Coupled 3D Earthquake Dynamic Rupture - Tsunami Models & the ASCETE framework

ASCETE: Advanced Simulation of Coupled Earthquake and Tsunami Events (www.ascete.org)

Geodynamics! Seismic cycling! Earthquakes! Tsunamis! ... *and linking these subduction zone processes across space and time.*

Elizabeth Madden, Michael Bader, Jörn Behrens, Ylona van Dinther, Alice-Agnes Gabriel, Leonhard Rannabauer, Carsten Uphoff, Thomas Ulrich, Stefan Vater, Stephanie Wollherr, Iris van Zelst

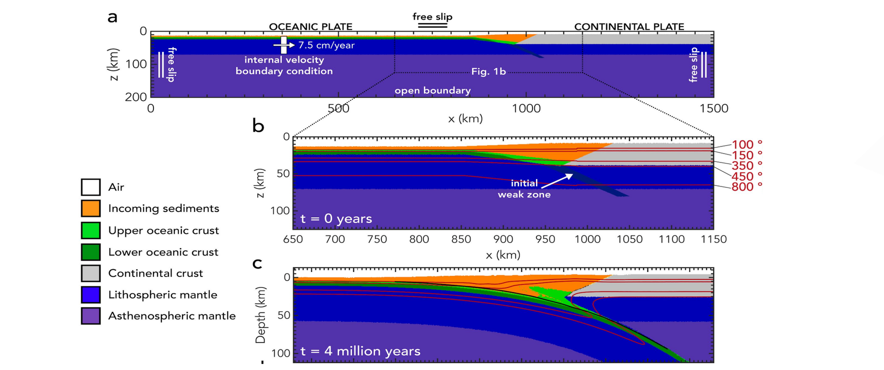
Geodynamics-seismic cycling-earthquake-tsunami modeling

What we do: the ASCETE workflow

We present methods to link together long term subduction, rupture of a single earthquake, and tsunami generation to study subduction zone behavior across spatial and temporal scales.

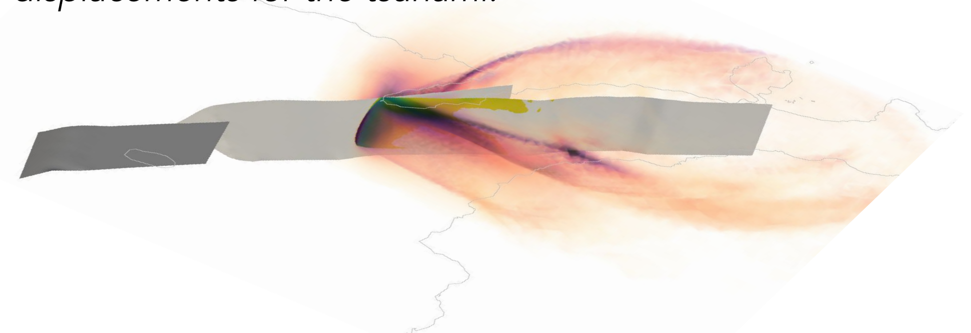
LONG TERM SUBDUCTION

Subduction zone geodynamics and seismic cycling. *Provides initial conditions for the earthquake.*



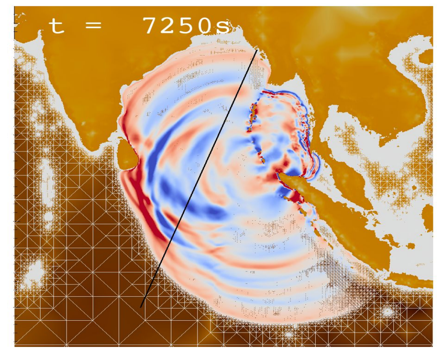
EARTHQUAKE

Dynamic rupture of a single earthquake with seismic wave propagation. *Provides time-dependent, coseismic seafloor displacements for the tsunami.*



TSUNAMI

Tsunami generation, propagation and inundation.



The tools we use: the ASCETE framework

SEISMO-THERMO-MECHANICAL MODEL (van Dinther et al., 2013a,b; 2014)

- Fully staggered Eulerian, conservative finite difference scheme to implicitly solve equations of conservation of mass, momentum, energy
- Velocity, temperature, composition, and visco-elasto- plastic rheology evolve in space and time
- Geodynamics (1000 yr time steps), then seismic cycling (5 yr time steps)

SEISSOL (PELTIES et al., 2014, https://github.com/SeisSol/, www.seissol.org)

- Solves the seismic wave equation in velocity-stress formulation
- Verified for complex geometries and constitutive laws(Käser et al. 2007; Uphoff; Bader 2016) and off-fault plasticity (Wollherr et al., 2018)
- Open source!

SAM(OA)² (https://github.com/meistero/Samoa)

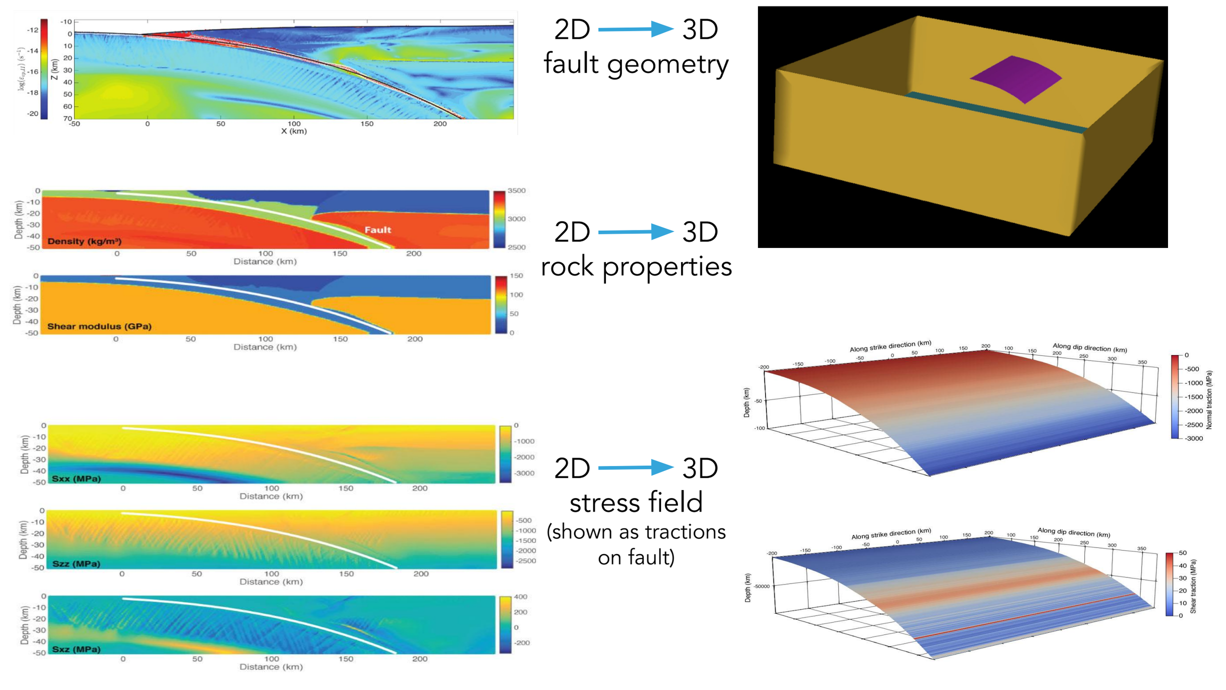
- Solves shallow water equations for non-linear, hydrostatic wave propagation and inundation
- Tsunami triggered by bathymetry perturbation
- Adaptive mesh refinement scheme allows for efficient meshing (Meister et al. 2016)
- Open source!

ASAGI: a pArallel Server for Adaptive GeoInformation (Rettenberger et al., 2016)

- An open-source library with a simple interface to access Cartesian material and geographic datasets in massively parallel simulation
- Provides scalable input of data at several stages of the framework

How we do it: ASCETE reference model

SEISMIC CYCLING TO EARTHQUAKE: We attain physically consistent initial conditions for a megathrust earthquake by using information for 1 slip event in the long term subduction model as initial conditions for the dynamic earthquake model.



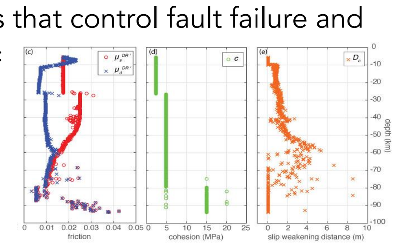
2D → 3D fault geometry

2D → 3D rock properties

2D → 3D stress field (shown as tractions on fault)

We also couple parameters that control fault failure and slip (shown on fault cross-sections):

- On-fault cohesion
- Static & dynamic friction
- Slip weakening distance

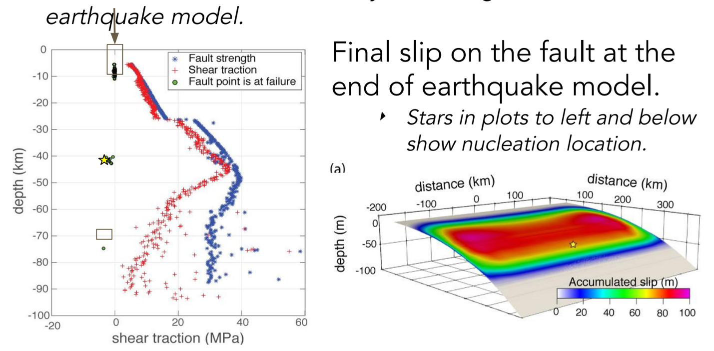


Coupled nucleation:

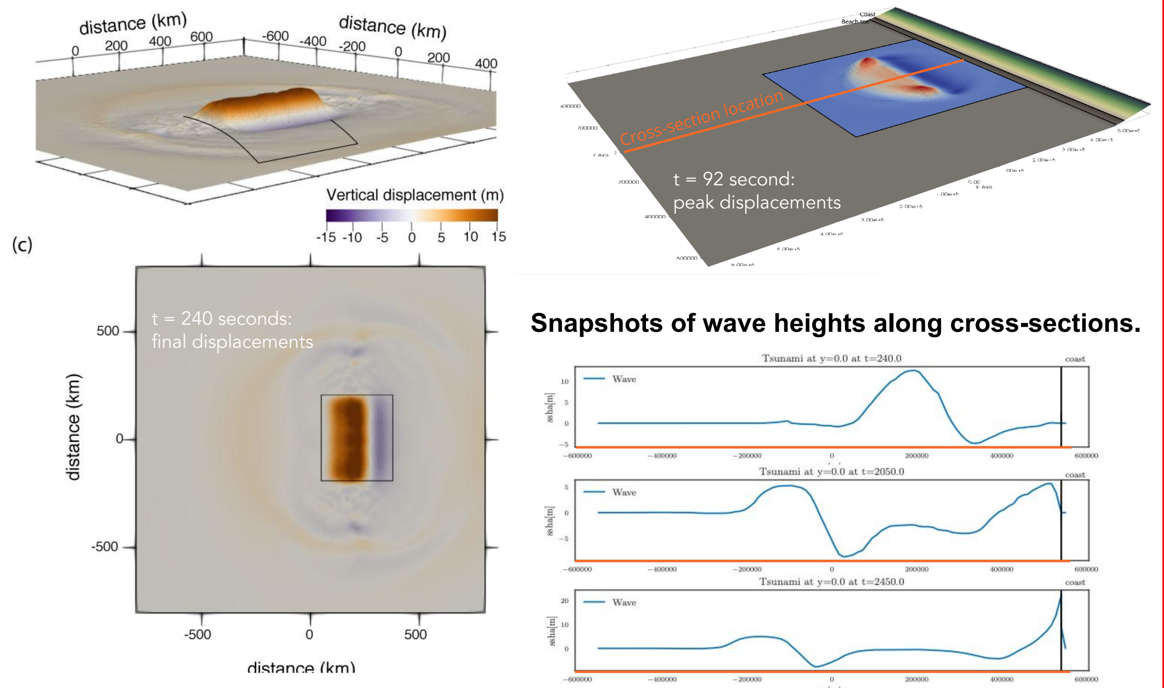
- The earthquake begins where the slip event begins! (shown on fault cross-sections)
- Failure in the velocity strengthening sediments in the subduction model is blocked by increasing static friction in earthquake model.

Final slip on the fault at the end of earthquake model.

- Stars in plots to left and below show nucleation location.



EARTHQUAKE TO TSUNAMI: We use the time-dependent vertical displacement during the earthquake as the tsunami source using ASAGI.



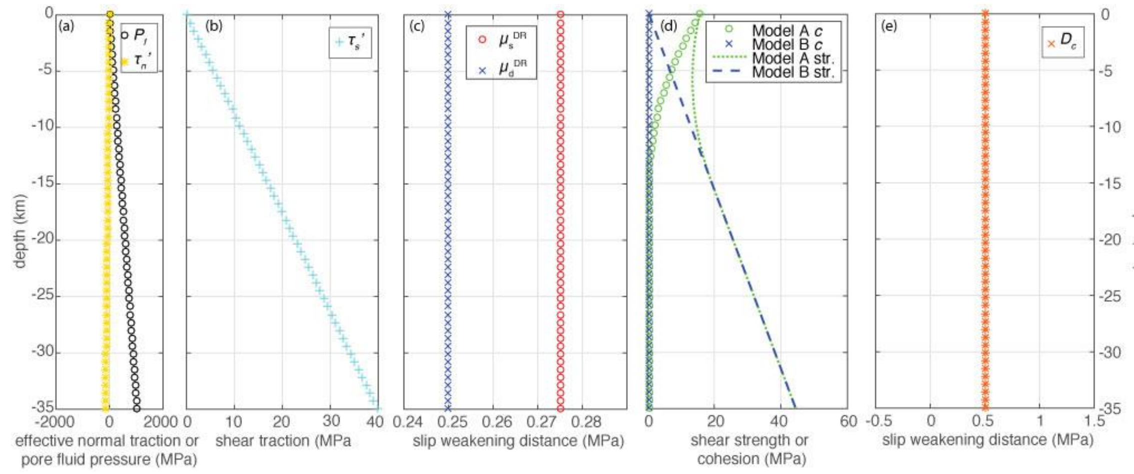
Snapshots of wave heights along cross-sections.

Earthquake-tsunami modeling

2 simple test cases

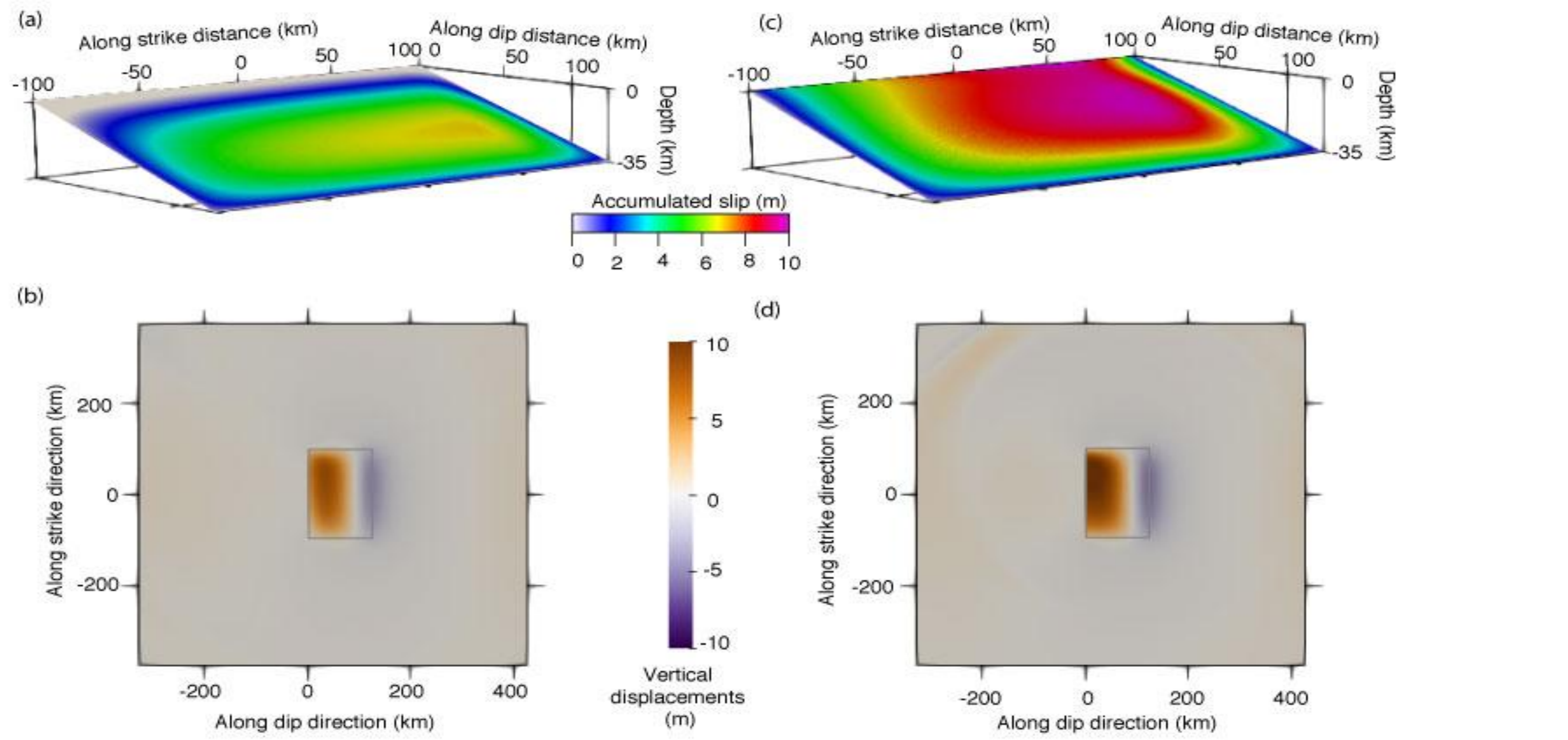
SIMPLIFIED EARTHQUAKE RUPTURE SCENARIOS:

The earthquake models incorporate a planar fault, extending from the seafloor to 35 km depth, dipping 16 degrees, and surrounded by a homogeneous crust. The Model A earthquake scenario has no slip to the trench; the Model B scenario has slip to the trench.



MODEL A: NO SLIP TO TRENCH M_w 8.5 earthquake

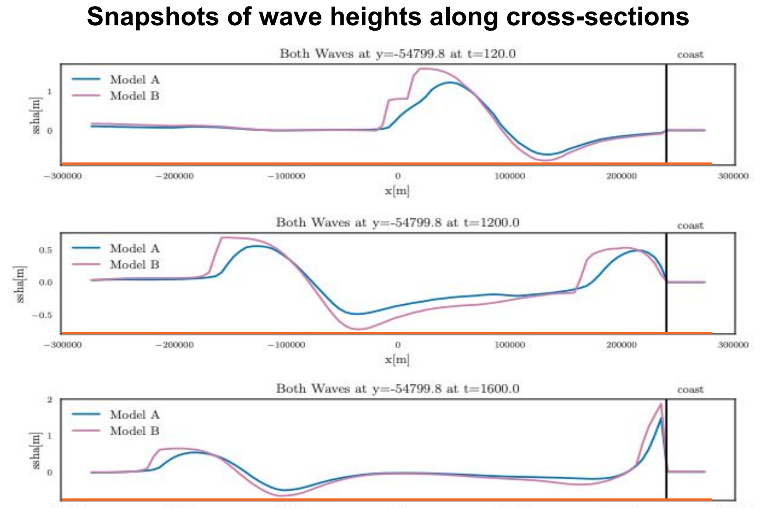
MODEL B: SLIP TO TRENCH M_w 8.6 earthquake



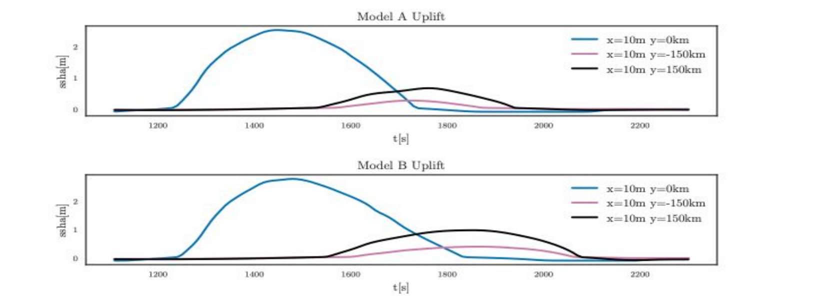
COUPLED TSUNAMI RESULTS:

The time-dependent vertical displacements from Models A and B are used as tsunami sources. The tsunami model domain is as for the ASCETE reference model, except that the beach toe is located at x = 240 km. The cross-sections in the snapshots of wave heights shown to the far right are along y = 0, as shown for the ASCETE reference model (below, left).

Snapshots of wave heights along cross-sections



Time series of the wave height at probes placed at the coast



How does slip to the trench influence the tsunami?

- Higher peak to trough height?
- Higher wave at coast?
- Longer coastal inundation? In both time & space?

Physics-based, coupled models *in action!*

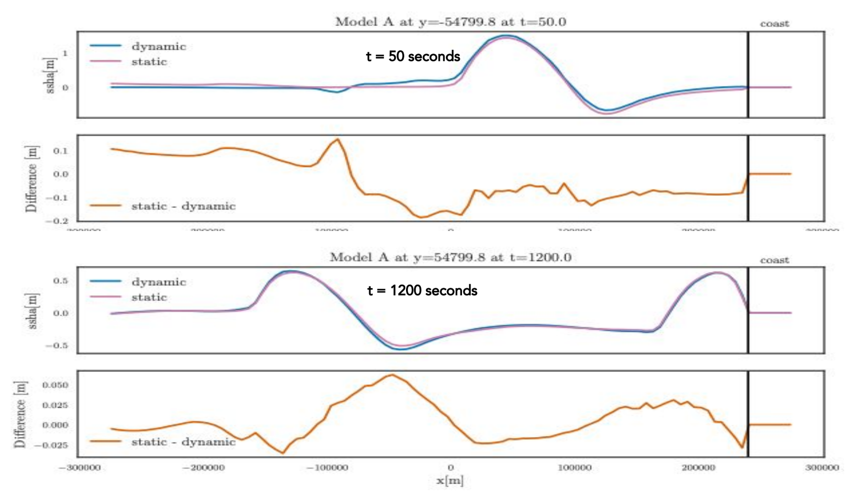
COUPLED MODELS SUCH AS THESE ARE USEFUL FOR:

- Isolating the influence of a single earthquake characteristic on tsunami behavior.
  - *We demonstrate this by comparing results for the 2 earthquake scenarios: one with and one without slip reaching the seafloor.*
- Isolating the effect of a model choice on modeled tsunami behavior.
  - *We demonstrate this by comparing tsunami models using the final (static) vs. time-dependent (dynamic) seafloor displacements as sources.*
- We do not aim to answer these geophysics questions, but present them as examples of the utility of coupled, physics-based models.

When are dynamic displacements required to make a relevant tsunami model?

- Slower earthquakes? (Model A tsunami vs. reference model tsunami)
- When point of interest is earlier in wave travel-time?

Snapshots of wave heights for Model A earthquake source
Average rupture velocity: 3.6 km/s



Snapshots of wave heights for reference model earthquake source
Reference model average rupture velocity: 2.8 km/s