Space and Earth System Modeling

Project Representative
Kanya Kusano Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology

Authors
Kanya Kusano[*1], Yoji Kawamura[*1], Akio Kawano[*1], Shin-ichiro Shima[*1], Tooru Sugiyama[*1] and Hiroki Hasegawa[*1]
*1 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology

Solar and astronomical dynamics as well as volcanic activity is widely believed to play some role for the variability of Earth's environment system in different time-scale. However, it is not well understood yet how the evolution of Earth's system is related to the outside as well as the interior of the Earth. The Earth Simulator Project "Space and Earth System Modeling" is newly established in order to advance our understanding of the environment variability caused by dynamics in space and in the deep interior of the Earth. In FY 2009, we have developed the several element models for space-earth environment system for the nucleation of aerosol, cloud, the acceleration of energetic particles, and aurora, respectively.

Keywords: space weather, space climate, multi-scale, multi-physics, plasma, cloud, aurora, nucleation, aerosols, particle acceleration, Earth Simulator

1. Introduction

Earth's environment is not isolated from the outside of the atmosphere as well as from the interior of solid earth. In fact, the several evidences indicate that there is clear correlation between the climate variation and sunspot activity. Also it is widely believed that giant volcanic eruption may impact the worldwide climate. However, the mechanism whereby the solar activity may affect the climate is not well understood yet. It is also a great issue for the study of geological history to reveal how the surface environment and the deep-interior of earth interact to each other.

Earth Simulator Project "Space and Earth System Modeling" was established in order to understand the mutual relationship between the surface environment and the activities in space and the interior of earth. In FY 2009, we have developed the several element models which will constitute a space climate simulation system. They are the molecular simulation of aerosol nucleation, the cloud simulation in terms of super-droplet method, the particle simulation of energetic particle acceleration, and the aurora simulation, respectively. In the following sections, we will explain about the detail of the each particular model.

2. Molecular Simulation of Aerosol Nucleation

It is an important research subject to quantitatively evaluate the production rate of atmospheric aerosols because atmospheric aerosols, which act as cloud condensation nuclei, significantly affect the Earth's climate. However, one cannot still directly observe the nucleation process of atmospheric aerosols occurring at the nanometer scale. We are trying to quantitatively understand the nucleation process of aerosols using a combination of classical molecular dynamics simulations and ab initio quantum calculations.

In this fiscal year, we performed molecular dynamics simulations of binary nucleation in the vapor mixture composed of sulfuric acid and water (Fig. 1). By analyzing the simulation results, we estimated the nucleation rate and the critical cluster size. However, the densities of sulfuric acid and water under the simulation conditions are very large compared to those under atmospheric conditions, so as to observe the nucleation process within the limited simulation time. Thus, we cannot directly compare the nucleation rate estimated by the simulations with that observed in the atmosphere. For this reason, we are now analyzing a kinetic aerosol model, whose kinetic coefficients are determined in such a way that the values estimated from the simulation results are divided by the ratio of the density in the simulation to that in the atmosphere. The combination of molecular dynamics simulation and the kinetic aerosol model can provide us a powerful methodology to understand the aerosol nucleation.

3. Macro-Micro Interlocked Simulation of Cloud Formation and Precipitation

Although clouds play a crucial role in atmospheric phenomena, the accuracy and the reliability of numerical

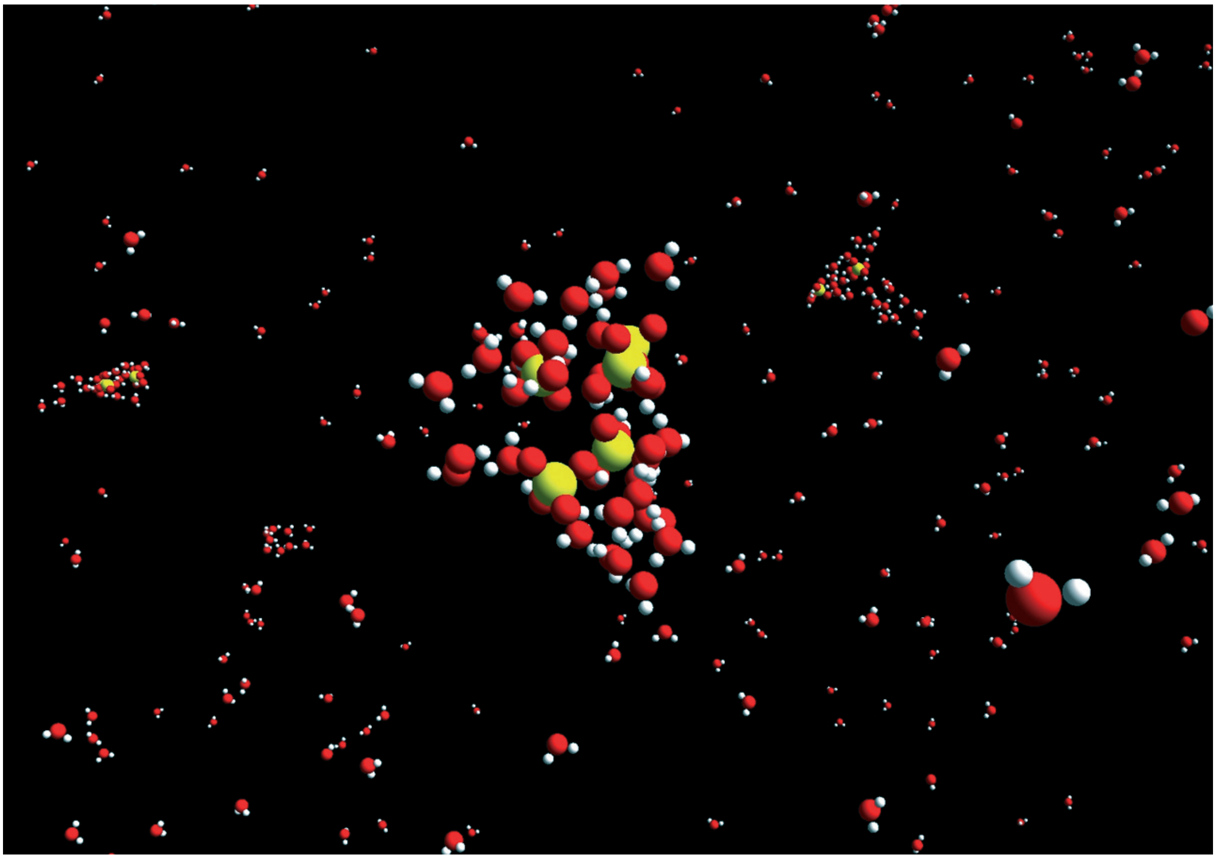

Fig. 1 Nucleation of sulfuric acid aerosols using molecular dynamics simulation.

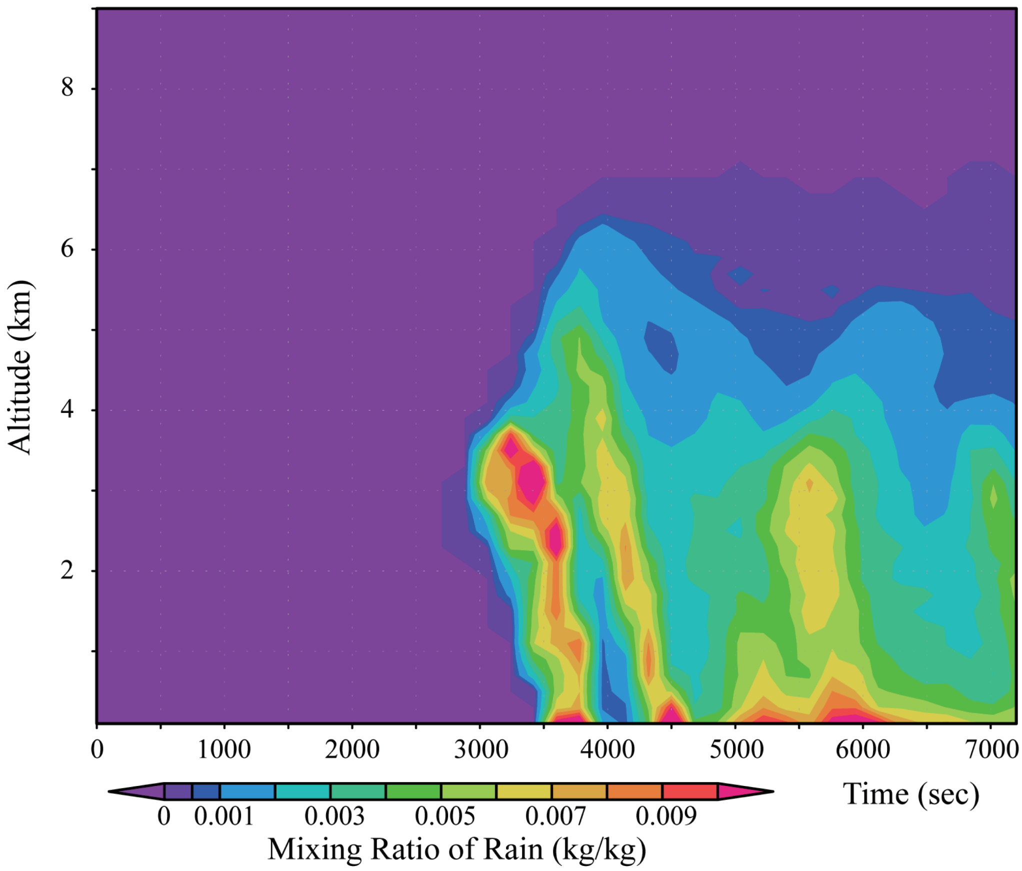

Fig. 2 Numerical simulation of cyclic development of a maritime convective cloud using the CReSS-SDM. This type of cloud was observed in a highly humid environment during the Baiu season around Miyakojima islands (D. Naito, 2005). We can see that the cyclic development of the cloud is successfully reproduced by the CReSS-SDM.

modeling of clouds are still limited. We have recently developed a novel, particle-based, probabilistic simulation scheme of cloud microphysics, named the Super-Droplet Method (SDM), which enables accurate numerical simulation of cloud microphysics with less demanding cost in computation [1].

In FY 2009, we have implemented the minimal components of the SDM to the Cloud Resolving Storm Simulator (CReSS), which is a well-established cloud-resolving model developed by K.Tsuboki and A.Sakakibara [2], and we call this new model the CReSS-SDM. Performance tuning has been carried out to use it on the Earth Simulator. As a result, the efficiency and the scalability of the CReSS-SDM have been improved. For example, the peak performance ratio is improved from 4% to 10% on average, and the vectorization of 99.54% and the parallelization of 99.977% were achieved on 128 nodes of the Earth Simulator. For testing the accuracy of the CReSS-SDM, its numerical output was compared with some observation and we confirmed that the oscillatory development of a shallow maritime precipitating cumulus, which are observed in Miyakojima island, is successfully reproduced (Fig. 2).

Currently, in order to simulate a one day behavior of 100 km-scale shallow maritime clouds, we are incorporating more detailed and advanced microphysical processes into the CReSS-SDM. In addition, to further accelerate the computation, we are constructing a general mathematical framework for a certain type of the Macro-Micro Interlocked Simulation, which is based on the mathematical idea that a macroscopic variable could be a set of coordinates on a certain invariant manifold embedded in the phase space of the microscopic model. The applicability of this framework to the cloud simulation is also under investigation.

4. Simulation of Energetic Particle Acceleration in Plasma

Energetic particles are widely observed in space and astrophysical plasmas. One of the possible accelerators is a collision-less shock wave. The diffusion-convection equation brings us knowledge about the particle acceleration, which is called diffusive shock acceleration (DSA) process [3]. However, since the wave amplitude observed around the shock is not small enough, the applicability of the quasi-linear theory to the DSA process is rather questionable. Therefore, the fully kinetic approach is necessary for more correct understanding of the shock acceleration process in large-amplitude wave. By using the Earth Simulator, we have performed a unprecedentedly large-scale simulation, in which the upstream region of the quasi-parallel shocks is elongated enough to include the accelerated particles within the simulation system. It means that the particles can hardly escape from the system boundaries and we can more precisely calculate the density and flux of the accelerated particles than the previous studies. Figure 3 shows the energy spectrum observed in the downstream region. The spectrum clearly shows the power-law with high energy cut-off. Although the cut-off profile has been discussed as a result of the escaping particles in the previous studies, the high energy cut-off in this simulation should be recognized as a real phenomenon which can be observed in the shock system, because any particles do not escape out of the system. Therefore, the cut-off energy may be used as a measure to evaluate the simulation by comparing with the observation. Figure 4 shows that the cut-off energy increases with time.

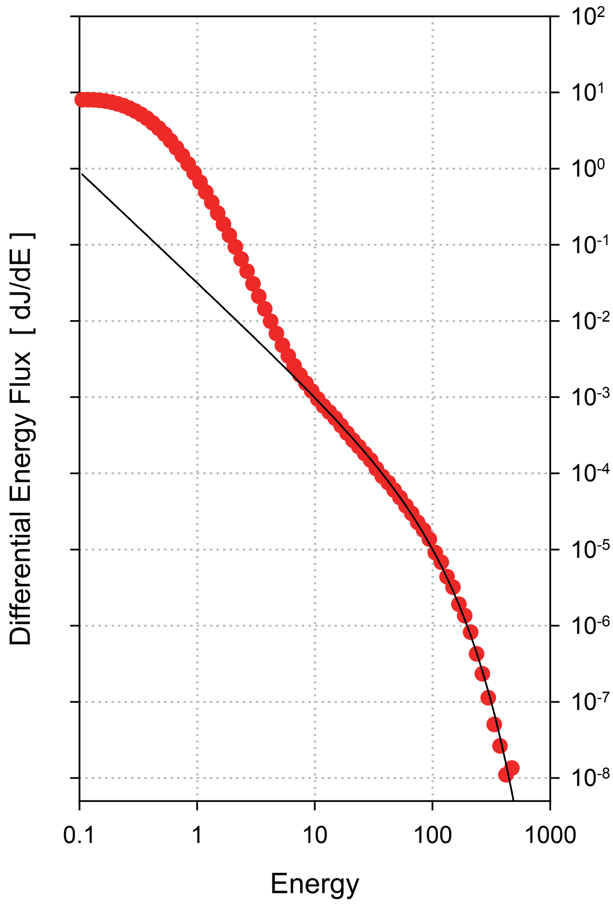

Fig. 3 Energy spectrum observed in the downstream region (red dots). The energy is normalized by the shock ram energy. Solid curve shows a fitting function of $E^{-1.45}$ exp(-E/73.2), where E is the energy of particle.

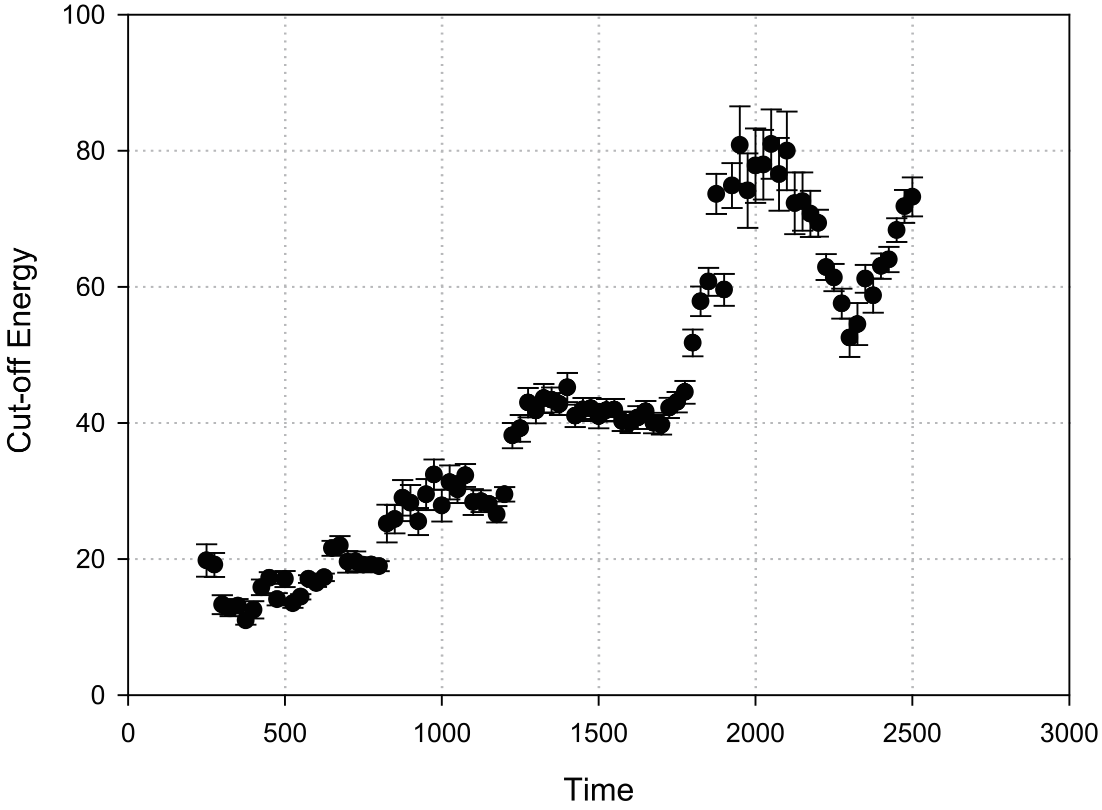

Fig. 4 Time profile of the cut off energy. It increases with time.

5. Multi-scale Simulation of Aurora

Aurora is a visible phenomena caused by the interaction between space and earth. We have investigated the process of quiet auroral arc formation. By using a three-dimensional magneto-hydro-dynamics (MHD) simulation of magnetosphere-ionosphere coupling system in a dipole coordinate, we have simulated that multiple longitudinally striated structures of the ionospheric plasma density and the field aligned current are formed as a result of the nonlinear ionospheric-feedback instability. The areas where these structures appear are consistent with the prediction by the theory of the ionospheric-feedback instability, in which the effects of the spatially non-uniform electric field and non-uniform plasma density are taken into account [4]. Furthermore, we have developed the macro-micro interlocked (MMI) simulation that consists of the MHD model and the plasma particle simulation model for the calculation of auroral energetic electron production [5]. Figure 5 shows the snapshots of the brightened aurora arcs, where the light emission from oxygen is calculated based on the particle simulation data. In Fig. 5, the left and right panels represent the sights of simulated aurora from the ground level and from some high altitude, respectively.

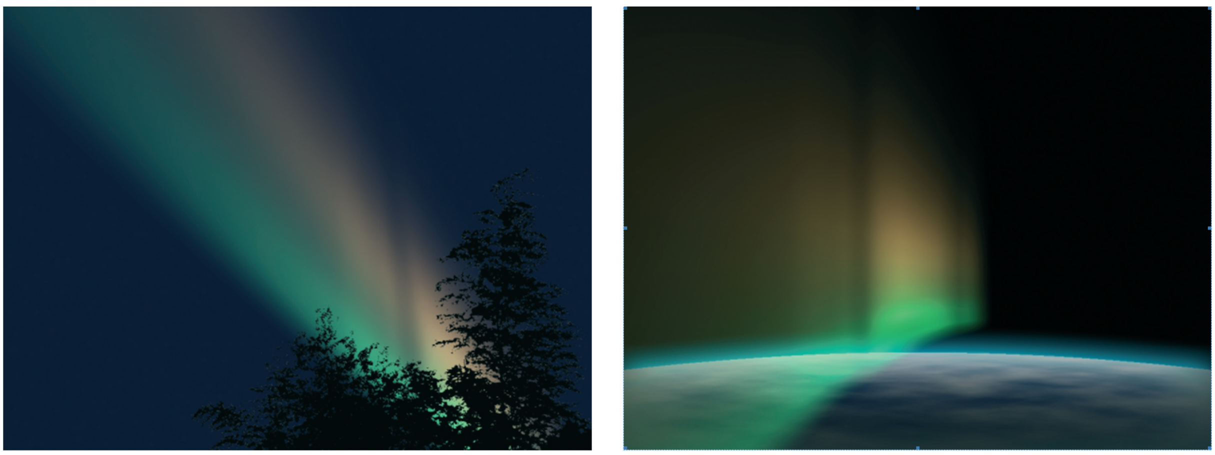

Fig. 5 Synthetic auroral lights of oxygen atoms seen from the ground (left panel) and from a high altitude (right panel) obtained by the MMI simulation.

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宇宙・地球表層・地球内部の相関モデリング

プロジェクト責任者
草野　完也　　海洋研究開発機構　地球内部ダイナミクス領域

著者
草野　完也 *1，河村　洋史 *1，河野　明男 *1，島　伸一郎 *1，杉山　徹 *1，長谷川裕記 *1
*1　海洋研究開発機構　地球内部ダイナミクス領域

地球システムは内部（地殻、マントル、コア）、表層（大気、海洋）および外部（宇宙）が互いに影響を及ぼしながら変動進化する相関システムである。本プロジェクトは地球環境の大規模変動と宇宙及び地球内部ダイナミクスの関係を探るために、先進的な相関モデルを開発する目的で 2009 年度より開始された。本プロジェクトでは、特に宇宙線と雲の関係に注目しその物理的因果関係を定量的に解明するため、ミクロスケールからマクロスケールに至る様々な物理過程を可能な限り第 1 原理に基づいてモデル化すると共に、それらのモデルを総合した包括的な宇宙地球システムモデルを構築することを目指している。2009 年度はプロジェクトの初年度として、エアロゾルの核形成に関する分子シミュレーション、超水滴法を利用した積雲成長シミュレーション、プラズマ中の高エネルギー粒子加速過程のシミュレーション、電磁流体力学モデルと粒子モデルを結合したマルチスケール・オーロラシミュレーションをそれぞれ開発した。

キーワード : 宇宙天気, 宇宙気候, マルチスケール, マルチフィジックス, プラズマ, 雲, オーロラ, 核形成, エアロゾル, 粒子加速, 地球シミュレータ