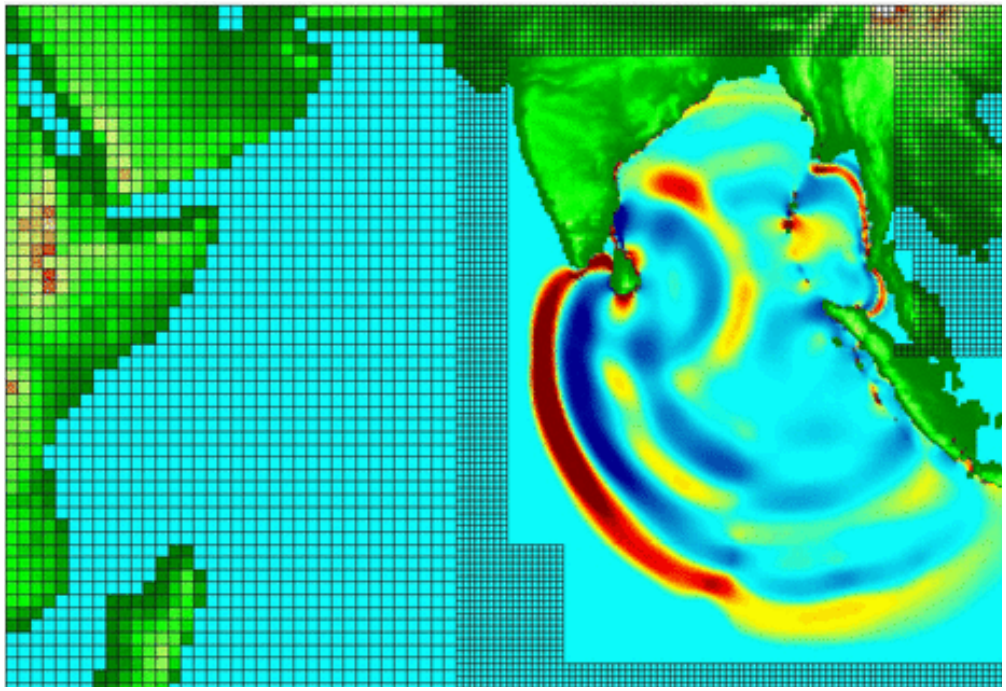
Simulation of Air-Burst Generated Tsunamis using GeoClaw



Marsha Berger
Courant Institute
New York University

AMS Seminar Series, NASA Ames Research Center, April 14, 2016

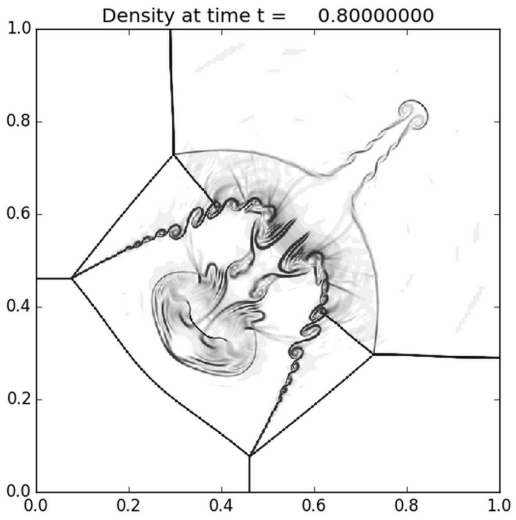
Outline of Talk

- Overview of GeoClaw
  - Description of software package for geophysical flows
  - Adaptive Mesh Refinement
  - Selected V&V
- Modifications for Air-Burst Simulations
  - Some analytic results
  - Coupling to NASA atmospheric propagation simulations (model)
  - Some numerical results
- Conclusions and Future Work

Overview of GeoClaw

Spin off from ClawPack - Conservation Law Package (LeVeque, 1994)

- high resolution explicit finite volume scheme based on wave propagation method
- Riemann solver based - robust for nonlinear problems
- includes adaptive mesh refinement
- OpenMP based parallelism
- open source software project



GeoClaw specialized for geophysical flows with bathymetry (2004) using depth-averaged shallow water equations

Sketch of SWE Derivation

Start with incompressible, divergence-free, irrotational Euler eqs:

$$u_t + uu_x + wu_z + p_x = 0$$
$$w_t + uw_x + ww_z + p_z = -g$$
$$u_x + w_z = 0$$
$$u_z - w_x = 0$$

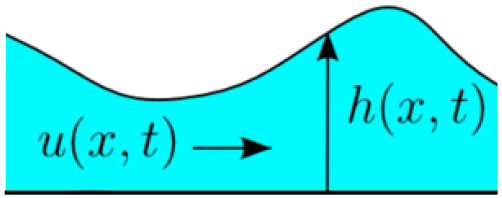
Boundary conditions:

$$w(z = 0) = 0$$
$$p = 0$$
$$h_t + uh_x = w$$

h is water height

Long wave length approximation: $h/L << 1$ L horizontal length scale

Asymptotics: solution of form



$$u = u_0(\frac{x}{L}, z, \frac{t}{L}) + \frac{1}{L}u_1((\frac{x}{L}, z, \frac{t}{L}) +$$
$$w = \frac{1}{L}w_1(\frac{x}{L}, z, \frac{t}{L}) +$$
$$p = p_0(\frac{x}{L}, z, \frac{t}{L}) + \frac{1}{L}p_1((\frac{x}{L}, z, \frac{t}{L}) +$$

Sketch of SWE Derivation

Leading term: $\frac{\partial p_0}{\partial z} = -g \quad \Rightarrow \quad p_0(z) = g(h_0(\frac{x}{L}, \frac{t}{L}) - z)$

Next term: $u_z = w_x \quad \Rightarrow$ u_0, u_1 independent of z

u_z: $O(1)$ $\qquad$ w_x: $O(\frac{1}{L^2})$

... O(1/L) terms give:

$$h_{0t} + u_0 h_{0x} = -h_0 u_{0x}$$

$$u_{0t} + u_0 u_{0x} + g_0 h_{0x} = 0$$

with $\boxed{w = O(\frac{1}{L}) \qquad u_z = O(\frac{1}{L})}$

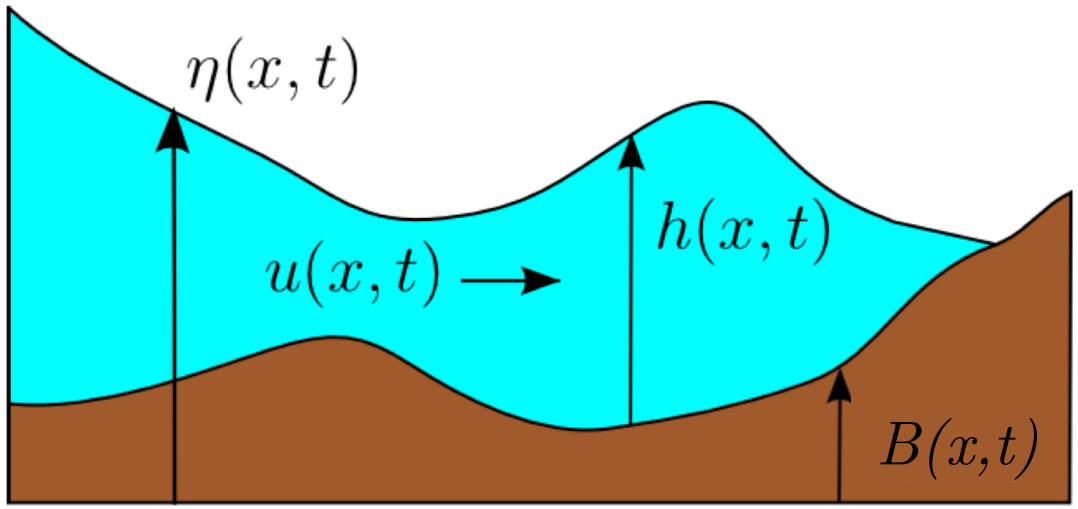
Overview of GeoClaw

Solve shallow water equations with bathymetry B(x,y,t)

$$\begin{aligned} h_t + (hu)_x + (hv)_y &= 0 \\ (hu)_t + (hu^2 + \frac{1}{2}gh^2)_x + (huv)_y &= -ghB_x \\ (hv)_t + (huv)_x + (hv^2 + \frac{1}{2}gh^2)_y &= -ghB_y \end{aligned}$$

Depth averaged, long wavelength approximation to Euler eq.

Reduces to 2D, removes free surface, but lots of numerical issues.



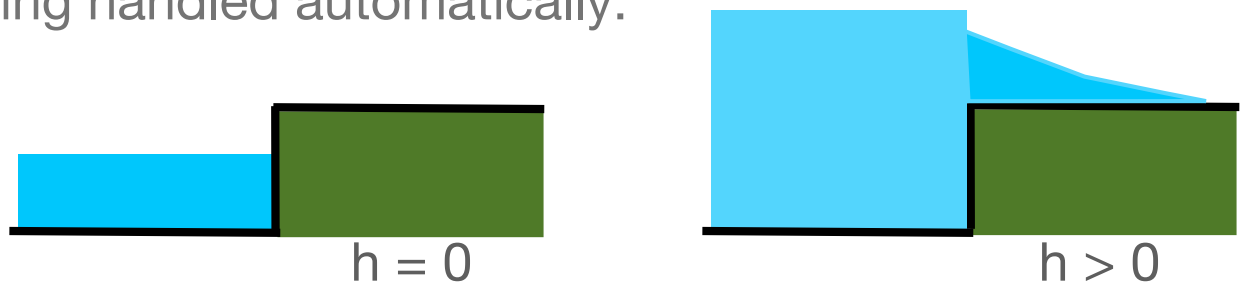
wave speed $c = \sqrt{gh}$

deep water $h \approx 4\text{km}$, c ≈ 200 m/sec

shallow water $h \approx 10\text{m}$, c ≈ 10 m/sec

Overview of GeoClaw

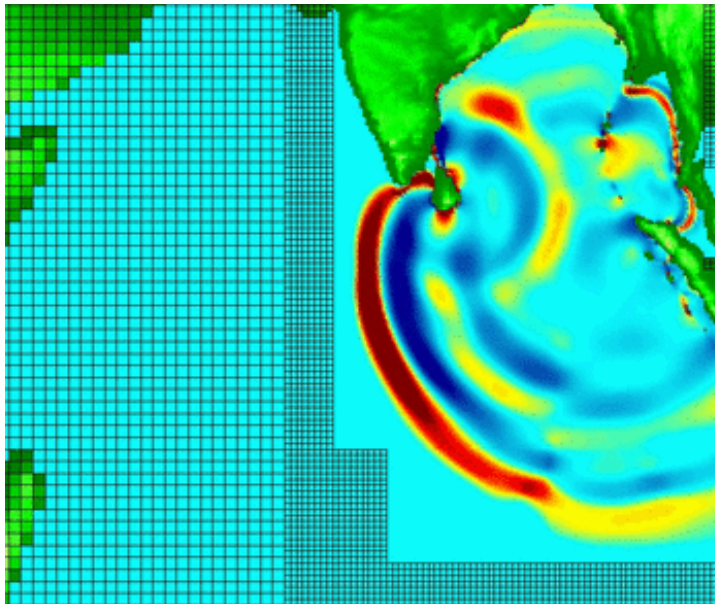
- Numerics:
  - Well-balanced schemes (small waves on deep ocean at rest)
  - Riemann solver - very robust, handles large jumps in bathymetry
  - Drying/wetting handled automatically:



- GeoClaw handles:
  - latitude/longitude coordinates
  - handles multiple overlapping bathymetry (topo) files, with different resolutions (uses DEM's (digital elevation model) on regular grid) Earthquake-generated tsunamis via moving topography (dtopo) files
  - moving shoreline:

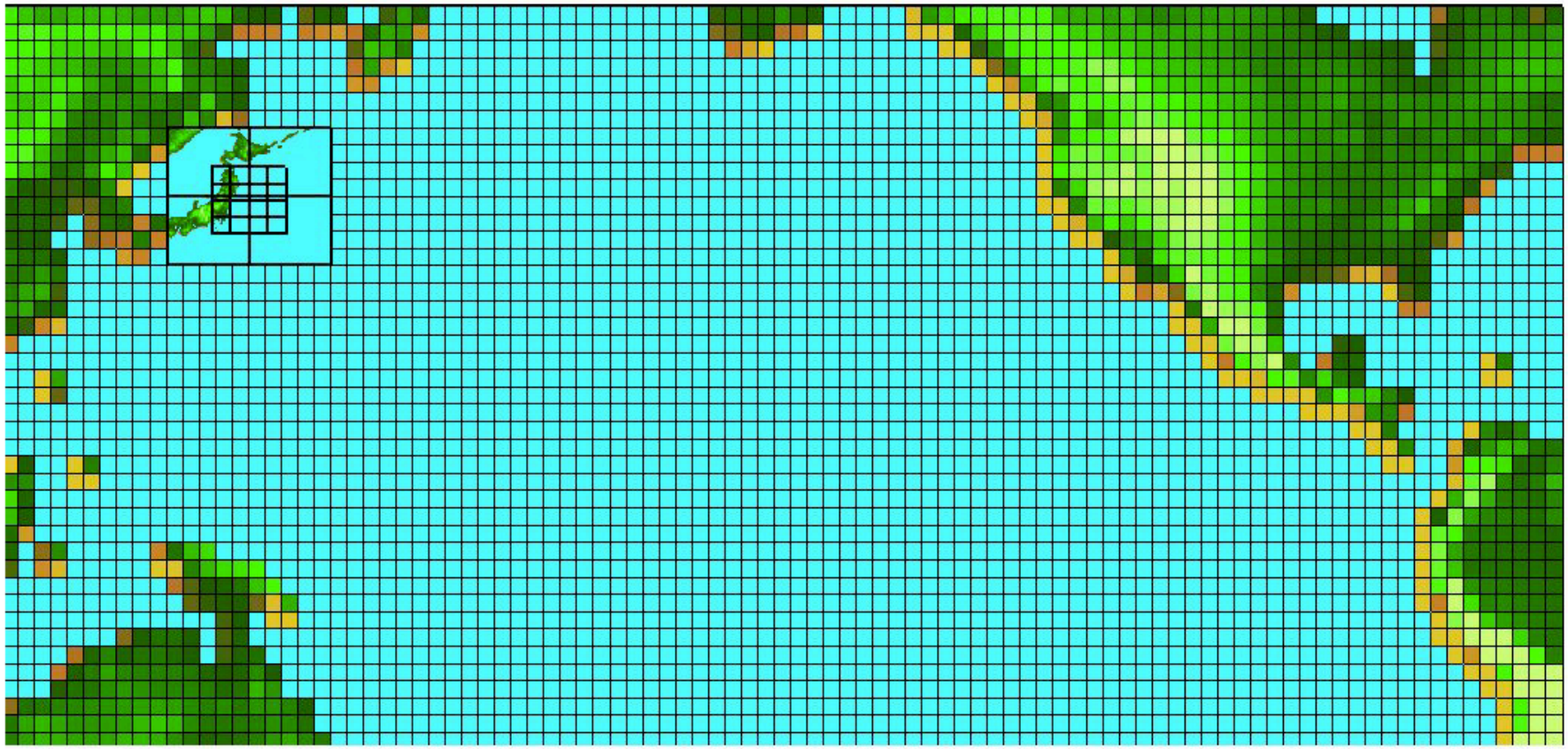
Adaptive Mesh Refinement

Patch-based mesh refinement to follow important features



- Adaptive in space and time - bridge scales from meters to hundreds of kilometers
- Refines automatically to follow waves and other features
- Interpolate between patches automatically (preserving sea-level)
- Grid generation for patches handled automatically

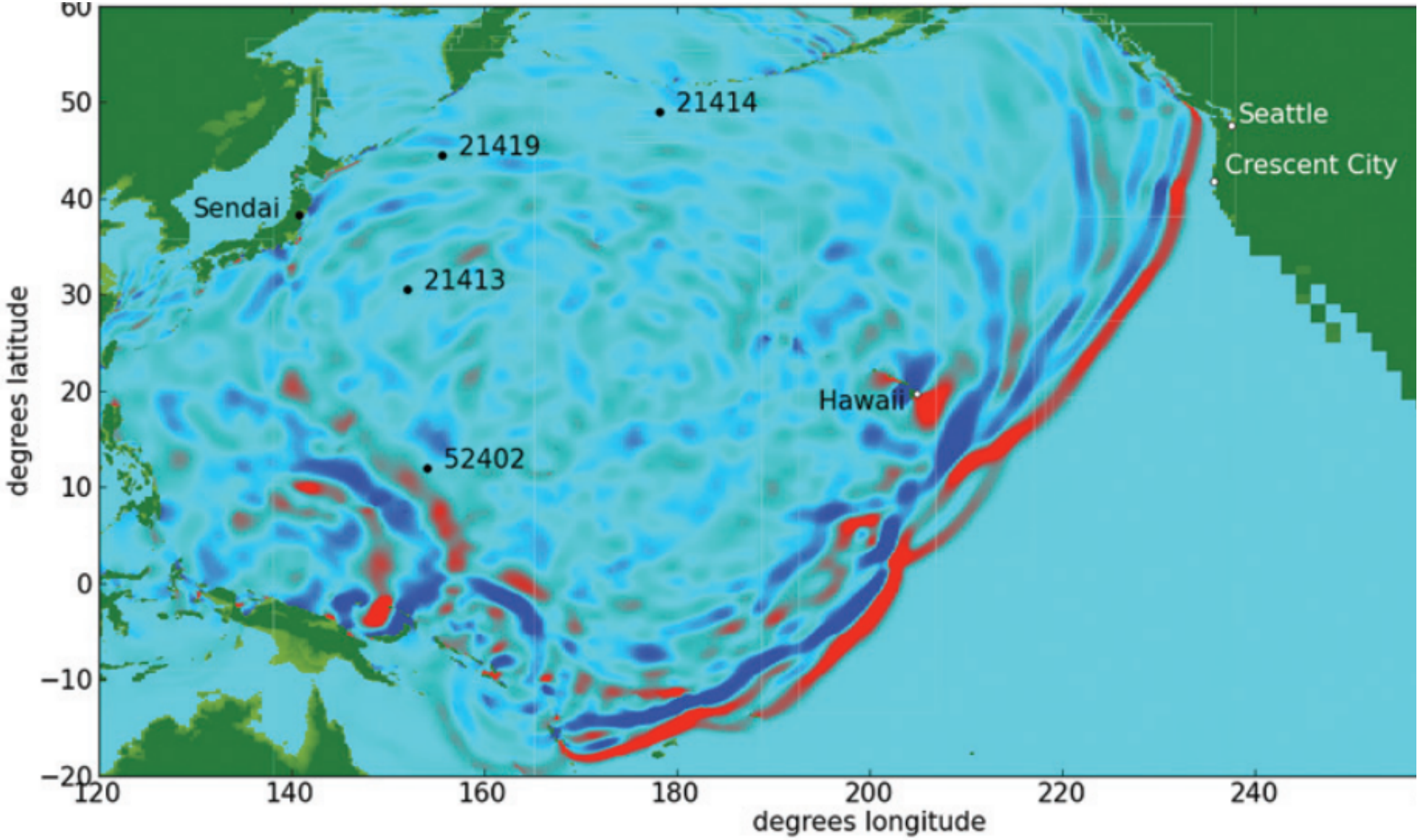
Tohuko Simulation



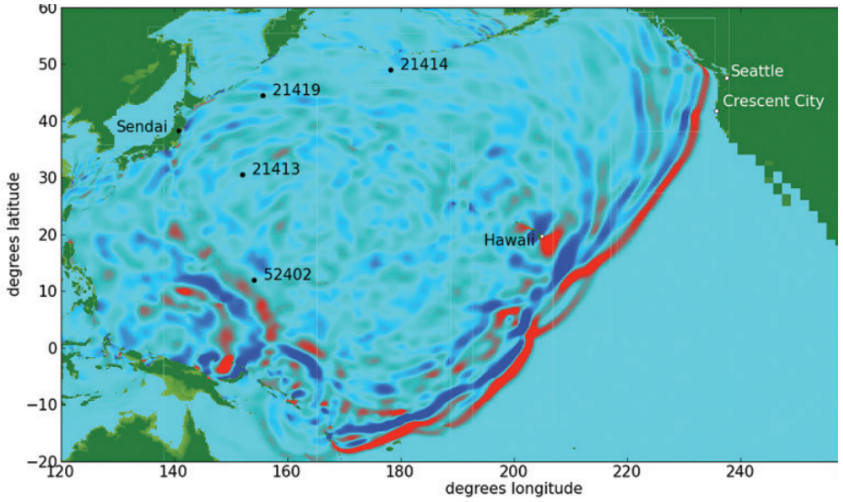
Computation by David George (USGS) and Randy LeVeque (UW)

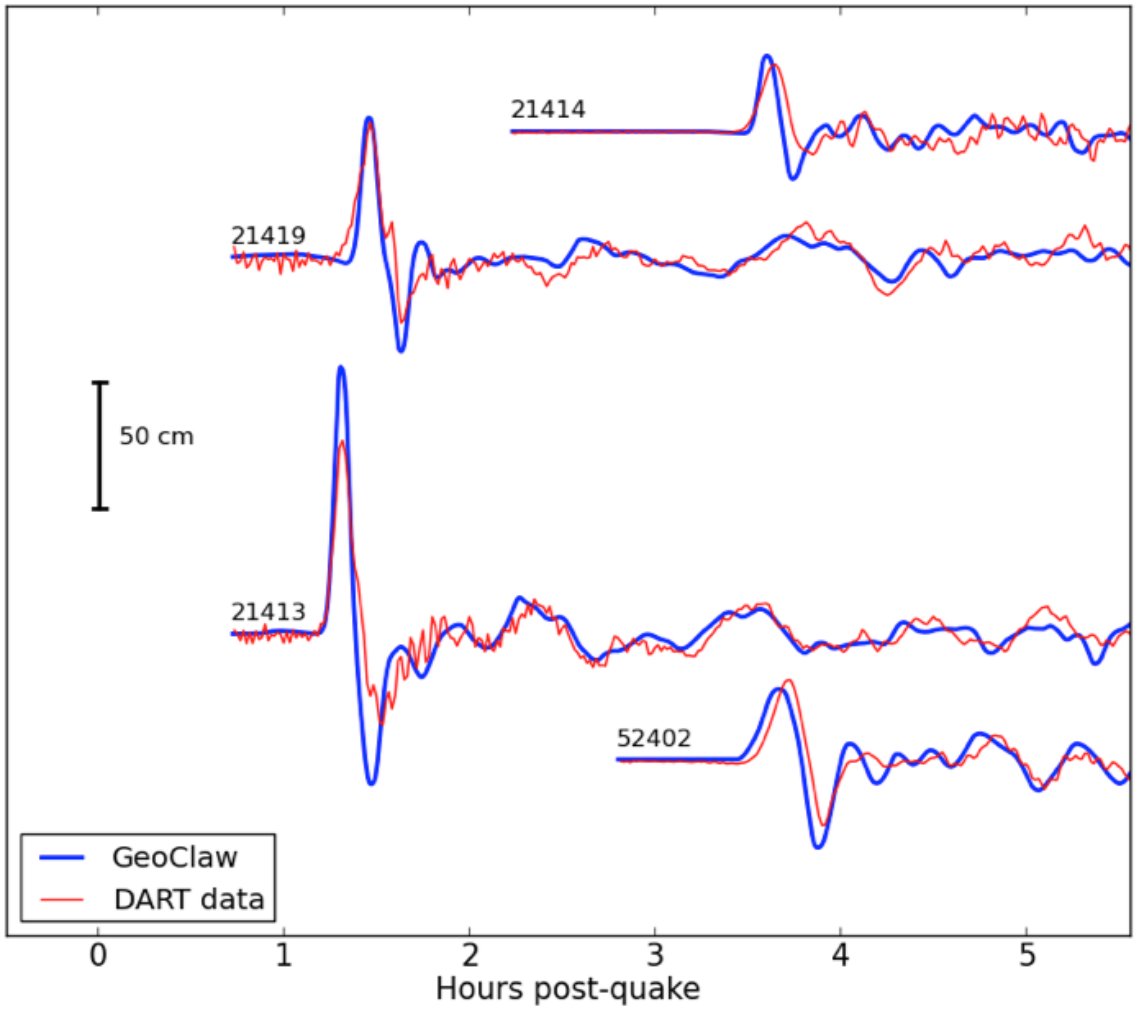
- 5 levels of refinement: 8,4,16, 32 (2^{14} in each direction!)
- Resolution: 160 km on level 1; 10 m on level 5;

Tohuko Simulation



Tohuko Simulation



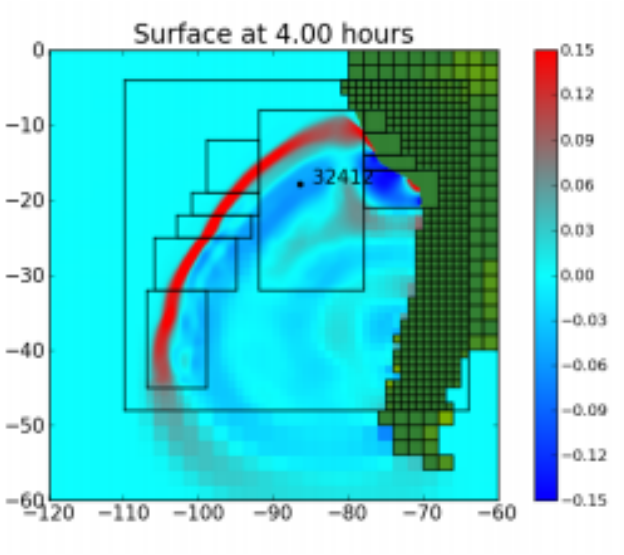


Wave height at selected DART (Deep Ocean Assessment and Reporting of Tsunamis) buoys from NOAA.

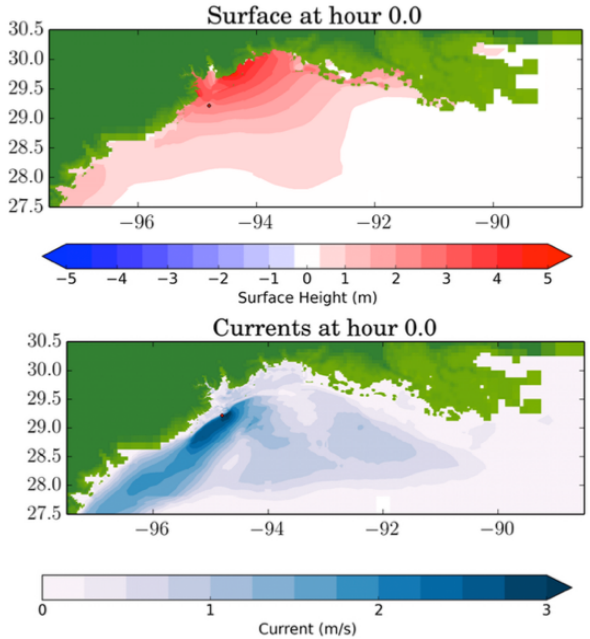
LeVeque currently working on comparing velocities.

Overview of GeoClaw

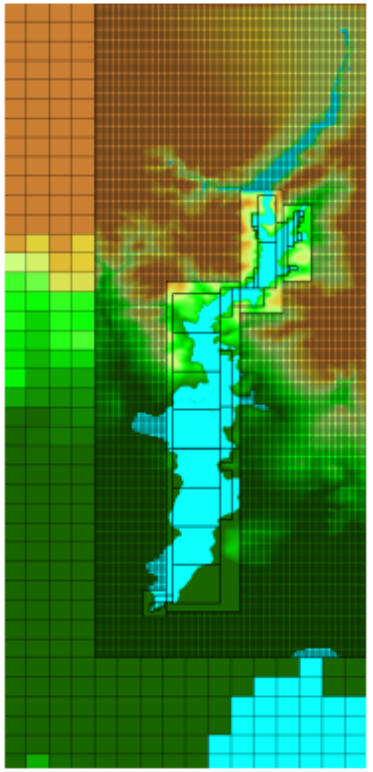
- Applied to tsunamis, flooding, storm surge, landslides, debris flows.
- Approved by NTHMP (National Tsunami Hazard Mitigation Program) for hazard mapping in 2011. Set of 9 benchmark problems, analytic, wavetanks, and tsunamis. Results available at *www.clawpack.org/geoclaw*



tsunami (Chile, 2010)

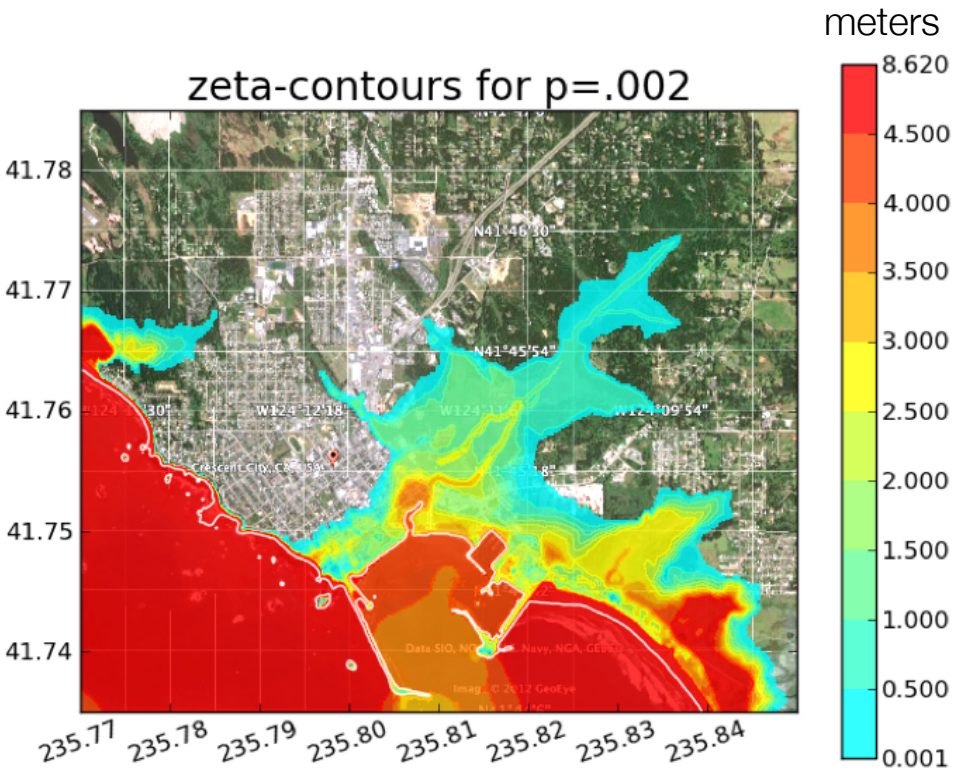


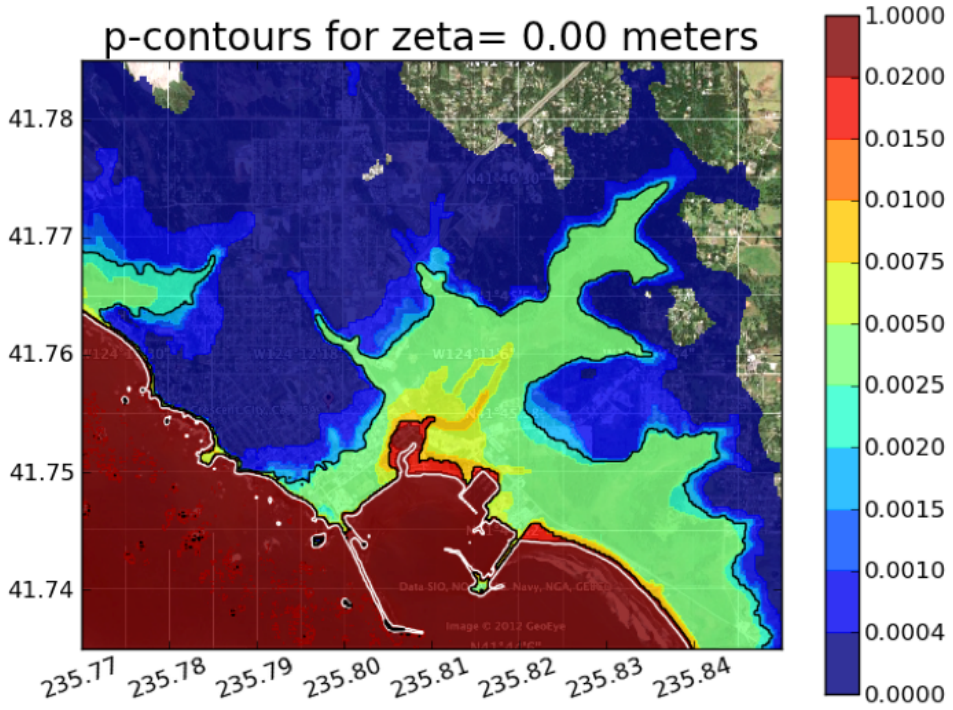
storm surge: Hurricane Ike at landfall
(Kyle Mandli)



Malpasset dam break
(David George)

Overview of GeoClaw





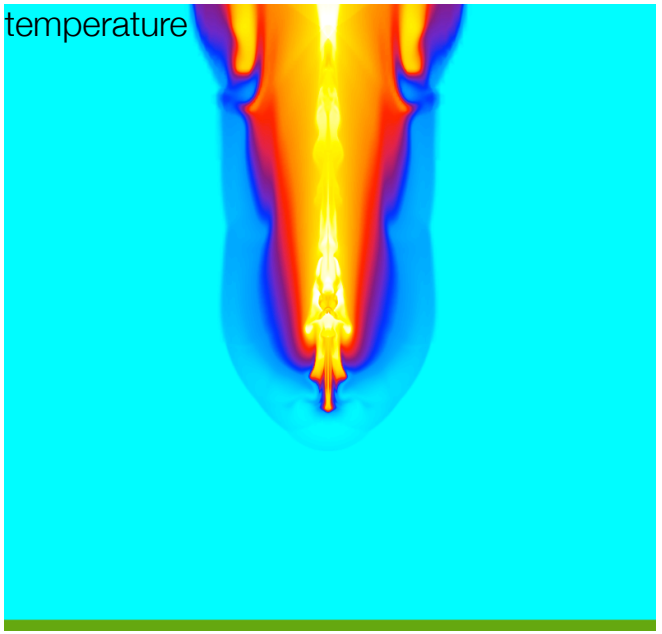
zeta (depth of flooding) contours for p = .002
with prob .002 the flooding is this level

probability contours of flooding
fix flooding level, ask what the prob. is

Ref: **Probabilistic Tsunami Hazard Assessment (PTHA) for Crescent City, CA.**
by Frank I. Gonzalez, Randall J. LeVeque, Loyce M. Adams, Chris Goldfinger, George R. Priest, and Kelin Wang

Air-Burst Generated Tsunami Simulations

- Bolide enters atmosphere, ‘explodes’ in air over water.
- Initial shock wave reaches water, followed by longer rarefaction (plus more)
- Modify shallow water equations: atmospheric pressure gradient is forcing function on rhs.



$$
\begin{aligned}
h_t + (hu)_x + (hv)_y &= 0 \\
(hu)_t + (hu^2 + \frac{1}{2}gh^2)_x + (huv)_y &= -ghB_x(x,y) - hp_{x_{\text{air}}}/\rho_{\text{water}} \\
(hv)_t + (huv)_x + (hv^2 + \frac{1}{2}gh^2)_y &= -ghB_y(x,y) - hp_{y_{\text{air}}}/\rho_{\text{water}}
\end{aligned}
$$

Some Analysis

Simplify to 1d without bathymetry:

$$\begin{aligned} h_t + (hu)_x &= 0 \\ (hu)_t + (hu^2 + \frac{1}{2}gh^2)_x &= -h\, p_{x_{\text{air}}}/\rho_{\text{water}} \end{aligned}$$

Look for traveling wave solutions:

$$p(x,t) = p(x - st)$$ for constant speed s

Turns pde into ode: define $m = x - st$

then $\frac{\partial}{\partial x} = \frac{\partial}{\partial m}$ $\frac{\partial}{\partial t} = (-s)\frac{\partial}{\partial m}$

$$-sh_m + (hu)_m = 0$$

$$-s(hu)_m + (hu^2 + \frac{1}{2}gh^2)_m = \frac{-hp_{m_{\text{air}}}}{\rho_{\text{water}}}$$

Some Analysis

Odes can be solved exactly! Resulting (exact) nonlinear relationship:

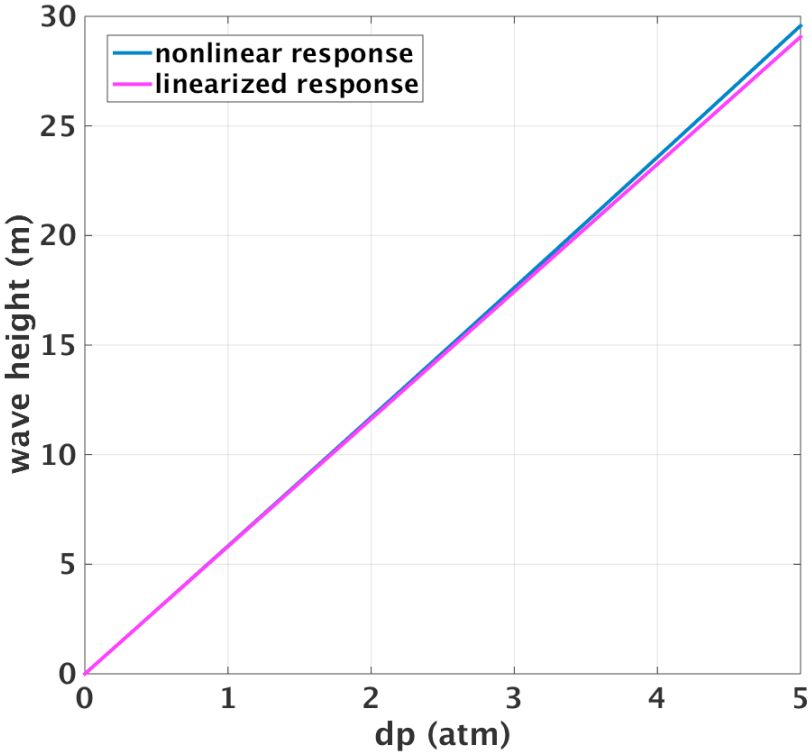
$$\frac{s^2}{2}\left(1-\frac{h_0^2}{h(m)^2}\right)+c^2\left(1-\frac{h(m)}{h_0}\right)=\frac{\Delta p_{\text{air}}(m)}{\rho_{\text{water}}}$$

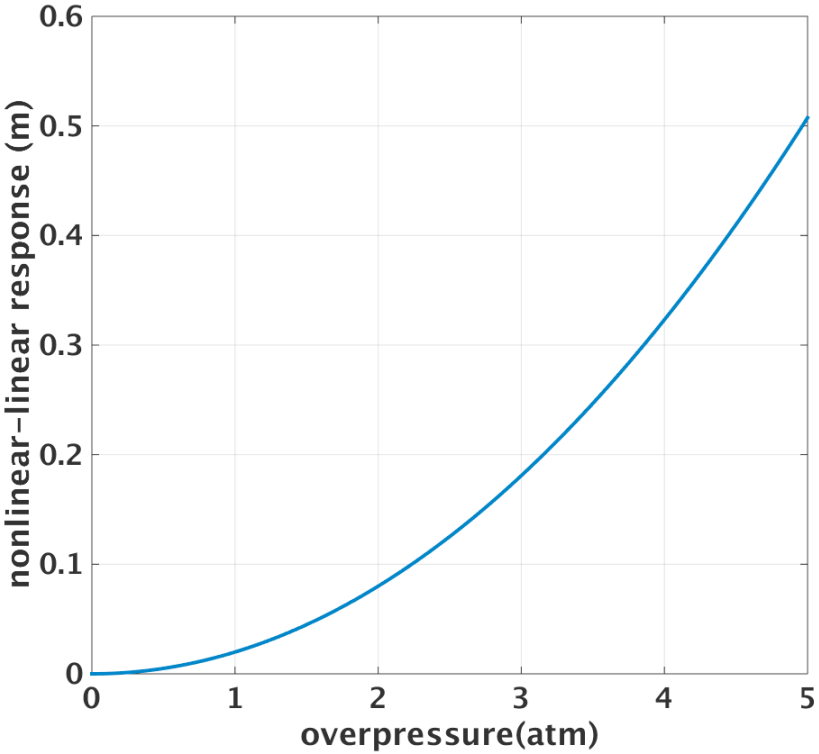
$$\begin{aligned} s &= \text{pressure wave speed} \\ c &= \sqrt{gh_0} = \text{water wave speed} \\ \frac{h}{h_0} &= \text{height ratio of wave to sea level} \end{aligned}$$

Linearized relationship: $(s^2-c^2)\Delta h = h_0\,\dfrac{\Delta p_{\text{air}}}{\rho_{\text{water}}}$ $\qquad (h \approx h_0 + \Delta h)$

- Effect stronger in deeper water. (response ~ height)
- If pressure increases and $s < c$, water height decreases ($\Delta h < 0$)
- If pressure increases and $s > c$, water height positive ($\Delta h > 0$)!
- Resonance when $s \approx c$

Some Analysis



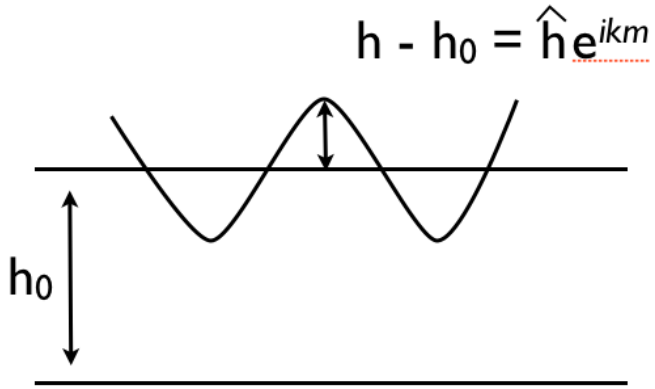


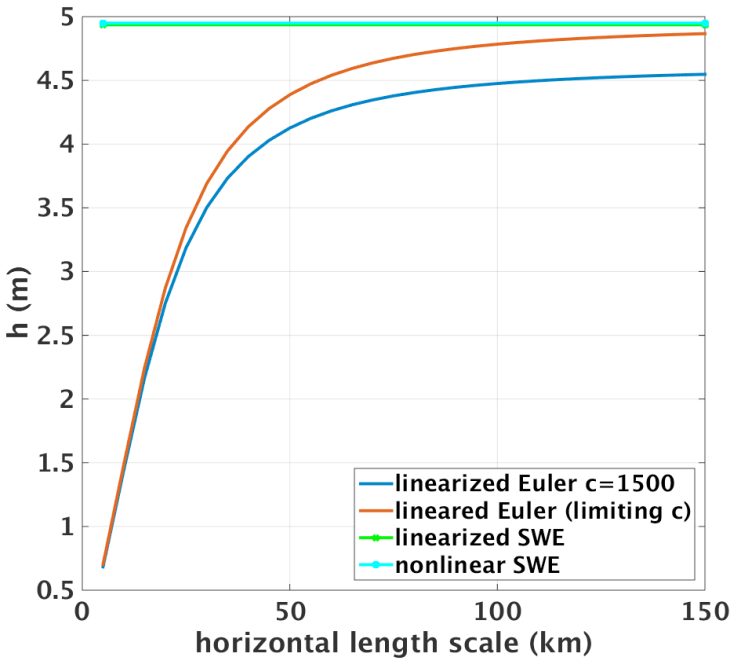
$$(s^2 - c^2)\Delta h = h_0 \frac{\Delta p_{\text{air}}}{\rho_{\text{water}}}$$

using h_0 = 4 km, ρ_{water} = 1000 kg

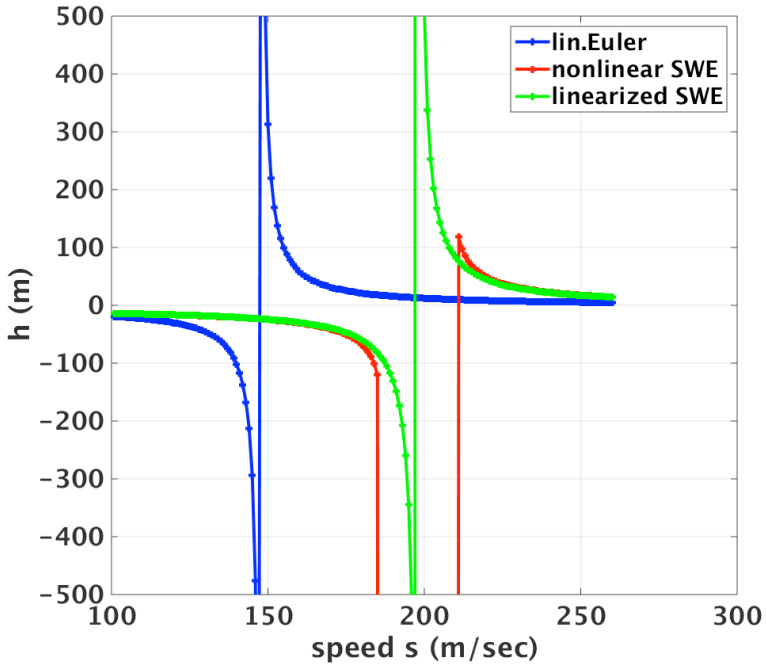
Some Analysis

- What about compressibility and dispersive effects?
- Do same analysis for linearized compressible Euler equations.
  - Results depend of wave number $k = 2\pi/L$





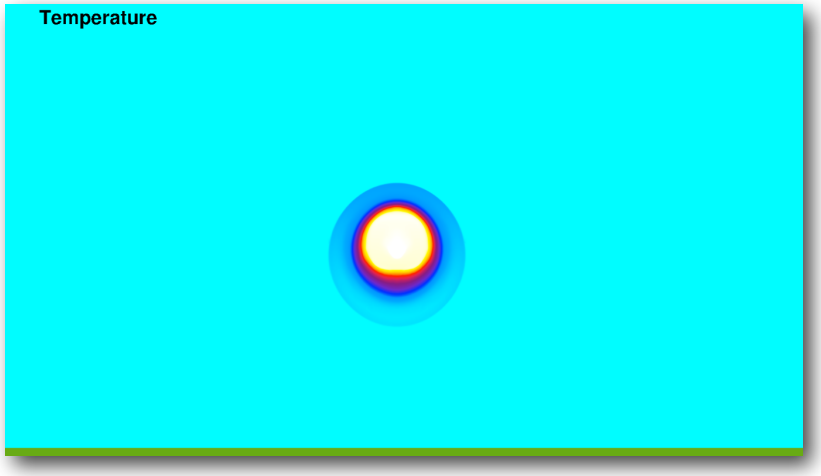
for 4 km ocean, s = 350 m/sec



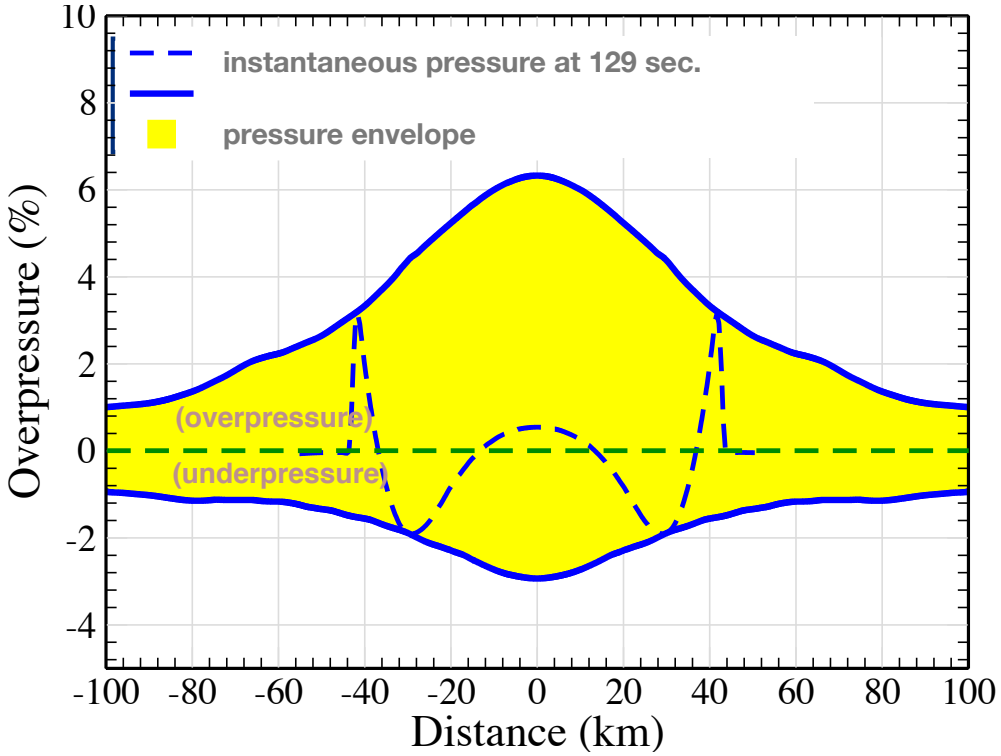
for 4 km ocean, L = 15km, c = 1500 m/sec

Pressure Coupling Model

Simulations of spherical blast (Aftosmis et al) for 520kt blast at ~30 km altitude used to provide ground pressure signatures

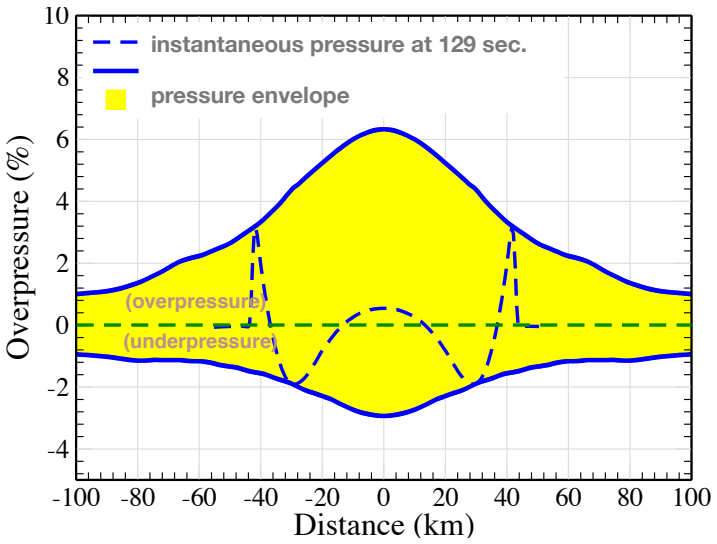


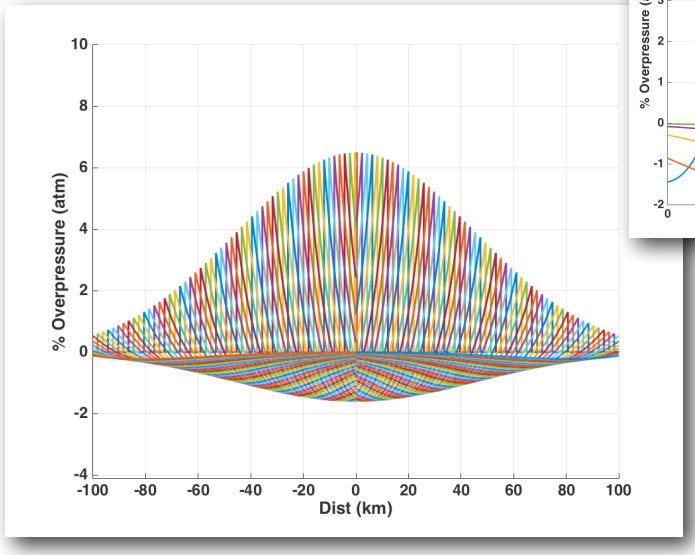
$$
\begin{aligned}
h_t + (hu)_x + (hv)_y &= 0 \\
(hu)_t + (hu^2 + \frac{1}{2}gh^2)_x + (huv)_y &= -ghB_x(x,y) - hp_{x_{\text{air}}}/\rho_{\text{water}} \\
(hv)_t + (huv)_x + (hv^2 + \frac{1}{2}gh^2)_y &= -ghB_y(x,y) - hp_{y_{\text{air}}}/\rho_{\text{water}}
\end{aligned}
$$

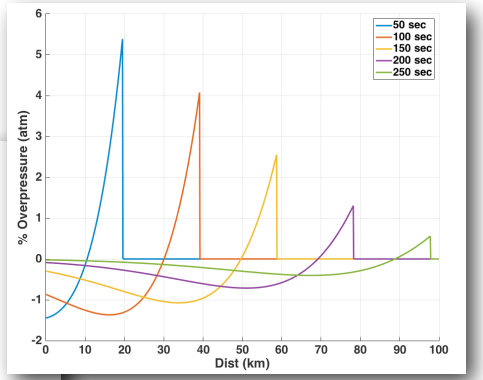


Pressure Coupling Model

Simulations of spherical blast (Aftosmis et al) for 520kt blast at ~30 km altitude used to provide ground pressure signatures

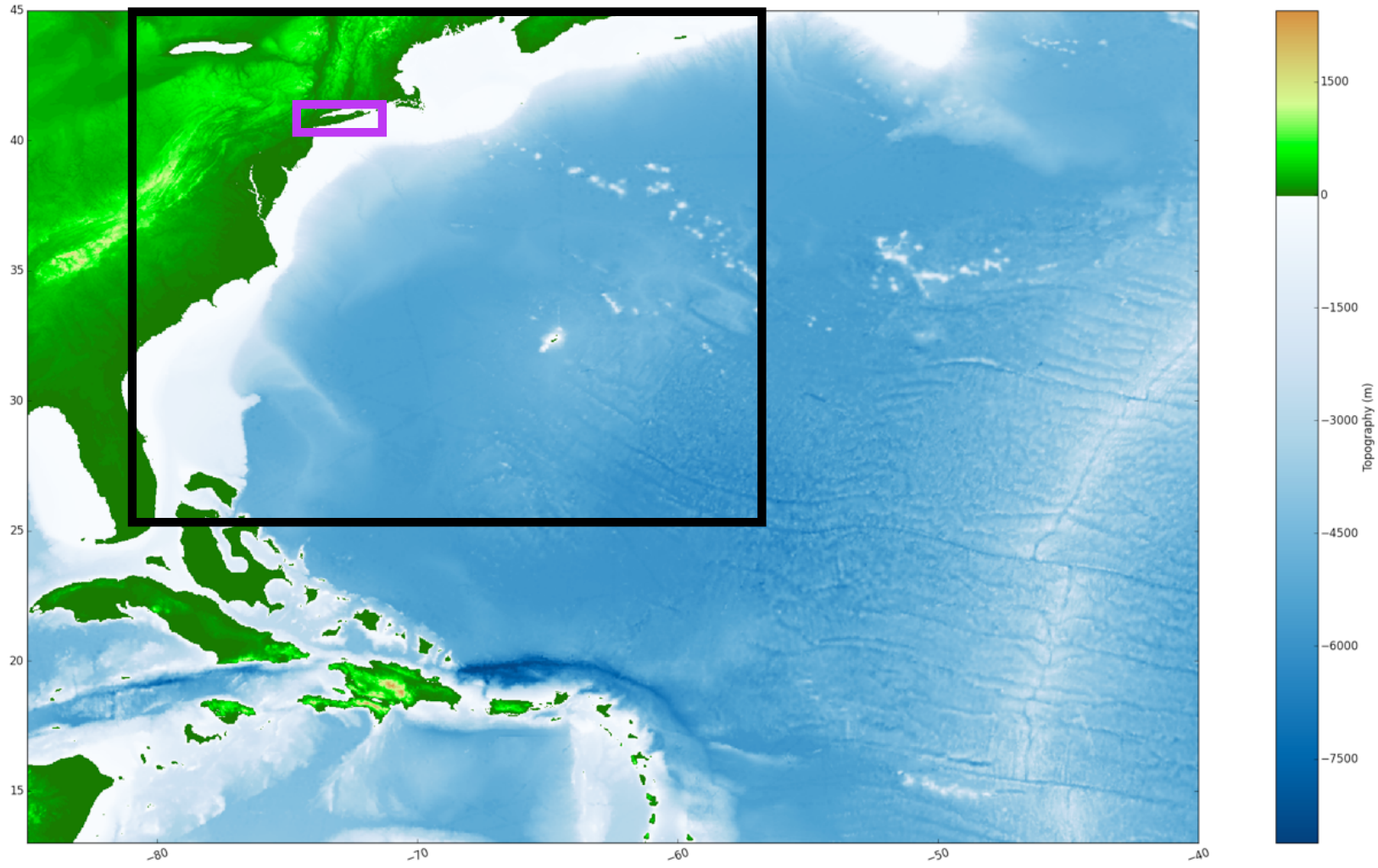






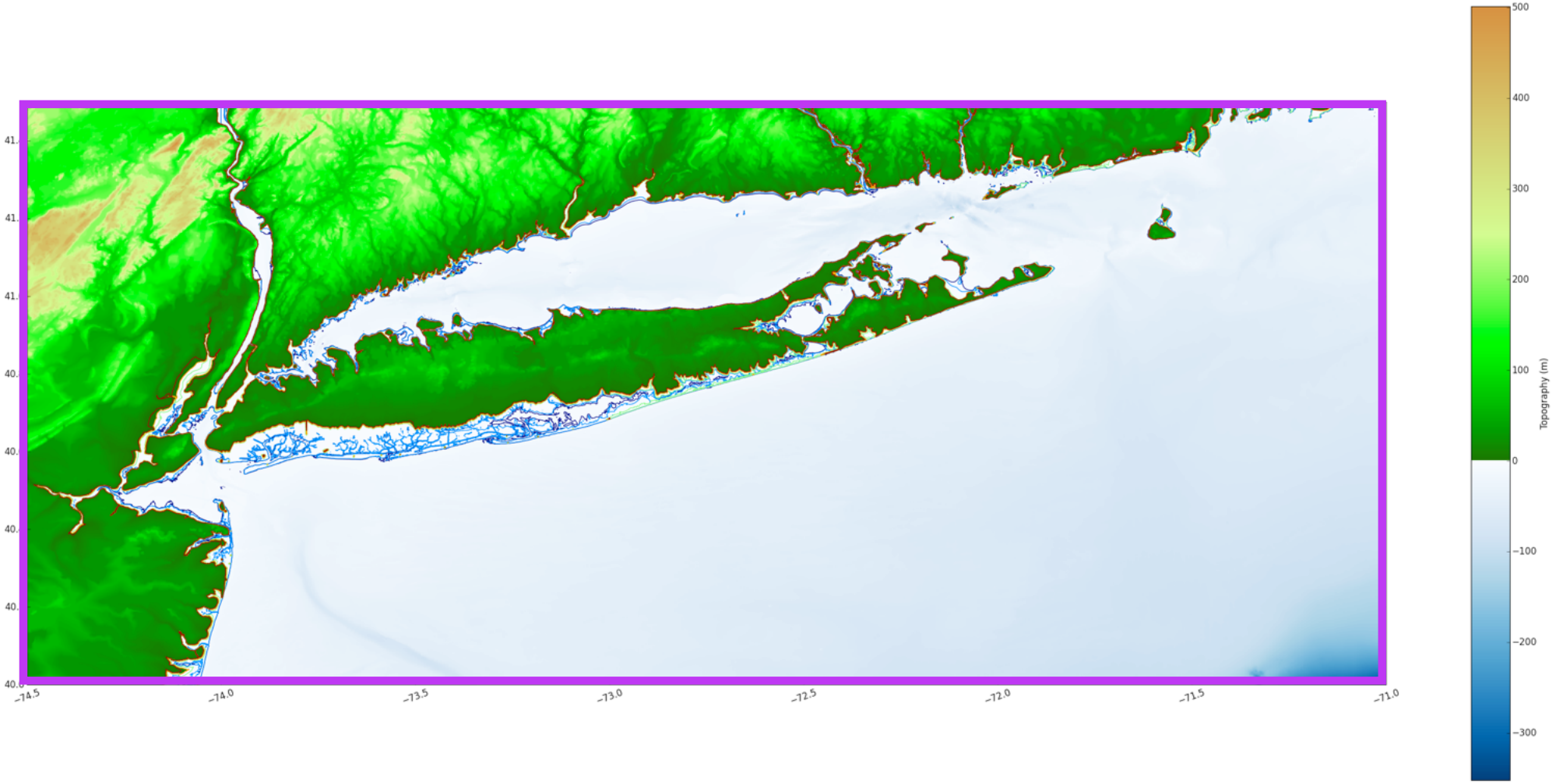
Fit to Chelyabinsk profile: use max. amplitude, width of envelope to fit Gaussian envelope for amplitude, inside are parameters for modified Friedlander profile, speed of pressure wave,

GeoClaw Simulations



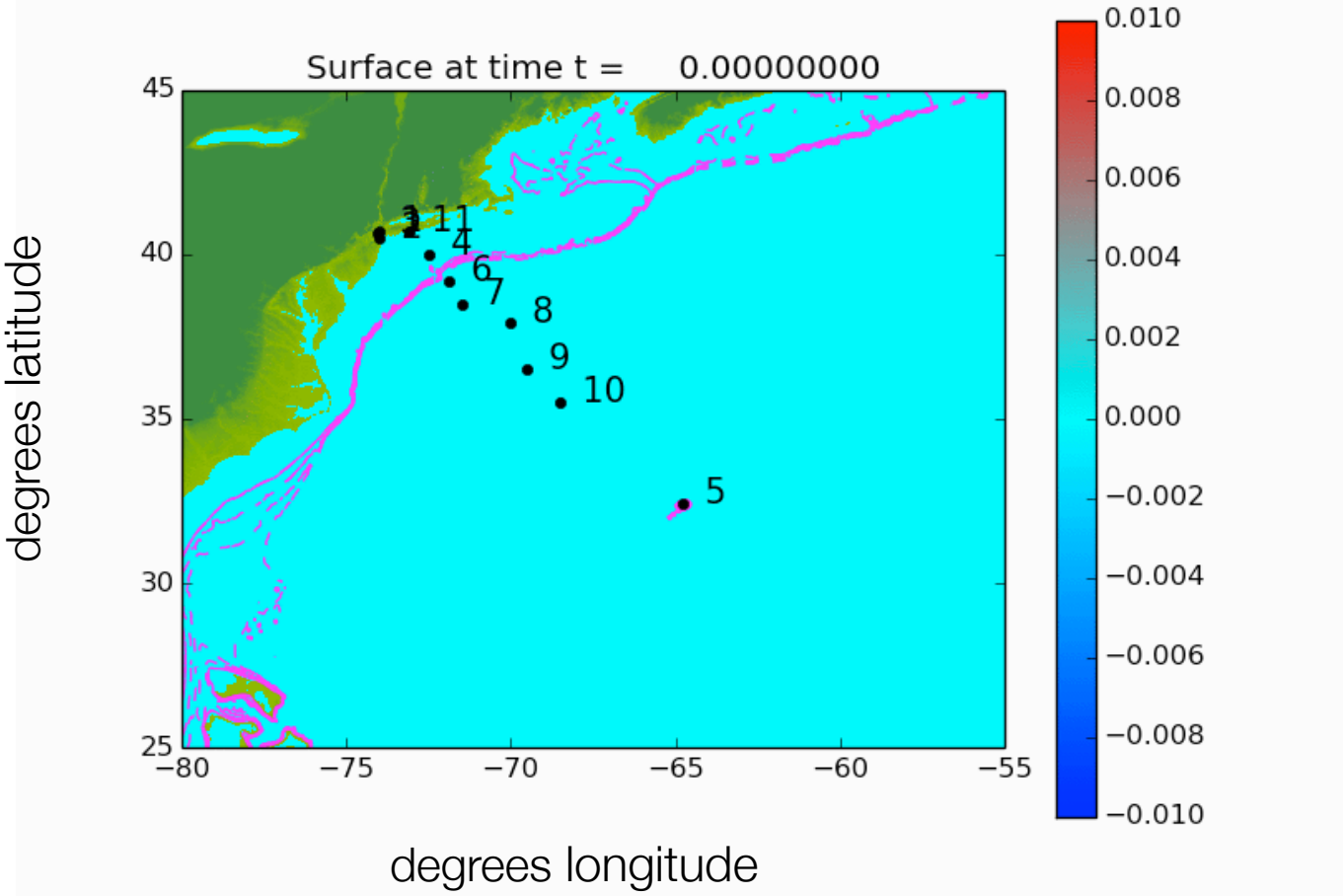
- Atlantic bathymetry grid 2 minutes (~ 3.6 km)
- NYC bathymetry grid 3 seconds (~ 80 meters)

GeoClaw Simulations



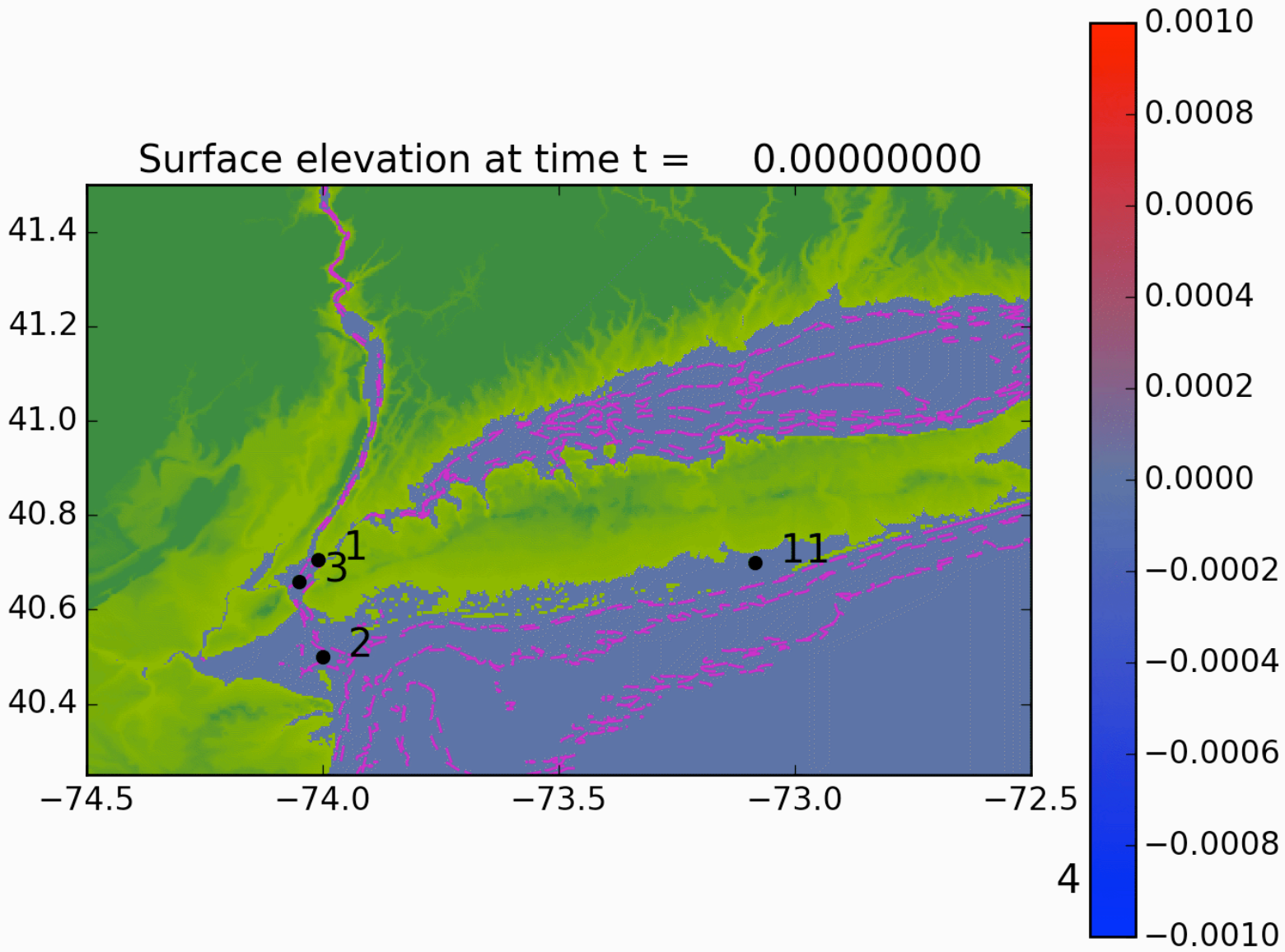
- Atlantic bathymetry grid 2 minutes (~ 2.6 km)
- NYC bathymetry grid 3 seconds (~ 66 meters)

GeoClaw Simulations (520kt, 29.6 km alt)



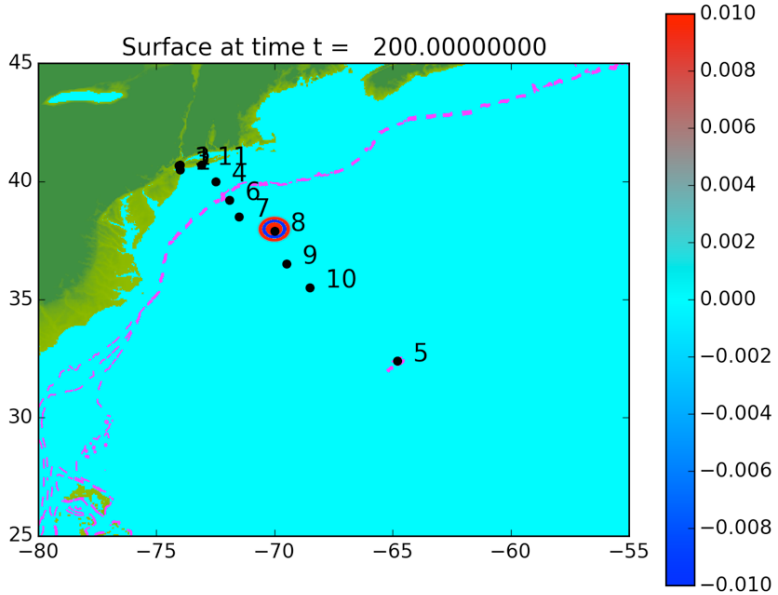
- Simulations use tiny time step until pressure wave decays, then time step appropriate for water waves
- Resolution on finest grid is 500 meters, or 125 meters to check. Coarse cells are 5 km. Domain side is 25° latitude ~ 2750 km.
- Max amplitude of pressure envelope 6.5% overpressure

GeoClaw Simulations (520kt)

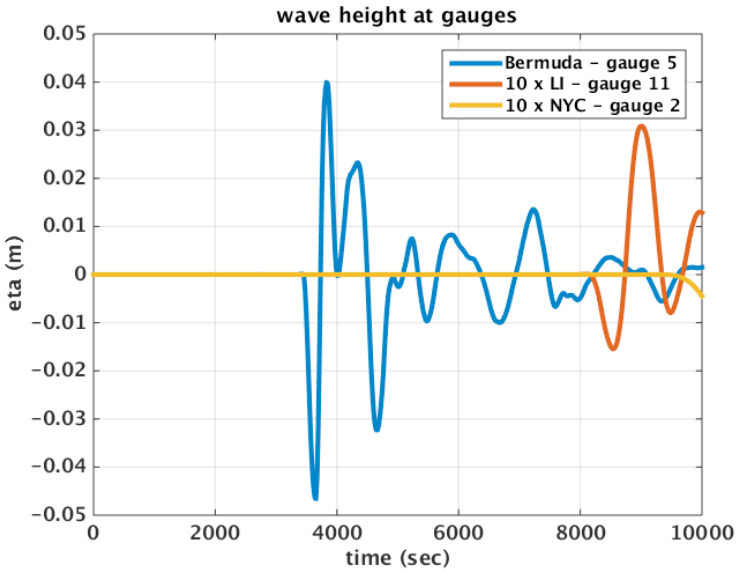


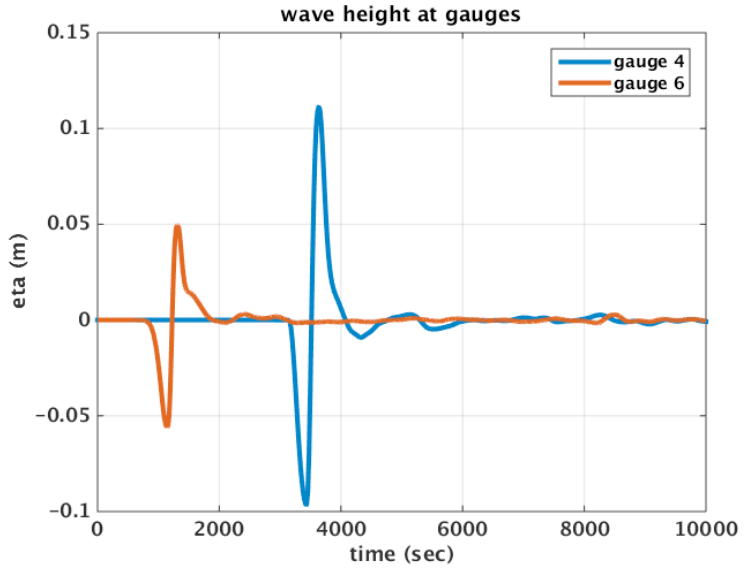
- zoom of NYC (scale 10 times finer)
- bathymetry contours every 30 m

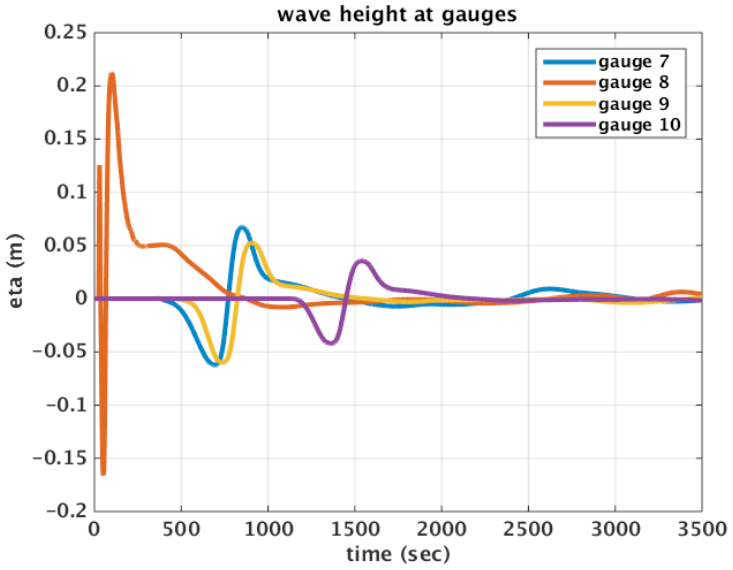
GeoClaw Simulation (520kt)



gauge 8 is ~ 10 km from blast

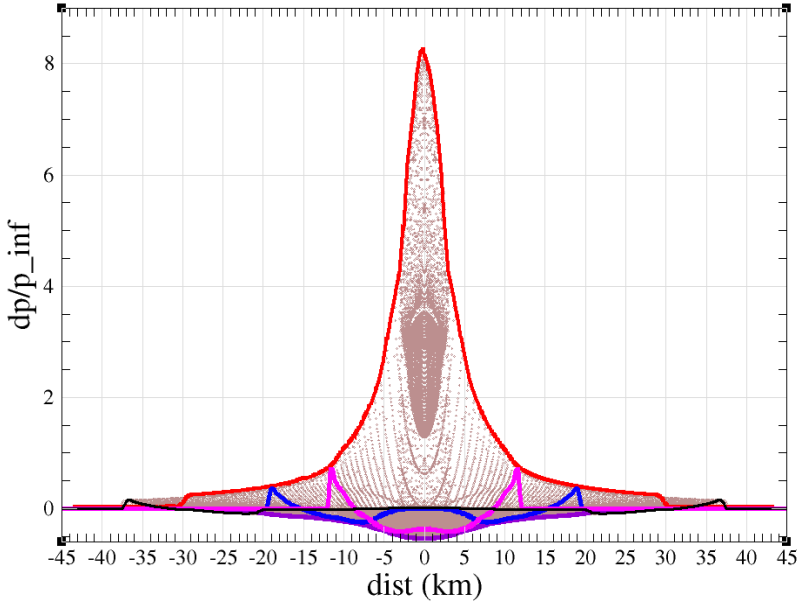


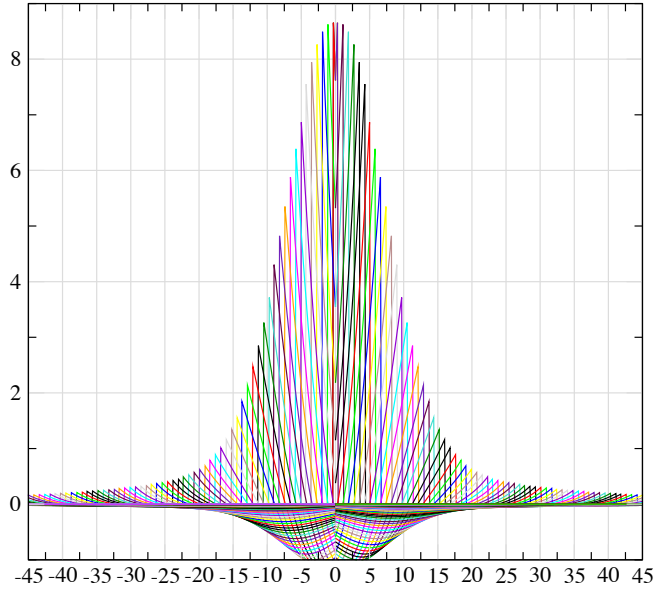


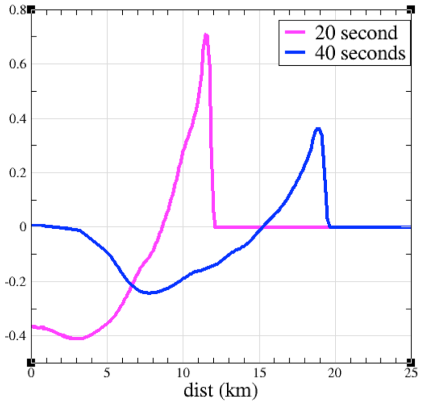


Pressure Coupling Model

25MT ground pressure signature with static air burst at 5km altitude



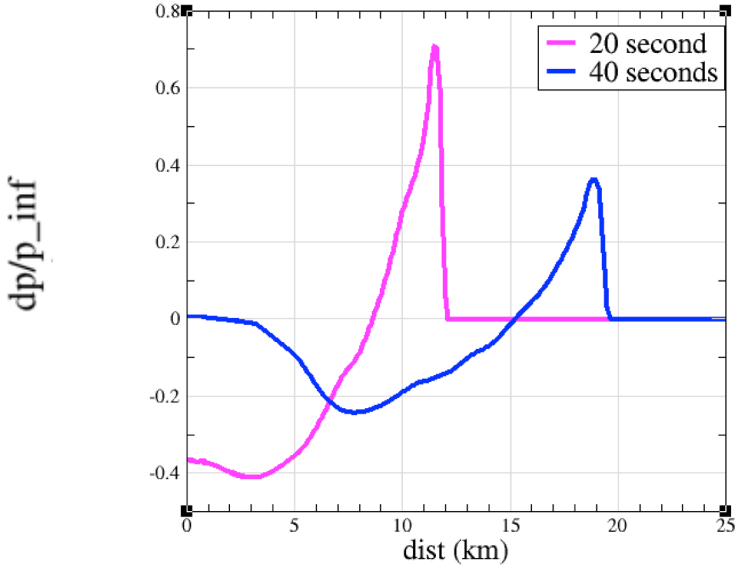




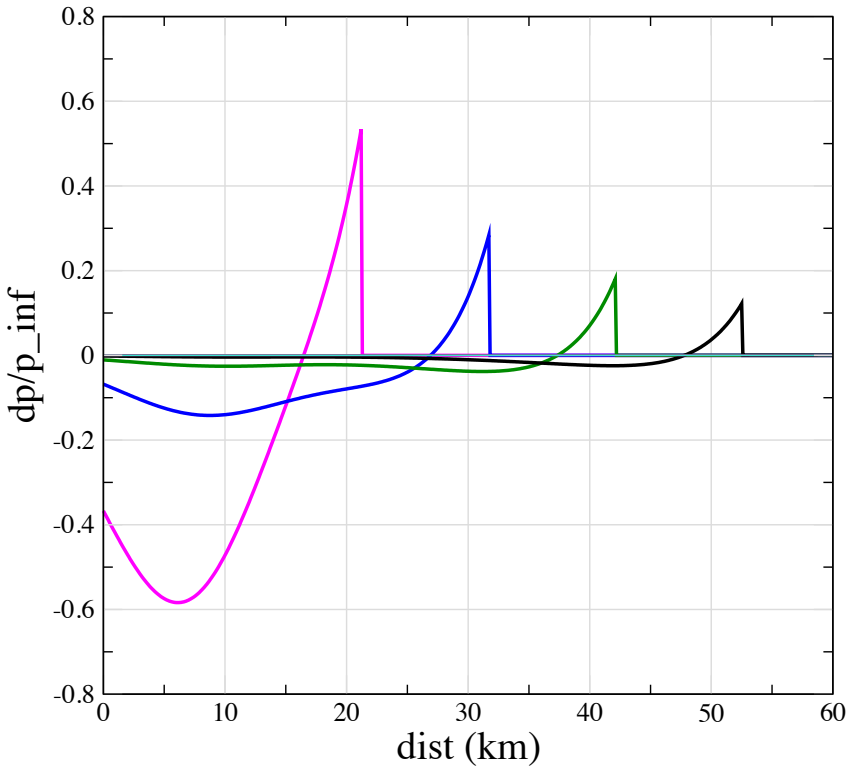
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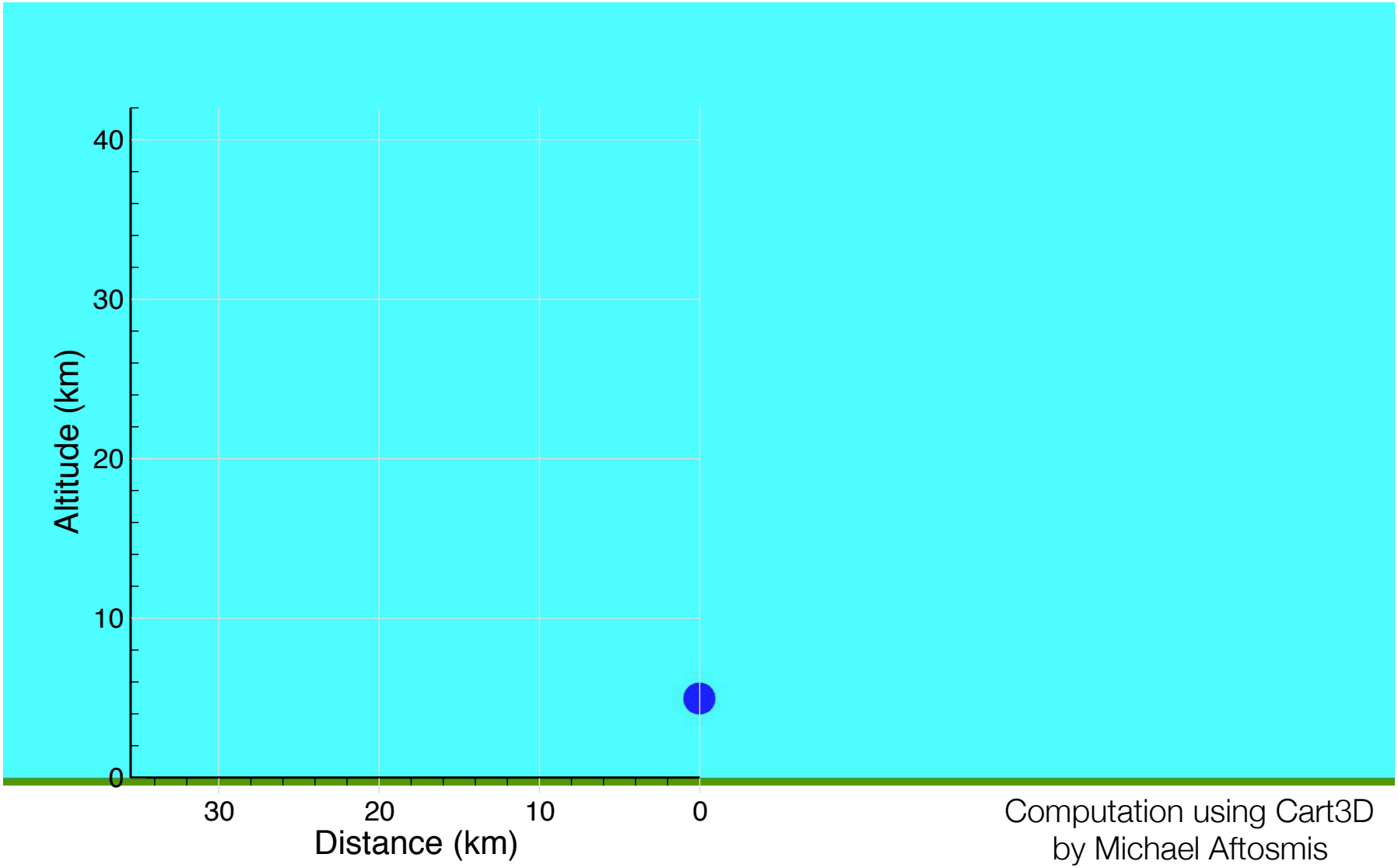
pulse is narrower, decays more quickly



max. amplitude overpress. ~ 850%

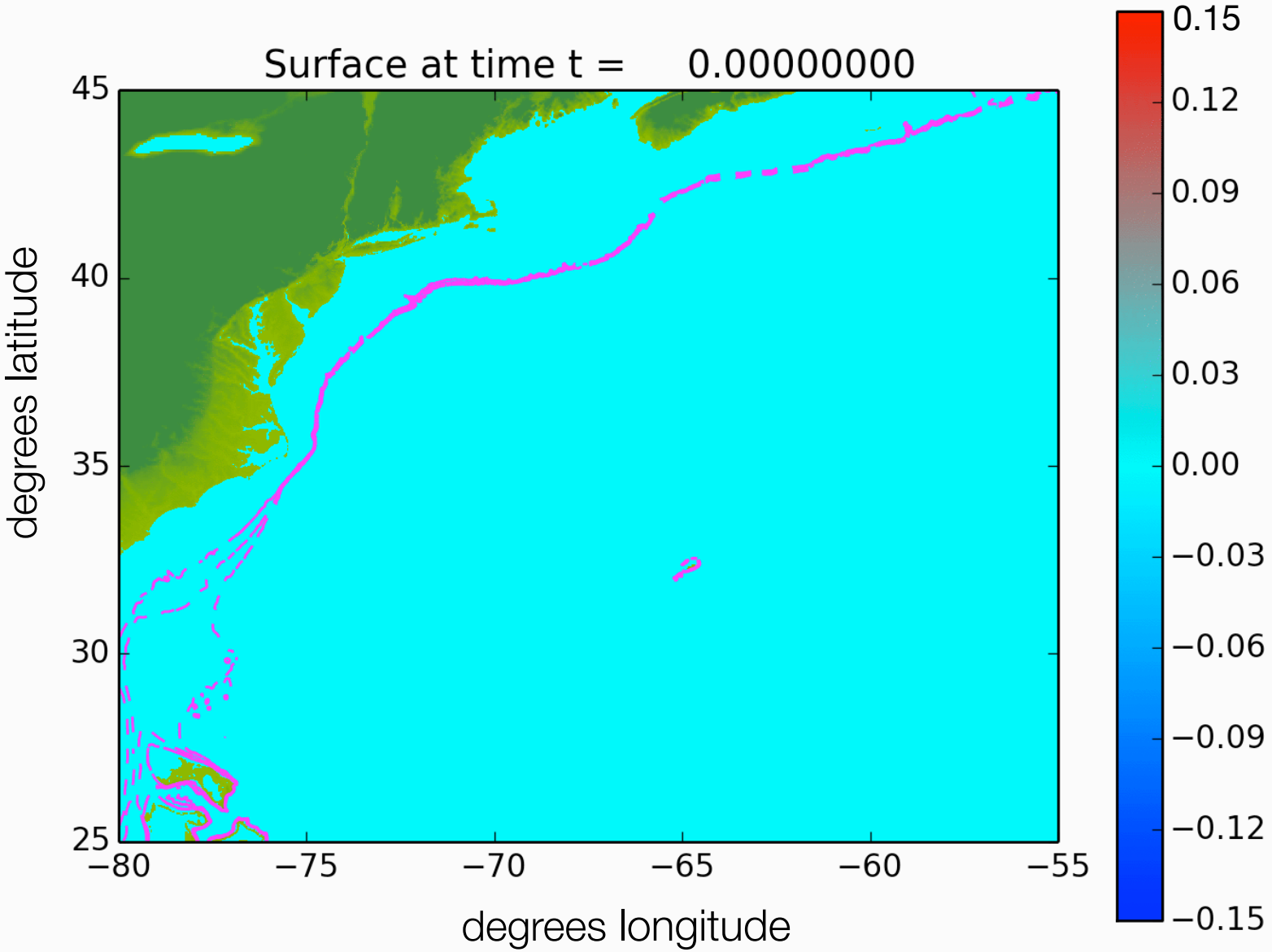


Simulation of 25 MT static spherical charge

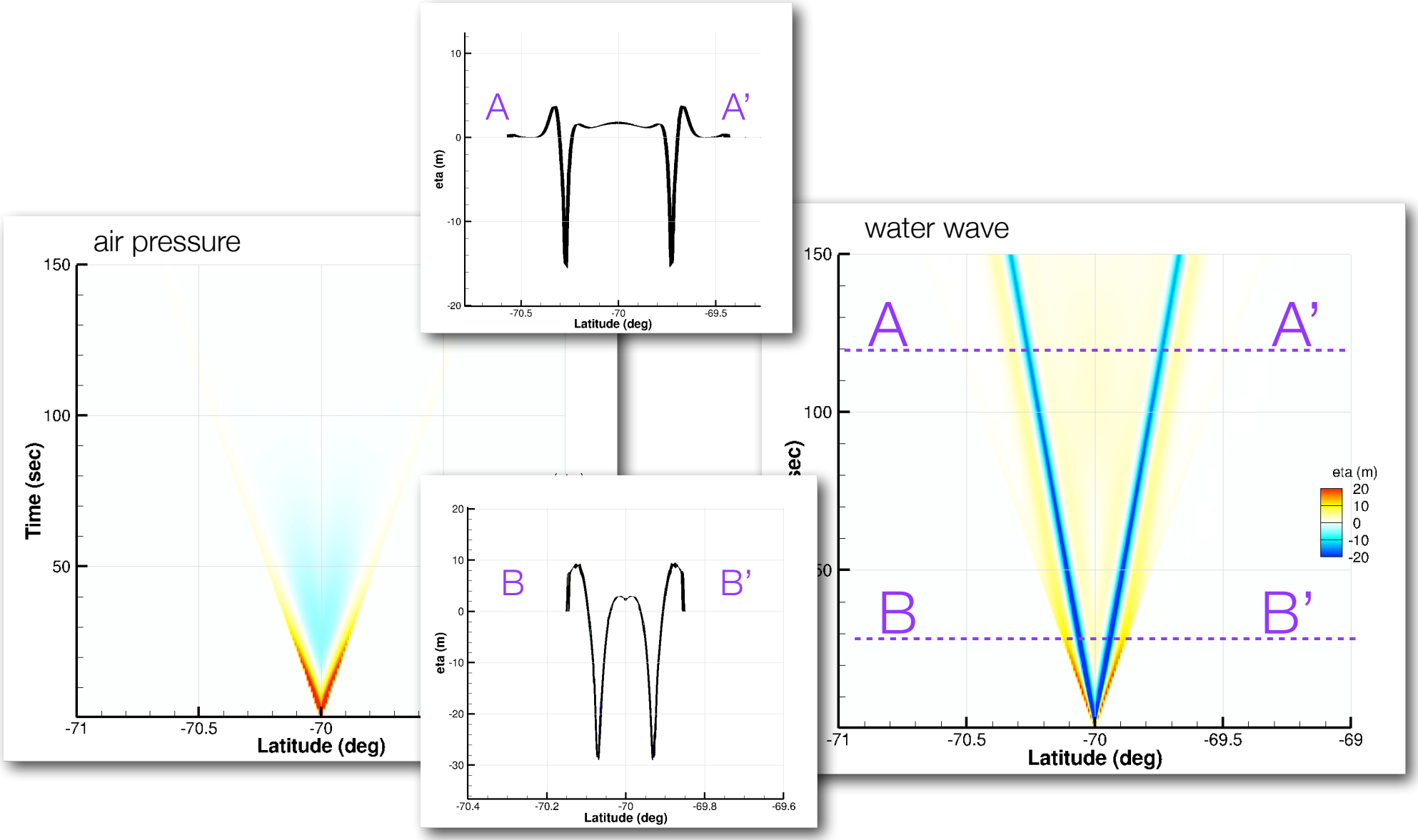


Contours of Mach number, buoyancy effects included

GeoClaw Simulations (25 MT)

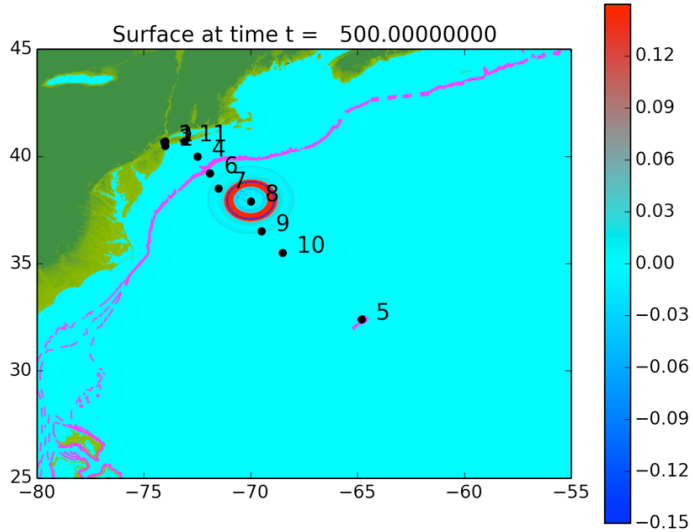


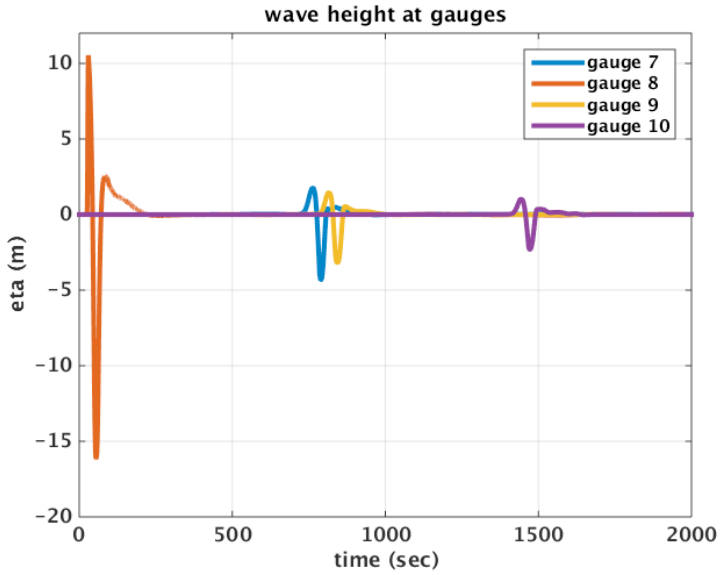
GeoClaw Simulations - 25 MT spherical blast

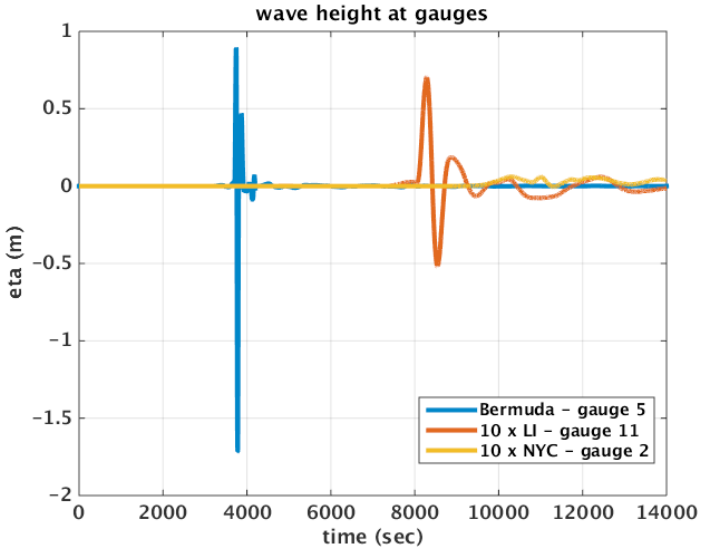


first 150 seconds: pressure travels faster and decays rapidly, wave continues to propagate

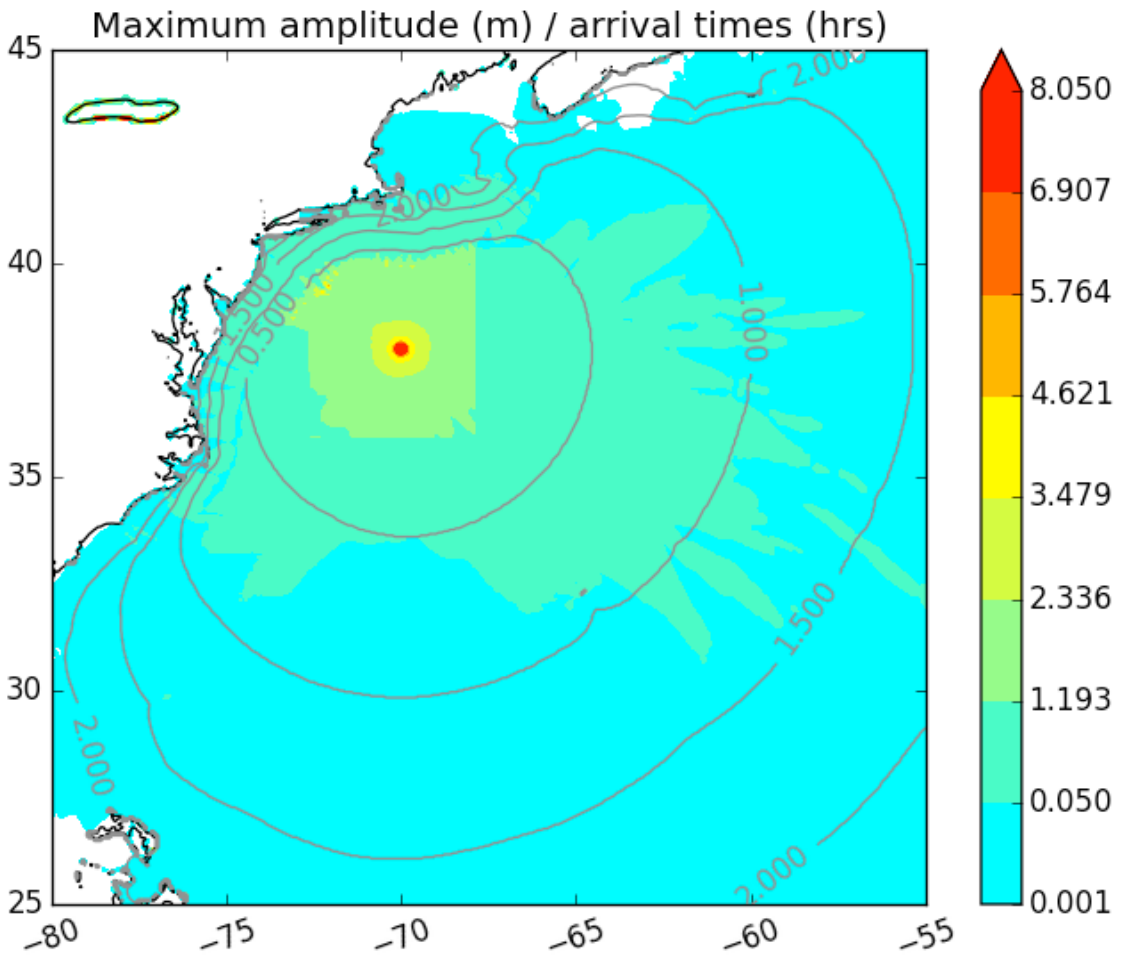
GeoClaw Simulations (25 MT)







GeoClaw Simulations (25 MT)



amplitude in center over 10 meters

Conclusions / Future Work

Some Conclusions

- continental shelf provides some protection
- unlike a tsunami, wave not as long duration

Some Thoughts

- need v&v (meteo-tsunamis, early nuclear explosion data, comparison with other models)
- still investigating whether shallow water equations are appropriate model? *(pressure time scale fast, not very long wavelength disturbance, compressibility of water may weaken effect, compare with full model)*
- *Compare with x-z -t model of full equations vs. shallow water eq.*