Space and Earth System Modeling

Project Representative

Kanya Kusano   Laboratory for Earth Systems Science, Japan Agency for Marine-Earth Science and Technology

Authors

Kanya Kusano[1, 5], Wataru Ohfuchi[2, 1], Shin-ichiro Shima[3], Yusuke Chikaraishi[4, 1], Ryohei Suzuki[4, 1]

∗1 Laboratory for Earth Systems Science, Japan Agency for Marine-Earth Science and Technology

∗2 Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

∗3 Graduate School of Simulation Studies, University of Hyogo

∗4 Tokyo Institute of Technology

∗5 Solar-Terrestrial Environment Laboratory, Nagoya University

The Earth is not isolated from the solar activities, which sometime play a crucial role for the variability of terrestrial environment and impact the infrastructure in different manners. However, it is not well understood yet how the terrestrial environment is related to space, and our predictability of space environment (space weather) is substantially limited. The objective of the Earth Simulator Project "Space and Earth System Modeling" is to advance our understanding for the variability of terrestrial environment caused by the dynamics in space. In FY 2012, we have continued the development of the several simulation models for space weather and space climate, respectively, for the prediction of solar flares as well as for understanding the influence of cloud microphysics onto the variability of weather and climate.

Keywords: space weather, space climate, multi-scale, multi-physics, plasma, cloud, aerosols, solar flares, Earth Simulator

1. Introduction

Earth's environment is not isolated from the outside of the atmosphere as well as from the interior of the 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.

Earth Simulator Project "Space and Earth System Modeling" was established in order to understand the mutual relationship between the surface environment and the activity in space. In FY 2012, we have continued the development of the several numerical models which will compose a space climate system simulation. They are the cloud simulation in terms of super-droplet method, the global circulation model for the study on the onset mechanism of snowball earth, and the magnetohydrodynamics simulation for solar flares. In the following sections, we will explain about the detail of the each particular model.

2. Simulation study on the stratus-to-cumulus transition of maritime shallow clouds

Although clouds play a crucial role in atmospheric phenomena, the numerical modeling of clouds remains somewhat primitive. We have 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 demand on computation [1]. The SDM is implemented on the Cloud Resolving Storm Simulator (CReSS), which is a widely used cloud-resolving model developed by Tsuboki et al., and we call this new model the CReSS-SDM.

In 2012 FY, we further investigated the bifurcation phenomena of shallow maritime clouds using the CReSS-SDM. The simulations are carried out using a set-up based on the RICO composite case defined in van Zanten et al. (2011) [2], which corresponds to the atmosphere measured and modeled in context of the Rain in Cumulus over the Ocean (RICO) field project [3]. We compared the equilibrium states of the system for various aerosol nucleation rates. As a result, we found that the change of aerosol nucleation rate can induce stratus-to-cumulus transition (Fig. 1).

3. Simulation Study of Snowball Earth Initiation

We aim to investigate the possibility of initiation of snowball Earth [4] due to changes in cloud droplet size. We plan to use an atmosphere-ocean coupled general circulation model (CGCM) to shed new light on this problem. Because the timescale of the
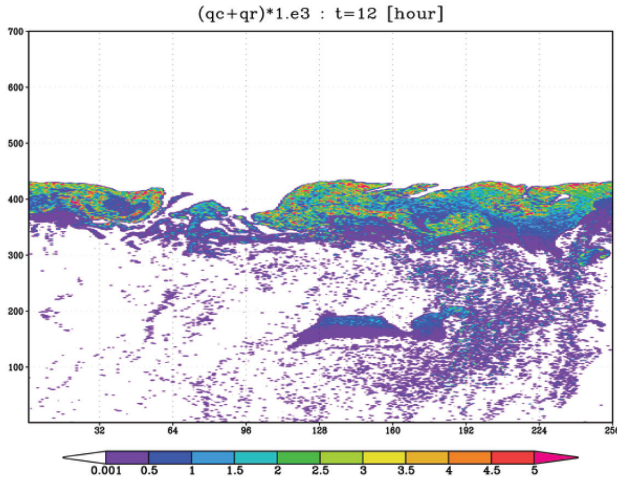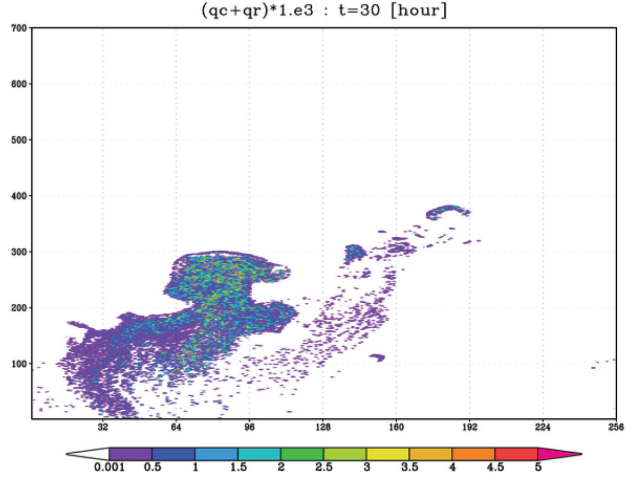
Fig. 1 Stratus-to-cumulus transition induced by the change of aerosol nucleation rate. (left) For higher nucleation rate, like 10^{-1} s^{-1}cm^{-3}, stratus is the equilibrium state of this system. (right) However, for lower nucleation rate, like 10^{-3} s^{-1}cm^{-3}, stratus loses its stability and cumulus becomes the equilibrium state of the system.

initiation could be more than 100 years, the CGCM must be computationally light and fast. We have reduced the resolution of a CGCM, CFES (Coupled general circulation mode For the Earth Simulator) [5], in order to tackle this task. The original horizontal resolutions of CFES-standard are about 50 km for the atmosphere and 25 km for the ocean, and of CFES-mini about 100 km and 50 km, respectively. Our CFES-micro's resolution is about 600 km for the atmosphere and 300 km for the ocean. The vertical levels have not been changed with 48 levels and 54 for the atmosphere and the ocean, respectively. It is possible to conduct a 100-year simulation within 3 to 5 days with CFES-micro. So far we have conducted several test runs without land to check our model. We plan to introduce geography and conduct a set of simulations, changing cloud droplet size and solar constant, to investigate the snowball Earth genesis.

4. Simulation Study of Solar Flares

Solar flares and coronal mass ejections are the most catastrophic events in our solar system, and they sometimes impact the terrestrial environment and our infrastructure. Although these solar eruptions are widely believed to be driven by magnetic energy stored in the solar corona, what triggers their onset remains poorly understood. Hypotheses for the trigger mechanism include the emerging flux model, which proposed that the small magnetic flux emerging onto the solar surface may lead to the solar eruptions. However, what kind of the emerging flux is capable to trigger the eruptions is unclear. This severely limits our capacity to predict the occurrence of solar eruptions and forecast space weather.

In this study, we systematically survey the nonlinear dynamics caused by emerging fluxes in terms of three-dimensional (3D) magnetohydrodynamics (MHD) simulations [6]. The initial and boundary condition of simulation model is composed of the force-free magnetic field with magnetic shear θ and the small magnetic flux emerging on the polarity inversion

line with azimuth ϕ as illustrated in Fig. 2.

Figure 3 shows the summary of simulation results, in which the flaring cases and the no-flaring cases are represented by colored diamonds and open squares, respectively. From this result, we found that there are two types of solar flares. The first type of magnetic structure causing flares is called the opposite polarity type, in which the small magnetic bi-pole opposite to the major magnetic polarity in an active region drives the solar eruption as shown in Fig. 4. The second type is called the reversed shear type, in which the cancellation of magnetic shear on the polarity inversion line may cause the onset of eruption. We have compared the simulation results and the data of Hinode solar observation satellite, and revealed that the four major flares observed by Hinode can be classified into these two types. These results suggest that solar flares are predictable if we can measure the detail structure of small magnetic field triggering solar eruption. Based on this study, we now extend the simulation box to the whole solar corona in order to simulate not only flare but also the formation and propagation of coronal mass ejection. (CME).
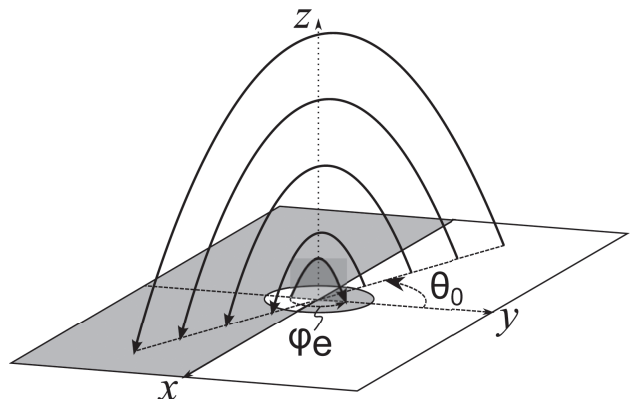

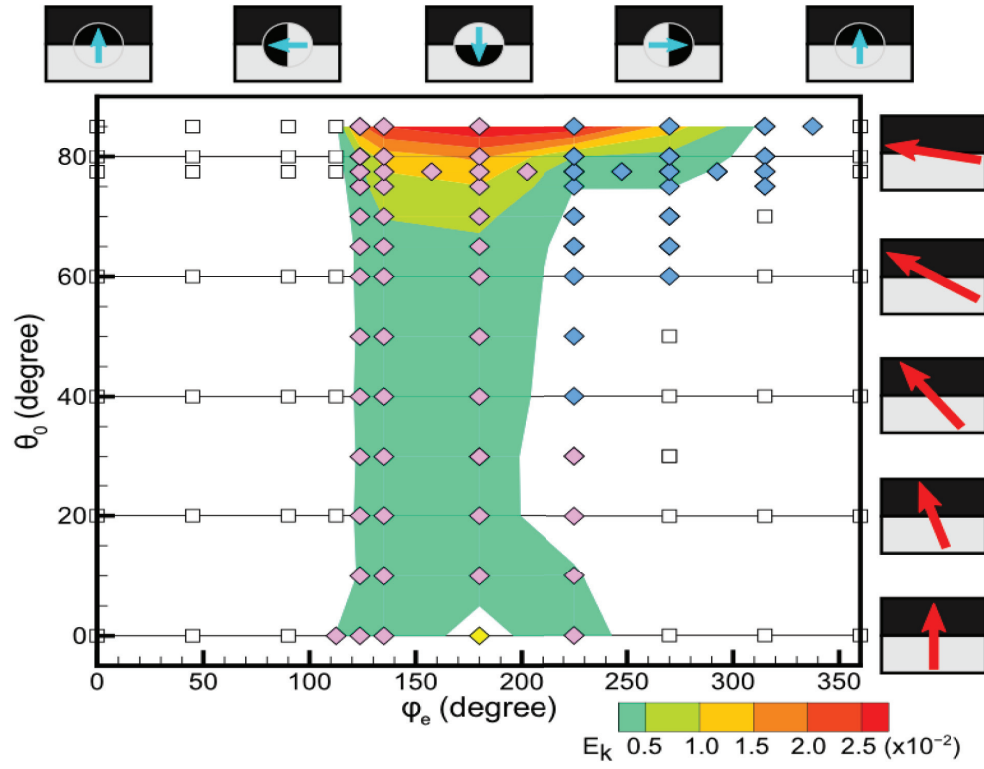Fig. 2 Magnetic field configuration of solar flare simulation.

Fig. 3　Summary of parametric study for the solar flare simulations on the parameter space for magnetic shear θ and the azimuth of emerging flux ϕ.
Colored diamonds correspond to the cases producing flares, and open squares correspond to the case not-producing flares.
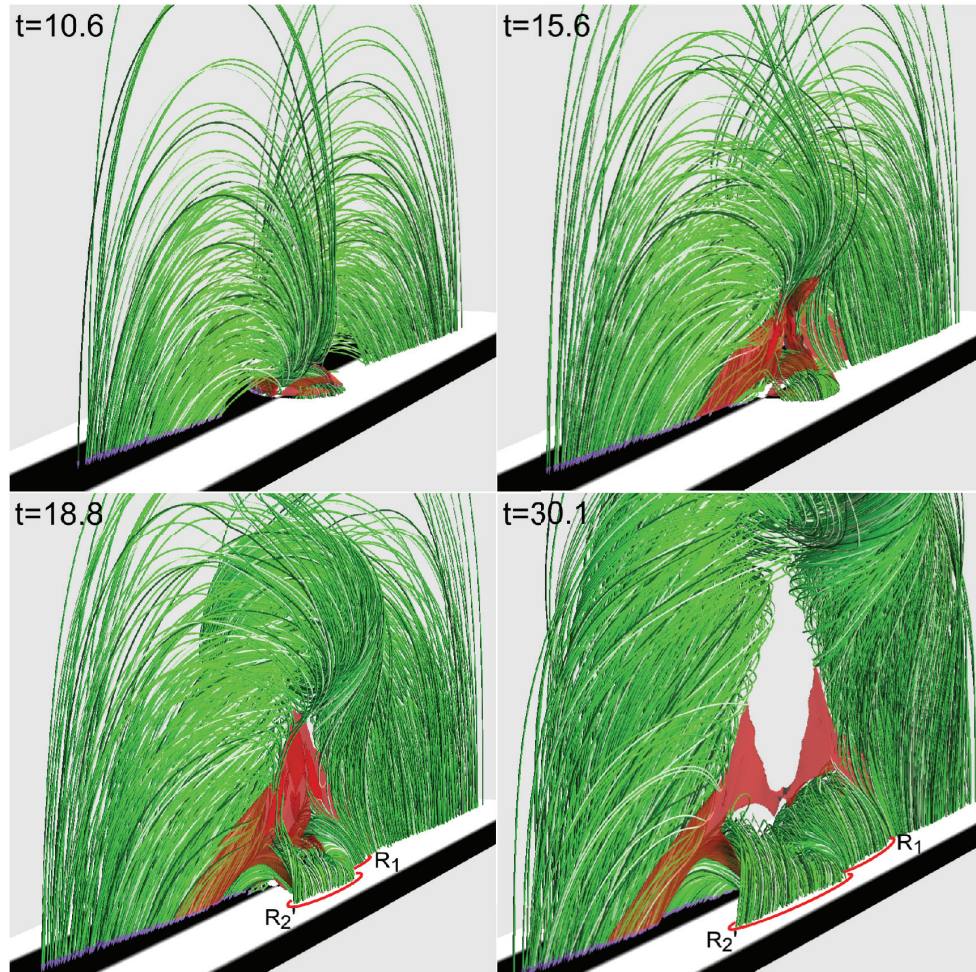

Fig. 4　Three-dimensional magnetohydrodynamic simulations of solar flares. Green tubes and red surface indicate magnetic field lines and electric current sheets, respectively.

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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　システム地球ラボ

著者

草野　完也 *1, 5，大淵　　済 *2, 1，島　伸一郎 *3，力石　祐介 *4, 1，鈴木　遼平 *4, 1

*1　海洋研究開発機構　システム地球ラボ

*2　海洋研究開発機構　地球シミュレータセンター

*3　兵庫大学　大学院シミュレーション学研究科

*4　東京工業大学　大学院理工学研究科

*5　名古屋大学　太陽地球環境研究所

　地球環境システムは内部（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太陽及び宇宙空間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及び太陽活動と地球環境の関係に注目し、それらの理解と予測を目指したシミュレーション研究を実施している。2012 年度はその結果、以下の 3 つの成果を得た。①超水滴法を利用した積雲成長シミュレーションモデル（CReSS-SDM）を開発すると共に、RICO プロジェクトの設定に基づいて熱帯積雲のシミュレーションを行った。その結果、雲降水システムが雲核生成率に対して双安定状態を持つことを示唆する結果を得た。②大気海洋結合全球循環モデルを用いて全球凍結事象のような地球史における大規模環境変動が宇宙線の急激な増加に伴う雲凝結核の変化によって発生する可能性を調べるため、高効率の大気海洋結合全球循環モデルの開発を開始した。このモデルを用いて雲核の数と大きさの変化が地球表面温度に与える影響を考察する。③地球環境に大きな影響を与える巨大太陽フレアの発生機構について 3 次元電磁流体シミュレーションを様々な磁場構造について系統的に実施することで調査した。その結果、2 つのタイプのフレア発生過程があることを解明した。この 2 つのタイプはフレア発生前の磁場構造によって分類できることから、精密な磁場観測によってフレア発生の予測が可能であることが示唆された。

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，エアロゾル，太陽フレア，
　　　　　　地球シミュレータ