Wind and temperature effects on thermosphere mass density response to the November 2004 geomagnetic storm

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Received 12 August 2009; revised 1 December 2009; accepted 9 December 2009; published 4 May 2010.

A unique conjunction of the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) and the Challenging Minisatellite Payload (CHAMP) satellites provided simultaneous columnar neutral composition, \( \Sigma O/N_2 \), and thermosphere density observations, enabling a novel study of thermospheric response to the 7–9 November 2004 geomagnetic storm. Both \( \Sigma O/N_2 \) and mass density showed profound response to this severe geomagnetic storm, but their latitudinal and temporal structures differed markedly. In particular, high‐latitude depletion and low‐latitude enhancement in \( \Sigma O/N_2 \) were observed throughout the storm period, especially during the main phase. In contrast, neutral density at 400 km altitude increased from pole to pole shortly after the storm, with strongest enhancement of order 200%–400% during the main phase. Comparisons of observed thermosphere response with simulations from the National Center for Atmospheric Research Thermosphere–Ionosphere–Electrodynamics General Circulation Model (TIEGCM) were carried out to interpret the observed contrasting characteristics of thermosphere composition and mass density in response to this geomagnetic storm. The TIEGCM simulations show that the contrasting characteristics occur not only in \( \Sigma O/N_2 \) and mass density at a constant altitude at 400 km, but also in \( O/N_2 \) and mass density on a constant‐pressure surface. At an altitude of 400 km (CHAMP altitude), storm‐time mass densities significantly increase due to an increase in scale height throughout the vertical column between the heat source and satellite altitude. For a given increase in scale height, the more scale height increments separating the heat source from the satellite altitude, the greater is the mass density response. It is shown that scale height change is caused partly by storm‐time neutral temperature enhancements due to heating and partly by changes in mean molecular weight due to winds. These findings indicate that wind effects can cause significant deviations from a mass density pattern resulting solely from neutral temperature changes by altering the mean molecular weight, particularly at high latitudes.


1. Introduction

[2] During geomagnetic disturbances, a large amount of energy in the form of Joule heating and particle precipitation is deposited in the high‐latitude thermosphere, resulting in heating and expansion of the neutral gas [e.g., Mayr et al., 1978; Prölls, 1980; and references therein]. In concert, momentum is transferred to the neutral gas through ion-neutral collisions imposed by convection electric fields of magnetospheric origin and related hydrodynamic forces, leading to horizontal and vertical motion. As we know, the vertical motion of the neutral gas includes two components, barometric motion and vertical winds [Rishbeth et al., 1987; Rishbeth, 2004; Rishbeth and Müller‐Wodarg, 1999]. The barometric part of the winds represents the vertical movement of constant‐pressure surfaces due to thermal expansion or contraction of the atmosphere, which is sometimes called atmospheric breathing. Vertical winds are associated with horizontal wind divergence through mass continuity and lead to differential constituent transport across pressure surfaces.

[3] Although changes in thermosphere mass density are susceptible to these processes, little attention has been given to the relative role of these two vertical components in producing changes in thermosphere mass density. Traditionally the \( O/N_2 \) ratio has been used to qualitatively...
Variations of the interplanetary magnetic field $B_z$ and $B_y$ and the $Dst$ index on 6–9 November 2004. The shaded bars represent the time intervals discussed in detail in section 4.

indicate vertical motion, but the combination of vertical winds, horizontal transport, and thermal expansion makes it challenging to separately determine their influence on thermosphere mass density. It is the intentions of this paper to (1) investigate the simultaneous response of the thermosphere composition and mass density to strong geomagnetic activity and (2) determine how changes in neutral composition and thermal expansion are reflected in changes of thermosphere mass density. In this study, we utilize nearly simultaneous mass density measurements by the Challenging Minisatellite Payload (CHAMP) satellite [Reigber et al., 2000] and thermospheric neutral composition observations by the Global Ultraviolet Imager (GUVI) instrument [Christensen et al., 2003] on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite during the geomagnetic storm of 7–9 November 2004, when CHAMP and TIMED were nearly coplanar. This will be the first time thermosphere mass density and composition changes are observed concurrently from pole to pole during strong geomagnetic activity.

[4] Although simultaneously observed over the same locations of Earth, the thermosphere mass density is an in situ measurement referenced to the altitude of the CHAMP satellite. Thus, the mass density measurement will experience different pressure surfaces during quiet and storm conditions. The GUVI O/N$_2$ ratio is an integrated column measurement and will largely remain on a common pressure surface during quiet and storm conditions. These different types of measurement can make their relative response complex to compare and contrast, but it is also this fundamental difference that enables more information to be extracted from their combined data sets than by looking solely at their individual response. The National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) [Richmond et al., 1992] will assist in the interpretation of these different types of measurement by providing output on constant-pressure and constant-altitude surfaces. The NCAR-TIEGCM will also be invoked to simulate the simultaneous response of the thermosphere mass density and composition to the geomagnetic storm and allow for their differing responses to be related to physical processes that contribute to barometric motion and vertical winds of the neutral gas.

2. Solar and Geophysical Conditions of the November 2004 Geomagnetic Storm

[5] The period 7–12 November 2004 was one of declining solar flux, with a daily $F_{10,7}$ index of about 130 ($\times 10^{-22}$ W m$^{-2}$ Hz$^{-1}$). Two severe geomagnetic storms hit Earth during the period of 7–12 November. In this paper, we will focus on the first storm, which occurred during 7–9 November when both CHAMP and TIMED satellites had similar local time sampling for a given Universal Time (UT). The first storm was selected so that there were no potential complications arising from previous geomagnetic activity.

[6] Figure 1 shows the interplanetary magnetic field $B_z$ and $B_y$ and the $Dst$ index during 6–9 November 2004. The interplanetary magnetic field (IMF) data (in GSM coordinates) were measured by the ACE satellite and have been shifted by 50 min to match high-latitude assimilative mapping of ionospheric electrodynamics (AMIE) co-ordinates) were measured by the ACE satellite and have been shifted by 50 min to match high-latitude assimilative mapping of ionospheric electrodynamics (AMIE) convection patterns [Deng et al., 2009]. This time shift accounts for the time that it took for the solar wind to propagate from the satellite location to the magnetopause and the reaction time of the magnetosphere. As the solar wind shock arrived at Earth around 1000 UT on 7 November, both the $B_x$ and $B_y$ components started to oscillate until around 2300 UT on this day, and then $B_x$ remained southward for a long time, except for a 3 h window of northward $B_x$ on 8 November. $B_y$ had negative values from 2300 UT on 7 November to 0300 UT on 8 November and was positive for the rest of the storm. During this storm period, both IMF $B_x$ and $B_y$ had large magnitudes of about 50 nT. The provisional $Dst$ index reached $-373$ nT on 8 November at 0600–0700 UT and recovered to $-100$ nT before the commencement of the second storm.


[7] Neutral composition observed by the GUVI instrument on the TIMED satellite and mass density from the CHAMP satellite are used in this study. The GUVI column O/N$_2$ ratio ($\Sigma$O/N$_2$), defined as the column density of O above an altitude where the N$_2$ column density is $10^{17}$ cm$^{-2}$ [Strickland et al., 1995], is determined from the O (135.6 nm) and N$_2$ (Lyman-Birge-Hopfield) emissions [Christensen et al., 2003]. Each GUVI scan provides an image covering an area 2500 km by 100 km at an altitude of about 150 km. Its nadir spatial resolution is 7 km by 7 km. The TIMED spacecraft has an inclination of 74.1°, and hence the local time sampling changes only slightly over consecutive days.
During 7–9 November, the TIMED GUVI sampled the local time sector of ~1430 h.

Thermosphere mass densities used here are obtained from accelerometer measurements of nongravitational accelerations on the CHAMP satellite [Reigber et al., 2000] using standard methods [Sutton et al., 2007]. The measured densities $\rho(z)$ at satellite altitudes are normalized to a constant altitude of 400 km using NRLMSISE-00 [Picone et al., 2002] as follows: $\rho(400) = \rho(z) \times \rho_M(400)/\rho_M(z)$, where $\rho_M(400)$ and $\rho_M(z)$ represent the mass densities calculated from NRLMSISE-00 model at 400 km and satellite altitudes, respectively. See Bruinsma et al. [2006] for a discussion of errors in density normalization. Because for this time period the CHAMP satellite was at 380–394 km, which was close to the 400 km normalization altitude, we expect the normalization error to be minimal. CHAMP is in a near-circular 87.3° inclination orbit and provides a density measurement every 80 km (10 s) along the orbit. The local time of CHAMP on the dayside during 7–9 November was also 1430 h, which varied little over several days. As a result, GUVI and CHAMP measured the dayside thermospheric neutral composition and mass density, respectively, nearly simultaneously at the same geographic location during the storm event in question.

3.1. GUVI $\Sigma O/N_2$

Figure 2a shows the GUVI $\Sigma O/N_2$ as a function of geographic longitude and latitude during the period of 7–9 November 2004. UT time in this plot runs from right to left in order to display the GUVI data on top of geographic maps. This projection is necessary because Earth rotates under the TIMED satellite orbital plane [see Meier et al., 2005]. For each day, the GUVI data almost cover all longitudes over the globe, but they present a time series (different UTs) of GUVI $\Sigma O/N_2$ rather than a simultaneous global snapshot because of the satellite precession.

$\Sigma O/N_2$ on the quiet day (6 November) is shown on the right side of Figure 2a. It exhibits the characteristic hemispheric asymmetry with high $\Sigma O/N_2$ values in the northern (winter) mid-high latitudes and low $\Sigma O/N_2$ at the corresponding latitudes in the southern (summer) hemisphere, which is caused by the summer-to-winter wind circulation [Roble, 1977; Fuller-Rowell et al., 1996]. On the other hand, there are obvious longitudinal variations in $\Sigma O/N_2$ in the mid-high latitudes of each hemisphere. Specifically, $\Sigma O/N_2$ values exceed 0.9 in European and Siberian regions, while they are lower over Canada and the United States. In the Southern Hemisphere, a low $\Sigma O/N_2$ band of less than 0.4 penetrated to the south coast of Australia, a much lower geographic latitude than in other longitudinal sectors. This longitude structure is suggestive of the effect of the northern and southern magnetic poles being located at different longitudes [Fuller-Rowell et al., 1994]. The hemispheric asymmetry and longitude structure in $\Sigma O/N_2$ on 6 November reappeared on 7 November with slight differences because of the day-to-day variability in the thermosphere before the onset of the storm.

As the main phase of the storm progressed, low $\Sigma O/N_2$ that was formerly in the polar regions at the initiation of the storm was transported equatorward in both hemispheres. At the same time, a band of large $\Sigma O/N_2$ occurred at low latitudes in the longitudinal sector over the Pacific Ocean. When the storm peaked at around 0600–0700 UT on 8 November, which is characterized by the $Dst$ minimum, the depletion of $\Sigma O/N_2$ in the Southern Hemisphere crossed over the geographic equator up to southeastern Asia. In the Northern Hemisphere, the low values of $\Sigma O/N_2$ also encroached toward the equator but over the
North American sector at around 2000 UT on this storm day. The decrease of $\Sigma O/N_2$ was as large as 100% at high latitudes, and its enhancement reached 50% at low latitudes compared with quiet times. Obviously, the observed longitude structure during quiet time (6–7 November) was severely exaggerated on 8 November; for example, the band of $\Sigma O/N_2$ enhancements extended to low latitudes over the east coast of Africa. Notably, this enhanced band of $\Sigma O/N_2$ is aligned with the magnetic equator, which could be due to high-latitude heating and resulting winds being organized by magnetic latitude. [12] On 9 November geomagnetic activity was not as strong as it was on 8 November (Figure 1), and $\Sigma O/N_2$ started to recover. However, it usually takes 12 h to 1 day for high-latitude neutral composition to recover [Burns et al., 1989]. During 0400–1100 UT, the depletion of $\Sigma O/N_2$ in the Southern Hemisphere still can be seen at the latitudes of around 40°S, although it did not penetrate into the equatorial region as it did on 8 November. During the same period, the depletion of $\Sigma O/N_2$ in the Northern Hemisphere only occurred in the polar region, whereas enhancements of $\Sigma O/N_2$ were observed over eastern Europe and Asia. As shown in Figure 1, Dst decreased after 1100 UT; $B_x$ and $B_y$ became variable again. Thus the neutral composition was further disturbed before its recovery, and the depletion of $\Sigma O/N_2$ persisted at low-middle latitudes over North America and the southern Pacific during 1600–2400 UT of 9 November.

3.2. CHAMP Neutral Density

[13] Figure 2b presents the latitude versus longitude (time) response of thermosphere density normalized to 400 km along the CHAMP ascending orbits (average LT = 1430 h) using the same format as for the GUVI data in Figure 2a. The CHAMP density was in the range of (2–5) $\times 10^{-12}$ kg/m$^3$ on 6–7 November, prior to the onset of the storm, with a maximum density at low latitudes over the Pacific Ocean. In addition, the density at high latitudes was relatively lower in the Northern Hemisphere than in the Southern Hemisphere.

[14] The mass density increase at all latitudes (from pole to pole) started at around 1600 UT on 7 November, following a weak enhancement during 1400–1600 UT on this day in the Southern Hemisphere. Although the mass density increased for all latitudes, significant latitudinal structure existed as to the magnitude of the increase. Pronounced density enhancements were observed by CHAMP first at Southern Hemisphere high latitudes in response to the sharp $B_z$ southward turning with a low value of ~50 nT at 2300 UT that occurred on 7 November. Then the significant geomagnetic response during the main phase was seen at most latitudes. Density enhancements reached 200%–400% with respect to quiet-time values, but without the significant hemispheric asymmetry in the absolute perturbation magnitude that was shown by Liu and Lühr [2005] and Bruinsma et al. [2006] for the November 2003 geomagnetic storm.

[15] After the main phase, when the geomagnetic activity weakened, the CHAMP density died out quickly from the largest enhancements at around 0600 UT on 8 November. During 0000–0800 UT on 9 November, the density was slightly higher than the corresponding quiet-time density. The density increased again at high latitudes in the Southern Hemisphere and then was gradually seen at low latitudes and also in the Northern Hemisphere in response to the beginning of the second geomagnetic storm, which occurred at 1000 UT on 9 November.

3.3. Comparison of GUVI $\Sigma O/N_2$ with CHAMP Neutral Density

[16] As shown in Figure 2, both $\Sigma O/N_2$ and mass density displayed remarkable changes in response to the severe geomagnetic storm of 7–9 November 2004. However, their respective structures with latitude and time are significantly different. Of particular interest are the high-latitude depletion and low-latitude enhancement seen in $\Sigma O/N_2$ throughout the storm period, in contrast to the enhanced but structured mass density extending from pole to pole. This is consistent with the findings of Lei et al. [2008a] and Crowley et al. [2008] in the studies of the thermosphere response to 9 day recurrent geomagnetic activity. Lei et al. [2008a] showed that 9 day perturbations in thermosphere mass density are clearly observed at all latitudes and well correlated with $Kp$. However, the $\Sigma O/N_2$ change observed by Crowley et al. [2008] is most pronounced at high latitudes, where it is anticorrelated with $Kp$, while the more modest response at lower latitudes is correlated with $Kp$.

[17] Temporal variations are also significantly different between thermosphere composition $\Sigma O/N_2$ and mass density. For the depletion in $\Sigma O/N_2$, it takes more than 12 h (in this fixed local time frame) to propagate gradually from high latitudes into the equatorial region during the main phase, although the time lag differs between northern and southern hemispheres because of the different offsets in geomagnetic pole positions. Conversely, mass density at 400 km increased from pole to pole within 3–4 h after the storm onset. Furthermore, remarkable density enhancements were observed promptly by CHAMP at Southern Hemisphere high latitudes in response to the sharp $B_z$ southward turning at 2300 UT on 7 November, while the response times of mass density enhancement at low latitudes occur within 2–3 h. This is consistent with the rapid response of the thermosphere to variations in the heating recently reported by Sutton et al. [2009]. The disparate response times between mass density and neutral composition during the storm are presumably related to the identification of change caused by a combination of thermal expansion and vertical winds.

[18] To interpret these contrasting characteristics of thermospheric neutral composition and mass density response to geomagnetic activity, the NCAR TIEGCM is used to simulate the global thermosphere/ionosphere response to the 7–9 November storm event and is described in the following section.

4. Simulations

4.1. Model Description

[19] The NCAR TIEGCM [Roble et al., 1988; Richmond et al., 1992] is a time-dependent, three-dimensional model that solves the fully coupled, nonlinear, hydrodynamic, thermodynamic, and continuity equations of the neutral gas self-consistently with the ion energy, ion momentum, and
ion continuity equations. The input parameters for the TIEGCM model are solar EUV and UV spectral fluxes, auroral particle precipitation, an imposed magnetospheric electric field, and the amplitudes and phases of tides from the lower atmosphere. In this study, ionospheric convection and auroral precipitation, two of the important upper boundary inputs to the TIEGCM, are specified from the outputs of the AMIE procedure \[Richmond and Kamide, 1988\]. The data input to AMIE in the study were obtained from various ground-based and satellite observations, and the details of the data used for AMIE for this event are given by Deng et al. [2009].

In the rest of the paper, we will look at the model fields on both constant-pressure surfaces and at constant altitudes as these two vertical coordinates best represent the GUVI and CHAMP observations, respectively. Thus, it is necessary to introduce the mathematics of the relationship between pressure levels and altitude in the model. The TIEGCM has 29 constant-pressure levels in the vertical, extending from approximately 97 km to 500–700 km in altitude. The total pressure \( P \) at each vertical coordinate pressure level \( Z \) is given by

\[
P = P_0 \exp(-7 - Z),
\]

where \( P_0 \) is a reference pressure surface \( (5 \times 10^{-4} \text{ mb}) \) at the lower boundary \( h_0 \) \((\sim 97 \text{ km})\). \( Z \) is the reduced height in units of pressure scale height \( H \) and ranges from \(-7.0 \) to \( 7.0 \) in the TIEGCM; that is, there are two vertical grid points per scale height in the model. These variables can be linked by the following equations from hydrostatic balance:

\[
Z = -7 + \int_{h_0}^{h} \frac{dh}{H},
\]

and

\[
h = h_0 + \int_{-7}^{Z} H dZ,
\]

where \( h \) stands for the geopotential height; the scale height \( H \) is equal to \( kT_n/mg \), with \( k \) being the Boltzmann constant, \( T_n \) the neutral temperature, \( m \) the mean molecular weight, and \( g \) the gravitational acceleration.

### 4.2. Data-Model Comparison

To compare the model with the observations, the corresponding \( \Sigma O/N_2 \) was obtained for the TIEGCM in the same way as it was for GUVI (see section 3), and the mass density from the TIEGCM was interpolated to a constant altitude of 400 km. Both \( \Sigma O/N_2 \) and mass density were then sampled along the GUVI and CHAMP orbits at about 1430 LT; they are depicted in Figures 3a and 3b.

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**Figure 3.** Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) (a) \( \Sigma O/N_2 \) sampled along the GUVI orbits, (b) mass density (in units of \( 10^{-12} \text{ kg/m}^3 \)), and (c) neutral temperature at 400 km sampled at CHAMP local time (around 1430 LT) on 6–9 November 2004. UT runs from right to left.
and $Z$ can be related to vertical and in Figure 3a in terms of both at high latitudes and its large enhancement due = 3 constant and mass density in responding to geomagnetic is too weak in the model over Zhang et al. $Z$ = 3 (Figure 5a) at 1430 LT during 6 to the magnetic $Z$ = 3 is opposite to that at a constant altitude of $Z$ on represents the neutral com-
and Mass Density on the and Mass Density = 3 surface, the mass density region [e.g., ratio on the = 3 surface and the constant altitude of $F$ = 3 band is Kil et al. A05303 Variation of (top) Joule heating and (bottom) hemispheric power from assimilative mapping of iono-
spheric electrodynamics in both hemispheres during 7–9 November 2004.

[22] As shown in Figure 3a, the TIEGCM model repro-
duces the hemispheric asymmetry and longitude structure of the quiet-time $\Sigma O/N_2$ measured by GUVI. It is also obvious that the model generally mimics the equatorward penetration of low $\Sigma O/N_2$ values from high latitudes to middle latitudes and large enhancements at low latitudes during the period of the geomagnetic disturbance. The hemispheric asymmetric response of O/N$_2$ to the magnetic storm, observed in both the GUVI data and the TIEGCM simulations, is likely caused by a seasonal effect and by larger Joule heating occurring in the sunlit Southern Hemisphere, as shown in Figure 4. There are many differences in the fine details between the simulations and GUVI data. For instance, the penetration of the $\Sigma O/N_2$ depletion in the TIEGCM does not extend as far into the equatorial region as it does in the GUVI observations. In addition, the longitudinal extension of high $\Sigma O/N_2$ band is narrower in the model than the one that is observed during 0400–0800 UT on 8 November; consequently, the enhancement of $\Sigma O/N_2$ is too weak in the model over central Europe compared with the GUVI data. By the way, the TIEGCM shows the $\Sigma O/N_2$ depletion extended from Southern Hemisphere to Northern Hemisphere over a narrow longitude range on 9 November 2004. However, in Figure 4, both Joule heating and particle energy from AMIE did not show a spike in the Southern Hemisphere.

[23] Figure 3b shows the mass density simulated by the TIEGCM and plotted in the same manner as the CHAMP data in Figure 2b. During quiet times, the model calculates a lower mass density at northern high latitudes than in the corresponding latitudes in the Southern Hemisphere, which is similar to the CHAMP observations. It is also clear that the TIEGCM mass density response to the storm initially occurs at all latitudes at about 1900 UT on 7 November, a few hours later than the CHAMP data showed. Strong enhancements of density in the model also occur during the main phase of the storm, with the increase being of the order of 100%–200%. However, the model does not reproduce the quick recovery of the density after the main phase that was observed by CHAMP.

[24] Simulated neutral temperature at 400 km along the CHAMP orbits at about 1430 LT is shown in Figure 3c. The storm-time temperature increases by more than 400 K in the southern high latitudes and by about 200 K at middle and lower latitudes. Mass density increases simultaneously with the storm-time enhanced temperatures. However, the detailed structure in the mass density response does not match the neutral temperature structure. The cause of these different spatial structures shown in the simulated temperature and mass density will be discussed later.

[25] In general, the TIEGCM reproduces the salient features observed by GUVI and CHAMP. These simulations will be analyzed further to elucidate the physical processes that govern the contrasting characteristics of thermospheric neutral composition and mass density response to geomagnetic activity.

4.3. Comparison of Modeled $\Sigma O/N_2$ and Mass Density at 400 km with O/N$_2$ and Mass Density on the $Z = 3$ Pressure Surface

[26] An obvious question can be raised from Figures 2 and 3: are the different spatial-temporal behaviors of the $\Sigma O/N_2$ and mass density in responding to geomagnetic activity the result of the different ways the $\Sigma O/N_2$ and neutral density are measured? In this subsection, we look at the variations of thermospheric composition and mass density on a constant pressure surface $Z = 3$ in the upper thermosphere (see equations (2) and (3)) using a format identical to that of Figures 2 and 3.

[27] It is immediately apparent that the O/N$_2$ ratio on the $Z = 3$ constant-pressure level (Figure 5a) has remarkable agreement with the $\Sigma O/N_2$ in Figure 3a in terms of both spatial and temporal variations. The equatorward depletion of O/N$_2$ at high latitudes and its large enhancement due to storm effects are also clearly seen. Figure 6a emphasizes the relationship between $\Sigma O/N_2$ (Figure 3a) and O/N$_2$ on pressure surface $Z = 3$ (Figure 5a) at 1430 LT during 6–9 November 2004. The correlation coefficient reaches a value as high as 0.97. Notably, the correlation coefficient calculated for the storm time (8–9 November) is 0.96. To some degree, this result directly confirms why $\Sigma O/N_2$ measured by GUVI has been widely used to investigate the neutral composition effects on electron density changes in the F$_2$ region [e.g., Kil et al., 2003; Zhang et al., 2004], even though the GUVI $\Sigma O/N_2$ represents the neutral composition measurement around 140–150 km. It also demonstrates that changes in $\Sigma O/N_2$ can be related to vertical and horizontal winds. The variations of the corresponding mean molecular weight on $Z = 3$ shown in Figure 4c are anticorrelated with those of O/N$_2$ and $\Sigma O/N_2$.

[28] Thermosphere mass density on pressure surface $Z = 3$ is given in Figure 5b. Obviously, the behavior of mass density on $Z = 3$ is opposite to that at a constant altitude of 400 km (Figure 3b). On the $Z = 3$ surface, the mass density during quiet time is larger than that during storm time. Even during quiet time, there are conspicuous differences between the $Z = 3$ surface and the constant altitude of 400 km in terms of the density hemispheric asymmetry. Larger mass density appears in the northern (winter) high
latitudes on $Z = 3$, which is expected from the requirement of pressure balance because the neutral temperature is lower in the northern polar region than in the south in November. It is also evident that the decrease of mass density on $Z = 3$ can be seen at all latitudes during the geomagnetically active period, with the largest depletions occurring during the main phase of the storm on 8 November and also during the second storm on 9 November. The relationship of mass density at 400 km and on pressure surface $Z = 3$ (shown in the contours of Figures 3b and 5b, respectively) is further demonstrated in Figure 6b. The mass density at 400 km is anticorrelated with the density on $Z = 3$, with a linear correlation coefficient of $-0.93$.

4.4. Analysis of the Processes Causing Changes in Mass Density on the $Z = 3$ Pressure Surface

Vertical winds are the only way to change the neutral composition ratio and mean molecular weight $m$ on a constant-pressure surface. These changes are then redistributed by horizontal neutral winds and molecular diffusion [Burns et al., 2006]. Furthermore, thermal expansion or contraction of the atmosphere changes the total neutral number density $n$ on a pressure surface, as indicated by the ideal gas equation in which $P = nKT_w$, where $P$ is the pressure at the considered surface and $T_w$ is neutral temperature. For simplicity, we refer to the above two processes as the wind effect and the temperature effect in the rest of the paper. In addition, the mass density on a constant pressure surface $\rho_z$ can be expressed as

$$\rho_z = n \times m.$$  \hspace{1cm} (4)

According to this equation, the temperature effect and wind effect responsible for the mass density change on a constant-pressure surface are separable and can be investigated through model simulations.

Figures 7–9 display polar contours of mass density $\rho_z$, mean molecular weight $m$, and total neutral number density $n$ on the $Z = 3$ surface in the Northern Hemisphere. Each of Figures 7–9 represents separately the various cases for the quiet time (0600 UT on 7 November) and the initial (2000 UT on 7 November), main (0600 UT on 8 November), and recovery (1000 UT on 9 November) phases of the 7–9 November geomagnetic storm. As shown in Figure 7, the mass density on the $Z = 3$ pressure surface is larger on the nightside than on the dayside during both quiet and storm times. During storm times, the density decreases by an order of 10%–20%, with some indication of greater declines on the nightside and in the polar regions. Note that the density pattern during the main phase (Figure 7c) is complex, primarily related to its small-scale spatial structure.

The mean molecular weight $m$ response to the storm on the $Z = 3$ surface is given in Figure 8, which
molecular weight is very small (Figure 8). However, at high latitudes and in the midnight-to-dawn sector, the total number density generally shows a larger decline (20%–30%) than the mass density. This is consistent with the mean molecular weight enhancement shown in Figure 8 offsetting the number density decline, resulting in only a modest decline in mass density. This is not surprising because the change in mass density on a constant-pressure surface must be related to both a temperature effect (change in number density) and a wind effect (change in molecular weight) according to the ideal gas law and equation (4).

[33] The decrease of total neutral number density on $Z = 3$ is explained by the enhancement of neutral temperature $T_n$ on the same pressure surface during the storm, when a large amount of Joule heating and particle precipitation occurred in the high-latitude atmosphere. As shown in Figure 10, a larger increase of $T_n$ corresponds to a stronger decrease of total number density, which is obvious on the basis of the ideal gas law $P = n k T_n$. During the main phase, $T_n$ shows a strong enhancement in the polar region (along the band of sunward neutral wind flow; Figure 10c) where the total neutral number density has a corresponding depletion (Figure 9c); however, the profound increase in the mean molecular weight does not occur exactly at the same region because of the redistribution of the N$_2$-rich air by strong horizontal wind advection in the dawn–dusk sector. A similar situation can be seen during the recovery phase. A larger increase in $T_n$ occurs in the 0600–1400 LT sector (Figure 10d), while a strong enhancement in the mean molecular weight occurs in the 0200–0300 LT sector (Figure 8d), resulting from strong sunward flow in neutral wind toward this sector when the IMF was weakly negative $B_y$ and positive $B_z$ (Figure 1). Referring back to Figure 7, it is interesting to note that a decrease of mass density (~10%–15%) is seen at low latitudes even during the initial phase, whereas the change in mean molecular weight is negligible.

[34] In summary, at low latitudes, the temperature effect is more efficient and quicker to alter the mass density on a constant-pressure surface during a period of elevated geomagnetic activity, and this is manifested through changes in the neutral number density. The wind effect alters the mass density at high latitudes, where the induced decline in mass density resulting from the temperature effect is somewhat offset by the enhancement in mean molecular weight due to the wind effect, particularly in the dawn–dusk sector. This molecular weight change is directly related to composition change, enabling observed O/N$_2$ changes on a constant-pressure surface to indicate wind effects and consequently molecular weight changes. Overall, both the temperature and wind effects can change the mass density on the $Z = 3$ pressure surface with magnitudes ranging from 10% to 30% during the storm time.

4.5. Interpretation of the Variations of Mass Density at the Satellite Altitudes

[35] We will now examine the variations of mass density on a constant height surface where the CHAMP satellite makes in situ measurements. Figure 11 illustrates the mass density at 400 km during the quiet time and initial, main, and recovery phases of the 7–9 November geomagnetic storm. The percentage change relative to the quiet-time density is also provided in Figures 11c and 11d. Distinct
differences are clearly seen between the mass density at 400 km and the mass density on the 
\(Z = 3\) pressure surface (Figure 7) \((Z = 3\) corresponds to an altitude of about 400 km). The density at 400 km is generally larger on the dayside than at night, opposite to the diurnal variation on the 
\(Z = 3\) pressure surface. On the other hand, instead of the decrease of mass density on the 
\(Z = 3\) surface during storm time, the density changes at 400 km are positive everywhere, with the maximum magnitudes of 100\%, 220\%, and 100\% during the initial, main, and recovery phases, respectively. Thus, the negative correlation between the density at 400 km and the density on 
\(Z = 3\) prevails at all local times.

These differences in storm-time response can be explained by using the schematic diagram in Figure 12 and relating the different response to the difference between altitude and pressure surfaces. The mass density at the satellite altitude during quiet time, \(\rho^q_{s}\), corresponds to mass density, \(\rho^q_{Z}\), on a certain pressure surface \(Z\); that is, \(\rho^q_{Z} = \rho^q_{s}\). This is position A in Figure 12. During storm time, the mass density on this pressure surface, \(\rho^s_{Z}\), will change, as discussed in section 4.4, as will its corresponding altitude. This is position B in Figure 12. Applying the ideal gas law and combining equation (4) yields the relationship

\[
\rho^s_{Z} = \frac{\bar{m}^q_{Z}}{\bar{m}^s_{Z}} \frac{T^q_{n}}{T^s_{n}} \rho^q_{Z},
\]

where \(T^q_{n}\) and \(T^s_{n}\) are the neutral temperatures during quiet and storm time, respectively, and \(\bar{m}^q_{Z}\) and \(\bar{m}^s_{Z}\) are the corresponding mean molecular weights on pressure surface \(Z\).

On the other hand, with the help of the hydrostatic law and under the assumption that the upper thermosphere temperature is exospheric and therefore isothermal, the mass density \(\rho^s_{s}\) at the fixed satellite altitude during storm time (i.e., position C in Figure 12) can be expressed as

\[
\rho^s_{s} = \frac{\bar{m}^q_{s}}{\bar{m}^s_{Z}} \rho^s_{Z} e^{\Delta Z},
\]
where $\Delta Z$ stands for the change of the pressure surface from quiet time to storm time for the constant altitude and can be computed from equation (2); that is, $\Delta Z = Z(\text{quiet}) - Z(\text{storm})$; $m_s^q$ is the mean molecular weight at the satellite altitude during storm time.

Substituting equation (5) into equation (6), we obtain

$$\frac{\rho_s}{\rho_h} = \frac{m_s^q}{m_s^h} \frac{e^{\Delta Z}}{T_n^s/T_n^h}, \quad \text{(7)}$$

which is similar to the formula derived by Prölss [2004, p. 129] when he explained the diurnal variations of neutral temperature and density driven by solar radiation.

It is obvious that $T_n^s/T_n^h > 1$ and $e^{\Delta Z} > 1$ in equation (7) during geomagnetic storms, considering the overall increase of neutral temperature. At the same time, $m_s^q/m_s^h$ is evidently close to 1 at low latitudes and is comparable to $T_n^s/T_n^h$ at high latitudes (see Figure 8). As mentioned by Prölss [2004], the exponential factor $e^{\Delta Z}$ already begins to dominate at an altitude of two scale heights above the peak heating altitude, thereby resulting in a net increase in mass density during storm time compared to that during quiet time (i.e., $\rho_s^q/\rho_h > 1$) at a constant altitude. An example shown in Figure 13 emphasizes the changes in neutral temperature and pressure surface at the equator for a constant altitude (400 km) at 1430 LT during storm time compared with those during quiet time. At this local time, neutral temperature increases from the quiet time value of about 1000 K to 1100–1250 K during storm time, leading to a change of the $T_n^s/T_n^h$ ratio ranging from 1.1 to 1.3 (Figure 13a). It can also be seen that the pressure level $Z$ at 400 km, calculated from equation (2), varies from 3.2 during quiet time to 2.2–2.7 during storm time. As a result, the exponential factor $e^{\Delta Z}$ is of the order of 1.3–3.2, that is, much larger than $T_n^s/T_n^h$.

Now we are in a good position to explain the variation of mass density at a constant altitude. As illustrated above, the increase of neutral temperature during geomagnetic storms results in the accumulative change of all scale heights between the heat source and the considered altitude, that is, the expansion of the thermosphere, and consequently a higher pressure (lower $Z$ value) for a fixed altitude. The mass density increases exponentially with an increase in the neutral gas pressure, and thus there is a greater mass density at a fixed altitude during a storm. That is why the increase in neutral temperature of less than 30% can result in a strong enhancement in mass density, on the order of 100%–200% (Figure 11). In addition, the contrasting behavior in mass density at a constant pressure and constant altitude in terms of hemisphere asymmetry (Figures 3b and 5b) and diurnal variation (Figures 7 and 10) during quiet time can also be interpreted this way.

Figure 8. Same as Figure 7, but for the mean molecular weight (in units of $1.66 \times 10^{-27}$ kg).
Temperature effects and wind effects on mass density at a fixed altitude are not as separable as on a constant-pressure surface. The mean molecular weight at a fixed altitude can change due to thermal expansion or by a redistribution of neutral constituents by winds. Furthermore, the number density at a fixed altitude is dependent on the scale height, which is a function of mean molecular weight and temperature. Thus, mass density changes at a fixed altitude constitute a mixture of temperature and wind effects.

For instance, one may notice that enhancements in the temperature at a constant altitude do not always show a one-to-one correspondence with enhancements in mass density at a constant altitude. As shown in Figure 13, neutral temperatures are strongly enhanced at around 1000 UT on 9 November, whereas pressure level \( Z \) or \( e^{\frac{Z}{H}} \) does not show the corresponding change, resulting in little change in mass density at 400 km. This is because the pressure level \( Z \) is the integral of scale heights from a reference altitude to the satellite altitude, as expressed in equation (2), and those increases in mean molecular weight offset the effects of neutral temperature increases. This effect can clearly be seen at high latitudes during the main phase of the storm when contrasting the mass density response at 400 km in Figure 11c with the temperature response at 400 km in Figure 10c. As illustrated in Figure 10c, the strongest increase in neutral temperature is found in the polar regions (along the band of sunward neutral wind flow). If mass density change is thought to result solely from neutral temperature change, the enhancement in mass density should be in excess of 220%. However, the mass density only shows a moderate enhancement (60%). The actual response is tempered by an increase of mean molecular weight in the same region, as illustrated in Figure 8.

Figure 14 shows mass density variations in the same format as Figure 11 but considering only barometric motion in the model density calculation. Here, mean molecular weight values are fixed at their quiet time values, and the height is recalculated using equation (3). Note that this approach is a first-order approximation to emulate barometric effects on the mass density because variations of neutral temperature can be influenced by the wind effect to some extent. It can be clearly seen that the density changes show good positive correlation with the temperature changes, as indicated by Figures 9 and 10. The differences in mass density changes between Figures 11 and 14 reveal the wind effects (i.e., neutral composition or mean molecular weight changes) on the mass density. Comparing the density variations in Figure 14 with those in Figure 11, we can see that 20% increase in mean molecular weight (Figure 8) at high latitudes, because of upwelling motion, results in an offset in mass density being as large as 150% during the main and recovery phases, while a 5% decrease in mean molecular weight due to downwelling motion at low latitudes (Figure 8) leads to an additional enhancement of...
∼40% in mass density with respect to the temperature effects.

The offsetting nature of temperature and mean molecular weight changes in modifying the mass density response were similarly discussed in section 4.4 for constant-pressure surfaces. However, as expressed in equation (5), on a constant-pressure surface the offsetting effect is a local and linear multiplication factor. For a constant altitude, the offsetting effect is amplified because of the cumulative effect of integration over many scale heights that contribute to the $e^{\Delta Z}$ term in equation (7), as well as the multiplying factor of $m_h/m_z$. For instance, an increase of 10% in mean molecular weight (i.e., $m_h/m_z \approx 1.1$) with constant temperature would lead to an offset change in mass density at constant altitude of 35% because $e^{\Delta Z} = 0.6$ if there are five scale heights between the satellite altitude and the heat source. That is, the contribution of mean molecular weight to mass density at a constant altitude can be significantly amplified because of the exponential relationship between mass density and $\Delta Z$. This differs from the situation on the constant-pressure surface, where the change in mass density is linearly correlated with the change in mean molecular weight on that pressure surface. Thus, the moderate response of a mass density enhancement at a fixed altitude to a significant increase in neutral temperature is caused by an offsetting increase in mean molecular weight that modifies the cumulative effect of the scale height.

5. Discussion

As illustrated through TIEGCM simulations, the thermosphere mass density response at a constant altitude during strong geomagnetic activity is more complex than on a constant-pressure surface because it depends on the cumulative effects of scale height changes between the altitude of study and the altitude of energy deposition, thermosphere state conditions that determine the initial scale height, and vertical and horizontal winds that drive composition and temperature changes. The impetus of this paper is to investigate whether combining simultaneous observations of $\Sigma$O/N_2 by GUVI and mass density by CHAMP can provide value-added information in understanding the mass density response during a geomagnetic storm. We established in the previous section that mass

Figure 10. Polar plots (latitude and local solar time) of neutral temperature (K) on the $Z = 3$ pressure surface overlaid by the neutral winds (m/s) in the Northern Hemisphere for the following UTs: (a) 0600 UT on 7 November, quiet time; (b) 2000 UT on 7 November during the initial phase; (c) 0600 UT on 8 November during the main phase; (d) 1000 UT on 9 November 2004 during the recovery phase of the 7–9 November storm. The four concentric rings in Figures 10–10d represent lines of latitude at 80°N, 60°N, 40°N, and 20°N, and the outer circle of these plots is at 2.5°N geographic and centered on the geographic pole.
density measured at a fixed altitude is influenced by both temperature and wind effects. If the wind effect were negligible, the mean molecular weight and neutral density change would be dependent only on temperature effects. Under this condition, the mass density change and the temperature change would be spatially and temporally correlated but tempered by the change in mean molecular weight created by thermal expansion. If the wind effect were comparable to the temperature effect, mass density changes would be modified further, by vertical winds affecting the mean molecular weight, and the spatial and temporal correlation of mass density with temperature would most likely diminish as horizontal winds redistribute the mean molecular weight over time and space. The TIEGCM modeling results allow for this behavior to be evaluated. Referring back to Figures 3b and 3c, the modeled mass density and temperature show only the coarsest level of correlation, in that the temperature and mass density both increased over the 2 day period and over the entire globe. On scales less than 1 day and over more confined regions, the mass density and temperature response show little correlation. For example, the largest enhancement in modeled mass density occurs in southern Asia around 1000 UT on 8 November, while no corresponding strong temperature increase is found in this region. As shown in Figure 3a, modeled \( \Sigma O/N_2 \) enhancement takes place in this area, or equivalently a decrease in mean molecular weight (Figure 5c). Consequently, this results in a significant enhancement in mass density. Conversely, the strongest enhancement in neutral temperature can be seen at high latitudes in the South Atlantic Ocean during 1600–2000 UT on 8 November, but the increase in mass density is not as significant as expected from just the temperature enhancement. This region is consistent with the \( \Sigma O/N_2 \) depletion seen in Figure 3a, that is, an increase in mean molecular weight, and subsequently the increase in mass density is lessened. Thus, changes observed in \( \Sigma O/N_2 \) can be used to identify regions of change in mean molecular

**Figure 11.** Polar plots (latitude and local solar time) of TIEGCM mass density (in units of \( 10^{-12} \text{ kg/m}^3 \)) at 400 km in the Northern Hemisphere for the following UTs: (a) 0600 UT on 7 November, quiet time; (b) 2000 UT on 7 November during the initial phase; (c) 0600 UT on 8 November during the main phase; (d) 1000 UT on 9 November during the recovery phase of the 7–9 November 2004 storm. The outer circle of these plots is at 2.5°N geographic and centered on the geographic pole. The lines with numbers in panels Figure 11b–11d stand for the percentage relative to the quiet values in Figure 11a, \([\text{storm} - \text{quiet}]/\text{quiet} \times 100\%\).
weight caused by winds, and the impact on the mass density response is significant.

Figure 2 provides the actual simultaneous and coincident observations of $\Sigma$O/N$_2$ from GUVI and fixed-altitude mass density from CHAMP for the 7–9 November 2004. Clearly Figure 2a shows significant depletions of $\Sigma$O/N$_2$ from 0000 to 1000 UT on 8 November, and this is interpreted as being caused by vertical transport across pressure surfaces through vertical winds and redistributed in latitude by horizontal winds over time, as confirmed by the TIEGCM simulations. Based on the $\Sigma$O/N$_2$ observations, an increase in mean molecular weight will occur in regions of $\Sigma$O/N$_2$ depletions and a decrease in mean molecular weight in regions of $\Sigma$O/N$_2$ enhancements. The simulations and discussions in section 4.5 then suggest that the mass density at a fixed altitude in Figure 2b would reflect this structure. Even though the mass density increased from pole to pole during the storm, there is moderation in thermosphere mass density response in Figure 2b from 0000 to 1000 UT on 8 November, where for latitudes below 40° the mass density response is greater than at higher latitudes, indicative of the changes in mean molecular weight implied by the $\Sigma$O/N$_2$ observations. However, the response is very structured, and no clear systematic relation is found. This is most likely due to the variable structure in neutral temperature that makes the potential correlation between mass density and neutral composition (or mean molecular weight) complicated. Conversely, this implies that attempts to derive exospheric temperature from mass density measurements at a constant altitude during geomagnetic storms can be in significant error if mean molecular weight changes are not properly represented.

It is important to point out the change of O/N$_2$ is nonlinear with that of the mean molecular weight. As shown in Figures 2a and 3a, the $\Sigma$O/N$_2$ ratio differs by a factor of 3–4 between northern and southern midlatitudes in both the GUVI data and TIEGCM simulations during the first half of 8 November. However, the mean molecular weight differs by a few percent (Figure 5c). Hemispheric changes in mean molecular weight are slightly higher in summer than in winter (the opposite of O/N$_2$), but a higher mean molecular weight reduces the scale height. As the temperature also has a similar summer-to-winter gradient and acts to increase the scale height, these two effects tend

Figure 12. Schematic explanation of the changes of mass density at the constant-pressure surface (pressure is $P_2$) and constant altitude (satellite altitude). A satellite flying at a constant altitude (dashed line) measures the density $\rho_Z$ at a certain pressure surface $Z$ during quiet time (point A), while it would measure the density on a different pressure surface ($P_1 > P_2$), $\rho_H$, during storm time (point C), as a result of the expansion of the thermosphere due to the increase of neutral temperature during storm time ($T_n^s > T_n^q$). $\rho_Z$ represents the mass density on the pressure surface $Z$ but during storm time (B), and $\Delta Z$ represents the change in the pressure levels for the constant altitude between quiet and storm time.
Figure 13. Variations of (a) neutral temperature (solid line, left-hand scale) and the ratio to quiet-time temperature (dashed line, right-hand scale) and (b) pressure surface levels (solid line, left-hand scale) at 400 km calculated from equation (2) and the exponential factor $e^{\Delta Z}$ (dashed line, right-hand scale), where $\Delta Z = Z(\text{quiet}) - Z(\text{storm})$. The thin dashed lines show the quiet-time temperature and pressure level, respectively. The plots are for the geographic equator of the CHAMP orbits at about 1430 LT during 7–9 November 2004.

Figure 14. Same as Figure 11, but only the barometric motion is considered in the density calculation, and mean molecular mass is taken from quiet time. See the details in the text.
to cancel each other out and result in comparable neutral densities over these regions.

[49] Thermosphere mass density and composition changes are observed concurrently by CHAMP and TIMED for sunlit conditions only, but the TIEGCM simulations in Figures 6–10 reveal greater wind effects on the nightside than dayside. Figure 15 depicts CHAMP mass density at 400 km along with TIEGCM mass density, neutral temperature at 400 km, and mean molecular weight on \( Z = 3 \) on the nightside (around 0230 LT) during 6–9 November of 2004. The TIEGCM simulations are sampled at CHAMP local time. UT runs from right to left. Neutral density and mean molecular weight are in units of \( 10^{-12} \) kg/m\(^3\) and \( 1.66 \times 10^{-27} \) kg, respectively.

[50] The wind effects on the mass density are also present on the nightside. Again, the small-scale variation in the nighttime mass density (Figure 15b) show little correlation with the neutral temperature (Figure 15c) on 8 November, particularly at high latitudes in the Southern Hemisphere. Similar to the situation on the dayside, the model indicated a weak increase in the nighttime neutral temperature associated with the TADs. However, both the CHAMP observations and the TIEGCM simulations show comparable TAD perturbations in neutral density at low latitudes to those at high latitudes, which is consistent with the combining effects of the decrease of mean molecular weight at low latitudes and increase at high latitudes (Figure 15d).

Figure 15. (a) CHAMP mass density at 400 km, (b) TIEGCM mass density and (c) neutral temperature at 400 km, and (d) TIEGCM mean molecular weight on \( Z = 3 \) on the nightside (around 0230 LT) during 6–9 November of 2004. The TIEGCM simulations are sampled at CHAMP local time. UT runs from right to left. Neutral density and mean molecular weight are in units of \( 10^{-12} \) kg/m\(^3\) and \( 1.66 \times 10^{-27} \) kg, respectively.

Similar TAD propagation was reported by Lei et al. [2008b] for the December 2006 storm. These TAD features were also registered in the CHAMP data; however, no clear TAD signature was seen in the CHAMP observations before 0400 UT on 8 November.
The nightside response is even more dramatic than the dayside response. This can be attributed to the greater number of scale heights between the source and the fixed altitude owing to the quiet-time thermosphere temperatures being lower at night than in the day.

6. Conclusion

[51] In this study, we use nearly simultaneous columnar composition ratio, $\Sigma$O/N$_2$, observed by GUVI and mass density measured by CHAMP at 1430 LT to study the thermosphere response to the 7–9 November 2004 geomagnetic storm. Both $\Sigma$O/N$_2$ and mass density profoundly changed during this severe geomagnetic storm. Simulations from the NCAR TIEGCM driven by AMIE were compared with these observations to help interpret the observed features and determine whether value-added information could be retrieved to interpret the CHAMP mass density response to the geomagnetic storm from concurrent observations of $\Sigma$O/N$_2$. High-latitude depletion and low-latitude enhancement in $\Sigma$O/N$_2$ were observed throughout the storm period, particularly during the main phase, while neutral mass density at 400 km increased from pole to pole shortly after the storm onset, with the strongest enhancement being of the order of 200%–300% during the main phase.

[52] The contrasting characteristics of storm-time $\Sigma$O/N$_2$ and the mass density response revealed by GUVI and CHAMP observations were reasonably well produced by the TIEGCM simulation once the model output was organized in the same manner as the observations. Furthermore, TIEGCM results were analyzed on a constant-pressure surface near 400 km and on a constant-height surface at 400 km to best interpret the response of $\Sigma$O/N$_2$ and mass density, respectively. On a constant pressure surface of $Z = 3$, the TIEGCM simulation demonstrated good correlation between $\Sigma$O/N$_2$ and O/N$_2$ and that changes in the ratio are caused by transport of composition across pressure surfaces by winds. A relation for the mass density change on the same constant-pressure surface illustrated the linear dependence of its storm-time response to changes in mean molecular weight and temperature. Because O/N$_2$ changes are directly related to mean molecular weight changes, the wind effect on mass density change for a constant-pressure surface can be separated from the temperature effect. It is found that the wind effect at storm time increases the mass density on a constant-pressure surface at high latitudes acting to offset the induced decline in mass density resulting from the temperature effect. Overall, both effects can change the mass density on the $Z = 3$ pressure surface with magnitudes ranging from 10% to 30% during the storm time.

[53] To properly interpret the CHAMP mass density response to the geomagnetic storm, the TIEGCM simulation on a constant-height surface was evaluated. Simulations indicate the thermosphere mass density response at a constant altitude of 400 km during strong geomagnetic activity is more complex than on a constant-pressure surface because it depends on the cumulative effects of scale height changes between the altitude of study and the altitude of energy deposition, thermosphere state conditions that determine the initial scale height, and vertical and horizontal winds that drive composition and temperature changes. Thus, wind and temperature effects are not easily separable on a constant-height surface.

[54] The increase in scale height during the storm is partly due to neutral temperature enhancements. However, the wind effect can change the mean molecular weight during the strong geomagnetic activity period. This change in mean molecular weight also contributes to the change in scale height and has an important impact on the response of the thermosphere mass density at a constant altitude that is multiple scale heights away from the heat source. The simulations show that a change in mean molecular weight can cause significant deviations (as large as 150% at high latitudes and 40% at low latitudes at 400 km) from a mass density pattern that would result solely from neutral temperature changes, particularly at high latitudes. Thus, this study finds that mean molecular weight changes primarily caused by winds can be as important as temperature changes in determining the mass density response at a constant height during strong geomagnetic activity. Conversely, this implies that estimating exospheric temperature from mass density observations under storm conditions at a constant altitude is problematic as composition changes due to winds can significantly alter the mass density response.

[55] GUVI $\Sigma$O/N$_2$ observations provide information on mean molecular weight changes that modify the mass density response when contrasted with simultaneous CHAMP mass density observations. The observed decrease (increase) in $\Sigma$O/N$_2$ (mean molecular weight) at high and middle latitudes and increase (decrease) in $\Sigma$O/N$_2$ (mean molecular weight) are indicated in the CHAMP mass density response with greater storm-time mass density at lower latitudes are indicated than at higher latitudes. However, the response is very structured, and no clear systematic relation between the changes in mass density and neutral composition is found, as the temperature is presumably highly structured as well. Finally, it should be noted that although $\Sigma$O/N$_2$ and mass density simultaneous observations are few, understanding the $\Sigma$O/N$_2$ response to storms on a statistical basis will help to better interpret the mass density response when wind and temperature effects are present.

[56] Acknowledgments. This work was supported by the AFOSR MURI Award FA9550-07-1-0565. A.B. was supported by the Center for Integrated Space Weather Modeling (CISM), which is funded by the STC program under agreement ATM-0120950. G.L. was supported in part by the NASA Heliophysics Guest Investigators program. Y.D.’s work was supported by the NSF through grants ATM-0823689 and the University of Colorado through a CIRES fellowship. J.L. thanks Wenbin Wang for his useful discussions and Yongliang Zhang for his assistance in processing the GUVI data, and also Jeffrey M. Forbes and Eric K. Sutton for providing the CHAMP data. The GUVI data are provided through support from the NASA MO&D program. The GUVI instrument was designed and built by the Johns Hopkins University Applied Physics Laboratory. The Principal Investigator is Andrew B. Christensen and the Chief Scientist and co-Principal Investigator is Larry J. Paxton.

[57] Wolfgang Baumjohann thanks the reviewers for their assistance in evaluating this manuscript.

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