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LARGE-SCALE SIMULATION OF SEISMIC-WAVE PROPAGATION OF THE 2011 TOHOKU-OKI M9 EARTHQUAKE

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ABSTRACT: We describe a large-scale simulation of the seismic wave propagation from the 2011 Tohoku-Oki earthquake. We combine structure models for topography, sediments, crust and subducting plates to construct a 3D structure model for the northeastern Japan area. Then we simulate the near-field wave propagation by using a FDTD method which is accelerated by the use of multi-GPUs (Graphics Processing Unit). The simulated wave-field exhibits strongly complex pattern reflecting the source complexity and the heterogeneities around the source region.

Key Words: Great East Japan earthquake, ground motion, finite-difference method, topography, heterogeneity, GPU computing.

INTRODUCTION

The Tohoku-Oki earthquake on March 11, 2011 (M_{JMA} 9.0; Fig. 1) generated strong shaking reaching the maximum intensity (seven) on the JMA's scale and caused devastating tsunamis with run-up heights exceeding 30 m. 15,845 people were lost, and 3,368 people are still missing (January 27, 2012). Such mega-thrust earthquake was not expected to occur along the plate interface off the northeastern Japan. Thus it is very important to study this event for understanding the geophysical condition of the generation of mega-thrust earthquake, the characteristics of the induced strong ground motions, and the mechanism of the excitation of the large tsunamis.

The ground motion records of this event are quite important data for the quantitative studies on the earthquake source and the induced damages. However, modeling of the ground motions is not a simple task because of the strong lateral heterogeneity in and around the Japan trench: steeply varying topography, oceanic water layer, thick sediments, crust with varying thickness and subducting oceanic plate can all affect the seismic waves radiated from suboceanic earthquakes (e.g., Okamoto 2002, Nakamura et al. submitted paper). Thus the structural model is an important factor in the study of waveform modeling.

The modeling of the ground motion induced by this event is a computational challenge: large memory size and fast computing devices are required because the huge fault size of the earthquake (about 500 km×200 km) imposes a very large domain size for the simulation. For example, for a finite-difference domain of 960 km long, 480 km wide and 240 km deep and for a (constant) grid spacing of 0.15 km, a quite large grid size of 6400×3200×1600 or 33 billion of grid points are necessary.

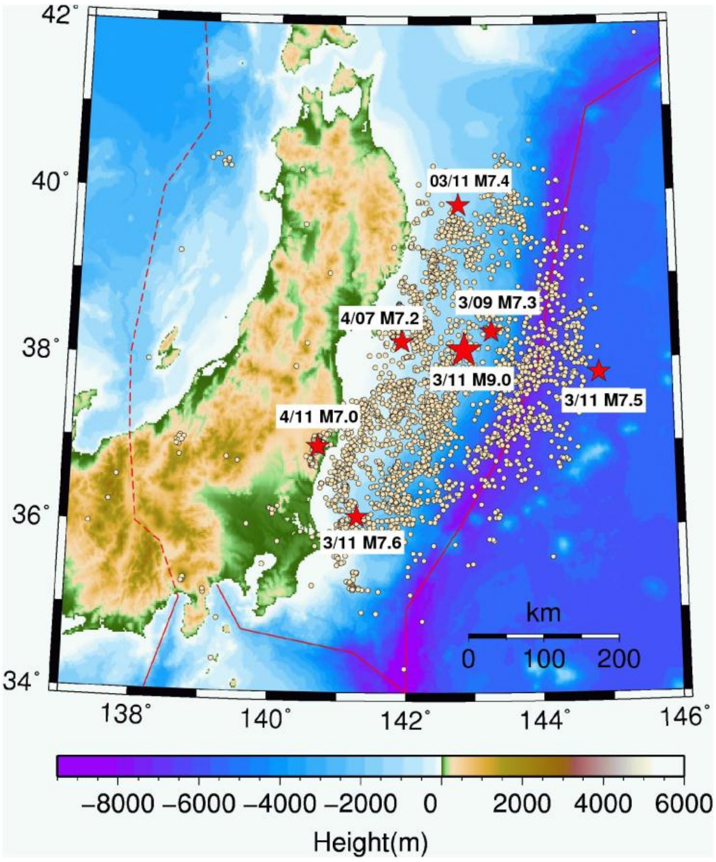

Fig. 1 Aftershock distribution of the 2011 Tohoku-Oki earthquake. The epicenters of earthquakes ($M_{JMA} \geqq 4.0$) from Mar. 09, 2011 to Apr. 11, 2011 (JST) are shown. Earthquakes with magnitude larger than or equal to 7 are shown by red stars. Hypocentral data determined by Japan Meteorological Agency are used.

Therefore, we need to develop numerical methods that can precisely incorporate the effects of the heterogeneous structure including the land-ocean topography. Further, we need to confirm the feasibility of the methods in the case of large-scale problem: the computation must be done within a tolerable time.

Thus, in this paper we first review our 3-D finite-difference time domain (FDTD) method (Okamoto et al. 2010 and 2011) to describe how we implement the land and ocean-bottom topography, oceanic layer and other lateral heterogeneity. In order to simulate the wave propagation with a large grid size, we adopt the GPU (graphics processing unit) computing to our finite-difference program. Next we show the preliminary structure model for the northeastern Japan region, which we constructed by combining models of sediment, crust and subducting plates. We then present the results of the simulation of the wave propagation based on a preliminary source model of the 2011 Tohoku-Oki earthquake.

SIMULATION METHOD

3D finite-difference time domain (FDTD) method

We apply the time domain, staggered-grid three-dimensional finite-difference scheme (e.g., Graves 1996). The components of the particle velocity (v_i; i=x, y, z) and the stress tensor (τ_{ij}; i, j=x, y, z) are the field variables. We use three material parameters (Lamé coefficients and density) as we assume isotropic and elastic material for the simulation. Thus twelve variables are assigned to a unit cell (i.e., a heterogeneous formulation: Fig. 2). The finite-difference is fourth-order in space and second-order in time. We apply the absorbing boundary condition (Cerjan et al. 1985) near the side and the bottom boundaries, and A1 absorbing condition (Clayton and Engquist 1977) at the bottom. A periodic condition is imposed on the side boundaries.

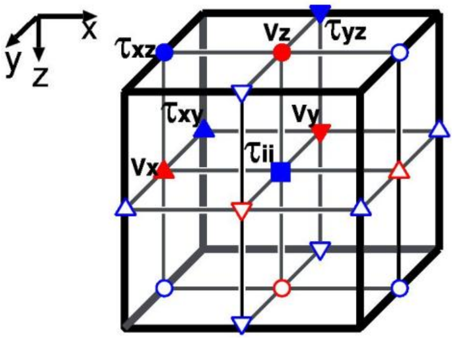

Fig. 2 A single unit cell of the staggered grid. Open symbols denote the variables that belong to the neighboring cells (from Okamoto et al. 2010b).

Unified implementation for land-ocean topography

Recent studies have been revealing the effects of land-ocean topography and oceanic layer on the seismic ground motions due to suboceanic shallow earthquakes: by using the finite-difference simulations Nakamura et al., (2009) and Nakamura et al. (submitted) showed that the coda waves were amplified and elongated when the land-ocean topography and oceanic layer were considered in the simulation. Therefore, such effects need be incorporated in the simulations of seismic wave propagation and be studied further for better understanding of the ground motions due to shallow suboceanic earthquakes.

In order to incorporate such structural effects, we have recently proposed an approach to model structures with both of the land and ocean topography in 3D seismic modeling with the finite-difference method (Takenaka et al. 2009). The approach unifies the implementation for irregular free-surface (i.e., the land topography) proposed by Ohminato and Chouet (1996), and that for irregular liquid-solid interface (e.g., ocean bottom) proposed by Okamoto and Takenaka (2005).

The liquid-solid interface scheme satisfies the boundary conditions between the elastic waves (solid side) and the pressure waves (liquid side) with an accuracy of *O(h)* where *h* being the space increment. For this, (1) we need to put the boundary (i.e. zero rigidity) thorough the grid points of the components of shear stresses and (2) to apply the standard second-order centered equation with averaged density (i.e., $(1/2)(\rho_{solid} + \rho_{liquid})$) to the normal velocity component at the grid points on the boundary. The second condition also imposes second-order operators instead of the fourth-order ones *near* (but *only* near) the liquid-solid boundary. Okamoto and Takenaka (2005) derived these conditions for the velocity-stress staggered grid finite-difference scheme, and numerically confirmed the validity by comparing the results with those of a wavenumber integration method (Okamoto and Takenaka

1999) in two-dimensional case. Nakamura et al. (2011) extended the liquid-solid implementation to three-dimensional case and studied the accuracy by numerical experiments.

For the irregular free-surface, the same conditions (1) and (2) must be imposed: in this case the average density becomes $(1/2)(\rho_{solid} + \rho_{air})$ at land and $(1/2)(\rho_{liquid} + \rho_{air})$ at ocean. In the method of Takenaka et al. (2009) the material parameters at the center of the cell are first defined. Second, in order that the above conditions for material parameters be automatically satisfied, the arithmetic average values of the densities of two adjoining cells are used for effective values on the faces of the cell, and the harmonic average values of the rigidities of four adjoining cells are used for effective value on the edges. Nakamura et al. (2009) and Nakamura et al. (submitted) applied this unified implementation. In the present study, we also apply the unified implementation in the FDTD program for the GPU computing.

GPU computing

The GPU (graphics processing unit) is a remarkable device due to its many-core architecture and high memory bandwidth (Fig. 3). The GPU delivers extremely high computing performance at a reduced power and cost compared to conventional central processing units (CPUs). The simulation of seismic wave propagation is a typical *memory-intensive* problem which involves a large amount data transfer between the memory and the arithmetic units, while the number of arithmetic computations is relatively small. This is the reason we adopt the GPU computing to the simulation of seismic wave propagation: it can benefit from the high memory-bandwidth of the GPUs. In the Appendix we describe how we adopt the GPU computing to our FDTD codes. We used NIVIDIA CUDA C (NVIDIA 2010) in programming the FDTD codes.

We use the *TSUBAME 2.0* supercomputer in Global Scientific Information and Computing Center, Tokyo Institute of Technology, for the seismic wave simulation employed in this paper. The TSUBAME 2.0 is a large-scale GPU cluster equipped with 1408 nodes and 4224 of NVIDIA M2050 GPUs, and has a peak performance of 2.4 PFlops (peta-flops). It is ranked as the world fifth fastest supercomputer in the November 2011 TOP-500 list (www.top500.org).

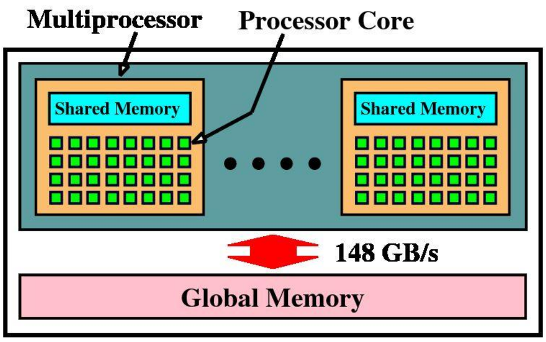

Fig. 3 A simplified diagram of a GPU (NVIDIA M2050) used in this study (modified from Okamoto et al. (2010b)). A single GPU has 14 processors (*multiprocessors*) and a single multiprocessor has 32 *processor cores*. Thus 448 processor cores are integrated in a GPU. The size of the global memory is 3 GB (giga-byte).

3D STRUCTURE MODEL

We compile several detailed structure models in and around the northeastern Japan region to construct the 3D model for the simulation. Table 1 summarizes the components of the 3D model and references for them. All these models are defined with several layers divided by irregular, curved interfaces. Some of the interfaces of the constructed 3D model are shown in Fig. 4. The total number of the layers used in the 3D model is 19 including the water layer as the top layer and the mantle at the base of the mode. The model area (red rectangle on the topography map) includes southernmost part of Hokkaido, almost all of the northeastern Honshu and Kanto area. It also includes some of the Izu islands in the southernmost part of the model. The whole Japan trench and outer-rise area are included in the model.

The 3D model constructed here is a preliminary one: the structure models for the land area and for the oceanic area have been developed separately so that there are differences in the structural parameters in the same areas between the models. Some interfaces from different models intersect each other. We have carefully removed such inconsistencies in compiling the models. It is required to improve the 3D model in the future work by waveform modeling.

Table 1 Components of 3D model and references

Components	Reference
Land and ocean topography	Kisimoto 1999
Sediments (Japan Seismic Hazard Information Station)	Fujiwara et al. 2009
Land crust	Baba et al. 2006
Pacific plate	Baba et al. 2006
Philippine Sea plate	Nakamura et al. 2010

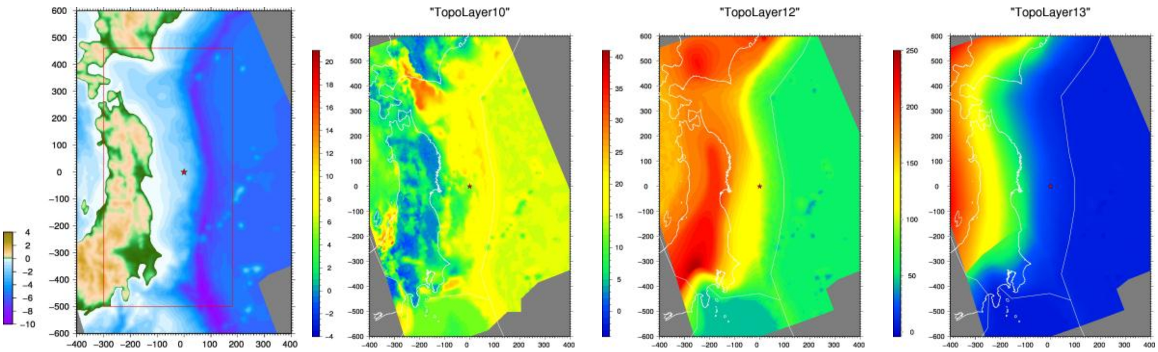

Fig. 4 Examples of the interfaces assumed in the 3D model. From left to right: the land-ocean topography, the base interface of the tenth layer (deepest sediment), the Moho, and the top interface of the Pacific and the Philippine Sea plates. The red star denotes the JMA epicenter of the 2011 Tohoku-Oki earthquake. The red rectangle on the topography map indicates the horizontal area of the FDTD domain used in the simulation.

SIMULATION OF TOHOKU-OKI EARTHQUAKE

In this section we discuss about an example of large-scale seismic waveform modeling of the 2011 Tohoku-Oki earthquake by using the GPU-accelerated parallel FDTD method.

FDTD parameters

As described in Introduction, a large-scale computing is required to model seismic waves from the 2011 Tohoku-Oki earthquake. As summarized in Table 2, for the example shown here we were required to use 1000 GPUs (334 nodes) of the TSUBAME 2.0 supercomputer. This is about 24 % of the entire resources of the TSUBAME 2.0.

The maximum frequency in Table 2 is obtained as follows: based on the argument by Moczo et al. (2000) we use $6 \times \Delta x$ = 0.9 km as the minimum wavelength. The minimum *S*-wave velocity is 0.55 km/s for the topmost sediment. Thus the maximum frequency f_{max} is: $f_{max} = 0.55 \div 0.9 = 0.61$ Hz. The area of the top sediment is quite limited and for most of the FDTD domain the seismic waves up to about 1 Hz are correctly modeled.

Table 2 Parameters for the parallel GPU-FDTD simulation

NX, NY (horizontal grid size) and NZ (vertical)	6400×3200×1600
NT (time steps)	44000
Δx (grid spacing common for all X,Y and Z)	0.15 km
Δt (time increment)	0.005 s
Number of unit cells	32.8 billion
LX, LY, LZ (dimensions of the FDTD domain)	960 km×480 km×240 km
Computed duration (NT×Δt)	220 s
Maximum Frequency	0.61 Hz
Number of GPUs	1000 (on 334 nodes)
Grid size of a single subdomain	320×320×320
Number of subdomains in X, Y, and Z directions	20×10×5
Total memory	1.4 TB
Total computation time	5768 s
Performance (single precision)	33.2 TFlops
Total size of output files	1.0 TB

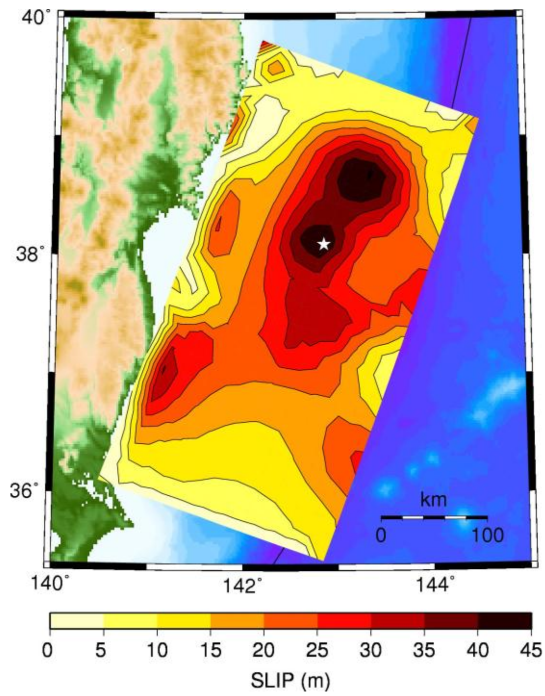

Fig. 5 Slip distribution of the preliminary source model (Okamoto et al. 2011) used for the simulation of 2011 Tohoku-Oki Earthquake.

Preliminary source model

We use a preliminary source model determined by ourselves (Okamoto et al. 2011) for the example of the simulation shown in this paper. The preliminary source model was determined by using a non-linear waveform inversion method (Okamoto and Takenaka 2009) applied to the teleseismic broadband body waveforms. We incorporated the effect of the near-source laterally heterogeneous structure (including the ocean layer and sediments) on the synthetic waveforms by using a 2.5-dimensional finite difference method. The final slip distribution of the preliminary model is shown in Fig. 5. We obtained a heterogeneous rupture process with large slips off Miyagi prefecture near the JMA epicenter. This feature is similar to that of the slip distribution obtained by Koketsu et al. (2011).

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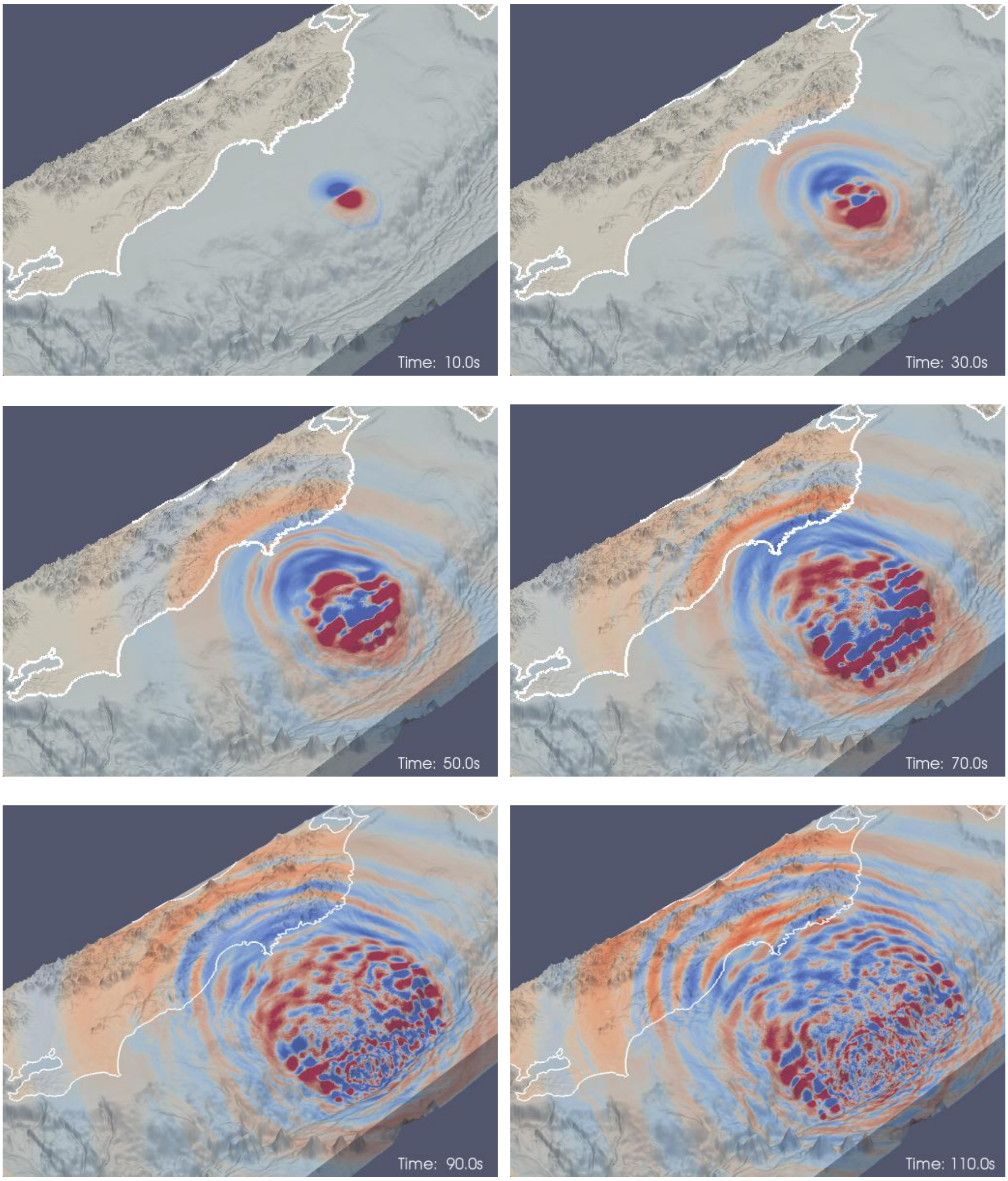

Fig. 6 Snapshots of the simulated wave-field. The vertical component of the particle velocity is visualized with color scale. Red and blue colors denote upward and downward motions, respectively. From left to right, top to bottom the snapshot at 10 s after the onset of the rupture, at 30 s, 50 s, 70 s, 90 s, and 110 s, respectively, are shown.

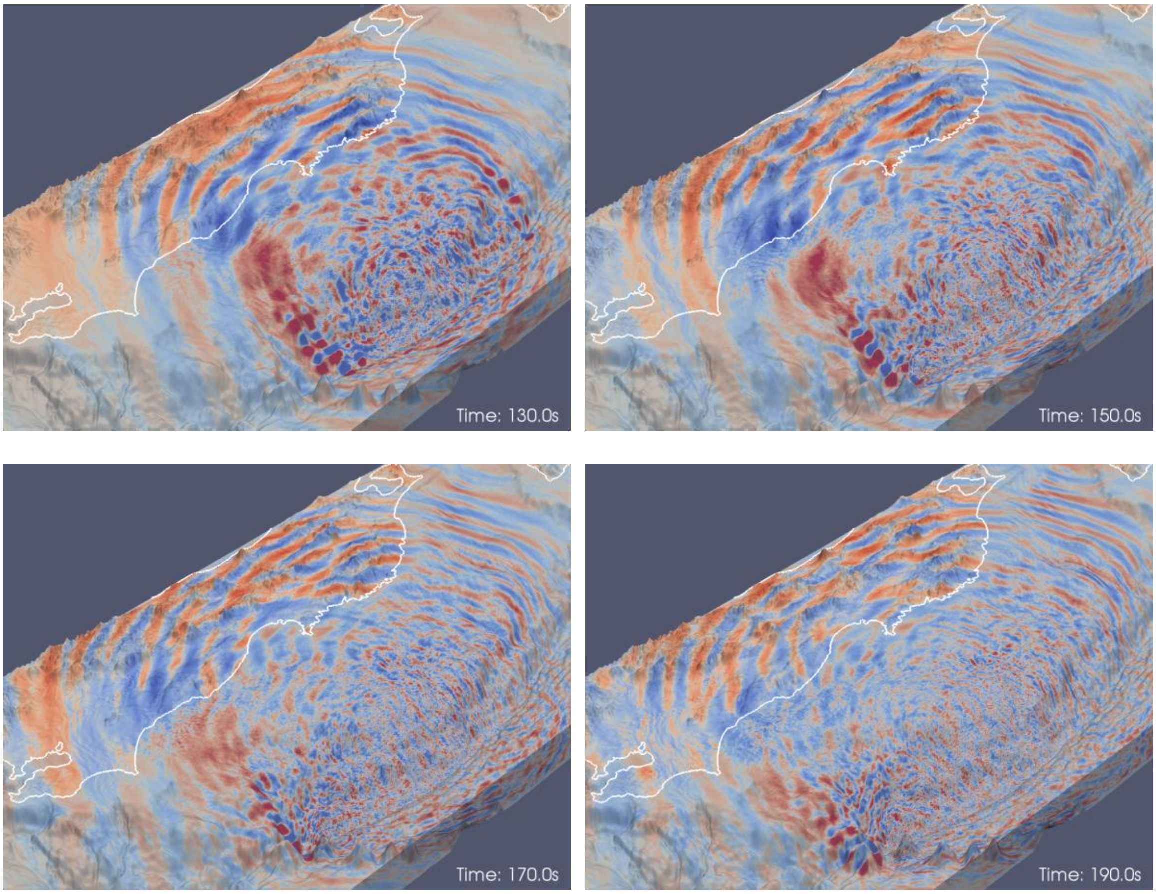

Fig. 7 Same as Fig. 6 but for snapshots at 130 s, 150 s, 170 s and 190 s.

The source model consists of point sources distributed on the grid points (23×11) on the fault plane with a spacing of about 20 km. The source terms (i.e., the moment tensors of each point source) are applied in the 3D FDTD using the stress components (Okamoto 1994; Olsen et al. 1995).

Results of the waveform modeling

Fig. 6 and 7 show the snapshots of the ground motion (particle velocity) computed for the preliminary source model of the 2011 Tohoku-Oki earthquake. The ground motions at the free-surface in the land area and at the solid side of the ocean bottom in the oceanic area are visualized in color scale. Although not visualized, the propagation of the pressure waves within the ocean water layer is also modeled in the simulation (see section "Unified implementation for land-ocean topography"). We are able to observe strong interference due to the complex source model and the heterogeneous structure. The complexity is especially significant in the later part of the simulation. It is also remarkable that, from about 130 s to 170 s, regions with strong positive motion (red) and negative motion (blue) emerge near the coast of the Fukushima prefecture. Motions in the regions overwhelm the wave-field propagated from around the epicenter, and largely distort the pattern of the wave propagation. The source that provides this feature is the relatively large slip near the Fukushima prefecture retrieved in the teleseismic waveform inversion result (Fig. 5). Such a feature was also observed in the strong ground motion records and the strong-motion-generation-areas (SMGAs) were identified below the coast of Miyagi to Fukushima prefectures (e.g., Kurahashi and Irikura 2011). These characteristics must be studied further in the future analysis, with improvements in the source model as well as in the 3D structure model.

CONCLUSION

In order to simulate the wave propagation from the 2011 Tohoku-Oki earthquake, we constructed a preliminary 3D structure model for the northeastern Japan region by compiling the models for topography, sediments, crust, and subducting plates. We adopted the GPU computing to accelerate the large-scale finite-difference simulation of the seismic wave propagation. By using about 24 % of the resources of the GPU supercomputer, TSUBAME 2.0, at Tokyo Institute of Technology, Japan, we are now able to simulate the seismic wave propagation from the source of the huge fault plane up to about 1 Hz within a tolerable computation time. The snapshots of simulated wave-field exhibit strongly complex pattern because of the complex source model, the irregular topography and the shallow heterogeneities. Such effect must be considered in improving the source model, the 3D structure model, and in the future quantitative study on the observed ground motion records.

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APPENDIX: GPU ACCELERATION FOR FDTD SEISMIC WAVE MODELILNG

We here briefly review how we adopt GPU computing to the simulation of seismic wave propagation (see Okamoto et al. 2010 and Okamoto et al. (in press) for detail).

Memory optimization in GPU computing

The GPU is characterized by its hundreds of cores for arithmetic instructions (Fig. 3): we need to provide sufficient amount of data to these cores. The bandwidth of the main memory (called “global memory” in NVIDIA GPUs) connected to the GPU is much faster than that of the memory system connected to the conventional CPUs (e.g., Kirk and Hwu 2010). However, 400 to 600 clock cycles of memory latency still occurs in transferring the data between the global memory and the GPU. It is thus critical for performance to optimize the memory manipulation in *memory-intensive* applications such as the simulation of seismic wave propagation. Therefore, we use the fast (but small) memories in the GPU, the *registers* and the *shared memory*, as software managed cache memories to reuse the data and hence to reduce the data transfer from the global memory (Abdelkhalek et al. 2009; Micikevicius 2009; Michéa and Komatitsch 2010; Okamoto et al. 2010a,b; see Fig. 8 for the method).

In order to reduce the access to the global memory, we define the material parameters only at the center of the unit cell. The material parameters at the grid points for particle velocities and shear stresses are computed by using the values defined at the center of the unit cells at every time steps. The unified implementation method mentioned above (Takenaka et al. 2009) allows us to compute the appropriate values of the material parameters. We further use the *look-up table* method for the material parameters: instead of the three material parameters (density and Lamé coefficients) only a single index is required for a unit cell in the look-up table method. This also reduces the access to the global memory. In addition to these techniques we optimize the number of grid points (i.e., the *block size*) assigned to a single execution unit (called a *multiprocessor*), because the memory transfer rate is better for grouped memory transaction using blocks of proper size (typically 16 to 64) than that for serialized, one-by-one memory transaction.

Parallel computing with multi-GPUs

For parallel computing with multi-GPUs, we decompose the FDTD domain into *subdomains* and allocate a single subdomain to a single GPU. This is necessary for large-scale simulations because the size of the global memory of a GPU is not large (e.g., 3 GB in the case of NVIDIA M2050). We here use the MPI library for our parallel FDTD program (i.e., we apply a MPI only parallel programming model).

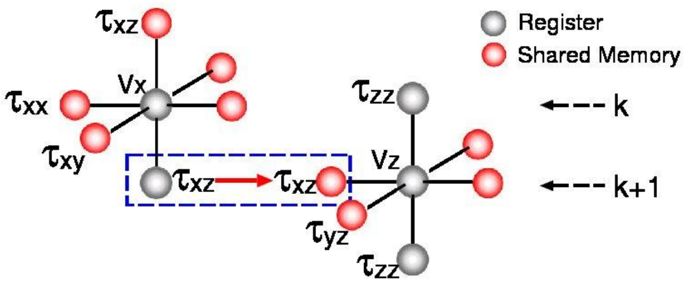

Fig. 8 Example of the use of the shared memory and registers. Values on red points are stored in shared memory and those on gray point in registers. In the computations for k-th depth the stress component τ_{xz} is stored in register. For the next depth the value in the register is moved to the shared memory to reduce the data transfer from the global memory (from Okamoto et al. 2010b).

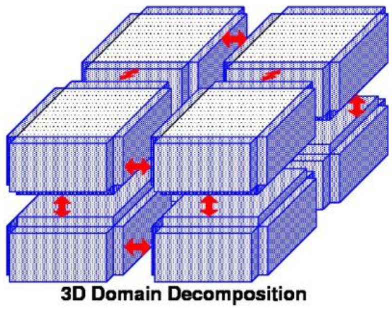

Fig. 9 Schematic illustration of the 3D domain decomposition (from Okamoto et al. 2010b). Blue regions indicate the ghost zones.

In the parallel computing we need to exchange the data in the *ghost zones* between the neighboring subdomains. We adopt the *three-dimensional* (3D) domain decomposition (Fig. 9). In this decomposition method the whole domain can be extended in all three Cartesian directions, and therefore the method brings large freedom in defining the shape of the domain. Also, for a fixed whole domain size, the communication time in the 3D domain decomposition decreases with the increasing number of the subdomain. This is because the communication time is proportional to the surface area which decreases with the size of the subdomain. Here we note that, in GPU computing, the data within the ghost zones in the GPU memory must be once copied to the host memory in order to exchange them with other GPUs installed on the other nodes. Thus in decomposing the domain, we use dedicated memory buffers for the ghost zones to improve the data transfer rate between the GPU memory and the host memory (see Okamoto et al. 2010b and Okamoto et al. in press for detail).

We also overlap the procedures for the communication and the computation to reduce the total processing time (see e.g., Abdelkhalek et al., 2009; Ogawa et al., 2010). In our program we first compute for the grid points at and near the sides of the subdomains for ghost point exchange. Then we start the exchange procedure for the ghost points and the computations for the internal grid points simultaneously.

With these optimizations, the performance of our 3D FDTD program scales well with the increasing number of GPUs: by using 400 nodes of the TSUBAME supercomputer and under the condition of 2 GPUs activated per a node, a very high single-precision performance of about 50 TFlops is achieved in the case of 800 GPUs (85 % of the complete scalability). Even higher performance of about 61 TFlops (69 %) is achieved in the case of 1200 GPUs under the condition of 3 GPUs per a node (Okamoto et al. in press). The reduced performance shown in Table 2 (33.2 TFlops) is primarily due to the overhead of the file output procedure during the computation.

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