New Tools for Tsunami Warning and Probabilistic Hazard Assessment

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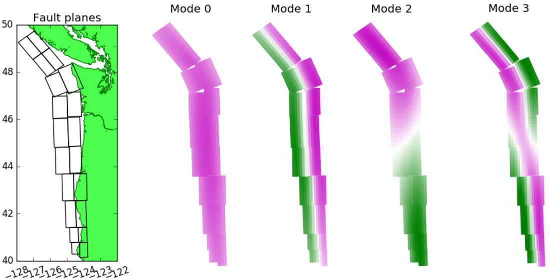
University of Washington



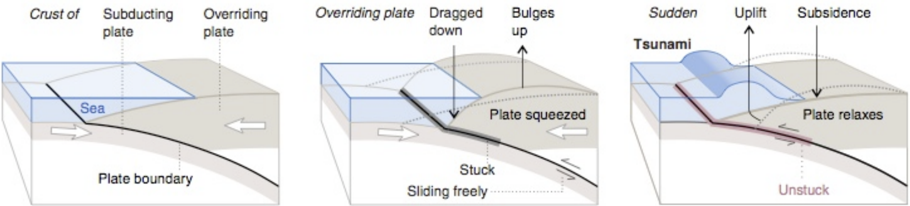
Some collaborators

GeoClaw software:
David George, USGS Cascades Volcano Observatory (CVO)
Marsha Berger, NYU
Kyle Mandli, Columbia
Many other Clawpack developers

Tsunami modeling and hazard assessment:
Frank Gonzalez, Loyce Adams, Donsub Rim,
Brisa Davis, Chris Vogl, UW
Knut Waagan, Norwegian Defence Research Establishment

Supported in part by...
NSF, ONR, AFOSR, PNNL, BakerAECOM, FEMA,
Washington State Emergency Management Division

Tsunamis caused by subduction zone earthquakes



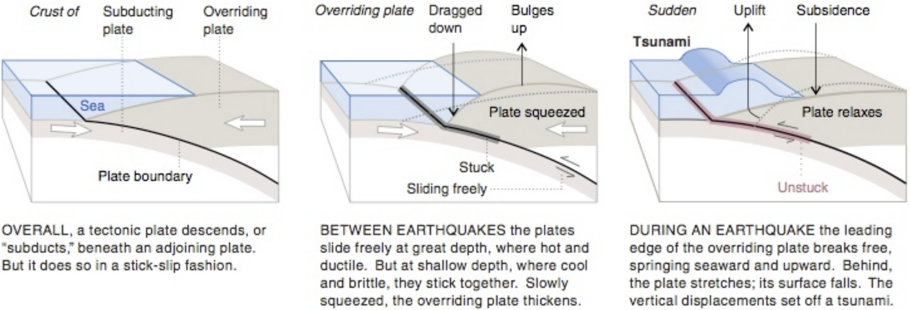
OVERALL, a tectonic plate descends, or "subducts," beneath an adjoining plate. But it does so in a stick-slip fashion.

BETWEEN EARTHQUAKES the plates slide freely at great depth, where hot and ductile. But at shallow depth, where cool and brittle, they stick together. Slowly squeezed, the overriding plate thickens.

DURING AN EARTHQUAKE the leading edge of the overriding plate breaks free, springing seaward and upward. Behind, the plate stretches; its surface falls. The vertical displacements set off a tsunami.

Source: Atwater et al., 2005.

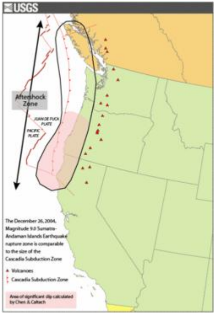
Tsunamis caused by subduction zone earthquakes

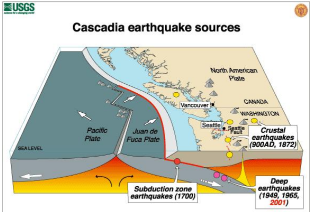


Source: Atwater et al., 2005.

- Uplift/subsidence of seafloor over large area creates long-wavelength disturbance.
- Propagates as waves across ocean at 400–500 mph.

Cascadia Subduction Zone (CSZ)

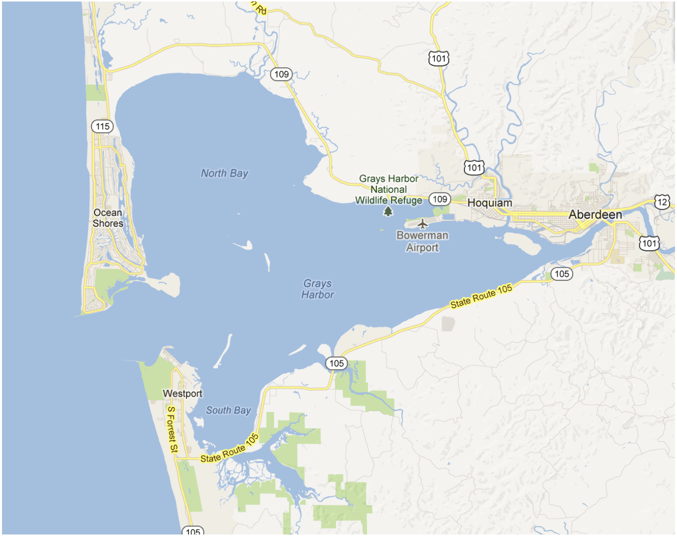




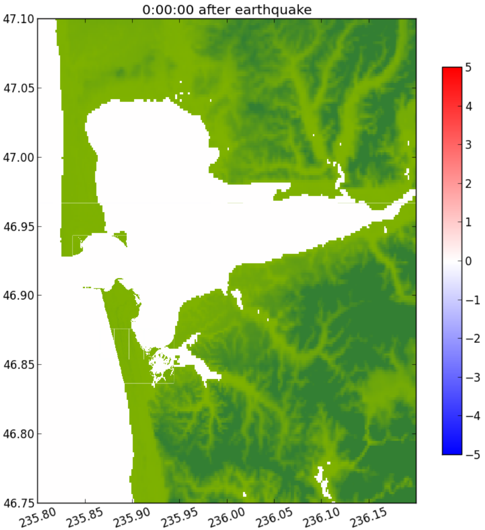
Source	Affected area	Max. Size	Recurrence
Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

- 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.

Grays Harbor



Mw 9.0 Cascadia event hitting Gray's Harbor



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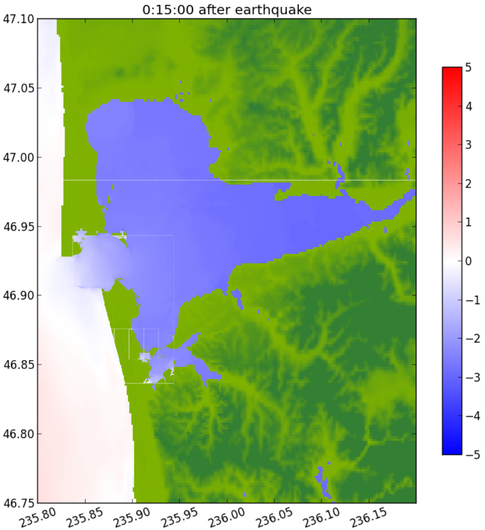

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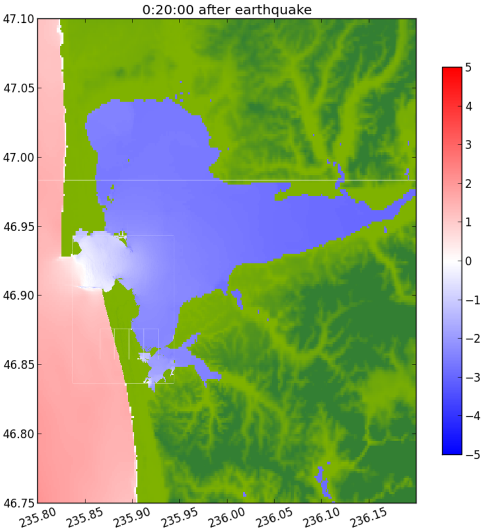

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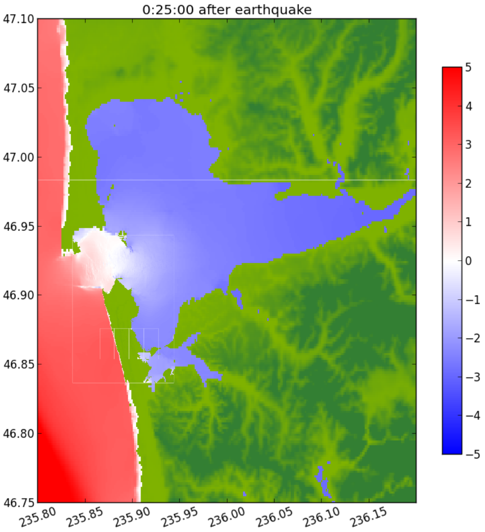

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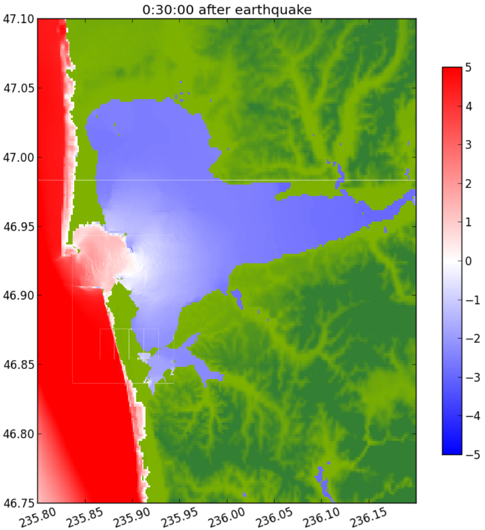

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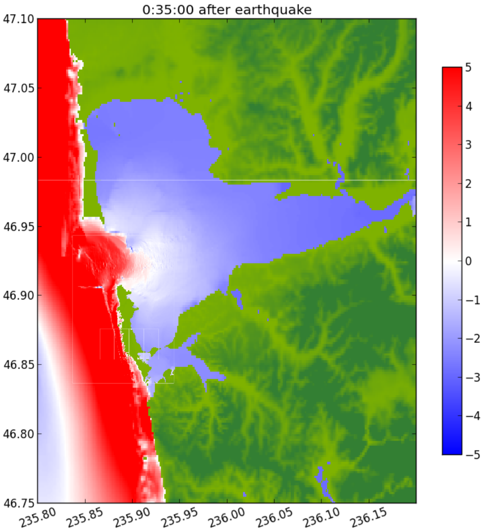

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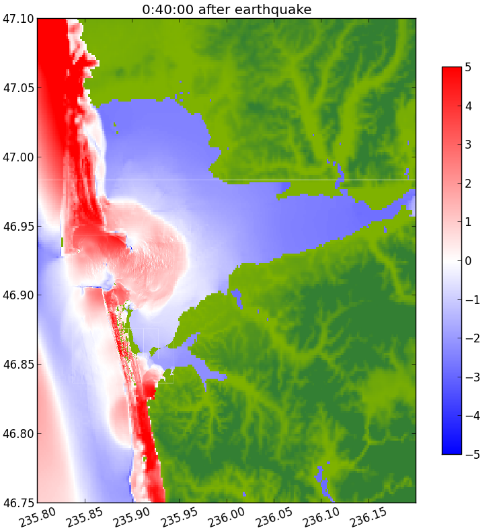

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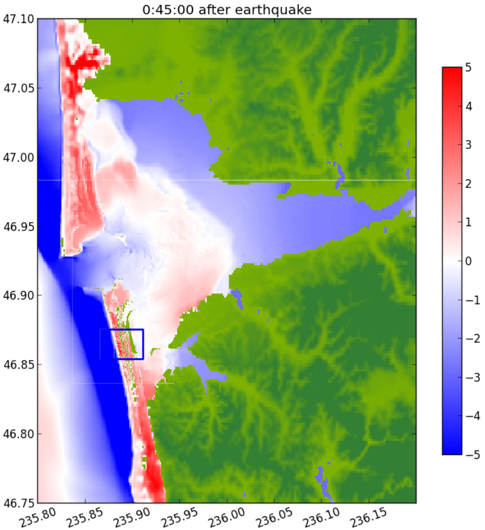
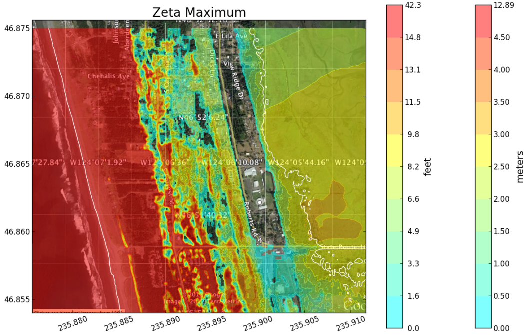
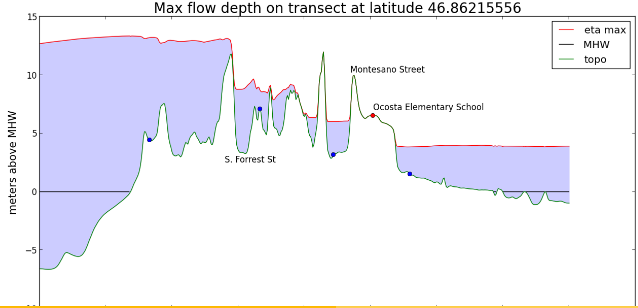




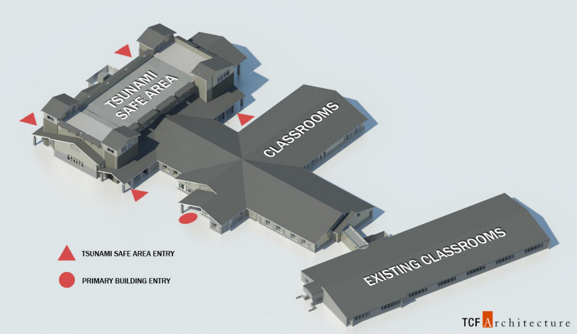
Zeta Maximum
feet
meters



Max flow depth on transect at latitude 46.86215556
eta max
MHW
topo
Montesano Street
Ocosta Elementary School
S. Forrest St
meters above MHW

First vertical evacuation structure in US

Ocosta Elementary School, Westport, WA



Designed by TCF Architecture of Tacoma, WA,
with structural engineering work by Degenkolb Engineers.

Tsunami Hazard Assessment of the Ocosta School Site in Westport, WA
by F. I. Gonzalez, RJL, L. M. Adams, 2013.

http://faculty.washington.edu/rjl/pubs/Ocosta

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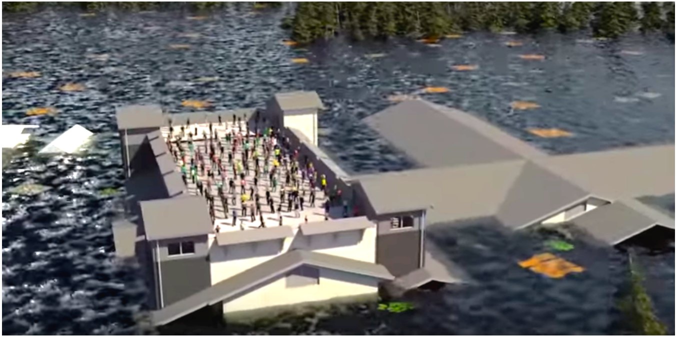


Simulated hypothetical event,
From the video Project Safe Haven by WSDOT
`https://www.youtube.com/watch?v=otI7bUrUOmI`

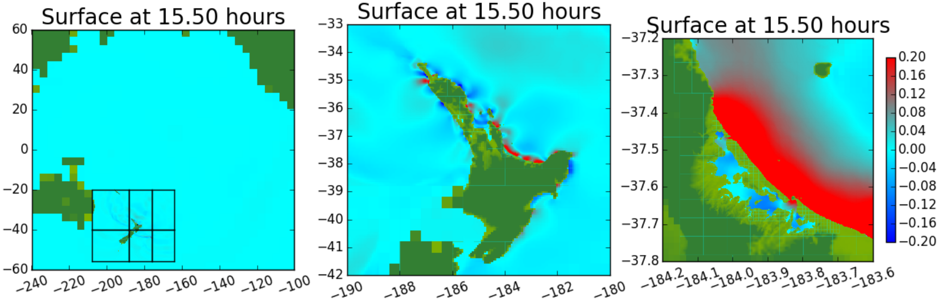
Shallow water equations with bathymetry $B(x,y)$

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

Some issues:

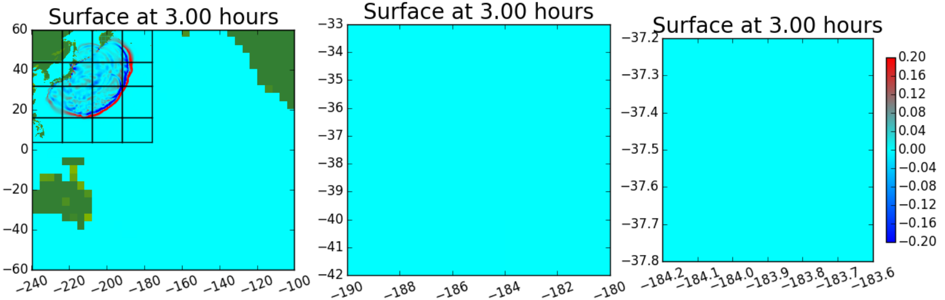
- Delicate balance between flux divergence and bathymetry:
  h varies on order of 4000m, rapid variations in ocean
  Waves have magnitude 1m or less.
- Cartesian grid used, with $h = 0$ in dry cells:
  Cells become wet/dry as wave advances on shore
  Robust Riemann solvers needed.
- Adaptive mesh refinement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

Tohoku to Tauranga Harbor, NZ with AMR



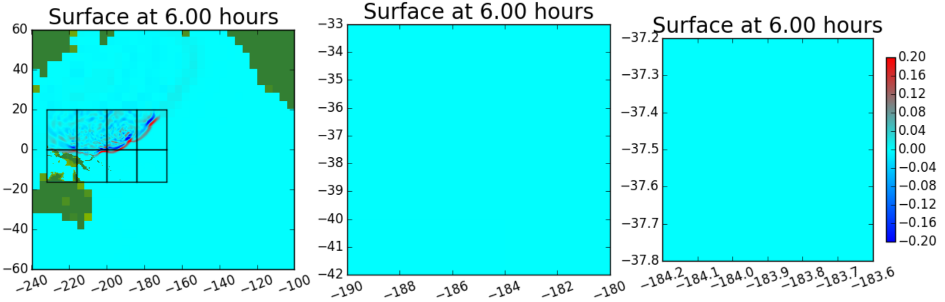
Elapsed time on quad-core MacBook: 3.5 hours

Tohoku to Tauranga Harbor, NZ with AMR



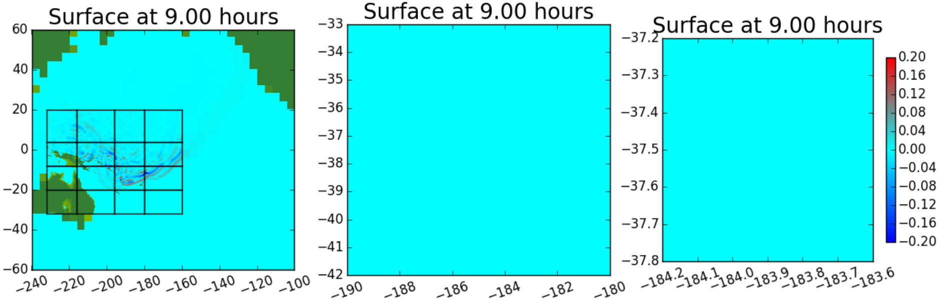
Elapsed time on quad-core MacBook: < 1 minute

Tohoku to Tauranga Harbor, NZ with AMR



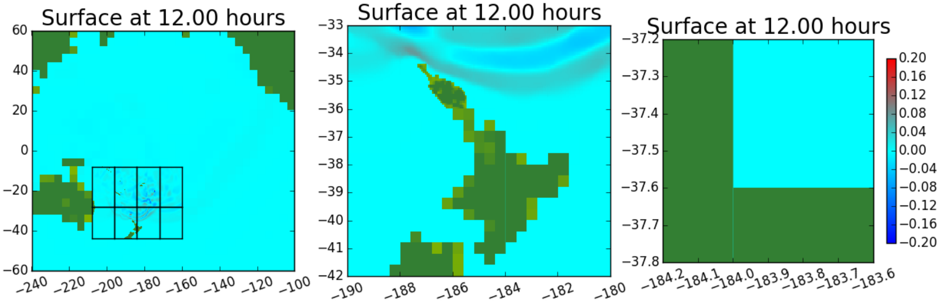
Elapsed time on quad-core MacBook: < 2 minutes

Tohoku to Tauranga Harbor, NZ with AMR



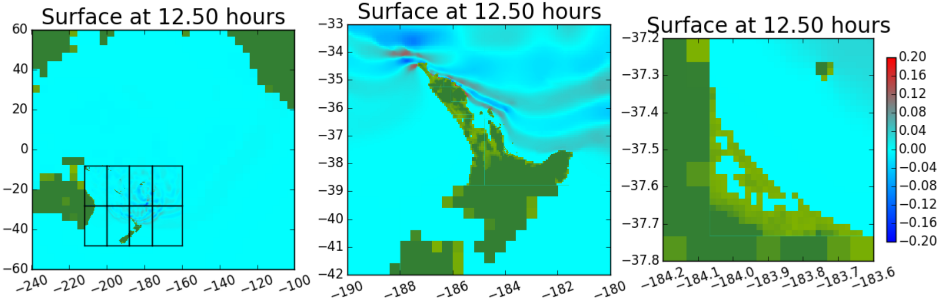
Elapsed time on quad-core MacBook: 3 minutes

Tohoku to Tauranga Harbor, NZ with AMR



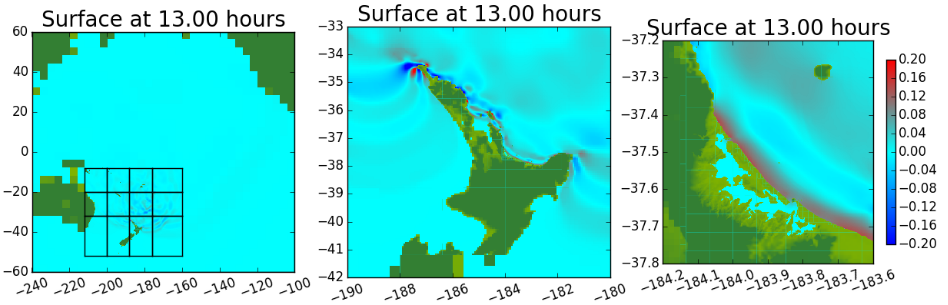
Elapsed time on quad-core MacBook: 5 minutes

Tohoku to Tauranga Harbor, NZ with AMR



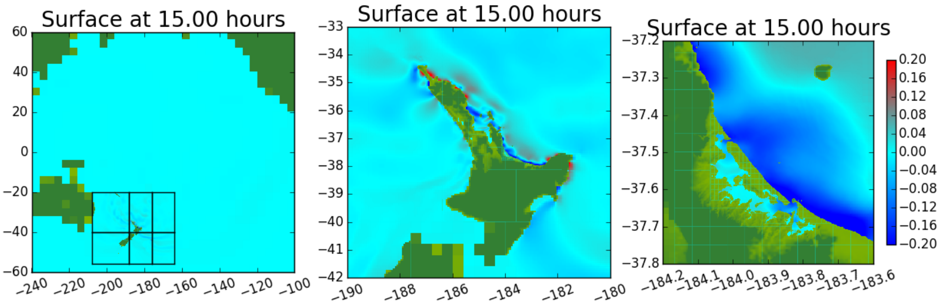
Elapsed time on quad-core MacBook: 6 minutes

Tohoku to Tauranga Harbor, NZ with AMR



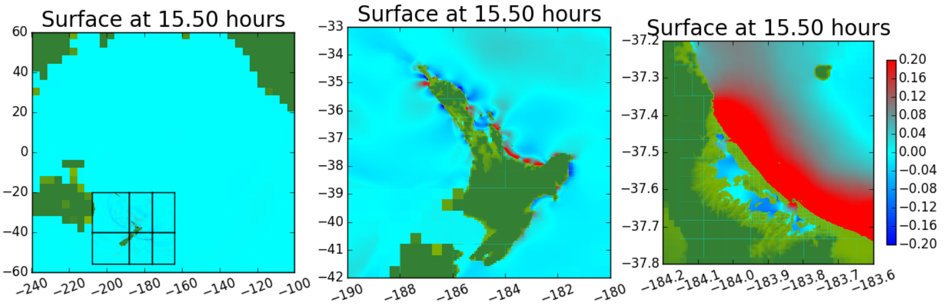
Elapsed time on quad-core MacBook: 19 minutes

Tohoku to Tauranga Harbor, NZ with AMR



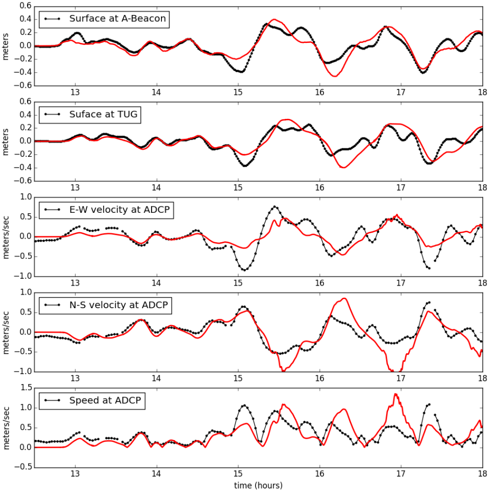
Elapsed time on quad-core MacBook: 3 hours

Tohoku to Tauranga Harbor, NZ with AMR



Elapsed time on quad-core MacBook: 3.5 hours

Tauranga Harbor gauges



Adjoint error estimation to guide AMR

Adaptive Mesh Refinement:

- Berger-Colella-Oliger style Block-structured
- Flag cells needing refinement (How?)
- Cluster into patches using Berger-Rigoutsis algorithm
- Repeat recursively

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Could flag based on:

- Elevation of surface,
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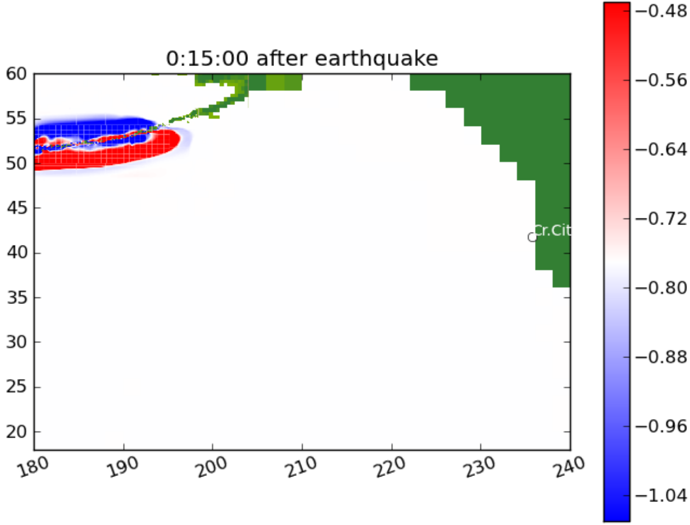
Adjoint methods can better identify important waves.

Joint work with Brisa Davis, ***Pure Appl. Geoph. 2016***

Earthquake on Alaska-Aleutian Subduction Zone



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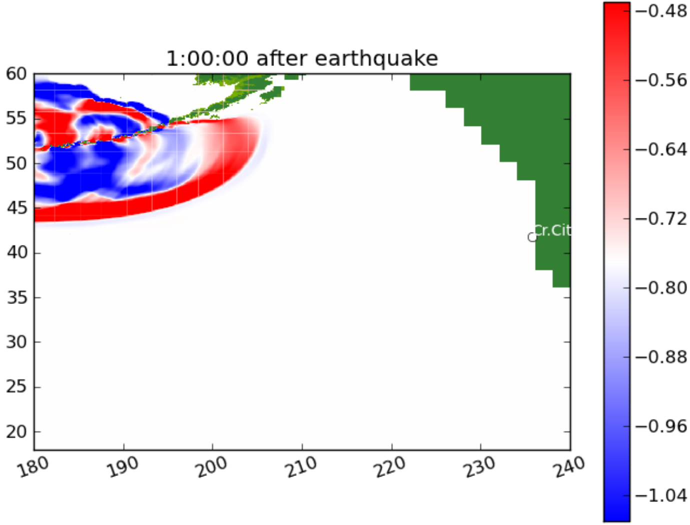

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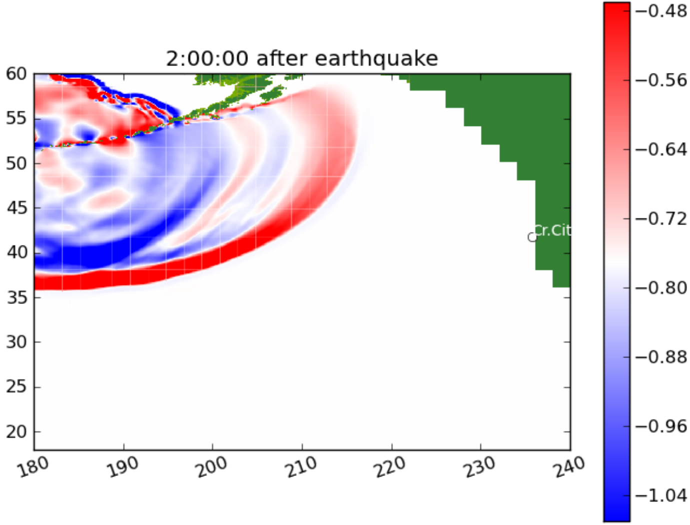

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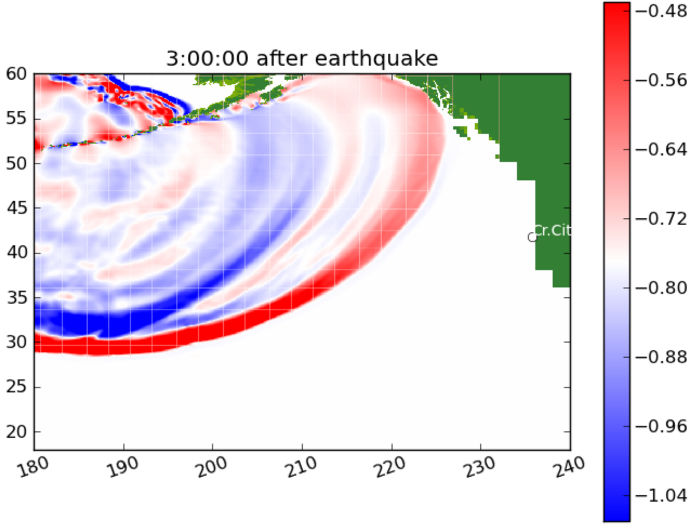

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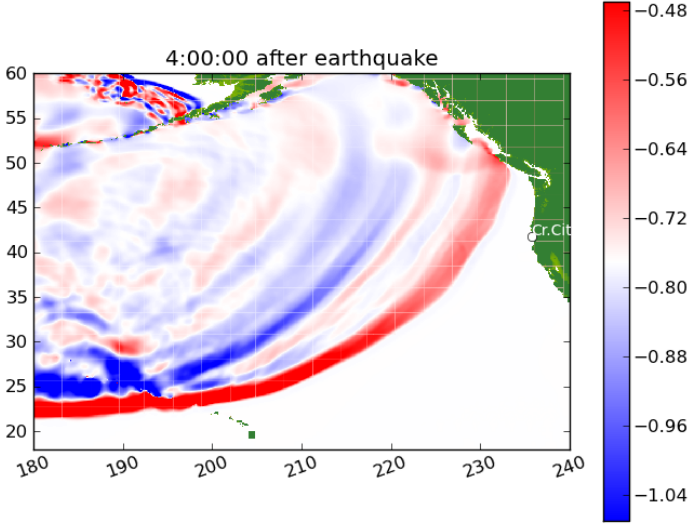

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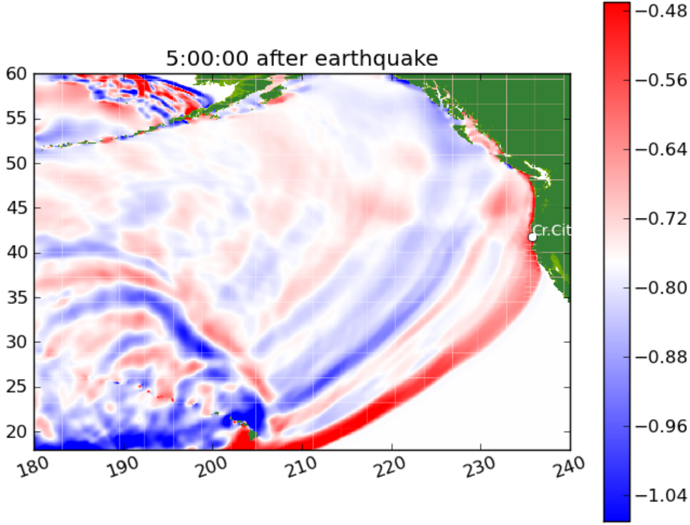

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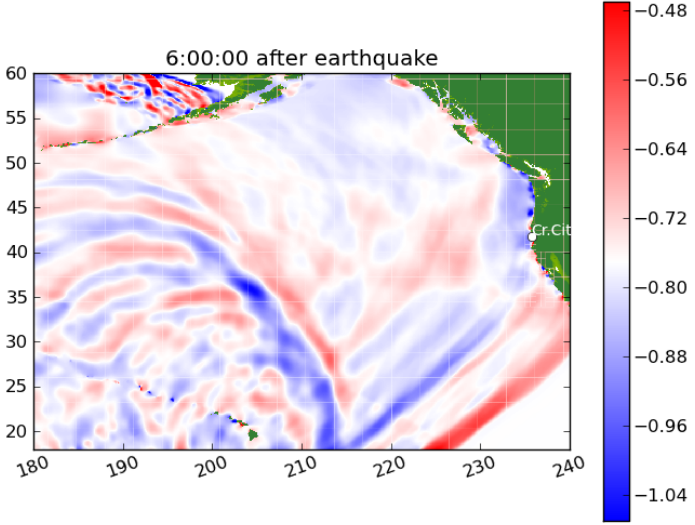

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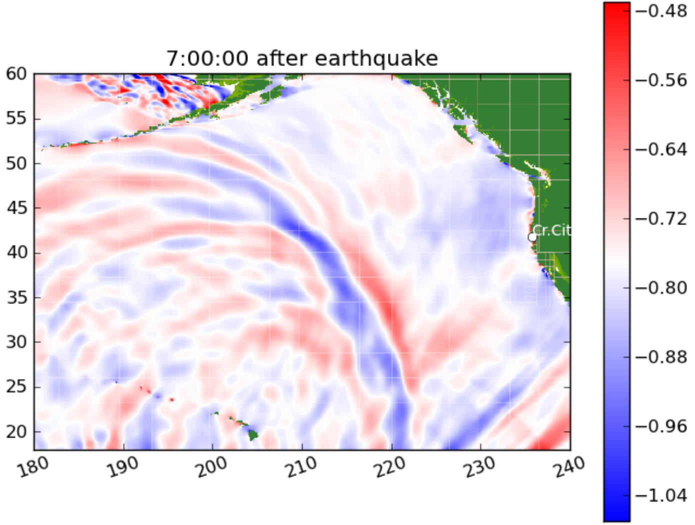

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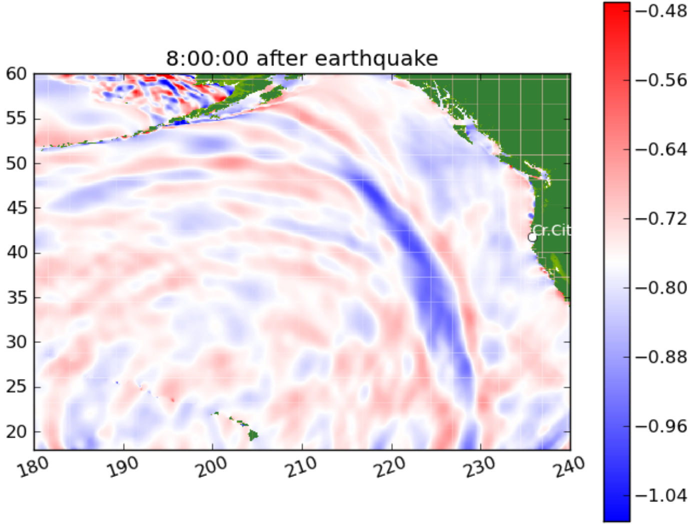

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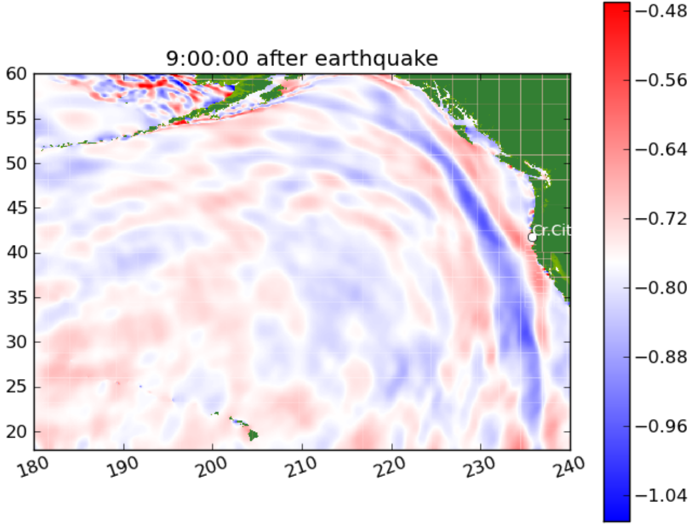
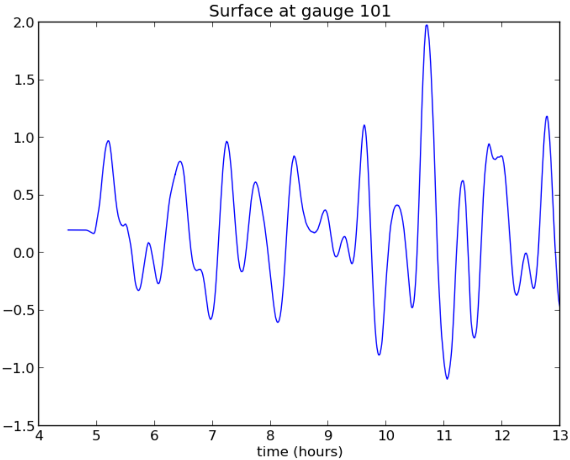


Sea surface at gauge in Crescent City Harbor



How do we optimally refine to capture biggest wave?

Combination of reflections and edge waves?

Adjoint equation:

Forward equation: $q_t + Aq_x = 0$ for $0 \le t \le T$

Quantity of interest: Some functional $\phi = \int \hat{v}(x)^T q(x,T)\,dx$

For example: $\hat{v}(x) = \delta(x - x_{\text{gauge}}) \left[\begin{array}{c} 1 \\ 0 \end{array}\right]$

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$$\int v^T(x,T)q(x,T)\,dx = \int v^T(x,t)q(x,t)\,dx + \int_t^T \int q^T(v_t + A^T v_x)\,dx\,d\tau$$

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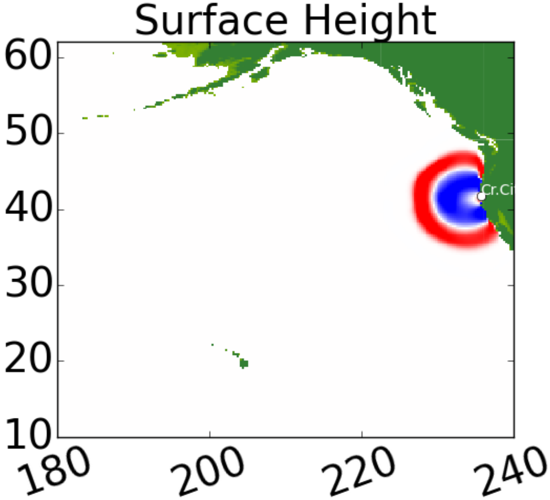
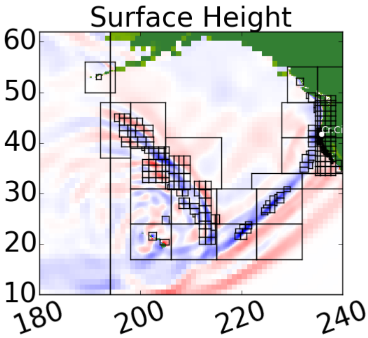
Adjoint equation: $v_t + A^T v_x = 0$ with $v(x,T) = \hat{v}(x)$.

Initial data for adjoint equation is delta function (sharp Gaussian) near Crescent City, CA.

Adjoint equation essentially same as linearized SW equations



AMR based on adjoint solution



Uses of Models

- Better understand the science / geophysics

  Exploring phenomena and possible explanations,
  Understanding past events, including pre-historic
  Calibrating against observations / measurements

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  Hurricane surge: several days, continuously updated
  Earthquake early warning: seconds to minutes

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  Tsunami: 10 hours from Japan to California
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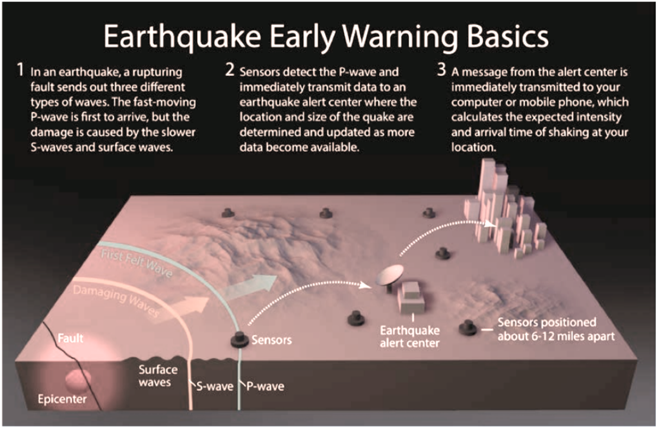
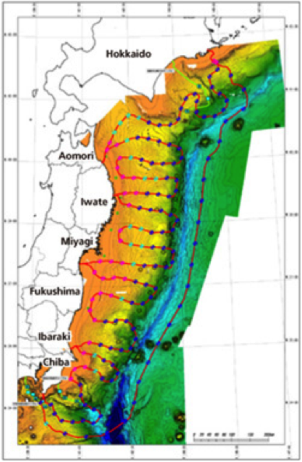
- Hazard mapping, emergency management planning
  (“Worst case” or probabilistic assessment of risks)
- Hazard mitigation, building codes, zoning,
  Urban design, vertical evacuation structures, etc.



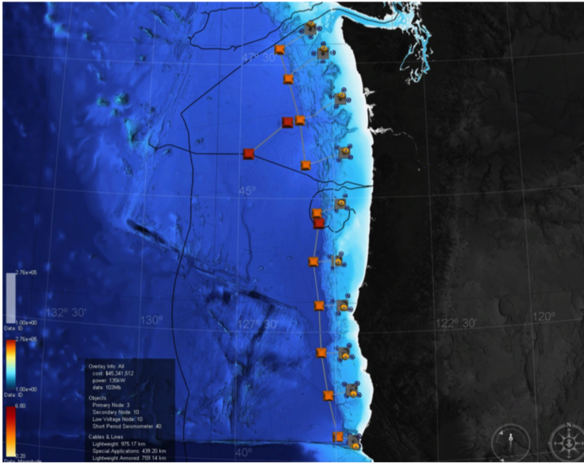
In an Earthquake Added Seconds Can be Critical...

Offshore Sensor Network

Japan:



Proposed:



Gordon & Betty Moore Foundation Funding for Analysis/Design

Crescent City PTHA Pilot Study

Supported by BakerAECOM, as part of a coastal modeling/mapping effort funded by the FEMA Region IX office as part of the new California Coastal Analysis and Mapping Project (CCAMP).

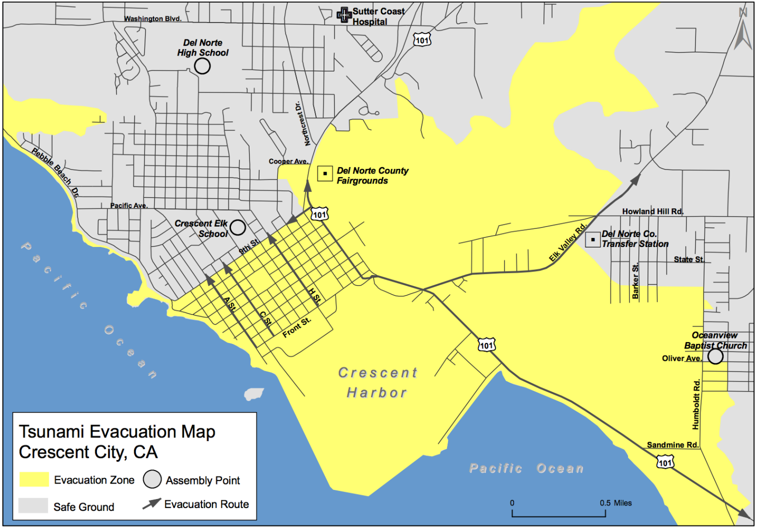
Probabilistic Tsunami Hazard Assessment (PTHA) for Crescent City, CA., by F. I. Gonzalez, RJL, L. M. Adams, C. Goldfinger, G. Priest, K. Wang, 2014.

Crescent City Harbor, 11 March 2011

From: Amanda R. Admire, *Observed and modeled tsunami current velocities on California's north coast*, Humboldt State University, 2013.

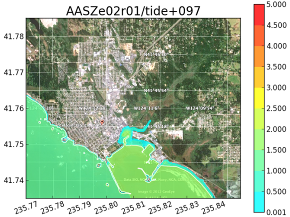
http://humboldt-dspace.calstate.edu/handle/2148/1458

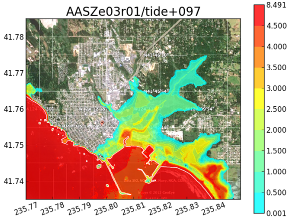
Crescent City Tsunami Evacuation Map

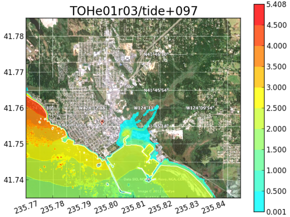


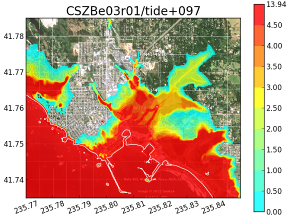
Note: This evacuation map is based on the State of California inundation projections and the best currently available scientific information. It is intended for emergency planning purposes only. This map may be revised as new information becomes available.

Four sample event realizations



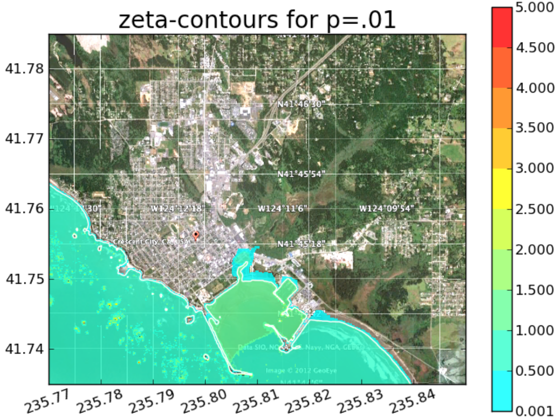






Probabilistic maps of flooding depth

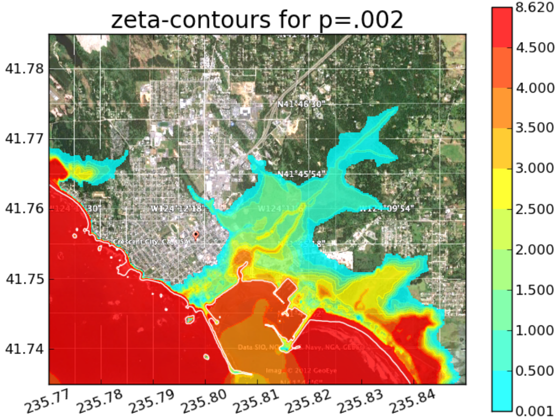
Standard view: Map of flooding depth for fixed probability



Preliminary Results — Not for Use

Probabilistic maps of flooding depth

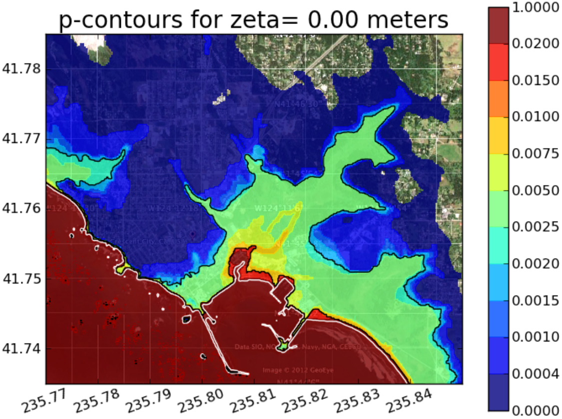
Standard view: Map of flooding depth for fixed probability



Preliminary Results — Not for Use

Probabilistic maps of flooding depth

Alternative map: Probability of exceeding fixed depth



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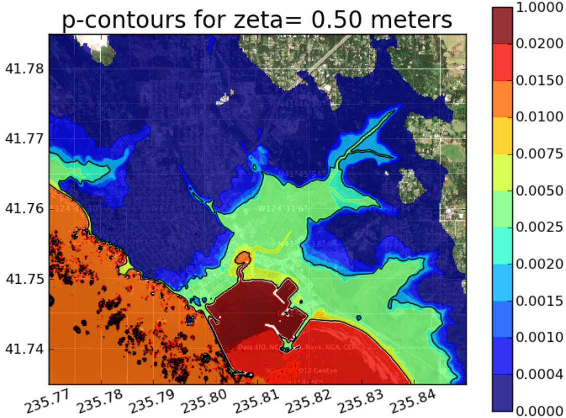

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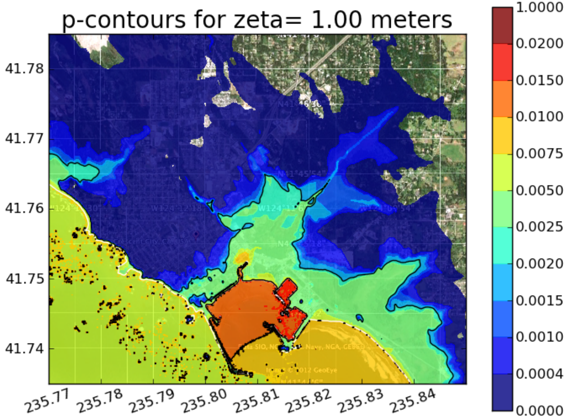

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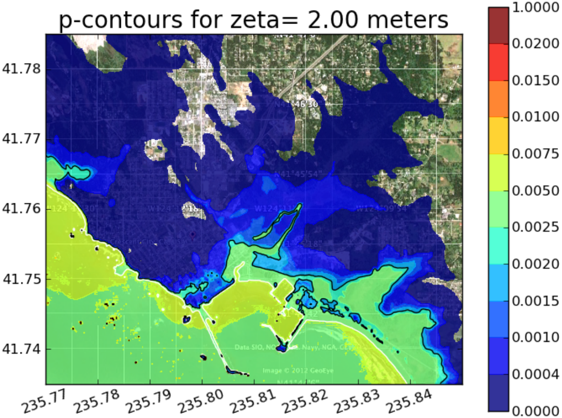

Preliminary Results — Not for Use

Probabilistic Tsunami Hazard Assessment (PTHA)

Some past work...

- Probabilistic Analysis of Tsunami Hazards,
  EL Geist, T Parsons, *Nat. Haz* 2006.
- Probabilistic tsunami hazard assessment at Seaside, Oregon, for near-and far-field seismic sources,
  FI González, EL Geist, B Jaffe, U Kanoglu, et al., *J. Geophys. Res.* 2009.
- Simulating tsunami inundation at Bandon, Coos County, Oregon, using hypothetical Cascadia and Alaska earthquake scenarios, RC Witter, Y Zhang, K Wang, GR Priest, C Goldfinger, LL Stimely, JT English, PA Ferro, DOGAMI Paper 43, 2011.

Sources of uncertainty

- Earthquake source (seafloor motion)
  Distant: Location, magnitude, return time
  Cascadia: Details of slip pattern very important
- Tides
- Bottom friction, effect of vegetation, structures
- Mathematical model (shallow water equations)
- Numerical method, grid resolution

Hazard Curves

First define hazard curve: for each location (x, y):

$$P(\zeta) = P(\zeta; x, y) = \text{Prob[inundation } \geq \zeta \text{ in one year]}.$$

Example: If only one possible event E_1 with recurrence time T_1 (Poisson rate $\nu_1 = 1/T_1$), that floods to level $H_1(x, y)$, then

$$P(\zeta) = \begin{cases} 1 & \text{if } \zeta = 0, \\ 1 - e^{-\nu_1} & \text{if } 0 < \zeta < H_1, \\ 0 & \text{if } \zeta > H_1. \end{cases}$$

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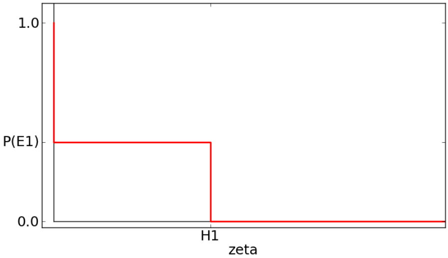
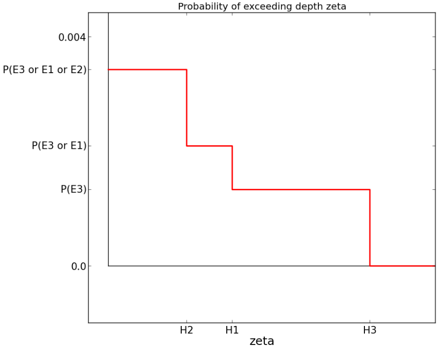


Hazard Curves

Example: Three possible events $E_1,\ E_2,\ E_3$ with recurrence times $T_1,\ T_2,\ T_3$, that flood to levels $H_1,\ H_2,\ H_3$.

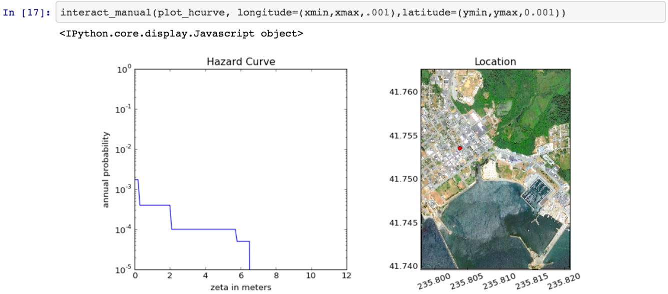


Where, for example, $H_2 < H_1 < H_3$ and

$$P(E3 \text{ or } E1) = 1 - (1 - p_3)(1 - p_1) = 1 - e^{-(\nu_3 + \nu_1)}.$$

Jupyter notebooks illustrating PTHA

Developed for **M9 Project Workshop on Communicating Hazard and Risk through Maps and Data Visualization**



View notebooks at

`https://github.com/rjleveque/ptha_tutorial`

Launch in the cloud using **binder** at

`http://mybinder.org/repo/rjleveque/ptha_tutorial`

Dealing with Uncertainties

Aleatoric uncertainties:

Given:

Discrete set of possible events and associated probabilities,
or Probability distribution of possible events,

Determine:

Probability distribution of some Quantity of Interest
(e.g. maximum depth of flooding at a point).

Epistemic uncertainties:

What is the correct (discrete or continuous)
probability distribution of possible events?

Dealing with Uncertainties

Aleatoric uncertainties: (Mathematical problem)

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Techniques for aleatoric uncertainty

Can only do high-resolution tsunami inundation runs for a "small" number of potential events.

Faced with a large catalog of potential discrete events, or continuous distribution over a high-dimensional space

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- Surrogate or reduced order models, statistical emulators,

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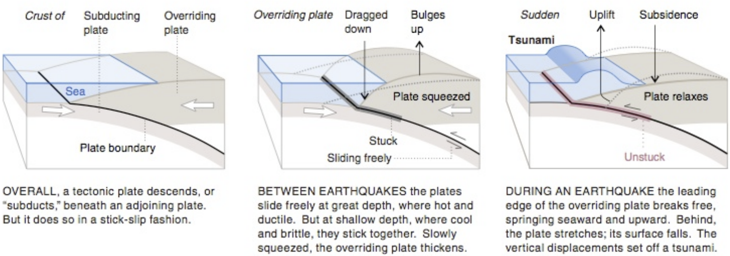
Faced with a large catalog of potential discrete events, or continuous distribution over a high-dimensional space

- Cheap-to-compute proxy models,
- Surrogate or reduced order models, statistical emulators,
- Monte Carlo sampling techniques, e.g.
    - Sample the surrogate / reduced order model,
    - Quasi-random, Latin hypercube, sparse grids,
    - Importance sampling (rare events may be most hazardous),
    - Multi-level or multi-resolution MC

Tsunamis caused by subduction zone earthquakes

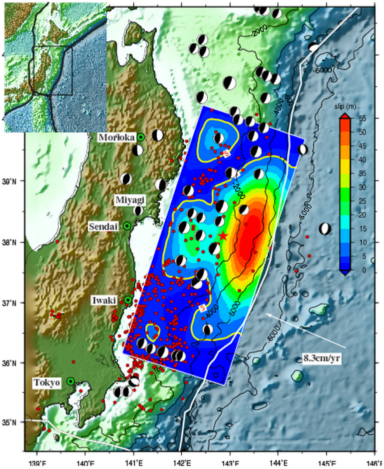


Source: Atwater et al., 2005.

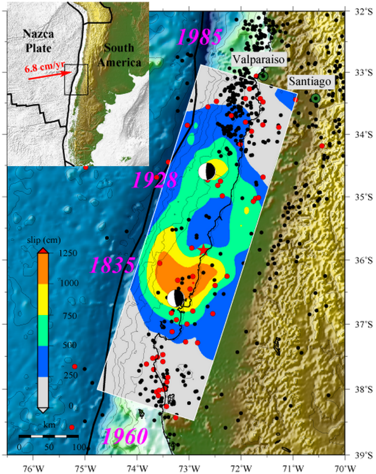
- Oceanic plate is subducting beneath continental plate.
- Stick-slip behavior gives rise to periodic earthquakes.
- Vertical deformation of sea floor lifts up entire water column over very large area.

Sample slip patterns

Tohoku 2011:

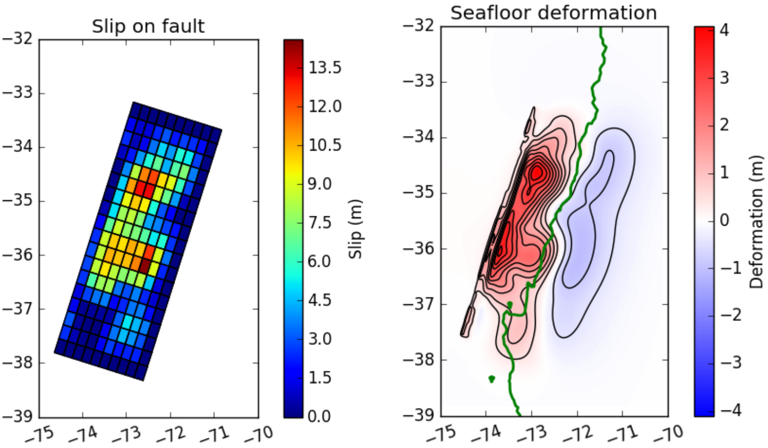


Chile 2010:



http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/home.html

Chile 2010 Maule Event



Seismic modeling of seafloor deformation

Slip of fault plane generates seismic waves and deformation of sea floor creates tsunami.

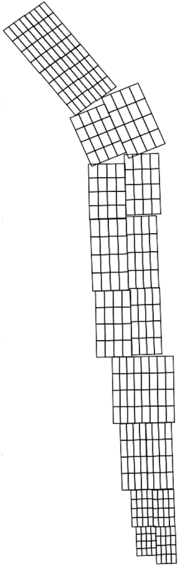
"Okada model": Green's function for dislocation on an imbedded fault plane in homogeneous elastic half-space (final displacement)

Work in progress: Solve 3d elastic wave propagation problem to compute time-dependent deformation. Can incorporate:

- Time-dependent behavior
- Topography of surface (ocean bottom, continental shelf)
- Heterogeneous rock properties
- Ocean on top of sea floor

Joint work with Chris Vogl, UW

Generating random slip patterns (Gaussian field)



Subdivide fault into m patches

Determine "distance" from patch i to j

Covariance matrix: $C_{ij} = \sigma_i \sigma_j \, \text{corr}(i,j)$

Compute eigenvalues λ_k, eigenvectors v_k of C

Karhunen-Loève expansion:

$$d = \mu + \sum_{k=1}^{m} z_k \sqrt{\lambda_k}\, v_k$$

where the z_k are chosen to be independent random numbers, normally distributed with mean 0 and variance 1.

Karhunen-Loève expansion for random spatial field

$$s = \mu + \sum_{k=1}^{m} z_k \sqrt{\lambda_k}\, v_k, \qquad \text{where } Cv_k = \lambda_k v_k$$

In matrix-vector form:

$$s = \mu + V\Lambda^{1/2} z, \qquad CV = V\Lambda$$

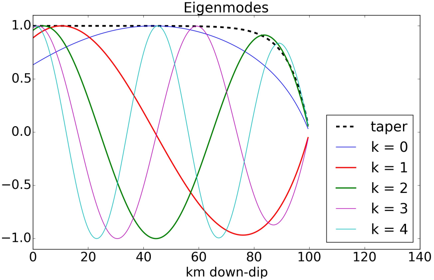
So $z \sim \mathcal{N}(0, I) \implies E[s] = \mu$ and:

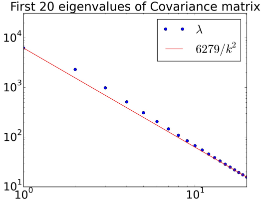
$$\begin{aligned} E[(s-\mu)(s-\mu)^T] &= E[V\Lambda^{1/2}zz^T\Lambda^{1/2}V^T] \\ &= V\Lambda^{1/2}E[zz^T]\Lambda^{1/2}V^T \\ &= V\Lambda V^T = C \end{aligned}$$

1D model: Down-dip section of subduction fault

Covariance: $C_{ij} = \sigma_i \sigma_j e^{-|x_i - x_j|/L}$

where $L =$ correlation length,
$\sigma_i =$ standard deviation (tapered to approach 0 at down-dip edge)





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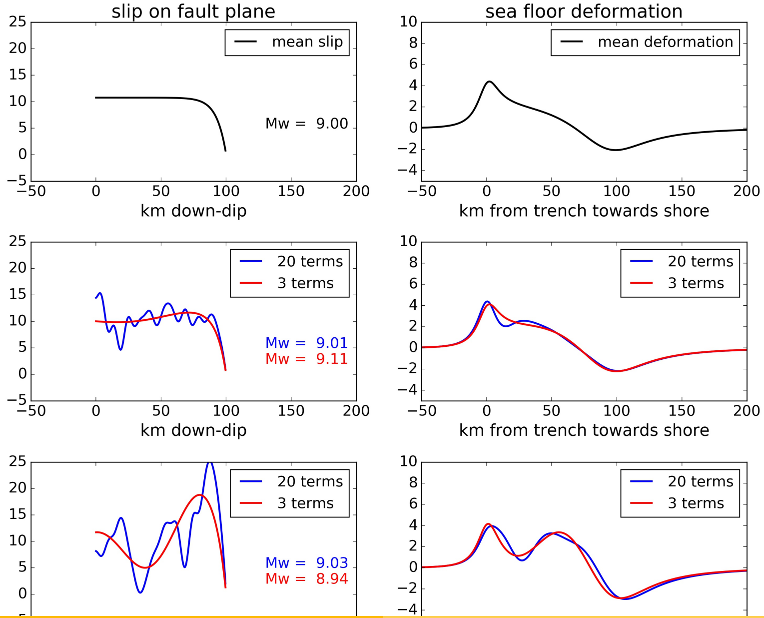
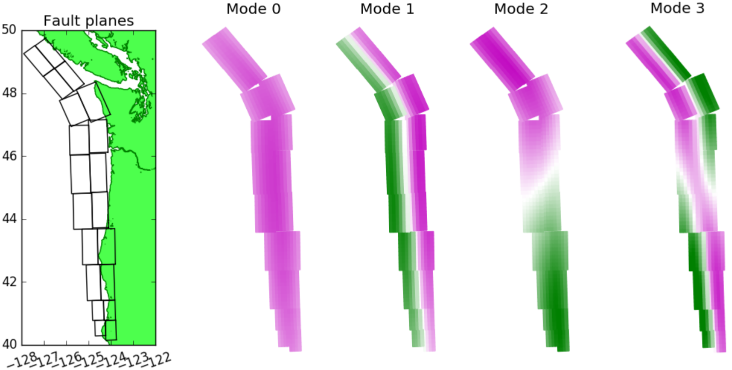
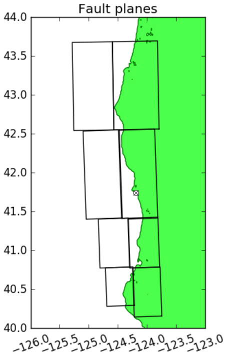
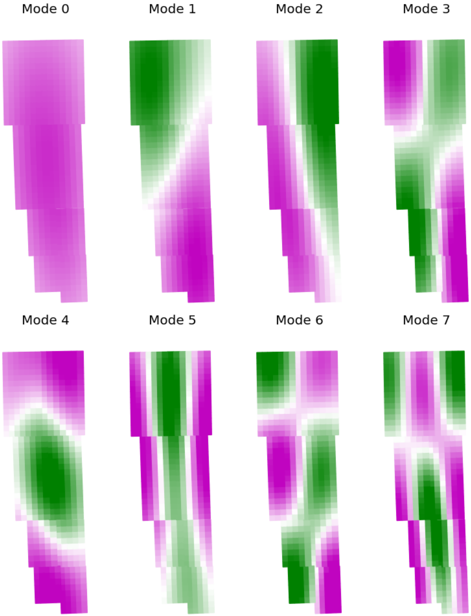


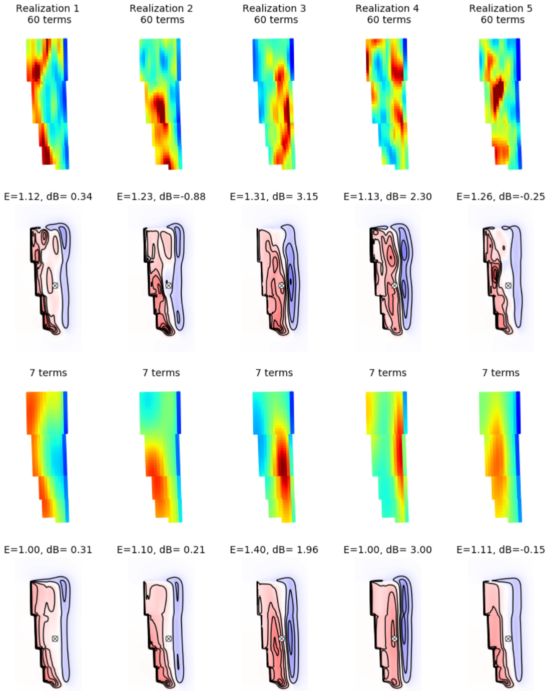
Karhunen-Loève Modes of CSZ



Karhunen-Loève Modes of Southern CSZ






Realization 1
60 terms
Realization 2
60 terms
Realization 3
60 terms
Realization 4
60 terms
Realization 5
60 terms
E=1.12, dB= 0.34
E=1.23, dB=-0.88
E=1.31, dB= 3.15
E=1.13, dB= 2.30
E=1.26, dB=-0.25
7 terms
7 terms
7 terms
7 terms
7 terms
E=1.00, dB= 0.31
E=1.10, dB= 0.21
E=1.40, dB= 1.96
E=1.00, dB= 3.00
E=1.11, dB=-0.15

Dealing with Uncertainties

Aleatoric uncertainties: (Mathematical problem)

Given the correct probability density of slip distribution, there are techniques to reduce dimension and sample efficiently.

Epistemic uncertainties: (Geophysical problem)

- What is correct distribution/recurrence of different magnitude quakes?
- What is correct fault geometry?
- Is there tapering of slip?
- Is K-L expansion with Gaussian weights correct?
- What is correct correlation function?

On-going and future work

- Characterization of CSZ fault and slip patterns
- Dimension reduction and surrogate models
- Adjoint equations - sensitivities, inversion
- Seismic model with topography and ocean, coupled to GeoClaw

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- Adjoint equations - sensitivities, inversion
- Seismic model with topography and ocean, coupled to GeoClaw
- Statistical inversion
- Further validation for currents, forces on structures
- Boussinesq equations for shorter wavelengths,
  Landslide-generated or asteroid impact tsunamis

Some references

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

Probabilistic Tsunami Hazard Assessment (PTHA) for Crescent City, CA., by F. I. Gonzalez, RJL, L. M. Adams, C. Goldfinger, G. Priest, K. Wang, 2014.

Generating Random Earthquake Events for Probabilistic Tsunami Hazard Assessment, by RJL, K. Waagan, F. I. Gonzalez, D. Rim, and G. Lin, 2016.

Kinematic Rupture Scenarios and Synthetic Displacement Data: An Example Application to the Cascadia Subduction Zone, by D. Melgar, RJL, D. S. Dreger, and R. M. Allen, Submitted to *J. Geophys. Res. – Solid Earth*, 2016.