Space and Earth System Modeling

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Solar activities may seriously impact terrestrial environment as well as our infrastructure in different manners. However, our predictability of solar activities and the influence upon the earth is substantially hindered, because the evolution mechanism of solar activities and the causal relationship between the solar variation and the climate change are not yet well understood. 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 including the sun. In FY 2013, we have continued the development of the several simulation models for space weather and space climate, respectively, for the prediction of coronal mass ejection 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, solar eruptions, snowball earth, 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. On the other hand, giant solar eruptive events such as solar flares and coronal mass ejections (CMEs) may seriously impact the infrastructure of satellite, power grids, and communication facilities. Therefore, the improvement in the predictability of solar activities and our understanding of the sun and earth connection is crucially important not only from scientific point of view but also from the social and economic aspects.

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 including the solar activities. In FY 2013, 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 eruptive events. In the following sections, we will explain about the detail of the each particular model.

2. Bifurcation analysis of the stratus-to-cumulus transition of maritime shallow clouds

Clouds play a crucial role in atmospheric phenomena. Since the galactic cosmic ray was suggested to induce the creation of cloud condensation nuclei (CCN) by various literatures, the mutual interaction between CCN and cloud is an important subject also for understanding the solar influence on climate. However, 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 (Shima et al. 2009). The SDM is implemented on the Cloud Resolving Storm Simulator (CReSS), which is a widely used cloud-resolving model developed by Tsuboki and Sakakibara (2002), and we call this new model the CReSS-SDM.

In 2013 FY, we investigated the behavior of marine stratocumulus near the stratus-to-cumulus transition point using the CReSS-SDM. The simulations are carried out on an idealized meteorological system in which aerosols are formed continuously. We constructed the system by modifying the set-up based on the RICO composite case defined in van Zanten, et al. (2011). The equilibrium states of the system are compared changing the aerosol nucleation rate and the initial number density of aerosols. As a result, we confirmed the final steady state of this system is determined by the aerosol nucleation rate, and it is irrelevant to the initial number density of aerosols, even near the stratus-to-cumulus transition point (Fig.1). This suggests that bistability of stratus and cumulus does not occur for this system.

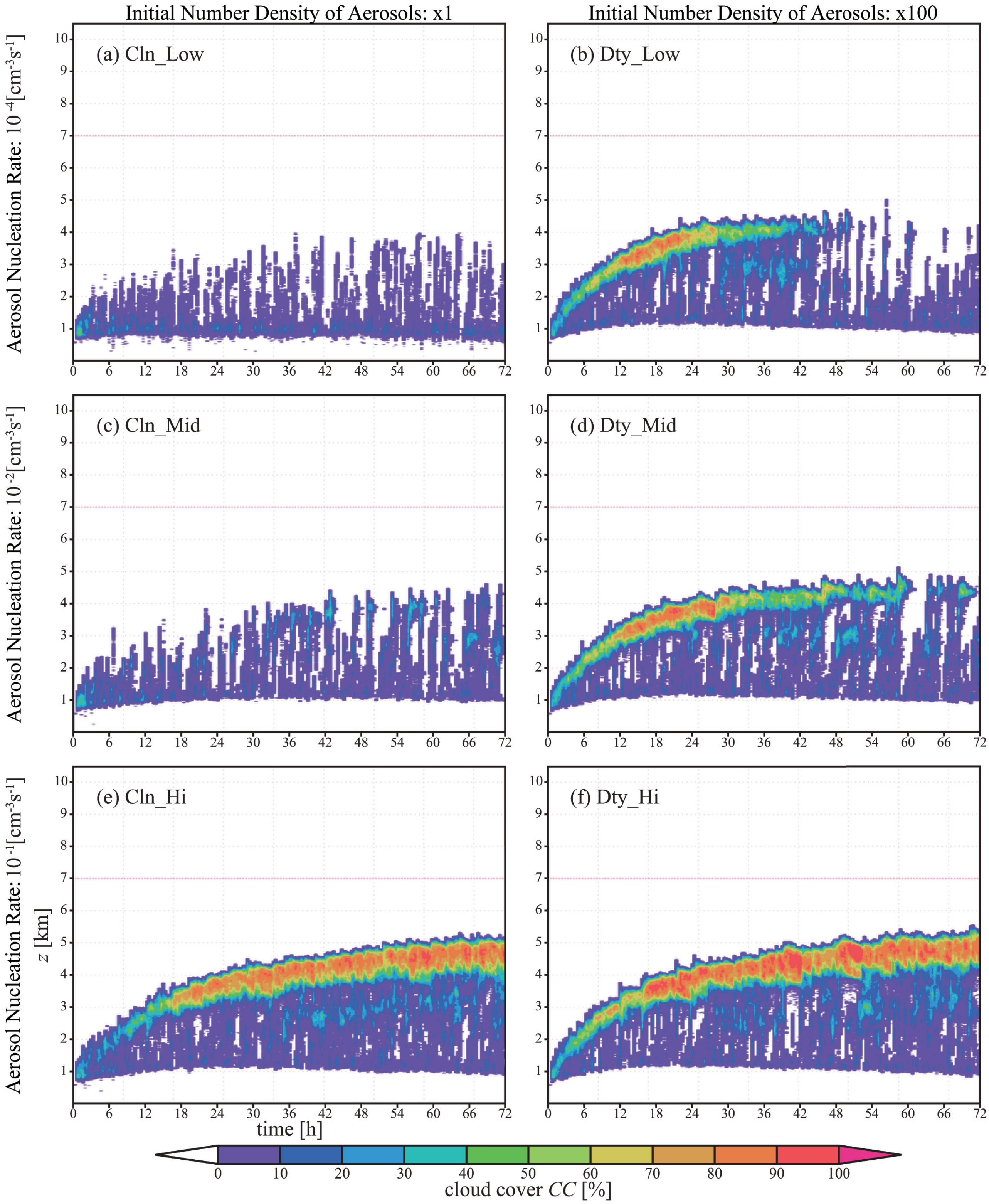

Fig. 1 Comparison of the time evolution of the cloud cover $CC(z)$ defined on each height between 6 experiments. The graph shows the height on the vertical axis and the time on the horizontal axis. The system gradually evolves to reach its final steady state, which is not affected by the initial number density of aerosols. A transition of the final steady state from cumulus to stratus occurs when the aerosol formation rate is increased.

3. Response of a coupled GCM to sudden changes in solar luminosity

It is known that the Earth has experienced a globally ice-covered condition a few times through its history [e.g. 4]. There are some factors that might have caused the snowball Earth. One is an impact of gigantic meteorite that injects a huge amount of ash into the atmosphere, and the ash reflects the incoming solar radiation back to the outer space. In this case, the net solar radiation into the atmosphere should be reduced suddenly after the meteorite impact. In this study, we investigate the response of the climate system to a sudden reduction of total solar irradiance (TSI) using a couple atmosphere-ocean general circulation model (CGCM).

Our CGCM is a very low-resolution version of CFES (Cgcm For the Earth Simulator) [5]. The horizontal resolution is about 640 km and 320 km for the atmosphere and ocean, respectively. The vertical levels are not changed from the original CFES, and the numbers of levels are 48 for the atmosphere and 54 for the ocean. The "CFES-micro" uses two nodes of the Earth Simulator and needs about one hour for one-model-year integration.

A set of aqua planet simulation was conducted. The modeled planet is covered globally with the ocean with a constant depth of 4,000 m. Firstly we ran CFES-micro with a current TSI (Case100) from an initial condition taken from a quasi-equilibrium state in a long-term realistic simulation of the original CFES. After 100 years, we continued Case100 for another 100 years while ran also TSI suddenly reduced cases, Case90 (TSI is reduced to 90 % of the current value), Case80, Case70 and Case60.

Figure 2 shows the time series of global average of surface temperatures of the set of our simulations. It is clearly seen that, in Case80, 70 and 60, the temperatures rebound after quick drops while it decreases steadily in Case90. The rebound happens probably because quick cooling from the surface of the ocean induces convection, and relatively "warm" water wells up to the surface in a sudden manner when the sudden TSI reduction is large. This result suggests that the Earth may not be cooled steadily after a meteorite impact. This process makes the ocean vertically unstable. Case80 and 70 were aborted probably due to this instability at years 185 and 148, respectively. We plan to continue Case90 and Case60. Case90 may result in the snowball Earth.

4. Simulation study of solar eruptions

Solar eruptions, such as 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 the 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.

Recently, we proposed that there are two types of magnetic field structures which favor the onset of solar eruptions. The first type 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. 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 [7].

In FY 2013, based on this study, we extended the simulation to the whole solar corona in order to simulate not only flare onset

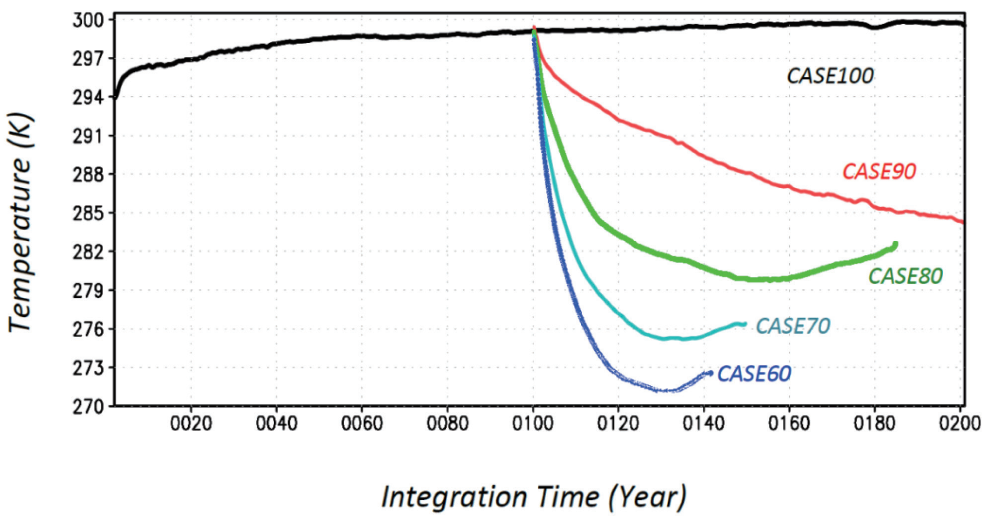

Fig. 2 Time series of global average surface air temperature from the set of CFES-micro aqua planet simulations. CaseN indicates the case of N % of the current TSI.

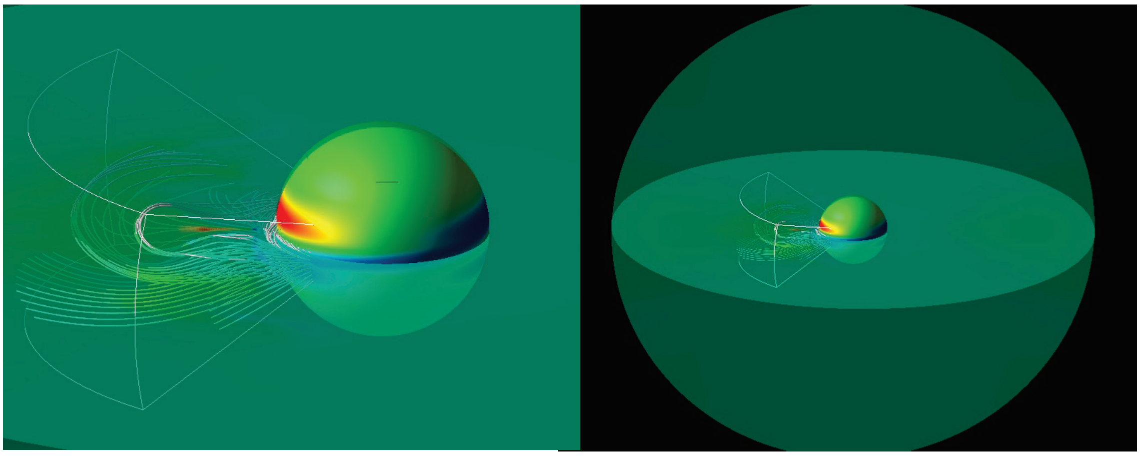

Fig. 3 The simulation results of solar eruption. The colored sphere corresponds to the sun, and color scale denotes the magnetic field on the solar surface. Thin strings show the three-dimensional structure of magnetic field lines connecting to an active region. Left panel is a zoom-in view of the whole simulation box (right).

but also the formation and propagation of coronal mass ejection. (CME). The simulation box covers the global solar corona, and we simulated the onset of solar eruption by imposing the rotation motion on a small portion in sheared magnetic field (see Fig. 3). As a result, we found that the sheared magnetic field becomes unstable when the rotation motion causes the opposite polarity type of magnetic structure, and the magnetic flux rope can be ejected out of the lower corona. Although the calculations are still preliminary, the results are consistent with our previous model [6], and suggest that some typical magnetic field structure in small scale may trigger a large-scale solar eruption.

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宇宙・地球表層・地球内部の相関モデリング

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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、太陽活動と地球環境の関係に注目し、放射変動、宇宙線変動の影響を中心にそのメカニズム解明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。2013 年度はその結果、以下の３つの成果を得た。第 1 に、超水滴法を利用した積雲層雲遷移の双安定性に関する研究においては、超水滴法を利用した雲分解モデル CReSS-SDM を用いて、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。特に、雲核生成率に対する雲の長期安定性を解析した結果、積雲層雲遷移に関する双安定状態が出現し難いことを示唆する結果を得た。第 2 に、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太陽放射の突然変動がその後の大気海洋結合システムにどのような影響を与えるかを、小型 CFES モデルを用いて調べた。その結果、太陽放射の変動量に対して表層温度の応答時間が大きく変化することを見出した。変動量がより小さい場合、平衡温度に達するためにはより長い緩和時間が必要であった。また、計算結果より太陽放射の 10% 減少によって全球凍結が可能であることが示唆された。第 3 に、地球環境に大きな影響を与える巨大な太陽面爆発のトリガ機構に関する３次元電磁流体シミュレーション研究を、全球コロナモデルを用いて実施した。その結果、コロナ全体の大規模爆発も我々が提唱した太陽フレアトリガモデルと同様の太陽表面磁場によって発生することを示唆する結果を得た。このことは、太陽面磁場の詳細観測に基づいて地球に影響を与えるように大規模な太陽面爆発を予測できる可能性を意味するものである。

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 ,
太陽面爆発 , 全球凍結 , 地球シミュレータ