Rapid recovery of thermosphere density during the October 2003 geomagnetic storms

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Received 30 September 2010; revised 10 November 2010; accepted 5 January 2011; published 5 March 2011.

1 Thermosphere densities from the CHAMP and GRACE satellites are utilized, for the first time, to study the recovery of the thermosphere as a function of latitude during the October 2003 storms. Our results show that the relaxation times, defined by the e-folding time of the poststorm recovery of thermosphere density, are about 6 and 8 h for two recovery phases of the October 2003 superstorms, respectively. Geomagnetic activity index $K_p$ or ring current index $Dst$ is incapable of describing the rapid recovery of thermosphere density. Moreover, a weak altitudinal dependence of the relaxation times was observed between the CHAMP and GRACE altitudes at middle and high latitudes, but no coherent latitudinal dependence was found. The MSISE00 and TIEGCM neutral densities are compared with the observations to assess their capability in predicting the thermosphere response during the recovery phase of extremely severe storms. Neither the MSISE00 nor the TIEGCM reproduced the rapid recovery of thermosphere densities seen in the CHAMP and GRACE, although the TIEGCM captured most of the salient features observed by CHAMP and GRACE when AMIE convection and precipitation patterns were used to specify the high-latitude drivers. The relaxation times of the MSISE00 and TIEGCM nighttime densities at 390 km are generally longer than those from the CHAMP observations by about 4 h, and even longer in the geographic latitudinal range of 25°N–50°N. The TIEGCM recovery times of thermosphere density are shorter on the dayside than on the nightside, whereas the MSISE00 densities show substantially longer relaxation times at low latitudes. Thus, not only are the relaxation times of the MSISE00 and TIEGCM densities longer than observed in the CHAMP and GRACE data, but they also show much larger day-night differences. No clear explanation can be found to fully understand the causes for the slower recovery of the thermosphere density simulated by the TIEGCM.


1. Introduction

The response of neutral temperature, composition and density in the upper thermosphere to geomagnetic activity has widely been studied for a few decades [e.g., Mayer et al., 1978; Prölss, 1980, and references therein]. Most of these studies focused on the thermosphere response to the onset and main phase of geomagnetic storms. However, there has been very little previous work devoted to the poststorm recovery of the thermosphere. Rishbeth [1975] attributed the recovery of the composition variation during the storm to the effects of molecular diffusion. Burns et al. [1989] carried out numerical simulations of the NCAR TIGCM and TGCM during the period of the Equinox Transition Study and found that thermospheric compositional recovery at high geomagnetic latitudes is driven mainly by vertical advection rather than molecular diffusion. Furthermore, they also concluded that high-latitude thermospheric compositional recovery has a time scale of 12 h to 1 day, which is in agreement with the observed time scales for the poststorm recovery of plasma density in the F region.

Besides the compositional recovery, the poststorm neutral temperature has been investigated by Maeda et al. [1989, 1992] on the basis of numerical simulation results from an earlier version of CTIP [Fuller-Rowell and Rees, 1980]. Maeda et al. [1989] demonstrated that enhancements in nitric oxide (NO) cooling rate during the geomagnetic active period dampened the increases of thermosphere temperature and thus shortened the temperature relaxation...
time. Maeda et al. [1992] showed the major cooling mechanism in the upper thermosphere is downward molecular heat conduction, which is an extension of the “thermostat” effect caused by dominant radiative cooling at lower altitudes [Mlynczak et al., 2005]. Meanwhile, they obtained a relaxation time of the temperature in the range from 12 to 15 h at around 350 km, which is comparable to the time scale of thermospheric compositional recovery shown by Burns et al. [1989].

As expected, thermosphere density would have a similar recovery time as that of thermosphere temperature, although Lei et al. [2010] revealed that the changes of mean molecular weight due to wind effects also play a role in the changes of thermosphere density. A large data set of thermosphere density data inferred from satellite orbits [e.g., Bowman et al., 2004; Emmert, 2009, and references therein] have been utilized to investigate the climatology of thermosphere density. However, these inferred density data with a temporal resolution of 1–6 days are not suitable to study the thermosphere variations during the storm recovery phase, given that the recovery phase of a severe storm has a typical duration of less than 1 day. Recently, the CHAMP and GRACE accelerometer measurements have been used to infer thermosphere densities with much higher temporal resolution (~1.5 h) than previous satellite drag data in the upper thermosphere. The CHAMP and GRACE density data have elucidated the thermosphere response to geomagnetic storms in unprecedented detail [e.g., Bruinsma et al., 2006; Forbes et al., 2005; Lei et al., 2010, 2011; Liu and Lühr, 2005; Sutton et al., 2005]. Nevertheless, to our best knowledge there is no observational study of thermosphere density recovery during severe geomagnetic storms.

The main objective of this study is to examine the recovery time scale of thermosphere density during the October 2003 storms, including its altitudinal and latitudinal dependence by utilizing the CHAMP and GRACE observations from pole to pole. Meanwhile, the MSISE00 [Picone et al., 2002] and TIEGCM [Roble et al., 1988; Richmond et al., 1992] neutral densities are compared with the satellite observations. In this way, both the widely used empirical and state-of-the-art theoretical models can be tested and validated to assess their capability in predicting the thermosphere response during the recovery phases of the extremely severe storms.

2. Data Source and Model Description

In this study, we used neutral densities from both CHAMP and GRACE satellites. The CHAMP satellite was launched in July 2000 at 450 km altitude in a near-circular orbit with an inclination of 87.3°. The Spatial Triaxial Accelerometer for Research (STAR) Level 2 observations were processed by the GeoForschungsZentrum Potsdam (GFZ) to remove maneuvers and anomalous spikes and smoothed over 10 s. The accelerometer data have a 0.1 Hz sampling rate, which translates to an in-track resolution of ~80 km. The two identical satellites GRACE-A and GRACE-B were launched in March 2002 at approximately 500 km altitude, in near-circular 89.5° inclination orbits with GRACE-B following approximately 220 km behind GRACE-A. The GRACE accelerometer data have a 1 Hz sampling rate. The mass densities are obtained from CHAMP and GRACE accelerometer measurements using standard methods [Sutton et al., 2007]. Note that only GRACE-A data are used for this study, given that the mass densities from GRACE-A and GRACE-B show very similar variations. The measured densities \( \rho \) at satellite altitudes are normalized to a constant altitude of 390 km for CHAMP and 485 km for GRACE using MSISE00 to minimize the effect of the altitude changes of the satellites during our study period. As discussed later, the MSISE00 densities show large differences with the observations. However, the satellite altitudes deviated insignificantly from their mean altitudes during this study period. Thus, we expect the normalization error to be minimal. See Bruinsma et al. [2006] for a discussion of errors in density normalization.

In addition, the thermosphere densities observed by CHAMP and GRACE are also compared with those predicted from the empirical MSISE00 model and theoretical NCAR TIEGCM model. The inputs for the MSISE00 are the solar flux index F107 and geomagnetic activity index \( A_p \) (the linear scale of \( K_p \)). For the TIEGCM model, the input parameters are (1) solar EUV and UV spectral fluxes from either the TIMED SEE data or the solar flux parameterization of Solomon and Qian [2005]; (2) high-latitude drivers, i.e., auroral particle precipitation and an imposed magnetospheric electric field from either the empirical parameterization or the outputs of the assimilative mapping of ionospheric electrodynamics (AMIE) procedure [Richmond and Kamide, 1988]; and (3) the amplitudes and phases of tides from the lower atmosphere from the Global Scale Wave Model (GSWM) [Hagan and Forbes, 2002]. In this study, we have conducted TIEGCM simulations with high-latitude drivers from both the geophysical index (gpi) parameterization and the AMIE outputs, which are named as TIEGCM-gpi and TIEGCM-AMIE hereafter. For the former case, the Heelis convection pattern [Heelis et al., 1982] is used, and cross polar cap potential (CPCP) and hemisphere power (HP) are determined from the parameterized formulae as a function of \( K_p \). Additionally, the characteristics of the auroral precipitation also come from the parameterization [see Wang, 1998]. For the latter case, high-latitude convection and auroral particle precipitation are specified by the AMIE outputs assimilated from various ground-based and satellite observations [see Lu et al., 2001].

3. Observations and Simulations

Two severe geomagnetic storms were triggered by coronal mass ejections (CMEs) reaching the Earth on 29 and 30 October 2003 when the Sun was extremely active [Skoug et al., 2004]. The time history of the solar wind speed, interplanetary magnetic field (IMF) \( B_z \) from the ACE satellite, geonatonic activity index \( K_p \), auroral activity index \( AE \), and ring current index \( Dst \) during 28–31 October 2003 are shown in Figures 1a–1e. As the solar wind shocks arrived at Earth around 0600 UT on 29 October and 1600 UT on 30 October, solar wind speed showed sharp increases for both shock events, and then rapidly reached their peaks exceeding 1500 km/s. Following the first shock, the IMF \( B_z \) component had a sharp southward turning with a short duration but reached ~60 nT. Another two strong southward intervals persisted nearly 12 and 8 h on 29 and 30 October, respectively, and their minimum \( B_z \) values were ~28 nT and
Variations of (a) solar wind speed, (b) interplanetary magnetic field $B_z$, (c) $K_p$, (d) $AE$, (e) $Dst$, and orbit-averaged neutral densities (in units of $10^{-12}$ kg/m$^3$) from (f) CHAMP and (g) GRACE satellites on 28–31 October 2003. (The time of the CHAMP and GRACE satellites across the equator is used in this plot). The red and green shaded curves represent thermosphere density on the dayside and nightside, respectively. The dashed lines stand for the reference (the value during the quietest period on 28 October).

$-35$ nT. Correspondingly, $K_p$, $AE$ and $Dst$ intensified; for instance, $K_p$ reached a high level with the values of 9 or 9-, and $AE$ exceeded 3000 nT during these strongly southward $B_z$ intervals, indicating that a large amount of energy was injected into the polar upper atmosphere. $Dst$ reached its minimum of $-180$ nT at 1000 UT on 29 October, $-363$ nT at 0100 UT and $-401$ nT at $\sim2300$ UT on 30 October. This is suggestive of two superstorms that occurred during this period on the basis of the definition by Gonzalez et al. [1994]. Their respective recovery phases started at 0100 UT on 29 October (identified throughout the text as R1) and at $\sim2300$ UT on 30 October (identified throughout the text as R2), facilitated by the northward $B_z$. In this study we will focus on the thermosphere variations during these two recovery phases.

The variations of the orbit-averaged neutral densities from CHAMP and GRACE during 28–31 October 2003 are also shown in Figure 1. The density variations from CHAMP are examined first (Figure 1f). Density enhancements can be seen on both the dayside (red) and nightside (green) on 28 October prior to the arrival of the first shock. This is mainly associated with the impact of an X17.2 flare on this day, as discussed by Sutton et al. [2006]. The abrupt increase of neutral density started at around 0600 UT on 29 October in response to the CME shock, and then pronounced density enhancements were observed during the main phases of the 29 and 30 October storms. The maximum increase of density reached 170% and 230% on the dayside and nightside, respectively, with regard to the reference (the value during the quietest period on 28 October). Interestingly, the CHAMP density died out quickly and recovered to values corresponding to quiet conditions before the beginning of the second superstorm. Subsequently, the CHAMP density increased at $\sim1600$ UT on 30 October in response to the second CME and reached the peak values within a few hours due to the persistence of the strong southward $B_z$ shortly after the shock. Again, the density recovered rapidly when the $B_z$ component turned to a northward direction.

The neutral density from GRACE is shown in Figure 1g to have similar response to the two geomagnetic storms as CHAMP, except for some details. The maximum increases of the GRACE density were about 390% (190%) and 330% (170%) on the nightside (dayside) during the main phases of the two superstorms, respectively. Lei et al. [2010] showed that storm-time mass densities at a fixed altitude significantly increase because of an increase in scale height. The magnitude of the mass density change for a fixed altitude depends on the number of scale height increments separating the heat source from the satellite altitude. Thus, the relative density response is greater at the higher GRACE altitude than at the CHAMP altitude. Furthermore, the nightside response for both satellites is larger than on the dayside for the same reason. Again, the GRACE density showed rapid recoveries during both R1 and R2. Obviously, the rapid recovery of thermosphere density cannot be reconciled by $Dst$ (Figure 1e), which does not support the suggestion of Zhou et al. [2009] to link density changes with $Dst$.

Next, the time scale for the thermosphere density relaxation is calculated from both the CHAMP and GRACE observations. Specifically, thermosphere densities during 0300–1200 UT on 30 October for R1 and during 0300–1600 UT on 31 October for R2 (when the $B_z$ component was mainly northward) are used to calculate the slope $\eta$ of the density changes. Then the relaxation time, defined by the $\varepsilon$-fitting for density evolving from $\rho_0 - \rho_{quiet}$ at 0300 UT to $(\rho_0 - \rho_{quiet}) \exp(-t)$ with a change rate of $\eta$, is computed ($\rho_0$ is the fitted density at 0300 UT, and $\rho_{quiet}$ is the quiet time reference density). On either the dayside or the nightside, the relaxation times derived from the CHAMP and GRACE observations are close and they are around 6 and 8 h for R1 and R2, respectively. These recovery times are much shorter than those for the Corotating Interaction Regions (CIRs) reported by Lei et al. [2011]. They found that thermosphere density during CIR storms in 2008 takes several days to recover to its prestorm level due to the continuous magnetospheric energy input into the polar atmosphere during the high-speed solar wind stream period. In addition, the longer relaxation time for R2 than R1 may be related with the stronger energy input during R2, as indicated by the $AE$ and $K_p$. Note that the thermosphere density fully

![Figure 1](image-url)
recovered for R1, such that there is no impact on R2. Obviously, the time scale obtained from our observations is much shorter than that from the numerical simulation of Maeda et al. [1992], in which the relaxation time of thermosphere temperature is in the range of 12–15 h.

Figure 2 shows the time evolution of neutral densities made from CHAMP and GRACE from pole to pole. Similar to the orbit-averaged density in Figure 1, thermosphere density profoundly changed during the geomagnetic active period. The complex latitudinal structures of the density response to the geomagnetic activity in Figure 2 are probably associated with the spatial distribution of the heating source, the propagation of Traveling Atmospheric Disturbances (TADs), and neutral composition effects [see Lei et al., 2010]. The rapid recovery of the thermosphere density is observed at all latitudes during R1 and R2 on the dayside and the nightside.

Figure 3 illustrates the latitudinal variations of the relaxation time of thermosphere density obtained from the best fitting as described above. On the nightside, the obtained relaxation times at all latitudes are similar to those from the orbit-averaged density, i.e., around 6 h for R1 and 8 h for R2, except that they become a little longer for GRACE at 485 km in the latitudinal range of 60°N–80°N for R1, and –40°S and 70°N for R2. On the dayside, the relaxation times are generally shorter by about 1 h than those on the nightside but they tend to become longer at high latitudes in the Southern Hemisphere for R1 and in both hemispheres for R2. There is also a weak altitudinal dependence of the relaxation time that is probably associated with neutral composition effects at different local times. As discussed by Lei et al. [2010], wind effects can cause composition changes in the thermosphere that alter the mean molecular weight and consequently can cause significant deviations in the mass density pattern, particularly at high latitudes, if only neutral temperatures are considered. Additionally, the possible soft precipitation between the CHAMP and GRACE altitudes might also contribute to the altitudinal dependence of the observed relaxation time on the nightside.

It should be pointed out that the latitudinal dependence of the relaxation time from the observations is not consistent with the simulation results of Maeda et al. [1992] who showed a longer relaxation time in the geographic latitudinal range of 50–70 degrees.

As discussed above, the CHAMP and GRACE density showed much shorter relaxation times than the simulations of Maeda et al. [1992]. However, Maeda et al. carried out the simulations for an idealized storm under solar minimum conditions. The different geophysical conditions with our present event might contribute to some differences between our observations and their simulations. Therefore, it is desirable to conduct simulations under the realistic conditions of our observations.
geophysical conditions of the 2003 storm event. Figure 4 compares the orbit-averaged neutral densities from CHAMP with those from the MSISE00 and TIEGCM models during 28–31 October 2003. Note that MSISE00 (Figure 4e) and the TIEGCM-gpi simulation (Figure 4f) do not predict the solar flare effect on 28 October because the F107 index was used as input, while TIEGCM-AMIE run (Figure 4g) does as solar fluxes from TIMED SEE observations were used to specify the solar radiative flux. As seen clearly in Figure 4, both MSISE00 and TIEGCM models show significant changes in neutral density during the main phases of the two superstorms, albeit the changes of neutral density from TIEGCM during storm time are in better agreement with the observations than those from either the MSISE00 model or the TIEGCM-gpi simulation. Although the predicted densities take about half day to evolve from the peak to the poststorm neutral densities, the models give much higher neutral densities during the poststorm period than the prestorm period. Thus, the MSISE00 and the TIEGCM share the common deficiency that the recovery rates of the modeled densities are lower compared with the observations during both R1 and R2.

[15] Figure 5 further demonstrates the differences in detail between the observations and the MSISE00 and TIEGCM-AMIE densities from pole to pole. Although the MSISE00 storm-time density increases significantly on the dayside and nightside, there are large discrepancies in the latitudinal structures of the disturbed density between the observations and MSISE00. Furthermore, the small-scale structures seen in the data are also missing in the MSISE00 prediction. The TIEGCM-AMIE captured most of the salient features observed by CHAMP, including the latitudinal structures of the storm-time density and the TADs. This indicates that the AMIE procedure represented the spatial distribution of the magnetospheric energy input well. However, neither the MSISE00 nor the TIEGCM is able to reproduce the rapid recovery of the storm-time density seen in the data from pole to pole during R1 and R2.

[16] A quantitative comparison of the relaxation time between the observations and those calculated from the modeled density is given in Figure 6. First, we will concentrate on the relaxation time on the nightside when the upper thermosphere is more directly disturbed by the magnetospheric energy input. At 390 km, the relaxation time of the MSISE00 density for R1 and R2 is longer than that from the CHAMP observations by about 4 h except in the geographic latitudinal range of 25°N–50°N where the relaxation time of the MSISE00 density is 2–3 times longer than that seen in the data. In addition, the relaxation time of the MSISE00 density at 485 km is a little shorter than that at 390 km. Surprisingly, the latitudinal dependence of the relaxation time calculated from either TIEGCM-AMIE or TIEGCM-gpi simulations resembles that of the MSISE00 density, whereas it differs with the observations greatly. On
Variations of (a) interplanetary magnetic field $\mathbf{B}_z$, (b) $K_p$, (c) $Dst$, and orbit-averaged neutral densities (in units of $10^{-12}$ kg/m$^3$) from (d) CHAMP, (e) MSISE00, (f) TIEGCM simulation driven by high-latitude forcing from the $Kp$ parameterization (TIEGCM-gpi), and (g) TIEGCM simulations driven by AMIE (TIEGCM-AMIE) on 28–31 October 2003. The red and green shading curves represent thermosphere density on the dayside and nightside of the CHAMP observations or the modeled densities sampled at CHAMP local times at 390 km. The dashed lines stand for the reference (the value during the quietest period on 28 October).

![Image of variations of interplanetary magnetic field, $K_p$, $Dst$, and orbit-averaged neutral densities.](image)

The planetary $3$ h $K_p$ is the mean standardized K-index from 13 geomagnetic observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude. The $K$ index is calculated from the deviation of the geomagnetic field $H$ component in a $3$ h window by removing its $S_q$ and $L$ variations [Xie, 2009]; however, it may contain a large contribution from the ring current during the main and recovery phases of the storm even though the larger time scale ($\geq 3$ h) variation of the ring current has already been removed. The auroral activity index $AE$ in Figure 6c can be used to estimate the effects of the ring current on the $K_p$ calculation during the recovery phases of this event. The $K_p$ values (Figure 7b) were around 6–7 during 0300–1200 UT on 31 October and ~3–4 on 28 October, although the $AE$ values during these two periods were comparable. Therefore, the ring current had a contribution of around 3 units in $K_p$ during 0300–1600 UT on 31 October (R2). Additionally, the $K_p$ values during 0300–1200 UT on 30 October (R1) were about 2–3 units higher than those on 28 October, albeit the $AE$ values during R1 were 100–200 nT lower than those on 28 October. This suggests that the ring current has a similar contribution in $K_p$ during R1 and R2. Thus the contamination of the ring current in $K_p$ (or $ap$) may partly explain the slow recovery in the MSISE00 and TIEGCM-gpi density when $K_p$ (or $ap$) was used as inputs of the models. By the way, the $e$-folding recovery time for $Dst$, calculated from the pure northward $B_z$ period, is about 11 and 12 h for R1 and R2, respectively. Therefore, $K_p$ or $Dst$ is not a good index to be used to describe thermosphere density in the recovery phase as suggested by Zhou et al. [2009].

Figures 7d shows the comparison of the cross polar cap potential CPCP between the AMIE outputs, TIEGCM-gpi, and Weimer05 [Weimer, 2005]. CPCP in the TIEGCM-gpi is substantially higher than the AMIE and Weimer05 potentials during the storm recovery phase. The same situation occurred in the comparison of the hemisphere power HP between the AMIE outputs, TIEGCM-gpi and intercalibrated NOAA/DMSP data [Emery et al., 2008] in Figure 7e. Namely, HP in the TIEGCM-gpi run during the two recovery phases is larger than that from AMIE and the average of the two hemispheres intercalibrated NOAA/DMSP data. The dayside, the relaxation times of the TIEGCM densities for R1 and R2 become shorter than those on the nightside, but they are still longer by a few hours than the observed relaxation times. Additionally, the MSISE00 model also shows longer recovery time at all latitudes when compared with the observations, particularly at low and middle latitudes where the relaxation times of the MSISE00 densities are 2–3 times longer than that of the CHAMP and GRACE data. It becomes immediately apparent that the MSISE00 and TIEGCM densities gave much larger day-night differences in the relaxation time than observed in the CHAMP and GRACE data.

4. Discussion

[17] Figures 4–5 show that the MSISE00 model and the TIEGCM-gpi simulation significantly overestimate the changes of neutral density during the recovery phases. As mentioned before, the MSISE00 model uses $ap$ to represent the impact of magnetospheric energy deposition on the thermosphere. High-latitude drivers in the TIEGCM-gpi run are also determined from the parameterizations as a function of $Kp$. Therefore, the variations of neutral densities from MSISE00 and TIEGCM-gpi simulations track those of the geomagnetic activity index $Kp$. As shown in Figure 7, $K_p$ was surprisingly high during the recovery phase when $B_z$ was northward, although $B_y$ was large during the early period of R2. Consequently, neutral densities from the MSISE00 and TIEGCM-gpi cannot recover rapidly.

[18] The planetary $3$ h $K_p$ is the mean standardized K-index from 13 geomagnetic observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude. The $K$ index is calculated from the deviation of the geomagnetic field $H$ component in a $3$ h window by removing its $S_q$ and $L$ variations [Xie, 2009]; however, it may contain a large contribution from the ring current during the main and recovery phases of the storm even though the larger time scale ($\geq 3$ h) variation of the ring current has already been removed. The auroral activity index $AE$ in Figure 6c can be used to estimate the effects of the ring current on the $K_p$ calculation during the recovery phases of this event. The $K_p$ values (Figure 7b) were around 6–7 during 0300–1200 UT on 31 October and ~3–4 on 28 October, although the $AE$ values during these two periods were comparable. Therefore, the ring current had a contribution of around 3 units in $K_p$ during 0300–1600 UT on 31 October (R2). Additionally, the $K_p$ values during 0300–1200 UT on 30 October (R1) were about 2–3 units higher than those on 28 October, albeit the $AE$ values during R1 were 100–200 nT lower than those on 28 October. This suggests that the ring current has a similar contribution in $K_p$ during R1 and R2. Thus the contamination of the ring current in $K_p$ (or $ap$) may partly explain the slow recovery in the MSISE00 and TIEGCM-gpi density when $K_p$ (or $ap$) was used as inputs of the models. By the way, the $e$-folding recovery time for $Dst$, calculated from the pure northward $B_z$ period, is about 11 and 12 h for R1 and R2, respectively. Therefore, $K_p$ or $Dst$ is not a good index to be used to describe thermosphere density in the recovery phase as suggested by Zhou et al. [2009].

[19] Figures 7d shows the comparison of the cross polar cap potential CPCP between the AMIE outputs, TIEGCM-gpi, and Weimer05 [Weimer, 2005]. CPCP in the TIEGCM-gpi is substantially higher than the AMIE and Weimer05 potentials during the storm recovery phase. The same situation occurred in the comparison of the hemisphere power HP between the AMIE outputs, TIEGCM-gpi and intercalibrated NOAA/DMSP data [Emery et al., 2008] in Figure 7e. Namely, HP in the TIEGCM-gpi run during the two recovery phases is larger than that from AMIE and the average of the two hemispheres intercalibrated NOAA/DMSP data. The...
overestimated CPCP and HP in the TIEGCM-gpi during the recovery phases, which is probably associated with the contamination of the ring current in \( Kp \), can contribute to the long relaxation time of the TIEGCM-gpi density during R1 and R2. From this point of view, the low time-resolution index \( Kp \) is not as good as \( AE \) to specify the high-latitude energy inputs in the upper thermosphere, especially during the recovery phase of the storm, although \( Kp \) (or \( ap \)) is widely used in empirical and theoretical models due to its long data record. It should be pointed out that the contamination of the ring current in \( Kp \) cannot fully explain the longer recovery time in the TIEGCM simulations because the recovery times for TIEGCM-AMIE were as long as those from TIEGCM-gpi as shown in Figure 6. A control simulation of the TIEGCM-gpi was conducted by using CPCP 30 kV and HP 20 GW to represent the quiet condition \( Kp = 1 \) during the northward \( Bz \) period of R1 and R2. In this case, the relaxation time of the TIEGCM density is still much longer than that from the data (not shown).

[20] It is expected that the TIEGCM should better reproduce the thermosphere response during the storm time that is seen in the CHAMP and GRACE when AMIE convection and precipitation patterns were used to specify the high-latitude inputs. Indeed, the TIEGCM-AMIE density captured most of the salient features observed by the CHAMP and GRACE data during the main phases of the 2003 29–31 October storms (Figure 5). As shown in Figures 7d–7e, the CPCP and HP from AMIE are in good agreement with those from the Weimer05 model and intercalibrated NOAA/DMSP data, respectively. Note that the HP from both NOAA/DMSP and AMIE during the main phases may be underestimated significantly when the HP was mainly determined from a few passes of the DMSP satellite for a given time, as indicated by the comparison between the intercalibrated NOAA/DMSP HP [Emery et al., 2008] and the TIMED/GUVI data [Zhang and Paxton, 2008; Luan et al., 2010] for high \( Kp \) conditions. Given that Joule heating is dominant over particle heating in the upper atmosphere, the underestimated HP would not greatly affect the thermosphere density response in the TIEGCM-AMIE during the storm time. In addition, even if the HP from AMIE during the main phases had the same magnitude as that from the TIEGCM-gpi, the total Joule heating would not change too much due to the feedback of the precipitation on the convection in the AMIE procedure. Nevertheless, as shown in Figures 4–6, the TIEGCM-AMIE is unable to reproduce

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**Figure 5.** Comparison of neutral densities (in units of \( 10^{-12} \) kg/m\(^3\)) from pole to pole between the CHAMP observations, MSISE00 model, and TIEGCM-AMIE simulations at 390 km sampled at CHAMP local times during 28–31 October 2003. The TIEGCM-gpi results are not given because they are similar in density recovery to those simulated by the TIEGCM-AMIE. The local times represent the medium values of the dayside and nightside orbits, respectively. \( Bz \) is shown in the bottom panels for reference.
the rapid recovery density during R1 and R2 either, although the realistic high-latitude convection and auroral precipitation forcing from AMIE are utilized to drive the model.

[21] The slow recovery of the thermosphere density in the TIEGCM-AMIE during the 2003 October storms could be due to the underestimation of the cooling rate for the neutral gas or the overestimation of its heating rate. As we know, under high solar activity conditions, the dominant acting cooling process in the lower thermosphere is NO radiative cooling [Roble et al., 1987], which results in enhanced downward heat conduction in the upper thermosphere. Recently, Qian et al. [2010] found that the TIEGCM NO cooling rate agrees with the TIMED/SABER measured NO cooling rate in a climatologic sense. Lu et al. [2010] compared the TIEGCM NO cooling rate with the SABER data for several storms, including the 2003 October storms, and also concluded that the TIEGCM did a good job in predicting the NO cooling rate. However, the studies of Qian et al. [2010] and Lu et al. [2010] used a daily average of the SABER NO power, and there is still a possibility that the NO cooling rate is underestimated by the TIEGCM for a particular interval. If only the cooling rate was considered responsible for the recovery time after the storm, then our simulations indicate that the TIEGCM is underestimating the NO cooling. However, it is the net heating and cooling rates that determine the response time of the thermosphere density, such that, both need to be properly specified. It is worth noting that the NO cooling rate depends on the Joule heating rate in the upper atmosphere [Lu et al., 2010], as the cooling rate is dependent on the temperature. As a result, increasing the temperature through Joule heating also increases the cooling rate. Therefore, it is difficult to assess whether the Joule heating rate or the NO cooling rate, or both, are improperly specified in the model. In the future, it will be desirable to compare the SABER NO cooling rate profiles along the TIMED orbits with the corresponding profiles simulated by the TIEGCM, while constraining the model with both the observed mass density and NO cooling rate during different phases of the storm. In this way, the relative contribution of Joule heating and NO cooling rates to thermosphere density change during a storm can be elucidated to better understand the rapid recovery of neutral density seen in the CHAMP and GRACE observations.

[22] Finally, it is worth noting that this study is devoted to examine the thermosphere recovery during the October 2003 superstorms only. The advantage of such severe storms is that the density changes are large, so the recovery periods are better defined. On the other hand, there is a value in determining how badly the models do, even though the convection pattern and precipitation might not be properly defined.
Robert Lysak thanks the reviewers for their assistance in evaluating this work. This work was supported by the AFOSR.

Acknowledgments.

Variations of (a) $B_z$ (black) and $B_y$ (blue); (b) $K_p$; (c) AE; (d) cross polar cap potential (CPCP) from AMIE, TIEGCM-gpi, and Weimer, 2005; and (e) hemisphere power (HP) from AMIE, TIEGCM-gpi, and average intercalibrated NOAA/DMSP data during 28–31 October 2003.

Figure 7. Variations of (a) $B_z$ (black) and $B_y$ (blue); (b) $K_p$; (c) AE; (d) cross polar cap potential (CPCP) from AMIE, TIEGCM-gpi, and Weimer, 2005; and (e) hemisphere power (HP) from AMIE, TIEGCM-gpi, and average intercalibrated NOAA/DMSP data during 28–31 October 2003.

In the future, a comprehensive analysis of the CHAMP and GRACE data is desired to characterize the latitudinal and altitudinal dependence of the relaxation time of the poststorm thermosphere as a function of season, solar activity and storm intensity. This is important to further validate and improve the empirical and theoretical thermosphere models. In addition, the available observations in conjunction with diagnostic simulations of the coupled thermosphere-ionosphere general circulation model will bring a better understanding of the physical processes involved in the recovery of the thermosphere and ionosphere. However, one of the potential difficulties to undertake such statistical analysis is that not many storms are suitable for thermosphere recovery studies. For the recovery time calculation, the solar wind/geophysical conditions should be checked carefully to ensure that $B_z$ is northward persistently, so that the magnetospheric energy deposited into the atmosphere is negligible during the recovery phase. Otherwise, the time constant cannot represent the real recovery of the thermosphere.

5. Conclusions

In this paper thermosphere densities retrieved from the CHAMP and GRACE accelerometer measurements are utilized to study the recovery of the thermosphere as a function of latitude during the October 2003 superstorms. Our results show that the relaxation times of the thermosphere density are around 6 and 8 h for the 29–30 and 30–31 October storms, respectively. This observed relaxation time did not show coherent latitudinal dependence as indicated in previous simulations by Maeda et al. [1992] where relaxation times increased for 50–70 degrees latitude. The weak altitudinal dependence of the relaxation times between the CHAMP and GRACE altitudes occurred at middle and high latitudes.

The MSISE00 and TIEGCM densities were compared with the observations to evaluate their capability in predicting the recovery response of the thermosphere during severe geomagnetic activity. However, neither the MSISE00 nor the TIEGCM reproduced the rapid recovery of the observed thermosphere densities, although the TIEGCM captured most of the salient features observed by CHAMP and GRACE during the main phases of the 2003 29–31 October storms when AMIE convection and precipitation patterns were used to specify the high-latitude inputs.

On the nightside, the relaxation time calculated from the TIEGCM is similar to that from the MSISE00 density, but differs from the observations significantly, including in its duration and latitudinal dependence. The relaxation times of the MSISE00 and TIEGCM densities at 390 km are generally longer than those from the CHAMP observations by about 4 h at most latitudes, and in the geographic latitudinal range of 25°N–50°N they are 2–3 times longer than those of the CHAMP data. Both the MSISE00 and TIEGCM densities show much larger day-night differences in the relaxation time than do the CHAMP and GRACE observations. The relaxation times of the TIEGCM densities on the dayside are shorter than on the nightside, especially in the geographic latitudinal range of 25°N–50°N, but the MSISE00 model shows much longer relaxation time at low latitudes than it does on the nightside. Higher neutral densities in the MSISE00 and TIEGCM-gpi than the observations during the recovery phase might be partly explained by the contamination of the ring current in $K_p$ (or $q_p$) when these geomagnetic indices are used as inputs of the models. Nevertheless, the causes of the slow recovery of thermosphere density in the TIEGCM are yet to be further explored.

Acknowledgments. This work was supported by the AFOSR MURI award FA9550-07-1-0565 and NASA grants NNX10AE62G and NNX10AQ52G. Work at HAO/NCAR was partly supported by NASA grants NNH09AK621, NNX08AH371, and NNX08AQ91G, and NCAR is sponsored by the NSF. The intercalibrated NOAA/DMSP HP estimates were taken from the CEDAR database which is sponsored by the NSF. J. Lei thanks A. Richmond, Y. Wei, and B. Chen for helpful discussions. ACE satellite data were provided by R. M. Skoug, and geomagnetic activity indices were obtained from World Data Center C2 and the NGDC database.

Robert Lysak thanks the reviewers for their assistance in evaluating this paper.
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