Advances in 3-D Spherical Mantle Convection Simulation Over the Past Quarter-century in Japan: From Viewpoints of Numerical Resolution and Visualization

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1. Introduction

Numerical simulations of global mantle convection in a 3-D spherical shell can be broadly classified into two categories: time-dependent mantle convection simulations and instantaneous mantle flow simulations. The former involves an understanding of the evolution of Earth over the past 4600 million years, and its future [e.g., 1]. The latter involves an understanding of the mechanisms of surface tectonics, such as plate motion, intraplate stress, topography, and geoid anomalies, using geophysical data of the present-day Earth's mantle structure, that is, primarily seismicity and seismic tomography models [e.g., 2]. The author is the only person in Japan engaged in studies in these two categories.

In this report, I briefly introduce the advances in massive 3-D spherical-shell mantle convection simulations using supercomputers from the viewpoint of numerical resolution and visualization. I also discuss the limitations specific to massive simulations of mantle convection based on my own experience.

2. History

During my fourth year of undergraduate studies in FY 1997, I engaged in the numerical simulation of mantle convection in 3-D spherical shells under the supervision of a professor at Hiroshima University. My first top-author paper examined the effect of the continental lithosphere on the mantle convection pattern [3] using a simulation code [4]. In April 2003, immediately after receiving my Ph.D. from the University of Tokyo, I started working at JAMSTEC as a Researcher and an initial member of the solid-earth research group at the Earth Simulator Center.

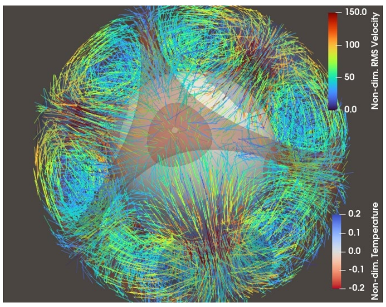

Figure 1. Simulated mantle convection with a steady-state pattern at low-Rayleigh numbers.

Until FY 2005, I developed a new simulation code for mantle convection in a 3-D spherical shell based on a finite-difference method and a Yin-Yang grid using the first version of the Earth Simulator (ES1). I studied the basic structure of mantle convection (Fig. 1) and published my first paper at JAMSTEC in 2004 [5]. The computational grids used for this study were 100 × 100 × 200 in r-, θ-, and φ-directions in spherical polar coordinates, which is equal to the total grid numbers of $N = 2{,}000{,}000$ (i.e., 2 million grids). However, this code was not parallelized at the time.

In April 2006, I moved to another department in JAMSTEC. Because of the usability of my research, I stopped using ES1, but instead, started to use a general-purpose (GP) parallel supercomputer available at JAMSTEC. Thanks to its usability, I could improve and parallelize my code using the finite-volume and marker-in-cell methods. Using this code, I could engage in many research topics on solid-earth dynamics, e.g., (i) mechanisms and driving forces of the supercontinental cycle and continental drift, (ii) onset conditions and mechanisms of plate tectonics, (iii) behavior of subducted crusts in the deep mantle, (iv) basic physics of mantle-core coupling, and (v) dynamic links between surface tectonics and mantle convection on a global scale and in specified target areas. It should be noted that in the above studies, I also used supercomputer systems at the Earthquake Research Institute, The University of Tokyo.

However, sadly, the GP supercomputer in JAMSTEC was no longer permitted for use in individual research projects by the end of FY 2021. Therefore, I started to use the Earth Simulator (the fourth version, i.e., ES4) for the first time in 16 years (!). In 2023, I published a paper on the intraplate stress of the Pacific Plate predicted by a numerical model of mantle convection [6]. In this study, simulations for the initial version of the paper were performed on GP supercomputers, while additional runs required to revise the paper were employed in ES4.

Then, after I moved to the current university in April 2024, I tried to study further high-resolution simulation of mantle convection. Recently, I proposed that the primal driving force of oceanic plate is “mantle drag" using an updated instantaneous mantle flow model (Fig. 2) (submitted in 2026).

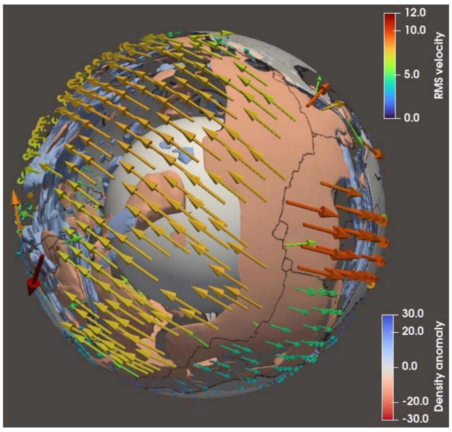

Figure 2. Simulated mantle flow of the present Earth.

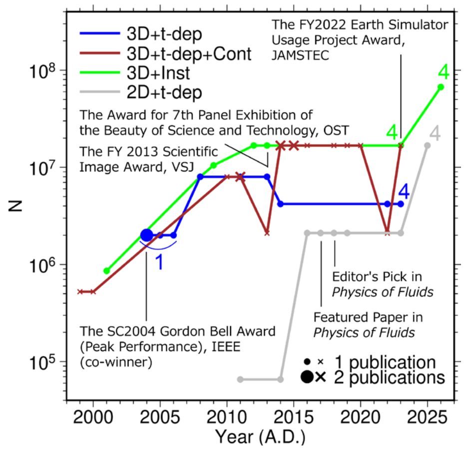

Figure 3. Publication years of the author's peer-reviewed papers and total gird numbers (N) used. "t-dep" and "Inst" mean time-dependent convection and instantaneous flow models. The label "Cont" means the models with continental lithospheres. The labels "1" and "4" mean that the simulations were performed by first and fourth Earth Simulators (ES1 and ES4, respectively).

Figure 3 shows a graph of the publication years of my peer-reviewed paper on the 3-D spherical-shell mantle convection simulation versus the total grid numbers (N) used. Although the required resolution varies depending on the research topic, overall, N has been increasing with the year. In particular, the computational grid used in the recent instantaneous simulation was 128 × 512 × 1024, which is equal to $N = 67,108,864$ (ca. 67 million grids). Considering that N in 2001 was 860,000 (ca. 0.9 million grids), N has increased approximately 78-fold over the past quarter-century owing to advances in supercomputers (green line in Fig. 3).

For reference, I show the recent remarkable advance in N used in 2-D spherical-shell simulation for the coupling between mantle convection and core convection. The computational grids for this simulation were 4096 × 4096 in r- and φ-directions in 2-D spherical polar coordinates [7] (gray line in Fig. 3).

3. Limitations

It should be noted that high-resolution simulation of mantle convection is constrained not only by the limitations of the performance of CPUs but also by the enormous data size and the transfer speed between supercomputers and the computer in my office. Owing to the complexities of the chemical compositions and mineralogical phase transitions of the mantle and crustal rocks, it is necessary to output 3-D data for individual compositions and phases, in addition to basic physical properties, such as velocity, pressure, viscosity, and temperature. Furthermore, in contrast to one time step on the order of 10,000 years, the total timescale required to obtain a statistically steady-state solution is usually larger than the order of Earth's age (i.e., billions of years). This is because the initial states of the past Earth are enigmatic. Therefore, it is necessary to output 3-D data at many time steps in every numerical model to analyze the results and make a movie using visualization software. Because over 100 models are required to study one research project, an enormous amount of data storage and ultrahigh transfer speed are required.

Regarding the 3-D visualization software, AVS/Express® (Visual Management Sciences, Inc.) was used, but since 2022, the open-source, free software ParaView (Kitware, Inc.) has been used. It was found that ParaView can be used to visualize massive and complex simulation data of 3-D spherical-shell mantle convection. Figures 1 and 2 were drawn using ParaView.

4. Summary

Thanks to the advances in supercomputers and many research collaborators over the past quarter century, I was able to study several important subjects in solid-earth science and lead my own research field in Japan. In the Future, I would like to contribute to the problems surrounding human life through massive numerical simulations. Recently, I engaged in data analysis and theoretical studies of the Earth's system, such as the mechanism of intraplate large earthquakes [8] and global sea-level change during Earth's history [9], which may help mitigate hazard risk and understand global environmental problems, respectively.

References

[1] Yoshida, M., *Geology*, 44(9), 755–758, 2016.
[2] Yoshida, M., *G-Cubed*, 9(7), Q07002, 2008.
[3] Yoshida, M. et al., *Geophys. Res. Lett.*, 26(7), 947–950, 1999.
[4] Iwase, Y., *Geomag. Geoelectr.*, 48, 1499–1514, 1996.
[5] Yoshida, M. and Kageyama, A., *Geophys. Res. Lett.*, 31(12), L12609, 2004.
[6] Yoshida, M., *Lithosphere*, 2023(1), 6563534, 2023.
[7] Yoshida, M., *Habitable Planet*, 1(1–2), 145–156, 2025.
[8] Yoshida, M., *Geosci. Lett.*, 11(1), 46, 2024.
[9] Yoshida, M., *Gondwana Res.*, 140, 146–157, 2025.