Model simulation of thermospheric response to recurrent geomagnetic forcing

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[1] We assess model capability in simulating thermospheric response to recurrent geomagnetic forcing driven by modulations in the solar wind speed and the interplanetary magnetic field. Neutral density and nitric oxide (NO) cooling rates are simulated for the declining phase of solar cycle 23. The simulated results are compared to neutral density derived from satellite drag and to NO cooling measured by the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) sounding of the atmosphere using broadband emission radiometry (SABER) instrument. Model-data comparisons show good agreement between the model and the measurements for multiday oscillations, as well as good agreement for longer-term variations. The simulations demonstrate that the multiday oscillation of density is globally distributed in the upper thermosphere but restricted to high latitudes in the lower thermosphere. The density variation in the upper thermosphere exhibits less latitude dependence than the temperature variation because of the effects of composition changes. Model simulations also show that NO density and temperature play primary roles in the multiday oscillation of NO cooling rates.


1. Introduction

[2] Periodicities at solar rotation (27 day), half-rotation (13.5 day), and shorter periods (~9 day, ~7 day, ~5 day) have been observed in the interplanetary magnetic field (IMF) and solar wind speed during the declining phase of solar cycle 23, caused by the appearance and disappearance of coronal holes as the Sun rotates [Temmer et al., 2007]. Consequently, these periodicities are also seen in auroral precipitation and various geomagnetic activity indices [Emery et al., 2009] as the solar wind generates auroral particle precipitation and ionospheric convection through its interaction with the Earth’s magnetosphere. Coronal holes usually exist at both high and low latitude on the Sun. Typically, there are two coronal holes that generate prominent 27 day and 13.5 day periodicities. However, during periods when there are more than two coronal holes, multiday periodicities appear in solar wind parameters and geomagnetic activity. In this paper we use the word “multiday” to refer to periodicities less than half of the solar rotation period. Temmer et al. [2007] found that three coronal holes presented during the declining phase of solar cycle 23 produced a strong 9 day periodicity in solar wind parameters. The resulting periodicities in geomagnetic activity affect the thermosphere and ionosphere through auroral particle precipitation and Joule heating. Lei et al. [2008a] discovered a strong 9 day periodicity in thermospheric neutral density observed by the Challenging Mini-Satellite Payload (CHAMP) satellite for 2005. Thayer et al. [2008] found 4–5, 6–7, and 9–11 day periods in CHAMP neutral density for 2006. These multiday periodicities are also seen in nitric oxide (NO) and CO2 infrared cooling observed by Thermosphere Ionosphere Mesosphere Energetics and Dynamics/Sounding of the Atmosphere using Broad-band Emission Radiometry (TIMED/SABER) [Mlynczak et al., 2008] and in thermospheric composition observed by the TIMED Global Ultraviolet Imager (GUVI) [Crowley et al., 2008, Lei et al. [2008b] and Pedatella et al. [2010] found corresponding multiday periodicities in the total electron content during 2005 and 2006. Recently, Ram et al. [2010] investigated the altitude and latitude dependency of ionospheric responses to recurrent geomagnetic activity during the extreme solar minimum period of 2008, using electron density profiles measured by the COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) satellites.

[3] The purpose of this study is to investigate the degree to which an upper atmosphere model can quantitatively describe these multiday oscillations, along with other prominent periods such as solar cycle variation, solar rotational variation, and seasonal variation. The declining phase of the solar cycle 23 presents a unique study period because it exhibited unusually large amplitudes of the multiday periodicities, particularly during 2005. In addition, simultaneous observations of solar ultraviolet spectral irradiance from TIMED Solar EUV Experiment (TIMED/SEE), thermospheric measurements by the SABER and GUVI instruments on TIMED, and neutral density observations are available throughout this period, for model input, and for model-data comparisons. In
this study, we simulate the upper atmosphere using a three-dimensional upper atmosphere general circulation model and compare simulated neutral density and NO infrared cooling rates to satellite drag-derived neutral density and NO cooling rates, with emphasis on the multiday oscillations. Neutral density and NO cooling were chosen as the thermospheric parameters for this investigation because density is a fundamental thermospheric parameter that controls satellite orbital evolution, and NO infrared cooling at 5.3 μm is an important “thermostat” that plays a crucial role in the thermospheric energy budget. NO is mainly produced by reactions between excited atomic nitrogen with O₂. Auroral energetic particles have sufficient energy to break the strong N₂ molecular bond and consequently to produce excited atomic nitrogen atoms. Therefore, NO cooling is likely to have a strong response to multiday recurrent geomagnetic forcing and thus may play an important role in determining how the thermosphere responds.

Section 2 gives a brief description of the model, section 3 introduces the satellite drag-derived neutral density data set and NO infrared cooling rates measured by TIMED/SABER, section 4 shows model simulation results and model-data comparisons, and section 5 concludes the study.

2. The NCAR TIE-GCM

The National Center for Atmospheric Research (NCAR) thermosphere-ionosphere-electrodynamics general circulation model (TIE-GCM) is a first principles upper atmosphere general circulation model that solves the Eulerian continuity, momentum, and energy equations for the coupled thermosphere/ionosphere system. It uses pressure surfaces as the vertical coordinate and extends in altitude from approximately 97 to 600 km [Roble et al., 1988; Richmond et al., 1992]. The main external forcing of the TIE-GCM is by solar irradiance in the extreme ultraviolet (EUV) and ultraviolet (UV) regions, geomagnetic energy input including auroral particle precipitation and magnetospheric convection, and perturbation at the lower boundary of the model by waves. In this study TIMED/SEE solar spectral irradiance measurements [Woods et al., 2005] were used as solar input [Solomon and Qian, 2005]. Ionospheric convection is specified by the empirical model of Heelis et al. [1982]. Auroral particle precipitation and its ionization and dissociation are calculated by an analytical auroral model described by Roble and Ridley [1987] but scaled upward in accordance with hemispheric power estimations from TIMED/GUVI [Zhang and Paxton, 2008]. These magnetospheric energy inputs are parameterized using the 3 h planetary K index (Kₚ). Migrating semidiurnal and diurnal tides are specified at the lower boundary using the global scale wave model [Hagan and Forbes, 2002, 2003]. The effect of gravity wave breaking in the mesosphere/lower thermosphere (MLT) region is included by specifying a seasonal variation of eddy diffusivity at the lower boundary that declines with altitude [Qian et al., 2009]. Effects of planetary waves and nonmigrating tides are not considered in the simulations shown here.

3. Data

3.1. Solar EUV Irradiance From TIMED/SEE

TIMED/SEE measures solar spectral irradiance from 0.1 to 194 nm [Woods et al., 2005]. It consists of two types of instruments: the EUV grating spectrograph component that covers wavelengths from 27 to 194 nm with a spectral resolution of 0.4 nm and the X-ray Photometer System component that covers wavelengths from 0.1 to 34 nm with nine photometers, yielding an effective spectral resolution of 5–10 nm. The SEE data products are solar spectral irradiance from 0 to 194 nm at 1 nm resolution, available on either a per-orbit or a daily average basis. The daily average (level 3), version 8 product is used in this study. The method of Solomon and Qian [2005] is used to convert SEE spectral irradiance measurements to the TIE-GCM solar input spectrum and account for ionization and dissociation by photoelectrons.

3.2. Neutral Density Derived From Satellite Drag

The neutral density data are daily averaged values obtained at satellite perigee locations from five low Earth orbiting satellites from 2002 to 2006. These five satellites are defunct radar calibration satellites launched by the former Soviet Union during the 1990s: Cosmos 660 (07337), Cosmos 807 (08744), Cosmos 1236 (12388), Cosmos 1238 (12138), and Cosmos 1508 (14483). They are spherical objects with moderately eccentric orbits. The average perigee altitude of the satellites is between 380 and 430 km, and the average apogee altitude is between 1300 and 1650 km. The satellite perigees scan approximately three latitude cycles and five local time cycles in a year. Thermospheric neutral density at satellite perigees were calculated using the method developed by Bowman et al. [2004], with errors within 2%–4%. The TIE-GCM-simulated neutral density was sampled at satellite perigee locations (altitude, latitude, and solar local time) for each day to be compared to the satellite drag-derived density. Further description of the methodology is given by Qian et al. [2009].

3.3. Nitric Oxide Cooling Rates From TIMED/SABER

The SABER instrument monitors the thermospheric energy budget by measuring infrared emissions from NO at 5.3 μm and from CO₂ at 15 μm [Mlynčak, 1997; Russell et al., 1999]. SABER obtains vertical profiles of NO emission rates in W m⁻³ using limb scans from 400 km tangent height down to ~20 km in equivalent height. Approximately 1600 globally distributed vertical profiles are recorded each day. The global power of the NO cooling rates is obtained by vertically integrating the corresponding emissions, sorting them into 5° latitude bins, and then summing over area-weighted latitude bins. Altitude range of the vertical integration is chosen from 100 to 200 km since emissions outside of that altitude range account for only a small fraction of the total global power radiated by the thermosphere [Mlynčak et al., 2007]. Error estimation of NO cooling measured by SABER is ~15% [Mlynčak et al., 2010].

4. Results

4.1. Model Simulations

TIE-GCM simulations were conducted for the period from 2002 to 2006. Simulated daily average neutral density was calculated at satellite perigees. Simulated NO cooling was integrated globally in the altitude range from 100 to 200 km with cosine of latitude weighting applied for global integration. The simulated neutral density and NO
infrared cooling were then compared to the satellite drag-derived neutral density and NO cooling measured by TIMED/SABER.

[10] The overall neutral density comparison between the model simulations and satellite drag data for the entire simulation period was shown in the study by Qian et al. (2009) and is not repeated here. It was found that the simulated neutral density was in good agreement with satellite drag-derived neutral density for the declining phase of the solar cycle 23 in terms of solar rotational, seasonal, and solar cycle variations. Figure 1 shows the simulated NO cooling rate and TIMED/SABER measured NO cooling rate [Mlynczak et al., 2008] from 2002 to 2006. NO cooling shown in Figure 1 is global NO cooling power, integrated over the globe and in the altitude range from 100 to 200 km. The magnitude and solar cycle variation of the simulated NO cooling are consistent with that of the measured NO cooling through the declining phase of solar cycle 23, although the model was relatively higher, about 20% on average. In addition, the SABER NO cooling rate exhibits a 60 day period corresponding to the solar time sampling of the precession period of the TIMED spacecraft [Mlynczak et al., 2008], with a recurring low NO cooling in the second half of each precession cycle that is not in the simulated NO cooling rates.

[11] Figure 2 shows comparisons of the simulated neutral density and NO cooling power to the measurements (Figures 2a and 2b), the corresponding geomagnetic input for the model (cross-tail potential and hemispheric power, Figure 2c), and $A_p$ index and solar irradiance input for the model (Figure 2d), for 2005, which is the year with a dominant 9 day period [Emery et al., 2009]. Both the simulated NO cooling and the simulated neutral density are in good agreement with the measurements. Contributions of solar forcing and geomagnetic forcing are evident in the time series of neutral density and NO cooling, as shown in solar rotational (∼27 days) and shorter-term, multiday oscillations in these two quantities. The global NO cooling has stronger multiday variability compared to neutral density at the perigees of satellite 12388. This multiday variability is the focus of this paper and is investigated in detail in the following sections.

### 4.2. Nitric Oxide Cooling

[12] We performed a Lomb-Scargle analysis [Lomb, 1976; Scargle, 1982] on the measured and the simulated global NO cooling power, TIMED/SEE integrated EUV (5–105 nm), and $K_p$ index for each year. Lomb-Scargle analysis is a least square spectral analysis method that estimates frequency spectra based on a least square fit of sinusoids to data samples. Since the focus of this study is the multiday periodicity in the thermosphere, Figure 3 only shows periods that are less than 30 days, for 2004, 2005, and 2006. The measured NO cooling power exhibits multiday periodicities of ∼7, ∼9, and ∼13 days as shown by M. G. Mlynczak et al. [2010]. The simulated NO cooling power shows similar multiday periods, with the most prominent periods of 13.5, 9, and 7 days, for 2004, 2005, and 2006, respectively. The amplitude of these multiday periodicities in the simulated NO cooling is relatively weaker than those observed by SABER.

[13] Possible sources of multiday periodicities in the thermosphere are geomagnetic activity, subharmonics of 27 day variation of solar irradiance and planetary wave forcing from below. The third and fourth frames of Figure 3 are periodograms for TIMED/SEE integrated EUV (5–105 nm) and $K_p$ index. It is clear that solar irradiance is the main forcing for periods longer than 20 days, but contributions of solar irradiance to periods less than 20 days are negligible. The multiday periods of $K_p$ correspond well with those of the NO cooling, indicating that geomagnetic activity is the main forcing of these multiday periodicities. Planetary wave forcing is not included in the model as we mentioned earlier. Although most planetary waves dissipate in the stratosphere and lower mesosphere, planetary waves with periods of 2, 5, 10, and 16 have been observed in the MLT region. These waves, when present, may also contribute to multiday periodicities observed in the thermosphere and ionosphere.

[14] NO cooling is due to vibrational excitation of NO and subsequent emission at 5.3 μm. In the thermosphere, the dominant excitation mechanism of NO is via inelastic collisions with atomic oxygen, under both quiescent and storm conditions [Mlynczak et al., 2003; Mlynczak et al., 2005]. NO may also be excited through collisions with particles other than O but collisions with $N_2$ and $O_2$ are not efficient at...
populating NO vibrational levels. In the TIE-GCM, the NO cooling rate (erg/cm³/s) is calculated using the following equation, based on Kockarts [1980]:

\[
\text{NO cooling} = \frac{4.956 \times 10^{-12} n(\text{NO}) \times (k_v n(\text{O}) + 2.4 \times 10^{-14} n(\text{O}_2))}{(k_v n(\text{O}) + 2.4 \times 10^{-14} n(\text{O}_2) + 13.3)} \times e^{-\frac{\text{TN}}{2700}},
\]

where \(n(\text{NO}), n(\text{O}),\) and \(n(\text{O}_2)\) are number densities of NO, O, and O₂, respectively; \(k_v\) is the vibrational excitation rate of NO by O; and TN is neutral temperature. \(k_v\) is equal to \(4.2 \times 10^{-11}\) cm² s⁻¹ [Hwang et al., 2003]. As discussed by Mlynczak et al. [2003] and also shown in this equation, major factors that can cause variation of NO cooling are (1) variation in NO abundance, (2) variation in neutral temperature, and (3) variation in O abundance.

[13] Figure 4 shows the model simulated NO cooling rate, neutral temperature, NO number density, and O number density at 120 km at 12:00 local time and 0:00 UT, from day 51 to day 110 of 2005. One hundred twenty kilometers was chosen since this is the altitude near the peak of NO cooling rate per unit volume. Regions and periods with high temperature and NO abundance correspond to enhanced NO cooling. This indicates that both neutral temperature and NO abundance play important roles in determining NO cooling. An increase in neutral temperature increases the rate of collisional excitation of NO, whereas an increase in NO density leads to more vibrationally excited NO via collisions with O. On the other hand, regions and periods of high O density correspond to low values of the other three parameters. O density is low at high latitude but enhanced at midlatitude in both hemispheres, and O density is relatively low in the equatorial region. These distributions of O density are primarily caused by large-scale circulations because of heating at high latitude and in the equatorial region. High O density is associated with downwelling region of the circulations, whereas low O density is associated with upwelling region of the circulations. In the lower thermosphere, when a parcel of air rises due to heating, the initial mixing ratio of O is sufficiently low that the increased density of the parcel, as it rises to higher altitude, is not sufficient to offset the difference in

![Figure 2](image.png)

**Figure 2.** Comparisons of model simulations to measurements for 2005 and forcing for the model. (a) Daily average neutral density at satellite perigees (black, satellite #12388); red, TIE-GCM. The estimated uncertainty of neutral density derived from satellite drag is 2%-4%. (b) Global NO cooling power, integrated over the globe and in the altitude range from 100 to 200 km (black: TIMED/SABER; red: TIE-GCM). The estimated uncertainty of SABER NO cooling rates is ~15%. (c) Time series of hemispheric power (green) and cross-tail potential (pink) used in the model. (d) Time series of TIMED/SEE integrated EUV (5–105 nm, blue) and \(A_p\) index (black).
the composition; therefore, O density decreases. Likewise, downwelling increases O density. A decrease of O density has the effect of reducing NO cooling since there is less O available to collisionally excite NO. Figure 4 indicates that this effect is secondary compared to contributions of NO density and temperature on NO cooling. In addition, multiday oscillation is evident in all the four parameters, especially in NO abundance, neutral temperature, and NO cooling. Neutral temperature and NO abundance increase responding to enhanced auroral particle precipitation and Joule heating during the rising phase of the multiday oscillation in geomagnetic activity, which in turn causes enhanced NO cooling. This enhanced NO cooling will then decrease temperature and cause subsequent restoration in other thermospheric quantities such as neutral density and composition. Therefore, NO cooling acts as a thermostat in controlling thermospheric responses to the multiday recurrent geomagnetic forcing.

4.3. Neutral Density

We performed similar comparisons of the simulated and the observed neutral density to examine the multiday oscillation. Model-simulated neutral density was sampled at perigees of three satellites (#08744, #12138, and #14483) for 2005, and periodograms of the modeled and the observed neutral density for the three satellites were obtained using Lomb-Scargle method. The first and second frames of Figure 5 show comparisons of periodograms (2–30 days) for neutral density at the perigees of the three satellites for 2005. Since neutral density at a given altitude is determined by neutral temperature as well as composition (O/N₂), model-simulated neutral temperature was sampled at perigees of the three satellites for 2005, and its periodogram is shown in Figure 5 in the third frame, whereas model-simulated column number density ratio of O and N₂ (O/N₂) was calculated at perigee latitude and solar local time, and its periodogram is shown in Figure 5 in the fourth frame. The top of the column for the calculation of O/N₂ is the top boundary of the model, whereas the base is where N₂ column number density is 10¹⁷ cm⁻² [Strickland et al., 1995]. This column O/N₂ is a measure of composition change primarily due to vertical motion of the atmosphere. Both the simulated and measured neutral density at the three satellite perigees show a dominant 9 day period, consistent with those for NO cooling during

Figure 3. Periodogram (2–30 days) of TIMED/SABER measured NO cooling power, TIE-GCM-simulated NO cooling power, TIMED/SEE-integrated EUV flux (5–105 nm), and the K₉ index, for 2004, 2005, and 2006. TIMED/SEE measurements are used as solar input for the model, while K₉ index is used to parameterize geomagnetic forcing (hemispheric power and cross-tail potential). NO cooling power shown here is global NO cooling power, integrated over the globe and in the altitudes range from 100 to 200 km.
2005. However, amplitude of this 9 day period for the simulated neutral density is relatively smaller than the measurements. This amplitude difference in neutral density between the model simulations and the data is similar to the amplitude difference seen in model-data comparisons of NO cooling power. The 9 day periodicity is evident in model-simulated neutral temperature for all three satellites, as shown in the third frame in Figure 5; whereas for column O/N2, this 9 day periodicity is only shown for satellite #14483 (fourth frame of Figure 5). The cause of this difference in the 9 day periodicity of temperature and column O/N2 is likely due to the fact that temperature response to the multiday recurrent geomagnetic forcing is a global phenomenon, whereas the corresponding response of column O/N2 only dominates at high latitude. This can be illustrated as follows.

Figure 6 shows model-simulated neutral density at 400 km (Figure 6a), neutral density at 120 km (Figure 6b), neutral temperature at 400 km (Figure 6c), and column O/N2 (Figure 6d), at 12:00 local time and 00:00 UT, from day 51 to day 110 of 2005 (the interval analyzed by Crowley et al. [2008]). Both neutral density and neutral temperatures at 400 km show clear 9 day oscillations extending to the equator. This indicates that neutral temperature and neutral density responses to the 9 day recurrent geomagnetic forcing are global. However, neutral density and neutral temperature at 400 km also show the following different characteristics: The highest temperature occurs at high latitude where lowest density occurs; neutral temperature has a larger latitude gradient, whereas neutral density is rather uniform in its latitude distribution. These differences are due to the effect of composition changes. Figure 5d shows column O/N2. As mentioned earlier, this quantity is an indicator of vertical motions in the thermosphere. Upward motion decreases this quantity and downward motion increases it. At high latitude, neutral temperature increases, responding to the multiday recurrent geomagnetic forcing through Joule heating and auroral particle precipitation. This causes upwelling, which reduces column O/N2 in the region as shown in Figure 5d. This upwelling causes downwelling at lower latitude through meridional circulation, and the downwelling enhances column O/N2 at lower latitude (Figure 5d). At high latitude, temperature enhancement causes density enhancement, whereas column O/N2 reduction decreases density; at lower latitude, there is less temperature enhancement, but there is
enhancement of column O/N₂. Therefore, the change of neutral density due to temperature is partly compensated by the change of neutral density by column O/N₂. Consequently, the latitudinal gradient of neutral density enhancements is much weaker than those of neutral temperature and column O/N₂. While neutral density and temperature at 400 km show a global 9 day oscillation, this oscillation is not clear in neutral density at 120 km (Figure 5b) and column O/N₂.

Figure 7 shows corresponding perturbations for quantities shown in Figure 6. The perturbation was calculated as percentage perturbation over an 11 day running mean. The black dotted lines represent the $A_p$ index. Density at 120 km (Figure 7b) and column O/N₂ (Figure 7d) show strong 9 day oscillations at high latitude, but the corresponding response at low latitude is very weak. Figures 7a and 7b indicate that the 9 day oscillation of neutral density at 400 km is stronger than that of density at 120 km, and the density response at 400 km is global, whereas the density response at 120 km is largely restricted to high latitude. This difference in the multiday oscillation of neutral density in the upper thermosphere and lower thermosphere is due to different mechanisms of this multiday oscillation in different altitude regions. Figure 7 indicates that both temperature and composition play role in the 9 day oscillation of density at 400 km; the contribution from temperature causes the global feature of the density response, whereas contribution from composition causes the largely uniform latitude distribution of the density response compared to the temperature response. On the contrary, the density response at 120 km is largely restricted to high latitude since it is mainly a composition effect (Figures 7b and 7d).

5. Conclusions

We conducted further analysis to understand the lower thermospheric density and composition responses to recurrent geomagnetic forcing. Figure 7 shows corresponding perturbations for quantities shown in Figure 6. The perturbation was calculated as percentage perturbation over an 11 day running mean. The black dotted lines represent the $A_p$ index. Density at 120 km (Figure 7b) and column O/N₂ (Figure 7d) show strong 9 day oscillations at high latitude, but the corresponding response at low latitude is very weak. Figures 7a and 7b indicate that the 9 day oscillation of neutral density at 400 km is stronger than that of density at 120 km, and the density response at 400 km is global, whereas the density response at 120 km is largely restricted to high latitude. This difference in the multiday oscillation of neutral density in the upper thermosphere and lower thermosphere is due to different mechanisms of this multiday oscillation in different altitude regions. Figure 7 indicates that both temperature and composition play role in the 9 day oscillation of density at 400 km; the contribution from temperature causes the global feature of the density response, whereas contribution from composition causes the largely uniform latitude distribution of the density response compared to the temperature response. On the contrary, the density response at 120 km is largely restricted to high latitude since it is mainly a composition effect (Figures 7b and 7d).

5. Conclusions

Model simulations of multiday oscillations in the thermosphere are compared to measurements during the declining phase of solar cycle 23. Model simulations show that TIE-GCM is able to reproduce the multiday oscillation in the thermospheric quantities, along with other prominent, longer-term variations in the thermosphere such as solar cycle variation, solar rotational variation, and seasonal variation. The simulated NO cooling power shows multiday periods similar to those of SABER measurements, with the most prominent periods at 13.5, 9, and 7 days for 2004, 2005, and
2006, respectively. Amplitudes of these multiday periodicities in the simulated NO cooling power are relatively weaker than those observed by SABER, especially for the dominant 9 day period. This may be due to inadequacy of the parameterization of geomagnetic forcing (hemispheric power and cross-tail potential) based on the 3 h $K_p$ index, resulting in underestimation of Joule heating. The model-simulated neutral density sampled at satellite perigees is consistent with the satellite drag data, and the simulated multiday oscillation of the neutral density is also relatively weaker than the neutral density measurement.

[20] Model simulations show that density and temperature responses to the recurrent geomagnetic forcing in the upper thermosphere is global in nature, whereas the response of density in the lower thermosphere and column O/N$_2$ is largely restricted to high latitude. Density response in the upper thermosphere is caused by both temperature and changes in column O/N$_2$. The temperature effect causes the global density response, whereas the composition (column O/N$_2$) effect reduces the latitudinal gradient of the density response compared to the temperature response. Density response in the lower thermosphere is largely restricted to high latitude since it is mainly due to composition change. These results are in accord with the analysis of composition measurements from TIMED/GUVI by Crowley et al. [2008].

[21] Furthermore, model simulation show that in the lower thermosphere, where NO cooling maximizes, responses of neutral temperature, and NO abundance to the recurrent geomagnetic forcing play primary roles in determining the corresponding response of NO cooling, whereas O abundance plays a secondary role. Neutral temperature and NO abundance respond to the recurrent geomagnetic forcing through auroral particle precipitation and Joule heating, which in turn cause the multiday oscillation in NO cooling. Enhanced NO cooling will decrease temperature and cause subsequent restoration in other thermospheric quantities such as neutral density and composition. Therefore, NO cooling acts as a thermostat in controlling thermospheric response to the multiday recurrent geomagnetic forcing.

Figure 6. Model-simulated neutral density at 400 km, neutral density at 120 km, neutral temperature at 400 km, and column number density ratio of O and N$_2$ (O/N$_2$), at 12:00 local time and 0:00 UT, from day 51 to day 110 of 2005.
As we discussed earlier, the recurrent multiday forcing for the thermosphere-ionosphere system is the variation in the solar wind and IMF, which cause magnetospheric perturbations that result in auroral and geomagnetic disturbances. The magnetometer-based indices used to parameterize this process in the model are imperfect geomagnetic indicators, and the parameterizations of auroral convection and precipitation based on them are known to be approximate. Future work will employ solar wind and IMF measurements directly to estimate geomagnetic inputs into the thermosphere, to improve model fidelity, and will extend the analysis of periodic variations to other observables, including ionospheric parameters.

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References

Figure 7. (a) Model-simulated neutral density perturbation at 400 km, (b) neutral density perturbation at 120 km, (c) neutral temperature perturbation at 400 km, and (d) perturbation of column number density ratio of O and N₂ (O/N₂), at 12:00 local time and 0:00 UT, from day 51 to day 110 of 2005.


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