Inundation Modelling of the December 2004 Indian Ocean Tsunami

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ABSTRACT

Geoscience Australia, in an open collaboration with the Mathematical Sciences Institute, The Australian National University, is developing a software application, ANUGA, to model the hydrodynamics of floods, storm surges and tsunamis. The free source software implements a finite volume central-upwind Godunov method to solve the non-linear depth-averaged shallow water wave equations. In light of the renewed interest in tsunami forecasting and mitigation, this paper explores the use of ANUGA to model the inundation of the Indian Ocean tsunami of December 2004. The Method of Splitting Tsunamis (MOST) was used to simulate the initial tsunami source and the tsunami's propagation at depths greater than 100m. The resulting output was used to provide boundary conditions to the ANUGA model in the shallow water. Data with respect to 4-minute bathymetry, 2-minute bathymetry, 3-arc second bathymetry and elevation were used in the open ocean, shallow water and on land, respectively. A particular aim was to make use of the comparatively large amount of observed data corresponding to this event, including tide gauges and run-up heights, to provide a conditional assessment of the computational model's performance. Specifically we compared model tsunami depth with data collected at two tide gauges and 18 coastal run-up measurements.

Comparison between observed and modelled run-up at 18 sites show reasonable agreement. We also find modest agreement between the observed and modelled tsunami signal at the two tide gauge sites. The arrival times of the tsunami is approximated well at both sites. The amplitude of the first trough and peak is approximated well at the first tide gauge (Taphao-Noi), however the amplitude of the first wave was underestimated at the second gauge (Mercator yacht). The amplitude of subsequent peaks and troughs, at both gauges, are underestimated and a phase lag between the observed and modelled arrival times of wave peaks is evident after the first peak.

The performance of the model could be improved by using finer bathymetric data, which at present cannot be obtained by the authors. The bathymetry data used was insufficient. Local topographic features, such as small islands and shoreline elevations near run-up locations are not accurately represented. The arrival time and tsunami height could also be improved by calibrating the tsunami source on observed data such as the satellite transect of Jason 1 following the procedure of Grilli *et al.* (2006). Improving modelled results through finer bathymetric data and source calibration is the focus of future work.

1 INTRODUCTION

Tsunamis are a potential hazard to coastal communities all over the world. These 'waves' can cause loss of life and have huge social and economic impacts. The so-called Indian Ocean tsunami killed around 230,000 people and caused billions of dollars in damage on the 26th of December 2004 (Synolakis *et al.* 2005). Hundreds of millions of dollars in aid has been donated to the rebuilding process and still the lives of hundreds of thousands of people will never be the same. Fortunately, catastrophic tsunamis of the scale of the 26 December 2004 event are exceedingly rare. However, smaller-scale tsunamis are more common and regularly threaten coastal communities around the world. Earthquakes that occur in the Java Trench near Indonesia (e.g. Tsuji *et al.* 1995) and along the Puysegur Ridge to the south of New Zealand (e.g. Lebrun *et al.* 1998) have potential to generate tsunamis that may threaten Australia's northwestern and southeastern coastlines.

For these reasons there has been increased focus on tsunami hazard mitigation over the past 24 months. Tsunami hazard mitigation involves detection, forecasting, and emergency preparedness (Synolakis *et al.* 2005). Unfortunately, due to the small time scales (at the most a few hours) over which tsunamis take to impact coastal communities, real time models that can be used for guidance as an event unfolds are currently underdeveloped. Consequently current tsunami mitigation efforts must focus on developing a database of pre-simulated scenarios to help increase effectiveness of immediate relief efforts.

Firstly areas of high vulnerability, such as densely populated regions at risk of extreme damage, are identified. Action can then be undertaken before the event to minimise damage (early warning systems, breakwalls etc.) and protocols put in place to be followed when the flood waters subside. In this spirit, Titov *et al.* (2001) discuss a current Short-term Inundation Forecasting (SIFT) project for tsunamis.

Several approaches are currently used to solve these problems. They differ in the way that the propagation of a tsunami is described. The shallow water wave equations, linearised shallow water wave equations, and Boussinesq-type equations are commonly accepted descriptions of flow. But the complex nature of these equations and the highly variable nature of the phenomena that they describe necessitate the use of numerical simulations.

Geoscience Australia, in an open collaboration with the Mathematical Sciences Institute, The Australian National University, is in the final stages of completing a hydrodynamic modelling tool called ANUGA to simulate the shallow water propagation and run-up of tsunamis. Further development of this tool requires comprehensive assessment of the model. In particular the model must be validated and tested to ensure it is sufficiently robust and that the interactions and outcomes demonstrated are feasible and defensible, given the objectives. These objectives include: simulating flow over dry beds and the appearance of dry states within previously wet regions; accurately describing steady state flows and small perturbations from these steady states over rapidly-varying topography; and accurately resolve shocks. Applications of ANUGA include, but are not limited to, dam-breaks, storm surges, and tsunami propagation.

The process of validating the ANUGA application is in its early stages, but initial indications are encouraging. As part of the Third International Workshop on Long-wave run-up Models in 2004[1], four benchmark problems were specified to allow the comparison of numerical, analytical and physical models with laboratory and field data. One of these problems describes a wave tank simulation of the 1993 Okushiri Island tsunami off Hokkaido, Japan (Matsuyama *et al.* 2001). The wave tank simulation of the Hokkaido tsunami was used as the first scenario for validating ANUGA. The dataset provided bathymetry and topography along with initial water depth and the wave specifications. The dataset also contained water depth time series from three wave gauges situated offshore from the simulated inundation area. Although good agreement was obtained between the observed and simulated water depth at each of the three gauges (Roberts *et al.* 2006) further validation is needed.

[1] http://www.cee.cornell.edu/longwave

Although appalling, the devastation caused by the 2004 Indian Ocean tsunami has heightened community, scientific and governmental interest in tsunami and in doing so has provided a unique opportunity for further validation of tsunami models. Enormous resources have been spent to obtain many measurements of phenomenon pertaining to this event to better understand the destruction that occurred. Data sets from seismometers, tide gauges, GPS stations, a few satellite overpasses, subsequent coastal field surveys of run-up and flooding and measurements from ship-based expeditions, have now been made available (Vigny *et al.* 2005, Amnon *et al.* 2005, Kawata *et al.* 2005, and Liu *et al.* 2005).

An aim of this paper is to use ANUGA to undertake a regional case study of the 2004 Indian Ocean tsunami for western and southern Thailand. The specific intention is to test the model results against the observed data obtained during and in the aftermath of the tsunami.

2 MODELLING THE TSUNAMI OF 24TH DECEMBER 2004

The evolution of earthquake-generated tsunamis has three distinctive stages: generation, propagation and run-up (Titov and Gonzalez, 1997) . To accurately model the evolution of a tsunami all three stages must be dealt with. Here we use the Method of Splitting Tsunamis Model (MOST) to model the generation of a tsunami and open ocean propagation. The resulting data is then used to provide boundary conditions for the inundation package ANUGA (see below) which is used to simulate the propagation of the tsunami in shallow water and the tsunami run-up.

Here we note that the MOST model was developed as part of the Early Detection and Forecast of Tsunami (EDFT) project (Titov *et al.* 2005). MOST is a suite of integrated numerical codes capable of simulating tsunami generation, its propagation across, and its subsequent run-up. The exact nature of the MOST model is explained in (Titov and Synolakis 1995, Titov and Gonzalez 1997, Titov and Synolakis 1997, and Titov *et al.* 2005).

ANUGA is an inundation tool that solves the depth integrated shallow water wave equations. The scheme used by ANUGA, first presented by Zoppou and Roberts (1999), is a high-resolution Godunov-type method that uses the rotational invariance property of the shallow water equations to transform the two-dimensional problem into local one-dimensional problems. These local Riemann problems are then solved using the semi-discrete central-upwind scheme of Kurganov *et al.* (2001) for solving one-dimensional conservation equations. The numerical scheme is presented in detail in (Zoppou and Roberts 1999, Zoppou and Roberts 2000, and Roberts and Zoppou 2000, Nielsen *et al.* 2005) . An important capability of the software is that it can model the process of wetting and drying as water enters and leaves an area. This means that it is suitable for simulating water flow onto a beach or dry land and around structures such as buildings. It is also capable of resolving hydraulic jumps well due to the ability of the finite-volume method to handle discontinuities.

2.1 Tsunami Generation

The Indian Ocean tsunami of 2004 was generated by severe coseismic displacement of the sea floor as a result of one of the largest earthquakes on record. The M_w=9.2-9.3 mega-thrust earthquake occurred on the 26 December 2004 at 0h58'53" UTC approximately 70 km offshore North Sumatra. The disturbance propagated 1200-1300 km along the Sumatra-Andaman trench time at a rate of 2.5-3 km.s^{-1} and lasted approximately 8-10 minutes (Amnon *et al.* 2005). At present ANUGA does not possess an explicit easy to use method for generating tsunamis from coseismic displacement, although such functionality could easily be added in the future. Implementing an explicit method for simulating coseismic displacement in ANUGA requires time for development and testing that could not be justified given the aims of the project and the time set aside for completion. Consequently in the following we employ the MOST model to determine the sea floor deformation.

The solution of Gusiakov (1972) is used by the MOST model to calculate the initial condition. This solution describes an earthquake consisting of two orthogonal shears with opposite sign. Specifically we adopt the parameterisation of Greensdale (2007) who modelled the corresponding displacement by dividing the rupture zone into three fault segments with different morphologies and earthquake parameters. Details of the parameters associated with each of three regions used here are given in the same paper. The resulting sea floor displacement is shown in Figure 1 and ranges between 3.6 m and 6.2 m.

2.2 Tsunami Propagation

We use the MOST model to simulate the propagation of the 2004 Indian Ocean tsunami in the deep ocean ocean, based on a discrete representation of the initial deformation of the sea floor, described above. Propagation is modelled using a numerical dispersion scheme that solves the non-linear shallow-water wave equations in spherical coordinates, with Coriolis terms. This model has been extensively

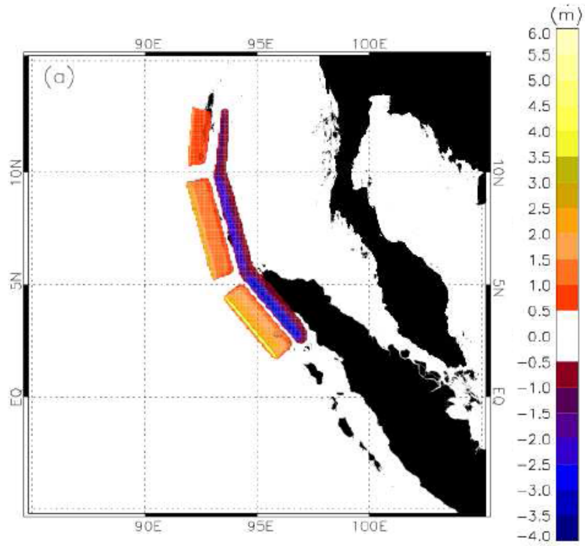

Figure 1. Location and magnitude of the sea floor displacement associated with the December 24 2004 tsunami. Taken from Greensdale *et al.* (2007)

tested against a number of laboratory experiments and was successfully used for simulations of many historical tsunamis (Titov and Synolakis 1997, Titov and Gonzalez 1997, Bourgeois *et al.* 1999, and Yeh *et al.* 1994).

The computational domain for the MOST simulation, was defined to extend from 79.067^0E to 104.933^0E and from 4.933^0S to 24.867^0S. The bathymetry in this region was estimated using a 4 arc minute data set developed by the CSIRO specifically for the ocean forecasting system used here. It is based on dbdb2 (NRL), and GEBCO data sets. The tsunami propagation incorporated here was modelled by the Bureau of Meteorology, Australia for six hours using a time step of 5 seconds (4320 time steps in total).

The output of the MOST model is produced for the sole purpose of providing an approximation of the tsunami's size and momentum that can be used to estimate the tsunami run-up. ANUGA could also have been used to model the propagation of the tsunami in the open ocean. The capabilities of the numerical scheme over such a large extent, however, have not been adequately tested. This issue will be addressed in future work.

2.3 Tsunami Inundation

When coupled with ANUGA, the utility of MOST diminishes as water depth decreases. Consequently the open ocean boundary of the ANUGA simulation was chosen to roughly follow the 100m depth contour along the Coast of Thailand. The North-South extent of the computational domain was chosen to maximise the number of locations for which run-up depths were measured, whilst keeping the computational domain 'small enough' to avoid excessively large computational time. The computational domain and locations of the tide gauges and run-up observations is shown in Figure 2

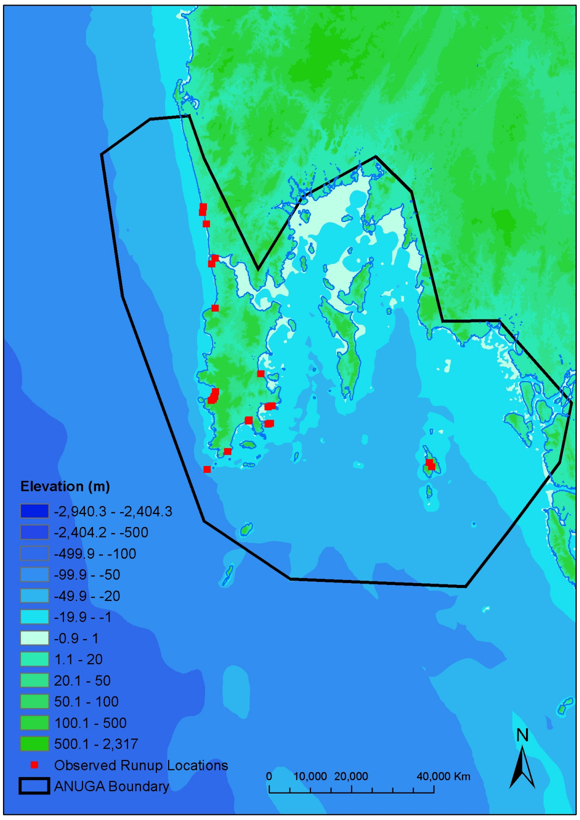

Figure 2. Locations of the Taphao-Noi tide gauge, the Mercator Yacht and observed run-up.

The domain was discretised into approximately 350,000 triangles. The resolution of the grid was increased in certain regions to efficiently increase the accuracy of the simulation. The grid resolution ranged between a maximum triangle area of 5×10^5 m^2 near the Western ocean boundary to 500 m^2 in the small regions surrounding the run-up points and tide gauges. The triangle size around islands and obstacles which "significantly affect" the tsunami was also reduced. The authors used their discretion to determine what obstacles significantly affect the wave through an iterative process.

The bathymetry and topography of the region was estimated using a data set produced by NOAA. Specifically the bathymetry was specified on a 2 arc minute grid (ETOPO2) and the topography on a 3 arc second grid. A penalised least squares technique was then used to interpolate the elevation onto the computational grid.

2.3.1 Boundary Conditions

The boundary of the computational domain comprises 16 linear segments. Those segments which lie entirely on land were set as reflective boundaries. The segments that lie in depths greater than 50m were set as Dirichlet boundary conditions with the stage (water elevation) equal to zero. Finally all other segments were time varying boundaries. The value at these boundaries was interpolated from the estimates of the wave depth and momentum obtained from the MOST simulation.

3 RESULTS

3.1 Tide Gauges

Tsunami wave heights were measured at two sites off the Thailand Coast. The tsunami was recorded at Taphao-Noi on the east coast of Thailand, sheltered on the east side of Phuket (Merrifield *et al.* 2005) and by the Belgian yacht "Mercator" with a depth echosounder. The tide gauge was positioned a small distance off Taphao-Noi Island (7.833^{0}N, 98.417^{0}E) in approximately 5m of water at the time of the event and the yacht was anchored approximately 1.6 km off Nai Harn Bay, SW of Phuket (7.733^{0}N, 98.283^{0}E), in approximately 12m of water.

Figures 3 and 4 graph the observed and simulated elevations at these sites. Both these tide gauges are close to the source area and display a leading depression wave. This agrees with observations that the ocean retreated on the eastern side of the tsunami source before the tsunami arrived. The model appears to be simulating the arrival times of the first depression of these waves well. At Taphao-Noi the first crest arrived 2h12' after the earthquake event, 4 minutes before the observed arrival time and the first crest arrived at the Mercator yacht 1h45' after the tsunami was triggered, 4 minutes before the observed arrival time.

After the first arrival the wave signal begins to distort. The amplitude of the second crest predicted at both sites is smaller than those observed and subsequent peaks are out of phase. From Figure 4 it is evident that the amplitude of the wave at the Mercator yacht is underestimated. Grilli *et al.* (2006) also had difficulty reproducing the wave signal at the Mercator yacht after the arrival of the initial depression.

The distortions of the tsunami signal, at both sites, are most likely caused by misrepresentation of the water depths at and surrounding the observation points during the simulation. For example, Taphao-Noi Island, which greatly influences local wave patterns (reflections, resonance, interference etc) is not resolved by the local bathymetry data. A similar inaccuracy is manifest in the region surrounding the Mercator yacht, in which the undisturbed water depth was overestimated. When simulated using coarse bathymetry data, the undisturbed water depth at the Mercator yacht was 36m in comparison to an observed depth of 12m.

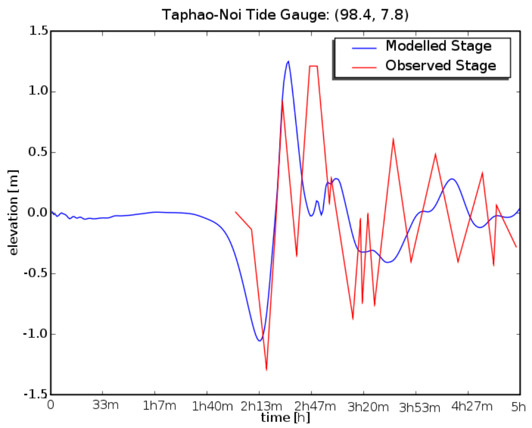

Figure 3. The simulated and observed tsunami elevations at Taphao-Noi.

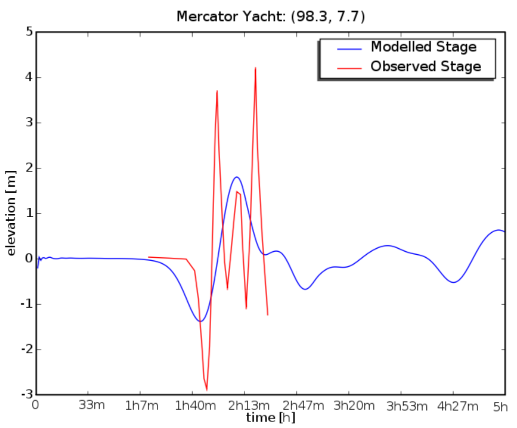

Figure 4. The simulated and observed tsunami elevations at the Mercator yacht.

3.2 run-up Measurements

Table 1 lists the locations and elevations of the observed maximum run-up measurements along the Thailand coast. The simulated run-up values are in good agreement with observations listed on the NGDC Tsunami database[2]. The simulated values presented are the maximum run-up predicted by the simulation in a 500m by 500m square centered at the location where the observed run-up value was measured. The distance between the observed and simulated sites where maximum run-up occurred ranged from 47.26 m at Patong Beach to 343.27 m at Rowai beach.

[2]http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml

Table 1 also highlights the misrepresentation of the local coastline. Large discrepancies, in the order of metres, exist between the modelled and observed elevation. Furthermore, three run-up observation sites were deemed to be initially underwater. This suggests that results could be improved further by employing finer bathymetric data when it becomes available. Yet, despite the poor bathymetric data there is still a moderate correlation between the observed and modelled run-up values suggesting that local variations in the energy of the tsunami are being approximated reasonably well.

4 DISCUSSION AND CONCLUSIONS

We have simulated the inundation of the tsunami of a small irregular region of the west Thailand coast surrounding Phuket using the inundation tool ANUGA. The tsunami size and position at the boundaries of this region were estimated using the MOST model which was used to simulate the generation and propagation of the tsunami in the deep ocean. Specifically the parameterisation of Greensdale *et al.* (2007) was used to describe the tsunami source and the subsequent wave elevation and momentum required by the inundation simulation were interpolated from the MOST simulation at each time step.

Comparison between observed and modelled run-up at 18 sites show reasonable agreement. We also find a modest agreement between the observed and modelled tsunami signal at the two tide gauge sites. The arrival times of the tsunami is approximated well at both sites. The amplitude of the first trough and peak is approximated well at the first tide gauge (Taphao-Noi), however the amplitude of the first wave was underestimated at the second gauge (Mercator yacht). The amplitude of subsequent peaks and troughs, at both gauges, are underestimated and a phase lag between the observed and modelled arrival times of wave peaks is evident after the first peak. Grilli *et al.* (2006) also could not reproduce the correct arrival time at the Taphao-Noi tide gauge or reproduce the signal at the Mercator yacht.

The performance of the model could be improved by using finer bathymetric data, which at present cannot be obtained by the authors, and by a more accurate estimation of the initial tsunami source. The wave height observed at a particular point along the

Table 1. Observed and stimulated run-up (meters) at 18 locations along the Thailand coastline. The modelled elevation column lists the elevation approximated by the model bathymetry data. The field survey column displays the observed topographic elevation and the model column lists the highest elevation inundated, during the simulation, within a 500m by 500m square centered at the listed location.

Location	Lat. N	Long. E	Modelled Elevation	Field Survey	Model
Khao Lak	8.272	98.28	3.60	4.30	4.68
Khao Lak	8.197	98.3	7.00	3.11	3.83
Khao Lak	8.184	98.292	6.28	4.83	4.75
Leam Him Phuket	7.943	98.401	-1.14	0.72	1.69
Moodong Canal Phuket	7.842	98.375	5.00	3.15	4.67
Nai Rai	8.31	98.273	8.00	5.29	4.73
Nai Yang beach Phuket	8.087	98.3	9.00	4.07	5.00
Patong Beach Phuket	7.884	98.292	0.00	5.09	8.31
Patong Beach Phuket	7.904	98.301	3.00	4.90	6.22
Patong Beach Phuket	7.892	98.298	10.00	5.02	7.02
Patong Beach Phuket	7.894	98.299	18.00	5.48	7.05
Patong Beach Phuket	7.887	98.296	13.00	5.44	7.86
Phalai Village Phuket	7.839	98.373	-0.34	2.75	4.67
Phi Phi Don (Nth Coast)	7.739	98.777	7.00	5.84	0.64
Phi Phi Don (Sth Coast)	7.748	98.772	-0.55	4.58	4.70
Rai Dan	8.297	98.272	-3.01	6.77	1.81
Rawai Beach Phuket	7.772	98.328	-7.05	2.43	0.55
Sire Village Phuket	7.873	98.425	2.00	2.67	5.92

coast is strongly influenced by relatively small scale bathymetric and coastal features which may be under-resolved by the current computational mesh or poorly represented by the sparse bathymetry and topography data set. These problems may also cause errors in simulated arrival times in coastal areas adjacent to regions consisting of inaccurate bathymetry data. Titov and Gonzalez (1997) state that for most cases 10-50m horizontal resolution of bathymetry data is essential. As mentioned above we could only obtain 2 arc minute (3.6km) bathymetry which is most likely insufficient. Topography is approximated using a 3 arc second (90m) grid which is much more appropriate. However, when combined, these data sets do not reproduce the position of coastline well. If a finer resolved bathymetric data set could be obtained for the shallow waters of the Thai coast (say in regions with important bathymetric features) a much better result could be expected.

The approximation of the tsunami source also affects the near shore amplitude of the tsunami wave. As the graphs and tables above show, the amplitude of the tsunami is at times misrepresented and this is partly due to an suboptimal reproduction of the initial coseismic displacement. Grilli *et al.* (2006) obtain improved reproduction of tsunami amplitude when they optimise the parameters of the tsunami source based on the model's ability to reproduce certain observed behaviour. We would like to think, and will explore, that it is this optimisation that yields more accurate results rather than any deficiency of the ANUGA model.

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