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Knowledge Sharing for a Better Tomorrow

Modeling and Resilient Design against Tsunami Hazards



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Knowledge Sharing for a Better Tomorrow

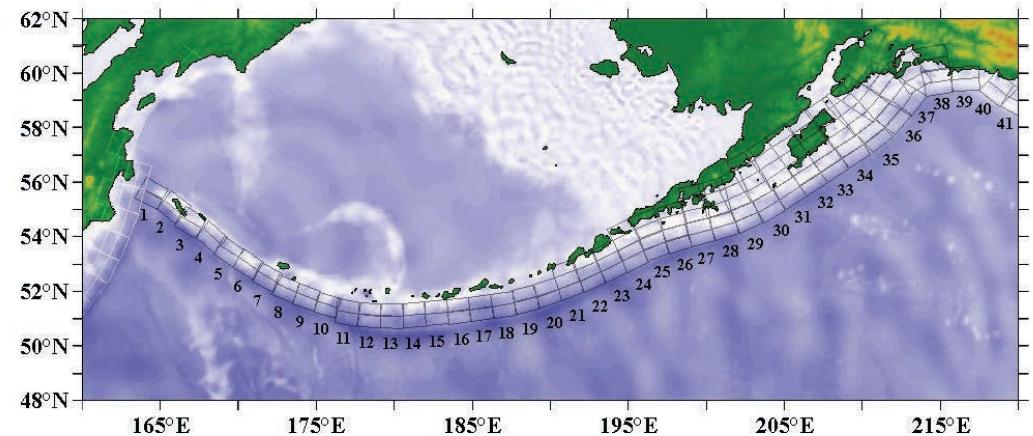
- Tsunami sources
- Tsunami modeling
- Tsunami models benchmarked by NTHMP datasets
- ASCE-16 standard for resilient design against tsunamis
- FUNWAVE-TVD model
- New features of FUNWAVE-TVD
- Content of tutorial



Tsunami sources

- Co-seismic source – earthquake
- Submarine mass failure (SMF)
- Submarine Volcano
- Combination of multiple sources

Unit sources along the Aleutian Islands (NOAA PMEL)
<https://nctr.pmel.noaa.gov/propagation-database.html>



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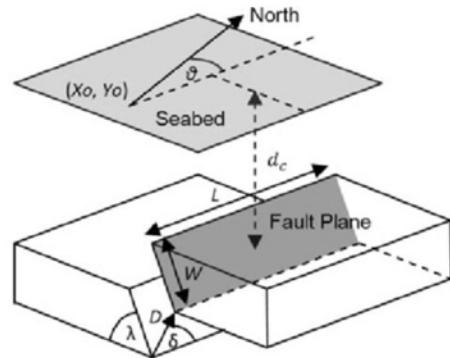


Tsunami sources

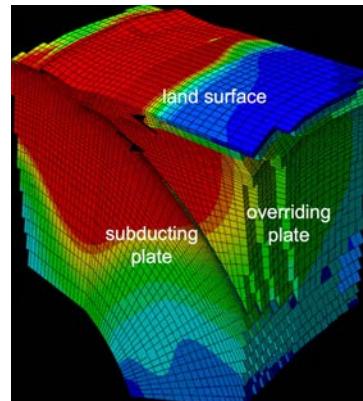
Modeling tsunami sources

- Co-seismic source

Okada source formulation (1989)



Numerical model (e.g., Masterlark, 2012)



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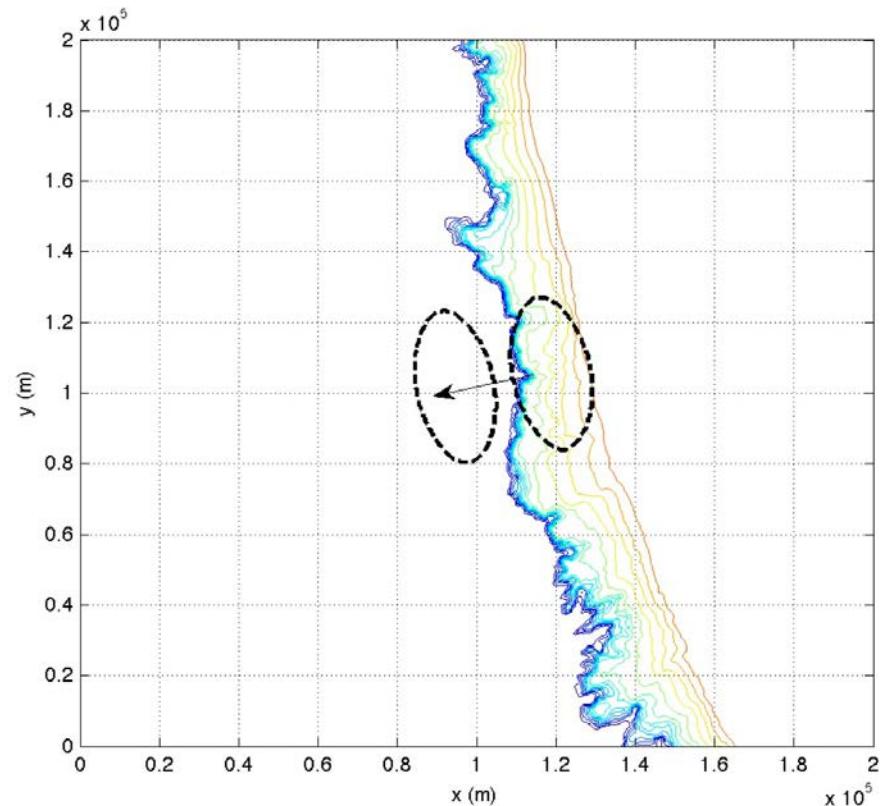
Tsunami sources

Modeling tsunami sources

- Submarine mass failure (SMF)

Static source

Conventional dynamic source



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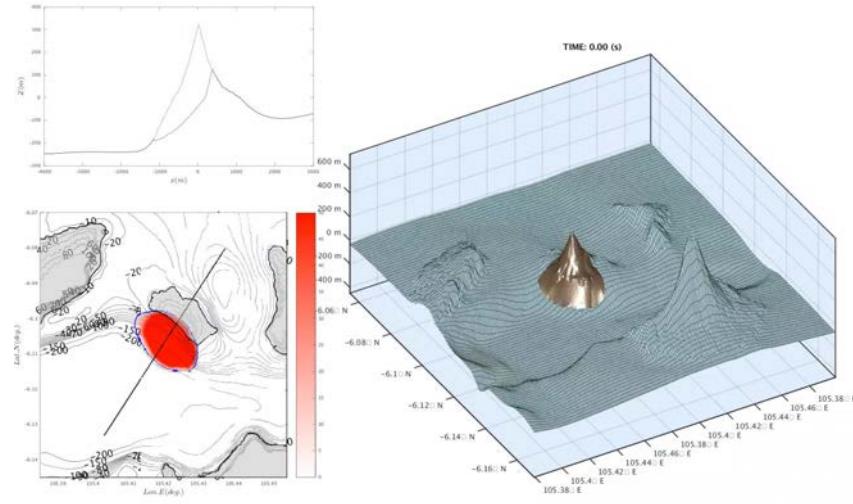
Tsunami sources

Modeling tsunami sources

- Submarine mass failure (SMF)

Modeled dynamic source

(e.g., numerical model NHWAVE)



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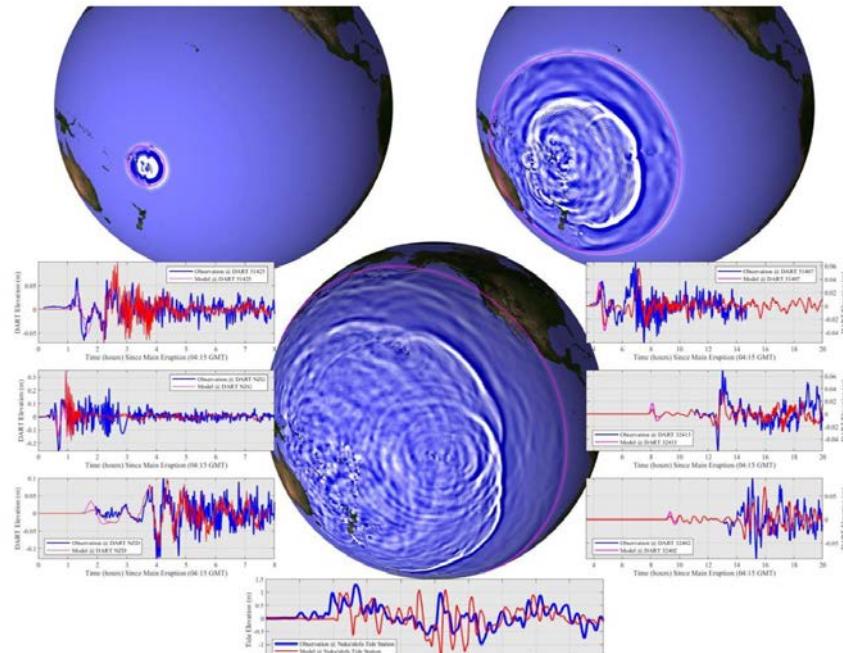
Tsunami sources

Modeling tsunami sources

- Submarine Volcano

(e.g., Hunga Tonga-Hunga Ha'apai eruption and tsunami)

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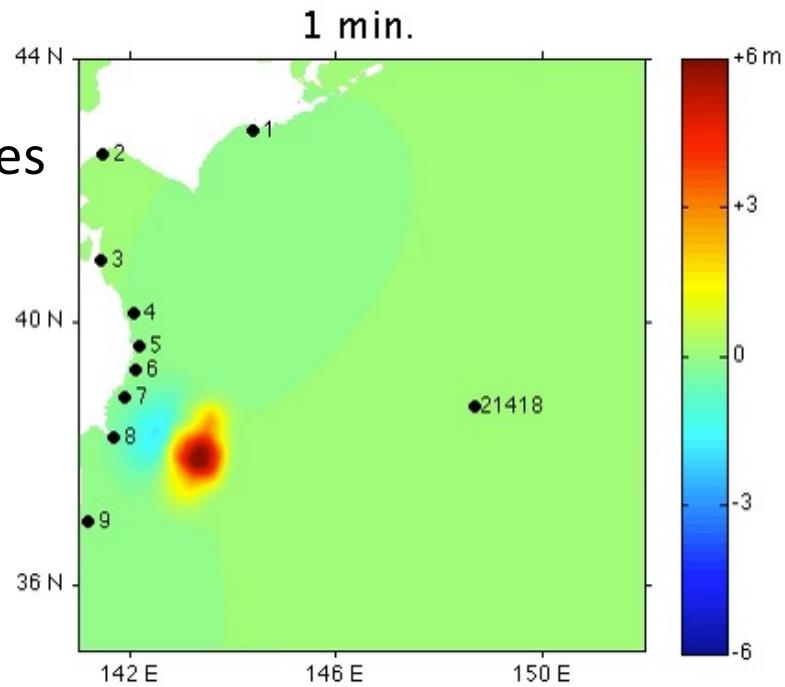


Tsunami sources

Modeling tsunami sources

- Combination of multiple sources

(e.g., Tappin et al., 2014)



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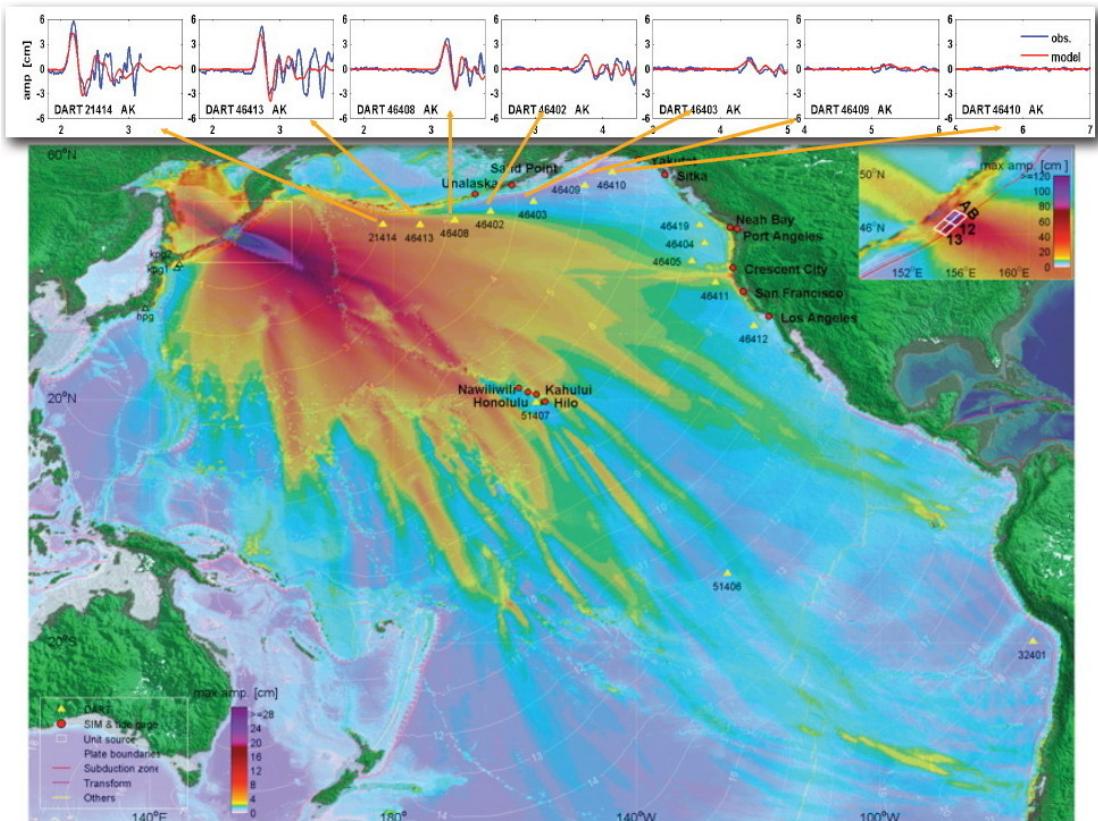


Tsunami modeling

Tsunami modeling for different purposes

- Tsunami prediction
(A lot of information online
e.g., NOAA PMEL, SIFT...)

<https://nctr.pmel.noaa.gov/propagation-database.html>



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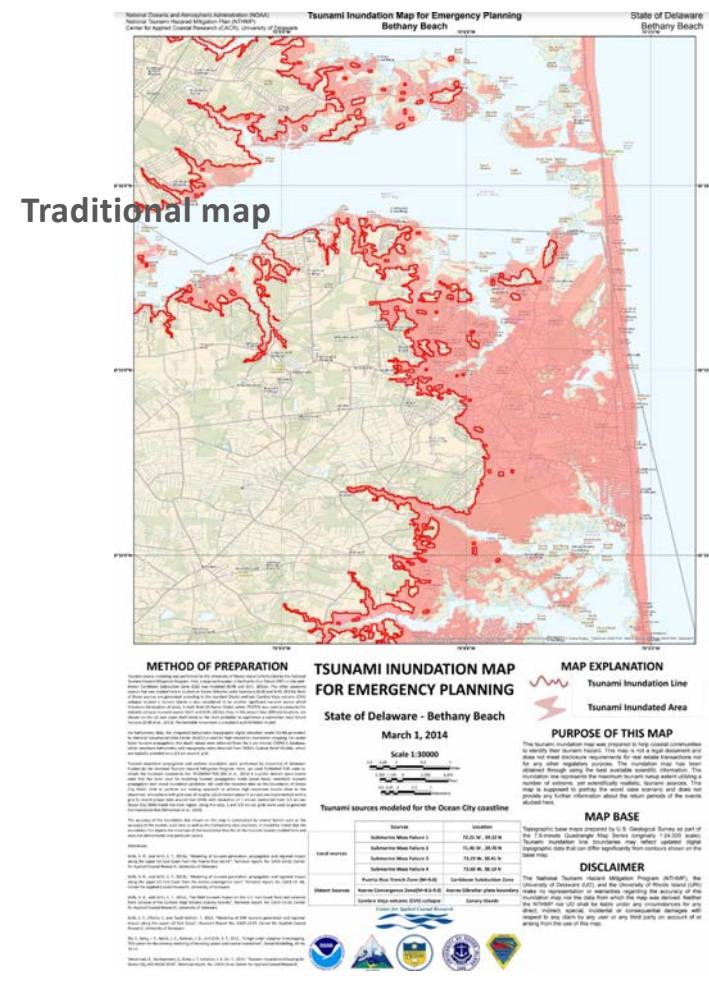
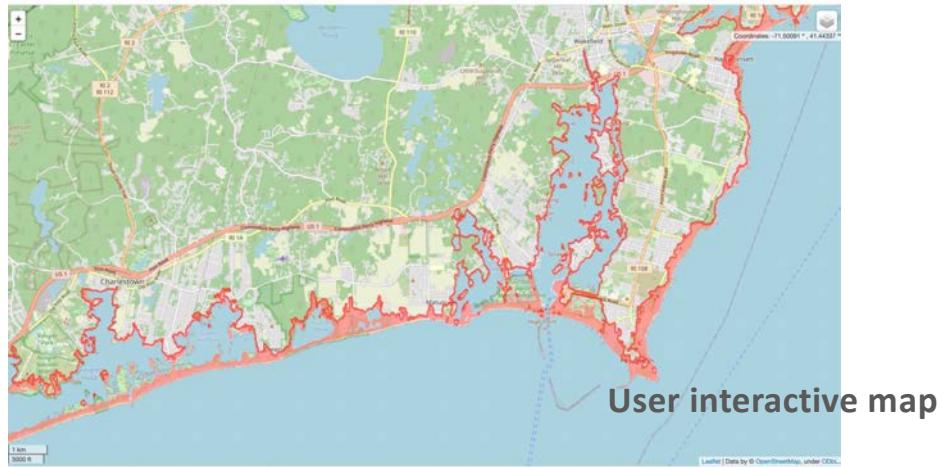
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Tsunami modeling

Tsunami modeling for different purposes

- Tsunami inundation maps
(National Tsunami Hazard Mitigation Program, NTHMP)



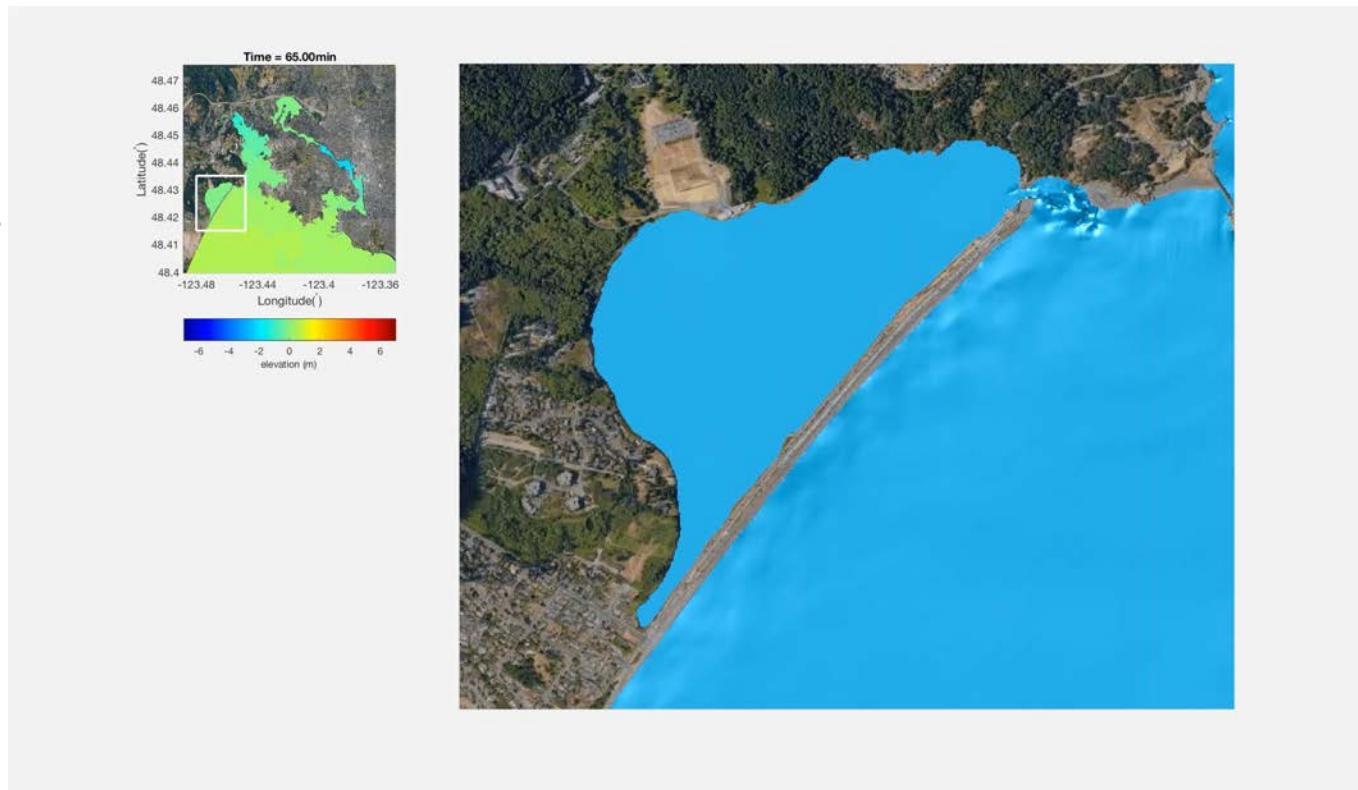
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Tsunami modeling

Tsunami modeling
for different purposes

➤ Education



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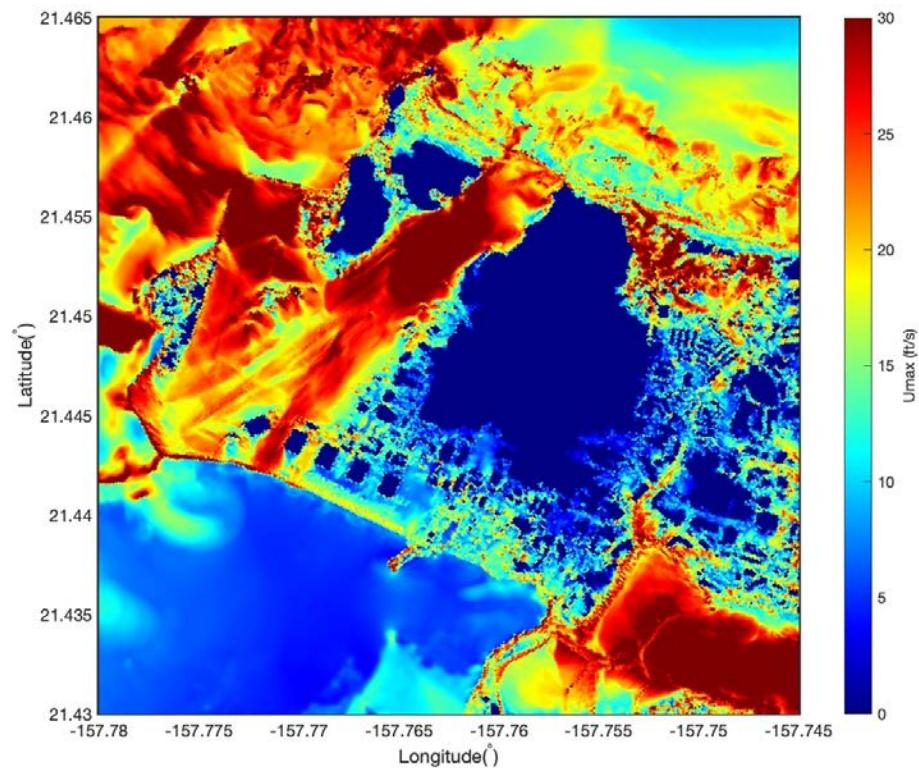
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Tsunami modeling

Tsunami modeling
for different purposes

- Engineering design



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Tsunami models

List of models benchmarked for tsunami applications by test data sets designated by the NTHMP program.

Model Name	Equations Solved [Spatial Dimensions]	Numerical Approach	Numerical Treatment of Convection Terms	Numerical Accuracy of Other Gradient Terms	Numerical Treatment of Time Integration
ALASKA GI'-T	Nonlinear Shallow Water (NSW) [2D]	FD	Upwind (1st-order accurate)	Centered (2nd-order accurate)	Semi-implicit (1st-order accurate)
NAMI DANCE	Nonlinear Shallow Water (NSW) [2D]	FD	Upwind (1st-order accurate)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
MOST	Nonlinear Shallow Water (NSW) [2D]	FD	Centered (2nd-order accurate)	Centered (2nd-order accurate)	Explicit (1st-order accurate)
Cliffs	Nonlinear Shallow Water (NSW) [2D]	FD	Centered (2nd-order accurate)	Centered (2nd-order accurate)	Explicit (1st-order accurate)
GeoClaw	Nonlinear Shallow Water (NSW) [2D]	FV	Limiter-based (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
GeoClaw -AECOM	Nonlinear Shallow Water (NSW) [2D]	FV	Limiter-based (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
Tsunami-HySEA	Nonlinear Shallow Water (NSW) [2D]	FV	Limiter-based (2nd-order near shocks, 3rd-order when smooth)	Centered (2nd-order accurate)	Explicit (3rd-order accurate)
pCOULWAVE	Highly Nonlinear Boussinesq-type [2D]	FV	Limiter-based (2nd-order near shocks, 4th-order when smooth)	Centered (4th-order accurate)	Semi-implicit (4th-order accurate)
FUNWAVE-TVD	Highly Nonlinear Boussinesq-type [2D]	FV / FD	Limiter-based (2nd-order near shocks, 5th-order when smooth)	Centered (4th-order accurate)	Explicit (3rd-order accurate)
BOSZ	Weakly Nonlinear Boussinesq-type [2D]	FV	Limiter-based (2nd-order near shocks, 5th-order when smooth)	Centered (5th-order accurate)	Explicit (2nd-order accurate)
NEOWAVE	One-Layer, Non-Hydrostatic [2D]	FD	Upwind (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Semi-implicit (2nd-order accurate)
TSUNAMI3D	Navier-Stokes [3D]	FD	Upwind (1st-order accurate)	Centered (2nd-order accurate)	Explicit (2nd-order accurate)
SCHISM	Navier-Stokes, Hydrostatic [3D]	FE / FV	Limiter-based (1st-order near shocks, 2nd-order when smooth)	Centered (2nd-order accurate)	Semi-implicit (2nd-order accurate)



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Tsunami modeling

Focus of this course

Simulation of earthquake-generated tsunami

- Okada source
- Wave modeling
- Postprocessing
- Optional: brief introduction to the landslide model NHWAVE



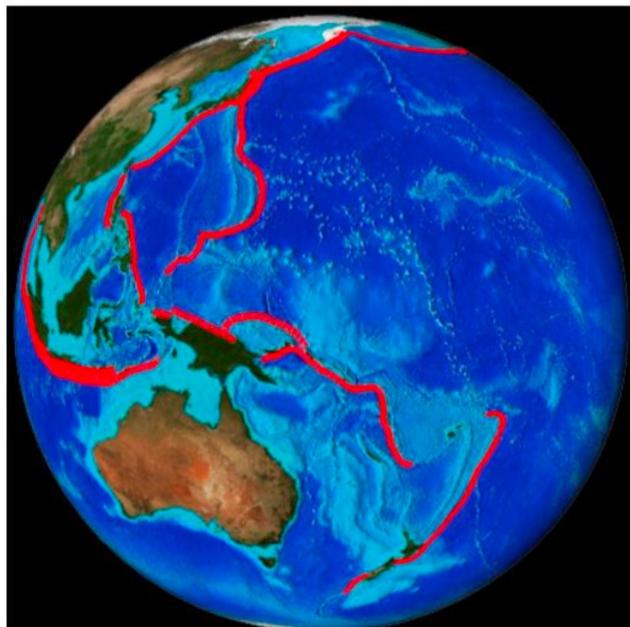
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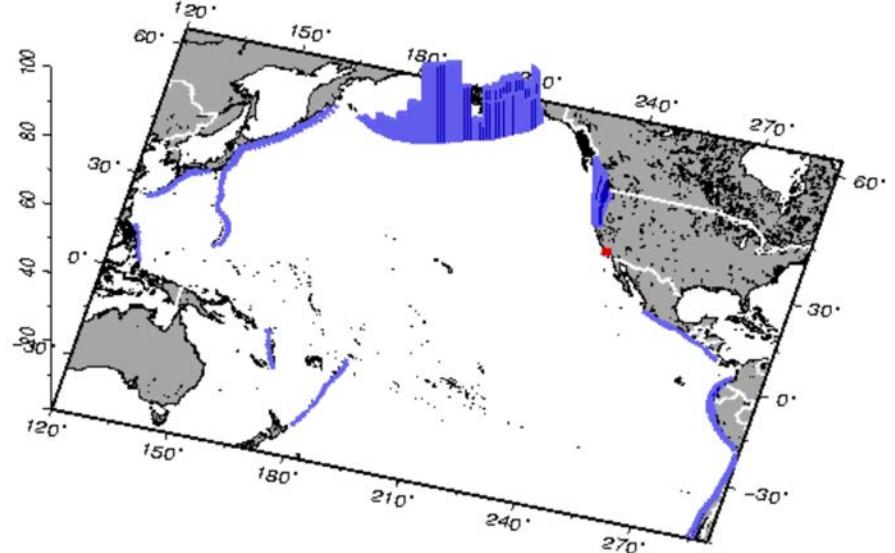
ASCE-7-16 Standard for resilient design against tsunamis

Unit sources (NOAA NCEP)



Probabilistic Tsunami Hazard Analysis (PTHA)

2500-year PTHA source disaggregation for a site

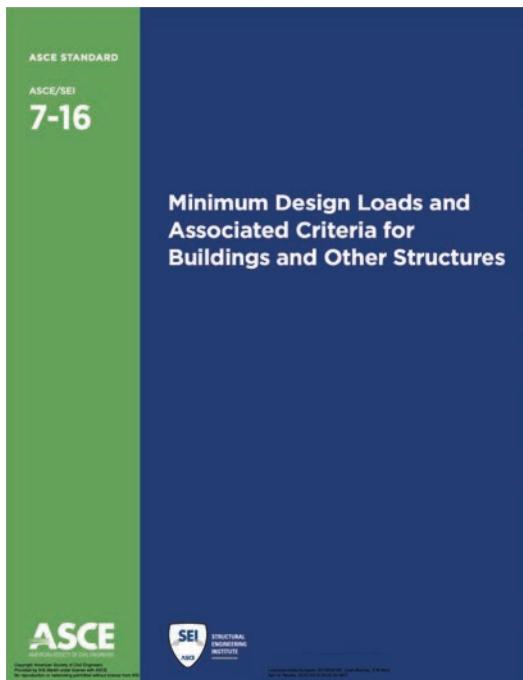


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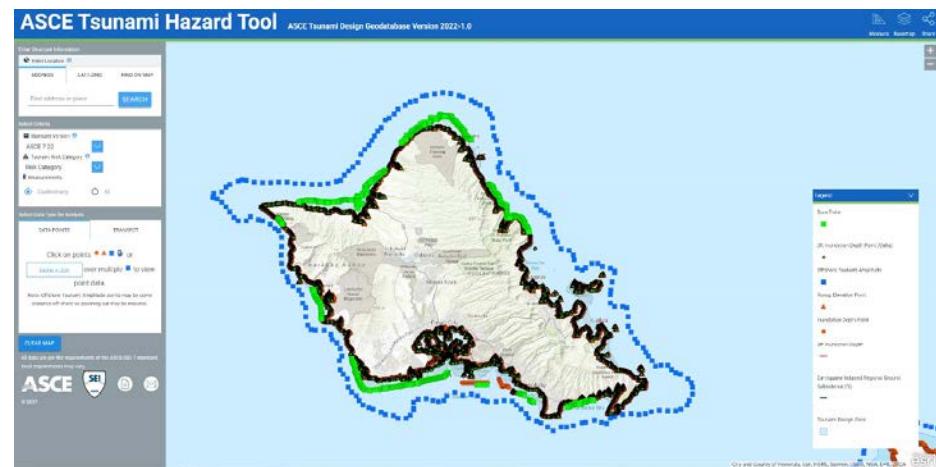
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PTHA results at Oahu



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ASCE-7-16 Standard for resilient design against tsunamis

Boundary condition at 100-m bathymetry contour

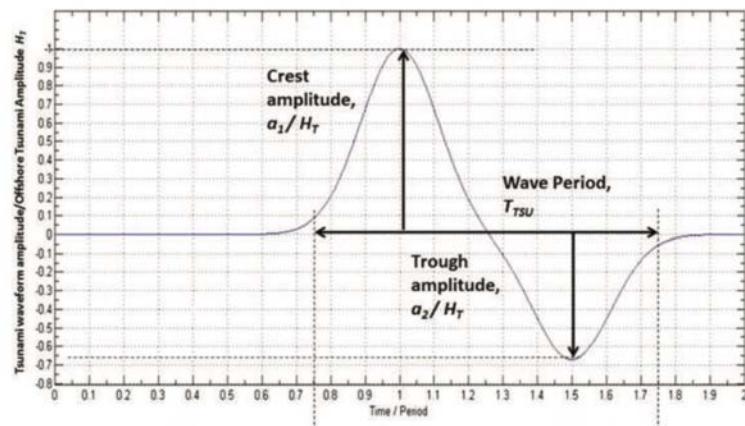


FIGURE 6.7-2 Illustration of Tsunami Offshore Incident Waveform Parameters at 328-ft (100-m) Depth

$$\eta = a_1 e^{-[\omega(t-t_o)]^2} + a_2 e^{-[\omega(t-\frac{T_{TSU}}{2}-t_o)]^2} \quad (6.7-1)$$

where the total wave height of the waveform is $= \text{abs}(a_1) + \text{abs}(a_2)$, and

η = the free surface elevation (in ft or m) as a function of time, t , used to drive the offshore boundary condition at the 328-ft (100-m) depth contour;

a_1 = the amplitude of the leading pulse (in ft or m); it shall be negative for a leading depression tsunami;

a_2 = the amplitude of the following, or second, pulse (in ft or m);

T_{TSU} = wave period, or the time from the start of the first pulse to the end of the second pulse;

ω = angular frequency of the waveform, equal to $2\pi/T_{TSU}$; and

t_o = offset time of the wave train, generally set equal to T_{TSU}



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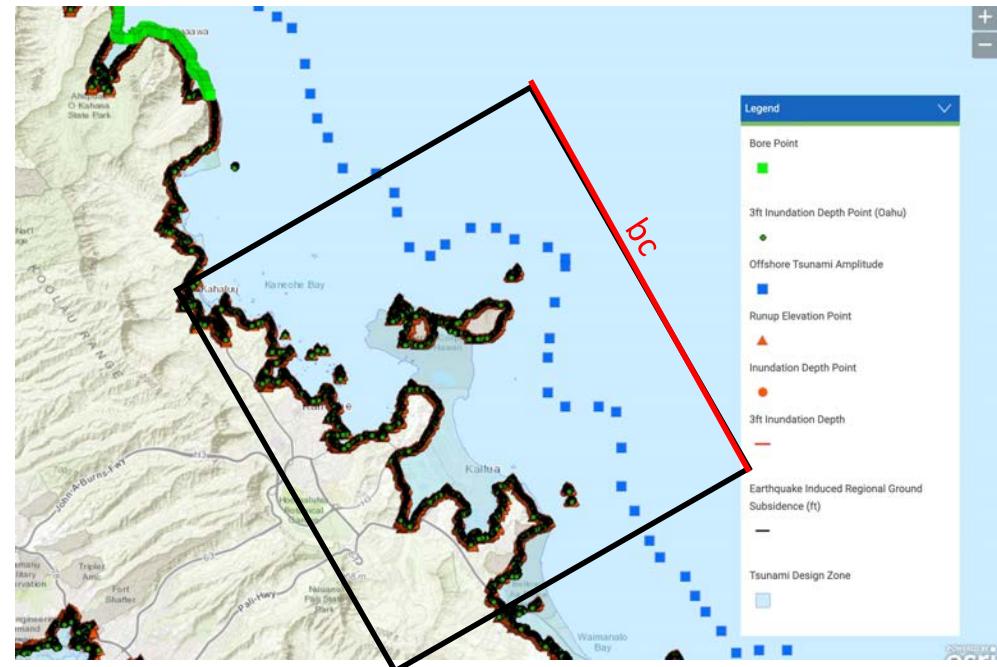
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ASCE-7-16 Standard for resilient design against tsunamis

An example of model domain setup

NOTE: no requirement for modeled wave direction in ASCE-7-16



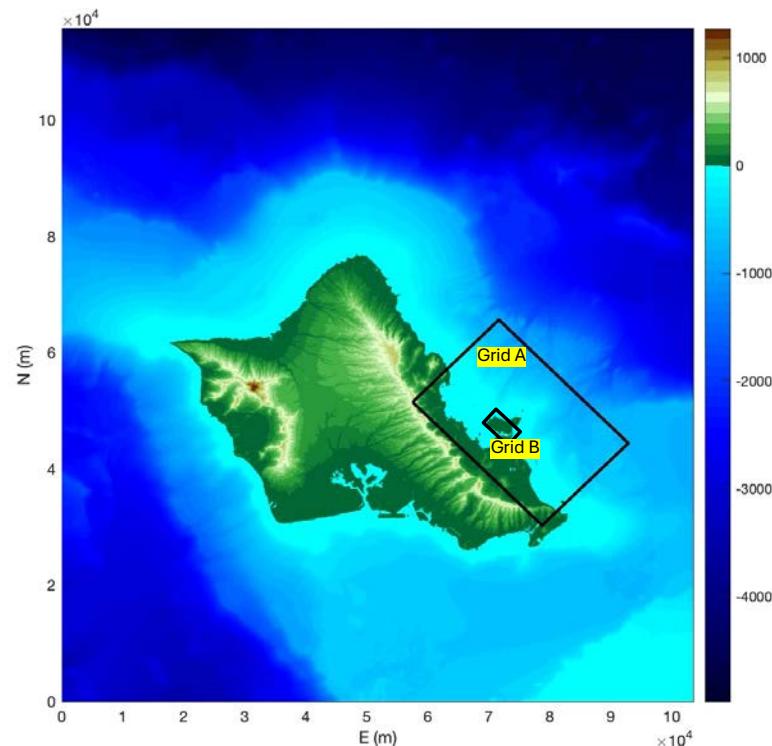
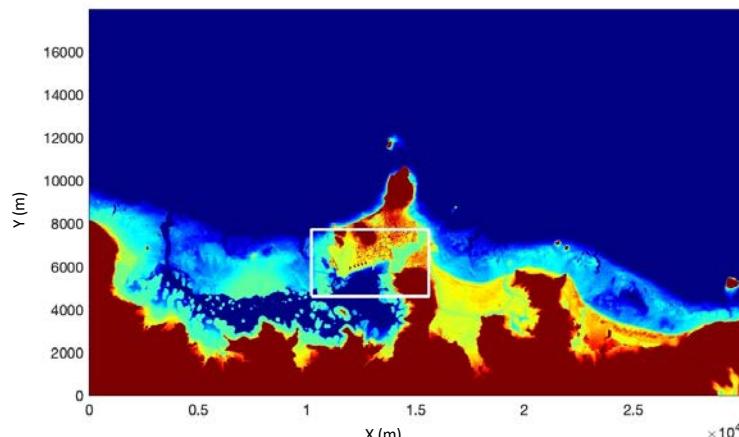
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ASCE-7-16 Standard for resilient design against tsunamis

An example of model domain setup



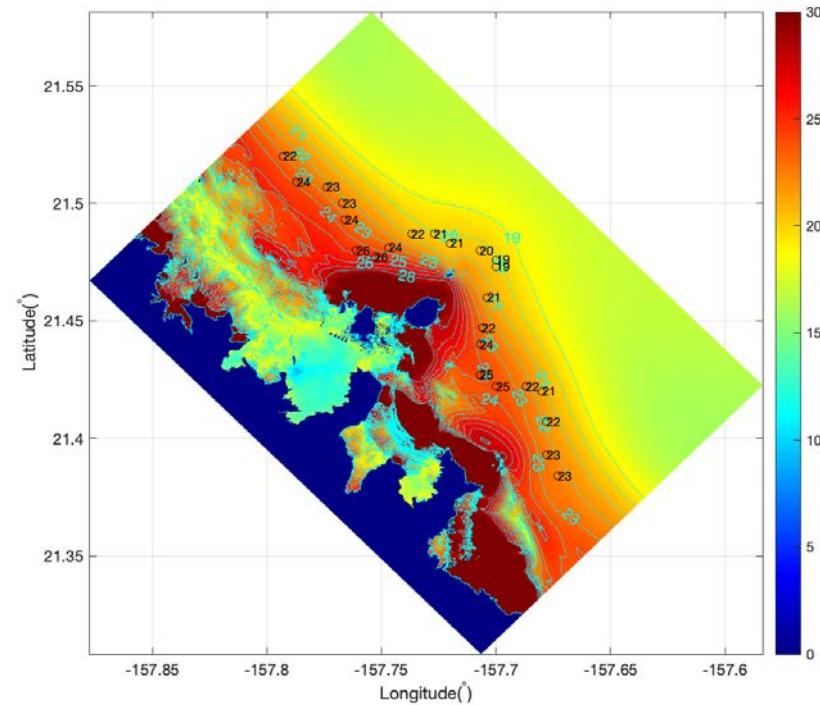
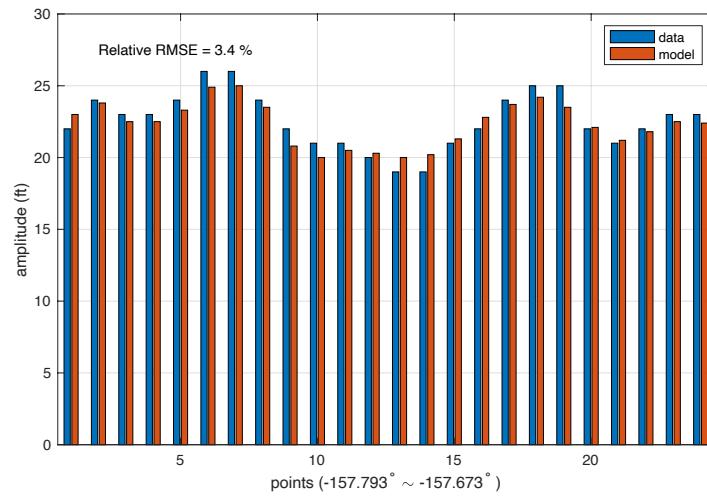
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ASCE-7-16 Standard for resilient design against tsunamis

An example of model domain setup



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ASCE-16 standard for resilient design against tsunamis

An example of
model domain setup



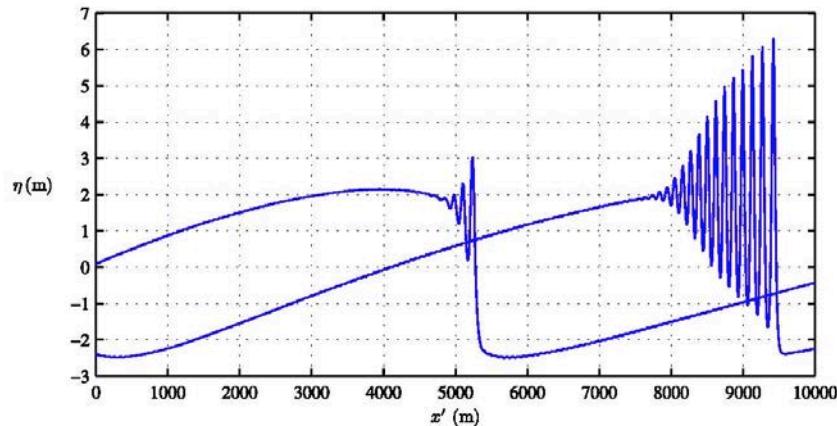
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FUNWAVE-TVD

Why Boussinesq?



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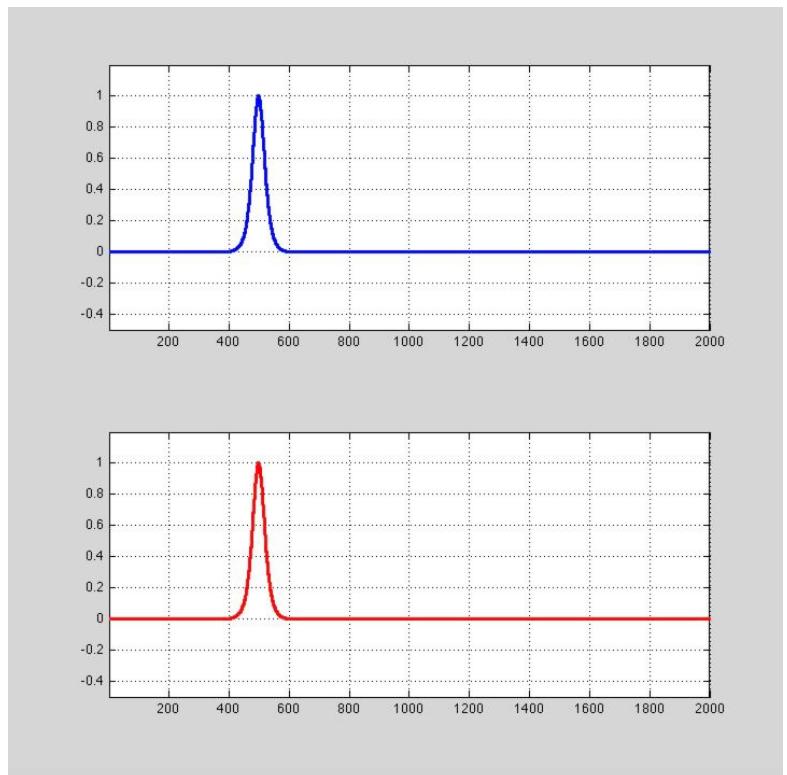
FUNWAVE-TVD

Why Boussinesq?

Boussinesq equations

Shallow water equations

$$c = \sqrt{g(h + \eta)}$$



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FUNWAVE-TVD

- Why FUNWAVE-TVD?

➤ **Open source and well documented**

<https://github.com/fengyanshi/FUNWAVE-TVD>

<https://fengyanshi.github.io/build/html/index.html>

➤ **TVD scheme, very stable**

➤ **Parallelized, CPU(MPI) and GPU codes**

➤ **Benchmarked (NTHMP standard)**

➤ **Large user group**

<https://groups.google.com/forum/?hl=en#!forum/funwave-tvd>



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FUNWAVE-TVD

- How many versions of FUNWAVE?
 - FUNWAVE (Wei et al., 1995, Wei and Kirby, 1995, Kennedy et al., 2000, Chen et al., 2000)
 - FUNWAVE 2 (Shi et al., 2001, Long and Kirby, 2006)
 - GEOWAVE (TOPICS+FUNWAVE, Grilli, Watts, 2003)
 - FUNWAVE-TVD (Shi et al., 2012)



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FUNWAVE-TVD

- FUNWAVE equations

Mass conservation

$$\eta_t + \nabla \cdot \mathbf{M} = 0$$

where $\mathbf{M} = H \{ \mathbf{u}_\alpha + \bar{\mathbf{u}}_2 \}$

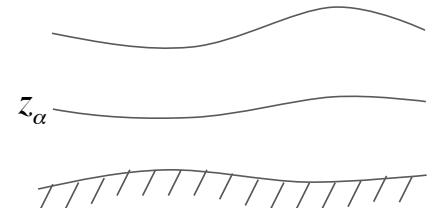
$$\bar{\mathbf{u}}_2 = \frac{1}{H} \int_{-h}^{\eta} \mathbf{u}_2(z) dz = \left(\frac{z_\alpha^2}{2} - \frac{1}{6}(h^2 - h\eta + \eta^2) \right) \nabla B + \left(z_\alpha + \frac{1}{2}(h - \eta) \right) \nabla A$$

$$A = \nabla \cdot (h \mathbf{u}_\alpha)$$

$$B = \nabla \cdot \mathbf{u}_\alpha$$

$$z_\alpha = -h + \beta H = (\beta - 1)h + \beta\eta = \zeta h + (1 + \zeta)\eta$$

Kennedy et al., 2001



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FUNWAVE-TVD

- FUNWAVE equations

Momentum equations:

$$\mathbf{u}_{\alpha,t} + (\mathbf{u}_\alpha \cdot \nabla) \mathbf{u}_\alpha + g \nabla \eta + \mathbf{V}_1 + \mathbf{V}_2 + \mathbf{V}_3 + \mathbf{R} = 0$$

Dispersive terms

$$\begin{aligned}\mathbf{V}_1 &= \left\{ \frac{z_\alpha^2}{2} \nabla B + z_\alpha \nabla A \right\}_t - \nabla \left[\frac{\eta^2}{2} B_t + \eta A_t \right] \\ \mathbf{V}_2 &= \nabla \left\{ (z_\alpha - \eta)(\mathbf{u}_\alpha \cdot \nabla) A + \frac{1}{2}(z_\alpha^2 - \eta^2)(\mathbf{u}_\alpha \cdot \nabla) B + \frac{1}{2}[A + \eta B]^2 \right\}\end{aligned}$$

Second order effect of the vertical vorticity (Chen, 2006)

$$\mathbf{V}_3 = \omega_0 \mathbf{i}^z \times \bar{\mathbf{u}}_2 + \omega_2 \mathbf{i}^z \times \mathbf{u}_\alpha$$

$$\begin{aligned}\omega_0 &= (\nabla \times \mathbf{u}_\alpha) \cdot \mathbf{i}^z = v_{\alpha,x} - u_{\alpha,y} \\ \omega_2 &= (\nabla \times \bar{\mathbf{u}}_2) \cdot \mathbf{i}^z = z_{\alpha,x}(A_y + z_\alpha B_y) - z_{\alpha,y}(A_x + z_\alpha B_x)\end{aligned}$$



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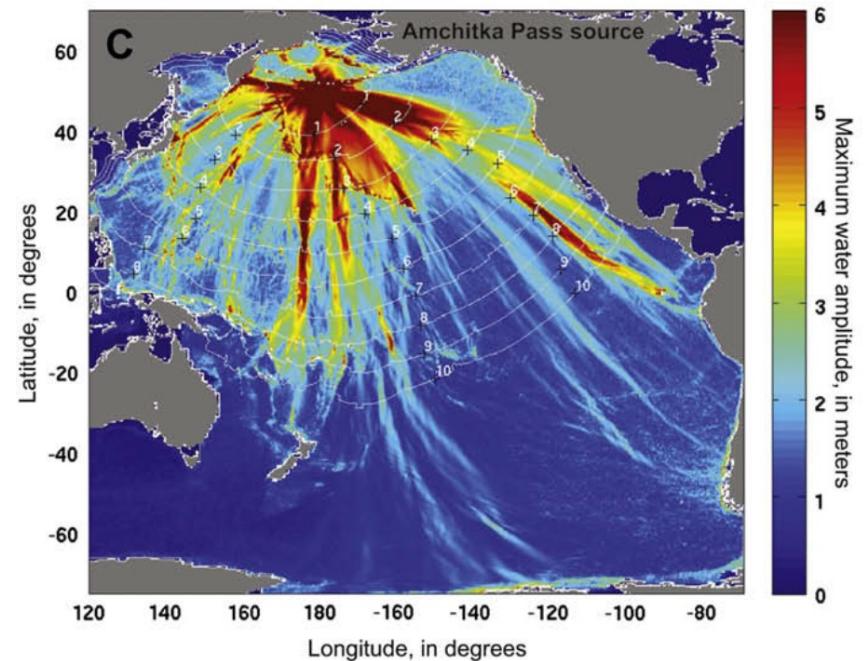


FUNWAVE-TVD

- FUNWAVE equations

Spherical mode: Weakly nonlinear Boussinesq equations
in spherical coordinates (Kirby et al. 2013)

$$\begin{aligned}
 H_t + \frac{1}{r_0 \cos \theta} \{(H u)_\phi + (H v \cos \theta)_\theta\} &= 0 \\
 u_t - f v + \frac{1}{r_0 \cos \theta} u u_\phi + \frac{1}{r_0} v u_\theta + \frac{g}{r_0 \cos \theta} \eta_\phi \\
 + \frac{1}{r_0^2 \cos^2 \theta} \left\{ \frac{h^2}{6} [u_{\phi\phi t} + (v \cos \theta)_{\phi\theta t}] - \frac{h}{2} [(h u_t)_{\phi\phi} + (h \cos \theta v_t)_{\phi\theta}] \right\} \\
 - \tau_b^x + \frac{1}{r_0 \cos \theta} (BFT)_\phi &= 0 \\
 v_t + f u + \frac{1}{r_0 \cos \theta} u v_\phi + \frac{1}{r_0} v v_\theta + \frac{g}{r_0} \eta_\theta \\
 + \frac{1}{r_0^2} \left\{ \frac{h^2}{6} \left[\frac{1}{\cos \theta} \{u_{\phi t} + (v \cos \theta)_{\theta t}\} \right]_\theta - \frac{h}{2} \left[\frac{1}{\cos \theta} \{(h u_t)_\phi + (h \cos \theta v_t)_\theta\} \right]_\theta \right\} \\
 - \tau_b^y + \frac{1}{r_0} (BFT)_\theta &= 0
 \end{aligned}$$



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FUNWAVE-TVD

- FUNWAVE equations

Numerical schemes

Spatial discretization

Combined finite volume and finite difference scheme

- Fourth-order MUSCL-TVD scheme (Yamamoto and Daiguji, 1993)
- HLL Riemann solver
- Surface gradient scheme for pressure gradient term (Zhou et al., 2001)

Time stepping

The third-order Strong Stability-Preserving (SSP) Runge-Kutta scheme

Adaptive time step

$$\Delta t = C \min \left(\min \frac{\Delta x}{|u_{i,j}| + \sqrt{g(h_{i,j} + \eta_{i,j})}}, \min \frac{\Delta y}{|u_{i,j}| + \sqrt{g(h_{i,j} + \eta_{i,j})}} \right)$$

Moving boundary condition

wetting and drying with correction of wave speed in Riemann solver

Wave breaking

switch between NSWE and Boussinesq (Tonelli and Petti, 2009)



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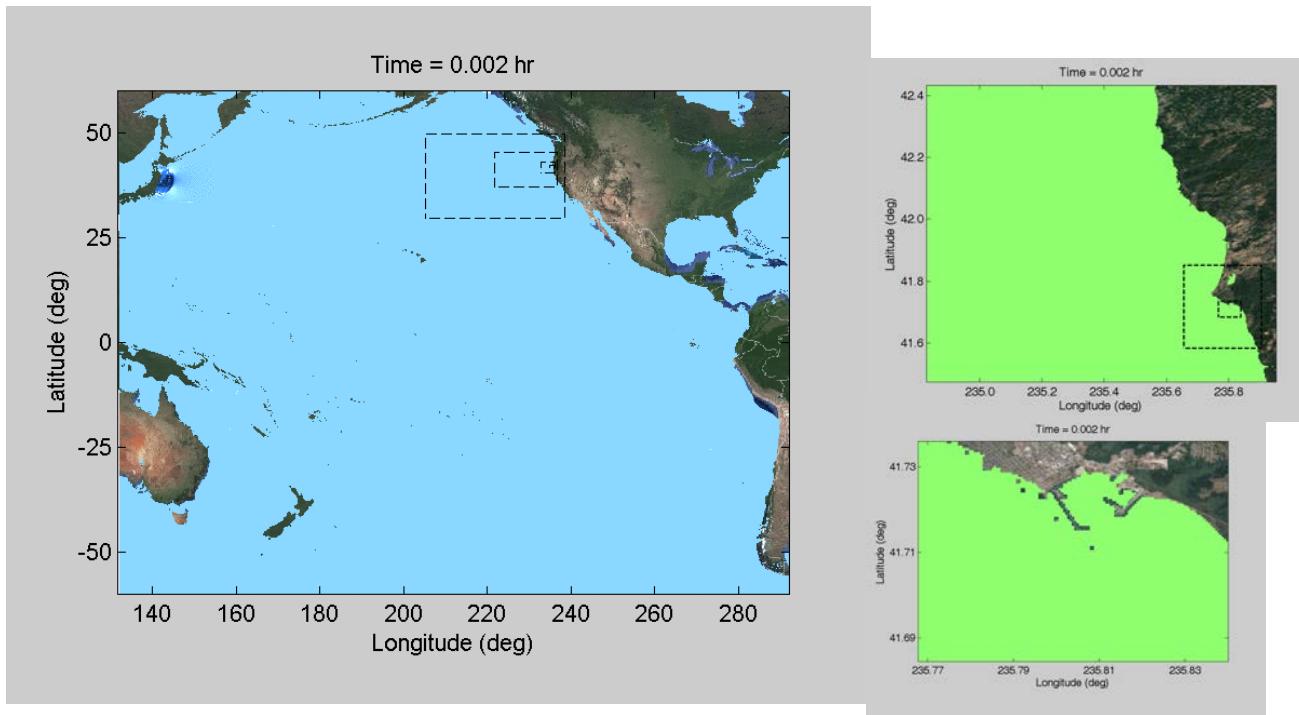
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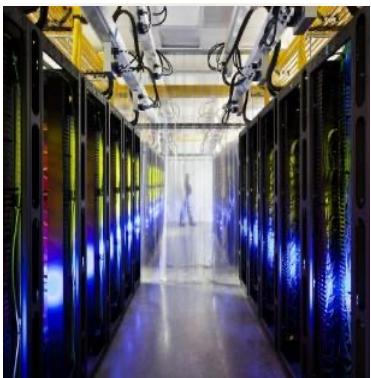
New features of FUNWAVE-TVD

Multi-grid Nesting Interface (Choi et al., 2022)



New features of FUNWAVE-TVD

HPC



40-node cluster based on
Intel Xeon Gold 6150
CPUs
 $40 \times 36 = 1440$ cores
 ~ 120 kW, \$600,000

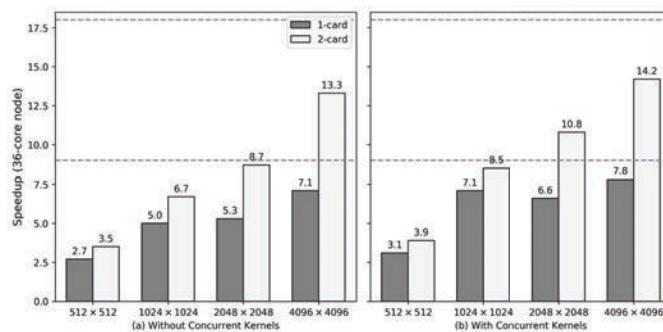
GPU



4 Nvidia V100 GPU cards
@
1 Intel 36-cores node
20480 cores
Performance: 56 TFLOPS
3.5 kW, \$40,000

Yuan et al., 2021

- PGI 18.4 Cuda Fortran
- CUDA 10.0
- MPI + Single/multi GPU



Speedup tests: GPU vs. CPU.
36 cores on 1 CPU node, 5120 cores/card



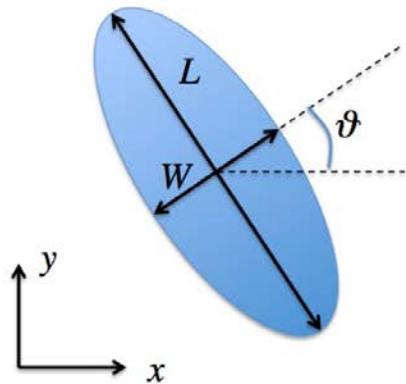
New features of FUNWAVE-TVD

Meteo-tsunami module

Meteotsunamis are modeled using a pressure source with a two-dimensional Gaussian distribution:

$$P = dP \exp \left(-\left(\frac{(x' - x_0)^2}{2\sigma_x^2} + \frac{(y' - y_0)^2}{2\sigma_y^2} \right) \right) \quad (97)$$

where dP is the pressure anomaly in mb, and (x', y') are the coordinates rotated to the pressure moving direction (angle is θ as indicated in the figure below). σ_x and σ_y are parameters representing the length and width of the pressure source, respectively.



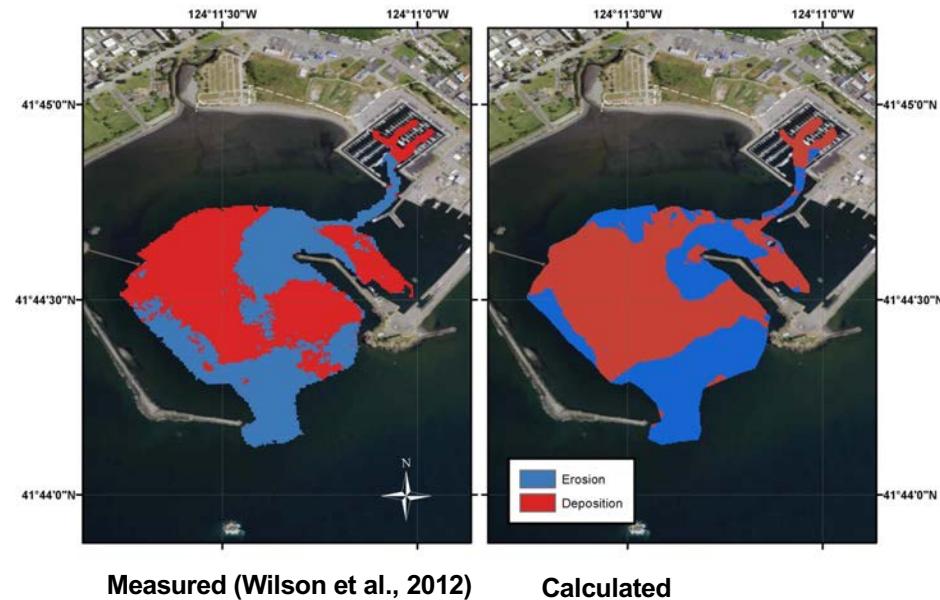


New features of FUNWAVE-TVD

Sediment transport module

Quasi-steady state-based sediment transport equation (Tehranirad et al., 2016)

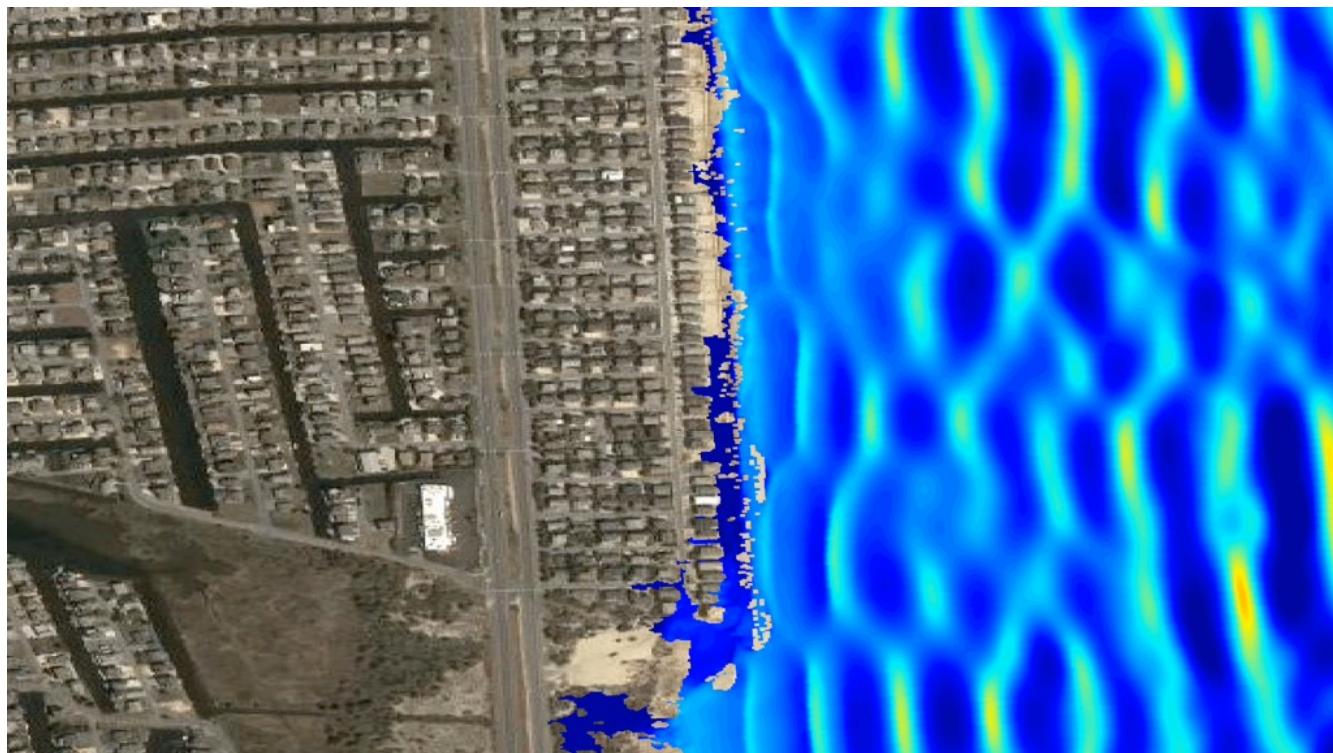
2011 tsunami inside Crescent City harbor.





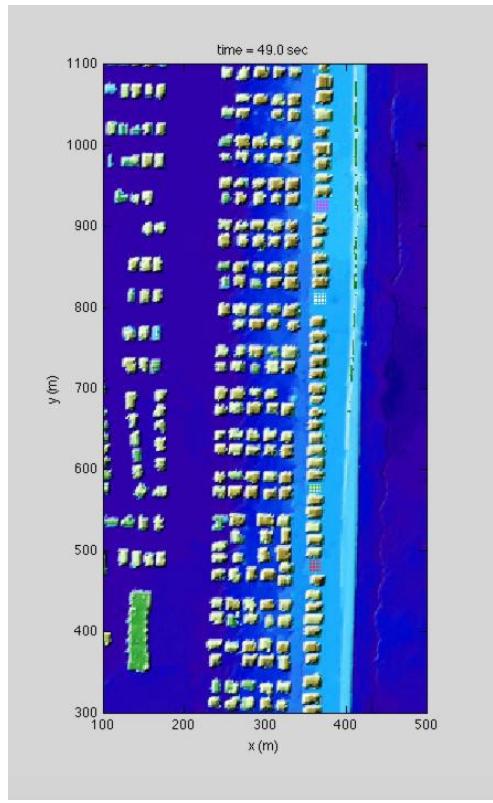
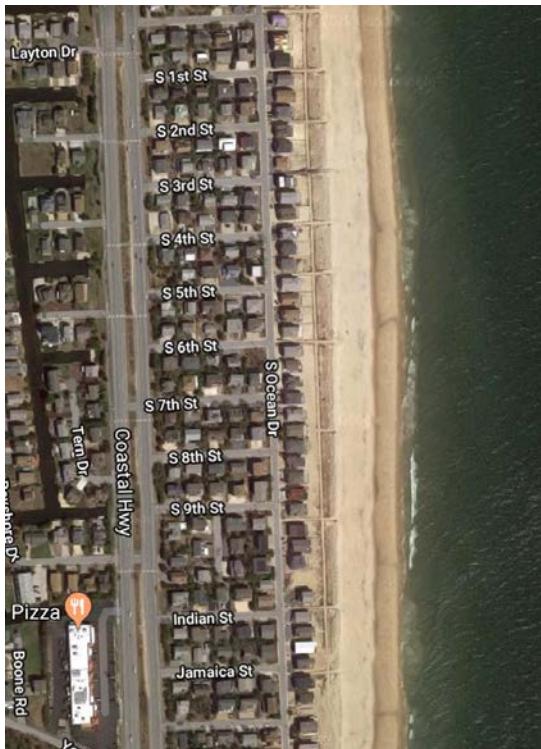
New features of FUNWAVE-TVD

Lagrangian Particle Tracking



New features of FUNWAVE-TVD

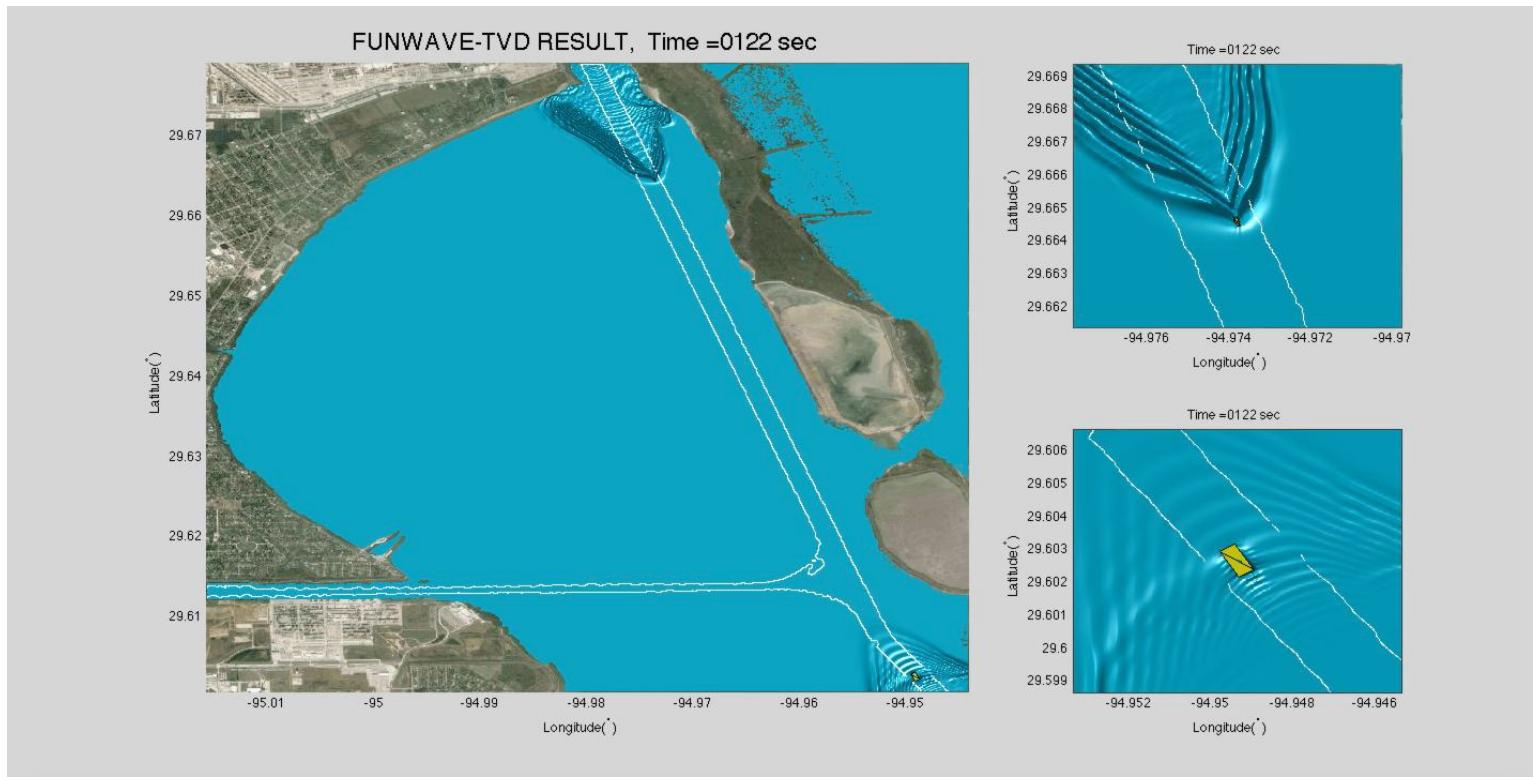
Lagrangian Particle Tracking





New features of FUNWAVE-TVD

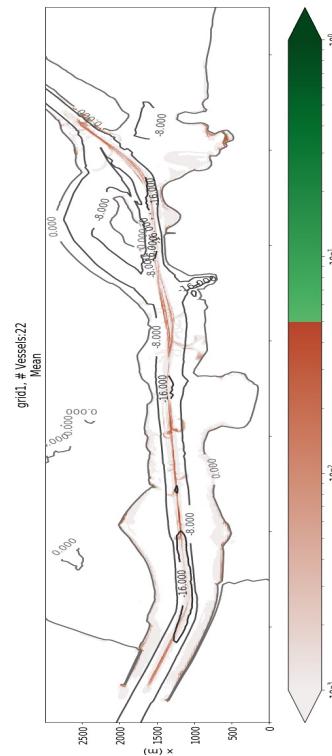
Ship-wake module





New features of FUNWAVE-TVD

Ship-wake module





Tutorial

- FUNWAVE WIKI page
- Install and compile the model
- Model input/output
- Simple cases
- Modeling Tohoku Tsunami (other sources, such as 1964 Alaska, Cape Fear Landslide, are provided for practice)
- Grid nesting/coupling
- Landslide tsunami generation (optional)