The Influence of Internal Atmospheric Variability on the Ionosphere Response to a Geomagnetic Storm

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Abstract The Whole Atmosphere Community Climate Model eXtended is used to investigate the extent to which neglecting the realistic day-to-day lower atmospheric variability introduces uncertainty in the ionosphere response to an idealized geomagnetic storm. A 10-member ensemble is generated by adding small temperature perturbations in the lower atmosphere 30 days prior to the imposed geomagnetic storm. Chaotic divergence, and internal atmospheric variability, lead to the geomagnetic storm occurring under an arbitrarily different, though climatically similar, atmospheric state for each ensemble member. The intra-ensemble variability, which we characterize by the ensemble standard deviation, of the day-to-day change in total electron content is generally ∼10%–20% during geomagnetically quiet time. During an idealized storm with a $K_p$ of 7 the ensemble standard deviation of the change in total electron content increases to ∼20%–40% at low and middle latitudes, with localized regions exceeding 100%. Examination of individual ensemble members illustrates that they all capture the same large-scale features of the storm time changes in the ionosphere but can exhibit notable (50%) differences regionally, especially during later stages of the storm. The results thus demonstrate that in order to accurately capture smaller-scale features of the upper atmosphere response to geomagnetic storms, it is necessary to include the effects of lower atmosphere variability.

Plain Language Summary Geomagnetic storms are an important driver of variability in Earth’s ionosphere and can have significant societal impacts through the ionosphere’s impact on communications and navigation systems (e.g., Global Positioning System). Numerical simulations are a common tool for the specification and forecasting of the ionosphere variability driven by geomagnetic storms. Simulations have historically only used a climatological spectrum of waves propagating upward from the lower atmosphere (i.e., troposphere, stratosphere, and mesosphere; 0–100 km). This neglect of the day-to-day variability of wave forcing from the lower atmosphere is a potential source of uncertainty when simulating the ionosphere variability during geomagnetic storms. The present study uses a whole atmosphere model, extending from the surface to ~500 km, to understand the uncertainty in the ionosphere response to a geomagnetic storm that is due to the day-to-day variability of the lower atmosphere. It is found that omitting lower atmosphere variability leads to an uncertainty in the ionosphere response to a geomagnetic storm that is typically ~20%–40% but can be as large as 100% regionally. Incorporating the day-to-day variability of the lower atmosphere is thus an important factor for reducing the uncertainty in numerical models that are used to specify and forecast the near-Earth space environment.

1. Introduction

The day-to-day variability in the Earth’s ionosphere is driven by the combined influence of forcing from solar processes, as well as the internal atmospheric variability propagating upward from the lower atmosphere. The influence of the Sun, in particular, geomagnetic storms, on generating ionospheric variability has long been recognized and is extensively studied (Buonsanto, 1999; Mendillo, 2006; Prölls, 1995). The lower atmosphere has gained increased recognition in terms of its contribution to the day-to-day variability of the ionosphere (Laštovička, 2006; Liu, 2016). Forbes et al. (2000) and Mendillo et al. (2002) estimated that lower atmospheric weather is comparable in importance to geomagnetic activity for generating day-to-day ionospheric variability. Furthermore, the variability driven by the lower atmosphere during periods of strong lower atmosphere variability...
forcing, such as sudden stratospheric warming (SSW) events, can reach magnitudes similar to those that occur during moderate geomagnetic storms (Goncharenko et al., 2010).

Despite the aforementioned importance for generating ionospheric variability, the effects of the lower atmosphere are typically neglected in numerical simulations, and observational analyses, of the ionosphere-thermosphere response to geomagnetic storms. This is largely due to the fact that the changes in the ionosphere-thermosphere due to geomagnetic storms, which can exceed 100% even during moderate storms, are thought to negate any influence of the lower atmosphere. However, the lower atmosphere forcing influences the background, or initial conditions, upon which any geomagnetic storm occurs. Given that the background ionosphere-thermosphere state is known to influence the response to geomagnetic storms occurring in different seasons (Fuller-Rowell et al., 1996; Wenn et al., 1987), one may hypothesize that lower atmosphere forcing can serve to precondition the state of the ionosphere-thermosphere, in-turn influencing the response to geomagnetic storms. The potential importance of the lower atmosphere on the ionosphere response to a geomagnetic superstorm was investigated by Pedatella (2016). They found that strong lower atmosphere forcing can play a role in modulating the storm time ionospheric disturbance. Although Pedatella (2016) established that the lower atmosphere can influence the ionosphere response to a geomagnetic superstorm, they focused on the influence of an extreme SSW event. Any influence of the lower atmosphere on the ionosphere-thermosphere response to a geomagnetic storm during more typical atmospheric conditions remains poorly understood.

The present study investigates how the internal, quasi-random, chaotic variability of the atmosphere can influence the response of the ionosphere to a geomagnetic storm. This is done by performing an ensemble of geomagnetic storm simulations under different lower atmospheric conditions in the National Center for Atmospheric Research Whole Atmosphere Community Climate Model eXtended (WACCM-X). The simulations serve to illustrate the importance of the internally generated lower atmosphere variability on the response to an idealized geomagnetic storm and quantify the potential uncertainty in simulations that neglect lower atmospheric effects.

2. Whole Atmosphere Community Climate Model eXtended

The simulations performed in the present study use WACCM-X version 2.0 (Liu et al., 2018), which is part of the National Center for Atmospheric Research Community Earth System Model. WACCM-X extends from the surface to the upper thermosphere (4.1 × 10⁻¹⁰ hPa, ~500–700 km). The model horizontal resolution is 1.9° in latitude and 2.5° in longitude, and the vertical resolution is 0.25 scale heights in the upper atmosphere. The chemical, dynamical, and physical processes in the troposphere, stratosphere, and mesosphere are based on the Whole Atmosphere Community Climate Model (WACCM) version 4 (Marsh et al., 2013), which itself is based on the Community Atmosphere Model version 4 (Neale et al., 2013). As discussed in Liu et al. (2018), WACCM-X version 2.0 incorporates additional thermosphere and ionosphere processes in order to model the upper atmosphere. The most notable changes are ionosphere transport of O⁺, self-consistent electrodynamics, and accounting for variable mean molecular mass and specific heat in the thermosphere. The reader is referred to Liu et al. (2018) for a detailed description of WACCM-X version 2.0. The effects of geomagnetic activity are incorporated in WACCM-X by imposing the Heelis empirical convection pattern (Heelis et al., 1982), which is based on the geomagnetic $K_p$ index, at high latitudes.

In the present study we perform an ensemble of WACCM-X simulations of an idealized geomagnetic storm with arbitrary atmospheric initial conditions. A 10-member ensemble is initialized on 1 October, and each ensemble member is initialized with slightly different random temperature perturbations. Owing to internal atmospheric dynamics (i.e., chaotic divergence), the ensemble members diverge over the subsequent ~20 days. The imposed geomagnetic storm occurs on 30 October and thus occurs during arbitrarily different atmospheric states in each ensemble member. We note that although the atmospheric states among the ensemble members are largely random, the seasonality of the ensemble members is the same, so the large-scale structures of the atmospheric are similar among all of the ensemble members. The imposed geomagnetic storm is idealized and corresponds to a step function in the geomagnetic $K_p$ index from 1⁺ to 7 on 30–31 October, before returning to 1⁺ (Figure 1). The F10.7 cm solar flux is held at a constant 100 solar flux units.
3. Simulation Results

The initial divergence among the ensemble members is evident in Figure 1, which shows the equatorial (±30° geographic) average total electron content (TEC) for the individual ensemble members (black lines) and the ensemble mean (red line). The results in Figure 1 illustrate that, although the ensemble members initially are all very similar, there are clear differences among the ensemble members after ∼20 days. As the external geomagnetic and solar forcing is identical for each ensemble member, the intra-ensemble variability can be attributed to internal atmosphere variability and is likely driven by differences in the lower atmosphere forcing of the ionosphere-thermosphere. Immediately prior to the geomagnetic storm, the maximum-to-minimum spread among the ensemble members is ∼0.5–1.0 TEC unit, or 5%–10%. We note that this is the spread in terms of the equatorial average, and thus, larger differences between ensemble members occur regionally. Although there is an apparent significant decrease in the ensemble spread in the initial ∼6–12 hr after the increase in $K_p$, the ensemble standard deviation (not shown) is only slightly reduced with respect to the diurnal and day-to-day variability that occurs prior to the storm. It is, however, clear that the variability among the ensemble members is more coherent than that prior to the storm. During later stages of the storm it is evident that the intra-ensemble variability is comparable to levels prior to the storm. This demonstrates that even during periods of strong geomagnetic forcing the internal atmospheric variability is not negligible and still has a considerable influence on the ionospheric variability.

Figure 2 illustrates the ensemble mean and standard deviation of the change in TEC at different universal times (UTs). Note that the change in TEC is calculated separately for each ensemble member by differencing the TEC with the TEC on the previous day at the same UT. The percentages are based on the ensemble mean TEC during the previous day. Figures 2a and 2e illustrate the behavior of the day-to-day variability in TEC during quiet times. During quiet conditions the ensemble mean day-to-day difference in TEC is small.
Figure 2. The ensemble (a–d) mean and (e–h) standard deviation of the change in total electron content (TEC). Results are shown for 29 October at 1200 UT (a and e), 30 October at 0600 UT (b and f), 30 October at 1200 UT (c and g), and 30 October at 1800 UT (d and h). The change in TEC is calculated for each ensemble member by differencing the TEC with the TEC on the prior day at the same UT.

(< \pm 25\%), and the standard deviation, which we use as a measure of the intra-ensemble variability, maximizes at low and middle latitudes with typical values of ~10\%–20\%. During the storm (Figures 2b–2d and 2f–2h), the ensemble mean results show ~50\%–100\% decreases in the low-latitude nighttime ionosphere and large (100\%–150\%) increases at middle latitudes during the daytime. This is consistent with the expected storm time behavior. Interestingly, the ensemble standard deviation increases during the storm, with typical standard deviation values of ~20\%–40\% occurring at low and middle latitudes. There are also localized regions where the ensemble standard deviation reaches 80\%–100\%, indicating locations of significant intra-ensemble variability. These regions tend to occur near dawn and dusk, which suggests that the location of the boundary between daytime enhancements and nighttime depletions is highly uncertain. The increased ensemble variability during the storm is, perhaps, opposite what one may have anticipated to occur, which would be a decrease in the standard deviation due to the strong external driving. We note that the increase
Figure 3. The change in total electron content (TEC) for individual ensemble members on (a–e) 30 October at 1200 UT, and (f–j) 1 November at 1200 UT. The change in TEC is calculated by differencing the TEC with the TEC on 29 October at 1200 UT.

in the ensemble standard deviation during the storm also occurs in absolute TEC and if a different day is used for the background TEC subtraction. This thus appears to be a robust feature especially during the later stages of the storm. The reason for the increase in standard deviation during the storm is presently unknown. However, it may be related to the lower atmosphere introducing small-scale differences in the response to the geomagnetic storm among the ensemble members.

To illustrate how different ensemble members respond to the geomagnetic storm, Figure 3 shows the change in TEC for ensemble members one through five at 1200 UT on 30 October and 1 November. For both times the change in TEC is calculated with respect to 1200 UT on 29 October. The dominant features of the change in TEC are broadly consistent among the ensemble members. However, close examination of Figure 3 reveals regions where the change in TEC can differ by ~25%–50%. For example, at 1200 UT on 30 October, the ensemble members exhibit clear differences around 30°N and 90°E–120°E, as well as the location of the regions
Figure 4. The mean correlation of the change in total electron content (TEC) between ensemble members 2–9 and ensemble member 1. Error bars represent the standard deviation.

of stronger depletions in the Southern Hemisphere middle latitudes between 180°E and 240°E. Differences among the ensemble members are more apparent on 1 November, with large differences in the longitudinal extent of the TEC enhancement at low latitudes in the Northern Hemisphere between 120°E and 240°E clearly evident among the ensemble members. The more notable differences among ensemble members on 1 November may be attributed to the evolution of the atmospheric conditions during the 3 days from 29 October to 1 November, or, alternatively, different storm phases may be more sensitive to lower atmospheric variability.

To better quantify the similarity among ensemble members, Figure 4 shows the global correlation of the change in TEC between ensemble members 2–9 and ensemble member 1. The results in Figure 4 are based on calculating the correlation coefficient of the change in TEC at every latitude-longitude grid point between two ensemble members, one of which is ensemble member 1. A high correlation indicates consistency among all ensemble members, while a low correlation indicates that the ensemble members are essentially randomly distributed. Note that in Figure 4 the change in TEC is calculated with respect to the previous day until 30 October when the change is calculated with respect to 29 October for the remaining days. In the days prior to the 30 October storm, the correlation coefficient is small, indicating that the internal atmospheric variability generates day-to-day ionospheric variability that is not coherent among the ensemble members. High correlation (0.9–0.95) among ensemble members is present on 30–31 October. This is consistent with the ensemble members all reproducing similar global-scale features of the storm, with minor differences among ensemble members reflected in the correlation coefficient not being 1.0. As the ionosphere-thermosphere recovers from the storm on 1–2 November (days 32–33), the correlation coefficient decreases considerably. The decrease in correlation is again thought to be due to the more significant changes in lower atmosphere forcing over the 3–4 days from before to after the geomagnetic storm, or, perhaps due to a greater sensitivity to lower atmospheric forcing during the recovery phase. Nonetheless, this again highlights the fact that significant uncertainty can arise if lower atmospheric conditions are not appropriately accounted for in numerical simulations as well as the interpretation of observations.

4. Discussion

Together, Figures 2 and 3 provide insight into the potential implications of neglecting lower atmospheric variability in simulations of geomagnetic storms in the upper atmosphere. The ensemble standard deviations in Figure 2 suggest that the potential uncertainty in simulations due to inaccurate specification of lower atmospheric forcing is 20%–40%, though could be significantly higher in certain regions. The uncertainty is most pronounced for simulating smaller scales. As shown in Figure 3, the large-scale features of the ionosphere response to a geomagnetic storm appear to be largely insensitive to lower atmospheric conditions. Simulations attempting to capture regional-scale features of the ionosphere-thermosphere should thus appropriately account for the day-to-day lower atmospheric variability. It should be noted that this is true for the lower atmospheric conditions considered in the present study, and large lower atmospheric disturbances, such as SSWs, can have a more appreciable impact on the large-scale response (Pedatella, 2016).

The present study has focused solely on the role of lower atmosphere forcing on producing uncertainty in the ionosphere response to a geomagnetic storm. There is additional uncertainty in simulations due to the specification of high-latitude forcing, especially in terms of the spatial and temporal variability of both large- and small-scale electric fields at high latitudes (Codrescu et al., 2000; Matsuo et al., 2003). The small-scale electric fields, which typically occur on subgrid spatial scales, are especially important in terms of their influence on the ionosphere-thermosphere response to geomagnetic storms (Deng et al., 2009). The extent that uncertainty in high-latitude electric fields is translated into uncertainty in the ionosphere-thermosphere is relatively unknown; however, a recent study by Pedatella et al. (2018) found that the uncertainty in the low-latitude ionosphere due to high-latitude electric field uncertainty is ~20% during quiet times and 30%–40% during storm times with regional enhancements exceeding 100%. Interestingly, these values are not drastically different than the uncertainty due to lower atmosphere forcing found in the present study. This suggests
that the uncertainty due to both lower atmosphere forcing and high-latitude electric fields is comparable in their importance for reducing uncertainty in ionosphere-thermosphere geomagnetic storm simulations. It should be recognized that the uncertainty considered in the present study is for arbitrarily specifying the lower atmosphere forcing conditions, and this uncertainty can be significantly reduced through the use of high-top reanalysis (Hoppel et al., 2008; Pedatella et al., 2014) or appropriately constraining the lower atmosphere in whole atmosphere models (Wang et al., 2014). However, stand-alone ionosphere-thermosphere models with lower boundaries near 100 km typically assume climatological lower atmospheric forcing, and the uncertainty in the present study can be considered as reflective of the uncertainty due to this assumption. In such simulations, the total uncertainty due to the combination of lower atmosphere and high-latitude forcing may thus be rather large, though this will depend on how they interact, which remains unknown. Their interaction is likely to depend on the spatial-temporal scales on which they operate and is thus unlikely to be purely additive. Research into quantifying the total uncertainty in simulations due to these two sources is thus required in order to better understand the uncertainties in geomagnetic storm simulations.

It is important to consider the results of the present study in the context of seasonal variations in the strength of lower atmospheric variability. The influence of the lower atmosphere on the ionosphere-thermosphere response to geomagnetic storms will likely exhibit seasonal variability that is related to how strong the variability is in the lower and middle atmospheres. The time period of the present study does exhibit moderate lower and middle atmosphere variability related to the amplification of planetary waves following September equinox (e.g., Lieberman et al., 2003; Liu et al., 2004). It is, however, less disturbed than Northern Hemisphere winter months, when SSW events drastically alter the lower, middle, and upper atmospheres (Goncharenko et al., 2010; Liu & Roble, 2002). One may therefore consider the results of the present study to be somewhere in the middle of the spectrum of potential lower atmospheric variability. There are thus time periods when the importance of the lower atmosphere on the geomagnetic storm response will be more or less important than the results shown in the present study.

5. Conclusions

This letter reports on the first whole atmosphere simulations of a geomagnetic storm occurring under different atmospheric conditions that arise solely due to the atmosphere’s own internal variability. The results demonstrate that the internal atmospheric variability, which influences the lower atmospheric forcing on the upper atmosphere, can appreciably impact the response of the ionosphere to a geomagnetic storm. Based on an ensemble of simulations, it is found that an arbitrary specification of the lower atmosphere can lead to uncertainties in the simulated change in TEC that are typically 30%–40% at low and middle latitudes, with localized regions exceeding 100%. The lower atmosphere variability is thus an important source of uncertainty in simulations. This is especially the case for simulations that seek to capture the smaller-scale, regional, response of the ionosphere to geomagnetic storms since the effects of the lower atmosphere appear to be more significant on these scales, at least for the moderate levels of lower atmospheric variability considered in the present study. Including the day-to-day atmospheric variability is thus critical for improving the overall accuracy of storm time simulations of the upper atmosphere and may also be an important component of increasing the skill of space weather nowcasts and forecasts.

References


