Operational Tsunami Modeling with TsunAWI - Examples for Indonesia and Chile

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Abstract

The numerical simulation code TsunAWI was developed in the framework of the German-Indonesian Tsunami Early Warning System (GITEWS). The model is based on a finite element discretization, employs unstructured grids with high resolution along the coast, and includes inundation. The simulation of tsunami scenarios plays a decisive role in the a priory risk assessment for coastal regions and in the early warning process itself.

This contribution gives an overview of the model itself and presents recent developments in two applications:

Tsunami scenarios for Indonesia

- Continuation of the GITEWS development phase by the PROTECTS project focussing on evaluation and training on modeling and the Simulation system (SIM).
- Extension of the initial model domain to cover all of the Indonesian coastlines.
- Extension of the scenario database to the Eastern part of the Sunda trench.

Scenarios for the Chilean coast

- Collaboration with the German Aerospace Agency (DLR) and the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA).
- Prototypical calculation of a database with 558 scenarios.
- Minor tsunami after the Iquique earthquake on 1 April 2014:
  - TsunAWI simulation with USGS finite fault source model.
  - Comparison of time series from this simulation as well as from database scenarios with tide gauge recordings.

TsunAWI Model Description

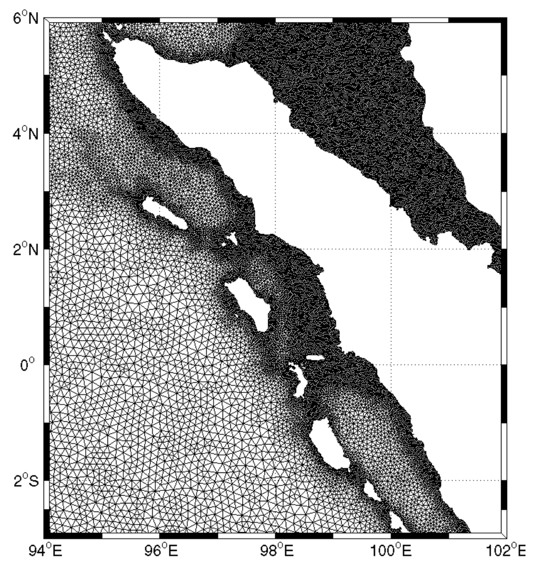
The triangular discretization of the model domain allows for an excellent representation of complicated coastlines and bathymetry.

- Model for the nonlinear shallow water equations with radiation boundary conditions at open boundaries.
- Finite Elements with linear basis functions for the sea surface elevation and nonconforming basis functions for velocity (P^1_{NC}-P^1) as described in Hanert et al. (2005).
- Surface triangulation with resolution depending on water depth and steepness of bathymetry:

$$\Delta x \leq \min\{c_t\sqrt{gh},\ c_g\frac{h}{\nabla h}\}$$

h denotes water depth

- Runup scheme based on extrapolation of model quantities to dry nodes in flooded areas.



Due to the flexibility of a triangular discretization, it is possible to resolve both ocean interior and coastal regions adequately without steep gradients in nodal density or internal boundary effects observed in models with nested grids.

The tsunami scenario repository

GITEWS

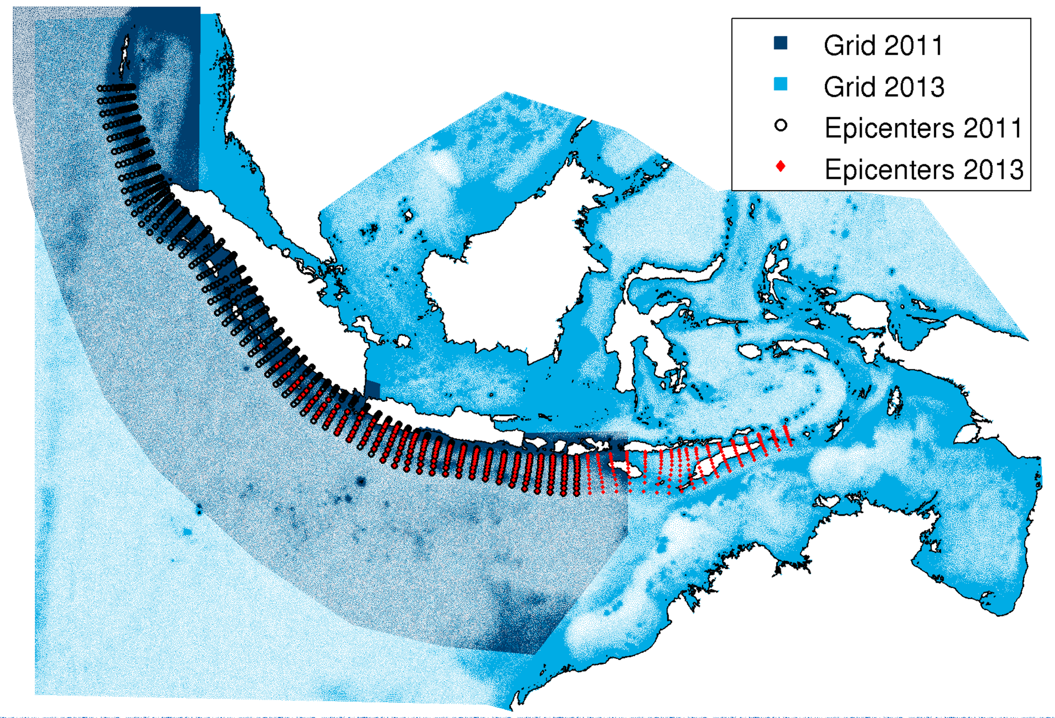
- covering the coasts of Sumatra, Java, and Bali.
- 3470 scenarios for 528 epicenters from 92°E to 117°E.
- Magnitudes 7.2, 7.4,...,8.8,9.0 (sources: RuptGen 2.1, GFZ, Babeyko).

PROTECTS

- Eastern Sunda Arc is added.
- Large tsunamis might pass the straits between the lesser Sunda Islands. Therefore the model domain covers the whole Indonesian area.
- 1100 additional scenarios for 187 epicenters up to 129°E.
- 1100 scenarios from initial database recomputed on the extended grid.

	Scenarios 2011		Scenarios 2013
Number of scenarios	3450		New 1100 Replaced 1100
Grid resolution	12km in the deep ocean 150m at the coast 50m in project reg., tide gauges		
Number of grid nodes	2.3M	full mesh	15M
	1.1M	reduced mesh (never flooded nodes removed)	7.5M
Model time	3h		12h
File size (reduced)	1.1 GB		22GB (500MB w/o time steps)
Comp. time	0:45 h 16 cores, Xeon, SGI, HLRN		15 h 8 cores Xeon, SGI, AWI
Coastal forecast points provided by DLR	14.973		134.770

Overview of model domains, mesh densities and epicenter locations of the database in 2011 (GITEWS) and 2013 (PROTECTS)



The resulting scenario file is too large to be permanently stored. After postprocessing, we delete the ssh time steps on the whole grid. Only time series at tide gauges, the initial elevation, MWH, ETA, other diagnostic values and meta data will be kept. The TsunAWI version and the model parameters are archived, such that the scenarios can be recomputed. The cost of computation decreases faster than the cost of storage.

Training

The operational use of the system at BMKG, Jakarta is supported by training courses for administrators and operators. Topics include:

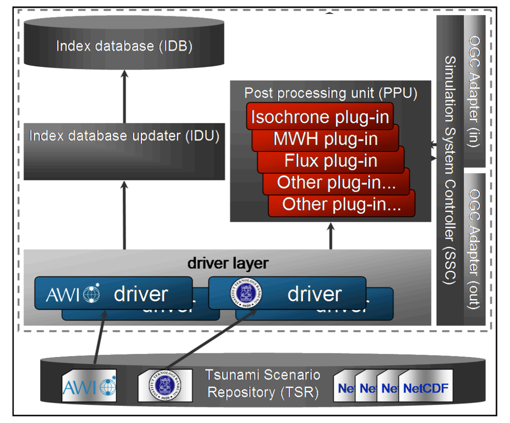
- Simulation with TsunAWI
  - Admins: 10 days in depth, practical, e.g. quality control, simulating scenarios for specific locations
  - Operators: theory and Decision Support System (DSS) products as result of simulation. On demand: hands on with small scale simulations.
- Simulation module SIM
  - Admins: 5 days in depth, e.g., full installation from scratch.
  - Operators: theory: multisensor matching algorithms, how is the warning in the DSS derived from the scenarios?

Training courses 2011-2014		
BMKG1	TsunAWI Admins	06/2011
BMKG14	SIM Admins	12/2011
BMKG19	TsunAWI Admins	03/2012
BMKG34	SIM Admins	06/2012
BMKG53	TsunAWI/SIM Op.	10/2012
BMKG54	SIM Admins	10/2012
BMKG112	SIM Admins	11/2012
BMKG65	TsunAWI/SIM Op.	03/2013
BMKG107	SIM Admins	03/2013
BMKG78	TsunAWI Admins	10/2013
BMKG108	SIM Admins	01/2014
BMKG104	TsunAWI Admins	01/2014

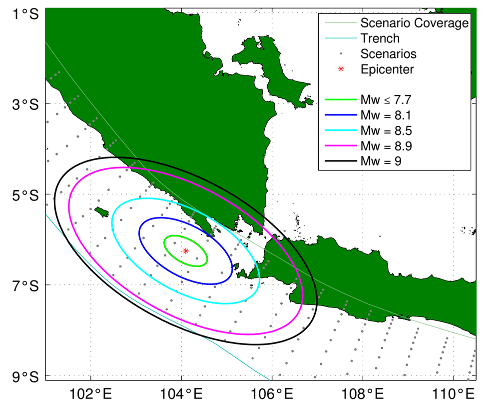
SIM - Warning System Design

Within the Tsunami Warning system, the simulation system (SIM) accesses the simulation repository and chooses the set of matching scenarios in case of an event.

- In an offline ingestion phase, data is extracted from the full scenarios, an index database is built, and warning products are prepared.
- In case of an event, in the first step, the seismic data is used to select scenarios within an ellipse around the measured epicenter.
- With GPS dislocation measurements, scenarios can be excluded from the seismic selection.



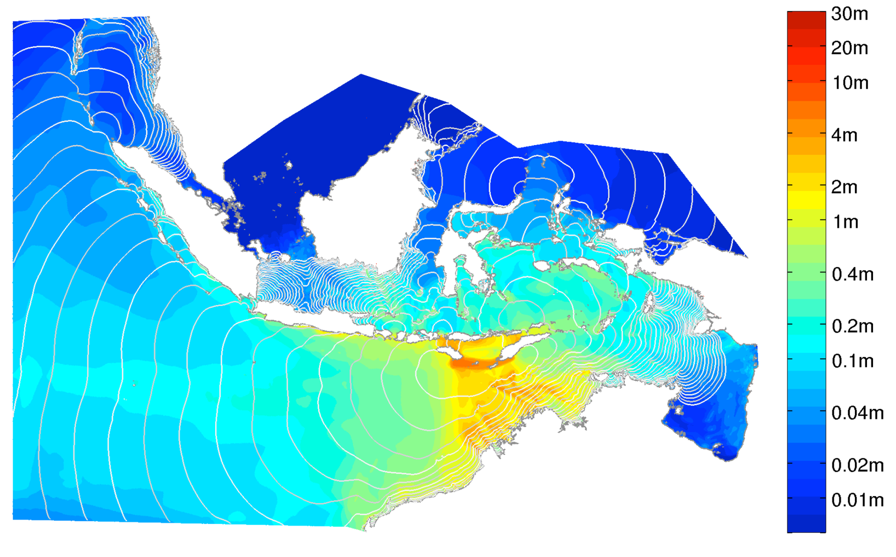
Overview of the Simulation System (SIM)



Visualization of the seismic uncertainty ellipse with different sizes for different magnitudes

Post processing and warning products

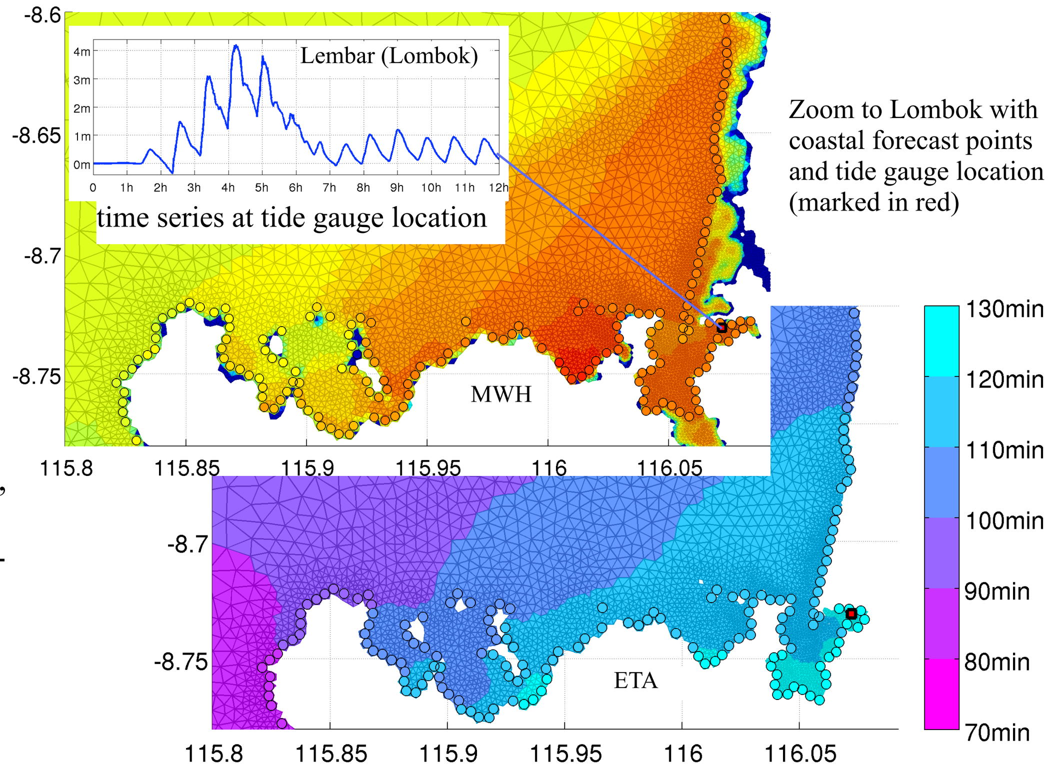
- In the post processing phase, the quality of each scenario is controlled.
- The most difficult part is the processing of isochrones. One fixed threshold is not suitable for all magnitudes and distances from the epicenter. Instead time series are analyzed at each grid node.
- The maximum wave height is far less crucial. Provided the grid is constructed with care (smooth, regular) and the time step reflects the CFL criterion, TsunAWI does not produce any outliers or peaks.



Isochrones and energy propagation for a source in the Eastern part of the Sunda arc close to the island of Sumba.

Visualization of warning products for one scenario:

- MWH and ETA on the whole grid (upper figure)
- MWH and ETA at 134.770 coastal forecast points (CFP)
- For each coastal forecast zone, some hundred CFPs are aggregated to one value. time series at tide gauge locations



Zoom to Lombok with coastal forecast points and tide gauge location (marked in red)

Summary and Conclusions

- The finite element approach with triangular elements enables the generation of meshes representing all necessary topographical features necessary for proper description of wave processes both in the deep ocean as well as coastal areas.
- The choice of forecast points right at the coast is possible provided the near shore bathymetry is well known.
- Determination of arrival times is based on time series analysis in each computational node.
- Comparison to observations from the minor tsunami on 1 April 2014 shows good performance of the simulation with the finite fault source as well as of the precomputed scenarios nearby.

Acknowledgements:

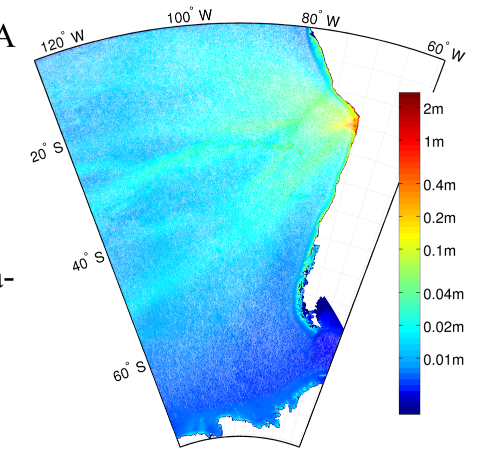
- Source parameters provided by SHOA, Chile.
- PROTECTS funded by BMBF.
- Simulations partly carried out at DKRZ and HLRN.
- Thanks to our project partners.

References:

- Hanert et al, An efficient Eulerian finite element method for the shallow water equations, Ocean Modelling (2005)
- USGS Finite fault source obtained from: http://earthquake.usgs.gov
- Tide gauge data obtained from www.ioc-sealevelmonitoring.org
- DART buoy data obtaied from www.ndbc.noaa.gov/dart.shtml

Scenarios for the Chilean coast

- In collaboration with DLR and SHOA prototypical scenario database for the chilean coast with 558 scenarios.
- Mesh covers part of the Pacific Ocean with resolution from 20 km to 50 m.
- Parameters provided by SHOA
- Magnitudes from 7.0 to 9.0
- Depth 20 km and 30 km

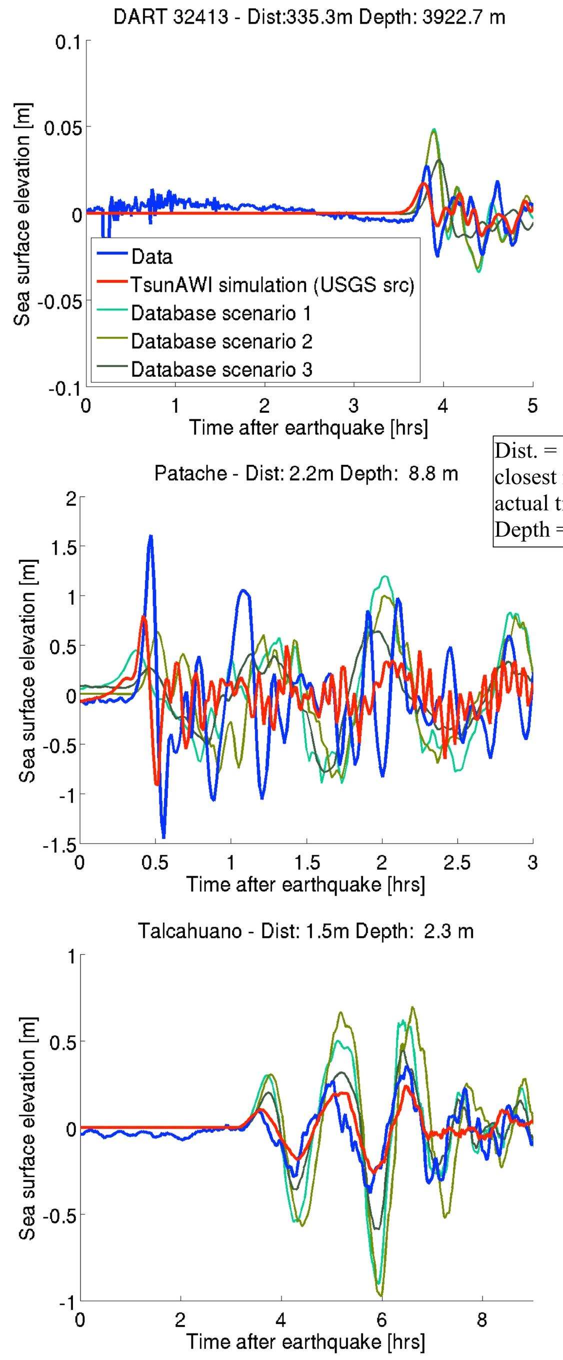


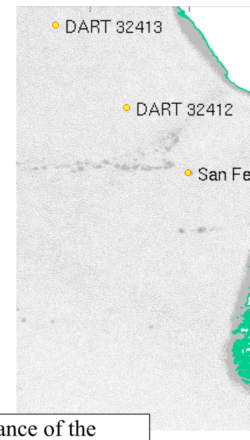
Maximum wave height [m] of the TsunAWI simulation in the model domain.

Earthquake on 1 April 2014

Observations after the Iquique earthquake are compared to simulation results

- Data:
  - Magnitude 8.2
  - Focal depth 20.1 km (USGS)
  - USGS Finite fault source
  - Tide gauge data from the IOC sea level station monitoring facility
  - DART Buoy data from the National Data Buoy Center
- TsunAWI Simulations:
  - S0 (using USGS source)
  - S1, S2 from the database (Mag 8.0, depth=20km)
  - S3 from the database (Mag 8.0, depth=30km)

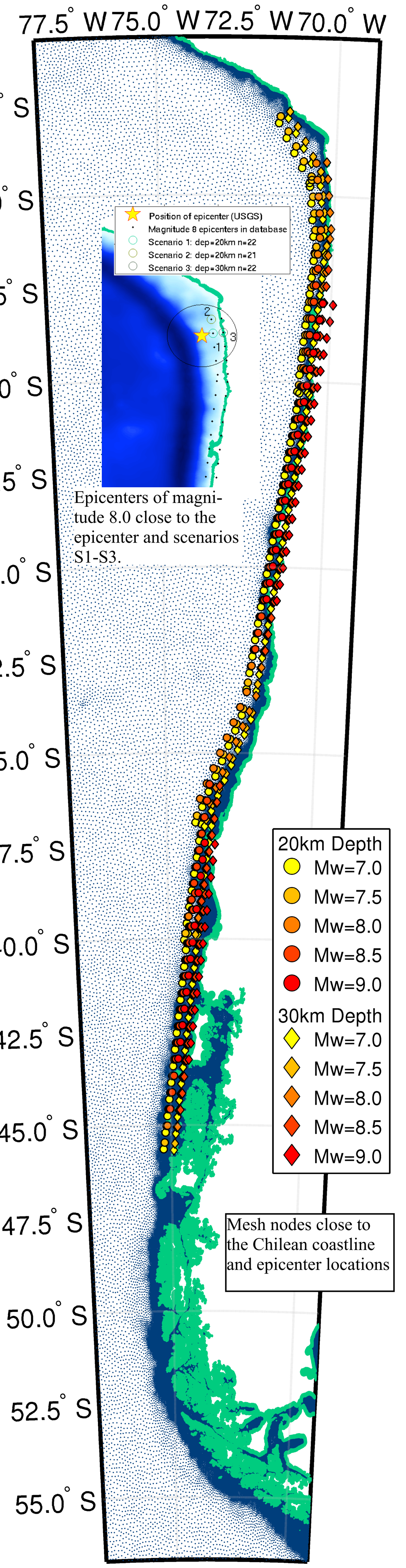




Dist. = distance of the closest mesh node to the actual tide gauge location. Depth = model bathymetry

Tide gauge observations and the corresponding results from simulations in some of the locations indicated above.

- S0 underestimates the amplitude in some locations but generally good comparison to data.
- S1-S3 underestimate the amplitude close to the source. Arrival times are predicted very well.
- Largest differences between the simulations occur close to the source where the actual shape and time line of the rupture is crucial



Epicenters of magnitude 8.0 close to the epicenter and scenarios S1-S3.

Mesh nodes close to the Chilean coastline and epicenter locations