Tsunami Modeling and Data Products for Early Warning

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Overview

The tsunami simulation code TsunAWI

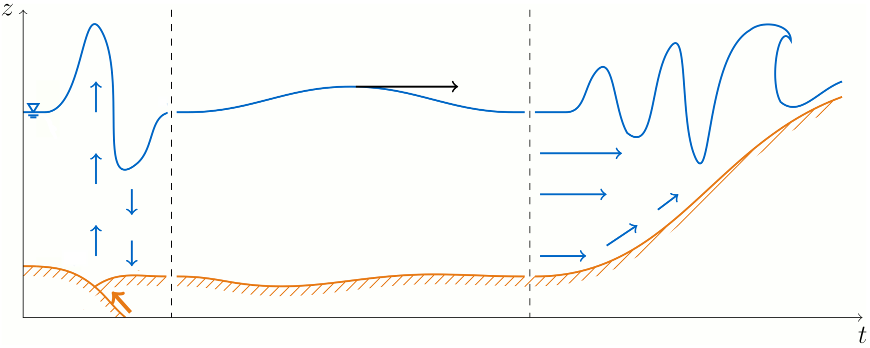
- Shallow water equations
- Numerical implementation in TsunAWI
- Verification, limitations

The Indonesian tsunami early warning system

- Basic concept
- The tsunami scenario database

The shallow water equations (SWE)

Phases of a tsunami

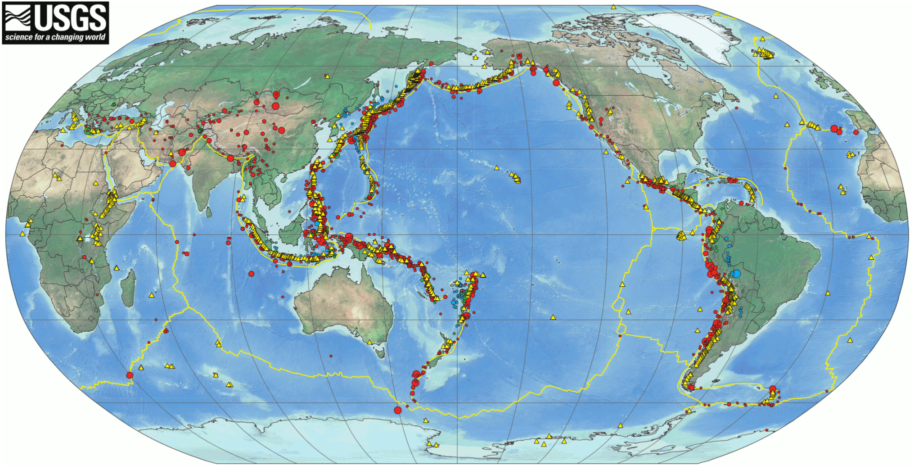


Origin | in deep water | at the coast

The shallow water equations (SWE)

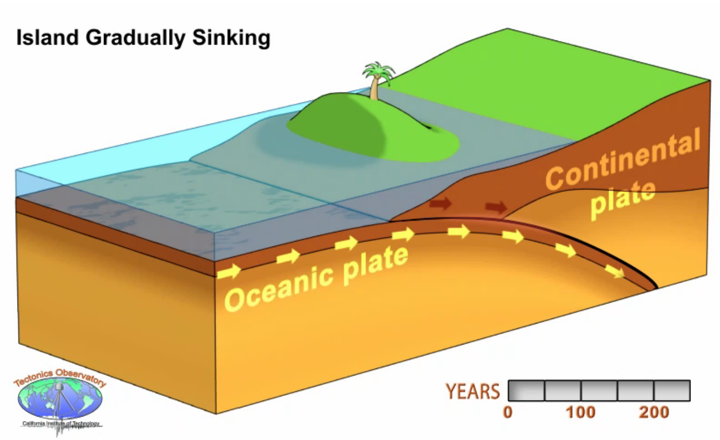
Phases of a tsunami: Origin

Plate Tectonics, Seismicity 1900-2012



The shallow water equations (SWE)

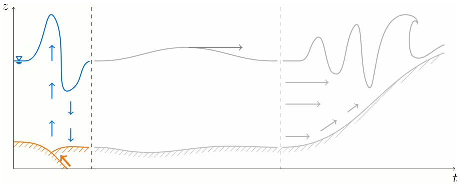
Phases of a tsunami: Origin



Courtesy: `http://www.tectonics.caltech.edu/outreach/animatic`

The shallow water equations (SWE)

Phases of a tsunami: Origin

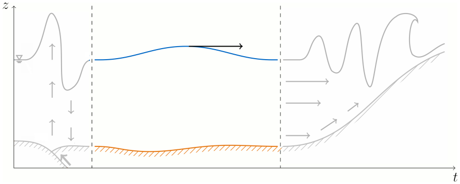


Model physics

- Complicated to simulate the full model physics
- Exact source often unknown - largest uncertainty in tsunami early warning!
- Simple approach: Add vertical bottom displacement to sea level. Works surprisingly well!

The shallow water equations (SWE)

Phases of a tsunami: Propagation in deep water



Model physics

- Shallow water equations
- Simple: Pressure gradient suffices
- Very fast models only simulate this phase

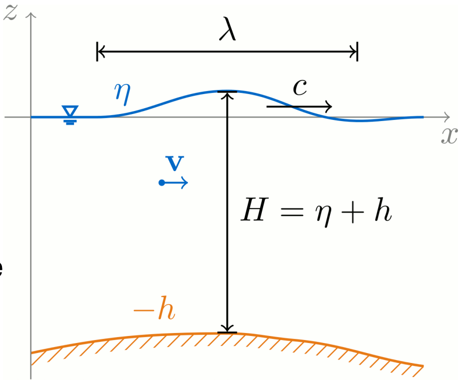
The shallow water equations (SWE)

Derived from the Navier Stokes Equations

with the assumptions

- $\lambda \gg H$,
- incompressible fluid,
- constant density ρ (neglect temperatur, salinity!),
- Vertical velocity constant in the water column.

$\Longrightarrow$ **vertical average**



The shallow water equations (SWE)

conservation of momentum

$$\frac{\partial \mathbf{v}}{\partial t} + \overbrace{g\nabla\eta}^{\text{pressure gradient}} + \overbrace{f\,\mathbf{k}\times\mathbf{v}}^{\text{Coriolis}} + \overbrace{(\mathbf{v}\cdot\nabla)\mathbf{v}}^{\text{non-lin. advection}} + \overbrace{\frac{r}{H}\mathbf{v}|\mathbf{v}|}^{\text{bottom roughness}} + \overbrace{\nabla(K_h\nabla\mathbf{v})}^{\text{viscosity}} = 0,$$

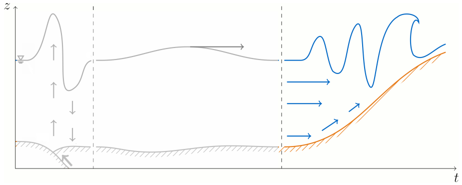
conservation of mass

$$\frac{\partial \eta}{\partial t} + \nabla\cdot(H\,\mathbf{v}) = 0$$

with Coriolis parameter f, coefficients for bottom roughness r and viscosity K_h.

The shallow water equations (SWE)

Phases of a tsunami: At the coast



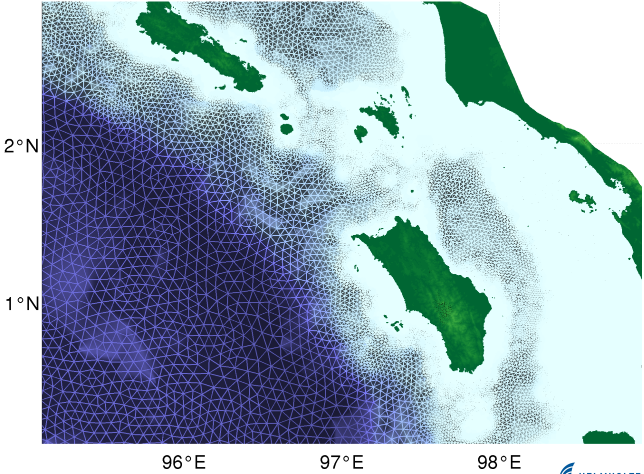
Model physics

- Shallow water equations stretched to the limit
- Very sensitive to bathymetry, topography, bottom roughness
- Compute intensive (high grid resolution, short timestep)
- Important for time series: Reflection at the coast
- Fast models assume border at 50m-100m depth, extrapolate wave height by Green's law: $\eta(1\text{m}) \approx \eta(x\text{m})\sqrt[4]{x}$

TsunAWI

The computational domain reflects the characterics of tsunamis:
Small triangles (50m-200m) at the coast,
large triangles in the deep ocean (up to 25km).

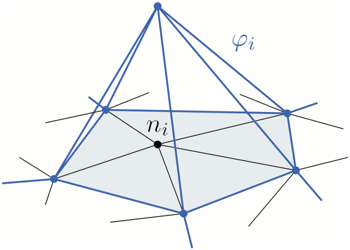
$$\Delta x \approx \min\left(\frac{c_{\text{CFL}}}{\sqrt{gH}}, \frac{c_{\text{bathy}}}{|\nabla H|}\right)$$



TsunAWI

Discretisation in space with finite elements

Triangulation $\mathcal{T}$ with N nodes $n_k \in \mathcal{N}$, $k = 1, \ldots, N$



Linear conforming basis functions

$$\varphi_i(\mathbf{x}(n_k)) = \delta_{ik}$$

TsunAWI

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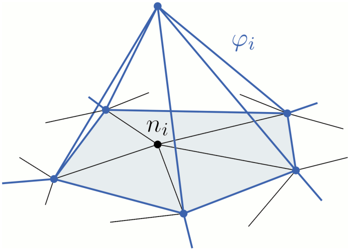

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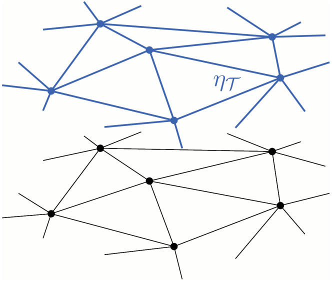
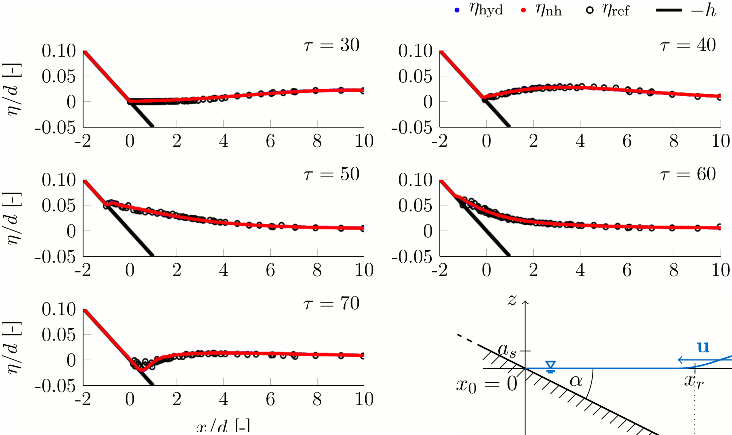


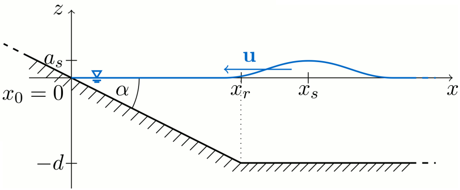
Approximate η as linear combination

$$\eta_\mathcal{T}(\mathbf{x}) = \sum_{i=1}^{N} \eta_i \varphi_i(\mathbf{x})$$

TsunAWI

Verification: Run-up on a sloping beach





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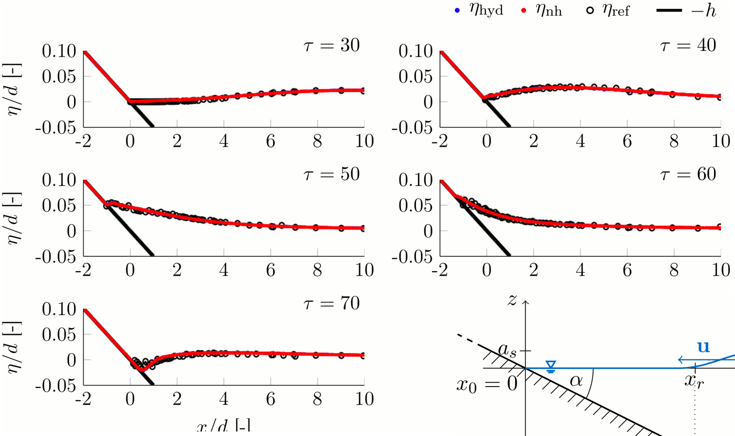
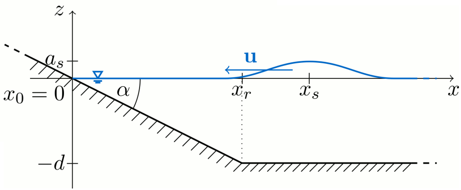


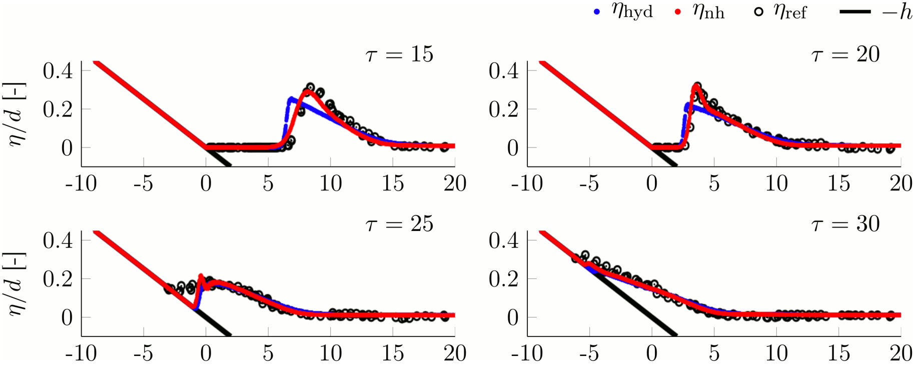


✓

TsunAWI

Verification: Run-up on a sloping beach

For higher initial waves, the hydrostatic shallow water equations are no longer valid. Furthermore, numerical errors occur.

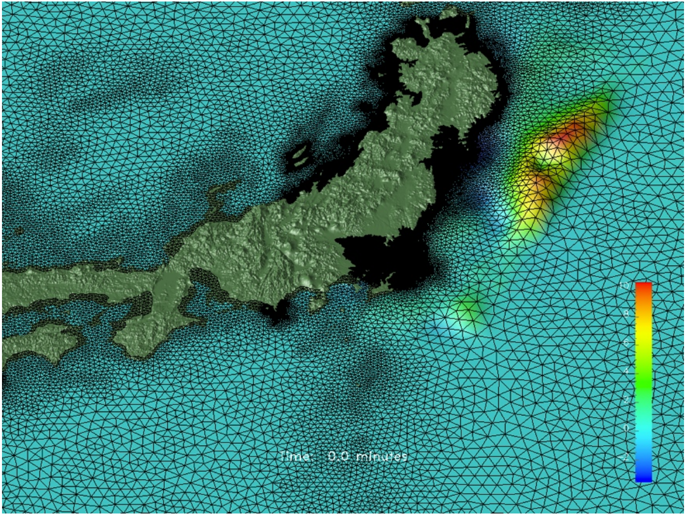


However, diagnostic variables like arrival time and maximum run up are still met well.

TsunAWI

Verification: Real event, Japan 2011

Source: USGS



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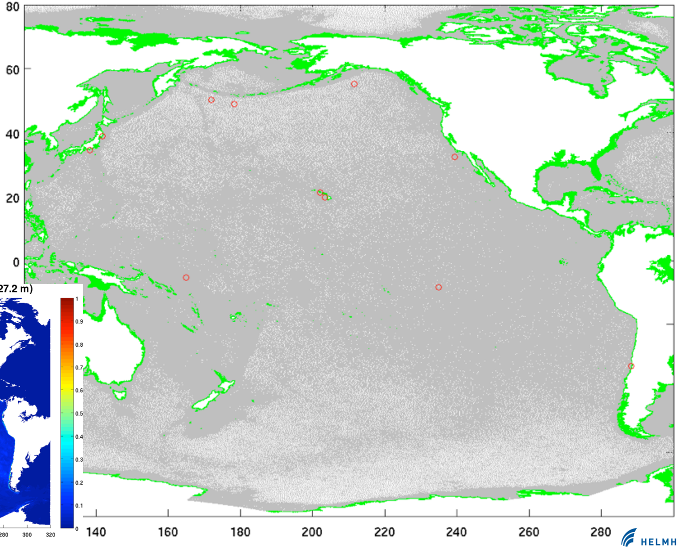

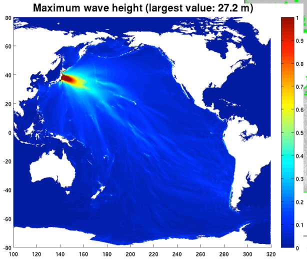

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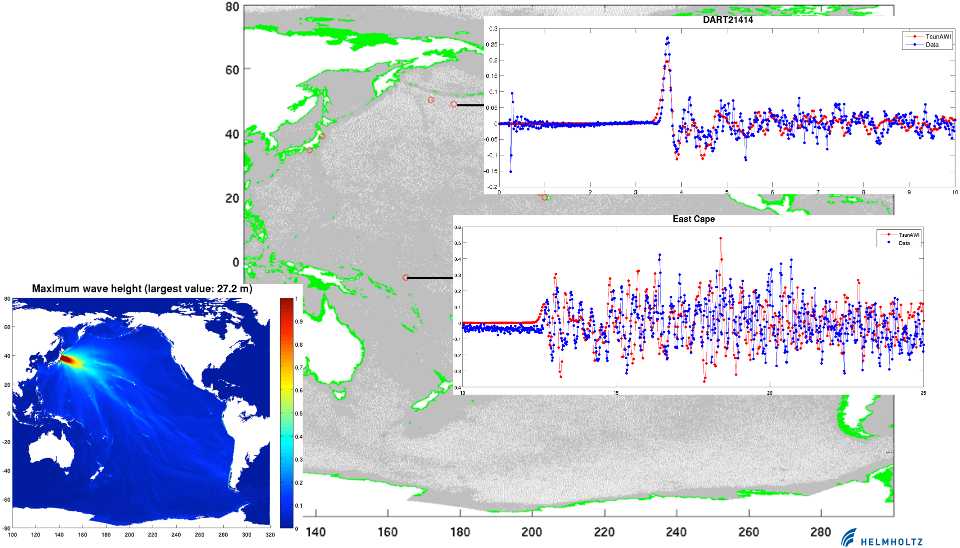

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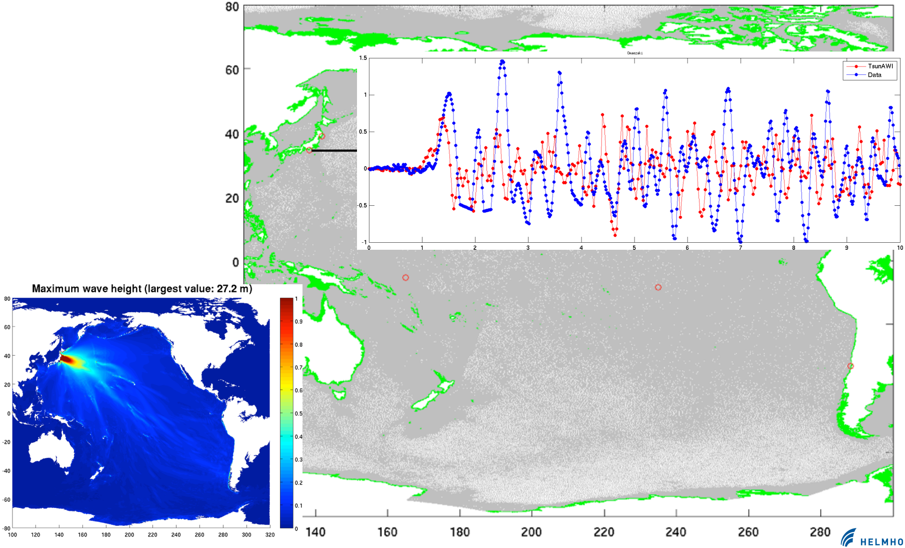

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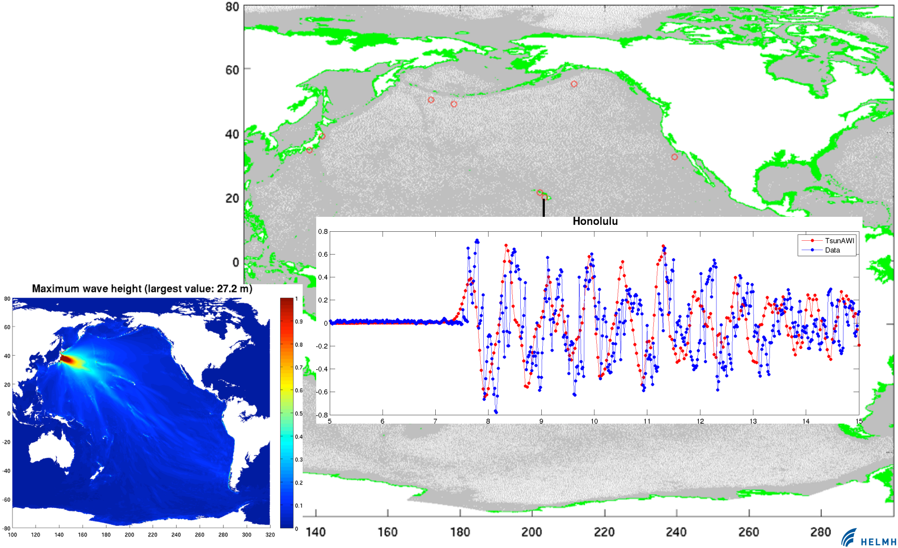

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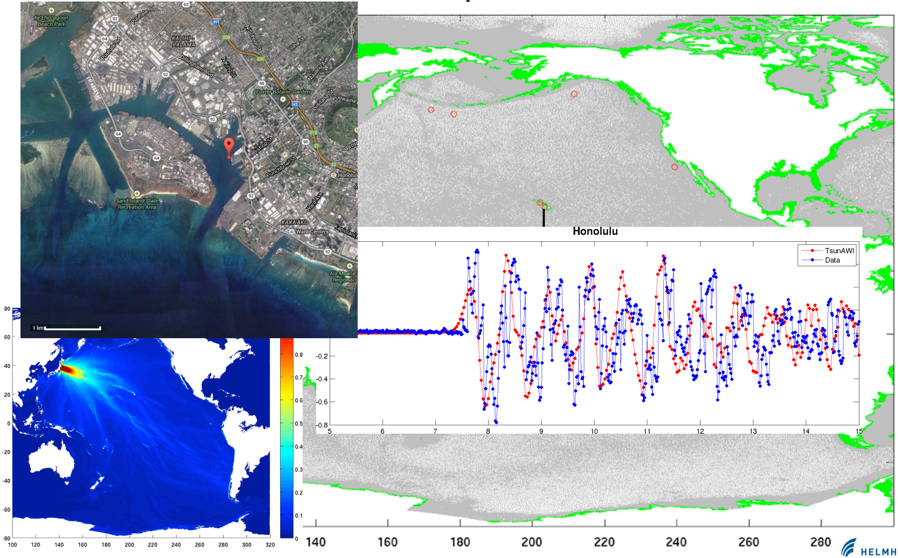

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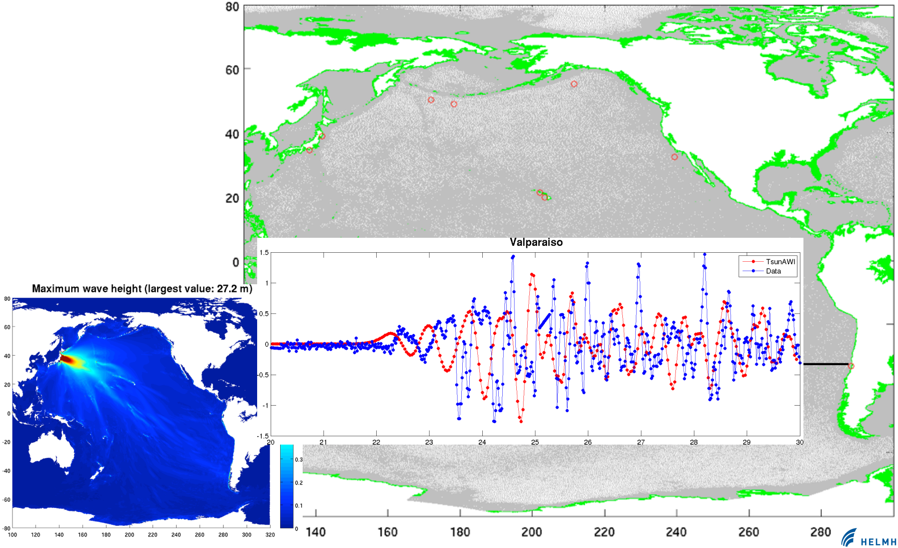

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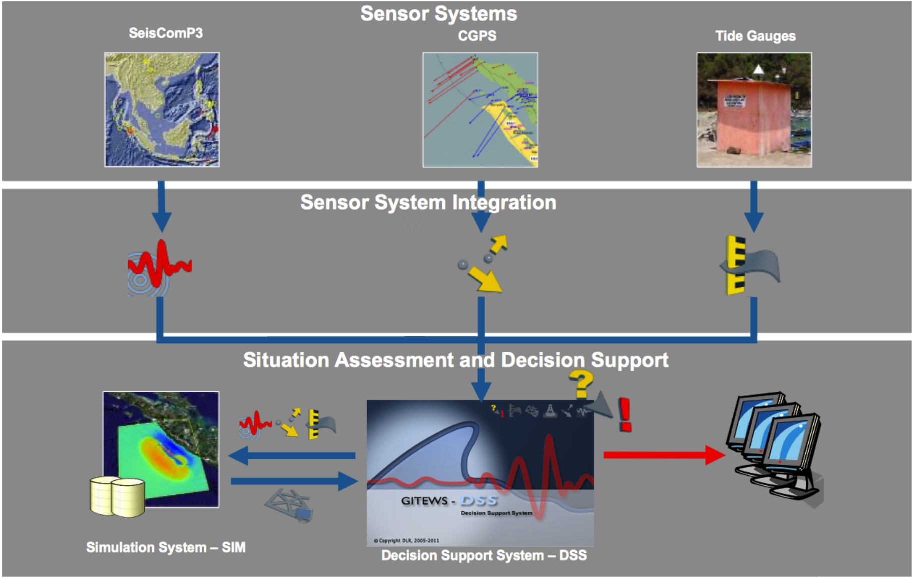
GITEWS System Overview

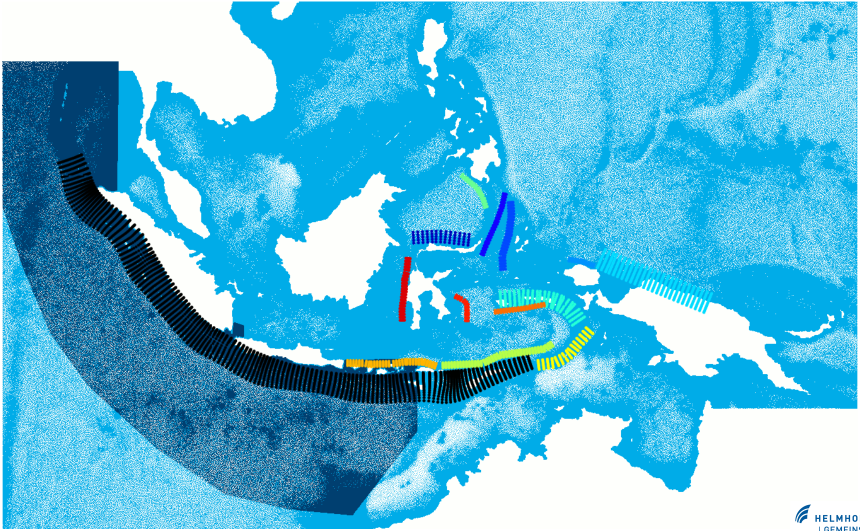
Warning Center Badan Meteorologi, Klimatologi dan Geofisika, Jakarta

GITEWS System Overview



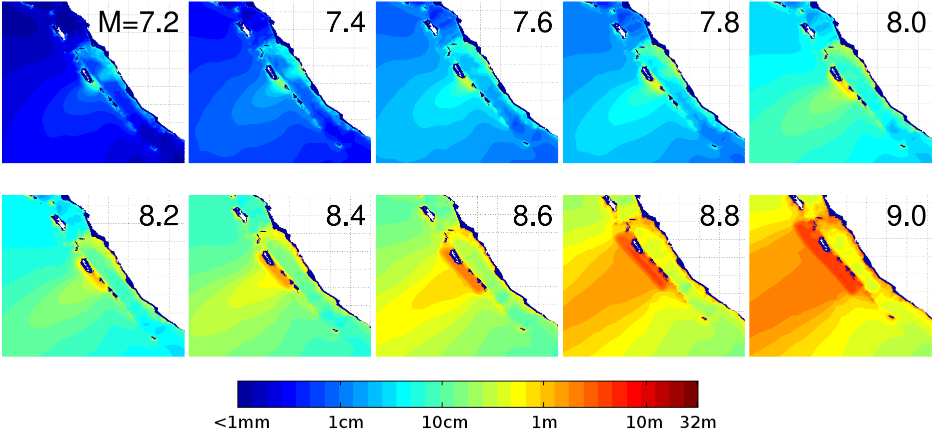
GITEWS System Overview

Model domain for scenarios 2011 and extension 2013



GITEWS System Overview

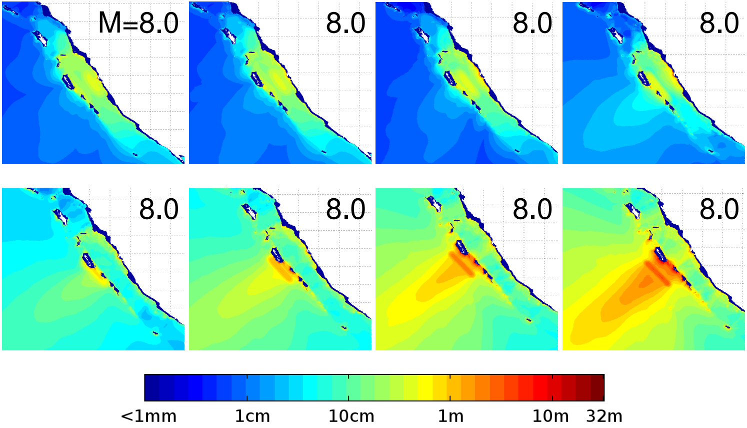
Earthquake magnitude and maximum amplitude



$M_w = \frac{2}{3}(\log_{10} M_0 - 9.1)$ with $M_0 = \mu d S$ [Nm], rigidity μ, displacement d, area of rupture S.

GITEWS System Overview

Epicenter location and maximum amplitude

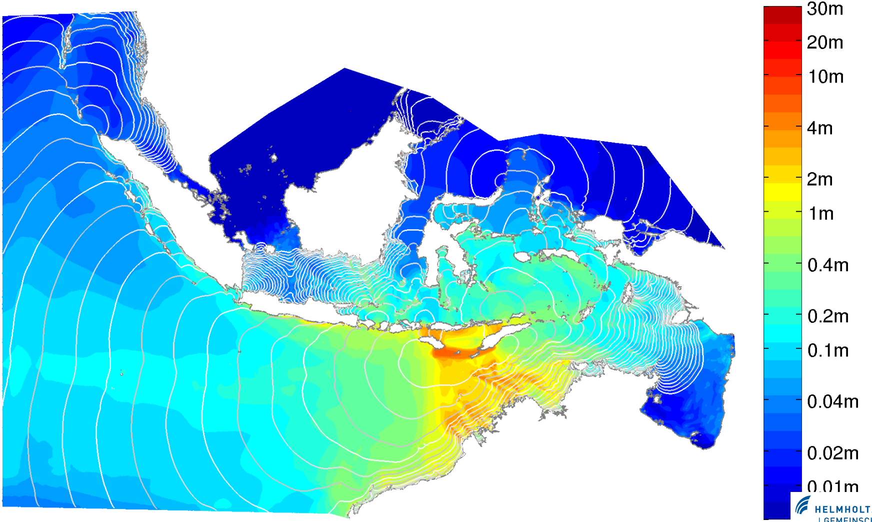


At the coast, epicenter at large depth in rigid rock (large μ),
at the trench, low epicenter in softer sediments and rock (small μ).

Scenario data products

ETA isochrones and maximum amplitude

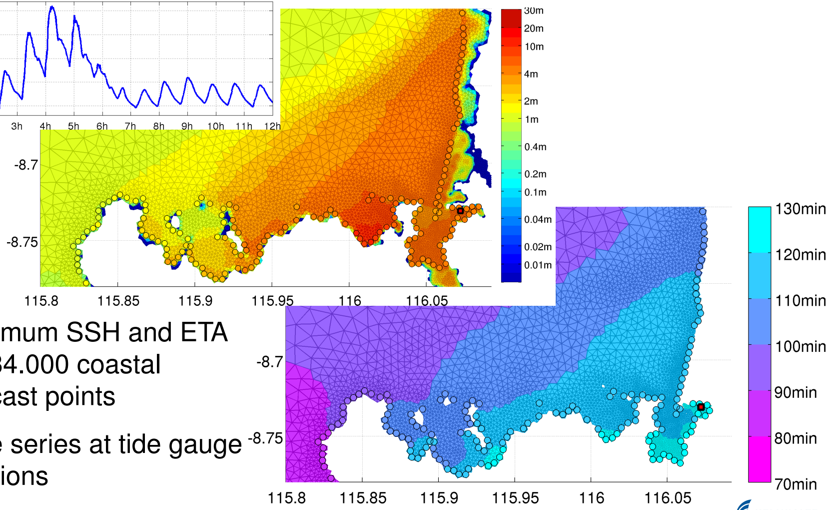
Example: Magnitude 9.0 in the Eastern Sunda Arc



Scenario data products

Coastal forecast points

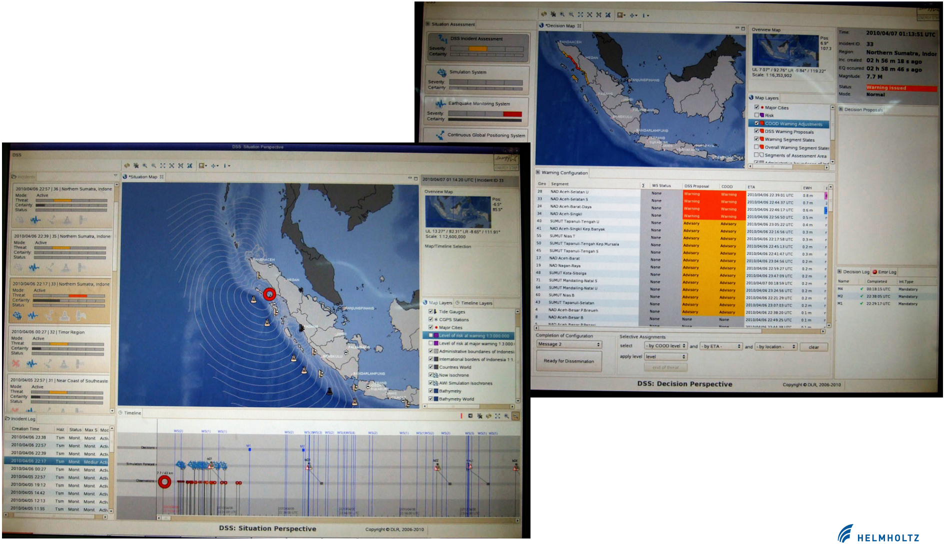
Example: Magnitude 9.0 in the Eastern Sunda Arc, zoom to Lembar, Eastern Lombok



- Maximum SSH and ETA at 134.000 coastal forecast points
- Time series at tide gauge locations

Scenario data products

Example: Small tsunami on 7 April 2010



Scenario data products

Deriving evacuation maps e.g., Kuta, Bali

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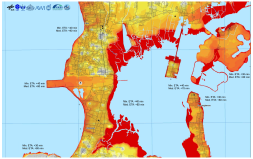
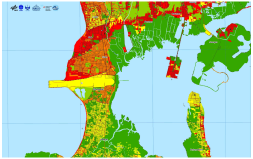
Zentrum für Material- und Küstenforschung

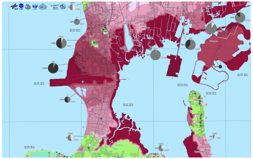
DLR



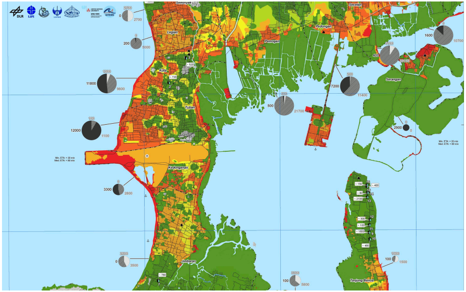
tsunami risk



exposed people



evacuation time



risk map (with shelters)

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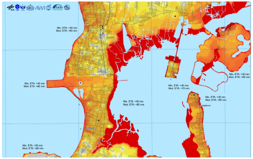
Deriving evacuation maps e.g., Kuta, Bali



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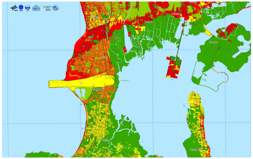

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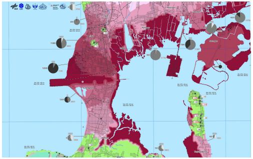

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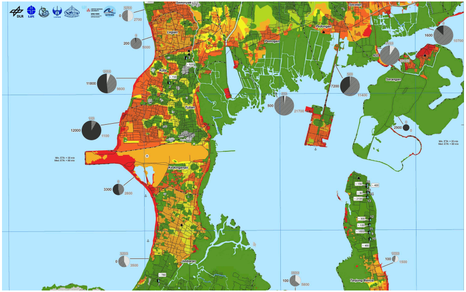
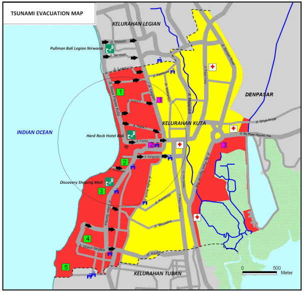


risk map (with shelters)

giz, local community



evacuation map

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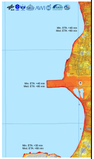
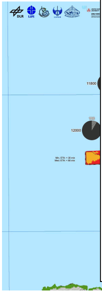
Scenario data products

Deriving evacuation maps e.g. Kuta, Bali



tsu



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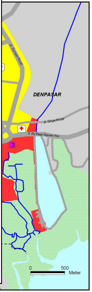

risk map (with shelters)

evacuation map

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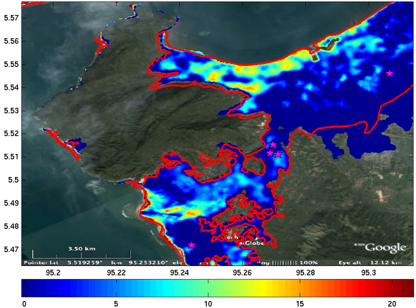
Scenario data products

Verification: Banda Aceh 2004

Simulation shows good agreement with measurements.



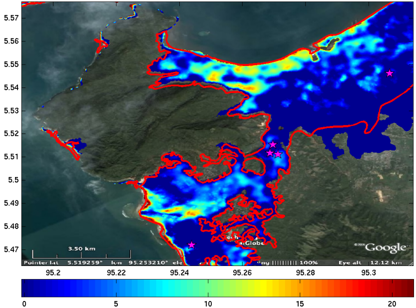
Scenario data products

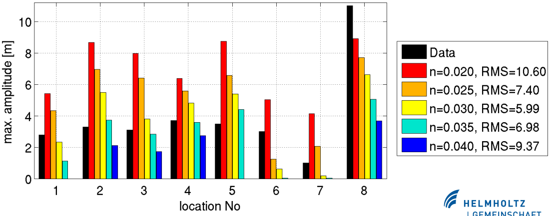
Verification: Banda Aceh 2004

Simulation shows good agreement with measurements.

However, calibration remains difficult. The result is sensitive to

- source model,
- Manning coefficient (bottom roughness),
- mesh resolution and numerical scheme,
- topography data.





Scenario data products

Sensitivity study on topography data

Three groups AIFDR, ITB, AWI,

Three models ANUGA, TUNAMI-N3, TsunAWI,

Three regions Padang (Sumatra), Maumere (Flores), Palu (Sulawesi)

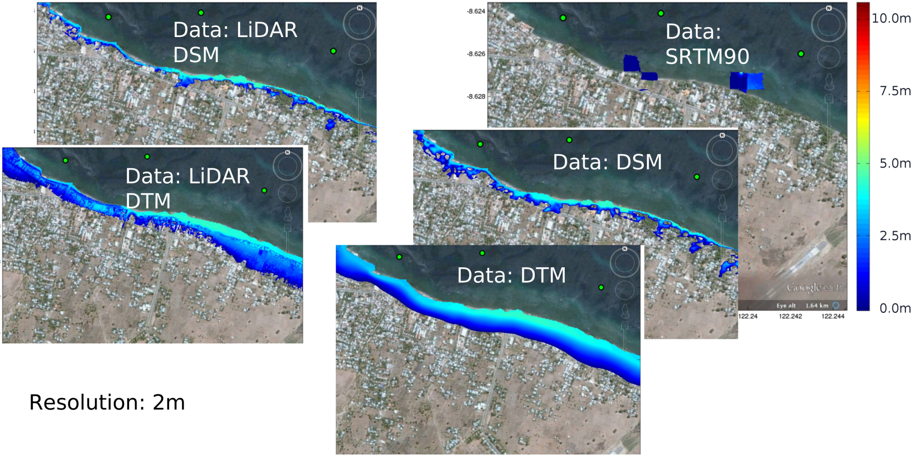
One conclusion **High quality topography data is crucial!**

- Free SRTM data (90m horizontal resolution, $\leq$16m vertical accuracy) only for rough estimates,
- Intermap (5m; 0.7m) and LiDar (1m; 0.15m) comparable for shallow water models,
- Results more sensitive to varying data sets than to varying resolution.

Scenario data products

Sensitivity study on topography data

Example: synthetic scenario for Maumere, Flores



Resolution: 2m