Simulation Science: Revealing the Future

Tetsuya Sato
The Earth Simulator Center/JAMTEC

Abstract

The Earth Simulator (ES) was born in March of 2002 in Japan. The most featuring impact of the ES is the fact that simulation becomes possible to deal with the evolution of a whole system at once, so that the future behavior of the system becomes foreseen in advance scientifically. The western science, which is based on Descartes reductionism, dissolves a system into elements and discloses the fundamental laws governing the elements. Accordingly, the western science has gone back to the past of the universe and has never paid attention to the future of the universe since it cannot be resolved into elements. The future evolution results from tangled complex interactions of macro and micro processes which can never be singled out. The ES is the first scientific tool that can make it possible to deal with the future world based on scientific laws. Several such examples obtained by the ES for future prediction are presented. Thus, the future becomes the world of 'Science Reality' in place of 'Science Fiction'. Then, some essential problems left behind for real prediction are examined carefully and an innovative simulation algorithm to resolve those problems is proposed. It is the Macro-Micro Interlocked (MMI) algorithm. The feasibility and practicability of this algorithm is demonstrated.

1. Prologue

In its 60 years history, Computer Simulation has experienced three essential revolutions. The first revolution was brought in 1976 when Seymour Cray developed the Vector computer CRAY 1. Since this genius invention of vector architecture for the so-called supercomputer, simulation develops into a feasible and practical tool to reveal nonlinear and non-equilibrium evolution of an attractive phenomenon based on the fundamental laws governing the nature. Nonlinearity and causality of a natural phenomenon are demonstrated to be consistently explained by simulations based on fundamental laws revealed by the Descartes reductionism. Conversely speaking, the gradual accumulation of those demonstrations has endorsed qualitatively and quantitatively the success of the Descartes reductionism and contributed to maturity of the modern western science. It is quite interesting that the simulation methodology was timely born after the world war when almost all fundamental laws governing the evolution of the nature had been disclosed. This is because the existing analytical method was not sufficiently powerful to prove the validity of the fundamental laws for naturally occurring phenomena, but simulation could do this.

The second revolution was brought by the Earth Simulator appeared in 2002. Conventional supercomputers certainly could contribute to the maturity of modern science. However, the performance was not big enough to go beyond that point, namely, the performance was so small that only a part of the system of interest could be dealt with, or an idealized condition (geometry, initial condition, etc.) must be invoked. In contrast, the Earth Simulator had a power to do an entire simulation of a system of interest. The fact that the entire system could be treated at once means that the future evolution of the system could be predicted based on the fundamental equations governing its evolution, which had never been possible. In the modern science based on the reductionism, only the fundamental laws creating the present universe had been disclosed. However, no practical methodology had been invented to make prediction of the future evolution. This is a natural consequence of the reductionism that reduces the system into elements. The Earth Simulator is the first tool to break this reductionism paradigm of modern science. The future evolution of a system is determined by unlimited interacting forces in the system. Therefore, at least it is invoked to deal with the whole system at once in order to make prediction of the future evolution of a system. The earth simulator has so far produced many important prediction results such as global warming, typhoon prediction and others. So, now the future world becomes the real target of science, I call "science reality", which used to be a world of science fiction (SF). In this sense, revolution in science has certainly come around.

Certainly, the future world becomes a science reality world. However, when one enters deep into the entity of the "entire" simulation, it turns out that only one physics layer (macro-layer), such as the Navier-Stokes equation, is simulated in the entire system, such as the whole globe, but the other physics layer (micro-layer), such as the cloud and rain drops formation, is represented by parameterization, in spite of the fact that the physics of cloud formation (condensation and collisions of cloud particles) is disregarded. This is because the scale range of macroscopic and microscopic processes is unbelievably large, such as 10^{10}, which is impossible to handle by any computer which would be developed in the future.

Thus, the third revolution is invoked in order to make a scientifically reliable prediction, taking into account the macro-micro interacting process. The revolution cannot be realized by machine (hardware) innovation alone. The only possible way of this revolution is to invoke human's intelligence. In the Earth simulator Center, a Macro-Micro Interlocked (MMI) Simulation Group is set up to challenge for this formidable task. Several cutting-edge algorithms have already been developed to demonstrate that macroscopic processes and microscopic processes can be simultaneously and self-consistently simulated.

2. Typical Results of Future Prediction Simulation

Simulation is carried out by solving the fundamental equation that governs the evolution of the system of interest. Usually, we are concerned with a real problem that is important in human life. The real system may well be described by a macroscopic equation. In doing actual simulation, the real system of interest is modeled by a grid system in such a way that the microscopic processes slipped out from the grid interval are negligible or substituted by some parameterization. Then, the chosen grid system may be approximated to represent the system evolution. Usually, the grid system could be satisfactory for doing macroscopic simulation if the number of grid points for a typical direction is taken to be thousands or ten thousands ($10^{3\sim4}$). In the following we pick up three simulations among many which prove that the entire simulation can be a really practical and feasible tool for scientific prediction of natural disasters and design of industrial products.

2.1 Prediction of Typhoon

The Earth Simulator Center has developed a sophisticated climate simulation code that excludes the hydrodynamic assumption and includes the coupling between the ocean and atmosphere dynamics. We have demonstrated that this code can predict the five-day typhoon behavior in three CPU hours[1]. Fig. 1 shows a comparison of the typhoon trajectory of the observation with that of the simulation which was predicted with 5.5 km resolution for the Typhoon 10 of 2003 attacked Japan. We also compare the precipitation predicted by the simulation where the neighborhood of Japan islands is nested with about 1 km with that of the observation to find an excellent agreement (see, Fig. 2). In this simulation about 10,000 grid points are used for the equatorial or meridian direction.

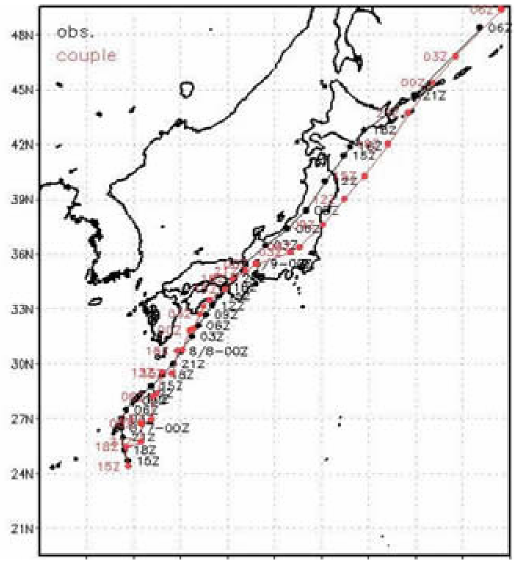
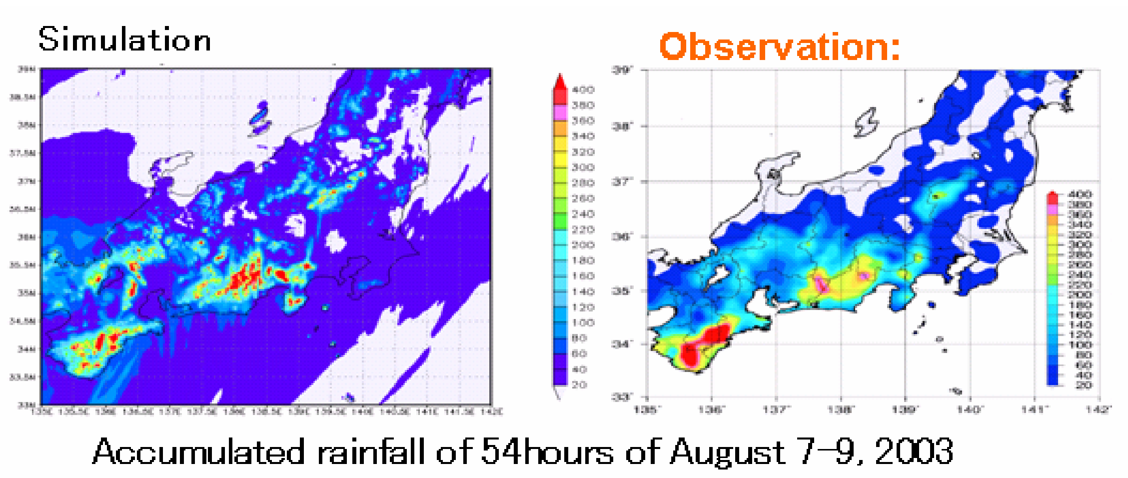


Fig.1 (left) Comparison of the typhoon trajectory (Typhoon10 of 2003) predicted 5 days in advance by simulation (red) with that of observation (black)

Fig.2 (down) Accumulated rainfall predicted by simulation (left) and that obtained by observation (right). Note for no observation over the sea in the observation data



2.2 Prediction of Heat Wave Attack

Once a year or so, a severe heat wave attacks Japan and Korea in summer. The temperature rises by about 10°C higher than the normal temperature for just one day. For the abnormal temperature rise occurred in Tokyo on July 20 of 2004, a global atmospheric simulation is performed by the Atmospheric code developed for the Earth Simulator (AFES) given the global satellite data of July 15 of 2004 (5 days ago of this abnormal event) as an initial condition. Fig. 3 is the comparison of the simulation result with the observation data for the temperature distribution on July 20 of 2004, which indicates a good agreement for both the location and the temperature[2]. When we trace the trajectory of the heat wave five days back, then the heat wave is found to originate at the eastern side of the Mediterranean Sea, from which the meandering jet stream engulfs the Tibetan and Pacific high pressures and creates an abnormally huge high pressure near the Far East to blow a heat wave into Korea and Japan (see, Fig.4). In this simulation about 2000 grid points were chosen for the equatorial direction.

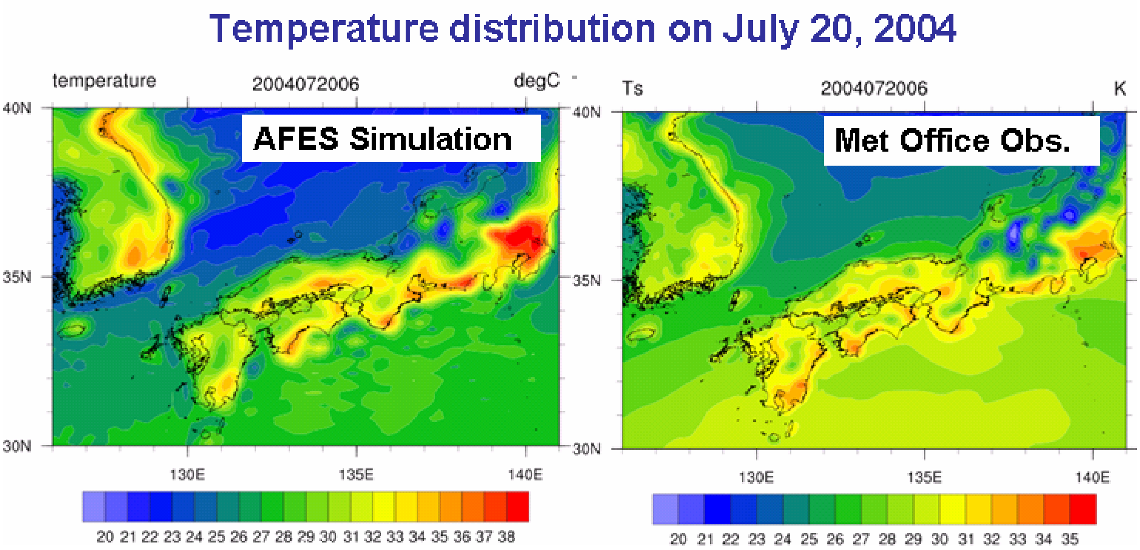


Fig.3 Comparison of the heat wave-caused temperature anomalies predicted 5 days in advance by simulation (left) with the anomalies obtained by observation (right)

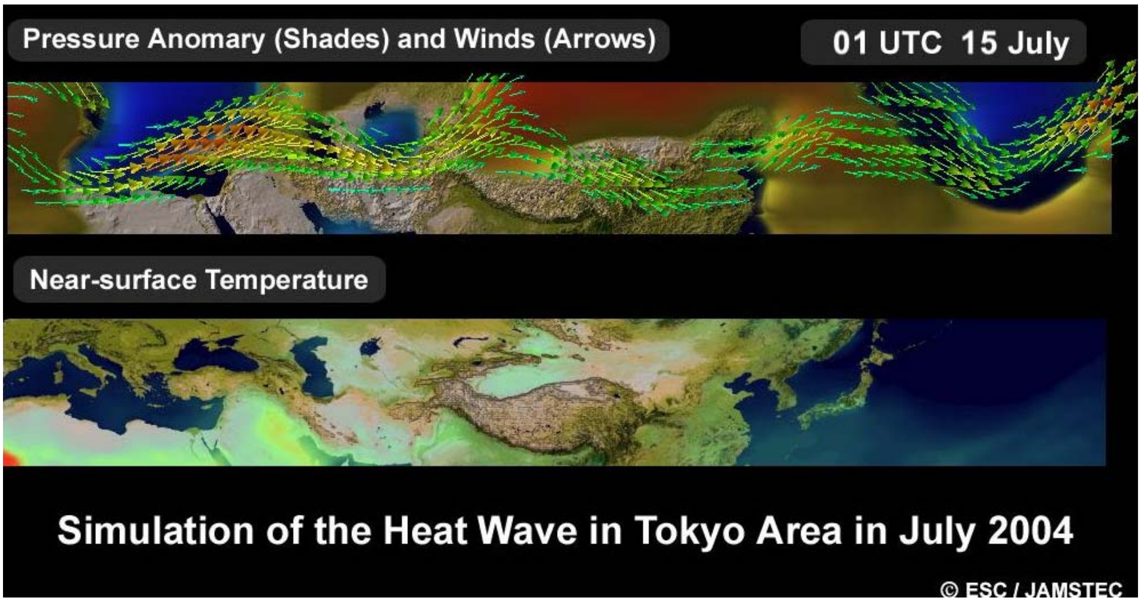


Fig.4 The panel indicates the pressure (shades), winds (arrows) and surface temperature on July 15, 2004 (5 days in advance of the heat wave attack on July 20, 2004)

2.3 Simulation of Automobile Collision

The most important necessary condition for simulation to be employed as the leading tool for designing and developing a new product is that the available computer be large enough to deal with the whole product at once. Otherwise, the would-be product could not be analyzed in a self-contained fashion. Unless the self-contained condition is satisfied, adequate information to design a new product could not be obtained by simulation, which means that simulation could not be a leading tool in the industrial production process.

One good simulation example[3] that demonstrates a revolution in the industrial world is shown in Fig. 5. This figure shows the damages caused by the collision of an automobile against a concrete wall for three cases. They are the real test automobile (right), the simulation done with the resolution of one million grid points (left), and the resolution of ten million grid points (middle). It is clearly observed that the low resolution simulation cannot reproduce the real collision at all (compare the left panel with the right). Only when the resolution is fine enough, the collision can be realized as it stands (compare the middle with the right). This guarantees that safe and sound automobiles can certainly be designed by the high-resolution simulation of automobile collision.

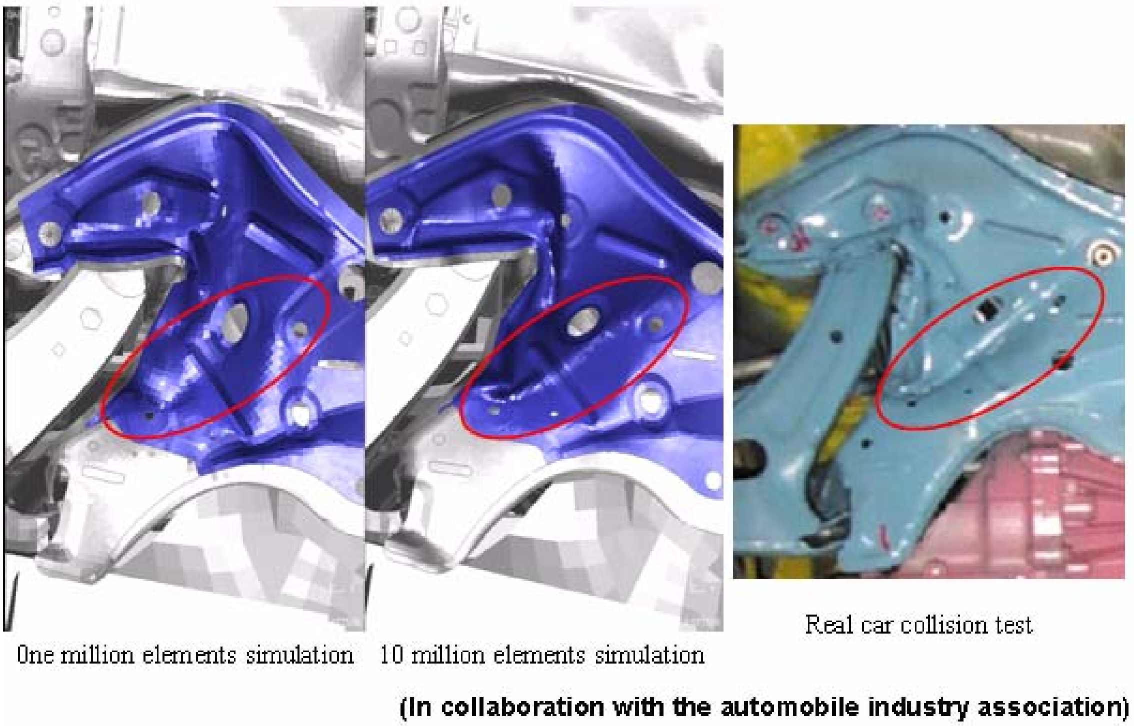


Fig.5 Car collision simulations (left for one million elements simulation and middle for ten million elements simulation) and the real car collision test experiment (right). The

white spots indicates the damages of a small portion of the car flour

3. Dawning of Simulation Culture

The three simulation examples shown in the previous section were macroscopic simulations that were done with high enough resolution to include the substantial amount of energy involved. In contrast with the conventional simulations that cannot resolve the essential small processes involved in the system evolution such as typhoon in the global behavior, local heat wave in the global climate change and the damages in the automobile collision, the global simulations obtained by the Earth Simulator have demonstrated apparent substantial contribution to the welfare of human society.

Strictly speaking, however, the global simulation is made only for a macroscopic equation with using parameterization for microscopic processes. In actuality, attractive phenomena can happen with strong interaction between the macroscopic and microscopic processes. If things evolve gently and slowly everywhere in the system, then parameterization approximation may work well. However, most interesting phenomena suffer from a sudden and abrupt change such as the earthquake and solar flare.

In such an event of interest, the microscopic process is forced to be activated by the concentration of macroscopic energy on a certain location, so that a phase transition or an energy release can be abruptly triggered. This indicates that the parameterization approximation can never be applied, but the microscopic process must be solved in a consistent way with the macroscopic evolution. If one tries to solve both the macroscopic and microscopic processes simultaneously and self-consistently, one must cover from the minimum scale of the microscopic process to the maximum scale of the macroscopic process which may range over the scale of 10^{10}. However, this scale range is impossibly so big that simulation can never been done practically.

In this respect, we have proposed an intelligent simulation algorithm that can wisely simulate the macroscopic and microscopic processes in a simultaneous and self-consistent way.

When one sees carefully the natural behavior, it turns out that nature repeats self-organization and the energy (information) is concentrated successively in a discrete space and time domain. Because of the successive self-organization, any natural system can never manifest itself as structure-less but is stratified into several discrete organizations in space-time domain. Each organization may be described by an independent governing equation. When one pays attention to one organization, the conventional simulation solves the governing equation with the assumption that the upper level organization can be given as the boundary condition and the lower level organization can be represented by prescribed parameters. The upper level may well be treated by choosing properly the boundary of the system. Nevertheless, the lower level process can never be treated by parameters when a microscopic phase transition or energy release can happen as a result of squeezing of the macroscopic energy into a localized location.

The most practical and attractive events we experience in real system are caused by a microscopic transition resulting from the global energy circulation in a real system such as the earthquake. This indicates that one must solve the microscopic process self-consistently with the macroscopic evolution.

Fig.6 shows the flow chart of resolving this formidable task of the macro-micro simulation. This simulation algorithm can reduce the simulation load by billions times. This is because in the conventional undistinguished way one must carry out microscopic simulation at each macroscopic grid point the number of which may be more than billions. As one can see from the flow chart of Fig.6, however, this algorithm invokes microscopic simulation only at one grid point among billions. I call this algorithm "macro-micro interlocked algorithm (MMI)"[4].

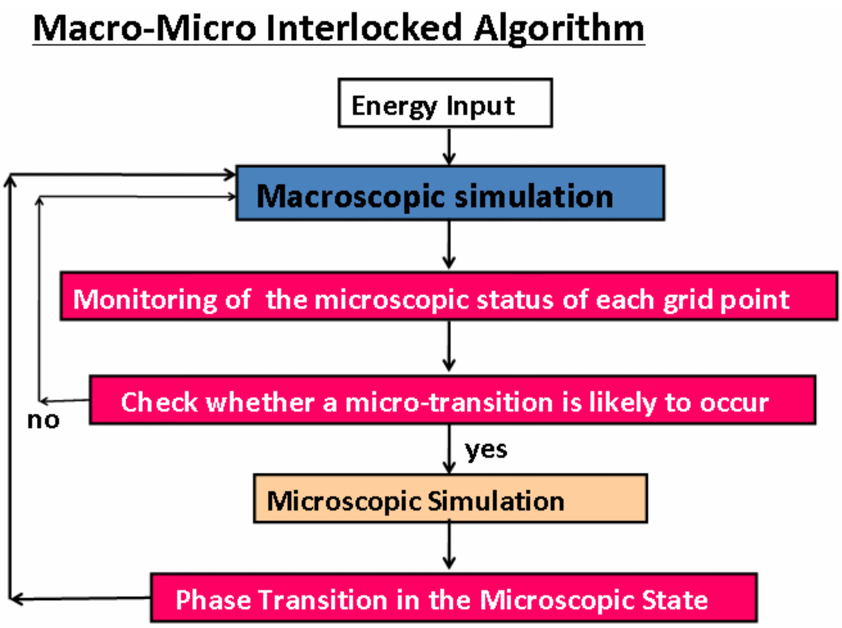


Fig.6 Flow chart of the Macro-Micro Interlocked (MMI) simulation algorithm

The Earth Simulator Center has already succeeded in developing several MMI algorithms for various situations. In this paper only one example is shown. That is the problem of global atmospheric circulation along with microscopic cloud formation and rainfall. The microscopic cloud formation is solved by a newly developed super-droplet method[5]. Fig7. Shows one snapshot of the cloud formation and rain falls starting from tiny water particles evaporated from the sea surface of the order of 10^{-7} m up to 10^{-3} m.

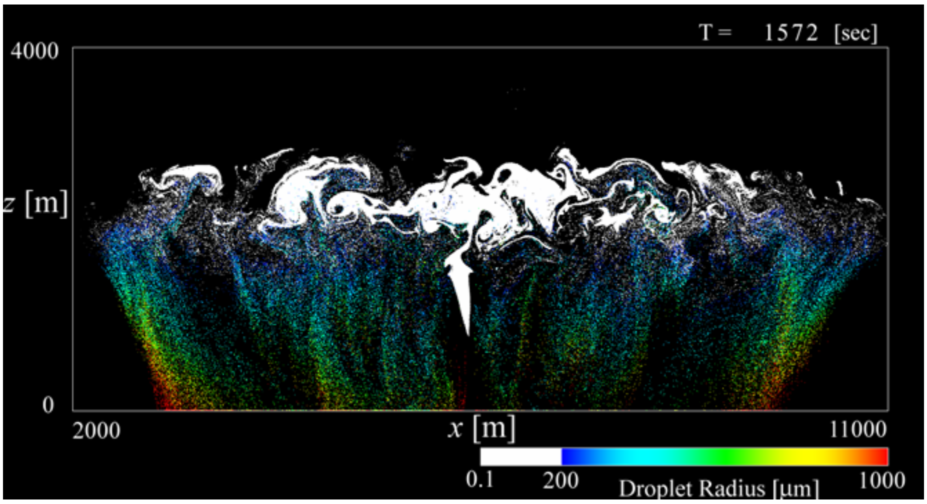


Fig. 7 One successful example of the MMI simulation for the cloud formation and rain falls in a macroscopic air circulation

We have demonstrated already several examples for various different physics problem such as aurora arc formation resulting from strong electron acceleration along geomagnetic field lines of a global feedback current coupling between magnetosphere and ionosphere, combustion flow resulting from chemical combustion reactions and abnormal viscous interaction of two colliding elastic bodies. This fact tells us that simulation has entered into a new age where the future world becomes the real target of science. In other words, future becomes “Science reality” rather than “Science Fiction”, which is suggestive of the arrival of “Simulation Culture” in the near future.

Reference

1. K. Takahashi, “Development of Holistic Climate Simulation Codes for non-Hydrostatic Atmosphere-Ocean Coupled Systems” Annual Report of the Earth Simulator Center, April2004-March 2005,p57-p62,December 1,2005.
2. Wataru Ohfuchi, Takeshi Enomoto, Munehiko Yamaguchi, Nobumasa Komori, Hideharu Sasaki, Yoshikazu Sasai and Yoshio Masuda, “High-Resolution

Simulation Studies on the Mechanisms and Predictability of Various Atmospheric and Oceanic Phenomena" Annual Report of the Earth Simulator Center April2004-March 2005, p51-55, December 1,2005.

3. Kazuhiro Iijima, Tamotsu Ito, Shoichi Tagami, Hiroyuki Umetani and Katsuhiro Miyoshi, "Interim Report on the Joint Study of Earth Simulator Center and Japan Automobile Manufactures Association", Annual Report of the Earth Simulator Center, April 2004-March 2005, p343-p346, December 1,2005.
4. Kanya Kusano, Shigenobu Hirose, Akio Kawano, Shinichiro Shima and Tohru Sugiyama, "Development of Macro-Micro Interlocked Simulation Algorithm", Annual Report of the Earth Simulator Center, April 2005- March 2006, p153-p156, January 19, 2007.
5. Tetsuya Sato, "Macro-Micro Interlocked Simulator", Journal of THE EARTH SIMULATOR,Vol.4 p46-p51. Dec.2005, Journal of Physics: Conference series Vol.16, SciDAC 2005, p310-p316.2005.