Calculating Storm Surge and Other Coastal Hazards Using Geoclaw

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Modeling and Computations of Shallow-Water Coastal Flows,
University of Maryland, 2010-10-14

Outline

Collaborators

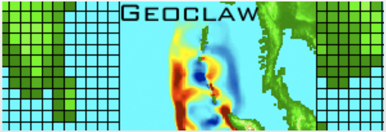
David George: Mendenhall postdoctoral Fellow at the USGS
Marsha Berger: Courant Institute, NYU
Randy LeVeque: Applied Mathematics, University of Washington

Supported in part by NSF, ONR

Outline

1. Single-Layer Storm Surge Modeling
   - GeoClaw
   - Storm Surge Modeling with GeoClaw
2. Multi-Layer Storm Surge Modeling
   - Multi-Layer Equations
   - GeoClaw and Multiple Layers

GeoClaw



- Wave-propagation class of high-resolution finite volume methods using a Godunov type scheme
- Available at `www.clawpack.org/geoclaw`
- Basic computation involves solving the Riemann problem at each cell interface

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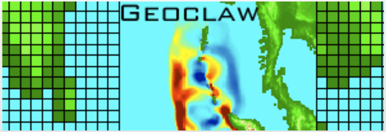

- Wave-propagation class of high-resolution finite volume methods using a Godunov type scheme
- Available at `www.clawpack.org/geoclaw`
- Basic computation involves solving the Riemann problem at each cell interface
- Currently includes:
  - 2d library for depth-averaged flows over topography
  - Well-balanced Riemann solvers that handle dry cells
  - General tools for dealing with multiple data sets at different resolutions
  - Tools for specifying regions where refinement is desired
  - Graphics routines (Matlab transitioning to Python)
  - Output of time series at gauge locations or on fixed grids

Chile Tsunami 2010

Source

- USGS parameterization of fault zone
- Okada model

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- Coarsest level $= 2^\circ$

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- Δt - Adaptive, based on CFL condition of grid

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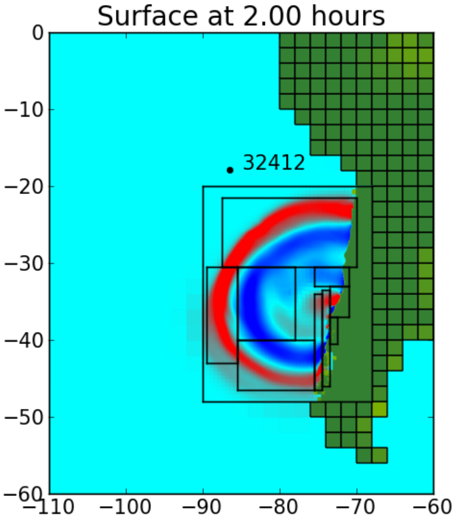

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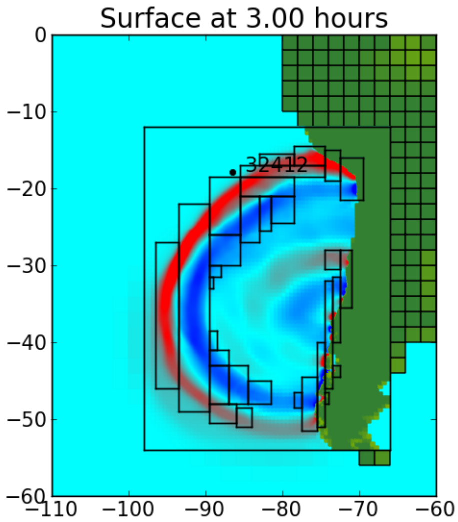

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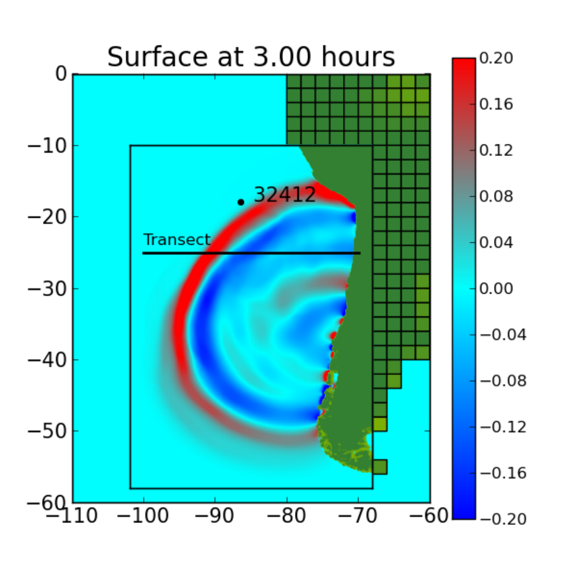

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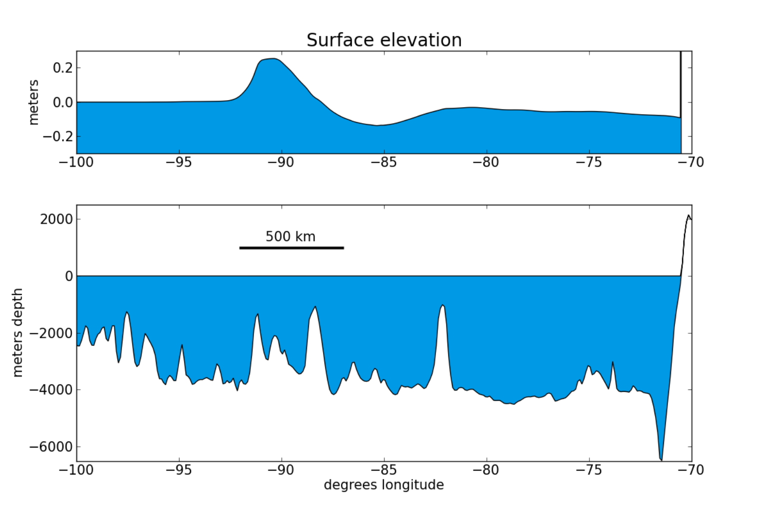

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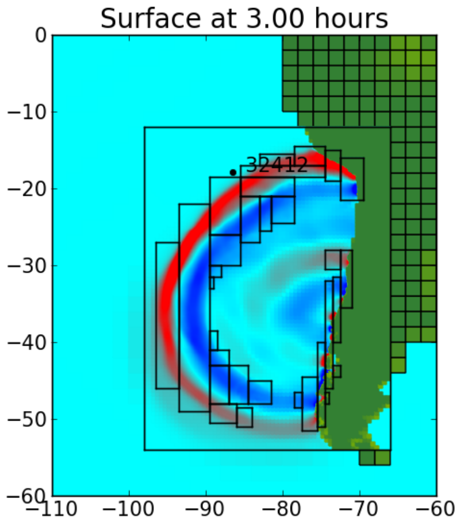

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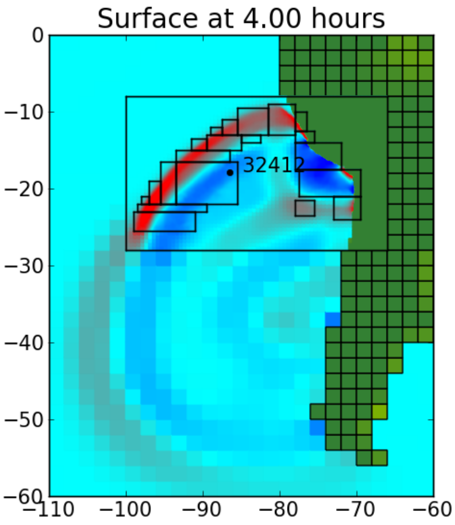

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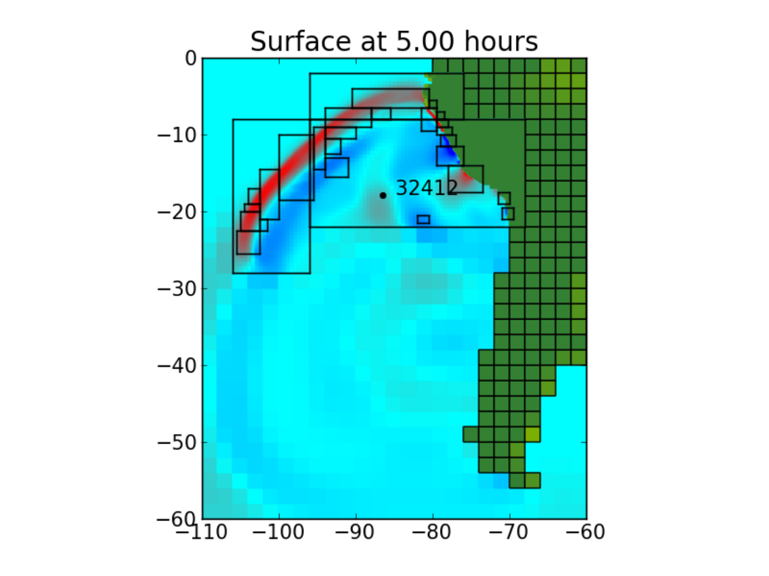

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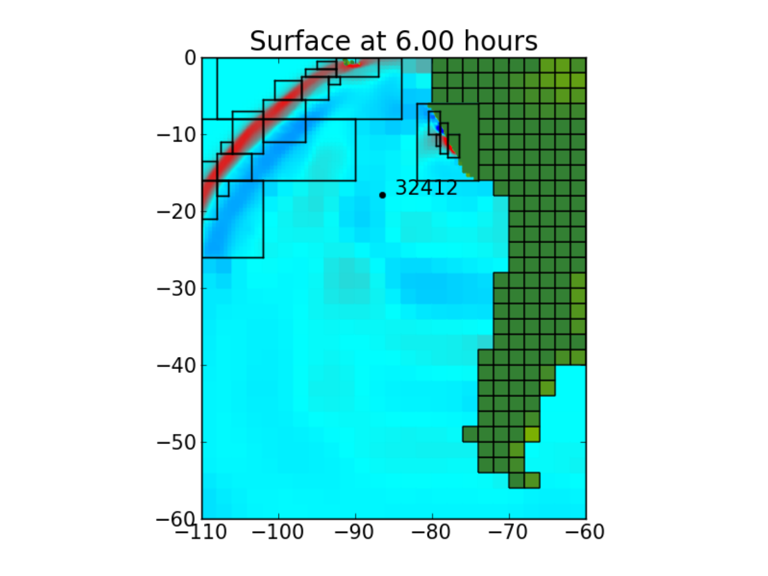

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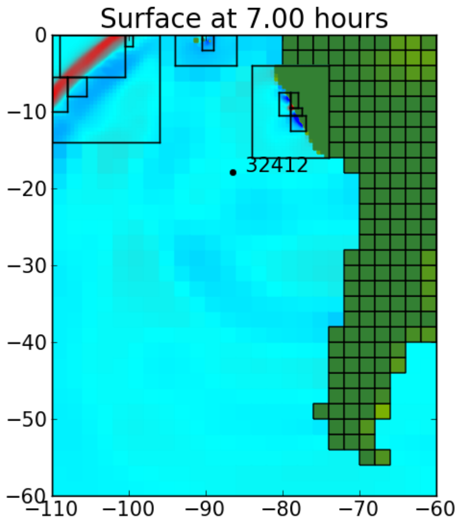

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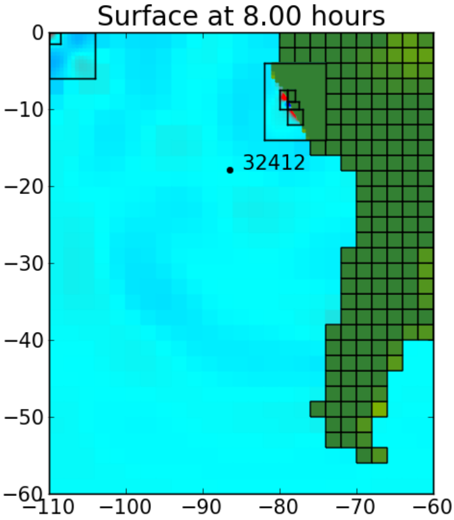
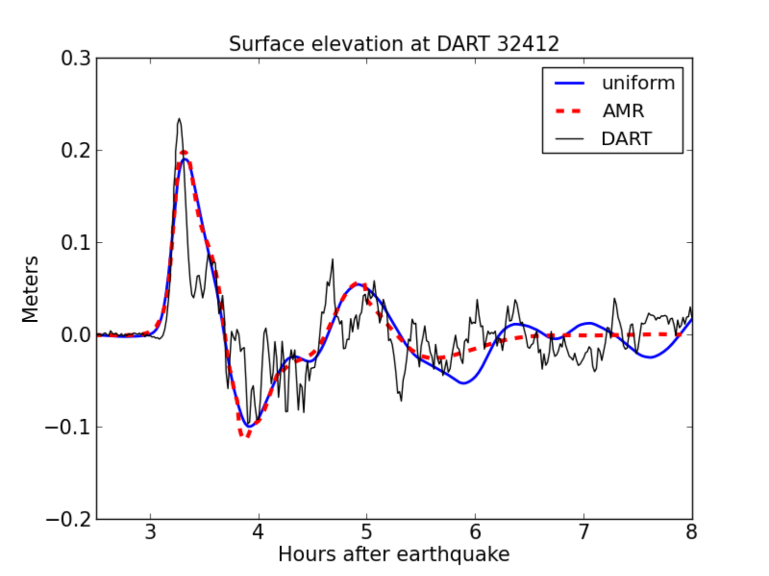
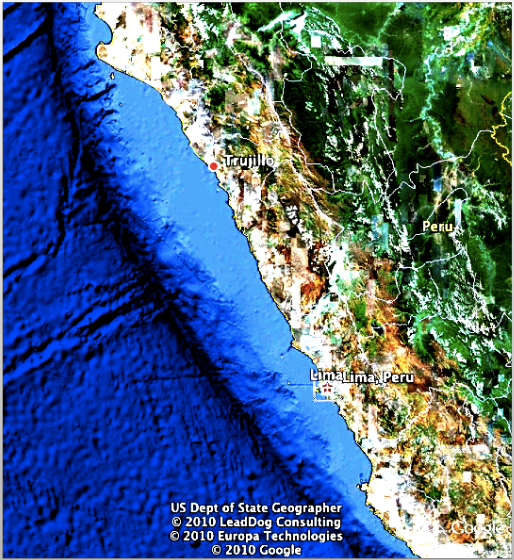


Chile Tsunami 2010: Dart Buoy Comparison



Chile Tsunami 2010: Continental Shelf



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Adaptive Refinement

- Currents are primarily used for the refinement criterion

Hurricane Forced Ocean Basin: Currents

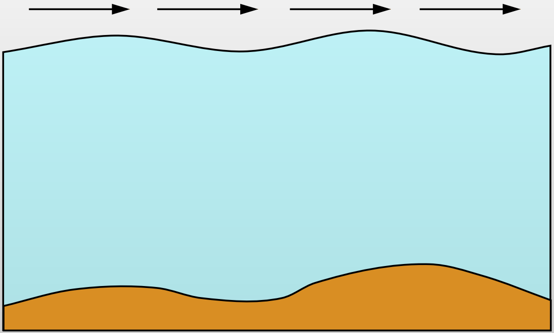
Hurricane Forced Ocean Basin: Surface

Hurricane Forced Ocean Basin: Currents (Deep)

Hurricane Forced Ocean Basin: Surface (Deep)

Outline

Beyond Shallow Water Storm Surge Modeling



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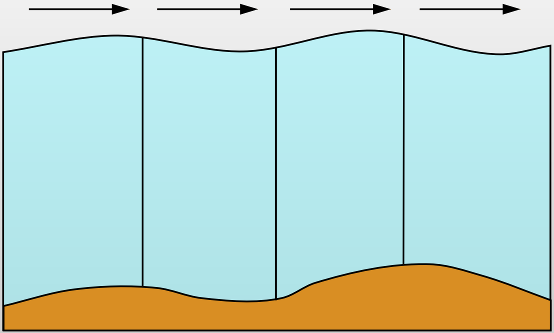

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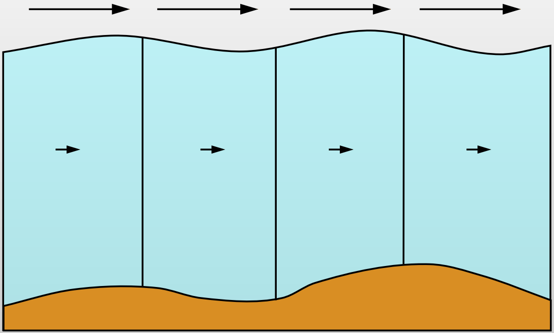

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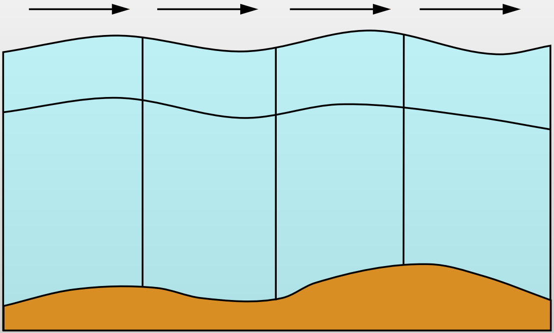

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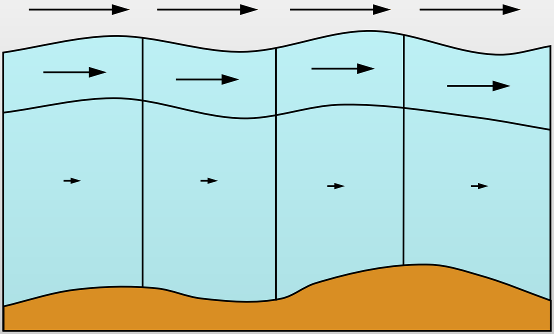

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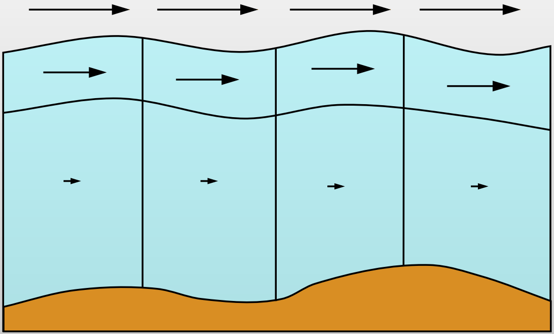

Storm surge model with two-layers:

- Use two layers - boundary layer and abyssal layer

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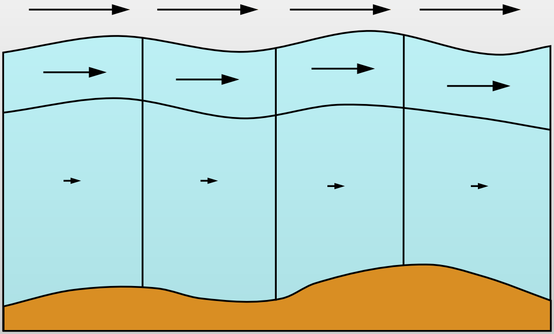

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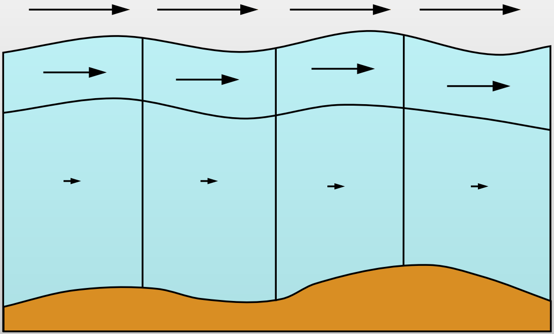

Storm surge model with two-layers:

- Use two layers - boundary layer and abyssal layer
- Wind only forces top layer
- Use thermocline as boundary between layers

Multi-Layer Equations

Motivation: Provide more vertical structure

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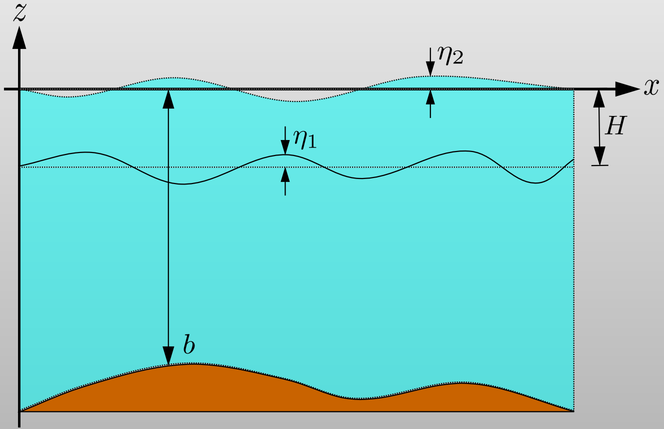
Integrate to an intermediate interface



Physics of Multiple Layers

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- Small surface waves can be accompanied by large internal waves
- Kelvin-Helmholtz instabilities

Multi-Layer Depth Integration

Horizontal momentum equation in bottom layer:

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$$P = \rho_2 g h_2 + \rho_1 g(\eta_1 - z) \qquad r = \rho_2/\rho_1$$

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&(h_1 u_1)_t + (h_1 u_1^2)_x = -r g h_1 (h_2)_x - 1/2 g h_1^2 - g h_1 b_x
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&(h_1 u_1)_t + (h_1 u_1^2)_x = -rgh_1(h_2)_x - 1/2 g h_1^2 - g h_1 b_x && \Rightarrow \\
&\boxed{(h_1 u_1)_t + (h_1 u_1^2 + 1/2 g h_1^2)_x = -rgh_1(h_2)_x - g h_1 b_x}
\end{aligned}$$

Full 1D Equations

$$\text{Bottom} \begin{cases} (h_1)_t + (h_1 u_1)_x = 0 \\ (h_1 u_1)_t + \left(h_1 u_1^2 + \frac{1}{2} g h_1^2 \right)_x = -g h_1 (r(h_2)_x + b_x) \end{cases}$$

$$\text{Top} \begin{cases} (h_2)_t + (h_2 u_2)_x = 0 \\ (h_2 u_2)_t + \left(h_2 u_2^2 + \frac{1}{2} g h_2^2 \right)_x = -g h_2 ((h_1)_x + b_x) \end{cases}$$

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Problem: Only conditionally hyperbolic

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$$

Problem: Only conditionally hyperbolic
Write system as non-conservative, quasi-linear form

$$
q_t + A(q) q_x = S(q)
$$

Wave Speeds

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Characteristic Polynomial:

$$((\lambda - u_1)^2 - gh_1)((\lambda - u_2)^2 - gh_2) - rg^2 h_1 h_2 = 0$$

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Internal waves: $g' = g(1 - r)$

$$\lambda^{\pm}_{\text{int}} = \frac{h_1 u_2 + h_2 u_1}{h_1 + h_2} \pm \sqrt{g' \frac{h_1 h_2}{h_1 + h_2} \left[1 - \frac{(u_1 - u_2)^2}{g'(h_1 + h_2)}\right]}$$

Oscillating Wind Field

Storm Surge Modeling with Multiple Layers

Augment multi-layer system with wind friction term in the top layer:

$$
\text{Top}\begin{cases}
(h_2)_t + (h_2 u_2)_x = 0 \\
(h_2 u_2)_t + \left(h_2 u_2^2 + \frac{1}{2} g h_2^2\right)_x = -g h_2((h_1)_x + b_x) + \tau_f |W|^2
\end{cases}
$$

$$
\text{Bottom}\begin{cases}
(h_1)_t + (h_1 u_1)_x = 0 \\
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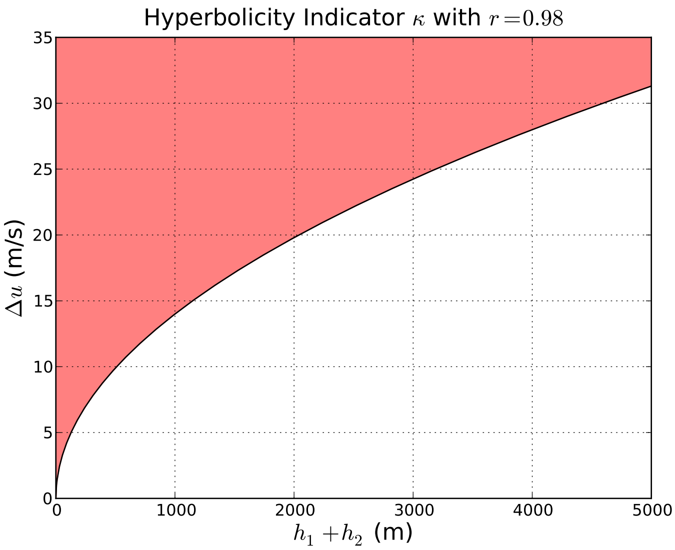
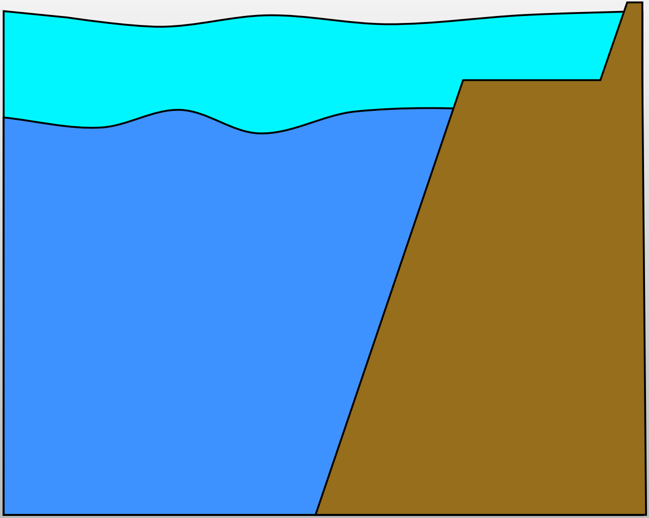
Possible Difficulties:

- Hyperbolicity - Off of continental shelf, velocities should not violate hyperbolicity
- Dry-state problem - Force bottom layer to become dry away from coastline
- Computation of eigenvalues - State is near linear regime, approximations should be valid

Modeling Considerations: Hyperbolicity



Modeling Considerations: Dry-State Problem



Linearized Eigenvalues

Linearize about $u_1 = u_2 = 0$ and expand about $1 - r$

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Internal waves:

$$\lambda^{\pm}_{\text{int}} = \sqrt{\frac{g h_1 h_2}{h_1 + h_2}(1 - r)} + \frac{g^{1/2}(h_1 h_2)^{3/2}}{2(h_1 + h_2)^{5/2}}(1 - r)^{3/2} + \mathcal{O}((1 - r)^{5/2})$$

GeoClaw Multi-Layer

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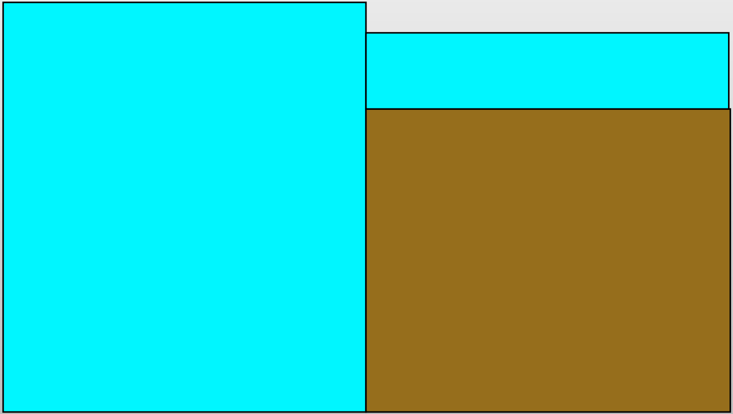
- Calculate linearized eigenvalues using only left and right states (no averaging)
- Use f-wave approach to handle source terms
  - Advantageous when problem is near steady state, $f(q)_x \approx S(q)$
- Refine based on speed of top layer and gradient of top surface and internal surface

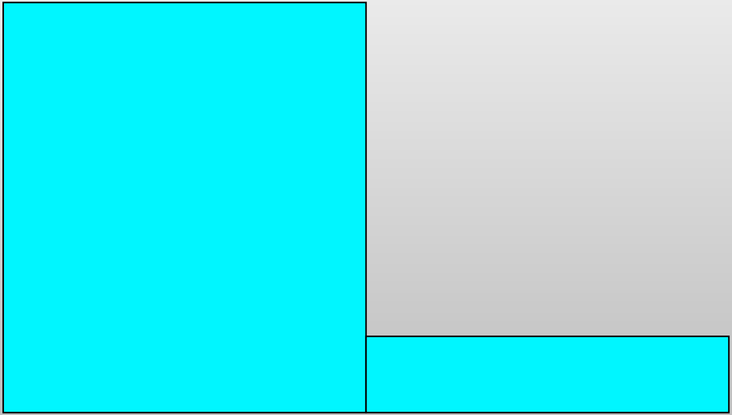
Importance of the Steady State

Want to solve this problem:



Steady State Figures

Not this:



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Wave Propagation:

1. Compute eigenspace (speeds s and eigenvectors R) of our system
2. Compute jump in conserved quantities $q_i - q_{i-1} = \delta$

Wave Approach

$$q_t + f(q)_x = S(q, q_x, ...) \qquad q_t + A(q)q_x = S(q, q_x, ...)$$

Wave Propagation:

1. Compute eigenspace (speeds s and eigenvectors R) of our system
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Hurricane Forced Ocean Basin: Currents

Hurricane Forced Ocean Basin: Depths

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References

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- Paper with details in *Acta Numerica* in preparation, draft available soon.