Duration of an ionospheric data assimilation initialization of a coupled thermosphere-ionosphere model

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1 Initial conditions provide a critical input for accurate numerical forecast models in meteorology and oceanography. In this paper, we address this problem in space weather forecast models of the thermosphere-ionosphere system by using the electron densities from the Global Assimilation of Ionospheric Measurements (GAIM) model to initialize the ionospheric part of the Thermosphere Ionosphere Nested Grid (TING) model. The electron densities from the GAIM-initialized TING model (G-TING) are compared with the output from the stand-alone TING model (S-TING) for geomagnetically quiet and disturbed times in the early April 2004 period in order to observe how long the effects of the initialization would last. Our study shows that the $e$-folding time of the initialization is about $2/3$ hours for most conditions, although this result would probably be different if the initialization for the thermosphere is also included. However, this relaxation time displays significant variations with latitude, local time, and height, and it may also depend on the initial electron density differences between G-TING and S-TING. Furthermore, positive (G-TING > S-TING) and negative (G-TING < S-TING) density differences have different time durations of the initialization effects. Our study also indicates that there is little variation of the relaxation time with the geomagnetic activity despite the impact of geomagnetic storms on the thermosphere-ionosphere system.


1. Introduction

Space weather forecasting is the application of current science and technology to predict the future state of the solar-terrestrial environment. It requires both complex numerical models and extensive observations, covering every physical domain from the Sun to the Earth’s upper atmosphere. In space weather forecast modeling, numerical models solve the physical equations governing the system of interest and evolve the current state of the system forward in time to predict the future state of the system. However, the prediction of the future state from this process has errors as there are uncertainties in the initial conditions, model drivers, and model equations. For example, numerical models for tropospheric weather forecasting are known to be extremely sensitive to initial conditions [Lorenz, 1963; Buizza, 2000]. Even though the troposphere is a forced and dissipative system, the forcings are relatively unimportant in numerical weather forecasting, compared with initial conditions, since the troposphere is forced only thermally on a global scale and the large-scale thermal forcing changes slowly on the timescale of 1 to 2 weeks [Ghil and Malanotte-Rizzoli, 1991]. The thermosphere-ionosphere system, in contrast, is strongly driven by external forcings on a relatively short timescale. These forcings, which come from solar, magnetospheric, and middle and lower atmospheric processes, may be dominant factors in determining neutral and plasma distributions, particularly during disturbed periods. At the same time, there is evidence of persistence of ionospheric features long after such forcings have ended. As early as 1959, Matsushita [1959] showed that the disturbed ionosphere lasted long after the end of the main phase of geomagnetic storms. As space weather gets more attention it is critical to identify how important initial conditions are for modeling space weather. This issue must be addressed...
to develop forecast models of the thermosphere-ionosphere system.

[5] In principle, the optimum initial conditions for a numerical weather forecast model should be obtained directly from observations of the current state of the system. However, obtaining pure database initial conditions is not possible when much of the system is in a region where observations are sparse, as is true in most of the solar-terrestrial environment including the thermosphere-ionosphere system and even in the troposphere. Furthermore, the available observations are irregularly distributed in space and time and they have different errors associated with them. The methodology of data assimilation has been extensively utilized in meteorology and oceanography in order to overcome these problems [Ghil and Malanotte-Rizzoli, 1991]. By merging available observations with a priori knowledge of a system contained in a previous forecast, not only does data assimilation provide an improved specification of the system, but it can also be used to prepare initial conditions for numerical weather forecast models.

[5] Data assimilation has begun to gain prominence since the availability of measurements in the thermosphere-ionosphere system has dramatically increased recently from both space and the ground. The first attempts at data assimilation in this system were local. The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure is an optimally constrained, weighted, least squares fit of the electric potential distribution to diverse types of high-latitude ionospheric observations that gives information about the high-latitude convection pattern and ionospheric conductivities [Richmond and Kamide, 1988; Richmond, 1992]. Howe [1998] made the initial attempt to demonstrate the possibility and practicality of obtaining four-dimensional global maps of the electron densities using a Kalman filter to assimilate ionospheric data into a time-dependent ionospheric model. More recently, Schunk et al. [2004] and Wang et al. [2004] have developed more sophisticated Kalman filter models for global ionospheric data assimilation. However, only limited efforts have been made to develop assimilation models for the thermosphere, mainly because of the lack of thermospheric measurements [Minter et al., 2004; Codrescu et al., 2004].

[5] Experience in the troposphere has shown that the most appropriate way of preparing initial conditions for forecast models is data assimilation, which currently produces the best available representation of the ionosphere. The aforementioned USU Global Assimilation of Ionospheric Measurements (GAIM) model [Schunk et al., 2004] is able to provide specification of the global ionosphere. We use this specification to provide initial conditions for the ionospheric part of the Thermosphere Ionosphere Nested Grid (TING) model [Wang et al., 1999] to test techniques that will be applicable for the Center for Integrated Space Weather Modeling (CISM) [Luhmann et al., 2004].

[6] Relaxation of the GAIM-initialized TING model back to the stand-alone TING model raises a number of questions such as; how long do initial conditions continue to influence the ionosphere and thermosphere; is this influence spatially and temporally homogeneous; and what are the physical mechanisms of any of these variations? It is these questions that we address in the rest of the paper. In the following sections, we will briefly introduce the GAIM and TING models and then the procedure and results of this study will be presented.

2. GAIM Model

[7] GAIM is a data assimilation model for the ionosphere that has been developed to provide a specification of the ionospheric plasma distribution by combining a physics-based model with observations [Schunk et al., 2004]. The GAIM model assimilates a variety of data from the ground- and space-based observations using a Kalman filter. There are two versions of the model: a Gauss-Markov Kalman filter (GMKF) model and full physics Kalman filter model. The GMKF uses the physics-based ionosphere forecast model (IFM) to provide background ionospheric densities and a statistical Gauss-Markov process to propagate density perturbations and the associated errors forward in time. The output of the GMKF is a global 3-D time-varying distribution of electron density from 90 to 1400 km [Thompson et al., 2006; Scherliess et al., 2006]. The full physics Kalman filter model is more sophisticated but computationally more expensive than the GMKF, since it uses a physics-based model not only to provide the background ionosphere, but also to propagate the ionospheric electron density field and its associated errors. In addition to significant improvements of the 3-D plasma density reconstruction over the GMKF, the full physics Kalman filter model is able to specify and improve the thermospheric and electrodynamic drivers that determine the plasma distribution in the physics-based model [Scherliess et al., 2004]. For this study, however, we used the electron densities calculated from the GMKF model, since it has been tested over extended periods whereas the full physics Kalman filter model is still undergoing testing and initial validation. The GMKF assimilated three types of measurements over the background electron density field to produce electron densities utilized for this study. The assimilated data sources consist of line-of-sight total electron content (TEC) measurements between ground stations and the GPS satellites, bottomside electron density profiles from ionosondes, and in situ electron densities from the Defense Meteorological Satellites Program (DMSP) satellites. However, these data are only assimilated by the model from +60° to −60° geographic latitude. Above about ±70° in latitude, the GMKF model output is purely from the background ionospheric model (IFM). Between these two regions, results are merged smoothly.

3. TING Model

[8] The TING model is an extension of the NCAR Thermosphere-Ionosphere General Circulation Model
(TIGCM) [Roble et al., 1988; Wang et al., 1999]. Within the TIGCM coarse grid ($5^\circ \times 5^\circ$ in longitude and latitude), one or more levels of nested grids can be inserted in regions of interest to simulate mesoscale and microscale processes occurring in the thermosphere-ionosphere system. The TING model is a time-dependent, three-dimensional model that solves momentum, energy and continuity equations of major and minor neutral species of the upper atmosphere self-consistently with the $O^+$ transport equations. Chemical equilibrium is assumed to obtain densities of other ions. The TING model has 25 constant pressure levels in the vertical between approximately 97 and 500 km altitude with a vertical resolution of 2 grid points per scale height. The upper and lower boundary conditions of the TING model are the same as those of the TIGCM and specified basically by assuming diffusive and chemical equilibriums, respectively. The input parameters of the TING model are $F_{10.7}$ and 81-day average of $F_{10.7}$ as proxies for solar EUV and UV radiations, the amplitudes and phases of tides from the lower atmosphere, auroral particle precipitation, and electrodynamic ion drifts specified using empirical models by Heelis et al. [1982] for high latitudes and by Richmond et al. [1980] for low and middle latitudes. The model outputs for the thermosphere are global distributions of neutral gas temperature, winds, mass mixing ratios of the major constituents, $N_2$, $O_2$, and $O$, and the mass mixing ratios of the minor neutral gas constituents, $N(\text{D})$, $N(\text{S})$, NO, He, and Ar. For the ionosphere, global distributions of electron and ion temperaturess, $O^+$, $O_2^+$, NO$, N_2^+$, $N^+$, and electron densities are calculated.

4. Procedure

[9] The early April 2004 period was chosen to study the relaxation time for the initialization on the ionosphere forecast model, as it was the part of the first Climate And Weather of the Sun Earth System (CAWSES) campaign [Basu and Pallamraju, 2006]. This campaign was run in association with the Coupling Processes in the Equatorial Atmosphere (CPEA) campaign (April/May 2004) and the ISR World Days campaign (29 March to 3 April 2004). This period occurred during solar minimum conditions ($F_{10.7} \sim 105$) and included a moderate geomagnetic storm ($Kp \approx 6$). The geomagnetic storm began with a small disturbance ($Kp = 2 \sim 3$) at the beginning of day 94 (2 April 2004) and reached its peak ($Kp = 6.3$) at the end of the day (Figure 1). In Figure 1, $Kp$ (top) and $Dst$ (bottom) indices are displayed for the period of 1 April (day 92) to about 5 April (day 96) 2004.

[10] Four cases are selected to represent different geomagnetic levels (shown in Figure 1 as vertical bars) to observe the geomagnetic activity dependency of the relaxation time: 0000 UT of day 93 (00–93), 1400 UT of day 94 (14–94), 2000 UT of day 94 (20–94), and 0000 UT of day 95 (00–95). First, the TING model was run for 24 hours without using...
GAIM initialization for each case to produce stand-alone TING electron densities. Output was produced with a 30-min cadence. For the USU GAIM-initialized TING model runs, the electron and O$^+$ densities in the initial conditions of the TING model were replaced with the GAIM electron densities before the model runs (the Gauss-Markov Kalman filter model, the version of GAIM used in this study, produces only the electron densities, but not the ion densities). This procedure was applied from the pressure level of $z = -2$ to the top boundary of the TING model (about 500 km), where the O$^+$ ion is a dominant species and its density is comparable to the electron density, but below this pressure level the replacement was not performed because of the lack of molecular ion densities in the output of the GAIM model. Since the spatial grid system of the GAIM model is different from the one used in the TING model, a linear interpolation was applied to modify the GAIM electron densities to the TING spatial grid system. In particular, height interpolation was performed for each time step of model run using calculations of the height of each pressure surface and interpolating electron densities at the GAIM heights to match. Resulting electron densities were then used as initial conditions to run the TING model to produce the GAIM-initialized TING electron densities.

5. Results

Figure 2 shows the global $N_m F_2$ maps at the initial time of the model runs from (left) the GAIM-initialized TING model, (middle) the stand-alone TING model, and (right) the initial differences between them. Four different cases are displayed from top to bottom. Each plot shows the global map of electron density in geographic latitude and longitude coordinates with local noon at the center of longitude.

Figure 2. Global $N_m F_2$ maps at the initial time of the model runs from (left) the GAIM-initialized TING model, (middle) the stand-alone TING model, and (right) the initial differences between them. Four different cases are displayed from top to bottom.
two models for 2000 UT of day 94 (20–94) in the top two plots and the difference maps between these two $N_mF_2$ maps from 2000 UT of day 94 to 0500 UT of day 95 over 9 hours. Most of the differences in $N_mF_2$ disappear over a few hours, although a large positive region over the equatorial American sector remains much longer.

[12] Since the differences display an approximately exponential decay with time, we used the $e$-folding time (the interval of time for differences to decrease by a factor of $e$, that is, about 70% of the initial differences) to represent the relaxation time of initialization to the state of the S-TING model. This can be seen in the average behavior of the relaxation of the initial differences in $N_mF_2$ as shown in Figure 4. In Figure 4, we used a global average of the initial differences in $N_mF_2$ for 2000 UT of day 94, which produced a smooth exponential decay curve, although the relaxation of the individual initial differences at different locations or local times may deviate from the exponential curve. Decrease of the initial difference by a factor of $e$ is indicated by the dashed line. The $e$-folding time is the corresponding time as shown in Figure 4. The $e$-folding time was calculated for positive (G-TING >
Local time variations of the $e$-folding time are presented in Figure 6, which are similar to the plots in Figure 5, but show variations with local time rather than latitude. Overall, these variations are a little smaller ($1 \sim 3$ hours) than the latitudinal variations ($1 \sim 4$ hours). However, they also have a different behavior for positive (G-TING > S-TING) and negative (G-TING < S-TING) differences; the negative differences (middle plots) have longer $e$-folding times during the day (about 3 hours) than those during the night (less than 2 hours), whereas local time variations for positive differences (left plots) do not have any systematic behavior. As with the latitudinal variations, the local time variations do not show any noticeable geomagnetic activity variations, except that the $e$-folding times for the case of 00–93 are slightly longer than the other cases.

Finally, we expanded the calculation of the $e$-folding time to all pressure levels and made the average $e$-folding times for each pressure level (Figure 7). Below the $F_2$ peak where pressure level is less than 0–1, the initialization effects disappear in less than 30 min. The $e$-folding time then increases from about pressure level 0 until it reaches its maximum value near the $F_2$ peak (i.e., pressure level 2 or 3). It decreases again at higher pressure levels. Unlike the variations in Figures 5 and 6, the height variations for the positive and negative differences are very similar. The differences in the $e$-folding time for different geomagnetic activity levels are also negligible.

The relaxation of the electron density profile from G-TING (solid line) to the one from S-TING (dotted line) at the location of 0° geographic longitude and 32.5° latitude for 2000 UT of day 94 is presented in Figure 8 to understand the height variations more clearly. When the gradients of the topside electron density profiles (i.e., plasma temperatures) from the two models are different at the initial time step (2000 UT), ambipolar diffusion quickly works (less than 30 min) to make the gradient of the topside profile consistent with the plasma temperature in the TING model. Note that the $F_2$ peak height from G-TING also moves down to the S-TING height in Figure 8. Thereafter, the G-TING electron density at the $F_2$ peak, and above, more gradually decreases back to the S-TING electron density with time.

6. Discussion

In this study, we address the importance of initialization in space weather forecast models. Initialization of forecast models in meteorology is an essential problem for the prediction of the future state of the system as the models are extremely sensitive to initial conditions. Therefore it is a prerequisite to have accurate initial conditions, which have been provided by data assimilation. As the number of available observations has increased in the thermosphere-ionosphere system, data assimilation models for this system have also been developed. Here, we have used the USU GAIM model to initialize the ionospheric part of the TING model and have studied the
behavior of the relaxation time (i.e., the $\tau$-folding time in this study) of the GAIM-initialized TING model (G-TING) back to the stand-alone TING model (S-TING).

[18] The initialization was performed for the early April 2004 CAWSES period, which includes quiet and disturbed periods (see Figure 1). The initial differences between G-TING and S-TING display significant spatial variations, ranging from negative (G-TING < S-TING) to positive (G-TING > S-TING) differences (Figure 2). Negative differences mostly occur during the day and positive differences are largely concentrated in the lower-latitude regions. These distributions of the differences should be considered in the interpretation of the results since the underlying physics for removing the positive and negative differences is different; the positive differences are removed by decreasing the plasma through recombination or transport and the negative differences are removed by increasing the plasma through production or transport.

[19] Rather evident latitudinal variations of the $\tau$-folding time (Figure 5) seem to be partially correlated with the

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**Figure 5.** Latitudinal variations of the $\tau$-folding times (asterisks) and initial differences (dotted lines) for (left) positive (G-TING > S-TING), (middle) negative (G-TING < S-TING), and (right) total differences. As in Figure 3, variations for four different geomagnetic activity levels are shown from top to bottom.
latitudinal variations of the initial differences. This correlation is particularly noticeable when the initial differences are positive. In this case, they show strong latitudinal variations, which are large at around the equator and get smaller at higher latitudes. However, the negative differences do not show these latitudinal variations, but rather display irregular variations with latitudes. The $e$-folding times in the areas with negative differences also show irregular latitudinal variations, but without much correlation with these differences. On the other hand, local time variations of the $e$-folding times for negative differences display systematic diurnal variations (larger $e$-folding time during the day than the one at night except for 00–93 case), but the positive differences have irregular variations of the $e$-folding times with local time (Figure 6). The initial differences also show similar local time variations, but they are not well correlated with the $e$-folding time, particularly for positive differences. It should be noted that latitudinal variations of the $e$-folding time are obtained from the longitudinally (with local time) averaged $e$-folding time for each latitude bin, while local time variations are from the latitudinally averaged $e$-folding time for each local time bin. These differences in the way the two sets of variations are averaged may have affected the results.
Height variations of the \( e \)-folding time display quite a systematic behavior; below the \( F_2 \) peak, the initial differences, regardless of their magnitude, disappear in less than 30 min, but the \( e \)-folding time increases to its peak value of 2–3 hours near the \( F_2 \) peak and then decreases back above this peak (see Figure 7). Below the \( F_2 \) peak, chemical equilibrium prevails and any initial differences quickly disappear. At the \( F_2 \) peak and above, however, the chemical processes, including production and loss, are not as effective as they are below the \( F_2 \) peak, so initial differences do not decay as quickly. Note that the \( e \)-folding times at topside altitudes are shorter than those near the \( F_2 \) peak. It is a rather surprising result, considering that production and loss rates in the topside ionosphere are much smaller than those near the \( F_2 \) peak. As illustrated in Figure 8, the gradient of the topside electron density profile from G-TING is rapidly adjusted by ambipolar diffusion to make it consistent with the plasma temperature in the TING model. It is this rapid initial adjustment of the density gradient that causes the average \( e \)-folding times at topside altitudes to be shorter than those near the \( F_2 \) peak, as shown in Figure 7. The relaxation time after this initial rapid adjustment is roughly the same at all heights above the \( F_2 \) peak. This rapid adjustment also

![Figure 7. Same as Figure 5 but for height variations of \( e \)-folding times (asterisks) and initial differences (dotted lines).](image-url)
shows the possible importance of the plasma temperature, particularly the electron temperature ($T_e$) as it is more persistent than the ion temperature ($T_i$). So initializing the model with $T_e$ as well as the electron densities will probably alter relaxation times.

[21] The results of our study indicate that there is not much variation of $e$-folding times with the geomagnetic activity. Although the $e$-folding times seem to be longer before the geomagnetic storm (0000 UT of day 93) despite smaller initial differences compared with other cases, this tendency is very small. Considering that significant disturbances in both the thermosphere and ionosphere occur during geomagnetic storms, this negligible variation with the geomagnetic activity was an unexpected result.

[22] The relaxation time for the GAIM-initialized TING model is far shorter than the recovery time after a geomagnetic storm. This implies that the disturbed electron densities after a geomagnetic storm are mainly driven by other factors such as the perturbed thermosphere or the electron temperatures at low and middle latitudes. Since the initialization of the TING model was applied only to the electron densities of the model, these disturbances in the

Figure 8. Electron density profiles from S-TING (dotted line) and G-TING (solid line) for the case of 20–94 at 0° geographic longitude and 32.5° geographic latitude. The profiles displayed are from 2000 UT of day 94 at the top left to 0500 UT of day 95 at the bottom right with a 30-min interval.
thermospheric parameters and the electron temperatures have not been accounted for. In order to fully understand the initialization effect on a coupled thermosphere ionosphere forecast model; therefore the model needs to be initialized not only by electron densities, but also by the thermospheric parameters and the electron temperatures.

[23] Overall, the results of this study show that the e-folding time of initializing the ionospheric part of the TING model is about 2 ~ 3 hours in the $F_2$ peak, which seems to imply that, when the data-driven initialization of the ionosphere is applied to a coupled thermosphere-ionosphere forecast model, the resulting forecast is good for short-term forecasts and nowcasts, but not for longer forecasts. That is, a forecast longer than 3 hours from the model becomes less dependent on the initial condition of the ionosphere. A model of this system therefore will only show improvements if it is initialized with the outputs from ionospheric data assimilation models at least every two hours or less.

7. Conclusions

[24] We successfully implemented the initialization of the ionospheric part of the TING model with output from the GAIM model. Although the differences in $N_mF_2$ can remain much longer locally (see Figure 3), the e-folding time of this initialization is largely about 2 ~ 3 hours, and this is far shorter than the recovery time after a geomagnetic storm. It was found that the relaxation times show significant variations with latitude, local time, and height, and it also possibly depends on the magnitude of the initial differences between the GAIM-initialized and the stand-alone TING models. Furthermore, the relaxation times are different for positive (G-TING > S-TING) and negative (G-TING < S-TING) initial differences. Our study also indicates that geomagnetic activity has little effect on the relaxation time despite the impact of geomagnetic storms on the thermosphere-ionosphere system. Further study is necessary to elucidate the underlying mechanisms of these results.

[25] The effects of the initialization of the electron density in the TING model last for a relatively short time. These effects would probably last for a longer time if initialization is also conducted with a state containing neutral parameters and the electron temperature.

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