2-3 Integrated Space Weather Simulation for Future Numerical Space Weather Forecast

2-3-1 Significance and Importance of the Integrated Space Weather Simulation

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The solar-terrestrial system consists of the sun, solar wind, magnetosphere, ionosphere, and atmosphere. There is a process of interaction between these regions, so that various phenomena have yet to be essentially understood by examining the regions independently. Integrated space weather simulation is expected to become an important tool in monitoring current space weather conditions and predicting disturbances. Recent years have witnessed major advances in simulation studies on various areas of the solar-terrestrial system and in the technology for linking models that include such inter-regional interaction, and full-scale efforts are now being made to develop realistic space weather models including all regions from the sun to the earth in various countries of the world. This paper reports the significance, importance, current conditions, and future prospects of integrated space weather simulation.

Keywords
Solar-terrestrial system, Space weather, Simulation, Interaction, Integrated model

1 Introduction

Past studies in the natural sciences focused on describing experiment and observation results based on linear theories and cause-and-effect relationships. However, only very few actual phenomena can be accurately described through a linear theory. It has become clear that, in the solar-terrestrial system and other systems where complexity and interaction are important, linear theories do not necessarily help elucidate physical processes. Numerical simulation generally enables actual phenomena including all related processes to be reproduced, making the reproduction of nonlinear processes and interactions possible without contradictions. Moreover, analyzing the physics created there allows us to discover a universal law.

Numerical simulation has undergone rapid development along with improved computer performance, and has now become indispensable as an effective analytical technique in many areas of research. In the areas of space and geophysics as well, numerical simulation studies have achieved dramatic development and are now being applied to research and the prediction of various phenomena. In the solar-terrestrial system, realistic numerical simulation studies were carried out relatively recently because of the difficulty in acquiring observation data, the complexity and nonlinearity of physical processes, and the wide range of the temporal and spatial scales of phenomena. In recent years, the technologies for satellites and ground observations have been vastly improved. Given the greater amounts of available observation data, significant efforts have been made in various parts of the world to develop realistic integrated space weather models that include all regions from the sun to the earth.

2 From synoptic forecast to numerical forecast

Monitoring and forecasting meteorological disasters, earthquakes, volcanoes, surges in seismic activity, and other natural phenomena have long been conducted. In the early days of forecasting, the main method was the “synoptic forecast” where humans would monitor observation data and, based on their knowledge and experience, determine current conditions and establish future prospects. However, such a method largely depends on the skillfulness and judgment ability of individual forecasters, thereby making objective forecasts impossible. In the 1950s when the first computers models began to spread, studies on “numerical forecast”—an objective and quantitative means of forecasting—were initiated in order to monitor and predict disasters more accurately. This was followed by a significant development of such numerical forecast studies, and with the emergence of the information society, even greater demand was seen for numerical data suited for information processing. Today, 50 years after the first numerical forecast, this method is now firmly established as a tool indispensable for weather forecasting. Moreover, global environmental simulation for predicting long periods ahead is becoming even more important in predicting global environmental changes as well.

In space weather forecasts, the synoptic forecast remains the main technique even today due to the large scale, diversity and complexity of the solar-terrestrial system. Numerical models in this area were initially developed in or after 1980. In recent years, models have been developed for the magnetosphere, ionosphere, atmosphere and other regions, along with advances made in the technology for linking models that include inter-regional interaction. Various attempts are now being made to develop realistic space weather prediction models in various parts of the world. The Space Environment Group of NICT is also developing integrated space weather models for practical space weather forecasts.

3 Modeling of inter-regional interaction

There is an idea of modeling the solar-terrestrial system whereby simultaneously and seamlessly simulating an entire region from the surface of the sun to the bottom end of the global atmosphere as “one complete region” with a unified scheme is deemed sufficient. To be sure, such simulation is possible in principle. In reality, however, the regions vary greatly in terms of scale and physical characteristics, so that an integrated scheme would entail huge amounts of calculations not possible with practical precision, even with the highest computer capabilities available today. For that reason, the present integrated model links separately built regional models having minimal contradictions, thereby causing it to function as one model in its entirety. In fact, this technique is more realistic and presumed sufficient for many important phenomena in space weather. The following outlines the process of inter-regional interaction based on that idea.

The sun radiates visible light, ultraviolet rays, X-rays, infrared rays, radio waves and other electromagnetic waves, while constantly releasing the solar wind. The solar wind propagates out to the earth, but is supersonic and has no effects until reaching the earth’s magnetosphere. The effects of the solar wind on the magnetosphere are therefore unidirectional, and it is not necessary to consider the effects of the earth on upstream the solar wind. As the solar wind approaching the earth interacts with the earth’s magnetism, the magnetosphere is formed, with particles, electric fields and energy entering the magnetosphere to cause convections, particle acceleration, and other phenomena. The region from the magnetosphere to the ionosphere is controlled by electric currents, electric fields, and auroral particles. These cause changes in the ionospheric electrical conductivity, and their effects eventually cause changes in the magnetospheric current system and convections, thereby generating feedback processes.

The ionospheric convection caused by the magnetosphere accelerates and heats up the thermosphere through the collision of ions with neutral particles. In contrast, the thermosphere affects convections in the ionosphere through dynamo electric fields, and also undergoes changes in neutral composition to affect the ionospheric electron density. These changes in the ionosphere will eventually exercise a certain degree of influence on the magnetosphere as well. The coupled system of the magnetosphere, ionosphere and thermosphere is extremely complex and characterized by its strong interactions.

Atmospheric waves propagated from the bottom-layer atmosphere are also known to affect the ionosphere through thermospheric dynamics and structural changes. A number of studies have also been conducted on how the ionospheric and thermospheric regions affect the atmosphere in the mesosphere and lower layers. Among the possible processes involved are the process where the density of nitric oxide increases and that of ozone decreases due to ionization and the subsequent chemical reaction processes in the bottom layer of the thermosphere as well as in the top layer of the mesosphere due to precipitating high-energy particles associated with auroras and other phenomena, the process where the polar ionospheric convection excites high-speed winds in the bottom layer of the thermosphere, thereby affecting the mesosphere as well, and the process where ionospheric electric potential changes the global current system of the earth's atmosphere. However, the degree to which the bottom layer atmosphere is affected remains unclear.

4 Development of an integrated model in the USA

An integrated model of the solar-terrestrial system is now being developed mainly by two groups in the USA. One is the Center for Integrated Space Weather Modeling (CISM) project. Boston University taking the leadership together with the National Center for Atmospheric Research, the University of Colorado, and many other research institutions are developing a model ranging from the sun to the earth's upper atmosphere[1][2]. The basic portion of this model is an integrated model that links a solar corona model, solar wind model, magnetospheric model, and ionospheric/thermospheric model. Moreover, efforts are also being made to develop inner magnetospheric models. This integrated model now makes it possible to calculate the solar wind including corona mass ejection (CME) on the surface of the sun, and to examine how it affects the earth's ionosphere and thermosphere.

Another project called Space Weather Modeling Framework (SWMF) is also under way at the University of Michigan. Similar to the model being developed at the CISM, this model combines a solar corona model, solar wind model, magnetospheric model, and ionospheric/thermospheric model. The model is also equipped with a CME model, solar high-energy particle model, radiation belt model, and inner magnetospheric model in order to reproduce various physical processes[3][4]. Some of these models have already been released to general researchers and are now being used for research purposes.

5 Development and future prospects of an integrated model at NICT

When viewed on a global level, it was not until about 1980 when computer capabilities underwent a dramatic leap, thereby making realistic simulation possible in the field of space weather. Like other countries, Japan saw a similar attempt being made. The Communications Research Laboratory of the Ministry of Posts and Telecommunications (the predecessor of NICT) introduced a supercomputer in the 1990s and developed an original numerical scheme to solve three-dimensional magnetohydrodynamics equations, and later began developing a magnetospheric simulation model that could reproduce the structure of the magnetosphere and magnetospheric storms. Near the end of the 1990s, a highly precise magnetospheric model was completed, making it possible to reproduce a realistic magnetosphere[5][6].

Real-time data is important in space weather forecasts. People have therefore focused on providing real-time data for simulation as well. NICT used real-time solar wind data obtained from the ACE solar wind observation satellite as input and developed a system that runs a magnetospheric model on a real-time basis. It then succeeded in developing a “real-time magnetospheric simulator” in 2003[7][8]. In 2008, in addition to this real-time magnetospheric simulator, NICT developed two real-time simulators (one for the sun and solar wind, and one for the ionosphere and thermosphere), completing a “Real-time Space Weather Integrated Simulator” that can reproduce conditions ranging from those on the surface of the sun to those at an altitude of about 100 km above the earth. This is the world's first system that can calculate space from the surface of the sun to areas surrounding the earth on a real-time basis and in an integrated manner.

The sun and solar wind simulator uses magnetic field observation data at the surface of the sun as obtained from the solar observation satellite for input to solve three-dimensional magnetohydrodynamics equations, and is thus able to determine and display the state of the solar wind from the surface of the sun to the earth’s orbit. At present, we have yet to achieve success in accurately reproducing changes in the solar wind, but will soon be able to predict when the high-speed solar wind—the cause of geomagnetic storms—will reach the earth.

The ionospheric/thermospheric simulator uses electric potential, electrical conductivity and other data of the ionosphere obtained by the magnetospheric simulator as a model input to solve the fluid equations for ionospheric plasmas and the neutral atmosphere. This has made it possible to determine the current state of the ionosphere and thermosphere, how auroras are generated in the polar ionosphere, and to display the results in a visualization system. In these calculations, solar wind data obtained from the ACE satellite is used as input for the magnetospheric model to calculate the magnetosphere, with the results being sent immediately to the ionospheric model for performing calculations of the ionosphere.

These real-time simulations are conducted by using the NEC SX-8R supercomputer introduced in 2007, and computed results have been made available on NICT’s website under the heading “Space Weather Forecast” since August 2008.

The Real-time Space Weather Integrated Simulator, which has been recently developed, has made it possible to reproduce the current state of the space environment from the sun to regions surrounding the earth, although it occasionally fails to reproduce the variations or disturbances in the space environment. At present, results obtained with this simulator and the data acquired by satellites and above-ground observation are compared and validated to proceed with model enhancement for improving the quantitative reproducibility of space disturbances.

Space weather forecast requires several hours to several days’ worth of forecasting. To that end, numerical forecasts of the solar wind are indispensable. The ordinary solar wind travels at a speed of about 300 km/s, so that it takes several days to reach the earth’s orbit from the surface of the sun. Increasing the precision of the sun and solar wind simulator would therefore presumably enable the prediction of space weather several days ahead with a certain degree of precision. However, CME, solar flares, and other sudden sun-surface phenomena that cause huge magnetic storms have yet to be quantitatively reproduced or predicted by any model in the world. This remains the greatest challenge we face today.

Atmospheric waves that propagate from the bottom-layer atmosphere also play an important role relative to plasma bubbles and other ionospheric disturbances that directly affect the positioning precision of the Global Positioning System (GPS). Predicting such phenomena requires a highly precise atmosphere-ionosphere coupling model, which is now being developed by the Space Environment Group of NICT.

6 Conclusion

A number of efforts have been launched in various parts of the world to develop an integrated simulation model of the solar-terrestrial system. However, the model includes nothing but representative physical processes. To examine space and the global environment even more comprehensively and quantitatively requires the buildup of a global solar-terrestrial model that self-consistently includes as many processes and regions as possible. At the same time, it is presumed necessary to study forecast technology itself. Studies on solar activity remain at a fundamental level, but research and development efforts are under way regarding numerical forecast technology toward the maximal period of solar activity which is expected to come a few years later, thereby proceeding with the buildup of a "Space Weather Numerical Forecast System."

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