Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

STT59-01 Room:104 Time:May 20 14:15-14:30

Large- and multi-scale earthquake cycle simulation

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Since the pioneering work of Tse and Rice (1986), earthquake (EQ) cycle simulations, based on rate and state friction laws, have been executed to successfully reproduce historical EQ cycles. In most of these simulations, we set a fault or plate interface in a half-space homogeneous elastic medium, on which frictional parameters are distributed, and simulate EQ cycles driven by a relative plate motion. In these simulations, we use a boundary-integral equation method to divide the fault or the plate interface into a number of cells smaller that the critical size determined from frictional parameters. And, by integrating the equation of motion combined with a rate and state frictional law, we trace the spatiotemporal slip evolution there. Current problems of these simulations are the needs for including 1) not quasi but fully dynamic rupture processes in earthquake cycle simulations, 2) the effects of structural heterogeneity and viscoelasticity in the medium, 3) the effect of pore pressure change in the fault zone throughout EQ cycles, 4) the examination of friction laws, especially at high slip rates. In addition, we are facing the need for large- and multi-scale EQ cycle simulations.

In this talk, we confine ourselves to discussing mainly quasi-dynamic EQ cycle simulations in a homogeneous elastic medium, taking into account the next generation super computer. First, we show the need for large- and multi-scale EQ cycle simulations, especially for interplate earthquakes at subduction zones. Namely, we need to 1) simulate cycles of giant EQs such as the 2011 Tohoku and the soon-coming Nankai EQs, and further the Japanese Island-scale EQ cycles including the interfaces of plates subducting beneath the whole Japan Islands, 2) simulate multi-scale EQ cycles including several sizes following the GR law in regional scales. These multi-scale simulations target the understanding of the different earthquake size distribution between the off-Tohoku and the Nankai focal regions, and of the temporal change in b-value before large earthquakes, and further the Nankai EQ simulations including short- and long-term slow slip events.

These large- and multi-scale simulations demand huge computational memories and CPU times. On the other hand, some researches have started to estimate frictional parameters based on physical models including rate and state friction laws through a method of data assimilation, which involves a large number of iterative computation. Therefore, we need to reduce memory sizes and CPU times required in EQ cycle simulations, and physics-based data assimilations. Dividing the fault or the plate interface into N cells, the multiplication of the slip response function matrix (NxN) and the slip deficit vector (N), that appears repeatedly in the simulations, requires memory sizes and CPU times of O(NxN). For reducing O(NxN) to O(N)-O(NlogN) in memory sizes and CPU times, we have used FFT(Fast Fourier Transform), FMM(Fast Multipole expansion Method) and recently H-matrices method. We review these reduction methods employed in EQ cycle simulations, and discuss the further challenge.

Keywords: Earthquake cycle, Large-scale simulation, Multi-sacle simulation, Interplate earthquake, Subduction zone

STT59-02 Room:104 Time:May 20 14:30-14:45

Construction of 3D hegerogeneous structure model in subduction zone and integrated simulation from earthquake generation

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Conventionally,elastic half space model is used for calculations of earthquake generation and crustal deformation. However, the structure in subduction zone is obviously heterogeneous in 3D and such heterogeneity of the structure and material properties should affect the deformation and stress changes due to earthquake faultings and subduction processes. Considering the future development in HPC for the comming 10-20 years, such heterogeneity will be fully introduced in the calculations. We have already developed a method for generating a high-fidelity 3D finite element (FE) model of crustal structure with more than 100,000,000 degree of freedom. A method for elastic wave propagation and crustal deformation analyses with the generated model is also proposed. Hence, it should be possible to demonstrate earthquake generation cycle simultaions with much finner resolution along the fault or stochastic FEM calclations considering the ambiguity of structure heterogeneity if we use 100 - 1,000 times faster super computers which will appear in 10-20 years. It enable us to calculate various scenarios of earthquake generations with more appropreate error estimation depending on the observed data. Furthermore, we can convine the above structure model, which is Japan arc scale, and regional and/or local finner structure models and integrate the simulations from earthquake generation to ground shaking in a city.

STT59-03 Room:104 Time:May 20 14:45-15:00

Large-Scale High-Performance GPU Computing for Seismology

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Simulation of seismic-wave propagation is essential in modern seismology in order to probe the Earth's and other planets' interiors, to study earthquake sources, and to evaluate the strong ground motions due to earthquakes for the seismic hazard analysis. The modeling of the seismic-waves is a computational challenge because of the effect of the structural heterogeneity and the required large domain size. The effect of the lateral heterogeneity is especially important for the shallow suboceanic earthquakes around Japanese islands where all the heterogeneities such as the steeply varying topography of the trenches, oceanic water layer, thick sediments, crust with varying thickness and subducting oceanic plate, can affect the excitation and propagation of the seismic-waves radiated from the earthquakes (e.g., Okamoto, EPS 2002; Nakamura et al. BSSA 2012). The scale length of the heterogeneity and topography is often small (a few hundred meters or even less than one hundred meters) and we need to use very small grid spacing in the simulation. Also, a very large domain size is often required because the fault size and the affected area can become large especially for the megathrust interplate earthquakes such as the 2011 Tohoku-Oki earthquake of which fault is roughly 200 km wide and 500 km long. Thus for the modeling of the seismic-waves we need all the resources for the high-performance computing, such as large-sized memory system, fast computing devices, fast interconnect network, and high-performance softwares.

In this paper we review our 3-D finite-difference time domain (FDTD) method developed for the simulation of seismic-wave propagation. As the accelerator, we use the GPUs in our simulation (Okamoto et al., 2010; 2013). The GPU (Graphics Processing Unit) is a remarkable device due to its multi-core architectures and high memory bandwidth. The GPU delivers extremely high computing performance at a reduced power and cost compared to conventional central processing units (CPUs): recent GPUs have achieved performaces of about 3.5 to 3.9 TFLOPS in single precision arithmetic at power consumption of 225 to 235 W. Simulation of seismic wave propagation is a memory intensive problem which involves a large amount of data transfer between the memory and the arithmetic units, while the number of arithmetic computations is relatively small. Thus, the simulation can benefit from the high-memory bandwidth of the GPU, and various approaches to adopt GPU to the simulation have been proposed recently (e.g., Abdelkhalek et al., 2009; Aoi et al., 2009; Komatitsch et al., 2009, 2010; Micikevicius, 2009; Okamoto et al., 2010, 2013; Michea and Komatitsch, 2010).

We will show our recent results that were done by using several hundred to more-than one thounsand of GPUs of the TSUBAME supercomputer in Tokyo Institute of Technology from the field of the seismology: the forward wave propagation in realistic 3D structure model for the Japanese islands, the inverse problem for the study of the earthquake sources using 3D Green's tensor waveforms, the computation of the sensitivity kernels for perturbations in the structural parameters of the earth model, and the simulation of scattering of seismic-waves from the moon-quakes as the feasibility study for the future seismic exploration of the moon and other planets. We will also discuss the future direction of the GPU computing in the field of seismology such as the real-time simulation of the wave propagation.

[References]

Okamoto et al. Earth Planets Space, 62, 939-942, 2010.
Okamoto et al, in GPU Solutions to Multi-scale Problems in Science and Engineering, ed. D.A. Yuen et al., Springer, 2013.

Keywords: GPU, seismic-wave propagation, rupture process, structure of the Earth, seismic exploration of planets, hazard analysis

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STT59-04 Room:104 Time:May 20 15:00-15:15

High refining tsunami inundation simulation of the 2011 Great East Japan Earthquake

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As for the tsunami hazard, it was shown that there was a possibility to be able to become a catastrophe with destruction by extending to not the flood damage but the large area in the specific region due to the East Japan great earthquake that had been caused in 2011.

Then, the technique that whether it destroys it is only judged but also very it destroys it is appreciable is needed as an obtained lesson like the situation to date.

Therefore, the simulation tool that can be examined is indispensable, and a pressing need in the large area and the high-refining.

The present study verifies the tool that can examine the flood from the source of the tsunami to the town inside as a first step of the research, and examines the computational efficiency of the simulator that does high minute calculation in the town.

Keywords: the Great East Japan Earthquake, Tsunami, Inundation, Numerical Simulation, VOF, High performance computing

STT59-05 Room:104 Time:May 20 15:15-15:30

Future issues and expected role of HPC to solve them for risk management for earthquake and tsunami disaster

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In risk management, it is necessary to prepare the organization that performs the following processes: risk assesment -> strategic planning -> construction of a standard emergency response system -> training. In Japan, for earthquake and tsunami disaster mitigation, it is constructed based on Disaster Countermeasures Basic Act. The important point is that it does not finish only with risk assessment but even construction of the system for making the strategy of how to response the risk. We will introduce the present condition of the organization and its future problems in the comming 10 - 20 years and also argue about the expected roles of next-generation HPC.

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STT59-06 Room:104 Time:May 20 15:30-15:45

Quantification of Collapse Margin to Respond to "Beyond Scenario Earthquakes"

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The 2011 March 11 Tohoku Earthquake caused the most serious damage to the land and society in the modern history of Japan. The earthquake brought about serious damage, both physical and social, and left us with a variety of lessons. Earthquake engineering faces many challenges of research to comply with those lessons and build the environment that is safer and more secure. Among those, the following two themes, namely, (1) Response to earthquakes beyond what is considered in structural design and (2) Continuing business and prompt recovery, are considered to be most urgent for research and development. To carry out research to this end, those themes must be translated into specific engineering research subjects, and they are identified as: (A) Quantification of collapse margin of buildings and (B) Monitoring and prompt condition assessment of buildings. The first research subject, i.e. "quantification of collapse margin" is most relevant to the first theme, i.e., "response to earthquakes beyond design load". For many plausible reasons, it is impractical that the design earthquake load is increased to the level of a very low-probability, huge earthquake event. Then, how should we compromise? A practical solution is to quantify the reserve capacity of the structure from the level corresponding to the design earthquake load to the level of "collapse" at which people may lose their life. With such quantitative information at hand, we can argue in a sensible manner what would occur if the building were hit by an earthquake that is twice as large as the design earthquake load and we can also estimate the consequences of such an extreme event.

Suppose we accept the importance of quantification of collapse, are we equipped with means that can do so? The answer depends on the capacity of our numerical simulation technologies to trace the collapse of structures. Numerous efforts have been underway to this end, and various high-fidelity, advanced numerical simulation codes have been made available. However, the accuracy of collapse simulation has not yet been calibrated, and the utmost reason is the lack of "actual, realistic data on structural collapse". To resolve this issue, a comprehensive, five-year research program has been launched since last year. The program is named "Special Project for Reducing Vulnerability in Urban Mega Earthquake Disasters" with the subtitle of: "Maintenance and Recovery of Functionality in Urban Infrastructures". In the project, large-scale tests on a steel high-rise building structure and a RC mid-rise building structure are being planned, and these structures are to be shaken to collapse. The project has a strong component of advanced numerical simulation in which the test data will be utilized as the benchmark data for the calibration of accuracies expected in the simulation. The paper introduces the outline and background of the new project, together with some preliminary outcomes.

Keywords: beyond scenario earthquake, collapse margin, large-scale shaking table test, numerical simulation

STT59-07 Room:104 Time:May 20 15:45-16:00

Creating future of solid Earth science with high performance computing (HPC): Introduction

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In this session, we explore scientific and social issues to be solved in Earth science for the next 10-20 years using high performance computing (HPC). We will discuss future problems and prospects in the development of solid Earth science, especially for simulation technology in earthquake and tsunami disaster mitigation, new methods for big data analyses of seismic waves and crustal deformation obtained by high-density observation networks, construction of multi-scale solid Earth model, and so on. We will introduce the contents of the white paper of the future plans for computer science in various fields including solid Earth science.

STT59-08 Room:104 Time:May 20 16:30-16:45

Mantle convection simulations on HPC: present and future

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In this presentation, we will discuss (a rather personal view of) the possible directions of the advanced numerical studies of mantle dynamics in concert with the progress of high-performance computing in the next era. We will start with a brief overview of the research targets and outcrops of the numerical modelings of mantle convection to date from a viewpoint of geosciences. Then we will discuss the scientific goals which the mantle dynamics researchers are to tackle with over a mid- to long-span of years, together with the technical issues in terms of both software and hardware developments.

Keywords: mantle convection, numerical simulations

STT59-09 Room:104 Time:May 20 16:45-17:00

An Approach to Exascale Visualization: Interactive Viewing of In-Situ Visualization

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In the coming era of exascale supercomputing, in-situ visualization is an inevitable approach to reduce the output data size. A problem of the in-situ visualization is that it loses interactivity unless a steering method is adopted. In this paper, we propose a new in-situ visualization method for exascale simulations. This method applies a lot of (hopefully millions of) in-situ visualizations at once with (thousands of) different visualizations taken from (thousands of) different cameras. The output in this strategy is not numbers, but movies. Even when a simulation produces one million of movies, the total output data size is only 10 TB when each movie is compressed to 10 MB. It should be noted that the size of 10 TB is rather small in the coming exascale era. The output of million movies will be analyzed as a post-processing in our proposed method. A specially designed movie player will read the million movie files and display a sequence of images in a window. By extracting a proper image sequence from different movie files, we can effectively walk through the visualization objects while the dynamic phenomena are shown in the window. To demonstrate the feasibility of the proposed method, we have performed a dynamo simulation in which 125 in-situ visualizations are applied. The visualization code is hybrid MPI-OpenMP. This calculation was performed on FX-10. We have also developed a movie player that reads hundreds of movie files and play a movie on a PC window. The movie player also has a function to show current position in or around the simulation region. We have confirmed that this method—in-situ visualization with interactive view—is not only feasible, but also practical for visualizations of large-scale simulations.

Keywords: large-scale visualization, in-situ visualization, parallel visualization

STT59-10 Room:104 Time:May 20 17:00-17:15

GPGPU-Accelerated Digital Signal Processing Method for Detection and Analysis of Repeating Earthquake

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Repeating earthquakes are occurring on the similar asperity at the plate boundary. These earthquakes have an important property; the seismic waveforms observed at the identical observation site are very similar regardless of their occurrence time. The slip histories of repeating earthquakes could reveal the existence of asperities: The Analysis of repeating earthquakes can detect the characteristics of the asperities and realize the temporal and spatial monitoring of the slip in the plate boundary. Moreover, we are expecting the medium-term predictions of earthquake at the plate boundary by means of the Quantitative analysis of repeating earthquakes. Detailed information of stress concentration at quasi-static slip area and mechanism of energy deposition is indispensable to prediction of earthquake. Nowadays, GPS observation network also gives the peculiarity of quasi-static slip area. It is, however, not enough for analysis of ocean trench-type earthquakes.

Although the previous works have shown the existence of asperity and repeating earthquake and relationship between asperity and quasi-static slip area, the stable and robust method for automatic detection of repeating earthquakes has not been established yet. Furthermore, in order to process the enormous data (so-called big data) to speed up the computation of digital signal processing is an important issue.

Recently, GPU (Graphic Processing Unit) is used as an acceleration tool in various study fields. This movement is called GPGPU (General Purpose computing on GPUs). In the last few years the performance of GPU keeps on improving rapidly. The use of GPUs contributes to a significant reduction of the execution time in the digital signal processing of the huge seismic data.

In this study, we examine the high-speed signal processing of huge seismic data using the GPU architecture. We employ two signal processing methods: First, the band-limited Fourier phase correlation is applied as a fast method of detecting repeating earthquake. Secondly, we employ coherence function using three orthogonal components (East-West, North-South, and Up-Down) of seismic data as a detailed analysis of repeating earthquakes. These methods give us the correlation between two seismic data. Then, we evaluate the effectiveness of these methods. Moreover, we also examined the GPGPU acceleration technique for these methods. We compare the execution time between GPU (NVIDIA GeForce GTX 580) and CPU (Intel Core i7 960) processing. The parameters of both analyses are on equal terms. In case of band limited phase only correlation, the obtained results indicate that single GPU calculation is ca. 8.0 times faster than 4-core CPU calculation (auto-optimization with OpenMP). In case of coherence function using three components, GPU is 12.7 times as fast as CPU. It was found that both band-limited Fourier phase correlation and coherence function using three orthogonal components are effective, and that the GPGPU-based acceleration for the temporal signal processing is very useful. On the other hand, these methods also have some problems in the present; acceleration of data transfer between RAM to VRAM, time reduction of input/output operations. We are going to examine multi-GPU computing algorithm for more acceleration of signal processing framework.

Keywords: Repeating Earthquake, GPGPU, CUDA, Fourier phase correlation, Coherence

STT59-11 Room:104 Time:May 20 17:15-17:30

Multivariate Analysis of Geophysical Time-Series Data on a Cloud Computing System

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[1]The Institute of Statistical Mathematics

A multivariate analysis of time-series data based on the Bayesian statistics is always time-consuming especially in its complex programing and much computation time. Although Research and Development Center for Data Assimilation, the Institute of Statistical Mathematics provides software related to such Bayesian analysis, multivariate analysis requires many computer resources, which are often hardly obtained.

We have developed web application "CloCK-TiME" (Cloud Computing Kernel for Time-series Modeling Engine), which enables users to analyze their time-series data by using a networked PC cluster in a cloud computing system. A state space model decomposes uploaded time-series data into trend, seasonal, autoregressive and observation noise components, each of which are estimated using the particle filter algorithm. We show an application example in the case of tide gauge data recorded along the coastline of Japan. Tide gauge observations along the coastline of Japan have recorded the land sinking due to the continuous subduction of the oceanic plates. The proposed software extracts such long-term activities of the Earth's crust together with rapid displacements related to earthquakes, even before the establishment of the global positioning system, from monthly mean data of the sea levels. The spatial and temporal distributions of the extracted trend component clearly indicate the subduction, near which giant earthquakes have occurred or are predicted to occur. A multivariate analysis of the observatories located at the northeast coast of Japan successfully determines the past crustal displacement in the case of the 1978 Off-Miyagi Earthquake.

Keywords: cloud computing, time-series analysis, multivariate analysis, tide gauge

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STT59-12 Room:104 Time:May 20 17:30-17:45

Paradigm shift in a scientific methodology driven by big data

Tomoyuki Higuchi[1*]

[1]The Institute of Statistical Mathematics

We will give a brief introduction to the big data R&D and consider how big data makes an impact on a research style in earth science.

Keywords: big data, data assimilation

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STT59-13 Room:104 Time:May 20 17:45-18:00

Creating future of solid Earth science with high performance computing (HPC): Concluding discussion

Ryota Hino[1*], Yoshimori Honkura[2], Yoshiyuki Kaneda[3], Taro Arikawa[4], Tsuyoshi Ichimura[5], Takuto Maeda[5], Takane Hori[3]

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How the evolution of "High Performance Computing (HPC)" contributes to progress in earth sciences? We will develop a perspective in the next 10 to 20 years based on comprehensive discussion provided in the session including invited talks. The aim of the concluding discussion is to integrate the opinions of attendees, both speakers and non-speakers, into a proposal for development of next generation HPC as a solution to important problems in terms of scientific break through and social relevance.

Keywords: High Performance Computing

STT59-P01 Room:Convention Hall Time:May 20 18:15-19:30

Accumulation of earthquake scenarios towards the construction of simulation database

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In recent years, earthquake cycle simulations based on plate motions and rock friction laws have been utilized for studies on the earthquake preparation process and repetition pattern of the earthquake which occurs in the plate boundary near the Japanese Islands (e.g., Hori et al., 2004, Nakata et al., 2012, etc.). In these studies, the target earthquakes are mainly events occurred in the past. Through the trial-and-error correction in the distribution of frictional property on faults, many forward simulations are carried out until the basic repetition patterns or magnitudes of target earthquake is reproduced. Then, for expecting the future repetition of target earthquakes, the extension of simulations for some tuned parameters might be utilized. However, an natural earthquake is a highly nonlinear problem with huge degrees of freedom, and the modeling error of forward simulations of earthquake cycles is generally large due to the simplicity. For this reason, "deterministic future prediction" is theoretically impossible through the above strategy based on the reproduction of old events.

That is, for the purpose of practical earthquake prediction, we need the prediction framework which can reflect the real-time observation data (such as crustal deformation) without large time lag, and can perform sequentially with increasing data. In order to realize such prediction, we propose the construction of a simulation database consisted of a large number of simulation results (scenarios) with various simulation models or model parameters. If such database is established, with the increase of realtime observation data, simulation results in the database are sequentially accessed and utilized to compare with observed data by likelihood evaluation. Then, the extrapolation of scenarios with higher likelihood values is regarded as the tentative prediction based on the last observation data. The large advantage of this prediction concept is that the resultant predictions have high flexibility according the real-time observation data.

Due to the recent development of domestic High Performance Computing Infrastructures(HPCI), such as K (RIKEN) or ES2 (JAMSTEC), within several days, we can calculate 100-1000 scenarios of quasi-dynamic earthquake cycle simulations, with moderate discretization (about 1km cell) of the plate interface (about 300kmx800km area). Now, for the Nankai Trough region where the next earthquake occurrence is anticipated, many earthquake scenarios with various frictional parameters are tried, and simulation database is under construction towards the establishment of earthquake prediction system.

In the presentation, we will introduce the more details of simulation database and the concept of our prediction system.

Keywords: High Performance Computing, earthquake cycle simulation, database, prediction system, realtime data

STT59-P02 Room:Convention Hall Time:May 20 18:15-19:30

Cause of Significant scattering of teleseismic P-wave near Japan Trench as Inferred by Large-Scale Numerical Simulation

Takuto Maeda[1*], Takashi Furumura[2], Kazushige Obara[1]

[1]ERI, The University Tokyo, [2]CIDIR, The University of Tokyo

We found a significant scattered wave train in Japan after the arrival of near-vertical incidence of P-wave of the Off West Coast, New Zealand Earthquake (Mw7.6) in 2009 by using a dense, high-sensitive seismograph network (Hi-net) operated by NIED. The scattered wave train is dominant in the vertical component at period band of 20-50 s with a propagation velocity of 3.5 km/s. It propagates cylindrically to west from Kanto area, central Japan. This signal contains only low-frequency components and no local earthquakes were reported at that time. All of these facts suggest that the observed wave train is a scattered wave originated nearfield by incoming P wave from distant earthquake.

To locate the conversion point of the scattered waves, we first separated scattered wave train from large-amplitude direct waves. Firstly, we stacked seismic traces along the wavefront of the direct waves to cancel out the scattered wave propagating from different direction to each station to make a clear direct wave packet. Then, the stacked trace is subtracted from the raw seismogram to enhance scattered waves. By analyzing the subtracted traces based on an array data processing technique, we located the scatterer at around the Boso triple junction of three plates, southeast of Kanto area.

To clarify what kind of structure develops such large scattered waves, we conducted a finite difference method simulation of seismic wave propagation using high-resolution subsurface structure model with topography and bathymetry. Simulation results revealed that strong scattered waves are generated along the Japan Trench, and are guided to the direction normal to the trench axis due to the reverberation between seafloor and the Pacific plate boundary. In addition, the reverberation of scattered waves in thick (~9000 m) seawater column above the Boso triple junction enhance and elongate the scattered waves significantly, which explains observed feature of scattered waves.

Acknowledgements: This study is supported by the Strategic Programs for Innovative Research field 3 ”Projection of Planet Earth Variations for Mitigating Natural Disasters”, by MEXT Japan. We used computer resources of the K computer by RIKEN-AICS.

Keywords: Seismic wave scattering, subduction zone, numerical simulation, high performance computing, array analysis

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Computation of teleseismic waves for large earthquake using Spectral-Element Method

Seiji Tsuboi[1*], Takeshi, Nakamura[1], Mikito, Furuichi[1]

[1]JAMSTEC

We calculate broadband synthetic seismograms with the finite source propagation model for a realistic 3D Earth model using the spectral-element method. Source model we used is that of Lee et al (2011), which uses teleseismic waveform, strong motion seismograms and GPS measurements. We use the Earth Simulator 2 of JAMSTEC to compute synthetic seismograms using the spectral-element method. The simulations are performed on 1014 processors, which require 127 nodes of the Earth Simulator 2. We use a mesh with 200 million spectral-elements, for a total of 13 billion global integration grid points. This translates into an approximate grid spacing of 2.0 km along the Earth's surface. On this number of nodes, a simulation of 30 minutes of wave propagation accurate at periods of 3.5 seconds and longer requires about 7 hours of CPU time.

Keywords: Theoretical seismic waves, Spectral-Element Method

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Three-dimensional numerical modeling of temperature, fluid flow and heat flow associated with subduction of curved slabs

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In order to simulate distributions of temperature and fluid flow associated with subduction of a curved slab, we constructed a three-dimensional thermal convection model. We assumed that slab extends with time in a given shape with velocity of 6cm/year, dip angle of 10 deg. for 10 million years. We investigated the relation concerning shape of slab upper surface, subduction direction, distributions of temperature and fluid flow, and surface heat flow for various types of curved slabs. The results revealed a very likely relation between temperature distribution and upper surface shape of a slab, and composite subduction angle which is a compound of a dip angle and slab gradient slope angle along subduction direction. Not only thermal field, but also flow velocity differed greatly on each side of a curved slab. A bent slab leads to a complex fluid flow around it. The results also exhibited how oblique subduction performs in such a curved slab. Although symmetric slab shape models are constructed, oblique subduction resulted in some asymmetric patterns of interplate temperature and heat flow distributions. Isotherm on the plate interface appears to be dragged to the direction of oblique subduction, and low heat flow anomaly appeared on the descent slope of the subducting slab. Most of these simulated results are related to the composite subduction angle. The slab surface shallower than a depth of 60 km has a corresponding relation with surface heat flow distribution above it, whereas the effect gradually disappears when it is deeper than 60 km. Cooling effect associated with subduction is generally related to slab length from the model surface and the composite subduction angle. Large bent slab shape also has a negative effect on cooling down as compared with a flat one .

Keywords: curved slab, temperature, fluid flow, heat flow, numerical simulation

STT59-P05 Room:Convention Hall Time:May 20 18:15-19:30

Numerical simulation of geodynamo with HPCs

Takehiro Miyagoshi[1]*, Yozo Hamano[1]

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Since magnetohydrodynamic (MHD) numerical geodynamo simulations in three-dimensinal spherical shell with super computer were started, about 18 years have passed. Many useful results have been obtained by the present. For example, MHD dynamo solution in nonlinear process, reproduce of magnetic dipole field like the Earth, and reversal of magnetic polarity. Inside the core cannot be observed directly, so knowledge from numerical simulations is very useful to understand core convection and geodynamo.

However, physical properties or non-dimensional parameters are very different from them in the Earth's core, due to limitation of present super computers. To understand the realistic core convection and geodynamo, physical properties or parameters, especially viscosity or Ekman number, should be closed to the real value in numerical simulations.

Factors from outside the core, not inside the core, for example climatic change, probably affect geomagnetic field variation, but this point is seldom considered in numerical simulations. To understand geomagnetic field variation and predict it, those factors are important.

In next generation HPCs, coupling geodynamo simulation with mantle convection simulation may become actual. Of course, then the parameters in each simulations are restricted. However, useful results are probably obtained to understand the connection among surface, mantle, and core activity.

We will talk about the directivity of geodynamo simulation studies associated with development of next generation HPCs.

STT59-P06 Room:Convention Hall Time:May 20 18:15-19:30

Development of a simulation code for a growing planet with core formation in 3D

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This talk introduces our developed a new numerical code for solving the Stokes flow in 3D to investigate the global core formation process in the planetary interior. The formation of a metallic core is widely accepted as the major differentiation event during planetary formation. In our simulation, the growing planet with the impact events and global sinking of the dense metal-rich material over long time scale are captured in the Stokes flow regime.

In order to simulate the core formation process in 3-D, we employ the spherical Cartesian approach. The surface of the material c is captured by the distribution of color functions. The dynamical boundary as a free surface is mimicked by surrounding low viscosity material with zero density, so-called sticky air. The viscosity of the sticky air varies laterally, depending on the neighbouring viscosity of planetary surface. Self-gravitating force is obtained by solving the gravity potential equation. For solving the momentum and continuity equations, we developed an iterative Stokes flow solver, which is robust to problems including jumps in the viscosity contrast. Our solver design consists of an inner and outer solver utilizing a strong Schur complement preconditioner and the Arnoldi type Krylov subspace method preconditioned with geometric multigrid method (GMG). We enhance the robustness of the inner solver for the velocity problem with a mixed (quad-double) precision Krylov kernel calculation. As the high precision calculation method, we employ the double-double precision algorithm which has high arithmetic intensity and is faster than normal quad arithmetic using a register or cache memory. Our mixed precision method improves the convergence of Krylov method without significantly increasing the calculation time.

All of our numerical algorithms are designed for the parallel-vector architecture especially for the Earth Simulator 2 (ES2). Our careful implementation of SOR smoother enables to achieve 34% of the peak performance of ES2 at the finest level of GMG. In the simulation with a grid size of $256*256*256$, our solver achieved 910.3Gflop using 8 nodes (13.9% of peak performance) which involves the cost for idling CPU for multigrid operations.

Keywords: core formation, Stokes flow, mantle convection, double-double method, Krylov subspace method