2-3-4 The Global MHD Magnetosphere Simulation and Prospect for the Space Weather Prediction

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This paper discusses the concept of a magnetosphere-ionosphere compound system introduced into magnetospheric physics by self-consistent magnetospheric MHD simulations with the ionospheric boundary. It also describes typical magnetospheric phenomena (e.g., sudden commencement of magnetism, theta-auroras, substorms) that occur with solar wind changes in terms of state transitions occurring in a magnetosphere-ionosphere compound system. Next, the paper discusses a certain technique used for meteorological purposes (weather prediction) considered useful for future space weather services. To this end, we introduce a preliminary attempt to estimate the optimal values of ionospheric conductivities through data assimilation. The data assimilation technique based on the present magnetospheric simulation, however, is still unsatisfactory for space weather prediction, since available numerical models still yield poor phenomenon reproducibility. Last, the paper discusses to implement the "guidance" scheme used in weather prediction services to space weather. The data created by the simulation from moment to moment are equivalent to objective analysis data in meteorology. Therefore, a guidance scheme equivalent to that used in weather prediction services might be introduced by deriving the relationships for predicting relevant physical quantities from accumulated objective analysis data on space weather.

Keywords
Magnetosphere-ionosphere compound system, MHD, Data assimilation, Guidance, Numerical weather prediction

1 Introduction

Attempts to reproduce the whole magnetosphere using MHD simulations date back to the 1980s[1][2]. With the dawn of the 1990s, advances in computer technology opened a way for performing calculations with minimum meshes needed to reproduce magnetospheric phenomena, and the implementation of magnetosphere-ionosphere coupling allows a magnetosphere-ionosphere MHD simulation model of practical use[3][4]. Through the 2000s, magnetosphere-ionosphere MHD simulations have evolved into computerized real-time MHD simulations capable of reproducing the temporarily changing behavior of the magnetosphere by using solar wind as an initial value[5]. Because a detailed description of the real-time MHD simulations developed at the National Institute of Information and Communications Technology is given in[5], this paper describes the impact of MHD simulations on magnetospheric physics. It should be noted that a code for more precise and stable calculations must be developed in order to implement a numerical method of space weather prediction of practical value. However, it might be useful to introduce advanced techniques used in the field of numerical meteorological prediction that maximize the use of limited computer resources, as in space weather prediction. Therefore, an example of data assimilation and the implementation of guidance are also presented for discussion.

2 Impact of magnetospheric models on magnetospheric physics

In the past, scientists studying global phenomena in the magnetosphere-ionosphere system would simply estimate an overall picture of the phenomena using ground-based or satellite observations, while resorting to MHD or the relevant physical laws where observational data was not available. Since the magnetosphere would take complex geometries after interaction with solar winds, it is difficult to draw a definite conclusion from a combination of ground-based or satellite observations with human imagination. For example, the existence of region 1 field-aligned current had already been known in the 1970s[6], but no conclusion had been reached regarding the source region of the magnetosphere and its path to the ionosphere. On the other hand, the emergence of numerical magnetospheric simulations capable of producing a realistic reproduction of global phenomena in the magnetosphere-ionosphere system has begun to shed clear light on the generation mechanism of such global phenomena. As for the region 1 field-aligned current system, simulation analyses presented in a document[4] have demonstrated the following scenario; through the interaction of a cusp characterized by enhanced plasma pressure with a convection flowing towards the nightside magnetosphere due to reconnection with solar wind magnetic fields, a current-generating region appearing on the nightside of the cusp region is formed. The current thus generated is led to the ionosphere as a field-aligned current through the magnetosphere.

The impact of magnetosphere-ionosphere MHD simulations on magnetospheric physics is not limited to explaining the phenomena observed. Moreover, it extends to the capability for providing grid-point data to MHD equations under ionospheric boundary conditions, because the artificial effects derived from numerical problems are eliminated to the extent possible. This means that the results are physically self-consistent. The only parameters needed to drive this numerical model are plasma data in solar winds. In other words, the model is capable of autonomous operation without the aid of additional observatory information. The resultant spatial 3D time-series data is equivalent to objective analysis data in terms of meteorology. An analysis of that data will help to quantitatively study the physical processes in the magnetosphere within the limits of MHD approximation. (The objective analysis will also be mentioned later.)

Another aspect of the impact of magnetosphere-ionosphere MHD simulations is the introduction of a new concept[7] known as a “compound system” into research on magnetosphere-ionosphere phenomena (see[8] for more details). MHD simulations provide us with the states of multiple physical processes (e.g., current and plasma distributions, magnetic configuration, magnetosphere and ionosphere convections) being self-consistent with one another. From this perspective, the procedure for understanding phenomena that occur in the magnetosphere-ionosphere system as a compound system should not simply entail an understanding of “how they occur” but proceed to a state of understanding “why they ought to occur.” In short, the first procedure above is concerned with the sequence of physical elements and focuses on understanding the cause and effect process, disregarding the issue of coherency of the whole magnetosphere-ionosphere system. The latter procedure suggests that the magnetosphere-ionosphere system needs to exist so every physical mechanism comprising that system is a self-consistent system.

This concept of the compound system is essential to understanding variations in the magnetosphere-ionosphere system resulting from disturbances in solar wind. The sudden commencement (SC) driven by impulses in the dynamic pressure of solar wind might, for example, be considered a transition between two states of a compound system that are fit to two solar wind conditions with different dynamic pressure. Within this framework, the preliminary impulse (PI) is a period of fluctuation composed primarily of waves generated upon impact with the magnetosphere system, during which the coupling between the magnetosphere and ionosphere convections (i.e., state of connection between electric fields in the magnetosphere and ionosphere through magnetic lines of force) is lost. Conversely, the main impulse (MI) can be considered a period of transition to a new state following recovery of the connection lost between the magnetosphere and ionosphere convections[9]. Numerical simulations have revealed that in the period of state transition, the field-alignment current increases and a transient convection vortex in the magnetosphere is generated. This fact suggests that extra energy is built up in the magnetosphere during state transition and then consumed in the ionosphere. Increases in field-aligned current have also been confirmed by ground magnetic field observations (for example, see[10]). In addition to variations in the dynamic pressure of solar wind, there are other state transitions caused by interplanetary magnetic field (IMF) variations. For instance, continuous state transitions will also occur when IMF is northward as a theta-aurora during changes in the east-west component of IMF[11]. Other quantities like field-aligned current also show the same behavior as SC. State transitions in a magnetosphere-ionosphere system with a multidimensional degree of freedom could cause catastrophic variations, because the coupling between physical processes fails to keep MHD self-consistent. With the onset of a substorm generated as southward turn of IMF, the failure of MHD will appear as a reconnection of the magnetic lines of force, thereby demonstrating discontinuous state transitions[12]. Such reconnection causes a high-speed plasma flow to appear in a region of the magnetosphere dominated by inertia current. Therefore, the coupling between the magnetosphere and ionosphere convections is lost at this time. In the expansion phase following the onset, the coupling between the magnetosphere and ionosphere convections recovers as in the MI period of SC[13].

Since the magnetosphere-ionosphere system described above constitutes a compound system, any one of the self-consistent physical elements (e.g., current system, plasma distribution, convection or magnetic arrangement) can be taken and discussed out of context. Among these physical elements, the magnetosphere convection will help promote understanding of the magnetosphere as a whole because it has a direct bearing on behavior of the field lines and generation of plasma pressure. In other words, "state transitions" might be comprehended as "convection transitions". SC, theta-auroras, and substorms can be understood by examining the physical elements derived relative to stationary convection systems before and after state transitions, as well as the transient convection system during the transition period.

If the magnetosphere-ionosphere system is regarded as a compound system as discussed above, one might realize that the meteorological system constitutes a compound system as well. A comparison of the two compound systems is interesting. The elements comprising the meteorological compound system are convection and pressure (temperature), namely, the difference in temperature between the poles and the equator drives the convection. The convection of the meteorological compound system has three cell structures (pole, mid-latitude and equatorial zones), because the earth's rotation prevents the difference in temperature between the poles and the equator from being resolved by direct convection between the two regions. This basic configuration corresponds to a single state of the magnetosphere-ionosphere compound system associated with steady solar winds. From an alternative perspective, the magnetosphere-ionosphere compound system can characteristically assume more states in association with solar wind conditions than the meteorological compound system. Hence, the state transitions resulting from solar wind changes described earlier do not occur in the meteorological

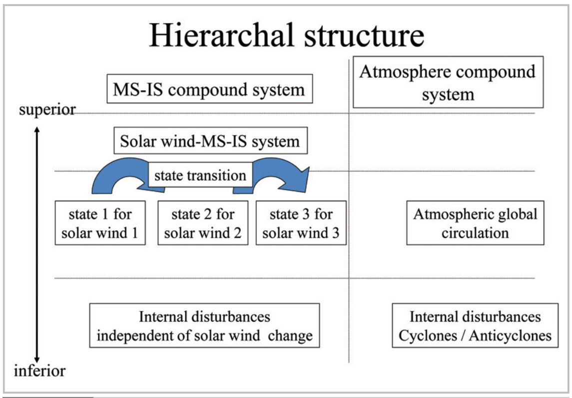

Fig. 1 *Hierarchical structures of the magnetosphere-ionosphere compound system and the meteorological compound system*

The magnetosphere-ionosphere compound system has a number of states according to solar wind conditions under which transitions occur, while the meteorological compound system only has one state.

compound system. After all, the magnetosphere-ionosphere compound system and meteorological compound system differ in terms of hierarchical structure as shown in Fig. 1. More specifically, in the hierarchical structure of the meteorological compound system, a three-cell global circulation system, with high and low pressures, meandering jet streams, is set at top and other synoptic-scale phenomena in its substructure. In contrast, the magnetosphere-ionosphere compound system has such substructures as ULF waves and structures inherent in the stationary magnetosphere convection system as synoptic-scale phenomena. Moreover, multiple states of the compound system associated with various solar wind conditions exist as its superstructure. As a result, compound system state transitions occur under varying solar wind conditions.

3 Possibilities and problems of real-time simulations

Real-time MHD simulations have been conducted at the National Institute of Information and Communications Technology since December 22, 2003. The world's first revolutionary project in this area uses ACE data as the initial values of MHD simulations from moment to moment, and predicts the behavior of the magnetosphere-ionosphere with a lead time of about one hour[5]. This project is meaningful in that it has made MHD simulations a practical tool for space weather prediction. While numerical models are being run daily for meteorological weather prediction purposes, the resultant data is time-series data on meteorological elements at the grid points in a three-dimensional atmosphere. This data represents a self-consistent solution to a set of equations in atmospheric physics, as well as a repository of information not available from a mere observational approach that presents ambient conditions consistent with the laws of physics.

Such numerical model products (called "objective analysis data" in terms of meteorology) are publicized by the Japan Meteorological Agency to researchers. (Past data is updated on the latest numerical models and released.) Real-time simulations for space weather create precise objective analysis data on the magnetosphere. It is most important to uncover information hidden in the objective analysis data and develop it at a higher level of refinement to discover something new (data mining). Objective analysis data surveys entail comparing measured AE index values with calculated values[14], comparing observation empirical models on potential distributions of polar electric fields with their calculated values[15], and estimating electron temperature on satellites orbiting in a geostationary orbit[16]. (This survey implements the guidance technique described later.) Such analytical studies should be promoted to discover new magnetosphere-ionosphere phenomena and enhance numerical models.

From a practical viewpoint of space weather prediction as well as research, it is essential to investigate the relationship between observed values with magnetosphere objective analysis data as a result of MHD simulations, by comparing both sets of data, as in correlated analyses. The concept is to identify tendencies in the numerical models as a preparatory step to their practical implementation in the guidance scheme discussed later.

Real-time simulations in operation involve certain problems that must be addressed in order to produce a realistic reproduction of phenomena as follows:

- Upper and lower limits are set for the solar wind parameters to eliminate extreme solar wind conditions from the scope of calculations for ensuring simulation stability. In comparing the observed data and calculation results, it is therefore necessary to ensure that the solar wind parameters are confined within those limits[5]. Considering the fact that the phenomena of interest are apt to occur under extreme solar wind conditions, a new real-time simulation code capable of running with added stability needs to be developed.
- No inclination of the magnetic axis is implemented. The code must therefore be improved to allow the magnetic axis to incorporate the effects of inclination from the ecliptic plane and meridian plane. The code addresses inclination of the magnetic axis on the meridian plane, but such inclination is not factored into the working calculation process. This improvement is essential to allow for coupling between the thermosphere-ionosphere model and the magnetosphere model being developed, because the thermosphere-ionosphere model is concerned with daily and seasonal changes.
- Since reflection of the field-aligned current incident on the ionosphere is not correctly represented, the ionosphere's electric field tends to have a somewhat larger value [Nakata and Yoshikawa, 2009, private communication].
- As the propagation of Alfvén waves along the magnetic field lines is not precisely reproducible, a spatial dissipation of Alfvén waves appears during their propagation from the ionosphere to the magnetosphere. As for phenomena in which waves play an important role, comparisons with simulation results should deserve special notice.

These problems need be resolved to make magnetosphere objective analysis data more realistic. The phenomena using MHD simulations are limited to those that can be described in the MHD approximation. This should be kept in mind when comparing the physical quantities observed on a satellite with the MHD simulation results.

4 Data assimilation - its present and recommended practice

For numerical models used for Earth Science, such as the magnetosphere model, atmospheric global circulation models (meteorological), and ocean circulation models once boundary conditions and parameters involved in the physical laws (e.g., coefficient of viscosity, ionospheric conductivity) are assigned, along with initial conditions, the numerical model which solves the laws of physics reproduces the realistic state. Practical numerical models, such as those for weather prediction, must use optimal values of such external parameters, in addition to treating the physical laws properly. Performing data assimilation helps achieve these goals.

The data assimilation technique will essentially be of no practical value, unless the numerical model is guaranteed to fully reproduce the phenomena. From this viewpoint, the magnetosphere MHD model is not yet ready for full-scale data assimilation aimed at prediction, because we do not know the accuracy of the model. It would therefore be meaningless to apply an advanced data assimilation technique called "4-dimensional variational data assimilation" to the magnetospheric model[17][18], whereby observed values are assimilated with the uncertainties of initial values from moment to moment to minimize prediction errors, as practiced in weather prediction tasks. Technically, using a data assimilation technique should require the iterative running of a numerical model. Because available computer capabilities are inadequate for running iterative calculations of our magnetosphere MHD model, the advanced data assimilation techniques will not work.

However, if we try to determine relevant parameter values by using a data assimilation technique to build a numerical model reproducing observed values with better accuracy, the data assimilation technique would not be meaningless (since the validity of results is to be reviewed separately). The data assimilation technique is mentioned in this paper for the purpose of introducing physical quantities that may be subject to data assimilation on the magnetosphere MHD model. We must confess that much remains to be developed in order to achieve practical use of the data assimilation technique.

This paper tries to estimate the optimal value of the ionospheric conductivity parameter as an example of typical data assimilation on the magnetosphere model. As the MHD model generates an ionosphere electric field, an ionosphere current can be obtained from conductivity and thus ground magnetic field changes can be calculated. Because continuous data of the ground magnetic field at multiple points are readily available, the observations and numerical model can be easily compared in terms of ground magnetic field changes. The current numerical model makes no allowance for inclination of the earth's axis, and since the location of each geomagnetic observatory and its position in the simulation do not agree, there is no way of comparing the values observed at each observatory with the numerical model values. Rather, the AE index that handles information in all longitudinal directions by 60 to 70 degrees latitude as a whole may provide more useful data for assimilation with the simulation.

Because the AE index (estimated by simulation) reproduces its observed value with some degree of accuracy for the data assimilation technique, both values are compared. It should be noted, however, that the position at which solar wind data is imported into the numerical model shifts from the actual ACE satellite location to a location near the earth in implementing numerical simulations; therefore, a time difference equivalent to this distance exists. The estimated value of the AE index is thus shifted in the time direction to estimate the time that maximizes the correlation coefficient with the observed value of the AE index. When we use the data collected during the ten hours from 0900 hours to 1900 hours on July 14, 2006, we find that both the observed AE index and the AE index estimated by simulation have a high correlation factor of 0.879, provided that the latter is delayed by 62 minutes. For now, the data assimilation technique for this period will be used to determine ionospheric conductivity.

Detailed procedures for data assimilation calculations are described below. With the magnetosphere model, the height-integrated conductivity tensors ($\Sigma_{\theta\theta}$, $\Sigma_{\varphi\varphi}$, $\Sigma_{\theta\varphi}$) are defined in relational expressions as:

$$\Sigma_{\theta\theta} = \frac{\sigma_0 \sigma_1}{\sigma_1 \cos^2 I + \sigma_0 \sin^2 I} \tag{1}$$

$$\Sigma_{\theta\varphi} = \Sigma_{\varphi\theta} = \frac{\sigma_0 \sigma_2 \sin I}{\sigma_1 \cos^2 I + \sigma_0 \sin^2 I} \tag{2}$$

$$\Sigma_{\varphi\varphi} = \frac{\sigma_0 \sigma_1 \sin^2 I + (\sigma_1^2 + \sigma_2^2)\cos^2 I}{\sigma_1 \cos^2 I + \sigma_0 \sin^2 I} \tag{3}$$

In these equations, I denotes inclination, and σ_0, σ_1 and σ_2 represent the field-aligned conductivity, Pedersen conductivity and Hall conductivity, respectively. σ_1 and σ_2 vary depending on the solar radiation and energy incident from the magnetosphere. According to [19], such changes are expressed as:

$$\sigma_1 = a_1(\rho, p, T, v_{\|}, \varphi)\sigma_{oval} + a_2(J, \varphi)\sigma_{curr} + f(\lambda)\sigma_{sun} \tag{4}$$

$$\sigma_2 = a_{1H}(T) a_1(\rho, p, T, v_{\|}, \varphi)\sigma_{oval} + a_{2H} a_2(J, \varphi)\sigma_{curr} + f(\lambda)\sigma_{sun} \tag{5}$$

$a_1(\rho, p, T, v, \phi)$, $a_2(J, \phi)$, $a_{1H}(T)$ and a_{2H} denote the functions of density (ρ), pressure (p), temperature (T), current (J), and velocity (v) on the magnetosphere internal boundary, respectively. All are normalized. $f(\lambda)$ is a function of cosine (λ) of the solar zenith angle (φ).

$$a_1(\rho, p, T, v_{\parallel}, \varphi) = \rho v_{\parallel} \frac{(\pi-\varphi)/2\pi + 0.1}{4} + \frac{T}{2(T+10)} \left(\frac{p^{3/2}((\pi-\varphi)/2\pi+0.1)}{5T^{1/2}} \right)^{1/2} \quad (6)$$

$$a_2(J,\varphi) = J_z \frac{\pi - \varphi}{2\pi} \quad (7)$$

$$a_{1H}(T) = 2 + \frac{T^{1/2}}{T^{1/2}+2} \quad (8)$$

$$a_{2H} = 2.5 \quad (9)$$

J_z in Equation (7) is a vertical component of current. Once all these preparatory steps are complete, the optimal values of (σ_0, σ_{oval}, σ_{curr}, σ_{sun}) are determined by using the data assimilation technique. The nudging method of the data assimilation technique is used to find the set of (σ_0, σ_{oval}, σ_{curr}, σ_{sun}) that minimizes error between the observed value (AE_{obs}) and calculated value (AE_{cal}), starting from an appropriate initial value.

$$H(\sigma_0, \sigma_{oval}, \sigma_{curr}, \sigma_{sun}) = \frac{\sum_{i=1}^{N} \left(AE_{obs}(t_i) - AE_{cal}(t_i) \right)^2}{N^2} \quad (10)$$

H is called an error function. For now, the following equation

$$\Delta H(\sigma_0, \sigma_{oval}, \sigma_{curr}, \sigma_{sun}) = \frac{\partial H}{\partial \sigma_0}\delta\sigma_0 + \frac{\partial H}{\partial \sigma_{oval}}\delta\sigma_{oval} + \frac{\partial H}{\partial \sigma_{curr}}\delta\sigma_{curr} + \frac{\partial H}{\partial \sigma_{sun}}\delta\sigma_{sun} \quad (11)$$

is numerically calculated to determine the direction in which minimal error function H exists. Then the optimal value of connectivity is determined by varying the values of (σ_0, σ_{oval}, σ_{curr}, σ_{sun}) in that direction. While four kinds of AE indices are available (AE, AO, AU and AL), only AE has been chosen as the target of data assimilation.

Figure 2 shows the observed values of the AE and AO indices collected for the 10-hour period from 0900 hours to 1900 hours on July 14, 2006. Figure 3 shows the values of the AE and AO indices estimated by simulation

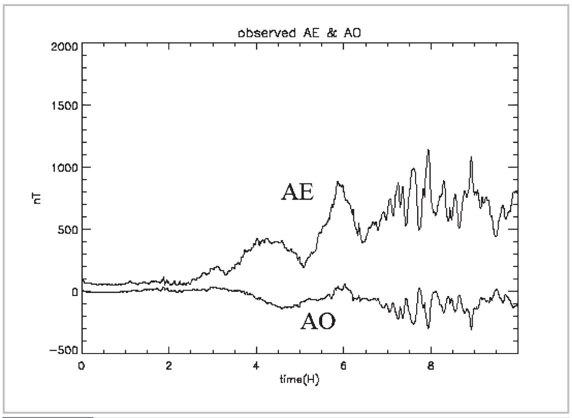

Fig.2 AE and AO indices (observed values) collected from 0900 hours to 1900 hours on July 14, 2006

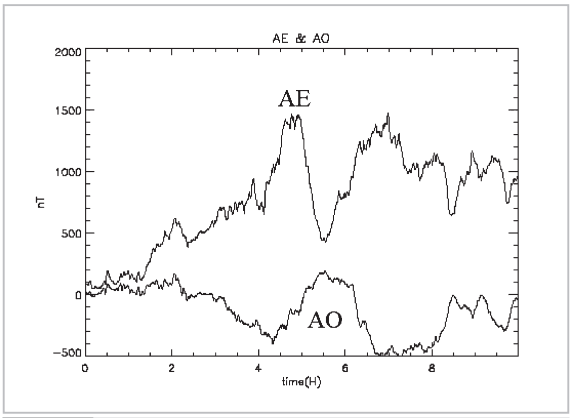

Fig.3 AE and AO indices calculated using ionospheric conductivity in effect before data assimilation

from 09:00 to 19:00, July 14, 2006

before the start of data assimilation. (While the AO index is also found in the diagram, it is unfit for data assimilation.) Starting from the state shown in Fig. 3, the values of (σ_0, σ_{oval}, σ_{curr}, σ_{sun}) are sequentially varied in such direction to diminish the error function in the method described above. Table 1 lists the steps and values in this process. Figure 4 shows the value of the AE index calculated using the value of ionospheric conductivity reached after five iterative runs of data assimilation. When comparing Fig. 3 and 4, we can see that the absolute value of the AE index has neared the observed value (in Fig. 2). Figures 5 and 6 show the distributions of $\Sigma_{\theta\theta}$ in effect before and after the data assimilation process. The conductivity is found higher in the day-

Table 1 *Optimal values of ionospheric conductivity determined using the nudging method*

Step	σ_0	σ_{sun}	σ_{oval}	σ_{curr}	H
0	27.0000	2.0250	0.1350	40.5000	208.03
1	26.9999	2.0257	0.1050	40.5000	150.36
2	25.8767	2.0258	0.1035	41.2488	136.46
3	25.8453	3.3744	0.0770	41.2022	122.19
4	25.8453	3.3741	0.0635	41.2023	104.59
5	25.8452	3.3740	0.0500	41.2023	88.05

(in mho) Changes in the factor and error function (H) used to determine step ionospheric conductivity

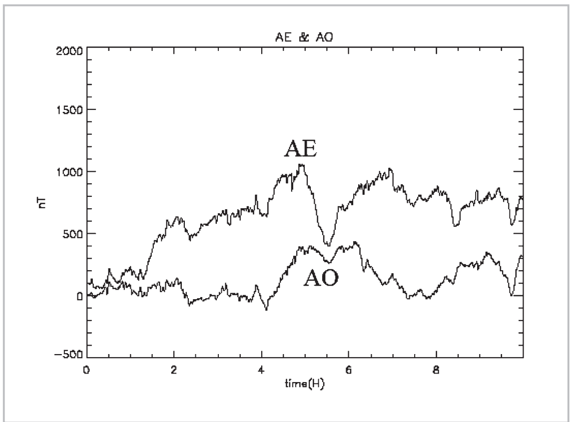

Fig.4 *AE and AO indices calculated using ionospheric conductivity in effect after data assimilation*

from 09:00 to 19:00, July 14, 2006

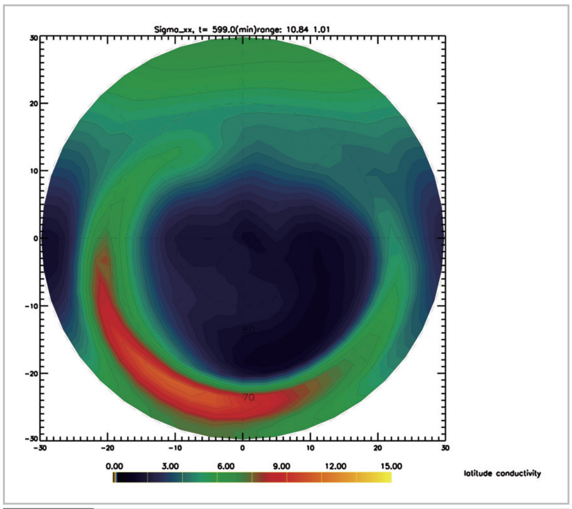

Fig.5 *Distributions of ionospheric conductivity ($\Sigma_{\theta\theta}$) in effect before data assimilation*

(in mho) 19:00, July 14, 2006

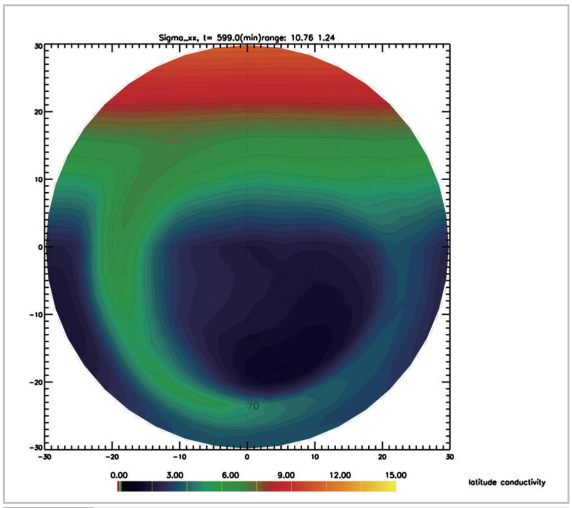

Fig.6 *Distributions of ionospheric conductivity ($\Sigma_{\theta\theta}$) in effect after data assimilation*

(in mho) 19:00, July 14, 2006

time after data assimilation, and is lower in the aurora zone. The value of conductivity derived here should depend on the kind of event adopted. Analyses must further proceed to determine and average the values of ionospheric conductivity that reproduce changes in the AE index optimally through data assimilation using multiple events. If the results are found to vary significantly, enhancement of the numerical model may take precedence over using data assimilation results to determine an optimal value of ionospheric conductivity. This paper simply introduces an attempt at data assimilation and leaves further analyses open as future tasks.

Here, it should be noted that the optimal conductivity value determined by the data assimilation technique and the actual value do not necessarily agree. This is because the numerical model does not encompass all physical processes at work, and the mesh intervals used on the numerical model remain inadequate for producing a realistic reproduction of phenomena. In particular, changing the mesh sizes would in turn change the optimal value derived from data assimilation. Thus, the conductivity determined by using the data assimilation technique might be deemed an artificial value intended to reproduce the AE index on the numerical model in an optimal manner. In other words, if the observed value of ionospheric conductivity is loaded into the current numerical model in its present form, whether the AE index and ground magnetic field changes are correctly reproducible will be unknown.

5 Numerical model limitations and implementation of a guidance scheme

It is truly important to further develop the numerical model at a higher level of refinement in order to compensate for its undisputable deficiencies, but there is a technique that leverages the capabilities of the existing incompetent numerical model to draw beneficial information. It is known that the numerical model used for weather prediction purposes does not necessarily deliver appropriate forecasts concerning ground meteorological conditions, such as ground surface temperature. In this context, guidance is available for examining the relationships between other physical quantities obtained on the numerical model and actually observed values to come up with predictions in a regressive manner. Regarding space weather, the ring current intensity and total quantity of radiation belt particles are essentially not available from the MHD model; however, by accumulating sufficient MHD simulation data to allow a comparison with actual measurements, prediction could be made possible by probing into the correlations between the quantity of MHD at a given point and the quantity of radiation belt particles. The electron temperature on a geostationary satellite orbit has been estimated from the pressure derived by real-time magnetosphere MHD simulations[16]. The pressure derived by MHD simulations is essentially that of ions, not electrons. Therefore, this attempt can be considered an implementation of the guidance scheme.

The method explained above seeks to do the same as the attempt made to determine ionospheric electron density on a neural net by using solar wind data and the K-index[20], except that it uses data from a numerical model. Regression analyses can be conducted by using multiple regressions, Kalman filters, etc. in addition to the simple least square method. For a more detailed description of the procedures, refer to “Discussions of Weather Prediction Guidance”[21].

Guidance-based weather prediction is a workaround and not a legitimate way of scientific research, because it involves vast amounts of time and cost in developing relevant technologies under the constraints of incomplete available techniques. The proper path to follow should be augmenting the phenomenon reproducibility of numerical models pursuant to the laws of physics.

6 Future challenges

To improve the magnetosphere numerical model, it is important to make a detailed check on real-time simulation results as produced from day to day in order to determine the extent to which the results match observations. As a matter of fact, meteorologists at the Japan Meteorological Agency and district/local meteorological observatories have made day-to-day comparisons of data obtained from the meteorological model with actual measurements, feeding back the results to refurbish the numerical model as we see it today. The comparative data collected thus far includes comparisons with the AE index[14], polar ionosphere potential[15], and geostationary satellite data[16]. Such data will prove useful in many ways, including quantitative comparisons with polar ionosphere observation (such as Super DARN) and comparisons of the times when substorms occur with the model and actual observations.

The numerical model also has much room for further improvement. In addition to allowing for inclination of the magnetic axis as mentioned earlier, the following areas of enhancement are important:

- Ionospheric boundary conditions require further improvement. The higher the ionospheric conductivity, the greater the current flow, thus providing an inappropriate solution under those conditions in case Alfvén conductance of the magnetosphere falls below ionospheric conductivity.
- Two-way connectivity between the magnetosphere and thermosphere-ionosphere is also needed. This requirement might have less significance to the magnetosphere than that mentioned above, but the numerical model representation of thermospheric effects in the magnetosphere is meaningful in geophysical research.
- While solar wind input data is derived from ACE satellite observations, not all observed data is put to use; in fact, the Bx component (solar-terrestrial direction) of the solar wind magnetic field, and the Vy and Vz components (east-west and south-north directions, respectively) of solar wind velocity are disregarded. Improvements are needed to accommodate such disregarded factors as input values to ensure the correct reproducibility of magnetospheric variations resulting from solar wind changes.
- It is important to factor in the behavior of high-energy particles that comprise the ring current into the numerical model, in order to reproduce magnetic storms. Consequently, it is necessary to combine the MHD model and ring current model. This has already been implemented in the U.S., but a full-scale coupling model should be worthwhile in Japan as well. The MHD model must be sufficiently robust to handle magnetic storms as the object of calculation. This can be implemented by taking such actions as varying the mesh geometry or narrowing the time steps to the extent possible.
- The meteorological numerical model involves a micro process known as the precipitation process. This process is microscopic and factored into the numerical model as a set of parameters, and also significant enough to determine not only the generation and extinction of clouds, but also the behavior of atmospheric global circulation as a whole. The magnetosphere model should also benefit from more precise handling of the magnetic reconnections included in substorms. Boosting the accuracy of predicting the occurrence of substorms should require the use of more advanced reconnection parameters or coupling with particle simulations.

7 Conclusions

This paper has discussed the impact that the magnetosphere-ionosphere coupling MHD model has had on magnetospheric physics as a numerical model. The paper also reviewed what kinds of technological developments are needed to implement a real-time simulation approach to space weather prediction. Principal findings are summarized as follows:

- MHD simulations of the magnetosphere-ionosphere handled in a self-consistent manner have proposed a new concept called the “magnetosphere-ionosphere compound system”. Magnetospheric phenomena associated with solar wind changes can be explained in terms of state transitions of the compound system.
- An attempt to estimate ionospheric conductivity by using the data assimilation technique with the AE index has been introduced. This method, however, has yet to reach a state of practical usefulness due to incompleteness of the numerical model and the vast amount of time it takes to perform assimilation calculations, but should become an integral part of future space weather prediction.
- The paper also introduced that those physi-

cal quantities that are not reproducible by running MHD simulations can be estimated using a scheme of guidance. A detailed analysis of real-time simulation results and a thorough probing of the relationships between calculated and predicted values are required to implement such MHD simulations.

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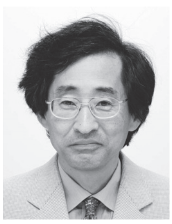

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Physics of the magnetosphere-ionosphere system