepping Schemes Review - WikiROMS. https://www.myroms.org/wiki/Time-stepping_Schemes_Review#Forward-Backward_Feedback_.28RK2-FB.29. Accessed 6 Dec. 2018.

Tinti, S., and R. Tonini. The UBO-TSUFD Tsunami Inundation Model: Validation and Application to a Tsunami Case Study Focused on the City of Catania, Italy. 2013. www.earth-prints.org, doi:10.5194/nhess-13-1795-2013.

---. “The UBO-TSUFD Tsunami Inundation Model: Validation and Application to a Tsunami Case Study Focused on the City of Catania, Italy.” Natural Hazards and Earth System Sciences, vol. 13, no. 7, July 2013, pp. 1795–816. Crossref, doi:10.5194/nhess-13-1795-2013.

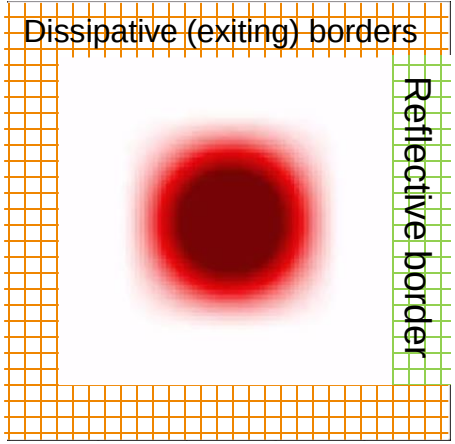
Watkins, Derek, et al. “Indonesia Earthquake and Tsunami: Before-and-After Photos of the Destruction.” The New York Times, 1 Oct. 2018. NYTimes.com, https://www.nytimes.com/interactive/2018/10/01/world/asia/map-tsunami-indonesia.html, https://www.theguardian.com/world/2018/oct/01/palu-earthquake-and-tsunami-what-we-know-so-far

Write-up, Harvey Segur, and Hiroki Yamamoto. Lecture 8: The Shallow-Water Equations. p. 9.

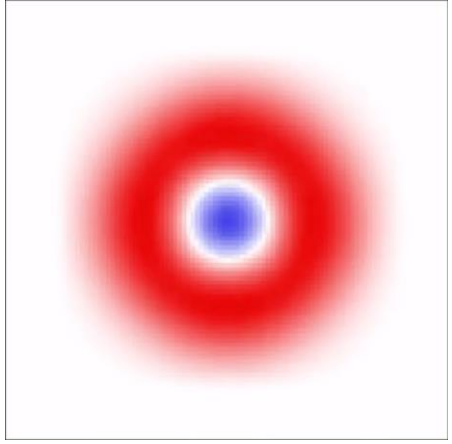
---. Lecture 8: The Shallow-Water Equations. p. 9.

Zaibo, Narcisse, et al. ESTIMATION OF FAR-FIELD TSUNAMI POTENTIAL FOR THE CARIBBEAN COAST BASED ON NUMERICAL SIMULATION. p. 21.

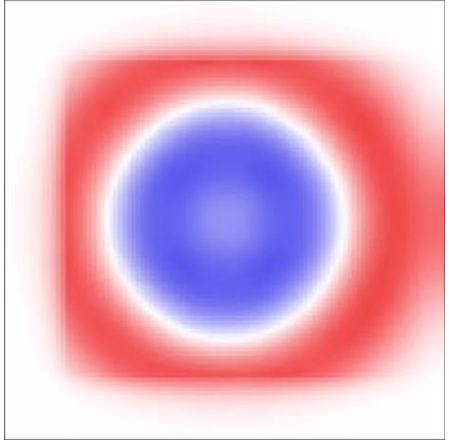
https://www.mechanismz.com/wp-content/uploads/2018/12/dessin-bateau-vague-genial-luxe-la-grande-vague-de-kanagawa-wikiwand-of-dessin-bateau-vague.jpg



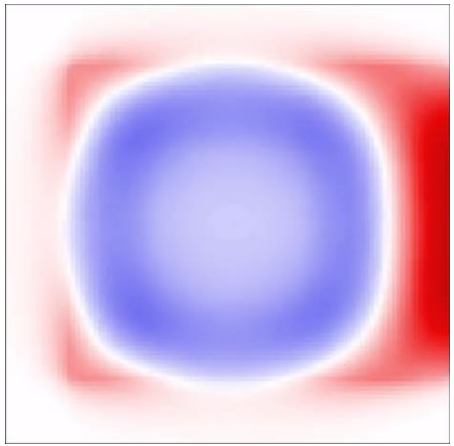
Initial disturbance



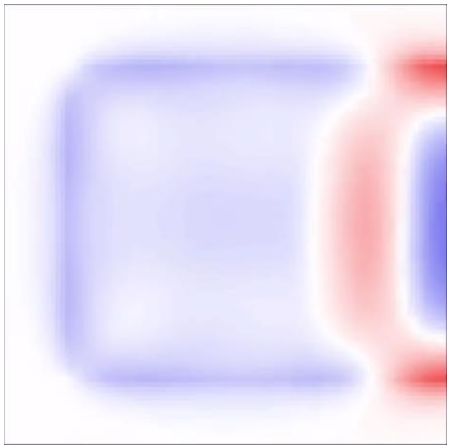
Collapses into ring



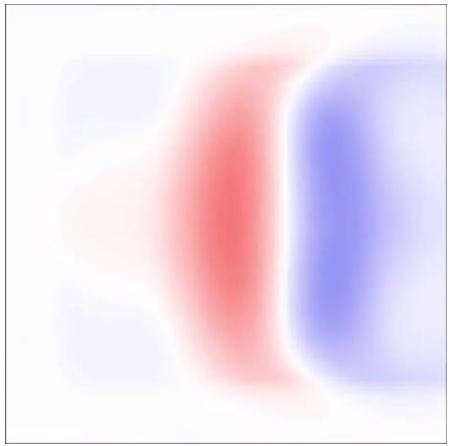
Begins to be dissipated



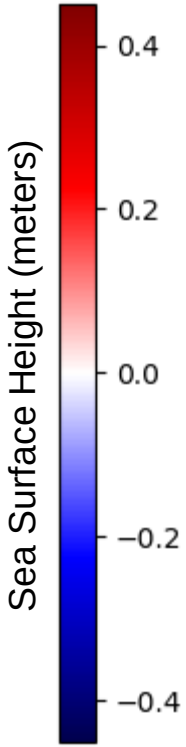
Piles up at reflective edge



Reflects



Reflection propagates



Refinement

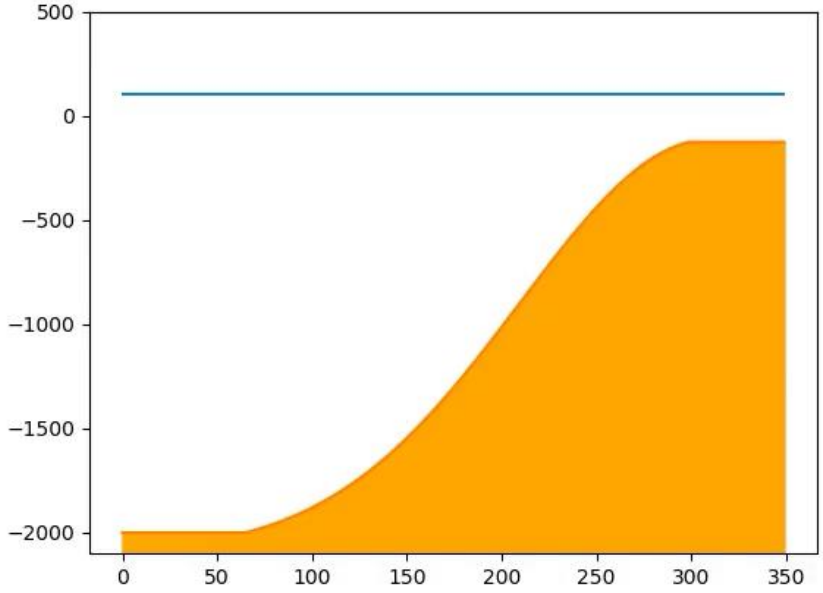
- Need to satisfy CFL condition or finite element instabilities arise
  - dt < ½ dx / maximum wave speed
- Advection term caused instabilities
  - Added friction term and viscous term to diffuse small-scale spikes in energy
- Waves reflected from grid boundaries interfered
  - Added attenuating margin to diffuse waves and so minimize reflection.
- Used forward-backward predictor-corrector integration method for accuracy and stability

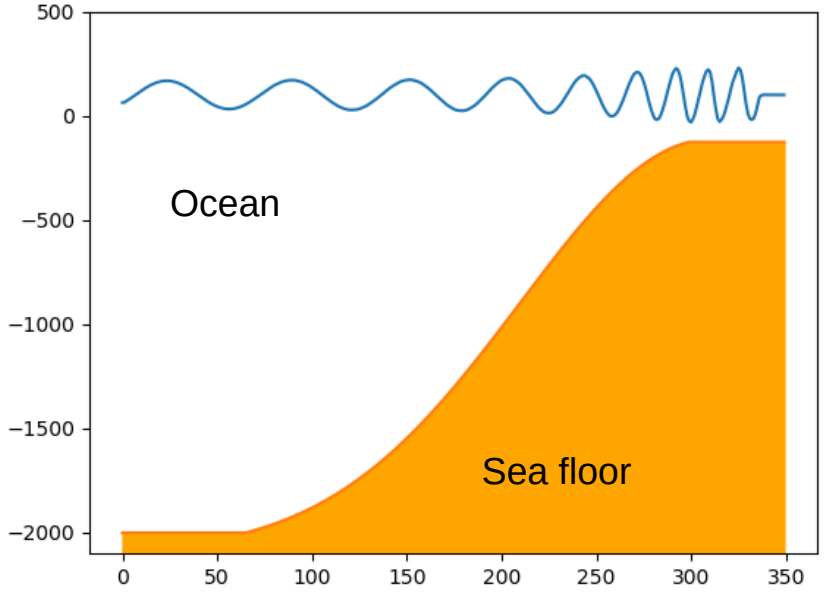
Verification & validation

- Created unit test for wave speed
  - Assuming n is much smaller than h wave speed can be approximated
    - $c = \sqrt{g*h}$
  - Calculated how far the wave traveled and compare to expected value of $\sqrt{g*h}$

Validation

- Used same equations as Caribbean paper with validation, and verified correct implementation
- Watch initial hump propagate out just like a stone in a lake





Waves go faster in deeper water and slower in shallower water. As waves approach the coast, going into shallower waters, they slow down. This causes the waves to compress, increasing in frequency and amplitude.