Development of an operational tsunami model for inclusion into the Indian Ocean Tsunami Early Warning System (GITEWS)

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Institute – in short

- 1980: Institute founded
- State 2005:
  - Budget: 103 Mio. Euro
  - 788 Staff
- Funding:
  - 90% Research State Dept. (BMBF)
  - 8% State of Bremen
  - 1% States Brandenburg and Schleswig-Holstein
  - Third party funding
- Member in Helmholtz-Gemeinschaft

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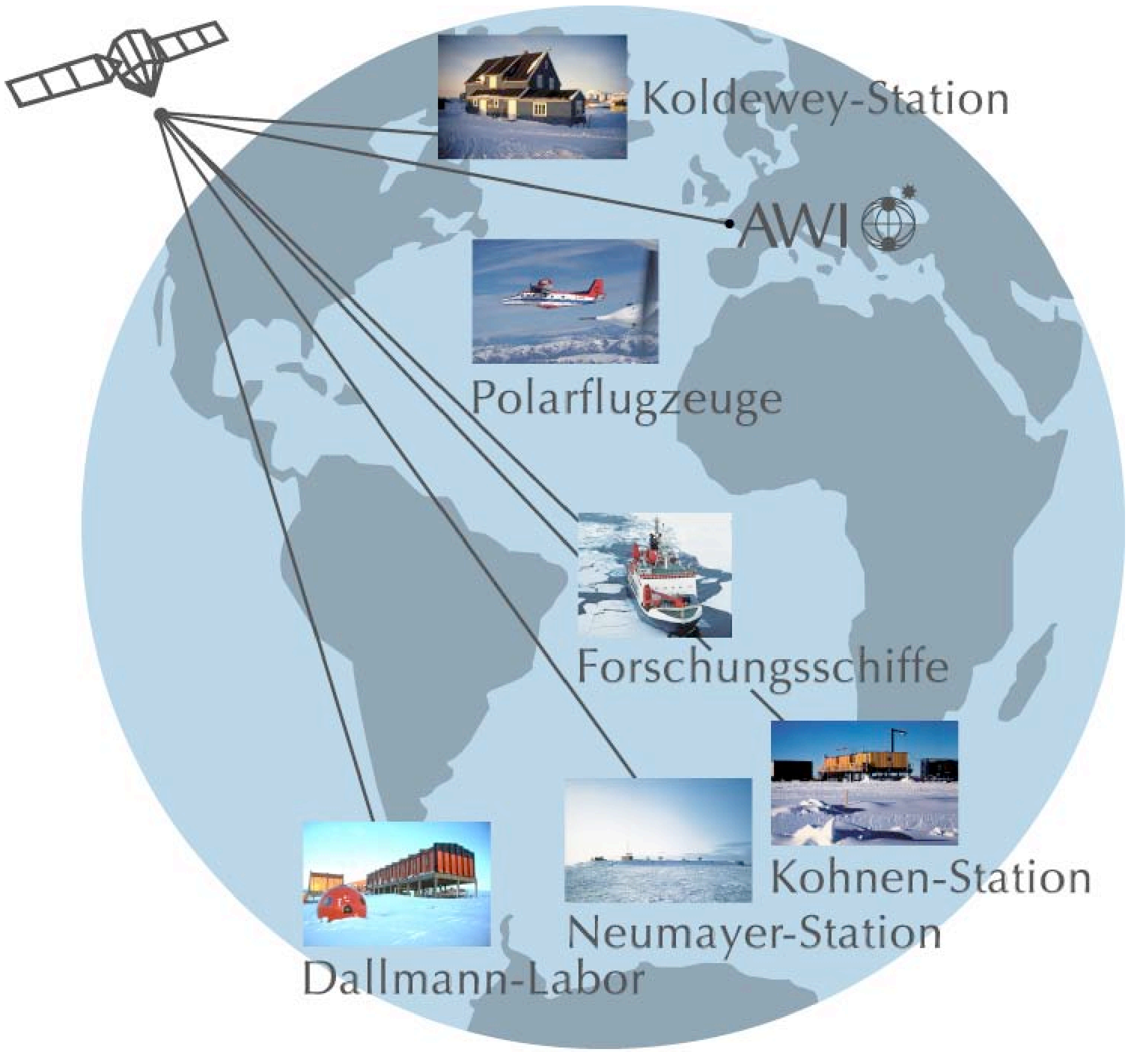
Institute – Research platforms



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Sven Harig
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Florian Klaschka
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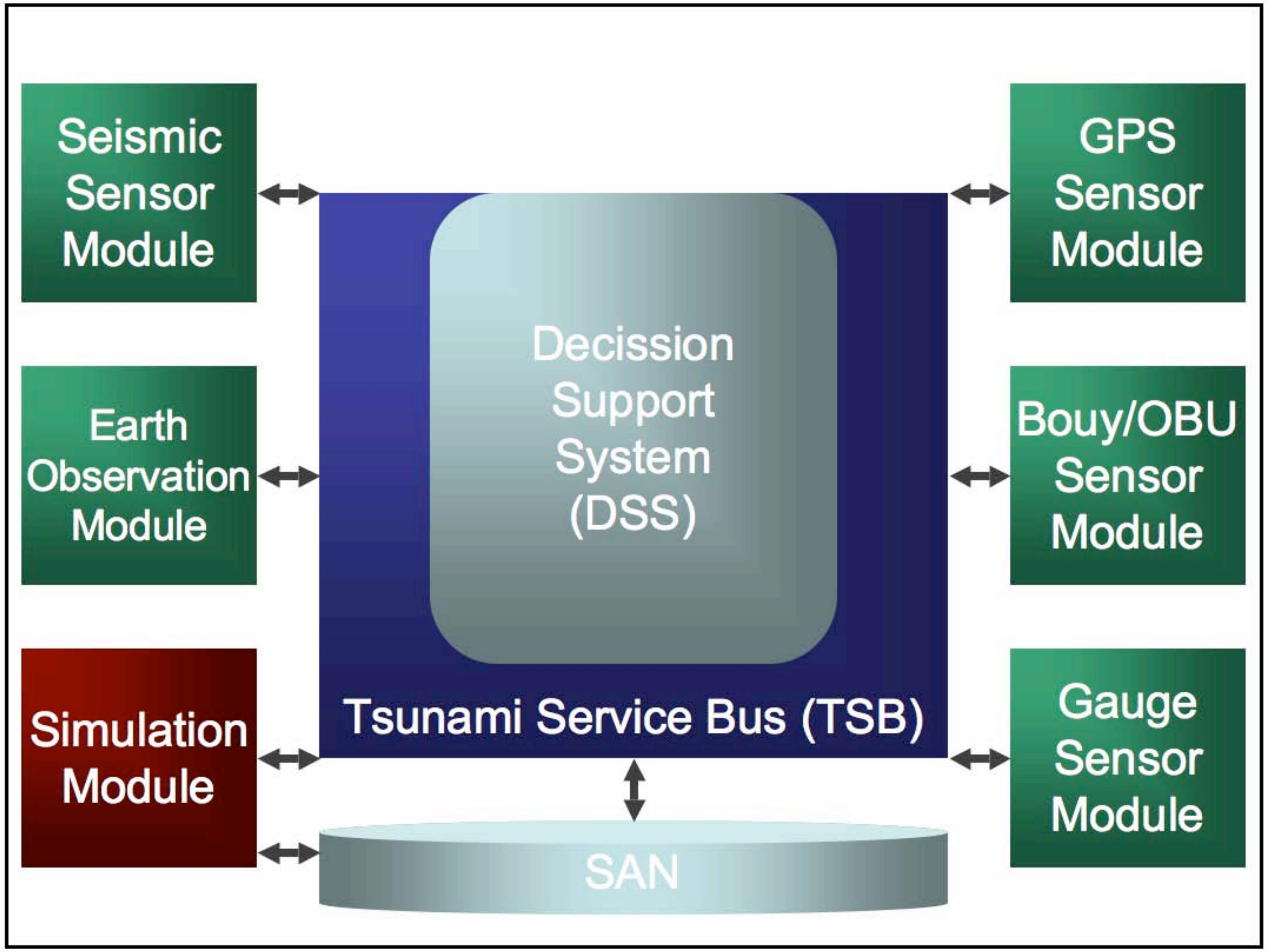
System Overview



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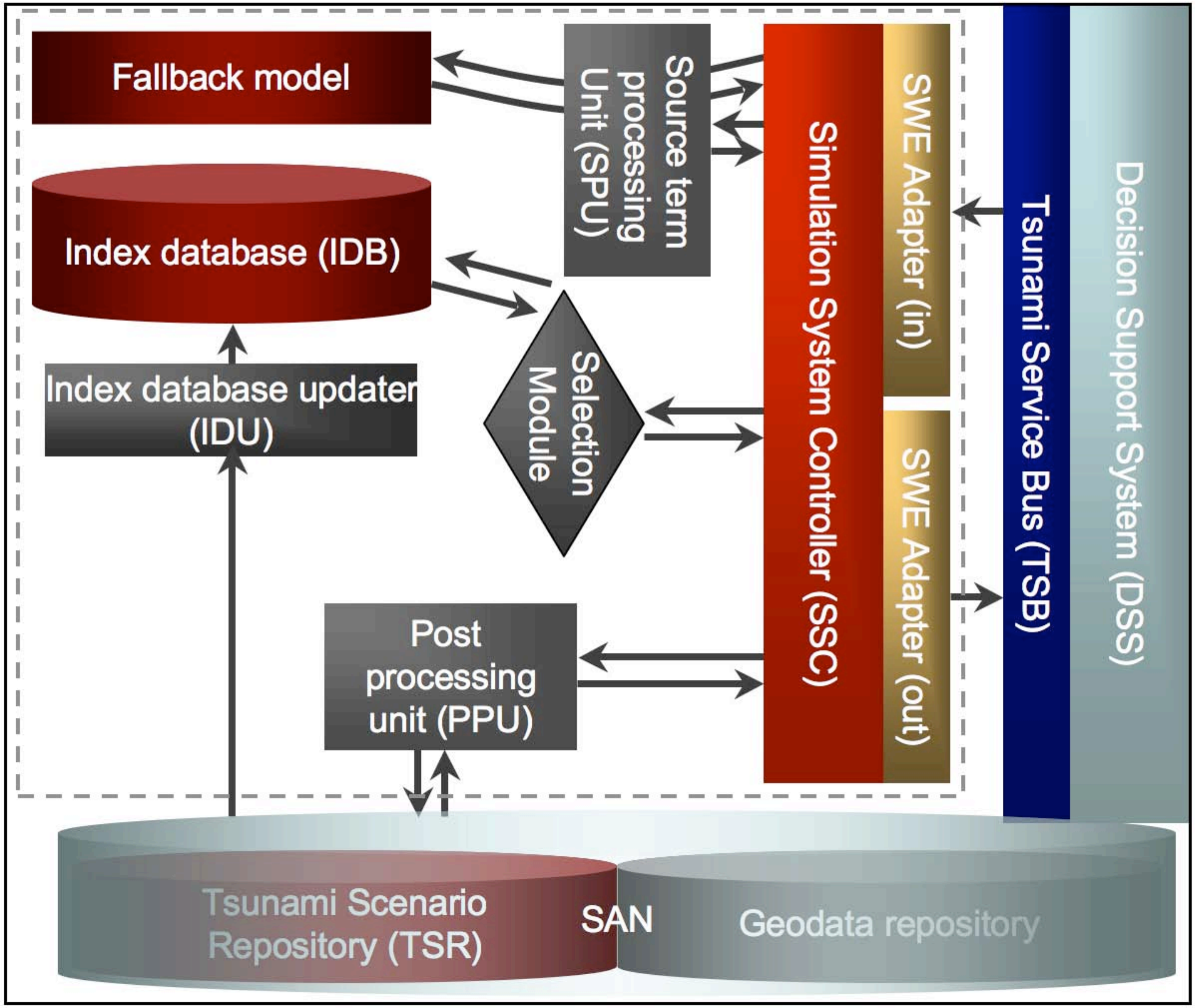
Simulation System



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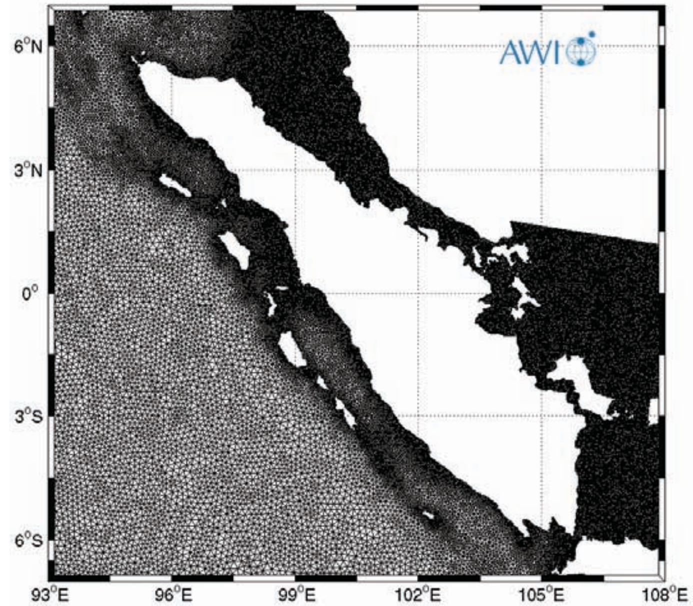
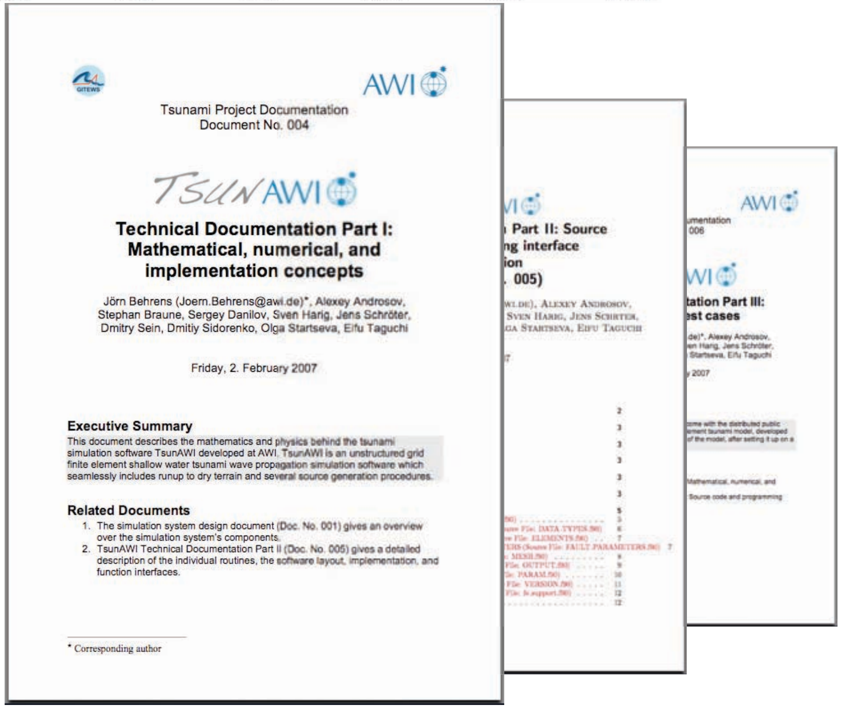
TsunAWI

- Unstructured mesh
- Finite elements
- Non-linear shallow water eq.
- With run-up/inundation
- Full set of documents
- License (GPL-like)
- First Evaluations (see below)

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Tsunami Project Documentation
Document No. 004

TsunAWI

Technical Documentation Part I: Mathematical, numerical, and implementation concepts

Jörn Behrens (Joern.Behrens@awi.de)*, Alexey Androsov, Stephan Braune, Sergey Danilov, Sven Harig, Jens Schröter, Dmitry Sein, Dmitiy Sidorenko, Olga Startseva, Eifu Taguchi

Friday, 2. February 2007

Executive Summary

This document describes the mathematics and physics behind the tsunami simulation software TsunAWI developed at AWI. TsunAWI is an unstructured grid finite element shallow water tsunami wave propagation simulation software which seamlessly includes runup to dry terrain and several source generation procedures.

Related Documents

1. The simulation system design document (Doc. No. 001) gives an overview over the simulation system's components.
2. TsunAWI Technical Documentation Part II (Doc. No. 005) gives a detailed description of the individual routines, the software layout, implementation, and function interfaces.

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2D shallow water equations

Shallow water equations used in TSUNAWI

Continuity equation

$$\frac{\partial h}{\partial t} + \nabla \cdot (\vec{v}(h+H)) = 0$$

Momentum equation

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} + f \times \vec{v} + g\nabla h + \frac{C_d \vec{v}|\vec{v}|}{\rho(h+H)} - \nabla \cdot (A_h \nabla \vec{v}) = 0$$

- Advection term: $(\vec{v} \cdot \nabla)\vec{v}$
- Coriolis term: $f \times \vec{v}$
- "Pressure gradient": $g\nabla h$
- Bottom friction: $\frac{C_d \vec{v}|\vec{v}|}{\rho(h+H)}$
- Viscosity term: $\nabla \cdot (A_h \nabla \vec{v})$

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2D shallow water equations

Boundary conditions used in TSUNAWI

Radiation boundary condition (open/liquid boundary)

$$\vec{v} \cdot \vec{n} = \sqrt{\frac{g}{h+H}}h$$

No-slip boundary condition (solid boundary)

$$\vec{v} \cdot \vec{n} = 0$$

Note: inundation boundary conditions according to Lynett/Wu/Liu (2002)

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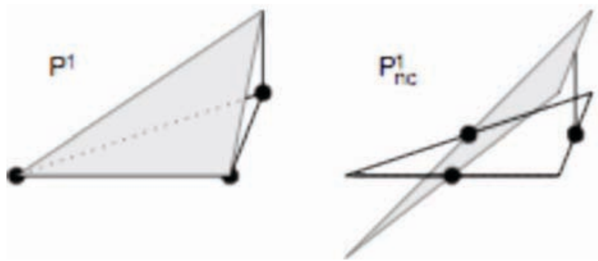
Variational form of SWE II

Basis functions:



Conforming linear for h and H:

$$\hat{h}: \quad \hat{h}_1 = 1 - x - y; \; \hat{h}_2 = x; \; \hat{h}_3 = y$$

Non-Conforming linear for v

$$\hat{v}: \quad \hat{v}_1 = 1 - 2y; \; \hat{v}_2 = 2x + 2y - 1; \; \hat{v}_3 = 1 - 2x$$

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Variational form of SWE III

Continuity equation:

Expand with linear conforming basis

$$\int_\Omega \frac{\partial h}{\partial t}\hat{h} - (h+H)\vec{v}\cdot\nabla\hat{h}\; d\Omega + \oint_{\partial\Omega}(h+H)\hat{h}\vec{v}\cdot\vec{n}\; ds = 0 \quad \forall\hat{h}$$

Ritz-Galerkin form (and other simplifications):

$$\sum_{i=1:N}\int_{\mathrm{supp}(\hat{h}_i)} h_i\frac{\partial\hat{h}_i}{\partial t}\hat{h}_j - (h+H)_i\hat{h}_i\vec{v}_i\cdot\nabla\hat{h}_j\; d\Omega +$$
$$+\sum_{i=1:N}\oint_{\partial\Omega\cap\mathrm{supp}(\hat{h}_i)\neq\emptyset}\sqrt{g(h+H)_i}\hat{h}_i\hat{h}_j\; ds = 0 \quad \forall j=1:N$$

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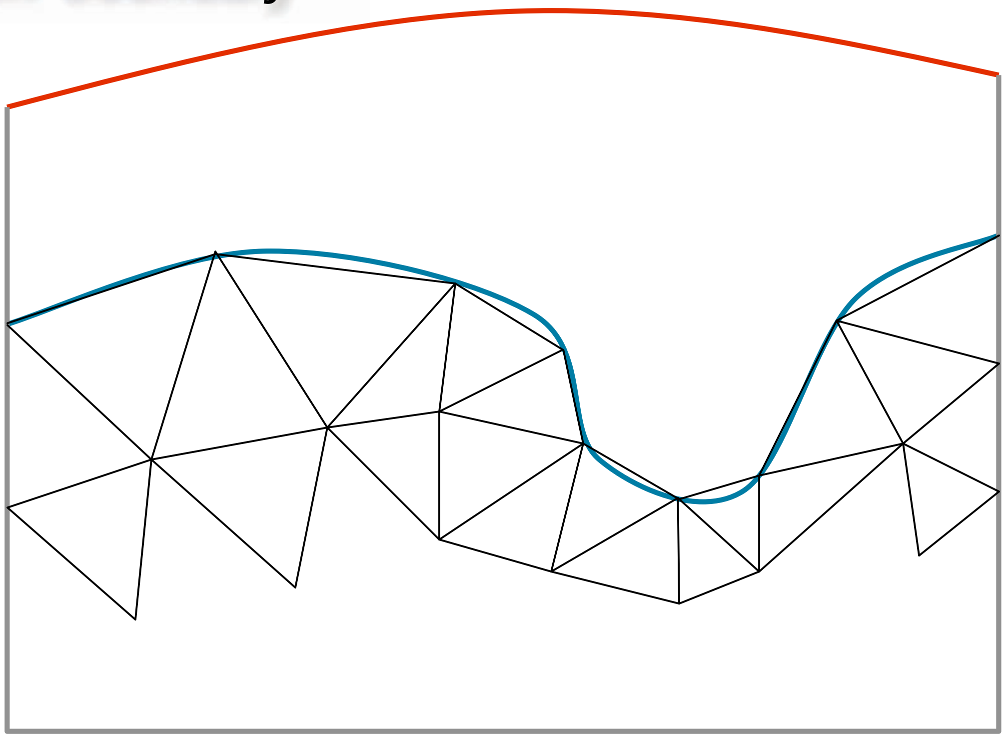
Grid generation I

Input:

- Coastline
- 50 m terrain isoline
- Bathymetry
- Topography
- Domain boundary



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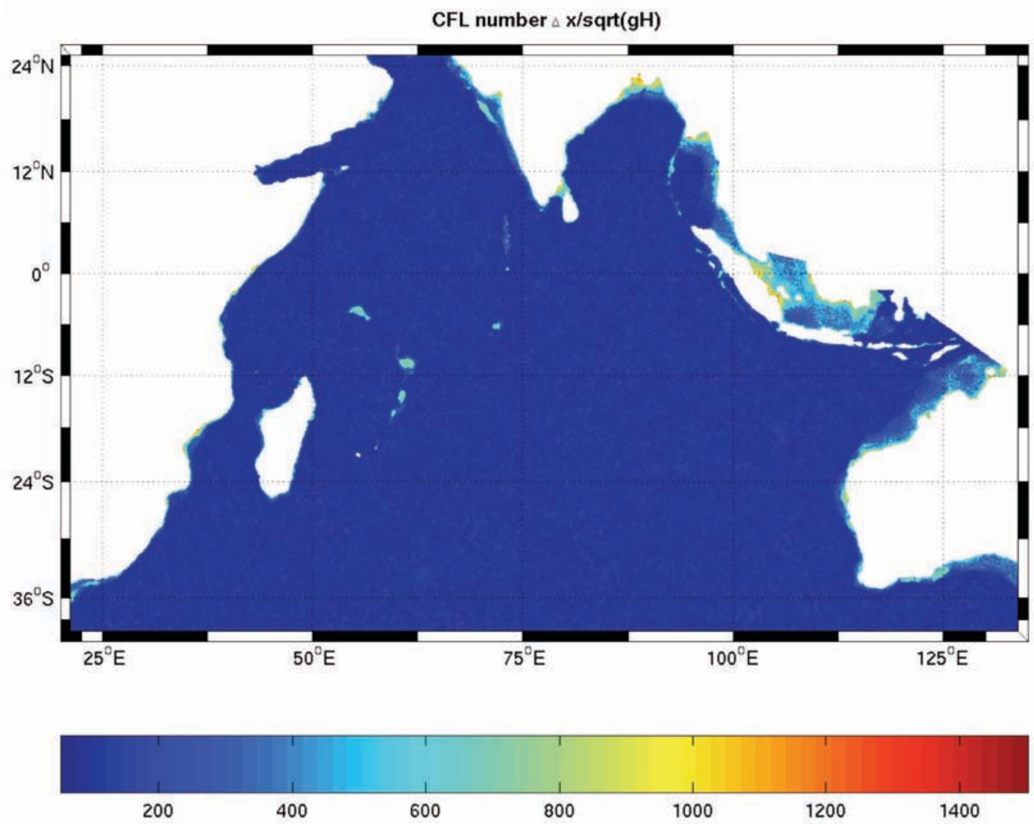
Grid generation II

Refinement criteria:

$$\sqrt{gH} \approx C_{\text{grid}} h$$

$$\nabla H \approx C_{\text{grad}} h$$

Mesh size: h



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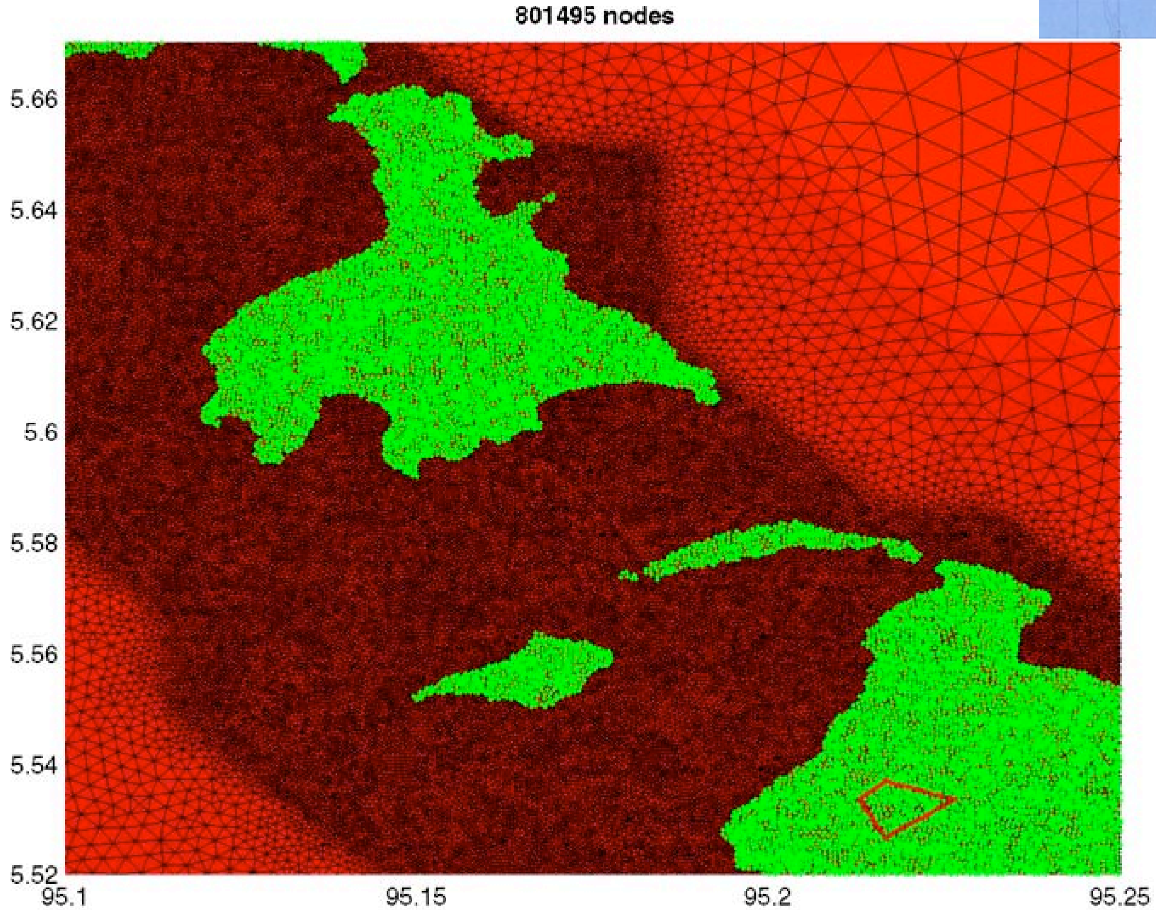
Grid Generation III

Gebco with SRTM land mask corrected



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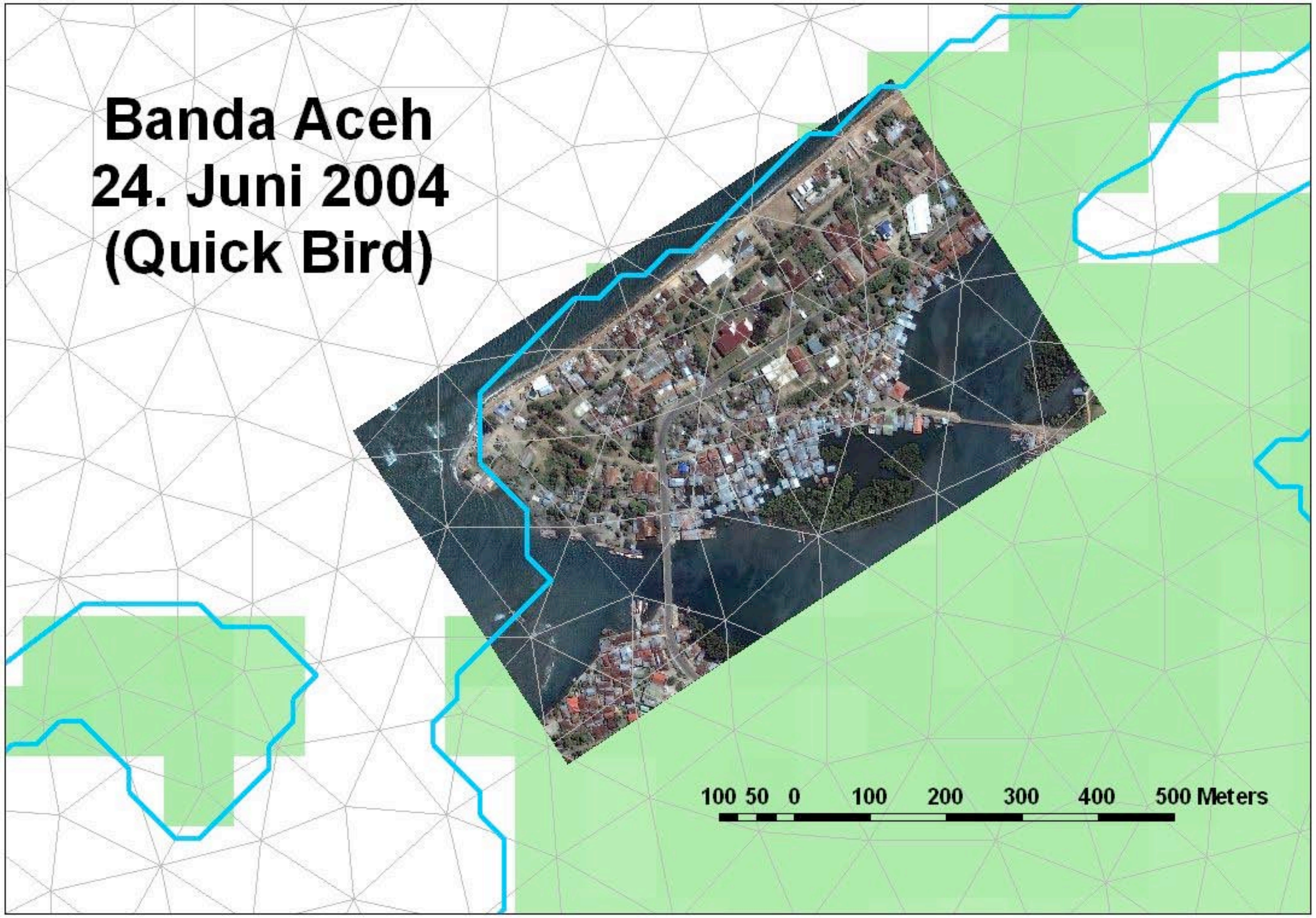
Grid Generation IV

Result (viewed locally)



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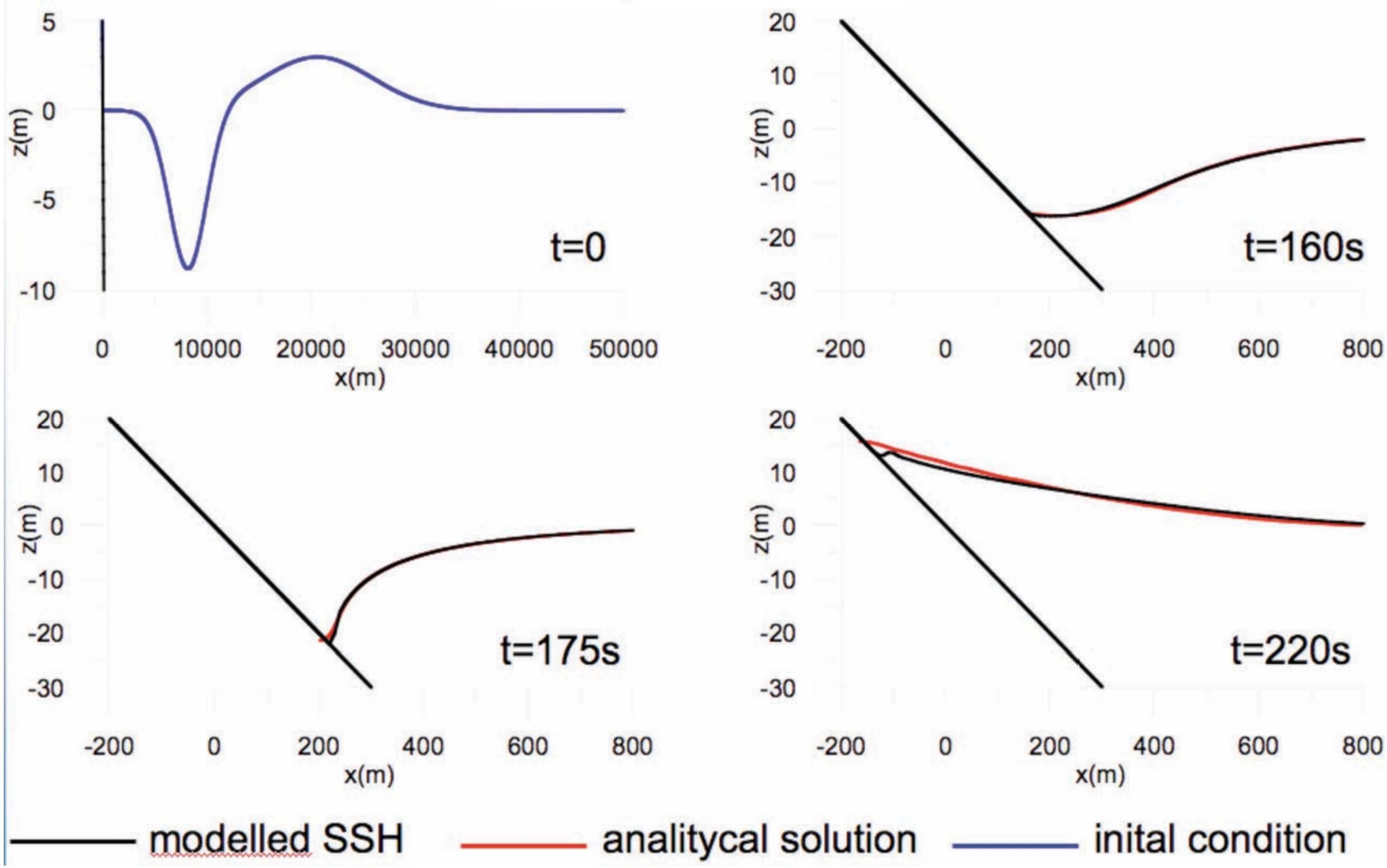
TsunAWI Validation

Run-up Benchmark



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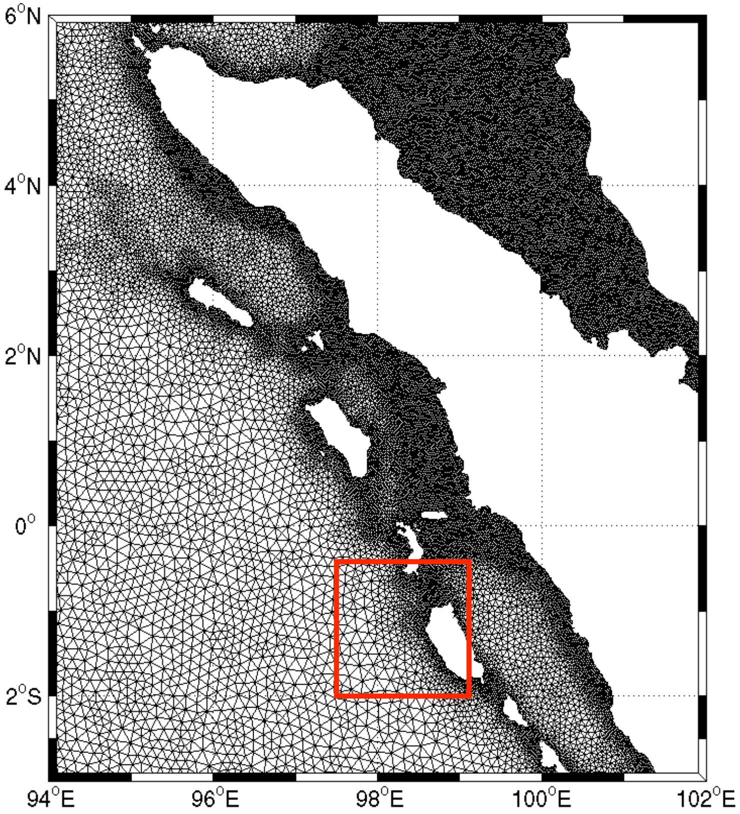
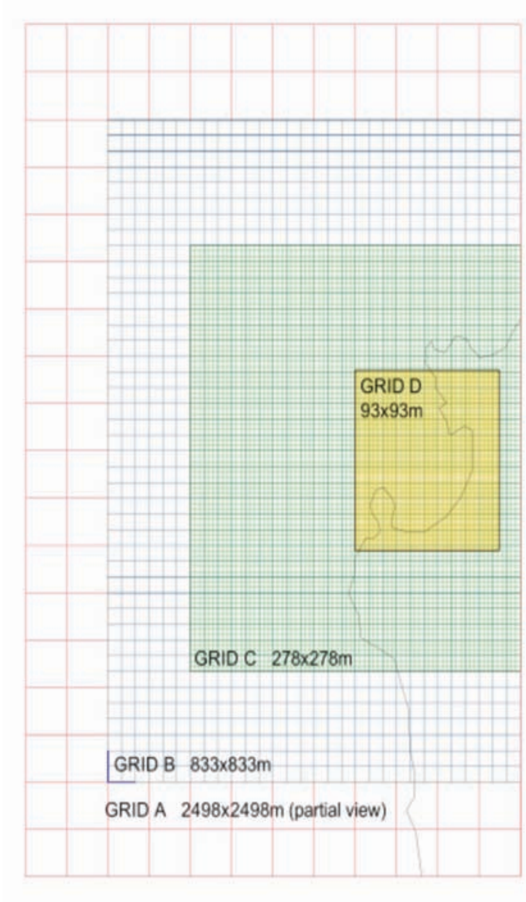
TsunAWI vs. Tunami-N3

TsunAWI



Resolution:
generally 200 m-10 km
in Aceh and Padang: 80 m

Tunami-N3



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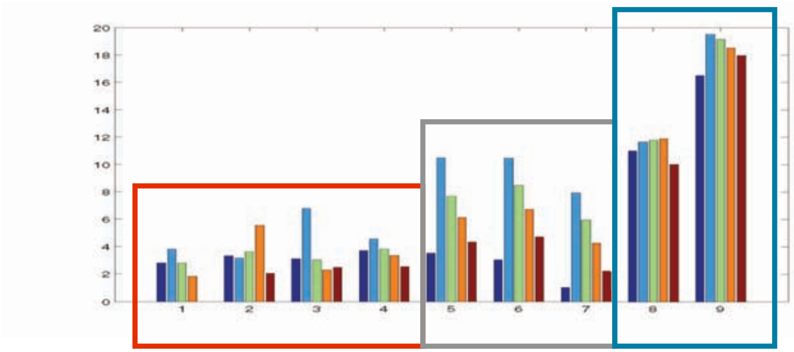
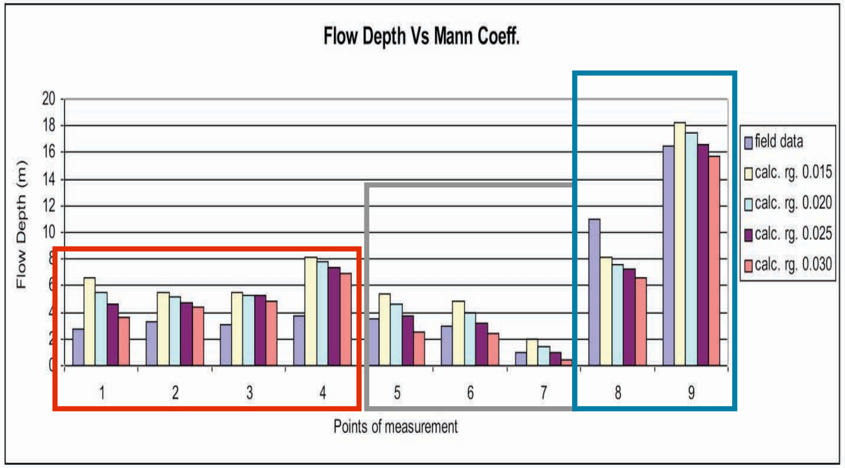
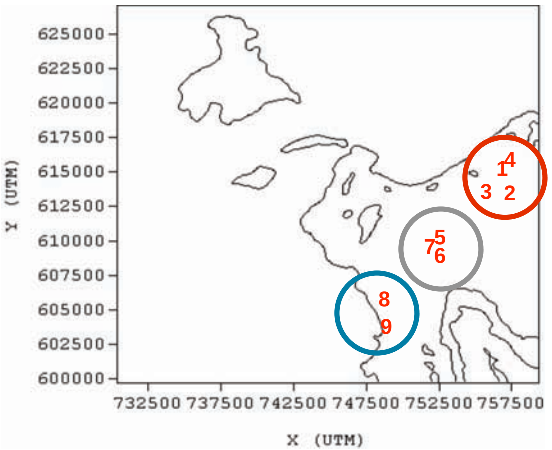
TsunAWI vs. Tunami-M3

TSUNAWI

Tsunami-M3







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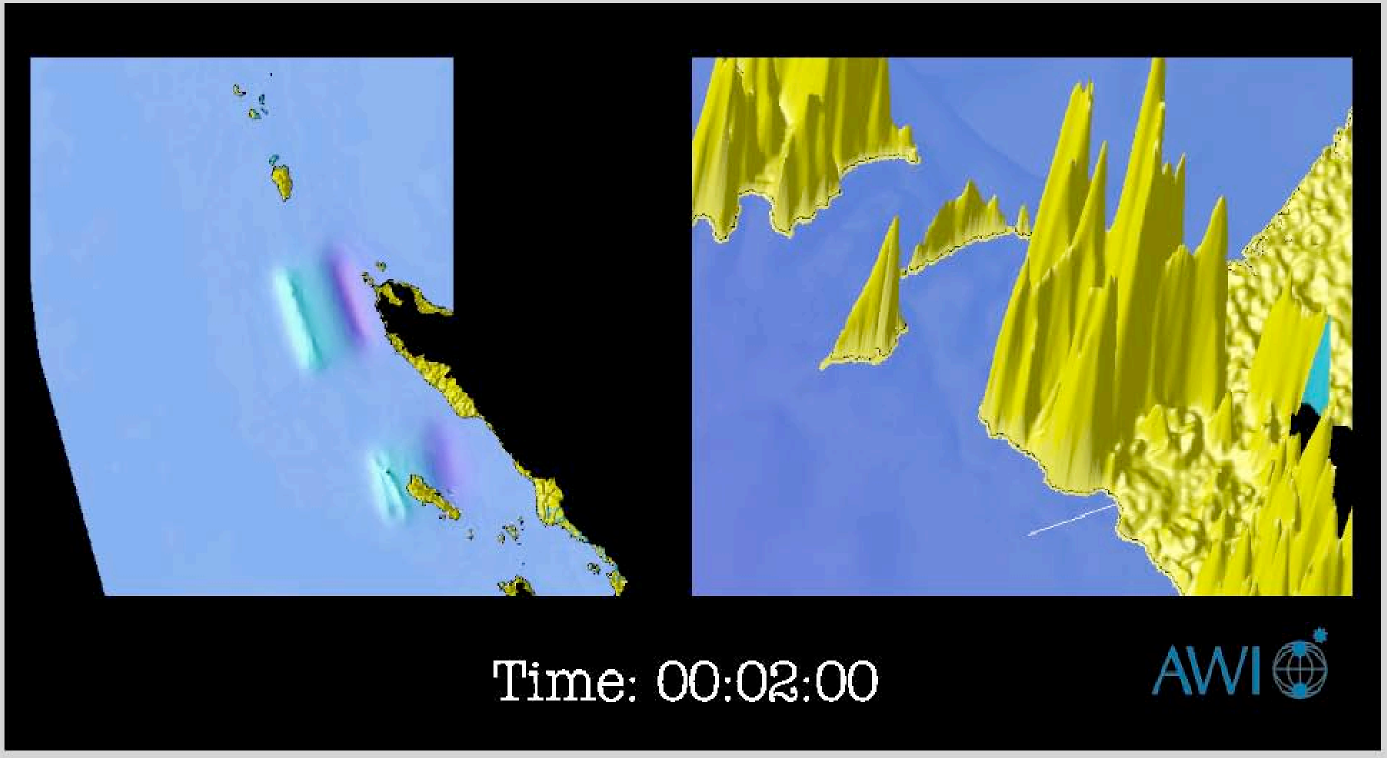
TsunAWI Animation

TSUNAWI



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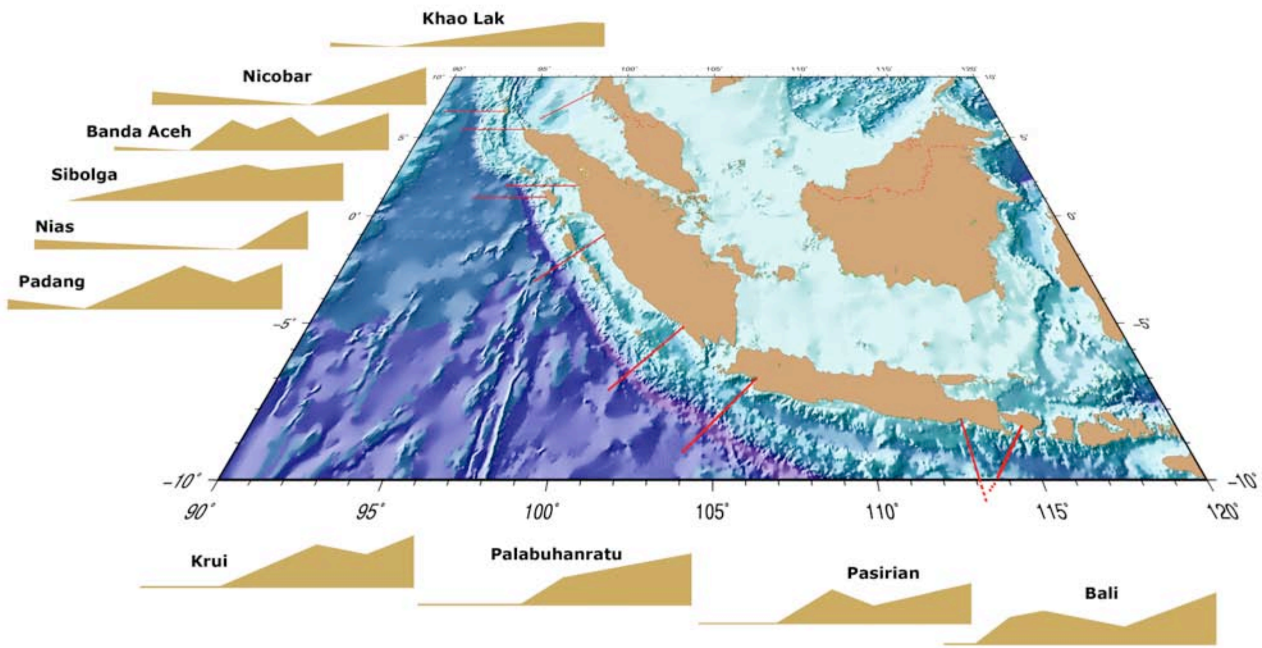
High Resolution Modeling

OUTLINE

Modeling the propagation, transformation, and run-up of tsunami waves in analytical test areas and selected „real“ areas with model systems

MIKE 21 HD (shallow water equations, amplitude dispersion) and

MIKE 21 BW (Boussinesq, amplitude and frequency dispersion, extended by a breaking wave model)



Map with linearized depth profiles (length: 375 km) at 10 pre-selected model areas

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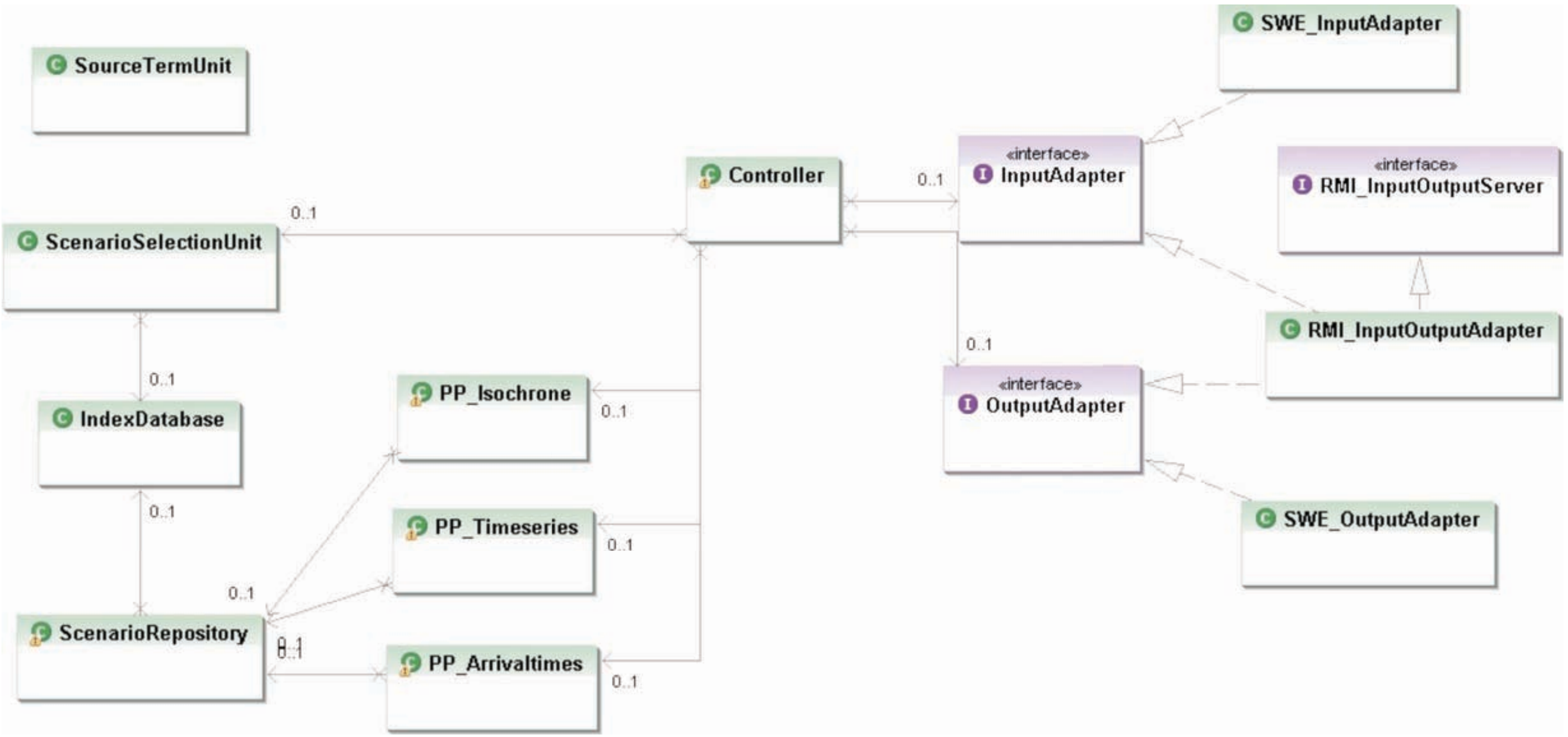
Framework

Java Implementation of Framework (delivered 26/02/07)



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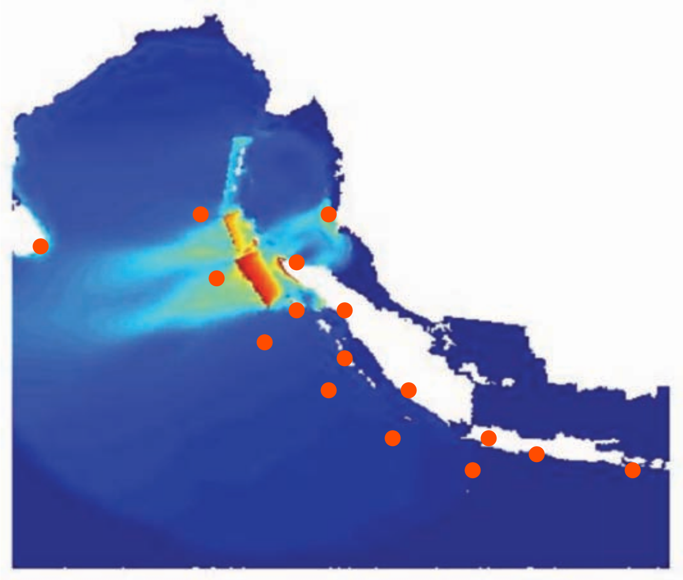
Indexing

Indexed positions:

- Seismic parameters
- Buoy positions
- GPS sensor positions
- Gauge positions
- Positions of interest

Indexed values:

- Epicenter, Magnitude
- Gauge time series
- GPS rupture vectors
- Wave heights
- Arrival times



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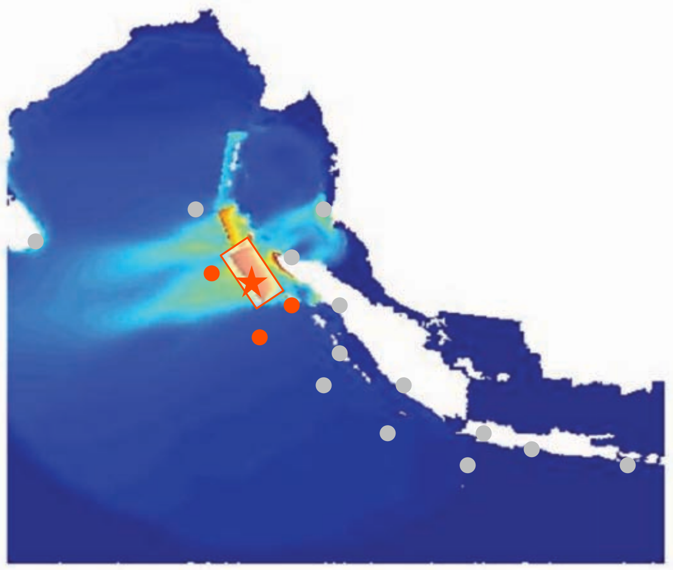
Selection

Comparison Data:

- Epicenter, Magnitude $(\lambda, \phi) + M$
- Gauge time series $\mathrm{ssh}_{\lambda,\phi}(t)$
- GPS rupture vectors $\vec{x}_{\lambda,\phi}$
- Wave heights $\mathrm{ssh}_{\lambda,\phi}(t_i)$
- Arrival times $t_{\lambda,\phi}$



Example:

$$(\lambda^0, \phi^0) + M^0$$

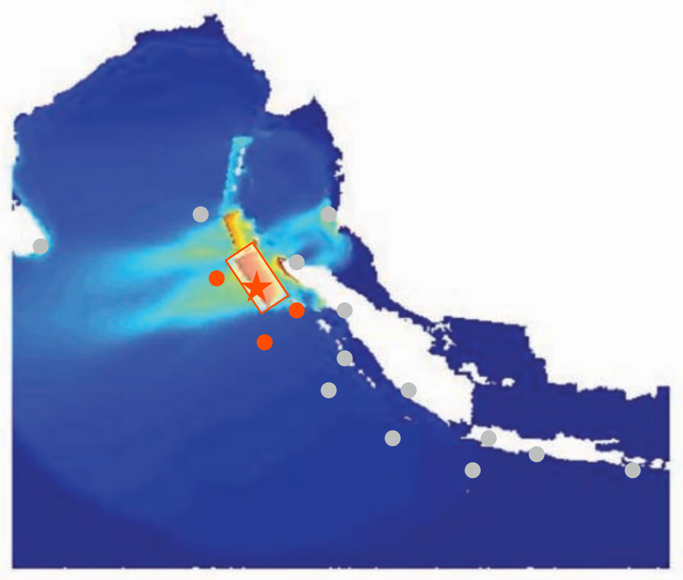
$$\mathrm{ssh}_{\lambda^i,\phi^i}(t) \qquad i = 1:3$$

Best fit

Given:

$$(\lambda^0, \phi^0) + M^0$$

$$\mathrm{ssh}_{\lambda^i,\phi^i}(t) \quad i = 1:3$$



Best fit in least squares sense:

$$\min_{\text{all scenarios } s} \Big[w_{\mathrm{loc}} \|(\lambda^0 -, \phi^0) - (\lambda^s, \phi^s)\|_2^2 + w_{\mathrm{mag}}(M^0 - M^s)^2 + \\ + w_{\mathrm{ssh}} \sum_i \|\mathrm{ssh}_{\lambda^i,\phi^i}(t) - \mathrm{ssh}^s_{\lambda^i,\phi^i}(t)\|_t^2 \Big]^{\frac{1}{2}}$$

$w_\star$, weights

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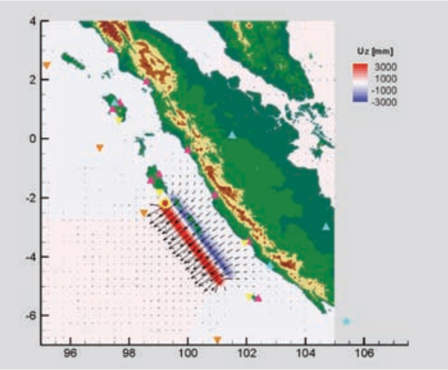
Use of multiple sensors

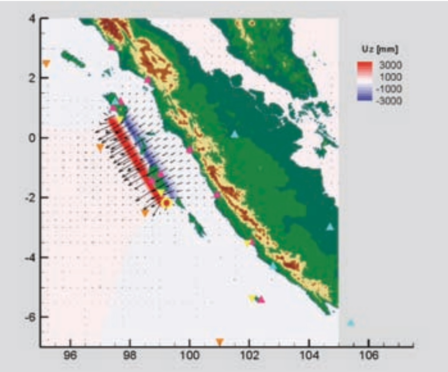
GITEWS

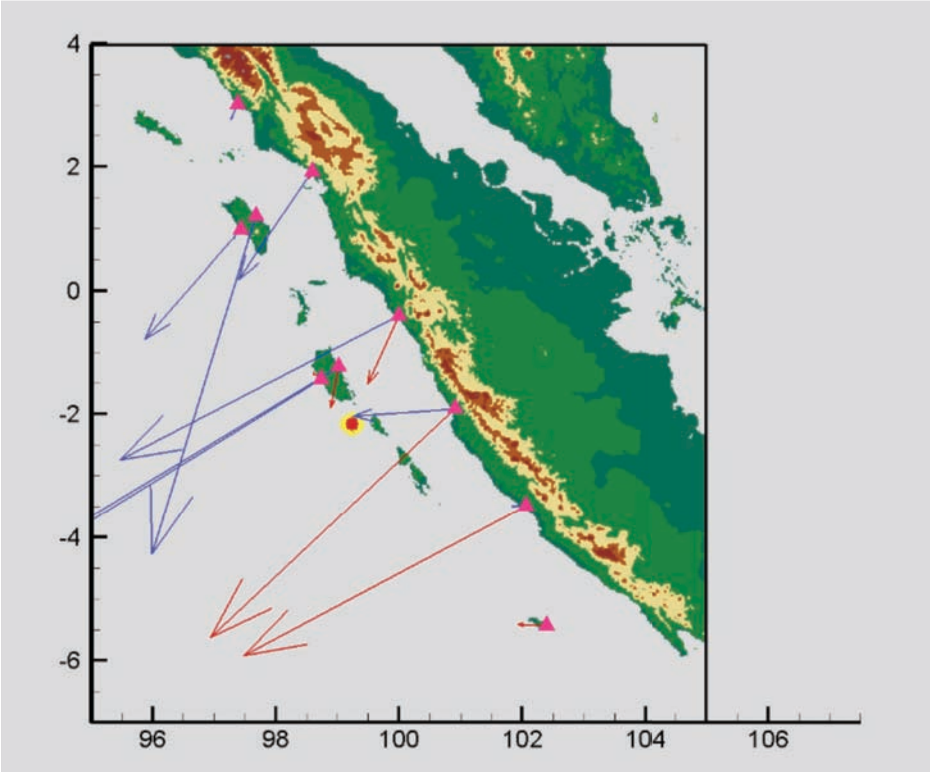
Bundesministerium für Bildung und Forschung

GeoForschungsZentrum Potsdam

Sophisticated source models (incl. deformation for GPS)







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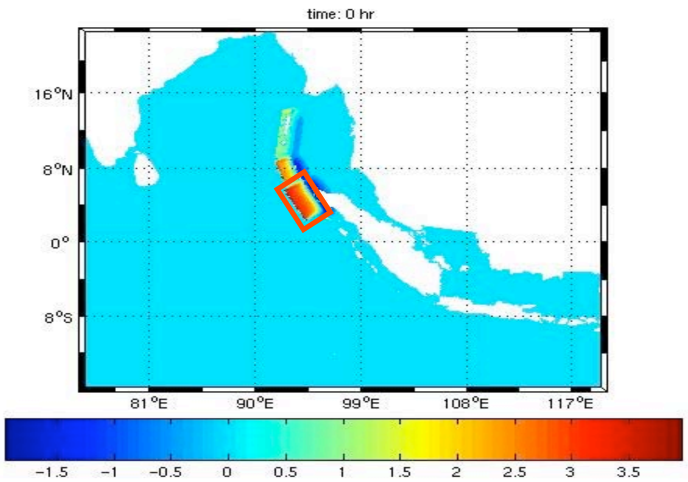
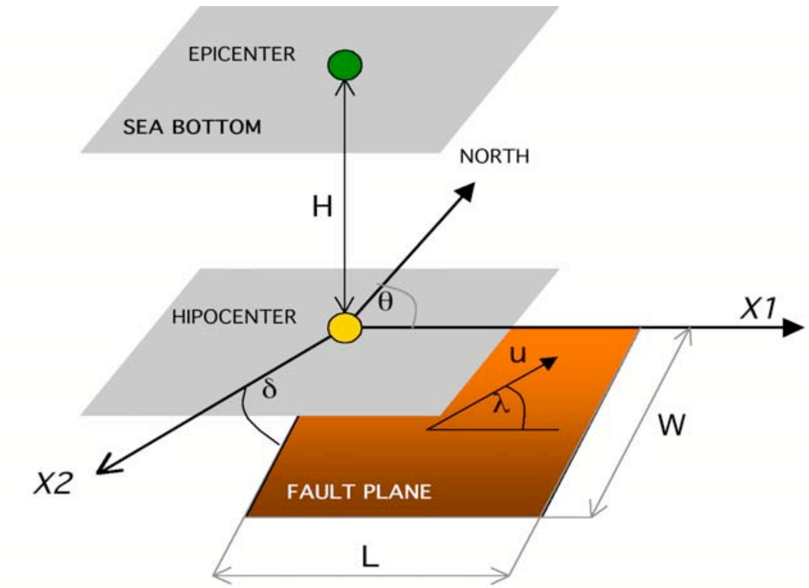
Sensitivity

Variation of fault plane





Parameter	Standard model	counter part
Slip amount	(14 m)	-4 m
Dip angle	(12 º)	+5 º
Strike angle	(-30 º)	-10 º
Rake angle	(120 º)	+10 º
Width	(200 km)	-50 km
Depth	(2 km)	+0.5 km
Location	(2.1 º)	0.5 º (to south)

Lay et al., Science, 2005

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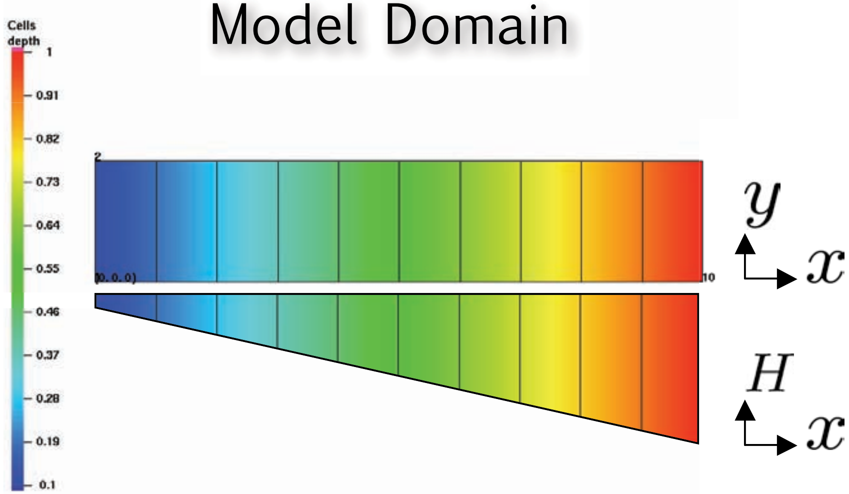
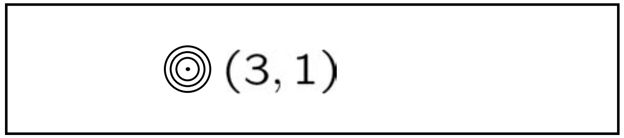
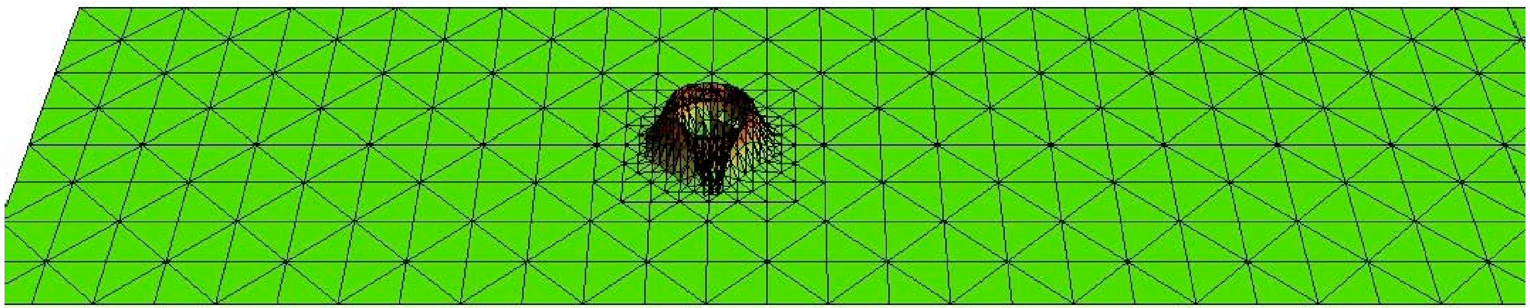
Future – Adaptive Mesh Refinement

Model Domain



Initial values





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TsunAWI Animation