Towards Adaptive Simulation of Dispersive Tsunami Propagation from an Asteroid Impact

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www.nasa.gov/planetarydefense

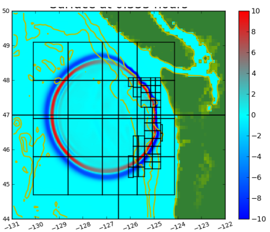
Tsunami Propagation

Overview:

- Impact tsunamis have shorter wavelengths than earthquake tsunamis; shallow water model not appropriate
- For ocean-scale propagation want depth-averaged velocities, reducing simulation from $3 \longrightarrow 2$ dimensions
- Boussinesq models include dispersion, need elliptic solve each time step. (This work uses Madsen and Shaffer).

Still need AMR:

- In deep ocean only need resolution of kilometers
- For coastal inundation want resolution of meters



Strategy: Boussinesq in deep ocean, switch to SWE near coast

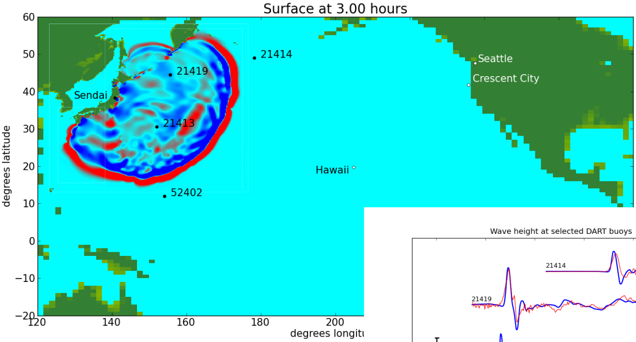
GeoClaw Software www.geoclaw.org

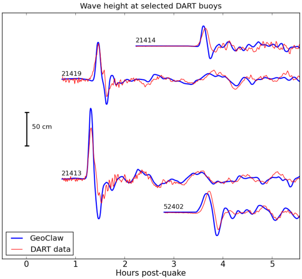
Based on Clawpack (www.clawpack.org)

- 2d library for depth-averaged flows over topography.
- Handles dry cells where depth $= 0$.
- Well-balanced Riemann solvers for small amplitude waves on ocean at rest.
- Well balancing and dry cells in conjunction with adaptive refinement.
- Well validated for earthquake-generated tsunamis.
- Other applications:
  Debris flows (Dave George, USGS — D-CLAW)
  Storm surge (Kyle Mandli, Columbia)
  Dam breaks / river floods (DG, M. Turzewski, UW,
  D. Calhoun, Boise State – ForestClaw)

DART Buoys — Tohoku 2011

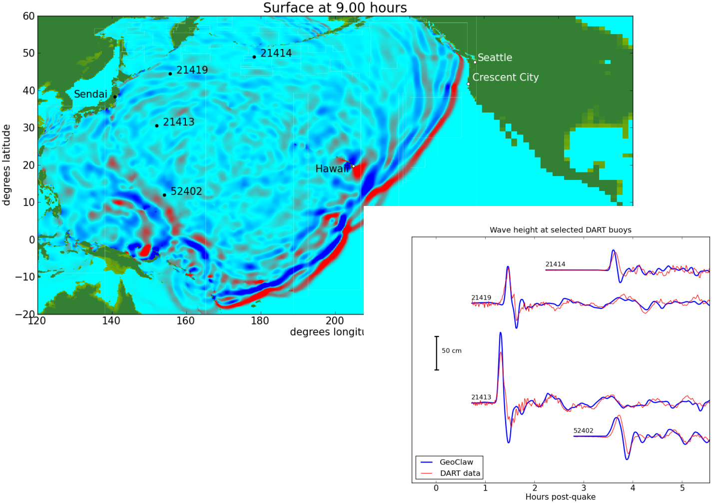
Deep Ocean Assessment and Reporting of Tsunamis



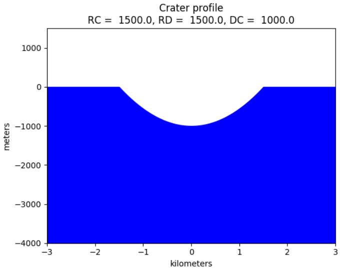


DART Buoys — Tohoku 2011

Deep Ocean Assessment and Reporting of Tsunamis



Asteroid Impact Tsunami – Static crater test case



Our tests used the crater with no lip as initial data.

Depth of crater: 1000 m, Depth of ocean: 4000 m.

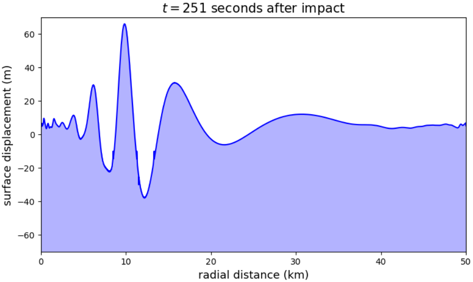
Initial conditions for 2D Boussinesq:

Full 3D multi-physics hydrocode (ALE3D) was run in 2D axisymmetric mode for this simplified initial condition.

(Darrel Robertson, NASA Ames Research Center).

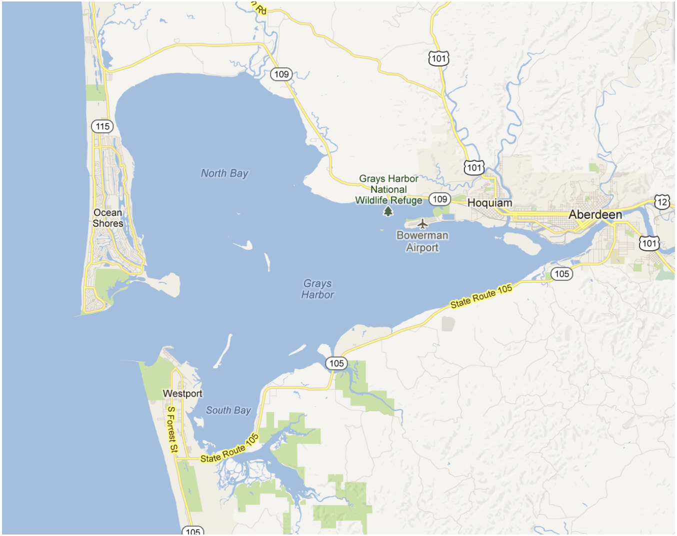
Asteroid Impact Tsunami – Static crater test case

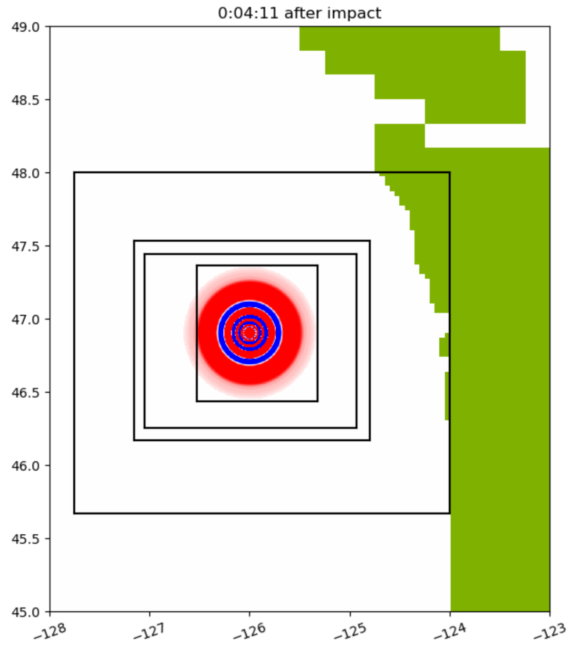
Surface at $t = 251$ seconds transferred as radially-symmetric initial data for depth-averaged Boussinesq.

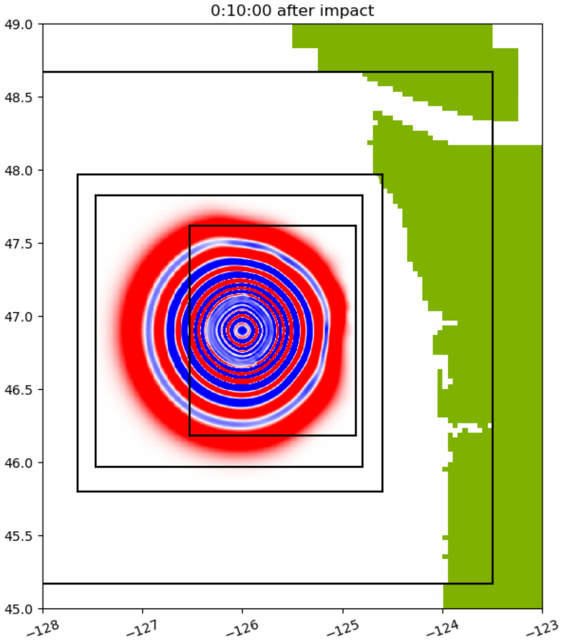


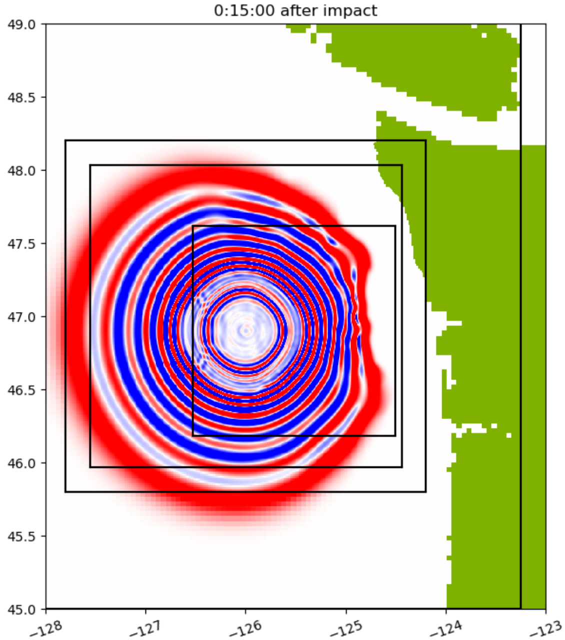
Impact placed ≈ 150 km off Washington coast.

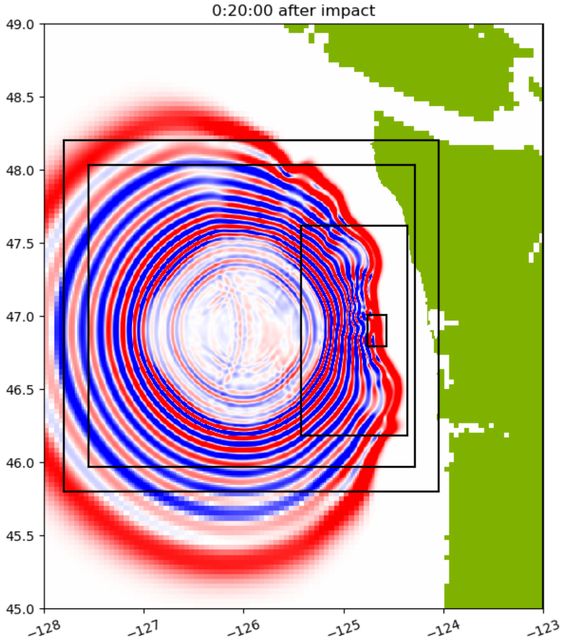
Grays Harbor




0:04:11 after impact
49.0
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
−127
−126
−125
−124
−123


0:10:00 after impact
49.0
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
−127
−126
−125
−124
−123


0:15:00 after impact
49.0
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
−127
−126
−125
−124
−123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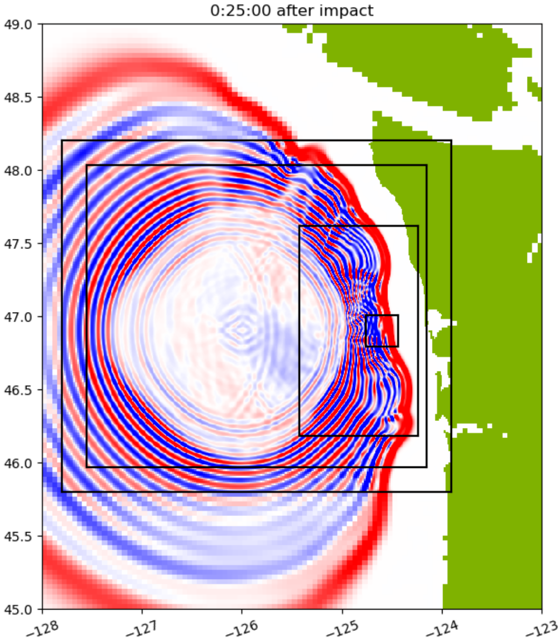
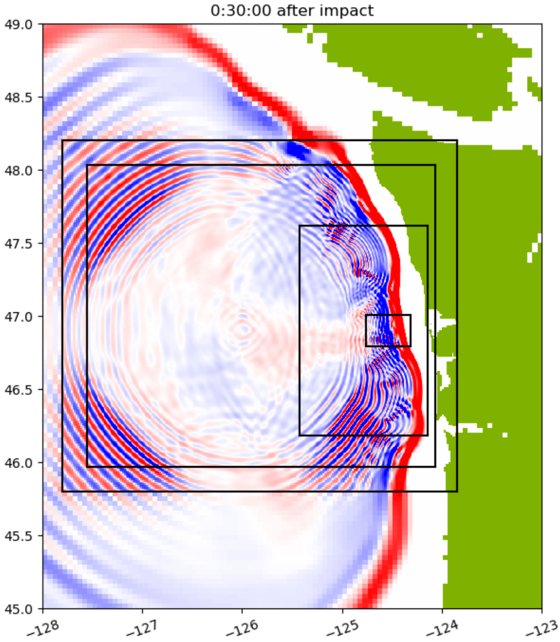
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
−127
−126
−125
−124
−123


0:25:00 after impact
49.0
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
−127
−126
−125
−124
−123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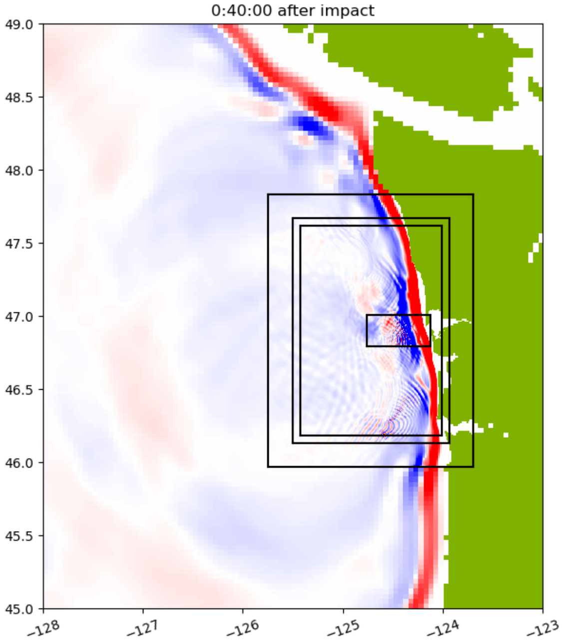
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
−127
−126
−125
−124
−123


0:40:00 after impact
49.0
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−128
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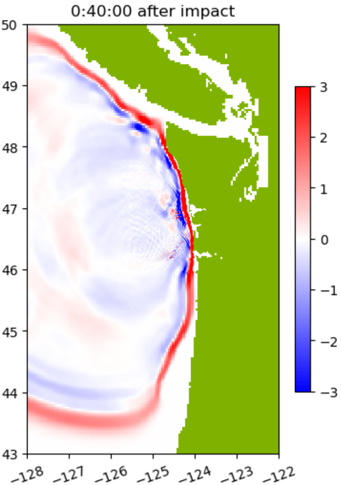
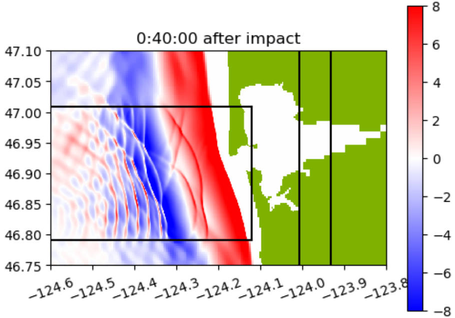
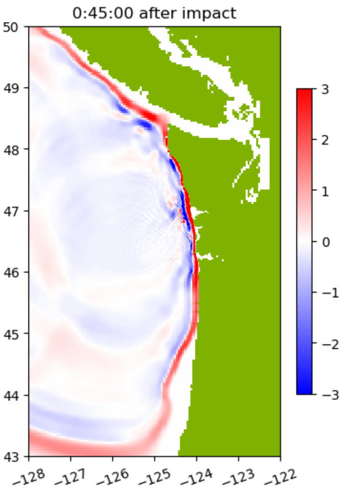
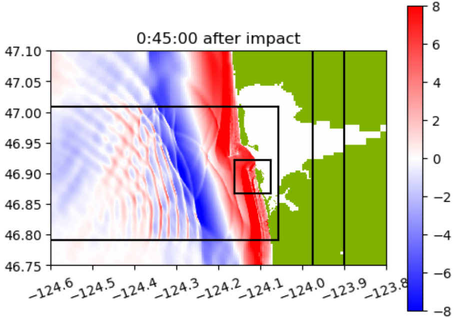
−126
−125
−124
−123



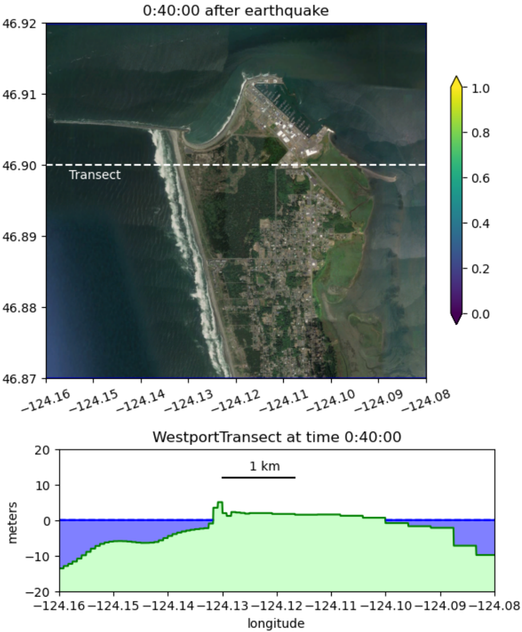


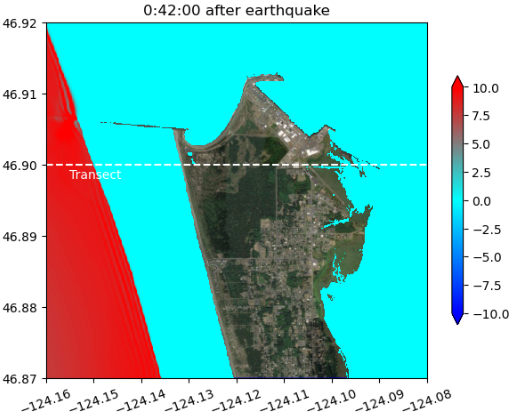
Dispersion leads to
“soliton fission” near coast.

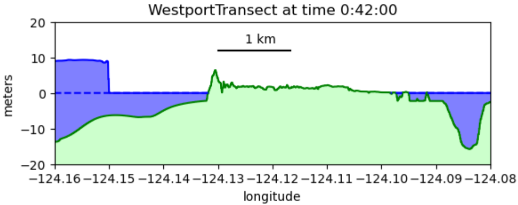


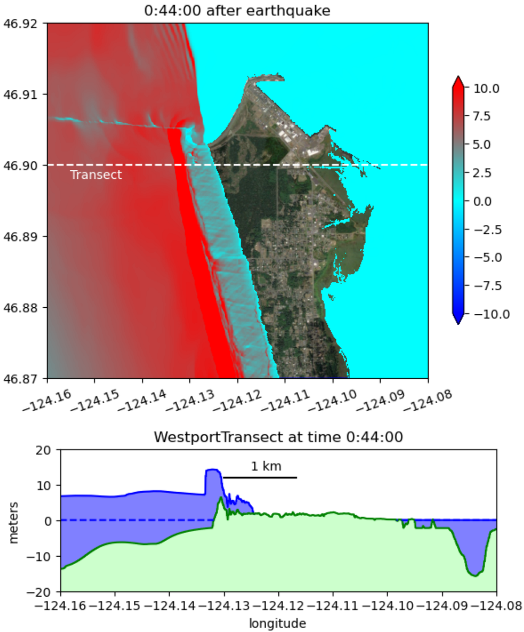


Dispersion leads to
“soliton fission” near coast.


0:40:00 after earthquake
46.92
46.91
46.90
46.89
46.88
46.87
Transect
−124.16
−124.15
−124.14
−124.13
−124.12
−124.11
−124.10
−124.09
−124.08
1.0
0.8
0.6
0.4
0.2
0.0
WestportTransect at time 0:40:00
1 km
20
10
0
−10
−20
meters
longitude


0:42:00 after earthquake
Transect
46.92
46.91
46.90
46.89
46.88
46.87
−124.16
−124.15
−124.14
−124.13
−124.12
−124.11
−124.10
−124.09
−124.08
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0


WestportTransect at time 0:42:00
1 km
meters
20
10
0
−10
−20
−124.16
−124.15
−124.14
−124.13
−124.12
−124.11
−124.10
−124.09
−124.08
longitude



0:44:00 after earthquake
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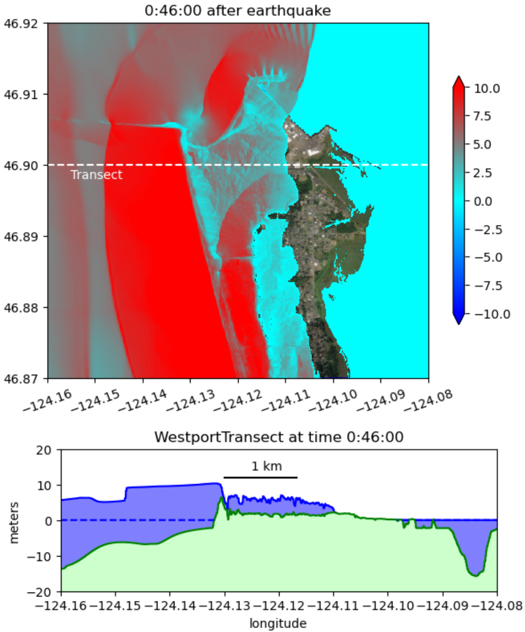
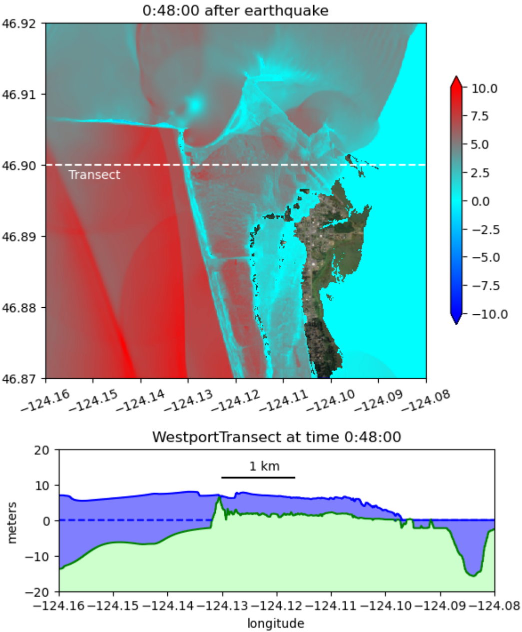
46.91
46.90
46.89
46.88
46.87
Transect
−124.16
−124.15
−124.14
−124.13
−124.12
−124.11
−124.10
−124.09
−124.08
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
WestportTransect at time 0:44:00
1 km
20
10
0
−10
−20
meters
longitude


0:46:00 after earthquake
46.92
46.91
46.90
46.89
46.88
46.87
Transect
−124.16
−124.15
−124.14
−124.13
−124.12
−124.11
−124.10
−124.09
−124.08
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
WestportTransect at time 0:46:00
1 km
20
10
0
−10
−20
meters
longitude



0:48:00 after earthquake
46.92
46.91
46.90
46.89
46.88
46.87
Transect
−124.16
−124.15
−124.14
−124.13
−124.12
−124.11
−124.10
−124.09
−124.08
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
WestportTransect at time 0:48:00
1 km
20
10
0
−10
−20
meters
longitude

Fractional step method

$$h_t + (hu)_x = 0$$
$$(hu)_t + \left(hu^2\right)_x + gh\eta_x = \psi$$

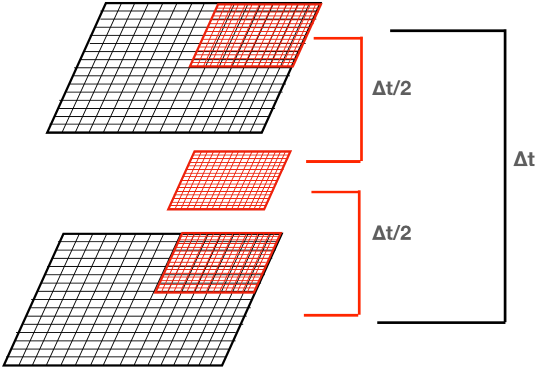
1. Solve elliptic equation for source term ψ:

   $$[I - D_{11}]\psi = -D_{11}\left[\left(hu^2\right)_x + gh\eta_x\right] + gh_0^2 B_1 (h_0\eta_x)_{xx}.$$

   $\Longrightarrow$ Difficulties for AMR algorithms.

2. Update momentum by $(hu)_t = \psi$ over time step
3. Take step with homogeneous SWE.

Patch-Based Adaptive Mesh Refinement



Ghost cells on border of level 2 (red grids) interpolated in space and time from level 1 (black grids), including extra variable ψ.

Conclusions and Future Work

Demonstrated: proof of concept using both Boussinesq and Shallow Water model combined with AMR.

But: cannot yet tell how much difference it makes for shoreline inundation; earlier 1D parameter studies showed significant differences

- How much does it depend on switching criteria?
  Currently switching at 10 meter depth
  Have not included “wave breaking” criteria yet
- Make more robust
  Some stability problems at patch edges
- Compare with other Bouss models
  ForestClaw $+$ Serre-Green-Naghdi