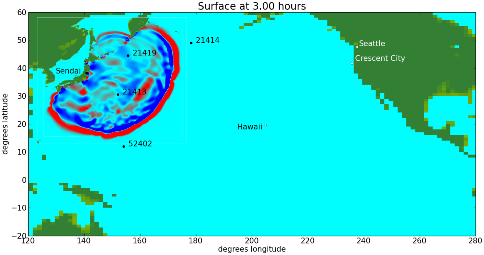
# The GeoClaw Software for Tsunamis and Other Hazardous Flows


Randall J. LeVeque
Department of Applied Mathematics
University of Washington


GeoClaw: **www.clawpack.org/geoclaw**

# Collaborators

David George, USGS Cascades Volcano Observatory (CVO)
Tsunamis, dam break, debris flows

Marsha Berger, Courant Institute, NYU
Adaptive Mesh Refinement (AMR)

Kyle Mandli, UT-Austin
Two-layer shallow water, storm surge

Frank González, Breanyn MacInnes, Beth Arcos
Earth and Space Sciences Dept, UW

J. Kim, J. Varkovitzky, B. Hirai, P. Chamberlain

Numerous other students and colleagues

Supported in part by NSF, ONR, AFOSR

# Outline

- Tsunami simulations
- Comparing proposed seismic sources
  - Great Tohoku Tsunami of 11 March 2011
- Finite volume methods
- Riemann solvers (also with dry state)
- Well-balanced methods
- Validation, verification, benchmarking
- Extensions to other applications:
  Debris flow, submarine landslides,
  dam failure, storm surge

# Tsunamis

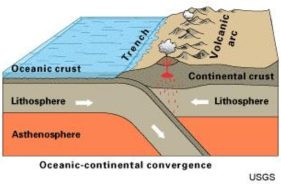
Generated by

- Earthquakes,
- Landslides,
- Submarine landslides,
- Volcanoes,
- Meteorite or asteroid impact

There were 97 significant tsunamis during the 1990's, causing 16,000 casualties.

There have been approximately 28 tsunamis with run-up greater than 1m on the west coast of the U.S. since 1812.

# Tsunamis caused by subduction zone earthquakes




- Small amplitude in ocean ($< 1$ meter) but can grow to 10s of meters at shore.
- Run-up along shore can inundate 100s of meters inland
- Long wavelength (as much as 200 km)
- Propagation speed $\sqrt{gh}$ (much slower near shore)
- Average depth of Pacific or Indian Ocean is 4000 m $\implies$ average speed 200 m/s $\approx$ 450 mph

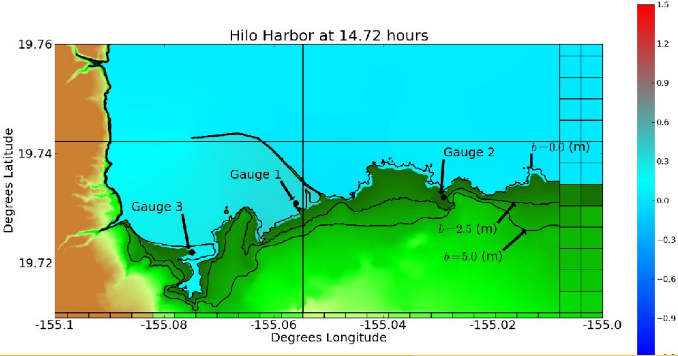
# Inundation of Hilo, Hawaii from 27 Feb 2010 event

Resolution $\Delta y \approx 160$ km on Level 1 (covering Pacific Ocean),
$\Delta y \approx 10$m on Level 5 (shown below).

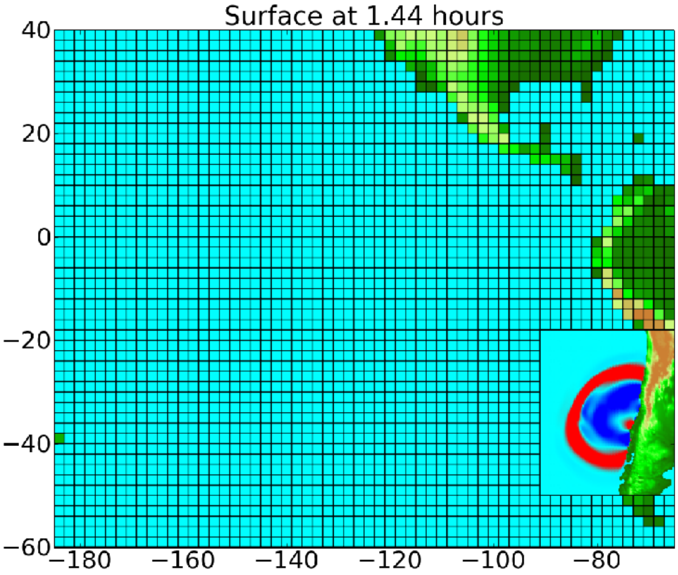
Using 5 levels of refinement with ratios 8, 4, 16, 32.

Total refinement factor: $2^{14} = 16,384$ in each direction.

With 15 m displacement at fault:



# 27 February 2010 tsunami



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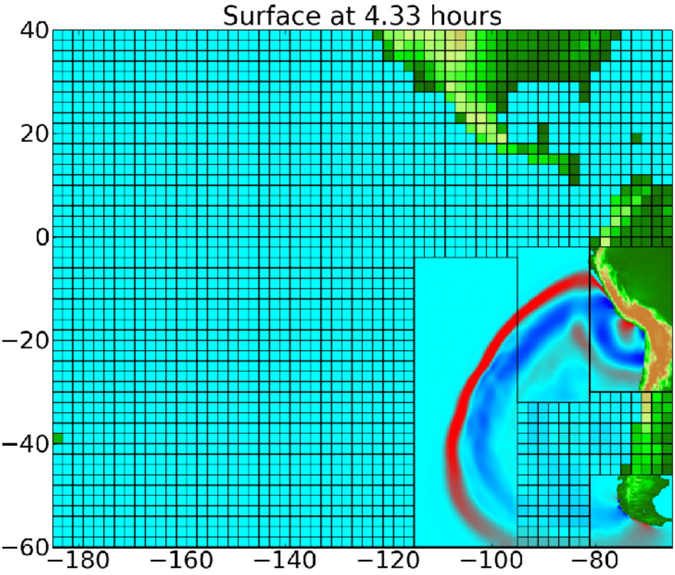
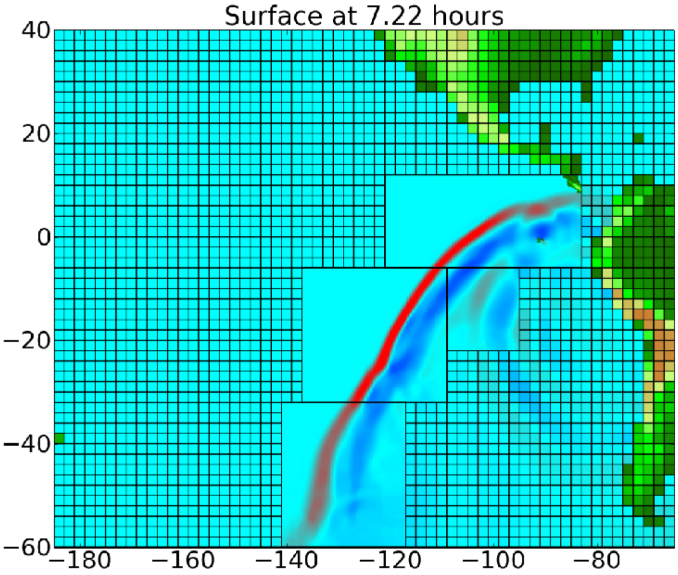


# 27 February 2010 tsunami



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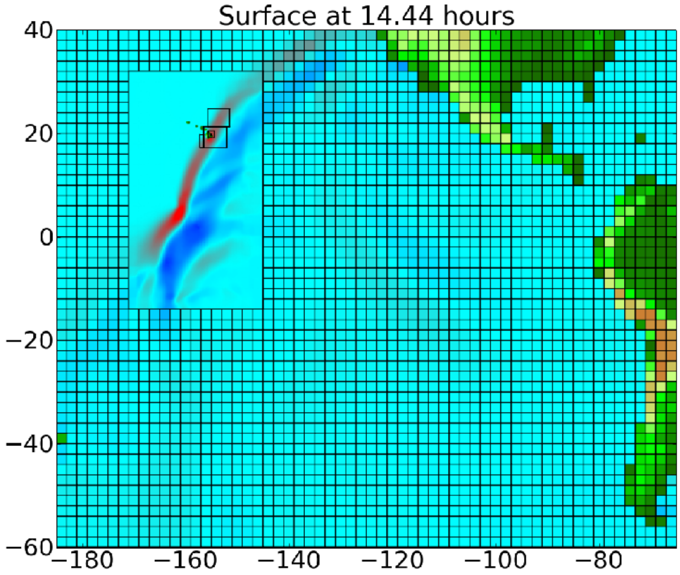

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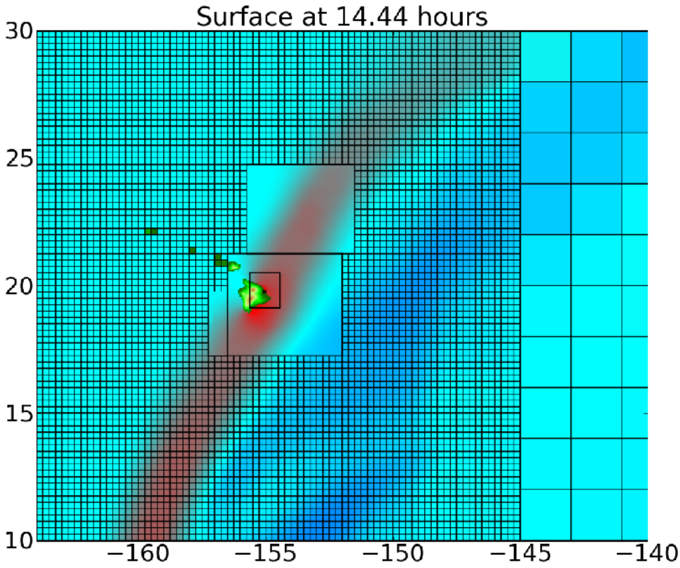

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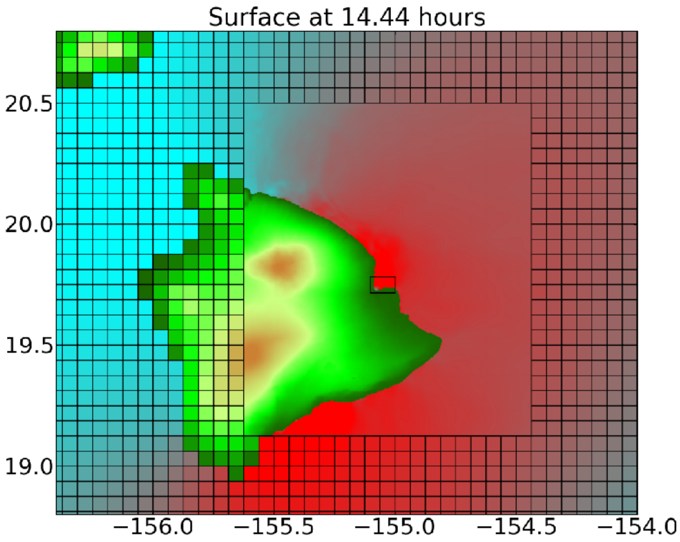

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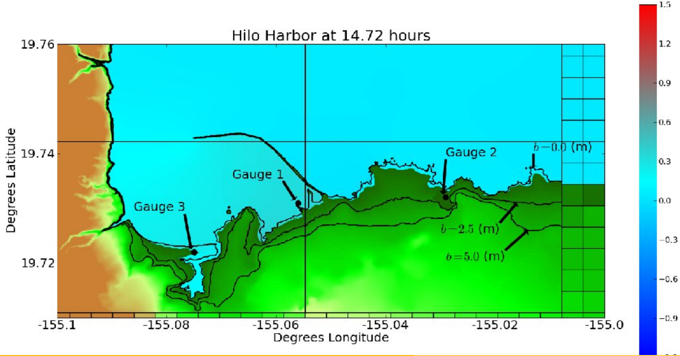

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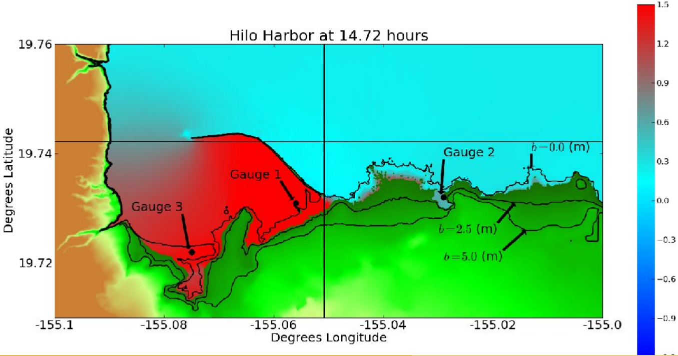
With 90 m displacement at fault (1960?):



# Depth-averaged models

Reduce three-dimensional free surface problem to...

Two-dimensional Shallow Water (St. Venant) Equations

$$h_t + (hu)_x + (hv)_y = 0$$

$$(hu)_t + \left(hu^2 + \frac{1}{2}gh^2\right)_x + (huv)_y = -ghB_x(x,y)$$

$$(hv)_t + (huv)_x + \left(hv^2 + \frac{1}{2}gh^2\right)_y = -ghB_y(x,y)$$

where $(u,v)$ are velocities in the horizontal directions $(x,y)$,

$B(x,y) =$ bathymetry (underwater topography),

$\frac{1}{2}gh^2 =$ hydrostatic pressure.

# Depth-averaged models

Advantages:

- 2D rather than 3D
  Often critical for realistic geophysical flows
  Vastly different spatial scales, e.g. ocean to harbor
  Need Adaptive Mesh Refinement even in 2D!
- No free surface $\eta(x, y, t)$.

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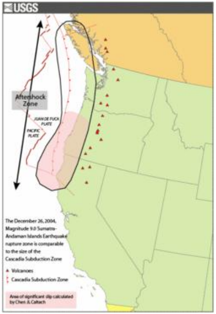
Possible problems:

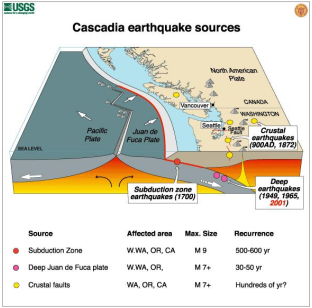
- When is this valid?
- What if fluid is not homogeneous, or
  shallow water assumptions don't hold?
- Often still a free boundary in the $x$-$y$ domain,
  at the shoreline or at the margins of the flow.
- Small perturbations to steady state hard to capture.

# Some applications of tsunami modeling

- Real-time forecasting, warning
- Hazard mapping, emergency management planning
  (Probabilistic assessment of tsunami hazards)
- Comparing proposed seismic sources for past events
  Tsunami measurements at DART buoys, tidegauges
- Solution of source inversion problem
- Paleo fluid dynamics: simulations aid in studying
  tsunami deposits, identification of possible sources

# Cascadia Subduction Zone (CSZ)




- 1200 km long off-shore fault stretching from northern California to southern Canada.
- Last major rupture: magnitude 9.0 earthquake on January 26, 1700.
- Tsunami recorded in Japan with run-up of up to 5 meters.
- Historically there appear to be magnitude 8 or larger quakes every 500 years on average.

# Tsunami Deposits

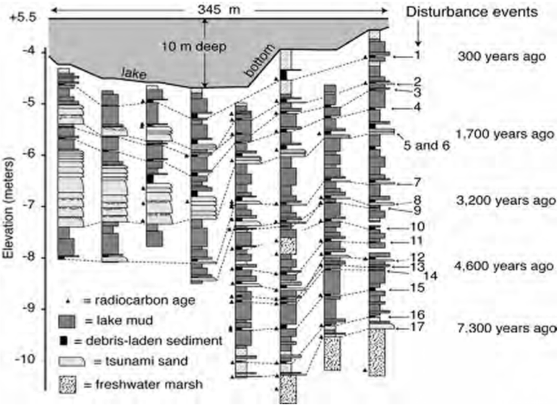



Figure 3.6. An example of long-term records of tsunami deposits interpreted to be from the Cascadia Subduction Zone; from Bradley Lake on the coast of southern Oregon (based on Kelsey et al., 2005).

From: J. Bourgeois, Chapter 3 of *The Sea, Volume 15: Tsunamis*, Harvard University Press, 2009.

# 11 March 2011 Great Tohoku Tsunami

Some preliminary results:
**www.clawpack.org/links/honshu2011**

Currently find best agreement with Preliminary Version 3 of a UCSB model

Guangfu Shao, Xiangyu Li, Chen Ji, UCSB
Takahiro Maeda, NIED

**`http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/2011/03/0311/Honshu_main.html`**

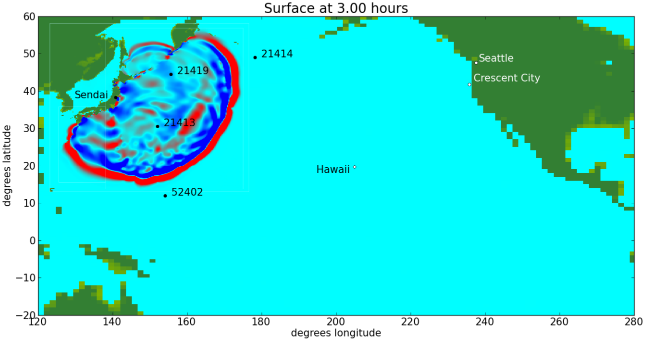
190 $25 \times 20$ km subfaults on a single fault plane

Common strike and dip, different rake and slip, rupture time.

Okada model used to convert into seafloor deformation.

Currently static deformation.
Should include dynamic rupture ($\approx 180$ sec).

# Great Tohoku Tsunami, 11 March 2011




Modeling and Simulating Tsunamis with an Eye to Hazard Mitigation, RJL and J. Behrens, SIAM News, May, 2011
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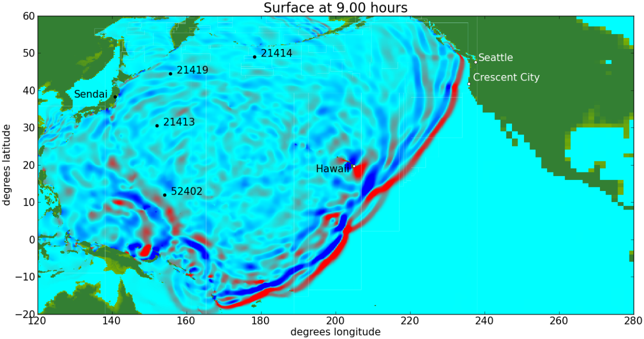


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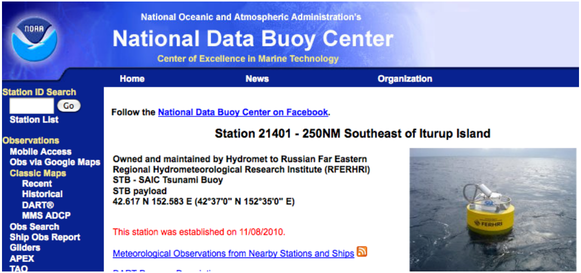
National Oceanic and Atmospheric Administration's
National Data Buoy Center
Center of Excellence in Marine Technology
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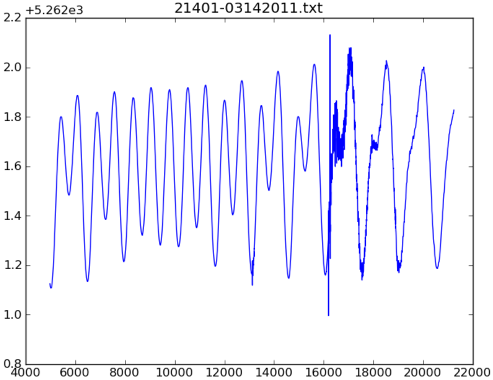
Historical
DART®
MMS ADCP
Obs Search
Ship Obs Report
Gliders
APEX
TAO
Follow the National Data Buoy Center on Facebook.
Station 21401 - 250NM Southeast of Iturup Island
Owned and maintained by Hydromet to Russian Far Eastern Regional Hydrometeorological Research Institute (RFERHRI)
STB - SAIC Tsunami Buoy
STB payload
42.617 N 152.583 E (42°37'0" N 152°35'0" E)
This station was established on 11/08/2010.
Meteorological Observations from Nearby Stations and Ships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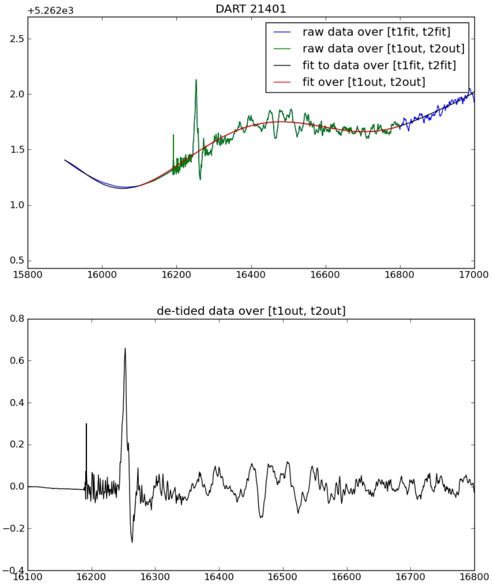
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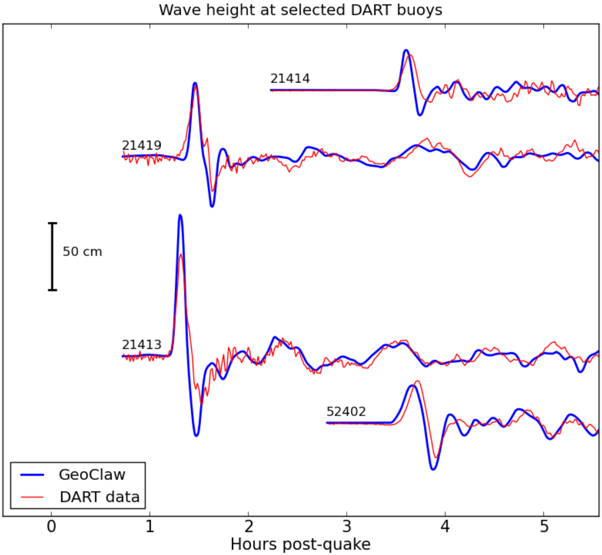
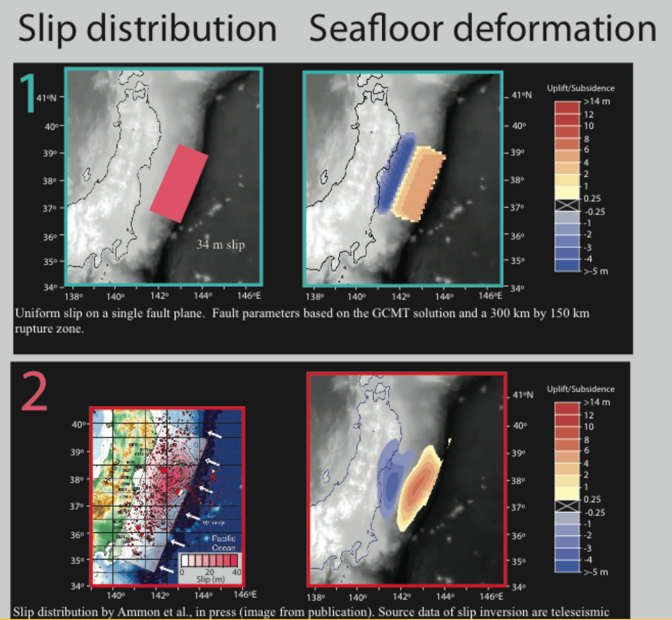
# Great Tohoku Tsunami, 11 March 2011



# Slip distribution of various source models



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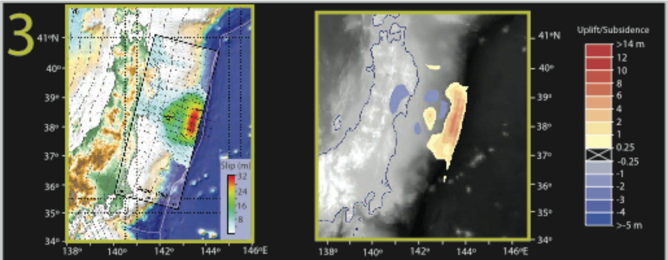
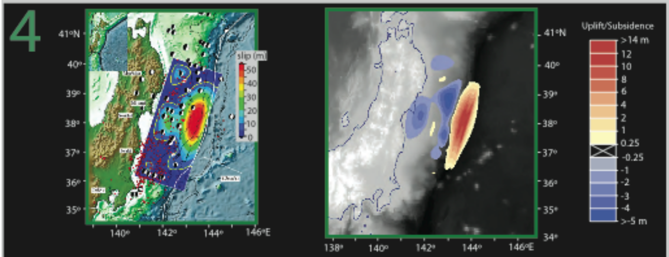



Slip distribution by Hayes, in press (image from publication). Source data of slip inversion are teleseismic (P, SH, and long-period) waves Data available at
http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/results/static_out




Slip distribution by Shao et al., in press (UCSB Model III). Source data of slip distribution are teleseismic (P, SH, and long-period) waves. Data and slip distribution image available at

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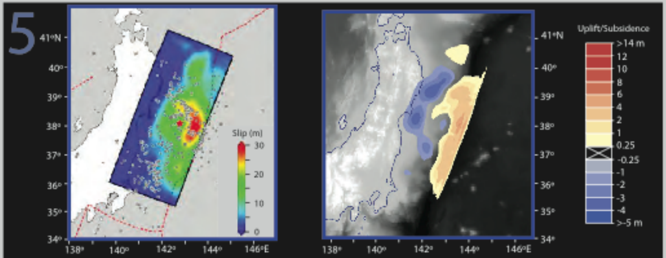
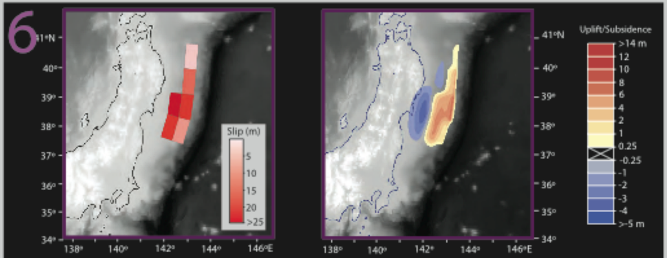



Slip distribution of Wei, Sladen and the ARIA group (Caltech-JPL). Source data of slip distribution are teleseismic (P, SH, and long-period) waves and GPS station motion. Data and slip distribution image available at http://www.tectonics.caltech.edu/slip_history/2011_taiheiyo-oki/




Slip distribution estimated from inversion of tsunami waveforms by the NOAA Center for Tsunami Research at the Pacific Marine Environmental Laboratory.

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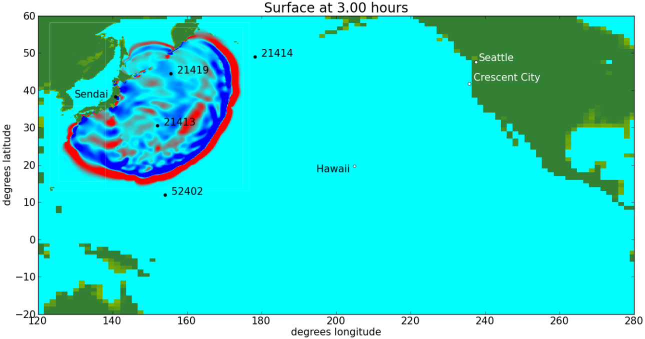


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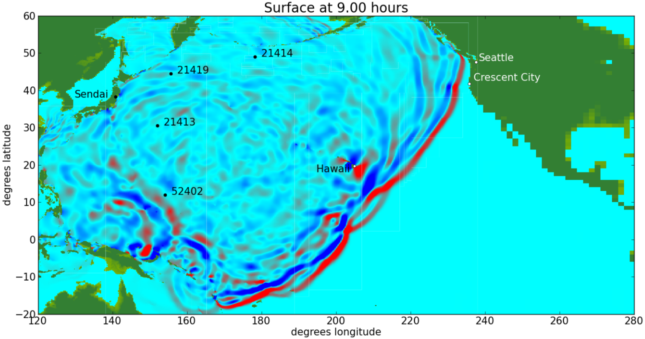


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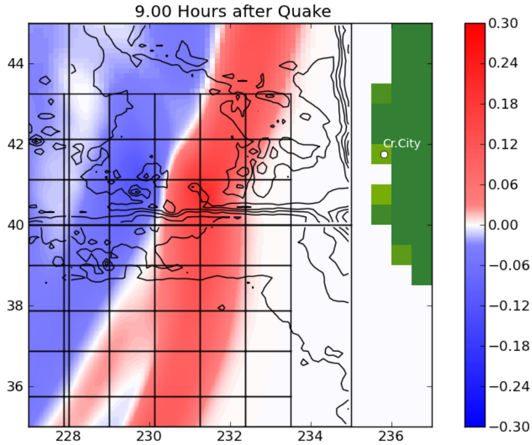
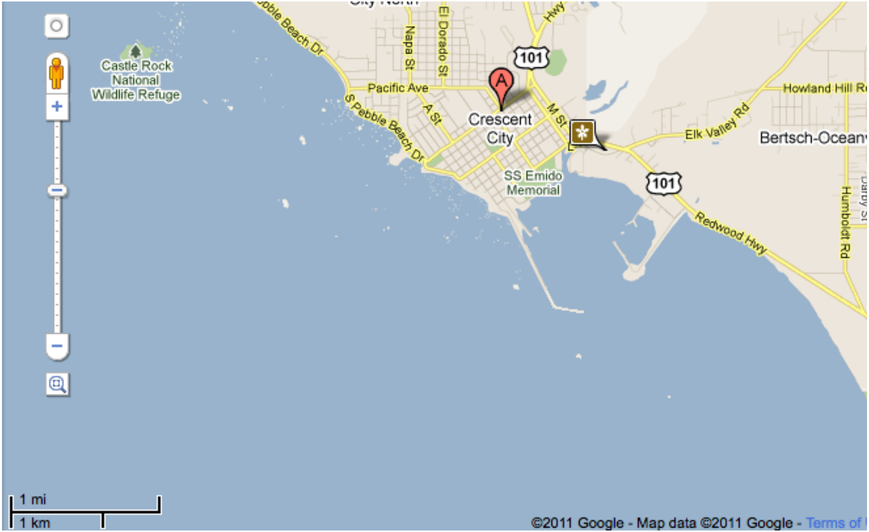
# Focusing at Crescent City

Waves focus due to Mendocino Fault Zone

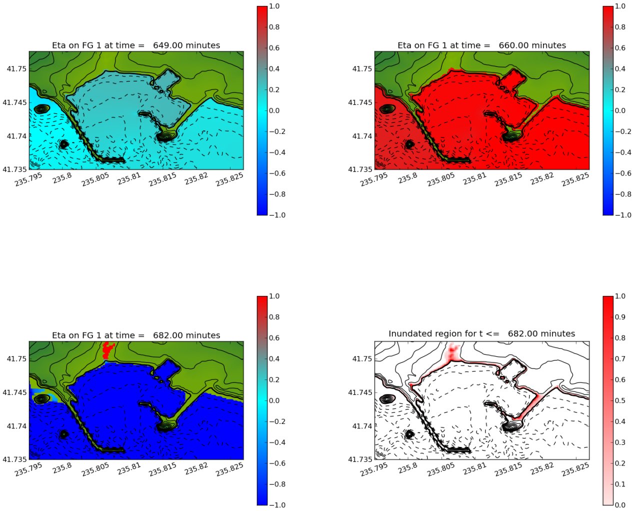
(Waves propagate more slowly in shallower water)



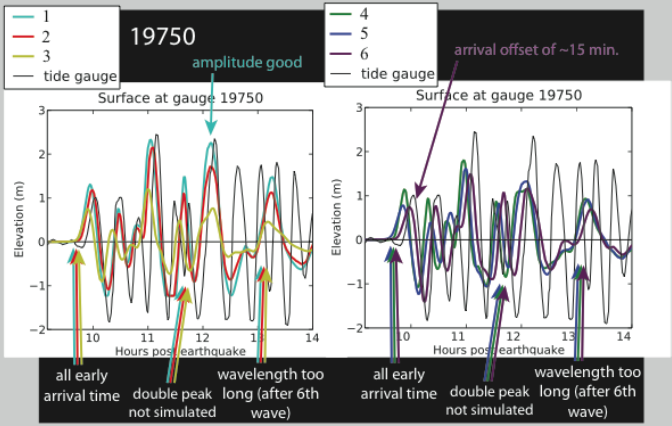
# Crescent City, CA



# Crescent City Harbor



# Comparison at Crescent City, CA




Assessment: All simulations arrive early than the observed wave at the Crescent City tide gauge (Simulation 6 is closest to observed, 4 and 5 are earliest). No simulation produces the two peaks seen between ~11.5-12 hours (simulations only produce one peak). After 12.5 hours, the wavelength of all simulations no longer matches observed. The amplitude of simulation 1 is closest overall to observed.

# Finite Volume Methods

- Hyperbolic systems, conservation laws
- Godunov-type methods
- Wave propagation algorithms
- Riemann problems, limiters
- Well-balanced methods
- Adaptive mesh refinement

# First order hyperbolic PDE in 1 space dimension

Linear: $q_t + Aq_x = 0, \qquad q(x,t) \in \mathbb{R}^m,\ A \in \mathbb{R}^{m\times m}$

Conservation law: $q_t + f(q)_x = 0, \qquad f : \mathbb{R}^m \to \mathbb{R}^m$ (flux)

Quasilinear form: $q_t + f'(q)q_x = 0$

Hyperbolic if $A$ or $f'(q)$ is diagonalizable with real eigenvalues.

Models wave motion or advective transport.

Eigenvalues are wave speeds.

Note: Second order wave equation $p_{tt} = c^2 p_{xx}$ can be written as a first-order system (acoustics).

# Finite differences vs. finite volumes

## Finite difference Methods

- Pointwise values $Q_i^n \approx q(x_i, t_n)$
- Approximate derivatives by finite differences
- Assumes smoothness

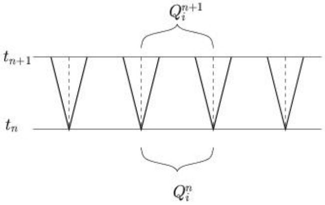
## Finite volume Methods

- Approximate cell averages: $Q_i^n \approx \frac{1}{\Delta x} \int_{x_{i-1/2}}^{x_{i+1/2}} q(x, t_n)\, dx$
- Integral form of conservation law,

$$\frac{\partial}{\partial t} \int_{x_{i-1/2}}^{x_{i+1/2}} q(x, t)\, dx \quad = \quad f(q(x_{i-1/2}, t)) - f(q(x_{i+1/2}, t))$$

leads to conservation law $q_t + f_x = 0$ but also directly to numerical method.

# Godunov's Method for $q_t + f(q)_x = 0$




1. Solve Riemann problems at all interfaces, yielding waves $\mathcal{W}_{i-1/2}^p$ and speeds $s_{i-1/2}^p$, for $p = 1,\ 2,\ \ldots,\ m$.

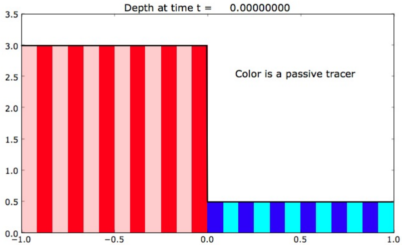
Riemann problem: Original equation with piecewise constant data.

# The Riemann problem

Dam break problem for shallow water equations

$$h_t + (hu)_x = 0$$

$$(hu)_t + \left(hu^2 + \frac{1}{2}gh^2\right)_x = 0$$



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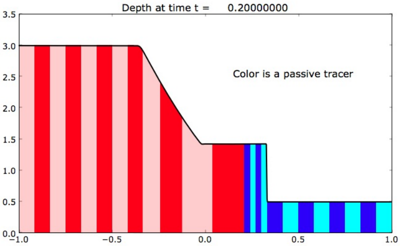

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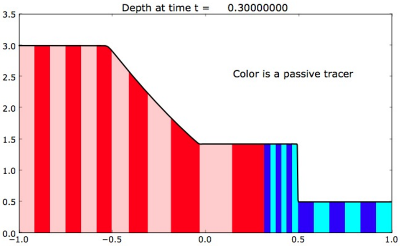

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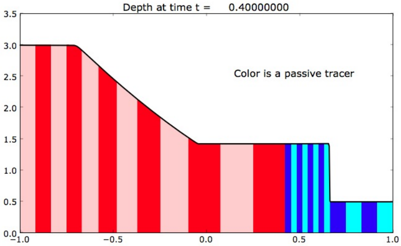

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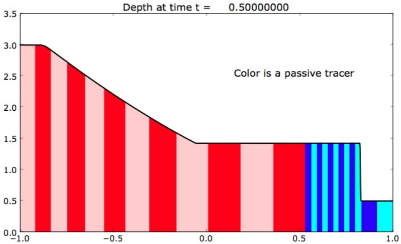
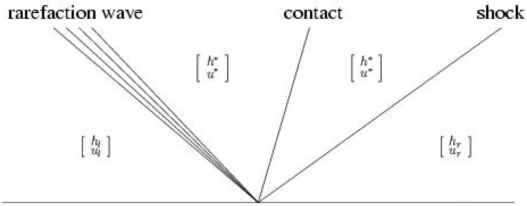


# Riemann solution for the SW equations



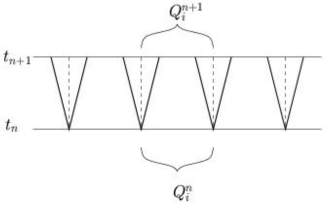

The Roe solver uses the solution to a linear system

$$q_t + \hat{A}_{i-1/2} q_x = 0, \qquad \hat{A}_{i-1/2} = f'(q_{\text{ave}}).$$

All waves are simply discontinuities.

Typically a fine approximation if jumps are approximately correct.

# Godunov's Method for $q_t + f(q)_x = 0$

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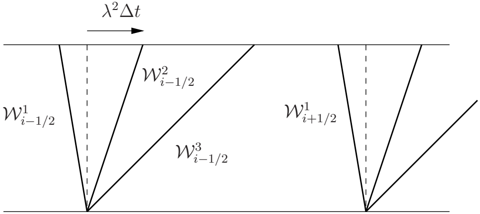
Riemann problem: Original equation with piecewise constant data.

# Wave-propagation viewpoint

For linear system $q_t + Aq_x = 0$, the Riemann solution consists of

waves $\mathcal{W}^p$ propagating at constant speed $\lambda^p$.




$$Q_i - Q_{i-1} = \sum_{p=1}^{m} \alpha^p_{i-1/2} r^p \equiv \sum_{p=1}^{m} \mathcal{W}^p_{i-1/2}.$$

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x}\left[\lambda^2 \mathcal{W}^2_{i-1/2} + \lambda^3 \mathcal{W}^3_{i-1/2} + \lambda^1 \mathcal{W}^1_{i+1/2}\right].$$

# Upwind wave-propagation algorithm

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x}\left[\sum_{p=1}^{m}(s_{i-1/2}^p)^+\mathcal{W}_{i-1/2}^p + \sum_{p=1}^{m}(s_{i+1/2}^p)^-\mathcal{W}_{i+1/2}^p\right]$$

where

$$s^+ = \max(s,0), \qquad s^- = \min(s,0).$$

Note: Requires only waves and speeds.

Applicable also to hyperbolic problems not in conservation form.

For $q_t + f(q)_x = 0$, conservative if waves chosen properly,
e.g. using Roe-average of Jacobians.

Great for general software, but only first-order accurate (upwind method for linear systems).

# Wave-propagation form of high-resolution method

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x}\left[\sum_{p=1}^{m}(s_{i-1/2}^p)^+\mathcal{W}_{i-1/2}^p + \sum_{p=1}^{m}(s_{i+1/2}^p)^-\mathcal{W}_{i+1/2}^p\right] - \frac{\Delta t}{\Delta x}(\tilde{F}_{i+1/2} - \tilde{F}_{i-1/2})$$

Correction flux:

$$\tilde{F}_{i-1/2} = \frac{1}{2}\sum_{p=1}^{M_w}|s_{i-1/2}^p|\left(1 - \frac{\Delta t}{\Delta x}|s_{i-1/2}^p|\right)\widetilde{\mathcal{W}}_{i-1/2}^p$$

where $\widetilde{\mathcal{W}}_{i-1/2}^p$ is a limited version of $\mathcal{W}_{i-1/2}^p$ to avoid oscillations.

(Unlimited waves $\widetilde{\mathcal{W}}^p = \mathcal{W}^p \implies$ Lax-Wendroff for a linear system $\implies$ nonphysical oscillations near shocks.)

# GeoClaw Software www.clawpack.org/geoclaw

Based on Dave George's thesis work TsunamiClaw.

Currently includes:

- 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.
- General tools for dealing with multiple data sets at different resolutions.
- Tools for specifying regions where refinement is desired.
- Python plotting tools.
- Output of time series at gauge locations or on fixed grids.

# Shallow water equations with bathymetry $B(x, y)$

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

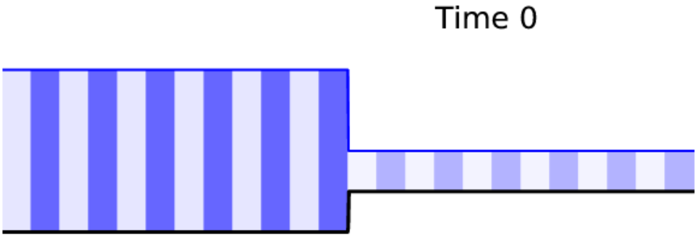
Some issues:

- Delicate balance between flux divergence and bathymetry:
  $h$ varies on order of 4000m, rapid variations in ocean
  Waves have magnitude 1m or less.
- Cartesian grid used, with $h = 0$ in dry cells:
  Cells become wet/dry as wave advances on shore
  Robust Riemann solvers needed.
- Adaptive mesh refinement crucial
  Interaction of AMR with source terms, dry states

# The Riemann problem over topography

$$h_t + (hu)_x = 0$$

$$(hu)_t + \left(hu^2 + \frac{1}{2}gh^2\right)_x = -ghB_x(x)$$



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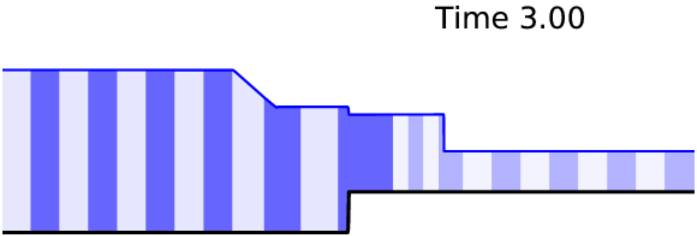

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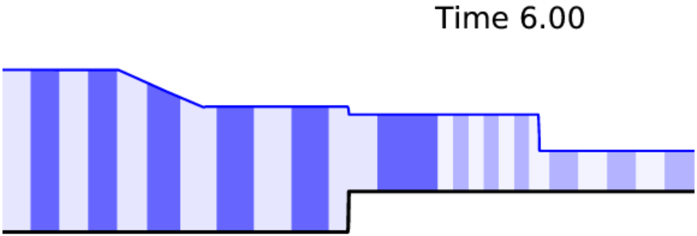

# The Riemann problem with dry state

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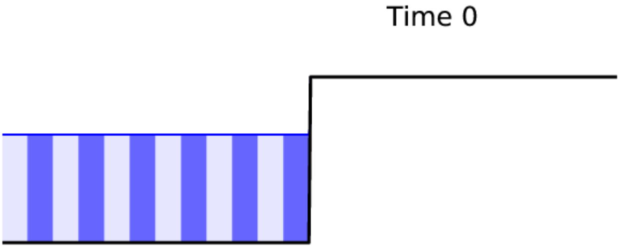
For small velocity $u_\ell > 0$, the shore acts as solid wall:



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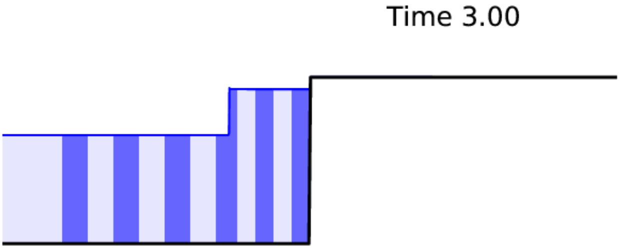

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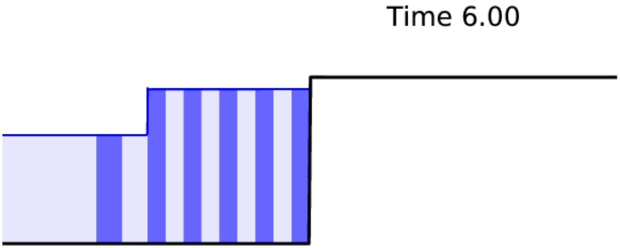

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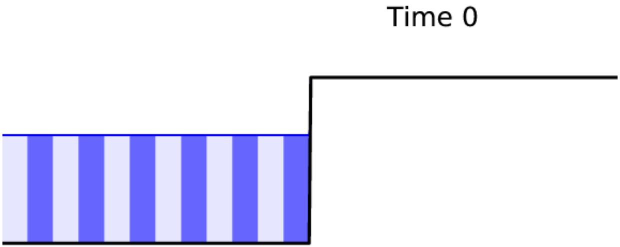

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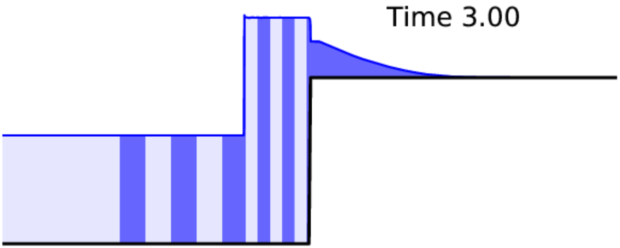

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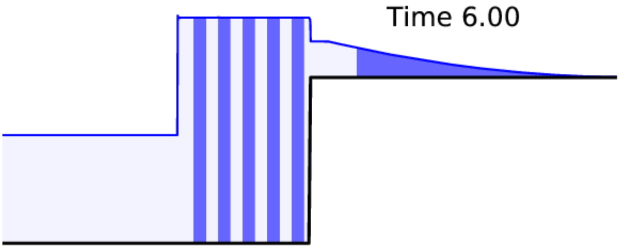


# Source terms and quasi-steady solutions

$$q_t + f(q)_x = \psi(q)$$

Steady-state solution:

$$q_t = 0 \implies f(q)_x = \psi(q)$$

Balance between flux gradient and source.

Quasi-Steady solution:

Small perturbation propagating against steady-state background.

$$q_t \ll f(q)_x \approx \psi(q)$$

Want accurate calculation of perturbation.

Examples:

- Shallow water equations with bottom topography and flat surface
- Stationary atmosphere where pressure gradient balances gravity

# Fractional steps for a quasisteady problem

Alternate between solving homogeneous conservation law

$$q_t + f(q)_x = 0 \tag{1}$$

and source term

$$q_t = \psi(q). \tag{2}$$

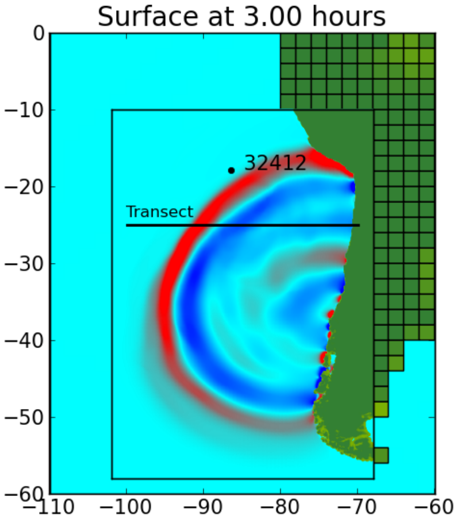
When $q_t \ll f(q)_x \approx \psi(q)$:

- Solving (1) gives large change in $q$
- Solving (2) should essentially cancel this change.

Numerical difficulties:

- (1) and (2) are solved by very different methods. Generally will not have proper cancellation.
- Nonlinear limiters are applied to $f(q)_x$ term, not to small-perturbation waves. Large variation in steady state hides structure of waves.

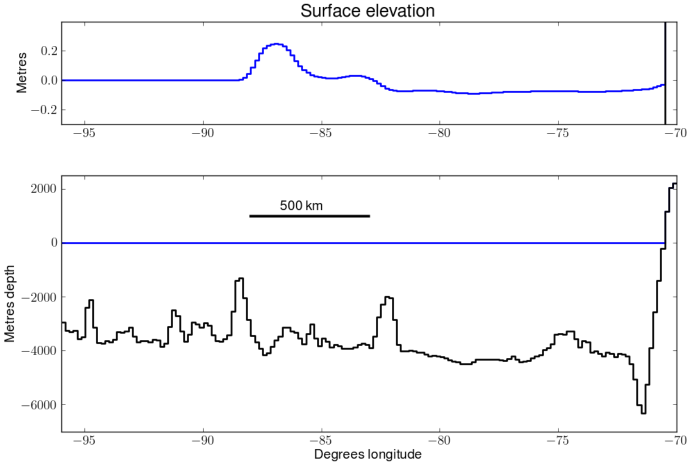
# Tsunami from 27 Feb 2010 quake off Chile



# Transect of 27 February 2010 tsunami

Bathymetry, depth change by $> 1000$ m from one cell to next,

Surface elevation changes on order of a few cm.



# Incorporating source term in f-waves

$q_t + f(q)_x = \psi$ with $f(q)_x \approx \psi$.

Concentrate source at interfaces: $\Psi_{i-1/2}\,\delta(x - x_{i-1/2})$

Split $f(Q_i) - f(Q_{i-1}) - \Delta x \Psi_{i-1/2} = \sum_p \mathcal{Z}^p_{i-1/2}$

Use these waves in wave-propagation algorithm.

Steady state maintained: (Well balanced)

If $\frac{f(Q_i)-f(Q_{i-1})}{\Delta x} = \Psi_{i-1/2}$ then $\mathcal{Z}^p \equiv 0$

Near steady state:

Deviation from steady state is split into waves and limited.

# Benchmarking project

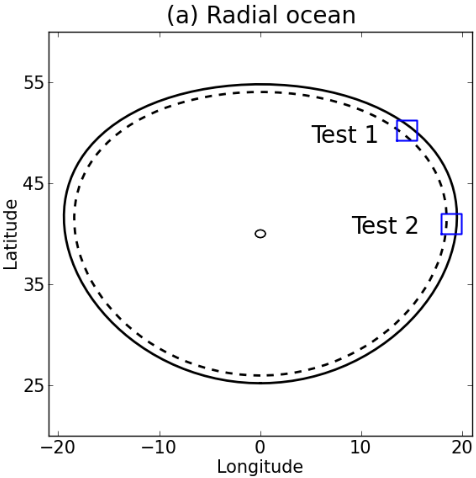
National Tsunami Hazard Mitigation Program
set of 9 benchmark problems.

- One-dimensional waves on beach: analytic and wavetanks
- Waves around conical island (wave tank)
- Okushiri Island tsunami of 1993
- Wave tank model of Monai Valley
- Wave tank experiments of submarine landslides

Recently solved by several teams and comparisons now underway.

Our results available at **www.clawpack.org/geoclaw**

# Radial ocean verification study



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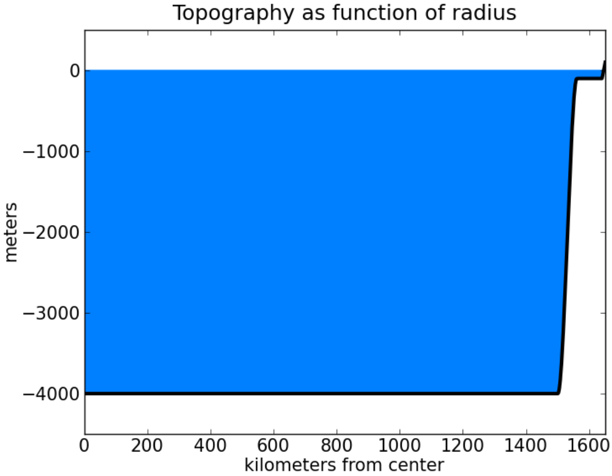

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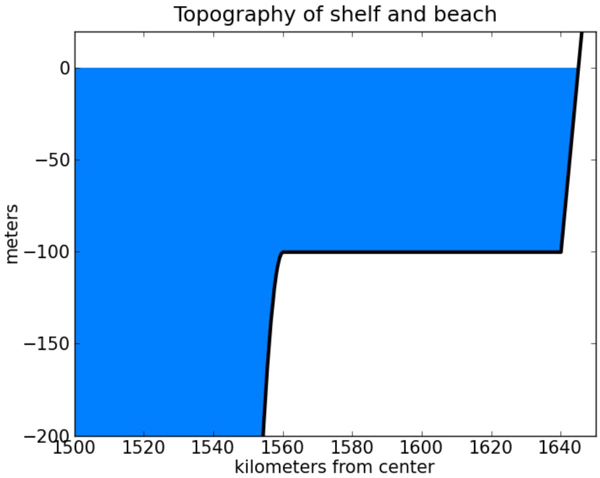

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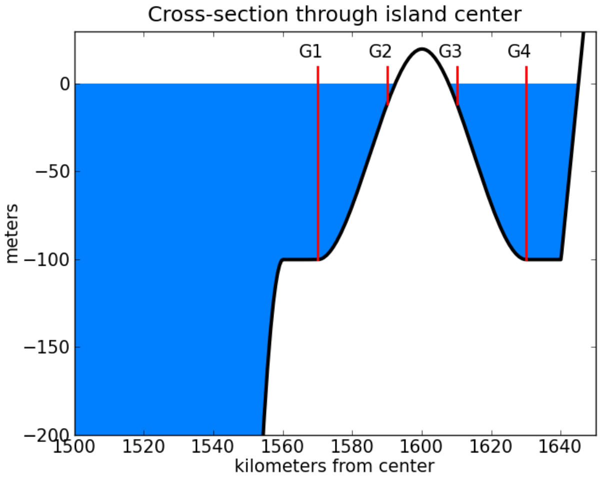

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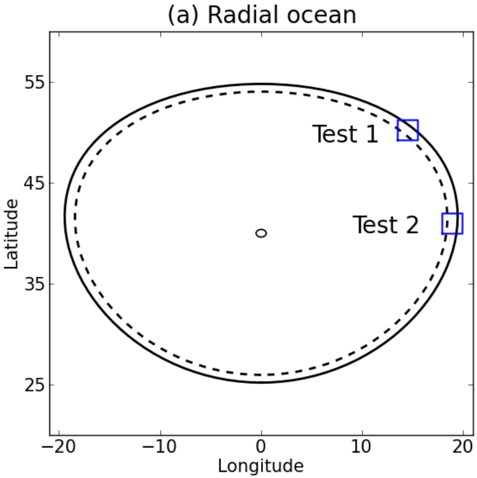
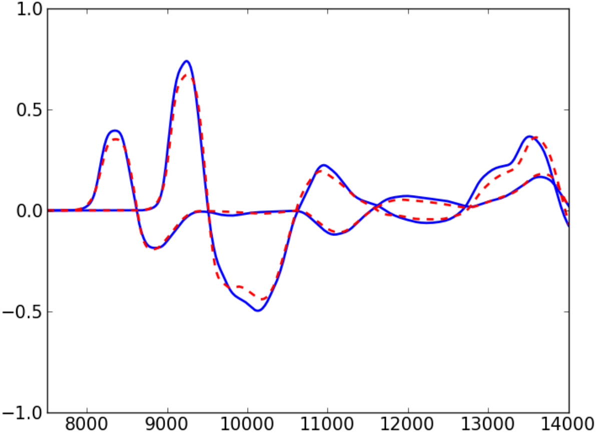


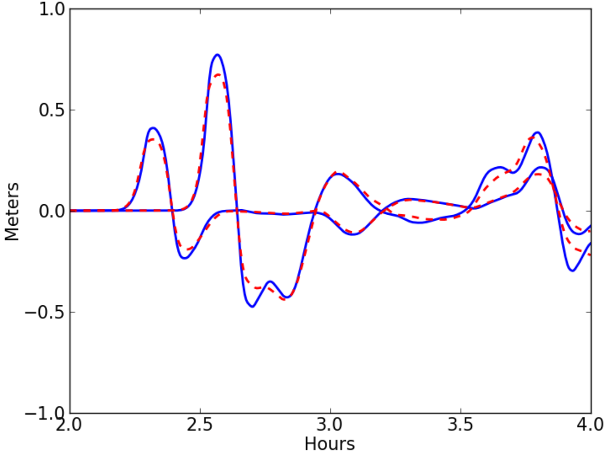
# Radial ocean verification study

Comparison of Gauges 1 and 2 from Test 1 and 2:



# Radial ocean verification study

Comparison of Gauges 1 and 2 with more refined grids (Test 1):



# Some other applications of depth-averaged eqns

Shallow water equations:

- Storm surges, hurricanes (K. Mandli)
- River flooding
- Dam breaks (D. George)

# Some other applications of depth-averaged eqns

Shallow water equations:

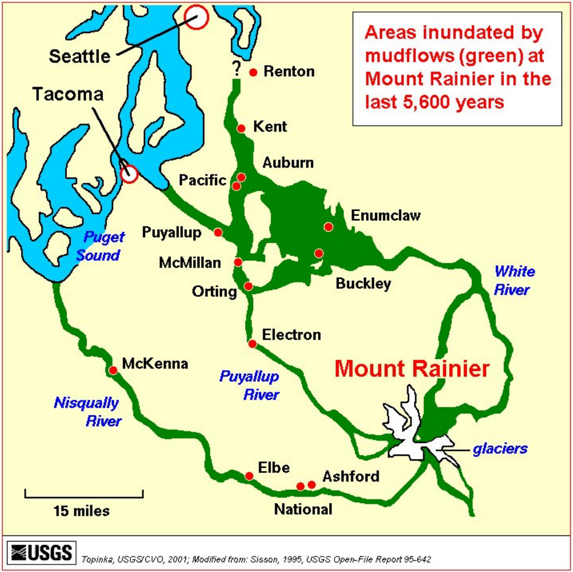
- Storm surges, hurricanes (K. Mandli)
- River flooding
- Dam breaks (D. George)

More complex flows:

- Flow on steep terrain (D. George, K. Mandli)
- Debris flows (D. George, R. Iverson, R. Denlinger)
- Lahars, landslides and avalanches
- Multi-layer, internal waves (J. Kim, K. Mandli)
- Underwater landslides / tsunami generation (J. Kim)
- Pyroclastic flows and surges (M. Pelanti)
- Sediment transport
- Lava flows

# Mt. Rainier and Tacoma

# Mud and debris flows from Mt. Rainier



# Some references

GeoClaw: **www.clawpack.org/geoclaw**
contains links to the recent paper with references and codes:

Tsunami modeling with adaptively refined finite volume methods, by RJL, D. L. George, M. J. Berger, *Acta Numerica* 2011

The GeoClaw software for depth-averaged flows with adaptive refinement, by M. J. Berger, D. L. George, RJL, and K. M. Mandli, 2011 *Advances in Water Resources*

GeoClaw results for the NTHMP tsunami benchmark problems, with Chamberlain, González, Hirai, Varkovitzky, 2011.