Geowave 1.1 Tutorial

Tsunami Community Models

This tutorial has been revised in December, 2009 for Geowave version 1.1, a new release of the software that supercedes version 1.0. Version 1.1 fixes several minor bugs in the original release, and provides a new tsunami source choice, in addition to extensive validation efforts. The two models discussed in this work, TOPICS and Geowave, are available to tsunami researchers around the world. The models are collectively referred to as Tsunami Community Models. A stated goal of the Tsunami Community is to mitigate tsunami hazards. These models facilitate tsunami research, tsunami hazard assessment, and tsunami risk assessment (e.g. Grossi et al., 2008), all aspects of tsunami hazard mitigation. Geowave has been available to tsunami researchers for more than 6 years, has been distributed to more than 40 research groups around the world, and is run in more than a dozen countries around the world. It is by now a well established modeling tool.

One fact stands above all others as the clearest testament of these Tsunami Community Models. Many Geowave case studies of historical tsunamis have reproduced all available tsunami observations and records. Such a standard of model accuracy is essential to the development and advancement of tsunami science. This tutorial will assist users to achieve this standard for themselves. The Tsunami Community Models are as accurate as the geology of tsunami generation, and the bathymetry grid being used. Accurate inputs and proper implementation should produce excellent simulation results. Alternatively, these models are accurate enough to inform the user about the geology of tsunami generation. A poor fit with observations is usually an indication of poor geological inputs. There is rarely much middle ground.

1. TOPICS

Version 1.2 of the "Tsunami Open and Progressive Initial Conditions System" (TOPICS) allows tsunami scientists to calculate six types of tsunami sources. These include earthquake tsunamis, underwater slide tsunamis, underwater slump tsunamis, subaerial debris flow tsunamis, pyroclastic flow tsunamis, and design wave tsunamis. TOPICS is an approximate simulation tool that provides surface elevations and water velocities as initial conditions for tsunami propagation models. In some instances, we are concerned with near-field wave dynamics shortly after tsunami generation. A three-dimensional fluid dynamic model, such as that of Grilli and Watts (2001) or Grilli et al. (2002), may be needed for such problems. TOPICS is a work in progress that is regularly being upgraded.

For vertical coseismic displacement, TOPICS is based on the half-plane solution of an elastic dislocation problem (Okada, 1985). A planar fault of length L and width W is discretized into many small trapezoids and the point source solution of Okada (1985) is used to sum the contributions made by each trapezoid to vertical coseismic displacement, based on the actual depth of each trapezoid. The shear modulus μ can be specified based on the depth of the earthquake centroid as well as other seismic and geological descriptors. TOPICS outputs a characteristic wavelength λ_o that is the smaller of the fault dimensions L or W, and a characteristic tsunami amplitude η_o that is the minimum depression found from the coseismic displacement. The seismic moment M_o is proportional to but slightly less than $\mu LW\Delta$ because a Gaussian slip distribution is assumed about the centroid, where Δ is the maximum slip. TOPICS allows for the superposition of multiple fault planes, which can be assembled into complex fault structures or slip distributions.

For underwater landslides, the initial free surface elevation and water velocities in TOPICS were derived from multivariate, semi-empirical curve fits as a function of non-dimensional parameters characterizing the landslide (e.g., density, geometry, etc.) and the local bathymetry (e.g., slope, depth, etc.). Water velocities are new to version 1.2 of TOPICS. Relevant non-dimensional parameters were selected based on the scaling laws of Watts (1998, 2000). Numerical experiments were carried out first with the 2D model of Grilli and Watts (1999) and the curve fits were then modified based on results from a more recent 3D model (Grilli and Watts, 2001; Grilli *et al.*, 2002). The curve fitting technique that led to TOPICS was initially proposed by Grilli and Watts (1999), applied in several geological studies (e.g., Goldfinger et al., 2000; McAdoo and Watts, 2004; von Huene et al., 2004), and derived more accurately by Grilli and Watts (2005) as well as Watts et al. (2005). The duration of landslide acceleration t_o in the numerical simulations is also the duration of tsunami generation (Watts, 1998; Watts and Grilli, 2003). Consequently, TOPICS provides a landslide tsunami initial condition at time $t = t_o$, as if results from the models of Grilli and Watts (1999) or Grilli *et al*. (2002) were being transferred directly to the tsunami propagation model at that instant of time.

A similar curve fitting approach provides tsunami initial conditions for subaerial landslides, debris flows, and pyroclastic flows impacting water. For these tsunami sources, the curve fits within TOPICS are derived from the experimental work of Walder et al. (2003). There is also experimental work that validates the underwater landslide tsunami sources within TOPICS (e.g., Enet and Grilli, 2007). Therefore, the tsunami sources within TOPICS have both numerical and experimental origins, and they have been subject to validation work. Consequently, it is correct to state that TOPICS provides free surface shapes from curve fits made at time $t= t_o$, as if experimental results were being transferred directly to a tsunami propagation model.

2. Geowave

FUNWAVE is a long wave propagation model based on the Boussinesq approximation of wave dynamics (Wei et al., 1995; Wei and Kirby, 1995). The Boussinesq approximation expands linear long wave theory into nonlinear and dispersive regimes. FUNWAVE has been developed over at least 15 years at the University of Deleware's Center for Applied Coastal Research (see Chen et al., 2000; Kennedy et al., 2000). The propagation model is fully nonlinear and able to simulate a wide range of wavelengths not limited to long waves (Wei et al., 1995). FUNWAVE is designed to generate wave sources (Wei et al., 1999), to produce open boundary conditions (Wei and Kirby, 1995), and to model the physics of breaking waves and runup (Chen et al., 2000; Kennedy et al., 2000). FUNWAVE details can be found in the PDF file "cacr-98-06.pdf", prepared for users in coastal engineering for which FUNWAVE is a community model. The file is available at http://chinacat.coastal.udel.edu/~kirby/programs/funwave/funwave.html.

Boussinesq models retain significant advantages over Nonlinear Shallow Water Wave (NSWW) models in coastal engineering. In the past, those advantages were not believed to extend to tsunami simulations, where the shallow water approximation is thought to remain valid. However, Boussinesq models have generally provided more realistic simulation results in the open literature than NSWW models wherever they are applied (e.g., Watts et al., 2003). There are several reasons for this, although the principal one is that the uniform horizontal velocity profile over depth assumed by NSWW equations become inaccurate during propagation of steep waves over a nonuniform bottom, during propagation into deep water, and during runup on intermediate slopes. Therefore, Boussinesq wave equations provide for a much more versatile and realistic range of wave dynamics. Specific tsunami wave dynamics captured by Boussinesq wave equations, and not captured by NSWW equations, are discussed below. Boussinesq models provide real progress in tsunami science.

The combined models TOPICS and FUNWAVE are collectively called Geowave, a name that reflects the geological origin of tsunamis. TOPICS accounts for tsunami generation, while FUNWAVE carries out tsunami propagation and inundation. Geowave includes significant original programming architecture needed to combine TOPICS and FUNWAVE. For earthquakes, the surface elevation from TOPICS is assumed to occur at the time of the main shock. For landslides, the surface elevation and velocities from TOPICS are input into FUNWAVE at time t_o after the landslide initiates motion or impacts the water. This is the only time at which TOPICS can transfer the initial conditions to the tsunami propagation model, and this time is fixed by landslide dynamics that are specific to each event. Tsunami source timing is handled automatically by Geowave.

There have been numerous publications that use Geowave to model tsunamis. The first such publication in the open scientific literature is Watts et al. (2003). Since then, the use of Geowave has expanded considerably. Geowave has been validated based on historical case studies of pyroclastic flows (Waythomas and Watts, 2003; Mattioli et al., 2007), underwater landslides (Watts et al., 2003; Fryer et al., 2004; Day et al., 2005; Greene et al., 2006; Rahiman et al., 2007; Tappin et al., 2008), earthquake generated tsunamis (Day et al., 2005; Grilli et al., 2007; Ioualalen et al., 2006, 2007), and debris flows (Walder et al., 2006; Waythomas et al., 2006). The user is encouraged to access and study these publications, as they provide templates for the uses and applications of Geowave.

a) Differences Between FUNWAVE and Geowave

The tsunami propagation part of Geowave has a number of important differences from FUNWAVE that are described here. First of all, FUNWAVE was designed for periodic or random waves traveling towards a beach located in the positive x-direction. Any software dedicated to this specific problem was removed. Second, FUNWAVE employed several linear approximations, assuming that the wave elevation was typically much smaller than the water depth. These approximations were removed because of the extremely nonlinear character of some tsunamis. Third, the input and output binary files were replaced with text-based input and output files that were interfaced with TOPICS. The number of output files was significantly expanded, and these output files were designed to be plotted by Surfer software. Fourth, a handful of FUNWAVE parameters were optimized for tsunami simulation stability, and these values were then hardwired into the software. They have not been changed since the birth of Geowave. Fifth, FUNWAVE requires free surface and velocity inputs at more than one time step in order to launch the fourth order predictor-corrector scheme. Geowave is set up to use a single set of input files at one time step as the initial condition.

b) Geowave Boundary Condition

There is no known and exact outgoing (or open) boundary condition for the Boussinesq equations. Instead, the outgoing boundary conditions of Geowave consist of sponge layers 10 nodes thick along the edge of the grid, whether land or water. The sponge layer divides the water wave amplitude and velocities by some number greater than one at each time step, thereby reducing the amplitude of water waves near the boundary to nothing. Some tsunami grids are open, while some are closed in by land. A simulation grid surrounded by land produces much less noise than open grids, in part because the sponge layer is a crude way to eliminate waves within the simulation domain. For example, a small amount of wave reflection occurs off of the sponge layers and back into the simulation domain. A user of Geowave must appreciate that twenty nodes in the x and y directions are dedicated to the sponge layers and that these nodes will not be part of a reasonable solution. If the boundary consists of land more than 10 nodes deep, then these sponge layers should have no noticeable effect on simulation results or appearance. Simulation results should not be sought anywhere near the edges of simulation domains and the sponge layers.

c) Running a Simulation

The first choice in Geowave is to run either fourth order Boussinesq or NSWW equations in the simulation. This feature enables comparisons between the two sets of wave equations for identical discretization scheme, identical software architecture, and identical simulation domain. For some simulations, the results are nearly identical. For many other simulations, the advantages of Boussinesq wave equations are readily apparent. Users are encouraged to use the Boussinesq wave equations almost exclusively. The simulation run times are similar. There are no known benefits for using NSWW equations.

A Geowave simulation requires a bathymetric grid file as well as precise geological data on the location, orientation, and description of up to nine tsunami sources. The quality of the bathymetry grid file will determine the quality of simulation results. The format of the bathymetry grid file is determined by the parameter “grid”. The current file format consists exclusively of Surfer ASCII grid files. The user may want to add other possible choices for the grid file format. This would require adding software to read and write another grid file format.

Current Geowave simulations are limited to 800 by 800 nodes, 8001 time steps, and 30 gauge or marker files in the “parameter” statement at the top of each program and subroutine. The user may need to change the values of “iq”, “jq”, “nq”, “ngm” in every "parameter" statement of the program and each subroutine to accommodate the size of a particular simulation domain. This is most easily done with the “replace all” function in a text editor. The user should be forewarned that the program may not compile or run if the values of “iq”, “jq”, “nq”, “ngm” are too large. Some compilers and operating systems limit FORTRAN applications to 512 Mb or 256 Mb of RAM, even if the machine has much more available memory. The image size or allocation of RAM should be noted whenever the source code is recompiled.

Geowave will prompt the user for a number of parameters that need to be entered, including the number of numerical wave gauges and floating Lagrangian markers. If that number is greater than zero, then the name of a free format text file will be requested that has either one (x,y) pair per row in grid units, or one (i,j) pair per row in node numbers. The maximum number of gauges and markers is 30 each. The gauges and markers can be at either distinct locations with separate text files, or synonymous locations with the same text file. The software checks if the gauges and markers are in the simulation domain. That is the only check carried out regarding gauges and markers.

There are seven choices for tsunami sources in Geowave. These tsunami sources cover many of the geological events and engineering requirements for tsunami hazard assessment. Each tsunami source asks the user to enter a number of input parameters, almost all of which are expected to have positive values, with the noted exception of tsunami source locations (i.e., the coordinates may be positive or negative). For example, all times are assumed to be positive, and all water depths are positive. SI units are used for the input parameters. The specific tsunami sources are as follows:

0) a coseismic displacement source
1) a translational slide source
2) a rotational slump source
3) a subaerial landslide source
4) a pyroclastic flow source
5) a design wave train source
6) a separate tsunami source

Earthquake tsunami sources have two different possible representations, either as a rectangular fault plane, or as a more general trapezoidal fault plane. Up to nine fault planes can be assembled to form complex fault structures, in a variety of shapes and configurations. There are four mass failure tsunami sources, specifically two kinds of submarine landslides, subaerial landslides plunging into the water, and volcanic pyroclastic flows flowing onto water. Partially submerged landslide tsunamis are often modeled as shallow submerged slides or slumps. A wave train coming from any direction can be constructed as a tsunami source. Wave trains often approximate tsunamis and provide significant engineering value (to study resonance issues, design criteria, etc.). Last of all, a separate tsunami source can be introduced, apart from TOPICS, and imported into Geowave. A program called “Separate.f” is available to generate these tsunami sources, although the user will need to modify the existing mathematical equations in the program. Each simulation can have up to nine distinct tsunami sources from any of the above choices. This enables simulations of geological events with both earthquakes and landslides, or geological events with volcanic eruptions and failures. Each tsunami source also has its own distinct time of tsunami generation, enabling the assembly and simulation of complex geological events.

Geowave provides the time step “dt” on the screen and then asks for the number of time steps in the simulation. When choosing the number of time steps for a tsunami simulation, it is often a good idea to have 2-3 times more time steps than the minimum necessary. This gives plenty of time for tsunami interactions in shallow water along an entire affected coastline. Even in simple tsunami scenarios, it is surprisingly common to find tsunami activity lasting for hours in some locations.

The number of time step between movie grid files (an integer called “itdel”) determines the frequency with which free surface grid files are output by Geowave into the folder “Movie”. Please note that a small number of time steps between movie grid files might fill a hard drive, especially for larger grid files or high resolution movies. The user should be careful to estimate the required hard drive space for all output grid files, something that can be estimated in advance. The user also specifies the time step for which movie grid files cease to be output. This is useful when a simulation continues well after a tsunami finishes attacking a coastline of interest. In such cases, long after tsunami attack, a movie will often fail to show substantial wave activity.

Geowave gives the user some flexibility over the times during which information is gathered about the simulation. Under certain circumstances, the user may want to limit the initial and final times for which the output grid files are calculated. This is done with the parameters “tout1” and “tout2”, the beginning and ending time limits, respectively. These two time parameters could be set to capture a) transient effects early in a simulation, such as shoaling of a specific wave at a specific location, or b) steady state effects later in a simulation, such as harbor resonance from tsunami attack. Otherwise, the user should specify tout1=0 and “tout2” greater than the last time of the simulation. In this case, the grid files provide values gathered over the entire simulation.

In order to assist in visually stacking the water surface with topographic data in plotting software, the user can specify the value of “zlim” as a no-data value wherever the land is currently uncovered by water. In output grid files, the value of “zlim” will appear wherever there is dry land. The specific value chosen for “zlim” depends on the software package used to plot results, and the purpose of the plots. Sometimes an extremely large positive or negative value is useful, and sometimes a value of zero will be useful. The user needs to establish post-processing software and procedures to find a useful value for this parameter.

d) Geowave Input Files

All input grid files are currently limited to be Surfer ASCII grid files. The required input files or initial conditions are the free surface elevation and water velocity components at the beginning of the simulation, “surface” and “uvel” and “vvel”, respectively. There is a specific file nomenclature used by Geowave for these initial conditions. For example, the free surface initial condition for the second tsunami source will be “surface2.grd” and so on. The initial conditions must match the size of the bathymetry grid file. This happens automatically for tsunami sources generated by TOPICS, but must be checked for separate tsunami sources.

The bathymetry grid file, typically called “bathy.grd” is needed to launch a simulation. Excessive noise and failure to converge may result if a dense bathymetry grid is used in a simulation. Higher order terms and derivatives in the Boussinesq scheme can rapidly exacerbate any noise that exists in the bathymetry file. The user should avoid generating grids with more than 30-40 nodes per wavelength, unless the bathymetry is also very smooth. Instability over deep water often appears first as a fuzzy free surface that ruins the simulation appearance. This instability can often be overcome or solved by smoothing the bathymetry. The program typically needs 7 or more nodes to resolve a water wave properly, so there is a practical grid size that works for every simulation, often 10-20 nodes per wavelength. Since tsunami wavelength changes with water depth, the chosen grid size corresponds to a chosen location for either tsunami propagation or tsunami inundation.

Geowave will make water depths positive and convert these depths to meters, as required within FUNWAVE. Moreover, Geowave will calculate typical grid node distances “dx” and “dy” by finding the conversion from grid units to meters. The program assumes a uniform grid with dx=dy, and checks the grid to see if dx and dy are close. Simulations carried out in UTM grid coordinates with uniform grid size will be the most accurate. Coordinate systems other than UTM will likely introduce errors due to grid distortion.

In FUNWAVE, the wave elevation nodes coincide with the velocity nodes. Therefore, “slots” or porous topography are used to simulate runup, because any node with zero elevation cannot receive a flux of water to change the elevation given the node structure. Dry nodes would have to remain dry if ground was not permeable. The porous topography allows the water to propagate within the land as if it were groundwater. Runup occurs when the elevation of the groundwater rises above that of the land, as in a water spring. This feature of Geowave may in fact capture some aspects of tsunami interaction with debris, vegetation, and topography that occur at scales smaller than the grid size. Therefore, while the specific physics of the permeable ground may not be correct, some of the outcomes may model or capture phenomena during real tsunamis. The runup results achieved with Geowave during case studies are typically excellent.

e) Geowave Output Files

Free surface grid files are placed in a folder called "Movie" that the user must create prior to running a simulation. The grid files placed in the folder “Movie” are often used to visualize the initial stages of tsunami attack, up to some time step where wave activity has reached a specific location, or reduced below a certain level. The grid files are readily turned into image files and sewn together into an animation of tsunami attack.

The files are also quite useful for tracking the progress of a simulation, either in real time, or after the fact. These snapshots of the free surface help describe what is going on.

The user must also create a folder called "Data" for the wave gauge files and the Lagrangian marker files. There can be up to thirty numerical wave gauges and up to thirty floating Lagrangian markers. These can be anywhere in the simulation domain. The numerical wave gauge files provide

- time of the record
- water elevation or depression from sea level
- x-direction velocity at depth $z = -0.531\ h$
- y-direction velocity at depth $z = -0.531\ h$
- x-direction flux in meters squared per second
- y-direction flux in meters squared per second
- water depth at the numerical wave gauge

in that order and at every time step. The numerical wave gauges provide a record of wave activity at a specific location. A wave gauge located (temporarily) on exposed sea floor will return zeros for water elevation or depression. The floating Lagrangian markers record

- time of the record
- x-position of the floating marker
- y-position of the floating marker
- water elevation at the marker
- x-direction velocity at $z = -0.531\ h$
- y-direction velocity at $z = -0.531\ h$
- water depth at the current marker location

in that order and at every time step. The floating Lagrangian markers provide the motion of water particles in the tsunami. They are particularly useful to estimate boat motion, debris field motion, and similar effects of tsunami impact.

Output grid files appear in the folder “Grid” of the simulation. These files are written under the condition that the simulation has completed without convergence problems, and that the last simulation time is greater than the input parameter “tout1”. Consequently, it is possible, although not advisable, to run Geowave without producing these files. In general, the output grid files collect and represent data from time “tout1” till the time “tout2” in a simulation. The file extension used below is “.grd” and is stored by the parameter “output” in Geowave. The format of the grid files is controlled by the parameters “type” and “itype”. These two parameters are called upon frequently throughout Geowave. Nevertheless, the user could program a different file extension and file format for some software other than Surfer. The user is advised to use the “find” command in a text editor when making such changes, to ensure that all uses of these parameters within Geowave are found. The output grid files produced are as follows:

Zmax.grd	Maximum free surface elevation at specified times
Zmin.grd	Minimum free surface elevation at specified times
Zwavht.grd	Difference between maximum and minimum
Tmax.grd	Time of maximum free surface elevation
Tmin.grd	Time of minimum free surface elevation
Tfirst.grd	First time that a grid node has elevation wave
Tlast.grd	Last time that a grid node was wetted
Curmax.grd	Maximum water velocity magnitude in time
Curang.grd	Orientation of the maximum velocity vector
Flxmax.grd	Maximum water flux magnitude in time
Flxang.grd	Orientation of the maximum flux vector
Brwvtim.grd	Time of latest wave breaking at node
Brwvvis.grd	Maximum value of breaking wave coefficient
Wetlnd.grd	Binary indication if node was ever wetted

Etn.grd	Free surface difference from sea level at last time step
Un.grd	Velocity in x-direction at z =-0.531 h at last time step
Vn.grd	Velocity in y-direction at z =-0.531 h at last time step

The grid files “tfirst” and “tmax” and “tlast” are particularly useful for tsunami warning and tsunami evacuation purposes. The grid files “zmax” and “curmax” and “flxmax” are particularly useful for tsunami hazard and risk assessment. The grid file “brwvvis” is great for locating regions of wave breaking. The grid file “wetlnd” can be used as a mask for certain kinds of plots or images involving tsunami runup and inundation. The grid files “etn” and “un” and “vn” are particularly useful as initial conditions for resuming a simulation. These are very useful grid files. All grid files output by Geowave have a postscript that identifies simulation parameters as well as the time at which the file is produced within the simulation. This allows the grid files to be distinguished with simulation specific information, in case many sensitivity analyses are being run for the same tsunami event.

Please note that some computer systems use "/" to denote a folder or file pathway, while others use "\" when describing a folder or file pathway. Users running the executable version of Geowave on a Windows operating system should not encounter any problems. This only matters if the user is going to recompile the source code on another operating system. In that case, the current designation of a folder or file pathway in Geowave could become a compilation error. This is an easy matter to fix with the “replace all” command in a text editor.

f) Geowave Fails to Converge

A grid that has more than 40 nodes per wavelength can in some instances experience stability problems attributed to noise in the bathymetry data. This effect becomes more pronounced as the nonlinearity of a tsunami increases. The simplest solutions are to smooth the existing bathymetry, or to reduce the node density by producing a new bathymetry grid file. In case a simulation does not converge at a given time step, then there are two diagnostic grid files that are output just before the program Geowave stops. The grid file “zdiff.grd” provides the convergence criterion encountered at the third iteration of the specific time step that failed to converge. This grid file helps locate the regions that prevented convergence. The grid file “idiff.grd” provides an integer that indicates the number of times the convergence criterion remained larger than the value stored in “zdiff.grd”, which is a reasonable indicator of failure to converge. The user should note that failure to converge can propagate rapidly throughout the entire simulation domain. Therefore, the grid file “zdiff.grd” may be a more important indicator of where instability began. Convergence matters are best addressed through the grid size and quality of the bathymetry grid file.

g) Geowave Test Case

The user can become more familiar with Geowave by installing the folder “Test” onto a hard drive, and (compiling the source code before) running the test case. The Papua New Guinea bathymetry file “PNG_Bathy.grd” is in the Surfer ASCII grid file format, and can be opened with a text editor. The grid spacing dx=100 m and dy=100 m has uniform spatial steps in both directions. The grid resolution is not sufficient to resolve runup for this tsunami (see Tappin et al., 2008), and the bathymetry grid provided here is not intended for scientific work. The grid file has positive depths in units of meters, and UTM grid spacing in units of meters as well. The Central Meridian for the UTM coordinates is 145 degrees East. The bathymetry grid should be smoothed, because it is based on noisy multibeam data, and because it involves a highly gullied underwater terrain. There are no numerical wave gauges or floating Lagrangian markers in this test case.

The tsunami sources are described in the two text files “PNG_out1.txt” and “PNG_out2.txt” for the earthquake and slump tsunami sources, respectively. The two text files were originally output by Geowave as the files “out1.txt” and “out2.txt”, respectively, and renamed so that users can access and enter the tsunami source data on their own. If the original files had not been renamed, then Geowave would have overwritten them. The tsunami source in “PNG_out1.txt” describes the earthquake main shock, which also serves as the origin of time in the test case. The tsunami source in “PNG_out2.txt” describes the underwater slump, which failed around 720 seconds after the main shock, and therefore has a tsunami source time of 720 seconds. Therefore, the beginning time of tsunami generation for the second source is 720 seconds, which is critical information to run this test case properly. The user needs to indicate that there are two tsunami sources, the first being an earthquake tsunami with generation beginning at zero seconds, and the second being an underwater slump tsunami with generation beginning at 720 seconds. While running the simulation, Geowave will automatically insert the second tsunami source at the appropriate time, which will be 720 seconds plus the duration of tsunami generation t_o. Tsunami sources are inserted into Geowave after tsunami generation is complete.

The user should double check the text files “out1.txt” and “out2.txt” output by Geowave, verify the earthquake tsunami grid file “surface1.grd” has maximum amplitudes of 0.2-0.3 m, and verify the landslide tsunami grid file “surface2.grd” has maximum amplitudes of 25-35 m. Moreover, the tsunami sources are geologically relevant. The user can verify that the earthquake coseismic displacement matches known geological features of the Sissano region. Sissano Lagoon itself subsided during this event, which was documented by various post-event surveys, and which is consistent with the lagoon shape and the formation of a mangrove swamp over time. Moreover, the offshore uplift from the main shock overlays a major uplifted feature called the “pop up block” situated in water 1600 m deep. The base of this feature was observed by an underwater ROV survey in 1999 to have fresh uplift on the order of 10 cm (Tappin et al., 2001, 2003). The precise dimensions of the slump come from seismic surveys over the mass failure, and its presence has been confirmed by multiple direct observation with both ROV and manned submersible (Tappin et al., 2008). These geological facts confirm the relevance and accuracy of the chosen tsunami sources. If the tsunami sources are geologically correct, then the tsunami observations will be reproduced by simulation results.

The complete simulation needs to run for a total of at least 25 minutes (or 1500 seconds) to capture tsunami inundation across Sissano Lagoon. This fact dictates the minimum number of time steps needed in the simulation. In this case, the user calculates the minimum number of time steps by dividing 1500 seconds by the time step dt=0.1475 seconds provided by Geowave. The user is encouraged to run the simulation for as long as possible, which would require changing the Geowave parameter "nq" such that N>10,000 time steps is allowed. Such a change would require recompiling Geowave. A smooth animation of this simulation would require at least 500 movie grid files. These same movie grid files can also be used to keep track of simulation progress in real time, although only 20-50 movie grid files are needed to do this properly. The difference in hard drive space between a smooth animation and just tracking the simulation is substantial. The user needs to have a clear agenda and use for these files.

h) Water Wave Phenomena

It would not be surprising to report that bathymetry grid size refinement tends to increase tsunami runup and inundation until convergence is reached. This is a well known and well studied fact that all users of Geowave should check for themselves during case studies (e.g., Ioualalen et al., 2007; Tappin et al., 2008). The only way to know if a bathymetry grid is sufficiently refined to capture runup is to keep on refining the grid. For example, it is common to use a 200 m grid for earthquake tsunamis, and a 50 m grid for shorter wavelength landslide tsunamis. There is a numerical artifact to look for that is a clear indicator that a bathymetry grid needs to be further refined. If the tsunami amplitude decreases suddenly as it starts shoaling in shallow water just before the shoreline, then this may be a numerical artifact. What happens is the wave equations simply do not admit wave propagation into such a wide grid spacing in such shallow water. The bathymetry grid needs to be refined. Sometimes the maximum tsunami amplitude will occur just offshore because of wave breaking, which is a real phenomenon familiar from observing wind waves at a beach. Therefore, the specific wave physics at play must be checked each and every time (with the output grid file "brwvvis.grd") to distinguish what is real physics from what are numerical artifacts.

There are important and hazardous wave phenomena that a Boussinesq model readily captures, and NSWW models capture with difficulty, if at all. One such example is shoaling of the highly nonlinear and relatively short wavelength landslide tsunami in the 1998 Papua New Guinea event, presented above as the test case for Geowave users. Tappin et al. (2008) show that three distinct NSWW models with three different discretization schemes all fail to propagate the tsunami past the 20 m depth contour, effectively causing the tsunami to vanish roughly 2000 m before it reaches the sand spit in front of Sissano Lagoon. The three NSWW models in question are TUNAMI-N2, MOST, and Geowave run in NSWW mode. None of these models propagated the tsunami into water shallower than 20 m deep, and numerical artifacts inherent to the NSWW equations cause the tsunami to literally disappear, when using a 100 m grid size.

Another wave phenomenon that Boussinesq models capture is edge waves propagating parallel to the coastline, often in a sequence of elevation and depression waves traveling along the coastline. Geowave produces an abundance of large amplitude edge waves when tsunamis attack a rough coastline (e.g., Waythomas and Watts, 2003; Day et al., 2005; Mattioli *et al.*, 2007; Rahiman et al., 2007). These edge waves almost always produce the greatest tsunami hazards and risks, and they tend to be commonplace or ubiquitous. What happens is that edge waves interact with shoreline features and with each other to produce the largest tsunami runup (e.g., Greene et al., 2006). That is, hazardous tsunami runup does not occur from tsunami attack perpendicular to the shoreline alone. Hazardous tsunami ruup also happens when positive edge waves interact with each other, or when edge waves are trapped by some shoreline feature. These edge waves are traveling parallel to the shoreline, not perpendicular to the shoreline, as assumed by analytical runup models. NSWW models hardly capture any edge wave activity, and therefore miss an important component of tsunami hazard and risk. NSWW models tend to produce a lot of small amplitude wave scattering when tsunamis strike a shoreline, and the amplitude of any edge waves are minimal at best.

The above examples demonstrate several important and hazardous wave phenomena that a Boussinesq model readily captures, and NSWW models can hardly capture. This is one of the fundamental reasons for making Geowave available to the Tsunami Community. NSWW models may do a poor job of capturing some important tsunami hazards and risks. The ongoing use and relevance of NSWW models in tsunami science needs careful consideration. Their use may seriously underestimate the hazards and risks of tsunami attack, particularly the broad variety and surprising intensity of tsunami activity along the shoreline. The benefits of a Boussinesq model come with few costs. Geowave has become the new standard in accurate tsunami simulations around the world.

i) Geowave Contact Information

Your questions regarding Geowave give us valuable feedback. Your comments and insights into simulation use and results are most welcome. With sufficient user feedback, regular updates and improvements in Geowave will be made on an as needed basis. Please contact Dr. Philip Watts at any of the following addresses:

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j) Geowave Header

The following text appears as comment lines at the top of the Geowave source code:

The user may need to replace the values of iq,jq,nq,ngm in every "parameter" statement of the program in each subroutine. Be forewarned that the program may not compile or run if the values of iq,jq,nq,ngm are large. Many compilers and operating systems limit FORTRAN applications to 512 Mb or to 256 Mb of RAM, even if the machine has much more available memory. Reduce iq,jq,nq,ngm whenever unexplainable errors occur. The program will output grid files for animations. These files are placed in a folder called "Movie" that you must create. Please note that some systems use "/" to denote a folder pathway, while others use "\". You must also create a folder called "Data" for the wave gauge files and the Lagrangian marker files and a folder called "Grid" for the mapping grid files. The outgoing boundary conditions consist of sponge layers 10 nodes thick along the edge of the grid, whether land or water. A simulation grid surrounded by land produces much less noise than open grids. Please note that a small value of "itdel" can easily fill a hard drive with grid files, so be careful and estimate the required hard drive space needed to store movie files and other output grid files. Also, excessive noise and failure to converge may result if a grid is too dense because of higher order terms and derivatives in the Boussinesq scheme. These higher order terms introduce instabilities. So, avoid *generating very dense grids (more than 40 nodes per wavelength) unless they are very smooth. At least 7 nodes per wavelength are needed in shallow water in order to resolve runup. Insufficient nodes will reduce the runup maximum value, and may even prevent shoaling waves from reaching the shoreline. There is a numerical resistance to wave shoaling if waves are poorly resolved. Instability will appear as a fuzzy free surface that ruins the simulation appearance, or as local perturbations that grow. Please note that "zlim" has important implications for graphing all movie and all output grid files. The graphing software used will determine if a large negative or positive value is needed, or simply zero. The output grid files produce various inundation maps starting at time "tout1" and ending at time "tout2". These can be used to map wave phenomena during an initial phase, steady state phase, or over all time.*

References

Chen, Q., Kirby, J. T., Dalrymple, R. A., Kennedy, A. B., and Chawla, A. (2000). "Boussinesq modeling of wave transformation, breaking, and runup. II: 2D." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 126(1), 48-56.

Day, S. J., Watts, P., Grilli S. T., and Kirby, J.T. (2005). “Mechanical Models of the 1975 Kalapana, Hawaii Earthquake and Tsunami.” Marine Geology, 215(1-2), 59-92.

Enet, F., and Grilli, S. T. (2007). “Experimental study of tsunami generation by three-dimensional rigid underwater landslides.” J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 133(6).

Fryer, G. L., Watts, P., and Pratson, L. F. (2004). “Source of the great tsunami of 1 April 1946: A landslide in the upper Aleutian forearc.” Marine Geology, 203, 201-218.

Goldfinger, C., Kulm, L. D., McNeill, L. C., and Watts, P. (2000). "Super-scale failure of the Southern Oregon Cascadia Margin." PAGEOPH, 157, 1189-1226.

Greene, H. G., Murai, L. Y., Watts, P., Maher, N. A., Fisher, M. A., Paull, C. E., and Eichhubl, P., (2006). “Submarine landslides in the Santa Barbara Channel as potential tsunami sources.” Nat. Hazards and Earth Sci. Systems, EGU, 6, 63-88.

Grilli, S. T., and Watts, P. (1999). "Modeling of waves generated by a moving submerged body: Applications to underwater landslides." Engrg. Analysis with Boundary Elements, 23(8), 645-656.

Grilli, S. T., and Watts, P. (2001). "Modeling of tsunami generation by an underwater landslide in a 3D numerical wave tank." Proc. of the 11th Offshore and Polar Engrg. Conf., Stavanger, Norway, 3, 132-139.

Grilli, S. T., Vogelmann, S., and Watts, P. (2002). "Development of a 3D numerical wave tank for modeling tsunami generation by underwater landslides." Engrg. Analysis with Boundary Elements, 26(4), 301-313.

Grilli, S. T., and Watts, P. (2005). "Tsunami generation by submarine mass failure Part I: Modeling, experimental validation, and sensitivity analysis." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 131(6), 283-297.

Grilli, S. T., Ioualalen, M., Asavanant, J., Shi, F., Kirby, J., and Watts, P. (2007). "Source Constraints and Model Simulation of the December 26, 2004 Indian Ocean Tsunami." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 133(6), 414-428.

Grossi, P., Watts, P., Boissonade, A., and Muir-Wood, R. (2008). "Estimating losses from tsunami risk: Focus on Southern California." Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China.

Ioualalen, M., Pelletier, B., Watts, P., and Regnier, M. (2006). "Numerical modeling of the 26th November 1999 Vanuatu tsunami." J. Geophys. Res., 111(C6), 2005JC003249.

Ioualalen, M., Asavanant, J., Kaewbanjak, N., Grilli, S. T., Kirby, J. T., and Watts, P. (2007). "Modeling the 26 December 2004 Indian Ocean tsunami: Case study of impact in Thailand." J. Geophys. Res., 112, 2006JC003850.

Kennedy, A. B., Chen, Q., Kirby, J. T., and Dalrymple, R. A. (2000). "Boussinesq modeling of wave transformation, breaking, and runup. I: 1D." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 126(1), 39-47.

Mattioli, G. S., Voight, B., Linde, A. T., Watts, P., Widiwijayanti, C., Young, S. R., Elsworth, D., Malin, P. E., Shalev, E., Van Boskirk, E., Johnston, W., Sparks, R. S. J., Neuberg, J., Bass, V., Dunkley, P., Herd, R., Syers, T., Williams, P., and Williams, D. (2007). “Unique and remarkable dilatometer measurements of pyroclastic flow–generated tsunamis.” Geology, 35(1), 25-28.

McAdoo, B. G., and Watts, P. (2004). “Tsunami hazard from submarine landslides on the Oregon continental slope.” Marine Geology, 203, 235-245.

Okada, Y. (1985). “Surface deformation due to shear and tensile faults in a half-space.” Bull. Seis. Soc. Am., 75(4), 1135-1154.

Rahiman, T. I. H., Pettinga, J. R., and Watts, P. (2007). “The source mechanism and numerical modelling of the 1953 Suva tsunami, Fiji”. Marine Geology, 237(2), 55-70.

Tappin, D. R., Watts, P., McMurtry, G. M., Lafoy, Y., and Matsumoto, T. (2001). “The Sissano, Papua New Guinea Tsunami of July 1998 -- Offshore Evidence on the Source Mechanism.” Marine Geology, 175, 1-23.

Tappin, D. R., Watts, P., and Matsumoto, T. (2003). “Architecture and failure mechanism of the offshore slump responsible for the 1998 Papua New Guinea tsunami.” In: Submarine Mass Movements and Their Consequences, J. Locat and J. Mienert (Eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands, 383-389.

Tappin, D. R., Watts, P., and Grilli, S. T. (2008). “The Papua New Guinea tsunami of July 17, 1998: Anatomy of a catastrophic event.” Nat. Haz. and Earth Sys. Sci., NHESS, 8, 243-266.

von Huene, R., Ranero, C. R., and Watts, P. (2004). “Tsunamigenic slope failure along the Middle America Trench in two tectonic settings.” Marine Geology, 203, 303-317.

Walder, J. S., Watts, P., Sorensen, O. E., and Janssen, K. (2003). “Water waves generated by subaerial mass flows.” J. Geophys. Res., 108(B5), 2236-2255.

Walder, J.S., Watts, P., and Waythomas, C.F., (2006). “Mapping tsunami hazards associated with debris flow into a reservoir.” J. Hyd. Eng., ASCE, 132(1), 1-11.

Watts, P. (1998). "Wavemaker curves for tsunamis generated by underwater landslides." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 124(3), 127-137.

Watts, P. (2000). "Tsunami features of solid block underwater landslides." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 126(3), 144-152.

Watts, P., Grilli, S. T., Kirby, J. T., Fryer, G. J., and Tappin, D. R. (2003). “Landslide tsunami case studies using a Boussinesq model and a fully nonlinear tsunami generation model.” Nat. Hazards and Earth Sci. Systems, EGU, 3(5), 391-402.

Watts, P., Grilli, S. T., Tappin D., and Fryer, G. J. (2005). “Tsunami generation by submarine mass failure Part II: Predictive Equations and case studies.” J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 131(6), 298-310.

Waythomas, C. F., and Watts, P., (2003). “Numerical simulation of tsunami generation by pryoclastic flow at Aniakchak Volcano, Alaska.” Geophys. Res. Letters, 3014, 1751-1755.

Waythomas, C. F., Watts, P., and Walder, J. S. (2006). “Numerical simulation of tsunami generation by cold volcanic mass flows at Augustine volcano, Alaska.” Nat. Haz. and Earth Sys. Sci., NHESS, 6, 671-685.

Wei, G., and Kirby, J. T. (1995). "Time-dependent numerical code for extended Boussinesq equations." J. Wtrwy, Port, Coast, and Oc. Engrg., ASCE, 121(5), 251-261.

Wei, G., Kirby, J. T., Grilli, S. T., and Subramanya, R. (1995). "A fully nonlinear Boussinesq model for free surface waves. Part 1: Highly nonlinear unsteady waves" J. Fluid Mech., 294, 71-92.

Wei, G., Kirby, J. T., and Sinha, A. (1999). "Generation of waves in Boussinesq models using a source function method." Coastal Engrg., 36, 271-299.