A comparison of the effects of initializing different thermosphere-ionosphere model fields on storm time plasma density forecasts

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[1] Data assimilation has been used successfully for real-time ionospheric specification, but it has not yet proved advantageous for forecasting. The most challenging and important ionospheric events to forecast are storms. The work presented here examines the effectiveness of data assimilation in a storm situation, where the initial conditions are known and the model is considered to be correct but the external solar and geomagnetic drivers are poorly specified. The aim is to determine whether data assimilation could be used to improve storm time forecast accuracy. The results show that, in the case of the storm of Halloween 2003, changes made to the model’s initial thermospheric conditions improve electron density forecasts by at least 10% for 18 h, while changes to ionospheric fields alone result in >10% forecast accuracy improvement for less than 4 h. Further examination shows that the neutral composition is especially important to the accuracy of ionospheric electron density forecasts. Updating the neutral composition gives almost all the benefits of updating the complete thermospheric state. A comparison with real, globally distributed observations of vertical total electron content confirms that updating the thermospheric composition can improve forecast accuracy.


1. Introduction

1.1. Experiment Outline

[2] Many aspects of the thermosphere-ionosphere system affect human activities. For example, satellite positioning and navigation errors occur because of ionospheric electron densities. High frequency communication systems are also affected by the ionosphere, while thermospheric densities are responsible for satellite drag. It is unfeasible to specify the full thermosphere-ionosphere system solely with observations because there are not enough observations to cover all the necessary fields across the whole globe. Furthermore, thermosphere-ionosphere modeling is challenging because the system has a wide range of external drivers, such as insolation, particle precipitation, high-latitude electric fields, and lower boundary forcings. In practice, many empirical and physics-based models represent climatological behavior accurately but struggle to capture day-to-day variability. This is especially true in the case of storms. A data assimilation scheme could combine ionospheric and thermospheric observations with a model in order to create improved forecasts.

[3] The term data assimilation refers to a series of techniques that adjust the current state estimates of models with the intention of improving forecasts. Assimilation techniques have been used successfully for this purpose in meteorology and other disciplines, but data assimilation is naturally most effective when the forecasts depend entirely on the initial values of the system. The ionosphere is a strongly forced system, especially during storms, so it is possible that any changes made to initial values by an assimilation scheme could quickly be overwhelmed by the effects of external driver changes. External drivers include lower boundary effects such as propagating gravity waves and tides, but during storms, the major inputs are from solar and geomagnetic sources. For example, the interplanetary magnetic field (IMF) components $B_x$, $B_y$, and $B_z$ frequently exhibit significant changes during storms, while the geomagnetic activity index, $K_p$, quantifies disturbances in the Earth’s magnetic field that are caused by IMF disturbances. Large negative values of $B_z$ drive strong convection and auroral precipitation in the high-altitude ionosphere. These two processes cause enhanced Joule heating, which results in changes to the neutral composition and thermospheric neutral winds. Typically, these thermospheric changes lead to a decrease in high- and midlatitude plasma densities. Richmond and Lu (2000), describe the role of penetration electric fields in causing large
increases in midlatitude plasma densities during storms. The direct penetration of electric fields from the polar regions down to the equatorial latitudes could enhance the daytime eastward electric field. This increase in eastward electric field strength would enhance the equatorial or Appleton anomaly, causing the density maxima to move further poleward and the trough at the magnetic equator to be enhanced. The competing negative and positive effects on storm time ionospheric densities cause each storm to be unique and difficult to forecast.

The aim of this paper is to establish whether a data assimilation scheme can produce accurate ionospheric forecasts in the absence of good external driver estimates. A coupled thermosphere-ionosphere model, described in section 1.2, is used for this study. The experiments test the storm time forecasting performance of an assimilation scheme in which a run of the model is taken to be the “truth” so that the assimilation update can be made perfectly. All the thermospheric and ionospheric fields are known, so there are none of the errors typically associated with the data assimilation process. The challenge is to produce accurate forecasts even when the external solar and geomagnetic drivers are significantly underestimated. Fields from the truth run replace fields from a run with underestimated drivers to simulate an assimilation scheme. As a first step toward creating a real assimilation scheme, the most successful simulated assimilation run is compared with real observations of vertical total electron content (TEC). These observations are described in section 1.3.

1.2. Thermosphere-Ionosphere-Electrodynamics General Circulation Model

The thermosphere-ionosphere-electrodynamics general circulation model (TIEGCM) is a coupled model of the thermosphere-ionosphere system by Richmond et al. [1992]. TIEGCM is used in this experiment because it contains the physics necessary to represent the interactions and temporal development of the thermosphere-ionosphere system and because it has been validated and approved for public release. The model has been extended upward to include the magnetosphere in the MTIEGCM and downward to include the mesosphere in the TIMEGCM. These extended versions of the National Center for Atmospheric Research (NCAR) General Circulation Model have not yet been approved for public release. TIEGCM is the first in the line of National Center for Atmospheric Research (NCAR) general circulation models to include a calculation of electric fields and currents from the dynamo effects of the thermospheric winds. These fields and currents are included in the calculations of neutral and plasma dynamics. The original three-dimensional thermospheric general circulation model (TGCM) is described by Dickinson et al. [1981]. TGCM had the same 5° grid that is used by TIEGCM, but TIEGCM has been extended to use 39 constant pressure surface layers as opposed to the 24 levels in the original model. The thermosphere is principally driven by heating caused by the absorption of solar EUV and UV radiation, characterized in the model by the $F_{10.7}$ solar index, as well as by auroral heating. TIEGCM also takes in forcing from the geomagnetic $K_p$ index and lower boundary processes, such as tides. Roble et al. [1988] coupled an ionospheric model to TGCM in order to create the thermosphere-ionosphere general circulation model (TIGCM). TIGCM includes a self-consistent description of the thermosphere-ionosphere system. The model calculates global distributions of O, O$_2$, N$_2$, NO, N($^2$D), N($^2$S), O$^+$, NO$^+$, O$_3^-$, N$_2^+$, N$^+$, electron density, and ion temperature as well as neutral winds, temperature, and major composition. The thermosphere and ionosphere are mutually coupled at every time step. Electron density is calculated as the sum of the ion densities, so any changes made to the electron density model fields are lost almost immediately. Other three-dimensional coupled thermosphere-ionosphere models are available, including the Coupled Thermosphere Ionosphere Plasmasphere with electrodynamics (CTIPe) by Fuller-Rowell et al. [2002] and the global ionosphere-thermosphere model (GITM) by Ridley et al. [2006]. Incidentally, CTIPe and GITM both use the same electrodynamic formulation as TIEGCM.

1.3. Vertical TEC Measurements

In order to gauge the potential of a real assimilation scheme using TIEGCM, the simulated assimilation results are compared with real observations of the ionosphere. The important vertical total electron content (TEC) parameter is used here. Vertical TEC is the sum of the free electrons in a vertical column. This is calculated from GPS observations and stored in Global Ionospheric Maps (GIMs), the production of which is described by Rideout and Coster [2006]. Vertical TEC could equally be extracted from tomographic images of electron density based on GPS observations of slant TEC. Examples of such techniques include MIDAS by Mitchell and Spencer [2003], IDA by Bust et al. [2000, 2004], Global Assimilation of Ionospheric Measurements (GAIM) developed by Schunk et al. [2004] at Utah State University, the Global Assimilative Ionospheric Model developed by the Jet Propulsion Laboratory and the University of Southern California [Mandrake et al., 2005], a technique by Hernandez-Pajares et al. [1998], and a data assimilation approach by Yue et al. [2012].

1.4. The Storm of Halloween 2003

Between 29 October and 1 November 2003, a severe solar storm occurred that included periods of elevated geomagnetic activity caused by two coronal mass ejections (CMEs). Solar and geomagnetic indices measured during this period, as well as a more typical control period, are used to drive TIEGCM in this study. Dramatic effects caused by this storm were observed in various aspects of the thermosphere-ionosphere system. Sutton et al. [2005] found that density observations from the Challenging Minisatellite Payload (CHAMP) exhibited enhancements of 200–300% at altitudes of around 410 km during periods of maximum geomagnetic activity. In addition, the authors showed that the accuracy of an empirical model, the Horizontal Wind Model 1993 (HWM-93), was compromised at low latitudes in disturbed conditions. HWM-93 overestimated the daytime westward wind intensification during severely disturbed conditions but underestimated westward wind speeds under moderately disturbed conditions. Immel et al. [2008] studied the same storm using a combination of CHAMP and Far Ultraviolet Spectrographic Imager observations. The authors attributed the large temperature and density changes observed by CHAMP at around 400 km to traveling atmospheric
disturbances as well as to the direct effects of Joule heating. These large temperature and density changes were caused by impulsive auroral inputs as well as downwelling in the global thermospheric storm time circulation. Richmond and Lu [2000] explained that storm time heating causes a polar upwelling that results in equatorward flow in both hemispheres (winter and summer). This equatorward flow results in downwelling at midlatitudes, which moves the air into regions of increasing pressure and therefore results in compressional heating. The result is that auroral heating is spread to all latitudes, leading to an expansion of the thermosphere that causes large increases in neutral density at high altitudes.

[8] The effects of the Halloween 2003 storm on TEC in the American longitude sector are difficult to model due to two potentially competing effects. Heelis et al. [2009] showed that the expansion of a high-latitude electric field to midlatitudes could potentially result in a dayside TEC enhancement of up to 300 total electron content units, 1 TECU = 10^16 el m^-2 (TECU). However, Sojka et al. [2012] showed that storm time thermospheric winds had a potentially equally large effect as the electric field changes. Those authors suggested both mechanisms could result in a 10–20% change in TEC, and that the neutral winds could either reinforce or counteract the effects of the electric field enhancement. The storm of Halloween 2003 makes an ideal case study for this simulation experiment because it exhibits extreme external drivers and because it is recent enough to have been well observed.

2. Method

[9] The overall aim is to determine whether a data assimilation scheme can produce accurate ionospheric forecasts in the absence of good external driver estimates. In order to establish this, several experiments are performed. Each of these experiments follows the same general concept. First, TIEGCM is run for a storm period in order to create a truth against which to compare forecasts. Then, a geomagnetically quieter period, referred to here as “typical”, is selected from a few days before the storm. The storm run is repeated, but at a given point, the model is switched over to use the drivers from the typical period. By comparing the results of this hybrid run with the truth run, we can establish the forecast accuracy that could be achieved with a perfect assimilation update and a perfect model using incorrect drivers. This generic procedure is shown in Figure 1.

[10] In the procedure described above, the drivers from the typical period are used to represent the drivers that could have been forecast for the storm—the values are underestimated compared with the real storm values—but they are typical of the period during which the storm occurs. The procedure simulates a perfect assimilation scheme because the forecast model’s initial state is identical to the initial truth state. The procedure also simulates the use of a perfect model because the same model is used for both runs.

[11] There may not be sufficient observations to constrain the whole system, so a data assimilation scheme might have to specify only some of the model fields. It would be useful to identify which groups of model fields have the greatest effect on forecast accuracy so that future observation campaigns can be directed toward measuring those fields. The effects of changing different groups of model fields on forecast accuracy can be tested by combining some fields from the truth run with other fields from the typical period in order to create a hybrid model state. This presents a greater risk than replacing the full set of fields because the resulting hybrid state might be unstable. However, we found no evidence of such instabilities in our experimental results. In this paper, different groups of model fields in the typical period run will be replaced with fields from the storm time run. The hybrid run is then continued under the influence of the typical drivers. This is done in order to determine which model fields are most important to the progression of the model state over time. An assimilation scheme could then focus on specifying the important fields more accurately in order to improve forecasts. In addition, these experiments should establish the maximum forecast accuracy that is achievable with underestimated drivers.

[12] The experiment described in section 3.1 determines whether the initial thermospheric or ionospheric model fields are more important to plasma density forecasts, using the storm of Halloween 2003 as a case study. The model is run for 29 and 30 October to cover the storm and for 15 and 16 October to represent a typical period. This typical period run is then repeated 3 times. Each time, some model fields are replaced with fields from the storm time run at 6 A.M. on 15 October to represent a typical period.

Table 1. Model Fields Replaced in Sections 3.1 and 3.2a

<table>
<thead>
<tr>
<th>Run type</th>
<th>Replacement Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Ionosphere</td>
<td>Ne, O, O_2^+, Ti, Te</td>
</tr>
<tr>
<td>(b) Thermosphere</td>
<td>Tn, Un, Vn, O, O_2, NO, N(S), N(D)</td>
</tr>
<tr>
<td>(c) Full state</td>
<td>Ne, O, O_2^+, Ti, Te, Tn, Vn, Un, O_2, NO, N(S), N(D)</td>
</tr>
<tr>
<td>(u) Typical period (unchanged)</td>
<td>none</td>
</tr>
</tbody>
</table>

aModel fields replaced in the experiments described in sections 3.1 and 3.2. The first two runs are intended to determine whether ionospheric or thermospheric initial conditions are more important to the forecast plasma density. The third run is included to control for synergistic coupling effects and to establish an upper limit for the effectiveness of full data assimilation. The final run is included to establish a lower limit for forecast accuracy. Where applicable, the fields include the previous time step version of the listed variables.
October. The different groups of fields replaced are listed in Table 1 and identified as (a), ionospheric fields; (b), thermospheric fields; and (c), all fields. After the replacement step, each model run is continued using the typical day drivers.

[13] The experiment described in section 3.2 validates the results shown in section 3.1 by repeating that experiment with the storm of 20 and 21 November 2003. Once again, the replacement fields are identified in Table 1. This time, the typical period is 16–17 November 2003.

[14] The experiment described in section 3.3 determines which of the thermospheric fields (neutral winds, neutral temperature, and neutral composition) is most important to plasma density forecasts, once again using the storm of Halloween 2003. The procedure of section 3.1 is repeated using different groups of replacement fields. These are listed in Table 2 and identified as (d), neutral winds; (e), neutral temperature; (f), neutral composition; and (g), full thermosphere.

[15] The $K_p$ values observed on 15 and 29 October 2003 are shown in Figure 2 in order to illustrate why 15 October 2003 was chosen as a typical day and 29 October 2003 was chosen as a storm time case. The 15th had moderate solar and geomagnetic activity for that period, whereas the 29th had some of the highest driver values of the Halloween 2003 storm. $F_{10.7}$ was 275 on the storm day and 95 on the typical day. This is a very large difference as $F_{10.7}$ generally varies between about 70 and 300. $K_p$ values started off similar on both days, but storm values hit the maximum possible value of 9 at 06:00 UT. For that reason, the replaced-field runs were started at 06:00 UT. This way, $K_p$ was consistently much higher in the storm time run throughout the test period.

3. Results

3.1. Model Runs With Replaced Fields

[16] This experiment is designed to measure the effects of changes to the initial ionospheric and thermospheric model fields on electron density forecast accuracy. Three groups of replacement fields are chosen: one to represent ionospheric assimilation, one to represent thermospheric assimilation, and one to represent full state (ionosphere plus thermosphere) assimilation. The model fields that were replaced are described in Table 1.

[17] The global RMS electron density error of the replaced model field runs is shown in Figure 3. The truth here is the 29–30 October 2003 storm run and the typical period is the 15–16 October 2003. Predictably, each modified run underestimates the storm time electron densities because the typical period external drivers are not able to sustain the production rates necessary to match the storm conditions. From this graph, it can be seen that each replaced-field model run heads back toward the typical day state. However, changes to the ionosphere and thermosphere initially improve the forecasts.

[18] Changes to the ionosphere (a) initially had more impact than changes to the thermosphere (b), but 90% of the electron density forecast improvement of run (a) was lost through recombination after 3 h and 30 min. In other words, run (a) relaxed back to within 10% of the typical day run, (u), by 09:30 UT. The ionosphere’s nightly return to low levels of ionization explains why any changes are normally wiped out within this time frame. One mechanism for ionospheric changes to persist longer than 12 h would be for the changes to feed into the thermosphere and then back to the ionosphere. It appears that this feedback effect did not occur here, even with a very strong update. The changes to the thermosphere, shown in (b), resulted in a persistent improvement in agreement with the storm time run that lasted for most of the test period. The thermospheric run, (b), returned to within 10% of the typical period run, (u), after 18 h and 30 min. This is not surprising since the thermosphere is less strongly driven than the ionosphere (especially if we consider the thermosphere as one of the ionospheric drivers and vice versa). It is natural that the initial values of the system will continue to affect its behavior for much longer, and that thermospheric changes will feed into improved ionospheric specification. The ionospheric change, (a), only produced better agreement than the thermospheric change, (b), at the first time step, before the thermospheric change had any chance to affect the ionosphere. As a side note, the improvement in forecast accuracy of the run starting with all storm time fields shown in (c), was generally about equal to the sum of the improvements from (a) and (b). This shows that the model was not unbalanced by starting from artificial hybrid states such as (a) and (b), and that any coupling effects were of secondary importance. The full-state run, (c), also returned to within 10% of the typical period run after 18 h and 30 min.

[19] The run using the full storm time initial conditions with drivers from the typical day, (c), produced the best fore-

**Table 2. Model Fields Replaced in Section 3.3a**

<table>
<thead>
<tr>
<th>Run type</th>
<th>Replacement Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d) Neutral winds</td>
<td>Un, Vn</td>
</tr>
<tr>
<td>(e) Neutral temperature</td>
<td>Tn</td>
</tr>
<tr>
<td>(f) Neutral composition</td>
<td>O, O₂, NO, N(4S), N(2D)</td>
</tr>
<tr>
<td>(g) Full thermosphere</td>
<td>Tn, Vn, Un, O, O₂, NO, N(4S), N(2D)</td>
</tr>
<tr>
<td>(u) Typical period (unchanged)</td>
<td>none</td>
</tr>
</tbody>
</table>

*aModel fields replaced in the experiments described in section 3.3. These runs are intended to determine which aspect of the thermospheric initial conditions is most important to the forecast plasma density. The full thermosphere run controls for synergistic effects. The typical period run is included to establish a lower limit for forecast accuracy. Where applicable, the fields include the previous-time step version of the listed variables.

![Figure 2.](chart.png) The $K_p$ on the storm day (29 October 2003) in orange and on the typical day (15 October 2003) in green.
cast of the storm. This shows that accurate specification of initial thermosphere-ionosphere conditions is an important part of the forecasting process. Even without accurate driver specification, data assimilation has the potential to improve forecasts for over 18 h. In practice, plasma density is the only well-observed model field in the system, so it might be impossible to specify the other model fields accurately. However, Matsuo and Araujo-Pradere [2011] demonstrated, using an ensemble Kalman filter Observation System Simulation Experiment, that inclusion of thermospheric variables in the assimilation state vector reduced electron density forecast error. The experiment assimilated simulated observations of electron density, so all changes to the thermosphere depended on the cross covariances calculated from the ensemble spread. A successful assimilation scheme will need to use correlations between plasma density and other fields to specify the important parts of the system. From these results, it appears that thermospheric model fields should not be omitted from an assimilation scheme if the intention is to forecast for more than a few hours. The experiment in section 3.3 will determine which of the thermospheric model fields is most important to the storm time ionospheric electron density forecast. In the following section, the results shown in this section will be validated by repeating the above experiment with a different storm.

[20] If there are no instabilities or coupling effects caused by the creation of a hybrid thermosphere-ionosphere system, the combined effects of the ionospheric and thermospheric replacement runs on the ionospheric plasma density forecast accuracy should match the effects of replacing the full state. In this case, the combined forecast accuracy improvement from the ionospheric and thermospheric replacement runs matched the forecast accuracy improvement of the full state replacement to within 20% of the full state improvement at all times and to a mean of 2.5% over the test period. These results show that, while there are some coupling effects, those effects generally do not have a significant effect on the forecast accuracy of different runs.

![Figure 3](image1.png)

**Figure 3.** The global RMS electron density difference of four runs with the truth model run starting on 29 October 2003. Each of these runs used the drivers from 15 October 2003 but had some model fields replaced with ones from 29 October 2003. In light blue is the typical period model run, (u), starting on 15 October 2003 (with no storm time fields), in red is the replaced ionosphere run (a), in dark blue is the replaced thermosphere run (b), and in green is the replaced full state (ionosphere + thermosphere) run (c).

![Figure 4](image2.png)

**Figure 4.** The global RMS electron density difference of four runs with the truth model run starting on 20 November 2003. Each of these runs used the drivers from 16 November 2003 but had some model fields replaced with ones from 20 November 2003. In light blue is typical period model run, (u), starting on 16 November 2003 (with no storm time fields), in red is the replaced ionosphere run (a), in dark blue is the replaced thermosphere run (b), and in green is the replaced full state (ionosphere + thermosphere) run (c).
3.2. Validation of Halloween Storm Results

Although the results of the experiment described in section 3.1 appear to be consistent with theory, it could be that unidentified physical processes have conspired to produce a seemingly reasonable set of results. The storm of Halloween 2003 did see a double coronal mass ejection (CME) that is not common in solar storms. In this section, the experiment from section 3.1 is repeated using the storm of 20 November 2003. Although this storm was not as spectacular as that of Halloween 2003, \( Kp \) still reached 9 at 1500 UT and 1800 UT while \( F10.7 \) was 171 that day. A typical day was identified as 16 November 2003. This day was used for comparison with the storm time results. Once again, runs were started at 0600 UT to 0600 UT the next day so as to simulate an assimilation just before the spike in geomagnetic activity. This typical period had \( Kp \) between 4 and 5 and \( F10.7 \) at 102.

The results shown in Figure 4 support the conclusions drawn in section 3.1. Once again, the run starting with all storm time fields, (c), has the lowest error, while the run with replaced thermospheric fields (b) performs much better than the run with replaced ionospheric fields (a) for the same period. The run with replaced ionospheric fields, (a), relaxes back to within 10% of the typical period run, (u), within 4 h. The run with replaced thermospheric fields, (b), relaxes back to within 10% of the typical period run, (u), within 15 h and 30 min, while the replaced full state run, (c), takes 16 h. This provides an upper bound on the potential benefits of thermosphere-ionosphere assimilation for forecasting. The relaxation times are somewhat shorter than in section 3.1 because the storm chosen for study in this section is less intense.

3.3. Model Runs With Replaced Thermospheric Fields

While the accurate initial specification of all model fields is clearly desirable in terms of forecasting, in reality, some compromises have to be made. Direct observation of all variables to the extent that would be required to specify the full thermosphere-ionosphere state would be prohibitively expensive. By identifying those variables most important to ionospheric forecasting, it will be possible to target future observation campaigns toward specifying the most valuable model fields. Groups involved in the development of space- and ground-based instruments may wish to target their efforts accordingly. In addition, known relationships with other, better observed variables may be used to update the most important model fields. This will be most effective if just the important variables are included in the assimilation state vector.

In order to determine which thermospheric fields are most important to the ionospheric electron density specification, each different thermospheric field is replaced in separate runs. With reference to Table 2, the different thermospheric fields to be replaced are the neutral winds, (d), the neutral temperature, (e), (both zonal and meridional) and the neutral composition, (f). The run with all thermospheric fields replaced (g) shows the combined effect of making all the changes in runs (d), (e), and (f), while the model run for 15 October 2003 with no fields replaced, (u), is included as a baseline that shows the forecast quality to be expected with poorly specified initial conditions and external drivers.

The results in Figure 5 show that neutral composition is by far the most important model field to specify accurately if the intention is to improve ionospheric electron density forecasts. In fact, the run with the storm time neutral composition field (f) outperforms the run with the full set of thermospheric fields (g) for a brief period during the first 3 h. The storm time neutral composition run, (f), takes 19 h and 30 min to return to within 10% of the typical period run, (u). This is an hour longer than the full thermosphere run, (g). The other runs—replaced neutral winds (d) and temperatures (e)—have a negligible impact, with both runs underperforming the run with no replaced fields, (u), at times. Neutral composition affects ionization and recombination rates, so it follows that modifications to this model field should result in improved electron density forecasts. It is worth considering the various constituents that make up neutral composition, all of which are listed in Table 2. Of these, the ratio of O and N\(_2\) is likely to have the most important effect on storm time ionospheric plasma densities. This is discussed in more detail in section 4.
3.4. Comparison With Real GPS Observations of Storm Time TEC

[26] The results described above show that a well-specified initial assimilation update could result in model forecast improvement compared with the model run that uses the correct drivers and initial conditions, which is taken to be correct. This section is intended to test the model’s performance against real data, in order to establish how accurately the model can perform under optimal conditions. Once again, the Halloween 2003 storm is used as the test period with typical drivers coming from 15–16 October 2003. The storm time model run, used as the truth against which to compare the runs in Figure 6, is compared with globally distributed vertical TEC observations from GIMs. Results of the run with replaced thermospheric composition, (f), are included to show what forecast improvements could be achieved if thermospheric composition was defined more accurately. The typical period run, (u), is also included to show how much difference the replacement of the thermospheric composition has made.

[27] The results in Figure 6 show that, over the selected period, the model performed best when provided with the correct initial conditions and external drivers. Starting with the correct neutral composition but the other initial conditions and the drivers from the typical day, as in run (f), the model was several TECU more accurate than the typical day run in reproducing observed TEC. Somewhat surprisingly, this improvement persisted for the whole 24 h period. The results show that the model is inaccurate even with the correct drivers and initial conditions, but changes to the initial conditions can produce long-lasting forecast improvements.

4. Discussion and Conclusions

[28] The results show that thermosphere-ionosphere data assimilation could produce significant improvement to forecasts of ionospheric electron density and TEC under optimal conditions. This is supported by the results shown in Figures 3 and 4, where a full thermosphere-ionosphere assimilation improved forecast accuracy by at least 10% for 18.5 h and 16 h, respectively. In situations with both an accurate model and a good update of the full model state but without good external driver forecasts, assimilation can produce up to a 50% improvement in agreement with the “true” state compared to a model run without the update or the correct drivers. However, ionosphere-only updates, such as are shown in run (a) in Figures 3 and 4, give less than 10% improvement after 4 h. These results support the findings of Jee et al. [2007], who showed that an ionospheric update of the Thermosphere-Ionosphere Nested Grid with values from the Global Assimilation of Ionospheric Measurements (GAIM) scheme resulted in an e-folding time of about 2–3 h under most conditions. The difference between the electron densities in the assimilation and control runs reduced by a factor of e in that time. The authors expected to find a different result if they had included an update of thermospheric fields in addition to the ionospheric update.

[29] The results in Figure 6 show that the storm time truth run reproduces the observed TEC most accurately during the Halloween 2003 storm. This is to be expected as that run uses all the correct initial model fields and the correct external drivers. However, run (f), which uses the initial storm time neutral composition but all other model fields and external drivers from the typical period run, is almost as good for the first 6 h. This is interesting as it suggests that accurate specification of the neutral composition may compete with the accuracy of external driver specification for short term plasma density forecasting. It is important to note that this situation is reversed after 6 h. Given that forecasts of external drivers may not be available or accurate in a storm time forecasting situation, assimilation of the most important model fields could be the most viable way to improve forecasts. None of the runs shown in Figure 6 were especially accurate, which shows that modeling improvements are also essential for accurate forecasts. The current crude driver specification is also a source of error—it should be possible to improve accuracy by using more informative measurements than $Kp$ and $F10.7$. For example, the full observed spectrum of solar flux could be used directly, rather than relying on a daily average spectrum generated solely from observations of 10.7 cm flux.
A data assimilation scheme would have the advantage of influencing the model with real observations, so it should be possible to get more accurate results than those shown here.

[30] This study addresses the issue of forecasting storm time ionospheric plasma densities with only the information available at the beginning of the storm. Quite different results might be expected if the exercise was repeated from the middle of the storm—it is likely that external driver forecasts for the remainder of the storm would be more accurate at that point, for example. The forecast time used in this paper was chosen to be close to the beginning of the storm. This time was chosen because it is more important to forecast a storm before it happens than it is to forecast the after effects of a storm whose major effects have already been observed. However, the authors acknowledge that there are applications for which a variety of forecasting scenarios are relevant. These situations could be explored in future studies.

[31] Systematic biases in the model may be overcome with an assimilation scheme. An ensemble Kalman filter approach to data assimilation allows for the tuning of certain parameters to correct model biases on an ongoing basis. These could be parameters such as the Burnside factor or the ion-neutral collision cross sections. Once identified, these parameters can be included in the state vector and updated at each assimilation step. A future study should identify those parameters that are important to the evolution of forecasts and are poorly specified. The presence of observations across the globe is required to prevent the scheme from tuning the entire model state to correct a local bias. The bias does not need to be permanent because the variable can be continually updated, but the bias must be long lasting enough to be observed at the assimilation update time and still be in effect for the duration of the forecast.

[32] The results in Figure 5 show that the neutral composition is the most important thermospheric field to update in order to improve plasma density forecasts. The ratio of O to N$_2$ is recognized to be an important component of storm time neutral composition, since Rishbeth and Mueller-Wodarg [1999] showed that the O to N$_2$ ratio is altered by high-latitude energy inputs and affects peak plasma densities, $N_mF_2$. This raises the question of how to specify the ratio of O to N$_2$ accurately. The most straightforward approach would be to assimilate observations directly—for example, with measurements from the Special Sensor Ultraviolet Spectrographic Imager [Paxton et al., 1992]—but this approach is limited by data availability. Alternatively, it might be that changes to the model’s neutral composition could be achieved indirectly by repeated assimilation of other model fields such as neutral temperature. Once again, this approach is limited by data availability, but the approach may also suffer from an additional problem—changes to other model fields are likely to take longer to feed into thermospheric composition changes than direct observations of the thermospheric composition. A third potential approach is to make use of known correlations between model fields. This would mean using observations of electron density and other well-observed parameters to adjust the neutral composition. Further work should investigate whether it is possible to improve estimates of thermospheric composition by using observations of other fields.

[33] The results in Figure 6 show that the model run with correct external drivers and initial conditions has significant inaccuracies, with RMS errors between 8.6 and 27.5 TECU during the test period. These errors would be best dealt with by improvements to the model itself, although accuracy could also be improved by characterizing the important drivers in a more complete and detailed manner. For example, direct observations of the full spectrum of solar flux could be used instead of assuming a standard spectrum based on the observed $F_{10.7}$ values. There are ongoing efforts to improve TIEGCM, notably the extension down to the mesosphere in TIMEGCM and up to the magnetosphere in the MTIEGCM, but it must be recognized that accurate modeling of the thermosphere-ionosphere system remains a significant challenge. It should be possible to reduce the model’s random errors and systematic biases in short term forecasts by using data assimilation. The results presented here show that a model run with one set of drivers can be made to behave more like a model run with another set of external drivers for over 12 h by making changes to the initial conditions. Future work should investigate whether a model that assimilates real ionospheric observations can produce improved plasma density forecasts.

[34] In summary, the results show that thermospheric data assimilation could provide plasma density forecast improvements of at least 10% for over 18 h, provided that it is possible to specify the neutral composition accurately. However, 90% of the effects of ionospheric data assimilation are lost within 4 h.

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