Tsunami simulations on several scales

Comparison of approaches with unstructured meshes and nested grids

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Abstract The tsunami event generated by the great Sumatra–Andaman earthquake on 26 December 2004 was simulated with the recently developed model TsunAWI. The model is based on the finite element method, which allows for a very flexible discretization of the model domain. This is demonstrated by a triangulation of the whole Indian Ocean with a resolution of about 14 km in the deep ocean but a considerably higher resolution of about 500 m in the coastal area. A special focus is put on the Banda Aceh region in the Northern tip of Sumatra. This area was heavily hit by the tsunami and the highest resolution in this area is about 40 m in order to include inundation processes in the model simulation. We compare model results to tide gauge data from all around the Indian Ocean, to satellite altimetry, and field measurements of flow depth in selected locations of the Aceh region. Furthermore, we compare the model results of TsunAWI to the results of a nested grid model (TUNAMI-N3) with the same initial conditions and identical bathymetry and topography in the Aceh region. It turns out that TsunAWI gives accurate estimates of arrival times in distant locations and in the same mesh gives good inundation results when compared to field measurements and nested grid results.

Keywords Tsunami · Numerical modeling · Finite element method · Unstructured meshes · Nested grids · Shallow water equations · Model comparison

1 Introduction

The devastating tsunami generated by the great Sumatra–Andaman earthquake on December 26 in 2004 has triggered many activities aimed at the establishment of a tsunami early warning system for the Indian Ocean. As part of the German aid contribution in the framework of the German–Indonesian Tsunami Early Warning System (GITEWS) (www.gitews.de), a tsunami wave propagation model (TsunAWI) is being developed at AWI (Behrens 2008). Numerical modeling relies on a discretization of the physical space. The two major strategies in this respect are the regular and the unstructured discretization of the domain under consideration. The largest part of models used for tsunami simulations at the moment are based on regular meshes. Many of these have been successfully applied to the December 2004 tsunami event (see Geist et al. 2007; Kowalik et al. 2007; Grilli et al. 2007; Titov and Gonzalez 1997). Even the global extent has been investigated in Kowalik et al. (2005) and Titov et al. (2005). On the other hand, ocean models based on unstructured grids are being developed by many institutions and wave propagation problems were among the first applications in the ocean successfully tackled with this technology (see, for example, Piatanesi et al.
TsunAWI is based on an unstructured grid approach employing finite elements to solve the governing equations. Development of this model has started as a spin-off from the 3D ocean model FEOM, which is being developed at AWI (see Danilov et al. 2004). Motivation for the choice of unstructured grids is the ability to simulate wave processes on different scales. In the deep ocean, coarse resolution (several kilometers) is sufficient to represent the wave adequately. However, while reaching the shoreline, the tsunami steepens, the wave may break, contributions of nonlinear terms become more important, and much higher resolution is needed to include even rough estimates of the inundation processes. In finite difference approaches, this problem is tackled by a series of nested grids ranging from about 1 km in the coarsest grid to less than 100 m in the finest (see Fig. 2). In an unstructured grid, all constraints on the local resolution mentioned above may be satisfied in one grid where, additionally, transitions of nodal density are smooth.

In the framework of an early warning system model, results are crucial as important quantities such as arrival time and estimated wave heights are derived from precalculated scenarios of future tsunamis [e.g., a description of the Japanese early warning system is given in Furumoto et al. (1999)]. TUNAMI is recommended within the Tsunami Inundation Modeling Experiment project and has been used in many countries for tsunami simulations already. A direct comparison of this model to TsunAWI is therefore especially helpful for gaining insights into possible advantages and disadvantages of the finite element approach in unstructured grids.

The subject of the present study is the tsunami generated by the Sumatra–Andaman earthquake on 26 December 2004. The initial conditions are taken from the reconstruction of the rupture as described in Tanioka et al. (2006). We compare model results to the following data:

- Arrival times and wave heights in tide gauge records from rim countries of the Indian Ocean
- Satellite altimetry data obtained from Jason-1, Envisat and Topex-Poseidon
- Field measurements in selected positions in Banda Aceh region

Additionally, we compare results of both models, TsunAWI and TUNAMI-N3, with respect to arrival times and wave height in virtual gauges, as well as the inundation obtained in Aceh region. It turns out that arrival times and estimated amplitude of the first wave crest coincide well, given the uncertainties in approximation and data. The same is true for the inundation area, which coincides well in both models. Field data in selected positions were used to adjust the friction parameters of the models.

Section 2 describes the model setup for the numerical experiments. Section 3 contains some details on the models TUNAMI and TsunAWI. Section 4 describes the results of both models before conclusions are drawn in Section 5.

2 Tsunami source model

There are many studies on the rupture process of the 2004 Sumatra–Andaman earthquake using seismic data estimating the moment magnitude (Mw) about 9.0 to 9.3 (Ammon et al. 2005; Park et al. 2005). For water wave modeling purposes, a precise description of the fault mechanism is needed. In Tanioka et al. (2006), the rupture process of the 2004 Sumatra–Andaman earthquake has been estimated by tsunami wave forms at tide gauges, as well as coastal coseismic vertical deformations. It turns out that a rupture speed of 1.7 km/s gives the best match between tide gauge data in five stations and the synthetic tsunami propagation. These results are used to derive initial conditions for both models. The source area of the 2004 Sumatra–Andaman earthquake is divided into 12 subfaults. The event is described by consecutive activation of the corresponding 12 fault plates located as shown in Fig. 1. Assuming the rupture speed mentioned above, the whole earthquake takes 12 min. Each fault plate moves as described by a set of Okada parameters (see Okada 1985, for a theoretical background) specifying the location, bearing, and slip of each plate. Table 1 gives the timing and amount of slip for the plates depicted in Fig. 1. The large slip values of plates A and C correspond to the largest bottom deformations in these regions. It is assumed that the bottom and ocean surface move at the same rate. Whenever a subfault is to be moved during model integration (as given in Table 1), the model is reinitialized, i.e., the bottom and sea surface height are adjusted instantly at the same rate in order to conserve volume.

There are other approaches to the parameters of the rupture mechanism. Banerjee et al. (2007) presents coseismic slip distributions inverted from GPS data, whereas Hirata et al. (2006) optimizes the earthquake