Collaborative Analysis of Large-Scale Simulation Data on Solid Earth Sciences

Project Leaders

Akira Kageyama The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

David A. Yuen Department of Geology and Geophysics and Minnesota Supercomputing Institute, University of Minnesota

Authors

Masanori Kameyama The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

Akira Kageyama The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

David A. Yuen Department of Geology and Geophysics and Minnesota Supercomputing Institute, University of Minnesota

The Solid Earth Simulation Group of the Earth Simulator Center (SESG/ESC) is in collaboration with Department of Geology and Geophysics, University of Minnesota (DGG/UMN) on analysis and visualization of large-scale simulation data of mantle convection. Our analysis revealed possible impacts of the post-perovskite phase transition on the dynamics in the Earth's lower mantle. Through the collaborative works, we also demonstrated that the ACuTEMan, a simulation code developed by SESG/ESC, shows an excellent performance on scalar architectures as well as on vector architectures like the Earth Simulator.

Keywords: solid earth simulation, mantle convection, data analysis, visualization

1. Large-Scale Three-Dimensional Numerical Simulation of Mantle Convection with post-perovskite phase transition

The Solid Earth Simulation Group of the Earth Simulator Center (SESG/ESC) is conducting numerical simulations of mantle convection in a three-dimensional rectangular domain, as a part of their own research project "Development of Advanced Simulation Tools for Solid Earth Sciences". Among them, the studies of mantle convection with newly-discovered post-perovskite (PPv) phase transition is chosen as a topic of the collaboration with Department of Geology and Geophysics, University of Minnesota (DGG/UMN). Here we performed time-dependent simulations of convection in a box of 3000 km height and aspect ratio of 6 × 6 × 1, using up to 512 × 512 × 128 mesh divisions. The details of numerical simulations can be found elsewhere [1, 2]. Our analysis in FY2004 and FY2005 demonstrated that under certain conditions a strong latent heat exchange during the PPv phase transition can exert a significant impact on convective flow patterns and thermal state in the lowermost

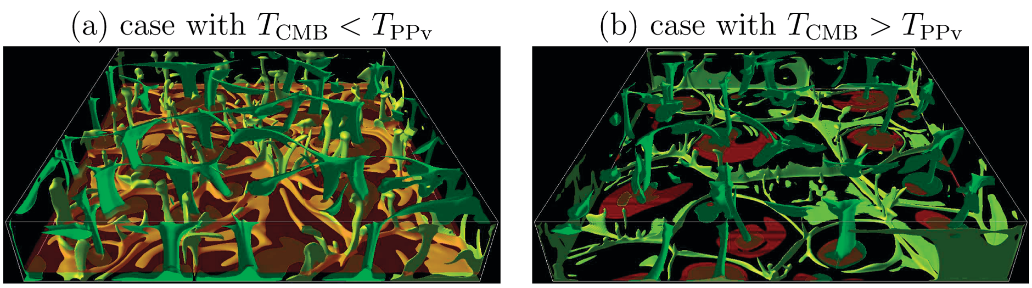

Fig. 1 Snapshots of convective flow patterns and distributions of post-perovskite (PPv) phase obtained for the cases (a) where the temperature at the bottom surface T_{CMB} is lower than that of the PPv transition T_{PPv} there and (b) where $T_{\mathrm{CMB}} > T_{\mathrm{PPv}}$. Indicated by opaque surfaces are the isosurfaces of the lateral thermal anomalies $\delta T \equiv T - \langle T \rangle$, where $\langle T \rangle$ is the horizontal average of temperature at each depth. Bounded by yellow surfaces are the hot thermal anomalies with $\delta T > 75$K, while by green surfaces are the cold anomalies with $\delta T < -125$K. The transparent red surfaces are the isosurfaces of the phase function $\Gamma = 0.5$ for the PPv phase transition, indicating that the PPv and perovskite phases are in equilibrium. In the figure the isosurfaces of δT are not shown in the thermal boundary layer along the top surface.

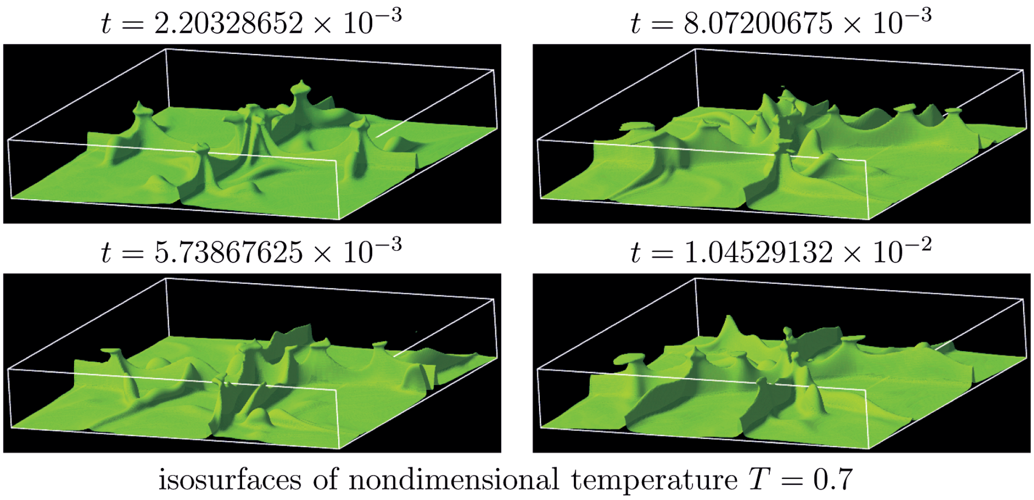

Fig. 2 Snapshots of convective flow patterns for four different elapsed times indicated in the figure. Plotted are the isosurfaces of the nondimensional temperature $T = 0.7$. In this calculation, the depth-dependence of thermal expansivity is assumed, in order to mimic the effects of adiabatic compression.

mantle [1] (see Fig. 1). In FY2006, we studied the possible influences of the PPv transition on the origin and formation of "superplumes" observed in the lower mantle of the Earth [2] (see Fig. 2).

2. Transportation and Analysis of Simulation Data

This collaborative research requires an exchange of a large amount of data between SESG/ESC and DGG/UMN. Mantle convection simulations contain, in general, at least four fundamental variables, namely temperature field and three components of velocity vectors. In the model problems employed here (512 × 512 × 128 mesh divisions), each file containing snapshot data of one variable is as big as about 130 MB when storing in single precisions. In addition, detailed analysis of the simulated results needs data of several tens or even a hundred snapshots. Taken together, we need to handle several hundred GB of data through the collaboration. Such a large amount of data transfer has rarely been attempted in the field of solid earth sciences.

In this collaborative works, we employed a "primitive" manner of data transportations. The simulation data are put in hard drives, which are transported between SESG/ESC and DGG/UMN. For the safety of these drives, the hard drives are brought together when either side of researchers visits the other. Since FY2004, SESG/ESC has transported the simulation data of more than 1 TB (corresponding to about 1500 snapshots) to DGG/UMN. The simulation data is analyzed and/or visualized by both sides of this collaboration. Some of the produced images are exchanged and shared with the two parties.

3. Training in Large-Scale Computing at DGG/UMN

In FY2006, a source code of "ACuTEMan", a simulation program of mantle convection in three-dimensional rectangular domains developed by SESG/ESC [3, 4], was given to DGG/UMN at their request. The ACuTEMan code was used for the training of graduate students and/or young researchers at DGG/UMN in large-scale parallel computing. Through their computing experiences, the ACuTEMan was proved to show an excellent performance on scalar architectures, including IBM BlueGene/L and SGI Altix, as well as on vector architectures like the Earth Simulator.

References

[1] M. Kameyama and D. A. Yuen. 3-D convection studies on the thermal state in the lower mantle with post-perovskite phase transition. *Geophys. Res. Lett.*, 33, L12S10, doi:10.1029/2006GL025744, 2006.

[2] D. A. Yuen, M. Monnereau, U. Hansen, M. Kameyama, and C. Matyska. Dynamics of superplumes in the lower mantle. In D. A. Yuen, S. Maruyama, S. Karato, and B. F. Windley, editors, *Superplumes: Beyond Plate Tectonics*. Springer, 2007. in press.

[3] M. Kameyama, A. Kageyama, and T. Sato. Multigrid iterative algorithm using pseudo-compressibility for three-dimensional mantle convection with strongly variable viscosity. *J. Comput. Phys.*, 206(1):162–181, 2005.

[4] M. Kameyama. ACuTEMan: A multigrid-based mantle convection simulation code and its optimization to the Earth Simulator. *J. Earth Simulator*, 4:2–10, 2005.

ミネソタ大学との MOU 共同研究: 固体地球シミュレーションに関する大規模データの解析

プロジェクトリーダー
陰山　聡　海洋研究開発機構　地球シミュレータセンター
David A. Yuen　Department of Geology and Geophysics and Minnesota Supercomputing Institute, University of Minnesota

著者
亀山　真典　海洋研究開発機構　地球シミュレータセンター
陰山　聡　海洋研究開発機構　地球シミュレータセンター
David A. Yuen　Department of Geology and Geophysics and Minnesota Supercomputing Institute, University of Minnesota

キーワード：固体地球シミュレーション, マントル対流, データ解析, 可視化

ミネソタ大学側のコンタクトパーソンであるYuen教授の地球シミュレータセンター訪問（平成16年1月）を契機に、固体地球シミュレーションデータの可視化を中心とした研究協力を行うこととなった。この目的は、固体地球シミュレーショングループで実施している大規模なシミュレーションデータの可視化・解析作業を効率化すること、及びこの作業を通してミネソタ大学側の若手研究者の啓蒙やトレーニングに資することである。その目的を達成するための工程として、ESCでは固体地球シミュレーショングループで実施している3次元箱型形状の高分解能マントル対流シミュレーションデータの一部をそのままの大きさ（即ち「間引き」や「領域の切り出し」をすることなく）でミネソタ大へ提供している。MOU締結以来、今年度までに提供したデータ量は1TB以上にも及ぶ。このデータの解析及び可視化の作業は固体地球シミュレーショングループとミネソタ大学の大学院生・若手研究者の連携のもとに行われ、ミネソタ大学側で作成された可視化画像や解析結果の一部はESCへも還元されている。

この共同研究では特に、最近発見されたマントル最深部での鉱物相転移（ポストペロブスカイト相転移）を考慮したマントル対流シミュレーションとそのデータ提供に重点を置いている。昨年度までの共同作業の結果、ポストペロブスカイト相転移がマントル深部の熱構造に与える影響が明らかになった［1］。また今年度は、この相転移とマントル深部からの巨大上昇流（「スーパープリューム」）の起源との関連性についての研究を行っている［2］。

これに加えて今年度は、ESCで開発した3次元箱型マントル対流プログラムACuTEMan［3, 4］のソースコード一式を提供した。この目的は、ミネソタ大学側の若手研究者に、シミュレーションデータの可視化だけでなく大規模計算そのものにも習熟する機会を与えることである。ミネソタ大学側では現在までのところ、IBM BlueGene/L、SGI Altixといったいくつかのスカラー計算機上でACuTEManのテストを行っている。この結果、ACuTEManは地球シミュレータだけでなく、これらスカラー並列環境でも良好な性能を示すことが確認された。

References

[1] M. Kameyama and D. A. Yuen. 3-D convection studies on the thermal state in the lower mantle with post-perovskite phase transition. *Geophys. Res. Lett.*, 33, L12S10, doi:10.1029/2006GL025744, 2006.

[2] D. A. Yuen, M. Monnereau, U. Hansen, M. Kameyama, and C. Matyska. Dynamics of superplumes in the lower mantle. In D. A. Yuen, S. Maruyama, S. Karato, and B. F. Windley, editors, *Superplumes: Beyond Plate Tectonics*. Springer, 2007. in press.

[3] M. Kameyama, A. Kageyama, and T. Sato. Multigrid iterative algorithm using pseudo-compressibility for three-dimensional mantle convection with strongly variable viscosity. *J. Comput. Phys.*, 206(1):162–181, 2005.

[4] M. Kameyama. ACuTEMan: A multigrid-based mantle convection simulation code and its optimization to the Earth Simulator. *J. Earth Simulator*, 4:2–10, 2005.